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Institut de Física Corpuscular (CSIC-UV)

Dark matter searches with the KM3NeT neutrino telescope

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CERTIFICAN,

Que la presente memoria, “Dark matter searches with the KM3NeT neutrino telescope”, ha sido realizada bajo su dirección en el Instituto de Física Corpuscular (Centro Mixto Universidad de Valencia - CSIC) por Adrian Šaina y constituye su Tesis Doctoral para optar al título de Doctor por la Universitat de València una vez cursados los estudios en el Doctorado en Física. Y para que conste, en cumplimiento de la legislación vigente, firman el presente certificado en Paterna, el 18 de julio de 2025.

Dr. Juan de Dios Zornoza Gómez

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Abstract

The particle nature of dark matter is one of the biggest mysteries in physics today. Experimental approaches to detect the dark matter particle can be divided into production efforts at accelerators, direct searches, and indirect searches. In this thesis, dark matter is indirectly searched for with the first data of the KM3NeT neutrino telescope. KM3NeT, currently under construction, has been taking data in partial configurations with 8, 19 and 21 detection units since 2021. In this work, the data sets of these partial configurations are analysed in search for neutrinos produced by dark matter annihilations in the Galactic Centre and in the Sun. No signal associated with neutrinos from dark matter annihilations in the Galactic Centre was found, resulting in limits on the thermally-averaged annihilation cross section of dark matter particles, $\langle\sigma v\rangle$. Similarly, a null observation in the direction of the Sun resulted in a limit on the WIMP-nucleon scattering cross section, $\sigma_{SD/SI}$. The uncertainties associated with theoretical assumptions made to estimate the signal flux, and uncertainties related to unconstrained detector properties are placed into context in terms of their impact on the constraining power of KM3NeT to the dark matter annihilation cross section. Finally, an alternative methodology to estimate the limits on $\langle\sigma v\rangle$ is presented, which allows for the combination of data sets from different experiments, including γ -ray telescopes.

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Introduction

The research conducted in this thesis aims at detecting signatures of dark matter annihilations in the form of secondary neutrinos using the KM3NeT (kilometre-cubed) neutrino telescope.

The existence of dark matter has been postulated to explain astrophysical phenomena at various scales, from the motions of individual stars in galaxies, to the observations of large-scale structure in the Universe. So far, only the indirect gravitational effects of dark matter on the surrounding baryons have been observed; the nature of dark matter, whether it is composed of fundamental particles or more exotic objects such as primordial black holes, remains unknown. This thesis will focus on the search for particle dark matter. Different strategies to detect the dark matter particle are employed in the field: attempts to produce dark matter particles at colliders, attempts to detect the scattering of dark matter particles off baryons in direct detection experiments, and efforts to detect the products of dark matter annihilation or decay at indirect detection experiments. An alternate indirect detection method consists of studies of the effect of dark matter particle presence on stellar evolution [1].

The primary physics goals of the KM3NeT neutrino telescope are the detection of astrophysical neutrinos and the determination of the neutrino mass ordering. To accomplish this, two underwater Čerenkov telescopes are currently under construction in the Mediterranean Sea: KM3NeT/ARCA (Astroparticle Research with Cosmics in the Abyss) and KM3NeT/ORCA (Oscillation Research with Cosmics in the Abyss). The capability of the detectors to detect neutrinos from GeV to PeV energies allows for the indirect search

for dark matter particles in a vast region of the parameter space: searches for thermal weakly interacting massive particles (WIMPs) in the GeV-TeV range, and searches for alternative, lighter or heavier dark matter candidate particles is possible with the instrument. The Galactic Centre and the Sun are the two sources with the largest predicted flux at Earth of neutrinos produced by dark matter annihilations.

In this thesis, neutrinos produced by dark matter particles are searched for towards the Galactic Centre and the Sun. Data sets of existing configurations of the ARCA detector in the time period between 2021-2023 are used. Chapter 2 describes the motivation for conducting searches for dark matter particles, including an overview of the current landscape of dark matter searches in the community and the possible WIMP theoretical models that have not been excluded by current searches. The principles of neutrino detection and the KM3NeT detector are described in Chapter 3. This includes a description of the detection principle of neutrinos, its interactions and the phenomenon of neutrino oscillations, and the relevant production mechanisms of high energy neutrinos that are considered a source of background when searching for neutrinos from dark matter annihilations. The KM3NeT detector is described in detail: the detection elements, the detector simulation, event reconstruction and detector calibration. Chapter 4 details the analysis method: the modeling of the spatial distribution of WIMPs in the Galaxy and the computation of the neutrino spectra produced by the annihilation of WIMPs into secondary particles. The uncertainties associated with the assumed distribution of WIMPs in the galaxy are described, along with the method of scanning the WIMP parameter space by creating neutrino spectra for WIMPs of different masses annihilating into a number of different annihilation channels. What follows is a description of the methodology used in order to define an event selection and produce signal expectations at the detector for each signal hypothesis. The likelihood method and the statistical approach followed to obtain limits and sensitivities to the dark matter annihilation cross section are described next. Finally, Chapter 5 reports the results of the search for dark matter particles with the KM3NeT/ARCA detector, followed by conclusions in Chapter 6.

2

The motivation to search for dark matter

The following chapter describes the observational evidence for the existence for dark matter in Section 2.1, followed in Section 2.2 by a description of the possible dark matter candidates. Section 2.3 describes the current approaches employed to observe dark matter particles, followed by a discussion on the possible extensions of the Standard Model that provide a viable candidate for the weakly interacting massive particles.

2.1 The observational evidence for dark matter

The existence of a large, unaccounted for amount of missing mass in the Universe has been postulated as soon as the 1930s. Fritz Zwicky estimated the amount of matter present in the Coma galaxy cluster using the virial theorem [2] [3]: he counted roughly ~ 1000 individual galaxies in the system, and computed the total mass of the luminous matter based on the amount of light emitted by individual galaxies. He compared this value to the mass obtained from the observations of rotational velocities of galaxies within the system, and concluded that the amount of mass is at least 400 times greater than the mass expected from the observed luminosity. He coined the term “dark matter” when referring to the non-luminous matter present in the cluster. The study did not garner serious attention in the scientific community and was not revisited until the 1970s, when Vera Rubin and Kent Ford studied the rotational velocities of stars in the Andromeda

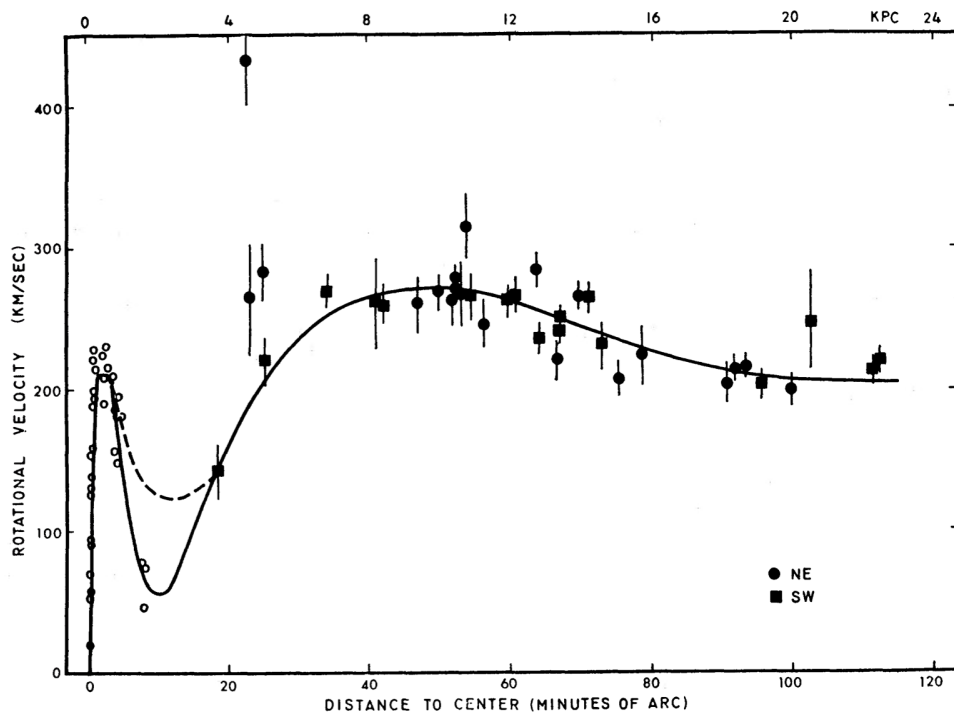


FIGURE 2.1: The observations of rotational velocities of emission regions of the Andromeda galaxy, observed by Vera Rubin and Kent Ford [4]. The solid line shows a polynomial fit to the rotational velocities, used to integrate the velocity distribution and obtain an estimate of the total mass of the galaxy. The dashed line shows an alternative fit, with a larger minimum velocity in the innermost regions of the galaxy.

galaxy [4]. Observations of H_α lines, among others, allowed for the determination of radial velocities from the Doppler shifts of the emission lines, which were then converted into rotational velocities under the assumption of circular motion. A disk model was assumed in order to integrate the mass distribution up to 24 kpc, and a polynomial was fitted to the velocity measurements in order to integrate the distribution, as shown in Fig. 2.1. The velocity distribution did not follow the expected shape, showing a significant amount of mass at large distances from the centre of the galaxy, which also resulted in an unexpected behaviour of the mass distribution, $M(R)$, indicating the presence of an extended halo of non-luminous matter.

Vera Rubin continued her observations of galactic dynamics, providing further evidence for mass distributions of various galaxies not following the pattern expected from observations of luminous matter [5, 6]. Her pioneering work paved the way for future studies on dark matter. Since then, the effects of dark matter on luminous matter have been observed at various scales, which will be described in following subsections.

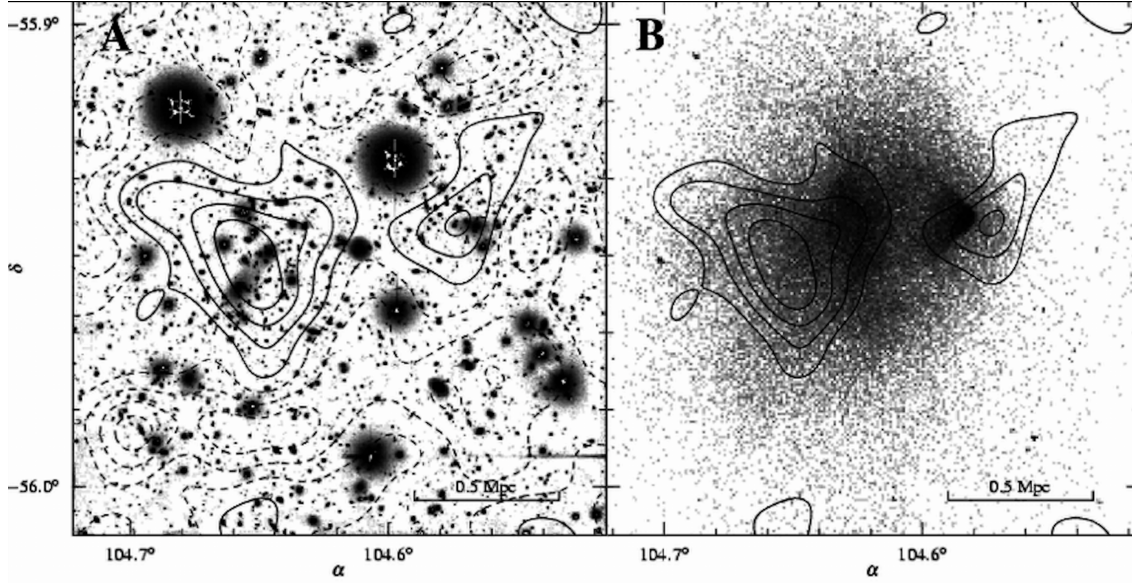


FIGURE 2.2: Left: shown in greyscale, an image of the Bullet Cluster taken in the infrared band with the Very Large Telescope used to measure the shapes of background galaxies and to trace the mass distribution. The surface mass density is represented with solid contours, where each contour represents a change in $2.8 \cdot 10^8 M_{\odot} \text{kpc}^2$ (dashed contours show negative mass with respect to the mean mass in the image). Right: Grayscale representation of the Chandra X-ray image, overlaid with the mass density contours. Taken from [8].

2.1.1 The Bullet cluster

An important evidence for dark matter comes from the observation of two interacting galaxy clusters, 1E0657-558 and 1E0657-56, the latter famously named the Bullet cluster. The cluster was observed in X-rays in the 1990s [7], and the extremely high temperatures observed in the system were an indicator of a large gravitational potential. In ref. [8], the mass of the system was traced with weak lensing reconstruction. Weak lensing utilises the phenomenon of light bending by a gravitational potential, predicted in General Relativity, to estimate the mass generating the potential. The images of objects located behind the gravitational potential will be enlarged, distorted, and deflected away from the object in the foreground. The distortion manifests as a tangential stretching of the image of the background object towards the centre of the potential, an effect called gravitational shear. The mass of the foreground object can be estimated from this shear. Weak lensing reconstruction of the interacting clusters revealed that the bulk of the mass of the two systems is displaced from the X-ray emitting regions. As seen in Fig. 2.2, the X-ray emitting regions of both clusters are more closely bundled together, they have been slowed down by electromagnetic interactions. On the other hand, the bulk of the mass observed

with weak lensing has travelled further away. Therefore, the bulk of the mass of the two clusters was not slowed down by interactions expected from baryonic matter, indicating the presence of a large amount of some non-baryonic form of matter, i.e. dark matter. Further studies have also placed limits on the dark matter self-interacting cross section based on the spatial offset between the interacting, X-ray emitting baryonic matter and the dark matter composing the Bullet cluster [9].

2.1.2 The cosmic microwave background and the Λ CDM model

In 1965 Arno Penzias and Robert W. Wilson turned on the Holmdel horn antenna and were surprised to observe an isotropic, unpolarized excess temperature that seemed constant in time [10]. They published their findings in the *Astrophysical Journal*. That issue of the journal included a companion letter by Dicke, Peebles et al. [11] that provided a possible explanation for the observed temperature excess: the letter hypothesised that the observed radiation is the primordial radiation produced when the Universe was in a hotter, denser state. If the Universe is expanding, they hypothesised, there must have been an earlier time at which the temperature was so high that neutral particles could not have formed. As the Universe expanded and cooled, it reached the recombination epoch: electrons and protons coupled to form hydrogen atoms. Photons could then free-stream through the Universe, and the photons observed by Penzias and Wilson, referred to as the cosmic microwave background (CMB), were photons from after this moment of recombination.

Since then, the temperature fluctuations have been mapped with generations of telescopes. A map of the temperature fluctuations taken with the Planck satellite is shown in Fig. 2.3. The study of the CMB became the basis for observational cosmology: the small anisotropies observed in the temperature map can be quantified by a multipole power spectrum as a function of the angular scale [13], shown in Fig. 2.4. The peaks observed in the multipole power spectrum depend on the cosmological history of the Universe: the inflation epoch, the curvature of the Universe, the baryon and dark matter content will all affect the power spectrum at different scales. The model fitted in Fig. 2.4 is referred to as the Λ CDM model: a model of a flat, expanding Universe composed of baryons and cold dark matter. When referred to as "cold", it signifies that dark matter particles move at non-relativistic velocities: as such, they form structure more efficiently. The matter content of the Universe is expressed in terms of the dark matter density, Ω_c , and the

CMB map LGMCA_WPR2 at 5 arcmin

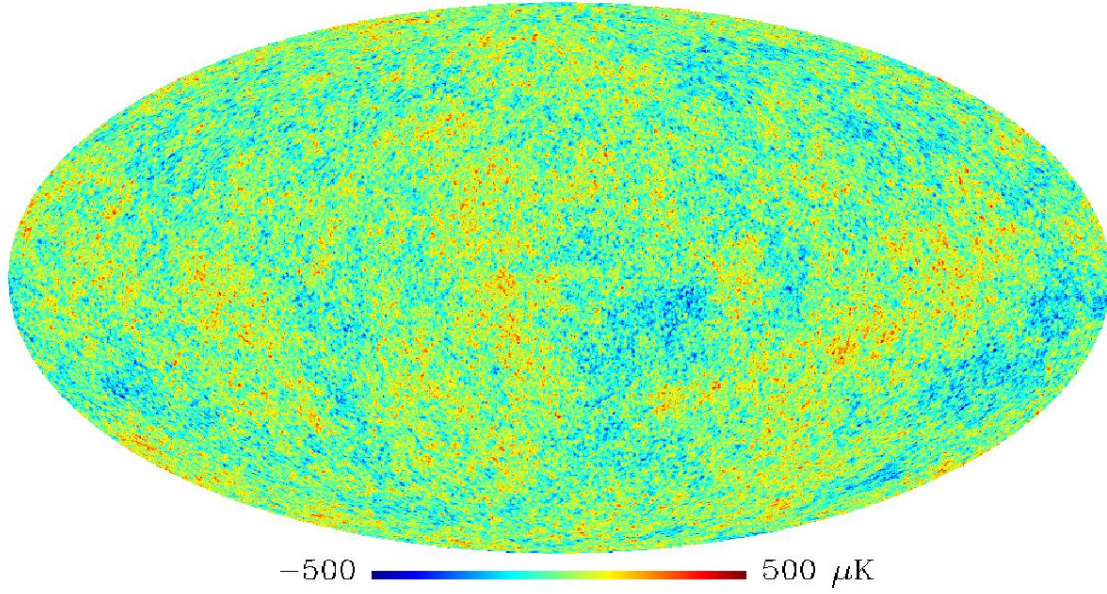


FIGURE 2.3: Temperature fluctuations in the early Universe observed with the Planck satellite. The variation in temperature indicates density fluctuations at the epoch of recombination. Taken from [12].

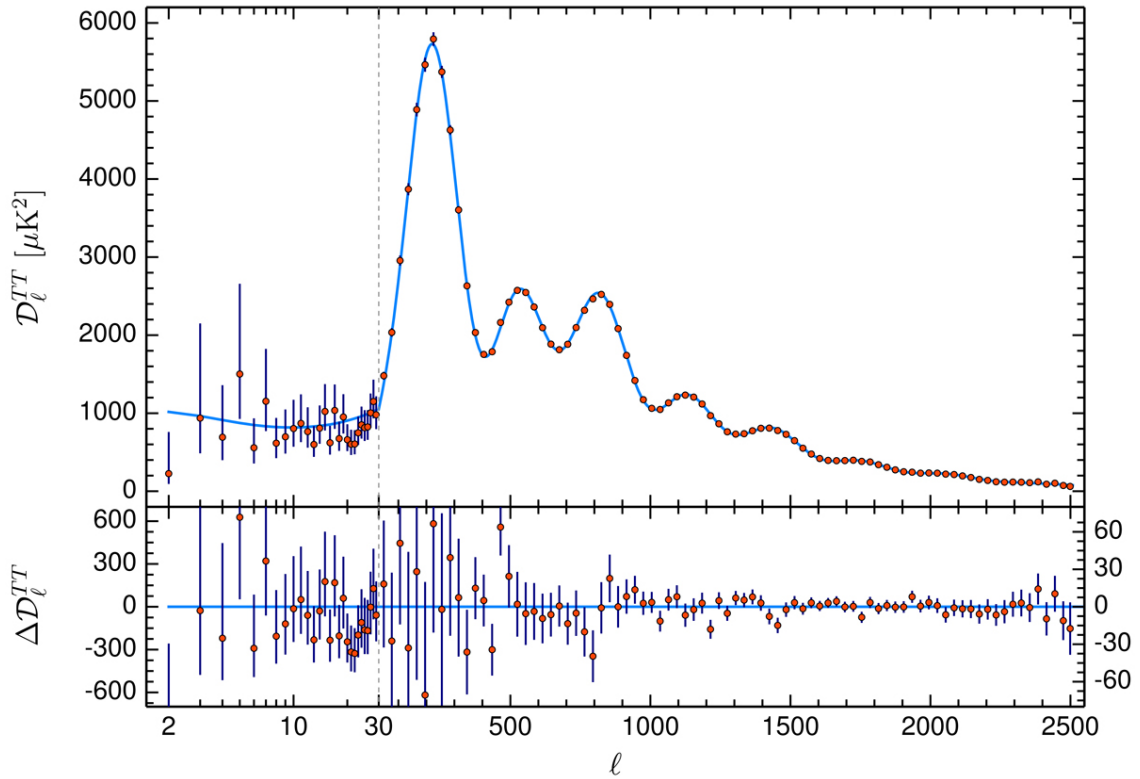


FIGURE 2.4: Temperature power spectrum of the CMB observed with the Planck satellite is shown in the upper panel, along with the fit to the ΛCDM cosmological model, shown as a solid red line. The lower panel shows the residuals of the power spectrum when compared to the fit to the ΛCDM model. Taken from [13].

baryon density, Ω_b . The energy densities are expressed as a ratio compared to the critical density, the density required for the Universe to be spatially flat, which is defined as $\rho_c = 3H_0^2/8\pi G$, where H_0 is the Hubble constant, $H_0 = 67.4 \pm 0.5 \text{ km/s}$ [13], and G is the gravitational constant. The values that best fit the data are [13]

$$\Omega_c = 0.120 \pm 0.001$$

$$\Omega_b = 0.0224 \pm 0.0001.$$

2.1.3 Structure formation

Besides the angular scale of the temperature fluctuations of the CMB, an argument for the existence of dark matter can be made from the amplitude of the temperature fluctuations. Given the size of the overdensities observed in the CMB, one can evolve these overdensities through time, and reach the conclusion that a cold form of matter not affected by the radiation pressure of the early Universe is necessary for the formation of structure we observe today [1982ApJ...263L...1p]. The argument for cold dark matter from large scale structure can be made by conducting numerical simulations, or by observing the clustering of galaxies as a function of redshift. The amount of galaxy clustering is measured by computing two-point correlation functions of galaxy positions and computing the power spectrum, which quantifies the amount of clustering as a function of scale. The properties of the dark matter particle, such as its velocity (cold/warm/hot), can be constrained by observing the clustering of baryonic matter on various scales and redshifts. Results are often reported in terms of the parameter $S_8 = \sigma_8 \sqrt{\Omega_m/0.3}$, a parameter dependent on the amount of clustering on a scale of 8 Mpc, σ_8 , and Ω_m , the total amount of matter. The observed correlations in surveys such as the Dark Energy Survey [14] can be compared to structure simulations [15], such as the one shown in Fig. 2.5, in order to test the Λ CDM model. Large scale surveys also compute the amount of weak lensing observed due to the mass of foreground objects, by computing the two-point correlation functions of galaxy shapes, referred to as the cosmic shear. Surveys such as the Dark Energy Survey [14] can use cosmic shear data to map out the dark matter distribution, providing information on the growth of structure.

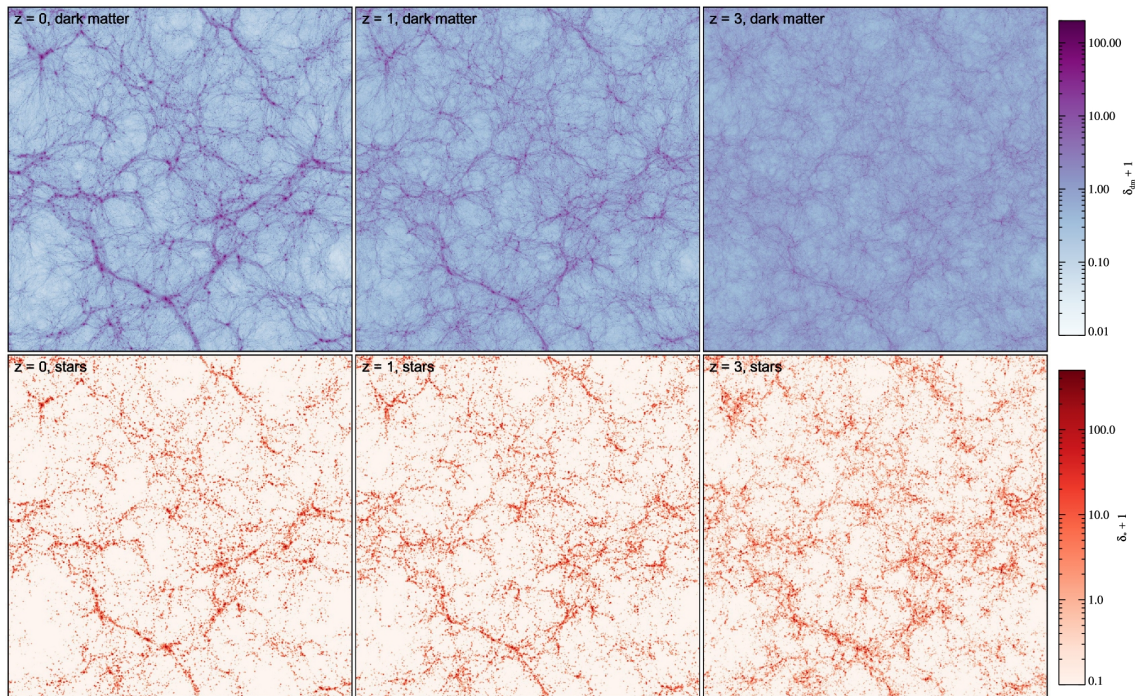


FIGURE 2.5: The dark matter and stellar density fields obtained from the IllustrisTNG simulations. Taken from [15].

2.2 Dark matter candidates

So far, the existence of dark matter has solely been inferred from its gravitational effect on surrounding baryonic matter. There are many possible dark matter candidates that could explain the observations described in the previous sections, and would comply with the current understanding of the cosmological history of the Universe. Some of these candidates fit our understanding of the missing mass problem better, and as such are probed more extensively with experiments. Nevertheless, a brief overview of all possibilities will be given in this section, including: theories of modified gravity, baryonic dark matter and the possibility that dark matter is made up of a new, non-baryonic particle.

2.2.1 Theories of modified gravity

One approach to account for the missing mass in galaxies and galactic systems is to modify the Newtonian laws of gravity at larger scales, first proposed by Mordehai Milgrom in 1983 [16]. The motivation for the modification is based on the assumption that Newtonian dynamics breaks down in the limit of small accelerations. To achieve this, Newton's

second law becomes

$$F = m\mu \times \left(\frac{|a|}{a_0} \right) \mathbf{a}, \quad (2.1)$$

where μ is a function that modifies gravity at some characteristic scale, a_0 . Particular models that realise this behaviour at the limit of small accelerations have been developed: the AQUAL (aquadratic Lagrangian) theory [17] derives the modified Newton force law from a Lagrangian with an added term containing a_0 , which then alters the Poisson equation. This theory successfully reproduces Eq. 2.1 in the limit of small accelerations and the symmetry of the Lagrangian under spacetime translations and rotations ensures energy and momentum conservation. The theory works at the scale of galaxies and galactic dynamics, but it breaks down when considering the dynamics of galactic clusters, most notably the observations of the Bullet cluster and also fails to reproduce certain features of the power spectrum of the CMB and to explain the phenomenon of gravitational lensing [18].

The tensor-vector-scalar gravity theory is another solution to modified gravity [19], a relativistic field theory which obtains the AQUAL theory in the non-relativistic limit. In addition to the Einstein metric, $G_{\mu\nu}$, a timelike vector field $\mathcal{U}_\mu$ and a scalar field, ϕ , is added to the model. The metric in this theory is obtained by stretching or shrinking the Einstein metric according to some factor relating to the direction of the vector field $\mathcal{U}$ and the scalar field ϕ , depending on how spacetime is oriented with respect to the vector field [19]. This theory and other relativistic realisations of MOND each face their own challenges, in addition to none of them being derived from first principles [20]. The same problem of missing mass in galaxy clusters appears in the relativistic theory, as does the separation of the X-ray emitting region and the surface mass density in the Bullet cluster. Furthermore, the cosmological history of the Universe is not predicted as accurately as in the λ CDM model: the third peak in the CMB power spectrum cannot be explained with baryons alone with relativistic MOND theories, and these theories struggle to reproduce the evolution of the large scale structure of the Universe [20].

2.2.2 Baryonic dark matter and compact objects

The hypothesis that dark matter consists of baryons faces a challenge from the point of view of cosmology and CMB observations, which require a large majority of the matter

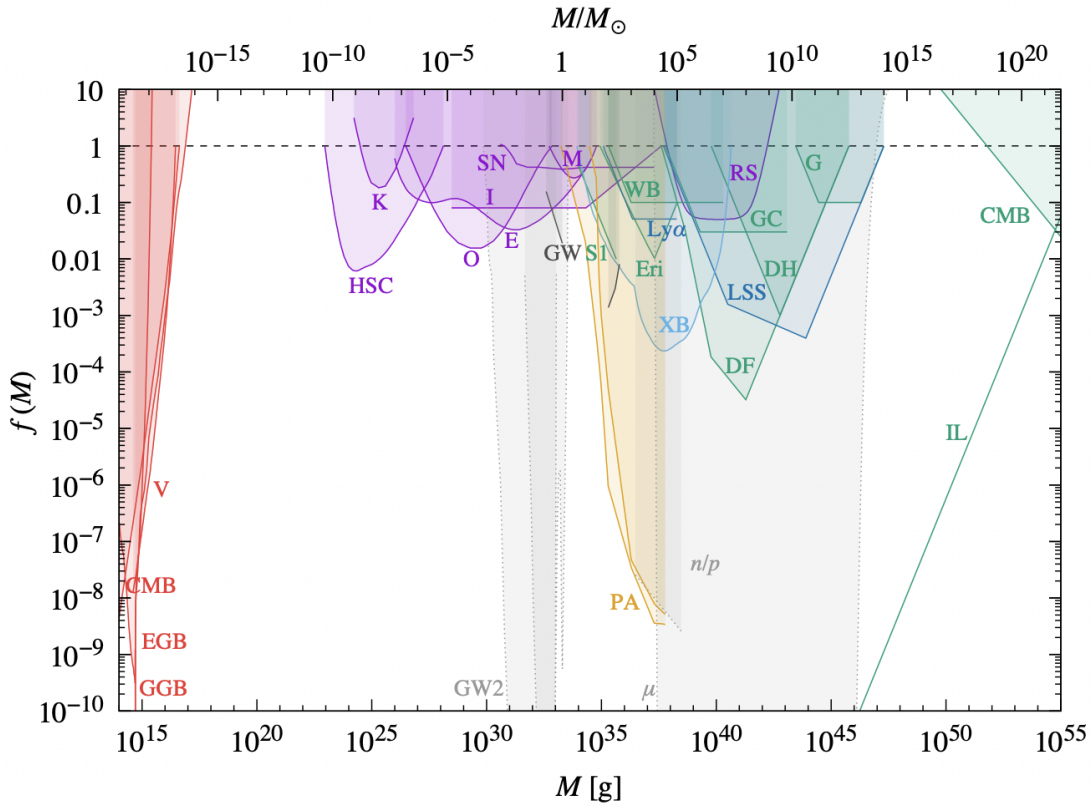


FIGURE 2.6: The current upper limits on the mass fraction of dark matter that could be contained in primordial black holes. Taken from [23].

budget to consist of some form of non-baryonic matter. This rules out massive astrophysical compact halo objects (MACHOs), objects with a negligible luminosity such as brown dwarfs, planets or black holes. However, a class of MACHOs that could still compose a significant portion of dark matter at certain masses are primordial black holes (PBHs). First proposed in the 1960s [21], these objects are expected to have formed in the early Universe from fluctuations in the mass-energy of the Universe [22]. If formed early enough, they act as pressureless gravitational wells during recombination. Therefore, they successfully evade CMB constraints, as they count toward the total matter budget, but not the baryonic matter budget of the Universe.

One method of estimating the mass fraction of MACHOs in the Universe is to attempt to observe the mass fraction of MACHOs in the Milky Way [24]. The fraction of missing mass that could be contained in MACHOs can be obtained in various ways: exploiting the microlensing effect (the increase in brightness due to MACHOs passing in front of light sources such as the Large and Small Magellanic Clouds) [25], studying how MACHOs could perturb wide binaries [26], or through observations of possible disruptions of stellar

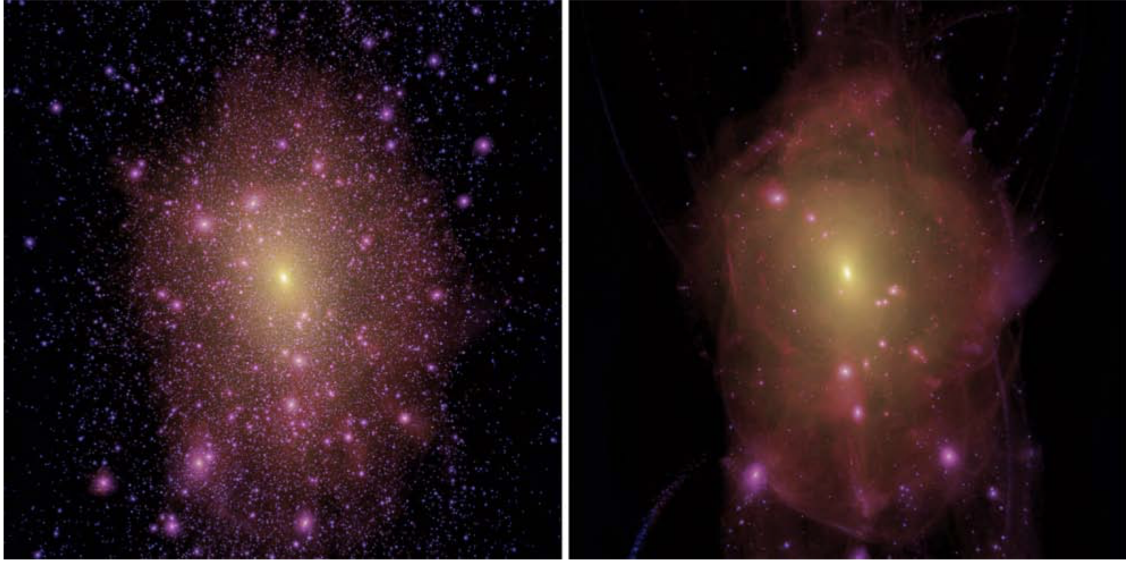


FIGURE 2.7: Structure simulations of a cold dark matter (left) and warm dark matter halo (right), illustrating the difference in the produced substructure of the two models.

Image taken from [30].

dynamics due to dynamical heating in dwarf galaxies [27]. The accretion of gas from the interstellar medium onto PBHs could also produce a detectable emission at X-ray or radio wavelengths [28]. The presence of PBHs could also be inferred from the fact that they would accrete matter in the early Universe, releasing accretion luminosity which would affect the CMB spectrum and the level of anisotropy [29]. The current constraints on the fraction of dark matter that PBHs could comprise are shown in Fig 2.6. A certain region of the parameter space still allows for PBHs to comprise all of the missing mass in the Universe. The constraints shown are obtained assuming a delta function for the mass distribution, whereas inflationary models predict extended mass distributions of PBHs, which would weaken the limits shown [24].

2.2.3 Non-baryonic dark matter

The above described solutions for the missing mass problem in the Universe fail to explain observations at various scales. This leaves the possibility of a non-baryonic form of matter. Proposed solutions for non-baryonic matter extensions to the SM can be distinguished based on their velocities at their decoupling from matter in the early Universe into hot or warm dark matter candidates and cold dark matter candidates. The decoupling velocity will affect the formation of structure in the early Universe. Hot and warm dark matter particles decouple from matter at relativistic velocities. This has consequences on the

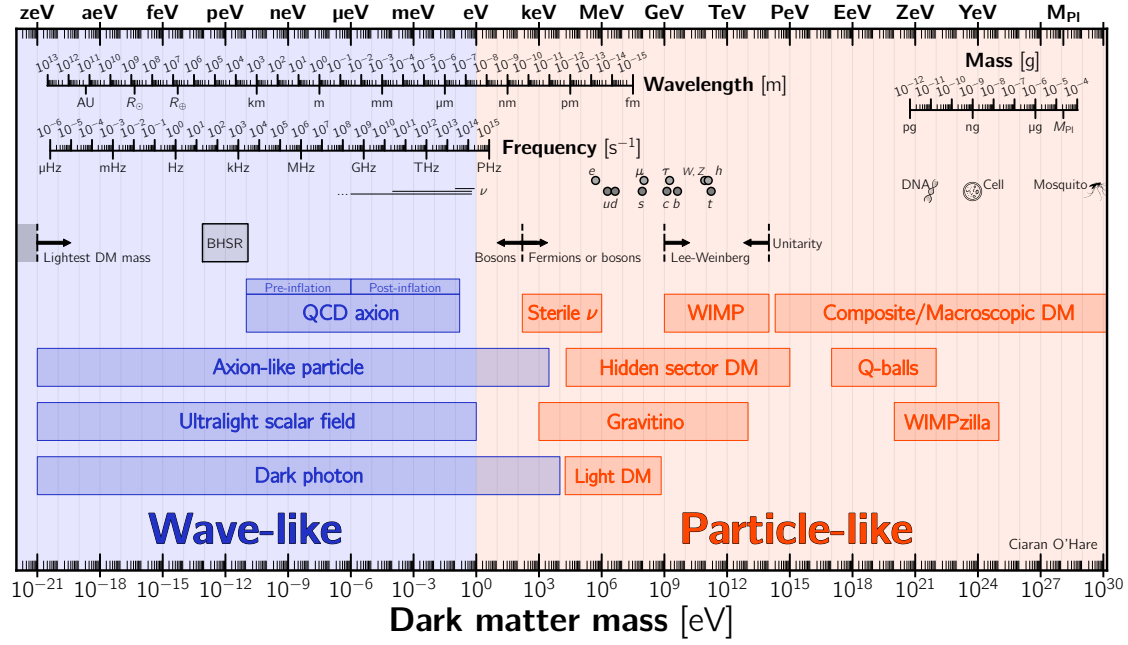


FIGURE 2.8: Parameter space of possible dark matter particle candidates. Taken from Wikipedia [31].

formation of structure: in warm dark matter structure simulations, top-down scenarios are observed: massive halos form first, which then fragment to form smaller structures. In cold dark matter simulations, the bottom-up scenario is observed: smaller structures form first, followed by the formation of larger structures, which is more in line with observations of structure in the early Universe [30]. Furthermore, cold dark matter simulations result in a larger abundance of substructure, as seen in Fig. 2.7, which also provides better agreement with current observations [30].

Possible dark matter candidate particles are shown as a function of the particle mass in Fig 2.8. The production mechanism for the observed abundance of dark matter in the Universe depends on the mass of the particle: it can be produced thermally, or via some other process. Thermal production assumes dark matter particles were in thermal equilibrium in the early Universe, until the temperature of the Universe dropped below the value required to produce a dark matter particle of some mass m_{DM} . After this decoupling from the SM bath, the dark matter density begins to drop, due to self-annihilation processes. After some time, the Universe expands to a point where the annihilation rate drops to a negligible rate, and the abundance of dark matter freezes out - hence why this production method is called freeze-out. This scenario is allowed in a certain mass range - the lower bound on the mass range at $\mathcal{O}(\text{MeV})$ arises from the bounds by *Planck* on the energy injection during recombination [13]. This bound comes from the fact that

any late-time energy injection during recombination reionises hydrogen, which alters the CMB and the observables *Planck* measures, such as the shape of the acoustic peaks in the power spectrum and the ionisation fraction. The upper bound around ~ 100 TeV is derived from the fact that above this mass, partial-wave unitarity of the annihilation process leads to the result that dark matter would overclose the Universe, $\Omega > 1$; thus masses above this value are forbidden [32].

For dark matter candidates with masses below the $\sim$ GeV scale (referred to as sub-GeV dark matter), the Lee-Weinberg bound [33] excludes a simple picture of thermal freeze-out via the weak force, requiring a more complex dark sector which interacts with the SM through a new light mediator, or the relic density could be set through interactions occurring entirely within the dark sector [34]. The simplest renormalizable models involve mixing with SM photons, Higgs particles or neutrinos, the dark photon being the benchmark model for such experimental searches [34].

In the GeV-TeV mass range, weakly interacting massive particles (WIMPs) constitute the most attractive candidate, motivated by cosmological and theoretical considerations. A particle in this mass range annihilating to SM particles with a 2-body process with a cross section at the scale of the cross section of weak nuclear interactions would produce the correct relic abundance of dark matter via freeze-out. This mass range also coincides with the masses of other weak particles in the SM, hence why this solution is often referred to as the "WIMP miracle".

Various extensions to the SM predict WIMPs: in supersymmetry (SUSY), each SM fermionic particle is assumed to have its bosonic counterpart, a sfermion, and each SM boson is assumed to have its fermionic counterpart, a bosino. The theory solves the hierarchy problem and can correctly explain the Higgs mass, and in certain realisations of the theory the lightest supersymmetric particle (LSP) naturally arises as a dark matter candidate. Namely, theories that conserve R-parity, a discrete symmetry introduced in supersymmetric models such as the minimal supersymmetric model, produce an LSP that is electrically neutral, stable and interacting weakly with the SM [35]. One potential WIMP candidate is the neutralino, a fermionic particle that is a linear combination of four SUSY partners, creating four mass eigenstates, the lightest of which is a potential WIMP candidate [35]. It would be non-relativistic and could pair-annihilate to a variety

of SM states, thus fitting into the freeze-out picture and obeying constraints of structure formation [36].

Other theories that attempt to unify fundamental forces through the introduction of universal extra dimensions, Kaluza-Klein theories [37, 38], also produce WIMP candidates. Universal extra dimension theories are a special class of extra dimension theories in which a discrete symmetry related to the extra dimensions remains unbroken. In these theories, additional heavier particles that propagate in extra dimensions appear. The masses of these particles are inversely proportional to the compactification of the additional dimension [39]. Because of the unbroken symmetry arising from the extra dimensions, this particle remains stable, making it a viable WIMP candidate, provided that the size or curvature of the extra dimension results in a particle at the TeV scale [40, 41].

Another possibility are dark matter particles interacting very feebly with the Standard Model, such that they are not in thermal equilibrium in the early Universe. The SM particles will gradually increase the abundance of dark matter until the temperature drops below the dark matter mass, resulting in a freeze-in of the dark matter abundance. Depending on the interaction strength, models with an expanded dark sector that mix with the SM could be produced via both freeze-out and freeze-in. Sterile neutrinos are another candidate class of particles that could be produced via freeze-in - this requires them to be in the $\sim$ keV mass range, which is in contrast with the $\sim$ GeV mass range needed to explain leptogenesis [42], requiring multiple generations of sterile neutrinos to explain both.

Further alternative mechanisms for the production of the correct abundance of dark matter exist, such as the misalignment mechanism in the case of axions and axion-like particles. Axions are an attractive dark matter candidate as they solve the strong CP problem, i.e. the observation that the parameter θ governing charge-parity violation in quantum chromodynamics seems to be extremely small [43]. The production of axions in the early Universe will depend on when the Peccei-Quinn (PQ) symmetry, which gives rise to the axion field, is broken [43]. Once the Hubble rate drops below the axion mass, the axion field begins oscillating coherently around the minimum of the potential, producing a condensate of axions [43]. The viable range of axion and ALP masses that could result in the observed cold dark matter abundance is vast, depending also on the

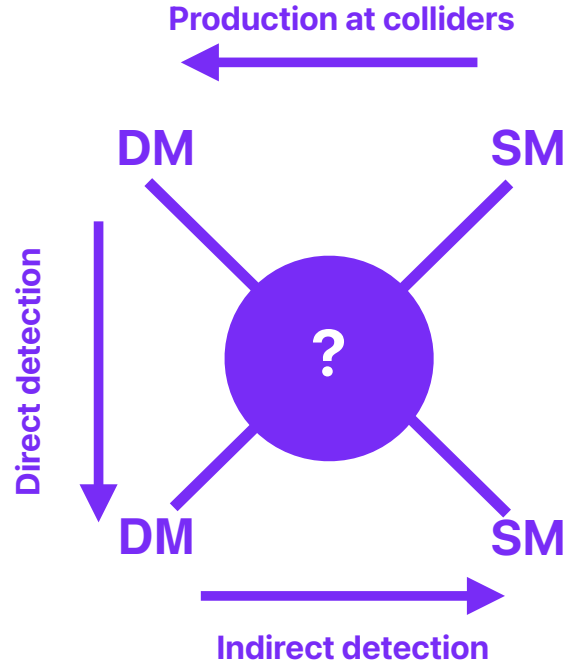


FIGURE 2.9: Simplified diagram of the possible interactions between dark matter and SM particles, and the detection strategies employed to observe these interactions.

moment when the PQ symmetry is broken: current experiments focus on the mass range $m_a \in [10^{-9}, 1] \text{ eV}$ [43].

2.3 Searches for WIMPs

The previous section gave an overview of proposed solutions to the missing mass problem of the Universe, arguing that cold dark matter seems to agree best with current observations. From this section onwards, this thesis will primarily focus on a particular form of cold dark matter, WIMPs. Methods of detecting lighter dark matter candidates differ substantially: axions can attempted to be produced in the lab, exploiting the phenomenon of axion-photon conversion in the presence of magnetic fields [43]; sterile neutrinos can be detected through their modulation of the neutrino oscillation probabilities [42]. The experimental effort to search for WIMPs consists of searches in colliders, direct detection and indirect detection. A simplified overview of the production mechanisms of dark matter particles exploited by the different search strategies is shown in Fig. 2.9. Each of these will be described in turn in this section.



FIGURE 2.10: Summary of the various searches performed at the LHC to search for dark matter. Taken from [49].

2.3.1 Collider searches

In collider searches, one attempts to produce dark matter through collisions of SM particles of adequate energies. Besides WIMPs, colliders, beam dump and fixed target experiments can also probe the sub-GeV dark matter landscape, as discussed in [34]. In the WIMP mass range, simplified benchmark models of dark matter particles and mediator particles are used to search for signatures of dark matter production at colliders such as the LHC and Tevatron [44]. These models can be divided into models with a spin-1 mediator, a spin-0 scalar/pseudoscalar mediator, the neutrino portal containing a heavy neutral lepton and the fermion portal containing a scalar mediator with a Yukawa coupling between dark matter and SM fermions [45]. Dedicated analyses are performed to interpret these results beyond simplified models, for specific cases such as SUSY [46], universal extra dimensions [47] and models with an extended scalar sector [48]. A summary of the event signatures searched for at the LHC in dark matter searches is provided in Fig. 2.10.

The most common technique of detecting dark matter particles in a collider involves the detection of missing transverse momentum, caused by long-lived dark matter particles escaping the detector. *Mono-X* searches look for dark matter particles recoiling against a SM particle, X , with a high momentum. SM states considered in these searches include: a jet produced from initial state radiation, searches for jets associated to production of b-quarks, *Mono-V* searches where dark matter is produced along with a vector boson ($W^{+/-}, Z^0, \gamma$). *Mono-Higgs* searches attempt to detect collisions in which a Higgs boson is produced, and decays to SM particles such as $b\bar{b}, \gamma\gamma, \tau\tau, WW, ZZ$. A summary of recent searches of this kind is given in [49].

A second category of searches looks for resonances, where a new dark sector particle decays into SM particles, leptons or quarks. The telltale sign of such resonances are bumps in the invariant mass distribution of the outgoing pairs of particles/jets [45]. A recent publication from ATLAS searches for such signatures in the production of dark quarks [50].

A final category of searches attempts to observe signatures of long lived particles, which decay far from the proton interaction vertex: this involves searches for displaced leptons, searches for hadrons produced by decays of long lived particles and searches involving displaced vertices and a large amount of missing transverse momentum [45]. A recent discussion on this topic can be found in [51]. So far, searches for dark matter candidates in colliders have yielded null results, severely constraining the parameter space in the GeV mass range for both dark matter and mediator masses in the context of different simplified models discussed above [52].

2.3.2 Direct detection

Direct detection experiments look for scatterings of WIMPs composing the ambient Milky Way dark matter halo with nuclei or electrons composing the detector medium. Due to the small cross sections expected for these interactions, different strategies are employed in order to isolate detectors from the SM background consisting of particles inbound from space, such as cosmic rays and their interaction products. The recoil energy produced by the nucleus or electron participating in the scattering can be measured in various ways. It can be measured from ionisation, detecting the charge produced from the ionised electrons. Another method involves the detection of scintillation radiation

produced by the excited atoms. Finally, the heat produced from the deposited energy can be detected in the form of phonons. The choice of detector medium will result in different recoiling signatures, with most experiments opting for the detection of at least two recoil signatures, in order to discriminate WIMP-nucleon scatterings from SM backgrounds.

Liquid xenon detectors such as XENONnT [53], LUX-ZEPLIN [54] and PandaX-4T [55] detect both the ionisation and scintillation signal within a dual-phase time projection chamber (TPC). The prompt scintillation light is detected with an array of photomultiplier tubes (PMTs), providing an estimate of the horizontal position of the event. Ionised electrons produced in nuclear recoils drift towards a gaseous region at the edges due to a permeating electric field. In the gaseous region, a secondary scintillation signal is produced, resulting in a delayed signal, the timing of which indicates at what depth the event occurred. The ratio between the amount of charge produced by the prompt and delayed scintillation signal provides a tool for discriminating nuclear recoils from electron recoils produced by backgrounds such as γ rays and β -decays. A similar principle to the one described above is also employed in liquid argon detectors such as Darkside-20k [56], which also contains a dual-phase TPC. On the other hand, DEAP-3600 [57] utilises a single-phase argon detector, relying solely on scintillation light as the means of detecting the nuclear recoil energy. Their background rejection is achieved through an excellent pulse shape discrimination, where electronic recoils resulting from background events are distinguished from the nuclear recoils due to their longer light pulse.

Crystal detectors are a second category of detectors - based on the material used, the detection of the recoil energy differs. Detectors constructed from germanium, such as SuperCDMS [58] or EDELWEISS-III [59], use ionisation and phonons in order to discriminate nuclear recoils. The measured ionisation and phonon energy provide an estimate for the recoil energy and the ionisation yield, the ratio between the ionisation and recoil energy. The bulk of the energy in an electron recoil event is deposited via ionisation, whereas the ratio for nuclear recoils is ~ 0.3 [59]. The experiments are operated at cryogenic temperatures at the order of $\sim$ mK, in order to lower the energy threshold for detecting nuclear recoils, achieving leading sensitivities in the mass range $< 10 \text{ GeV}/c^2$. [59]. A second class of crystal detectors operating with similar detection principles are sodium iodide crystals, the most famous of which is the DAMA/LIBRA experiment [60], whose claim of detection will be discussed in section 2.3.4. The claim of detection inspired a second generation of sodium iodide experiments, including the ANAIS-112 [61]

and COSINE-100 [62] experiments, built with the aim of confirming the DAMA/LIBRA signal. These experiments are usually composed of multiple crystals, which allows for background discrimination by requiring that events only produce recoils in one of the crystals, as weakly interacting dark matter particles would. The recoil energy is detected in the form of scintillation light: WIMP recoils would appear as an excess of events with respect to the background in the low energy recoil region, and would have a time dependence. The movement of the Earth around the Sun combined with the Sun's movement through the dark matter halo can be exploited to observe annual modulations of the counts [63]. The Earth's velocity direction will at times coincide with the direction the Sun is moving towards, whereas at other times it will be opposite. When the velocity directions coincide, the relative velocity of WIMPs with respect to the detector rest frame on Earth is higher, therefore WIMPs carry more kinetic energy and produce more energetic recoils in the detector. The DAMA/LIBRA experiment has controversially detected an annual modulation signal with a period of one year, with a maximum in June: the interpretation is discussed in more detail in Sec. 2.3.4.

Most searches opt for a model-independent approach in the search, where the WIMP-nucleon cross section is decomposed into a spin-dependent and spin-independent component. The spin-independent component scales with the square of the atomic number, hence the popular choice of experiments to use detection mediums with a large atomic number, such as xenon or germanium. Spin-dependent scatterings will scale with the net spin of the target nucleus. Most of the stable isotopes of detector materials have zero spin, so the sensitivity to spin-dependent interactions arises from less abundant isotopes with net spin. The expected rate of scatterings in the detector will also depend on properties of the dark matter halo, such as its velocity distribution and the local density.

The current results in the direct detection community remain inconclusive: the claims of detection described in Sec. 2.3.4 have been refuted by other experiments, which have a higher sensitivity to WIMP-nucleon scattering. A summary plot of the current limits is shown in Fig 2.11. Searches in the most sensitive detectors such as LZ and XENONnT are approaching the neutrino floor: below a certain cross section for the WIMP-nucleon scattering, the flux of neutrinos produced in the Sun in fusion processes, atmospheric neutrinos, geoneutrinos, reactor neutrinos and the diffuse supernova neutrino background begin to produce a significantly higher number of nuclear recoils from coherent elastic neutrino-nucleus scatterings than WIMPs at this interaction cross section do. Future

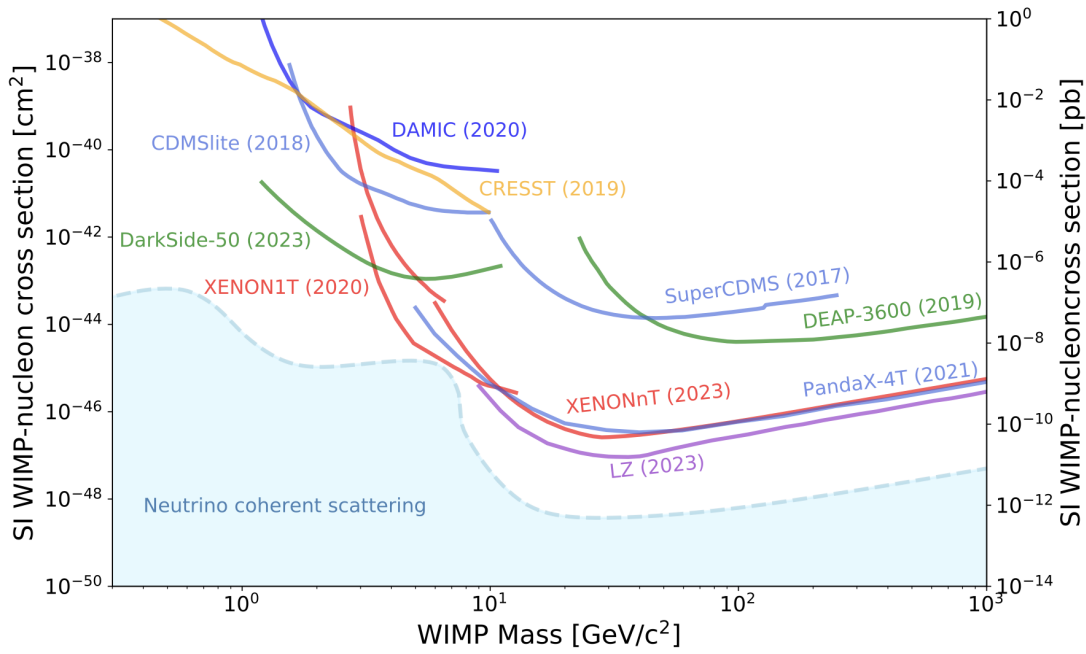


FIGURE 2.11: Current upper limits on the spin-independent WIMP-nucleon scattering cross section as a function of the WIMP mass from different direct detection experiments. The neutrino floor, described in the text in this section, is also denoted. Figure is taken from [64].

experiments aim to go below this floor by constraining the flux of neutrinos from the described processes, and distinguishing the WIMP-nucleon scattering events from this background by utilising directional information and the fact that the energy distributions of events will slightly differ for the background neutrino flux and the signal events: a more detailed discussion is provided in [65].

2.3.3 Indirect detection

Indirect detection of dark matter attempts to detect the SM products of dark matter pair-annihilation or decay processes in regions of space where a large quantity of dark matter is expected to accumulate. The final state products that are searched for include cosmic rays, γ rays and neutrinos. The targets of indirect detection searches depend on the SM particle being detected: cosmic ray detectors attempt to detect an isotropic excess of anti-particles above the background expected from astrophysical processes. γ -ray detectors look for an excess of photons in objects with a large density of dark matter and a small predicted emission of γ rays due to astrophysical processes. The most common such search target are dwarf spheroidal galaxies (DSphs). A search target studied both in γ rays and neutrinos

is the Milky Way. Neutrino telescopes can also study a second class of sources: massive objects inside of which WIMPs could accumulate through multiple scatterings with nuclei composing the object, causing them to be trapped in the gravitational potential of the object. Possible search objects of such type include the Sun (also the Earth, to a lesser degree). For any source, the flux of secondary particles produced by WIMP annihilations in some source at a distance D from the Earth can be written as

$$\frac{d^2\Phi}{dEdt} = \frac{\Gamma}{4\pi D^2} \frac{dN}{dE}, \quad (2.2)$$

where Γ is the annihilation rate of WIMPs, and $\frac{dN}{dE}$ is the spectrum of secondary particles produced in one pair-annihilation process. In the case of cosmic rays and gamma rays, this equation needs to be corrected by the absorption and deflection that occurs on the way to the Earth. On the contrary, neutrinos produced in WIMP annihilations arrive at the Earth unimpeded.

2.3.3.1 Cosmic ray searches

The Milky Way's magnetic field affects the trajectories of cosmic ray particles, so these experiments cannot determine the direction from which the detected particles were emitted (except at ultra-high energies, which are not expected in dark matter searches). Instead, these detectors look at the amount of anti-particles in their data: anti-matter production occurs only in a few astrophysical sources, making any excesses more easily identifiable. The most recent publication of the AMS-02 experiment [66], the most sensitive cosmic ray instrument in the GeV – TeV energy range with the ability to distinguish between positively and negatively charged particles, has shown an excess of anti-protons over the known astrophysical background. The excess exhibits similar spectral features when compared to the positron excess measured by the same instrument, appearing as a break in the overall spectrum at similar energies, indicating a common origin. This is an important feature, as astrophysical objects such as pulsars can account for the positron excess [46], but not the anti-proton excess. Furthermore, the unknown positron flux component also fits the electron flux data well, indicating an equal production of electrons and positrons at this unknown source. Further studies of the anti-proton data indicate that uncertainties in the anti-proton production cross-section and propagation could account for the excess, eliminating the need for WIMP annihilation as an extra component

to the flux [67]. Antihelium particles are another probe of WIMP dark matter, having no astrophysical background that could produce it. Studies of the AMS-02 data show a few detections which could possibly be antihelium particles, but the detection is not statistically significant [68].

2.3.3.2 γ -ray searches

γ -ray instruments reach excellent pointing resolution and the photon trajectories do not bend on their way from the source to the detector, thus allowing for directional searches of signatures of WIMP annihilations in areas of expected dark matter overdensities. On the other hand, photons can be absorbed or scattered by matter on their way to the Earth: this absorption reduces the overall flux expected at detectors from a given process at the source. Another limiting factor in these searches is the background emission due to astrophysical processes in these objects, or in their foreground and background. The largest dark matter container in our vicinity, the Galactic Centre (GC), is a difficult search target for γ -ray telescopes due to the amount of luminous objects emitting γ rays in that region, the nature and population of which is not very well known and is thus difficult to model and discriminate from the signal data. Given these considerations, a target better suited for indirect searches with γ -ray telescopes are dwarf spheroidal galaxies (dSphs) - they have a high mass-to-light ratio, meaning that the amount of dark matter, and thus γ -emission due to WIMP annihilation processes, is large with respect to baryonic matter and astrophysical emission from baryonic processes. The dynamics of dSph objects can also be studied in detail due to the ease of observation compared to observations of stellar dynamics in the inner parts of the Milky Way; thus the density of dark matter within dSph objects is better constrained compared to our own galaxy. The dark matter density determines the number of WIMP annihilations occurring within a given volume of space and is thus an important parameter in estimating the total flux of SM particles due to WIMP annihilation processes. Furthermore, these objects are observed as point-like sources, independent of the source morphology, whereas the emission profile from the Galactic Centre is extended and will differ with what density profile for the Milky Way is chosen.

The reduced systematic uncertainties with respect to larger targets, combined with the excellent photon efficiency of γ -ray telescopes, results in leading upper limits on the

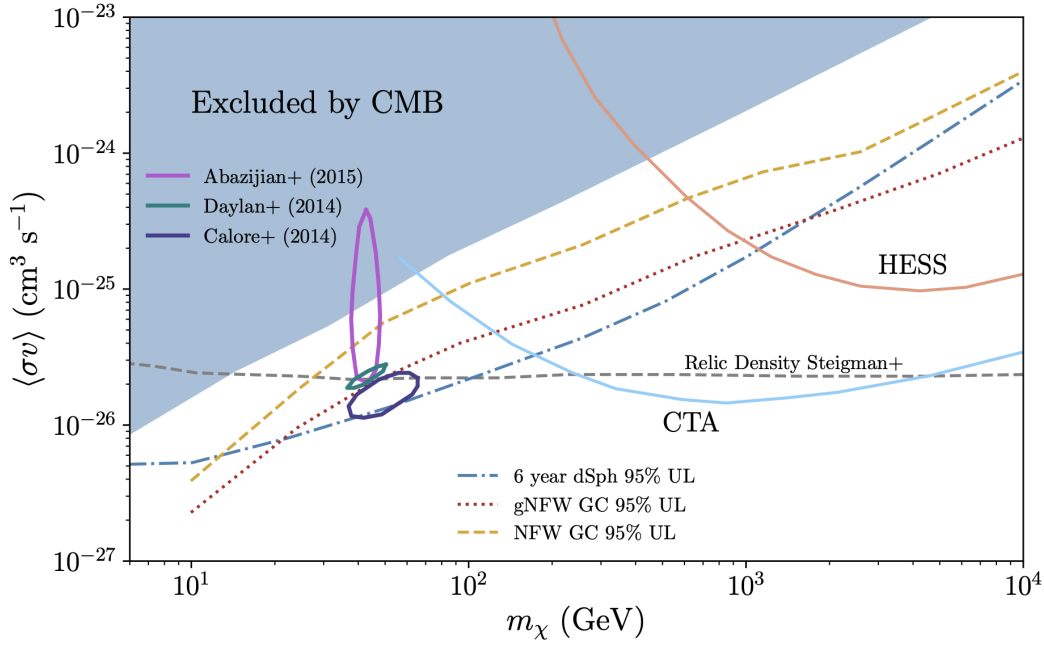


FIGURE 2.12: The 90% C.L. upper limits on the thermally-averaged WIMP pair-annihilation cross section as a function of the dark matter mass, shown for several γ -ray experiments, along with projections from the Cherenkov Telescope Array. Closed contours denote best-fit confidence regions corresponding to the Galactic Centre γ -ray excess. Taken from [64].

thermally-averaged WIMP annihilation cross section in the field for most annihilation channels, as seen in Fig. 2.12. The figure shows limits obtained by γ -ray instruments from dSphs and from the GC, along with projections from the planned Cherenkov Telescope Array (CTA). The shaded area shows the parameter space excluded by CMB observations, while the dashed gray line denotes the cross section required to produced the relic density of dark matter. Finally, closed contours show the best-fit confidence regions corresponding to the Galactic Centre γ -ray excess, discussed in more detail in Sec. 2.3.4.

The limits shown above are only valid for a subclass of WIMP models, due to the assumptions made to derive these limits. The same assumptions on the dark matter interaction must be made when computing limits in neutrino searches. Thus the range of validity of these limits will be discussed in more detail in the following subsection.

2.3.3.3 Neutrino searches

Neutrino telescopes can search for signatures of WIMP annihilations in the same targets as γ -ray telescopes, with the advantage of a reduced astrophysical background and no

absorption or deflection when passing through matter. Furthermore, the fact that neutrinos can escape dense environments allows for a study of a new type of source where a sizeable neutrino flux from WIMP annihilation could be detected: celestial bodies such as the Sun and the Earth. Dark matter particles making up the Milky Way halo are constantly impinging on these objects and may scatter off nuclei, causing them to lose a fraction of their energy. If the energy of the WIMP particle falls below the escape velocity needed to escape, the WIMP becomes trapped in the celestial body, losing energy through repeated scatterings and sinking towards the centre of the object. The time evolution of the number of particles in the object, N , is given by

$$\dot{N} = C - C_A N^2. \quad (2.3)$$

C is the capture rate and $C_A = 2\Gamma/N^2$ is given as the annihilation rate, Γ , divided by the total number of particles squared. WIMP evaporation has purposefully been left out of this equation, as it is not a relevant process at the WIMP masses that are probed in this work: in the Sun it is relevant in the mass range up to a few GeV/c^2 [69]. The density of WIMPs in this object, and consequently the annihilation rate, keeps increasing over time. Solving Eq. 2.3 results in the following solution for the annihilation rate at any given time:

$$\Gamma = \frac{1}{2} C \tanh^2\left(\frac{t}{\tau}\right), \quad (2.4)$$

where $\tau = (C/C_A)^{-1/2}$ is the time scale for the capture and annihilation processes to equilibrate. Given enough time, an equilibrium between the annihilation rate and the capture rate, caused by the repeated WIMP scatterings, is established, such that $\Gamma = C/2$. A steady flux of SM particles is thus emitted from the object, of which only neutrinos can escape and be detected. An observation or non-observation of a potential signal allows for the measurement or constraint on the parameter governing the capture rate of WIMPs, the WIMP-nucleon scattering cross section. Similarly to the case of direct detection, the nature of the interaction is assumed to be either spin-dependent (cross section increases with net spin) due to an axial-vector coupling, or spin-independent (cross section increases with nucleon mass), if the coupling between WIMPs and nucleons is scalar in nature. Limits or results are computed for both cases, assuming all scatterings proceed through either one or the other mode. This allows for the recasting of limits in the case of realistic models where a certain probability for each type of interaction is assigned.

In the case of spin-dependent scattering, WIMPs only scatter off hydrogen nuclei, so the capture rate only depends on the WIMP-proton scattering cross section and a kinematic suppression factor for the hydrogen nucleus, along with the dark matter halo density and velocity dispersion:

$$C = A_{SD} \frac{\rho_\chi \sigma_{SD} S(m_\chi/m_H)}{m_\chi v}. \quad (2.5)$$

The constant A_{SD} accounts for unit conversion, ρ_χ is the local halo mass density, S is a kinematic suppression factor dependent on the proton and WIMP mass, v is the dark matter velocity dispersion, and σ_{SD} is the WIMP-proton spin-dependent cross section, the parameter being measured or constrained. The factors m_H and m_χ denote the mass of hydrogen and the mass of the WIMP.

If the coupling between WIMPs and nucleons is assumed to be spin-independent, WIMPs can scatter off any element composing the Sun, each with its own cross section of interaction. The expression for the capture rate then becomes

$$C = A_{SI} \frac{\rho_\chi}{m_\chi} \sum_i \phi_i f_i F_i(m_\chi) \frac{S(m_\chi/m_{N_i})}{m_{N_i}} \sigma_{SI}^i. \quad (2.6)$$

The first two factors, f_i and ϕ_i , are the relative abundance and relative gravitational potential of element i in the Sun. The factor F_i represents a form factor suppression of nucleus i , S is the kinematic suppression factor and σ_{SI}^i is the WIMP-nucleon scattering cross section for nucleus i . The parameter being measured or constrained in these analyses is the average cross section of interaction; there is no way to determine what fraction of neutrinos was produced by scattering of a certain element i . For both the spin-dependent and spin-independent case, the limit is computed by assuming equilibrium is achieved, replacing the annihilation rate in Eq A.1 by the capture rate expressions given above and solving for the cross section.

A special case can be considered in order to produce limits for leptophilic dark matter models [70], i.e. models in which the interaction strength of the scattering off electrons far exceeds the scattering cross section off nucleons. In the mass and cross section regime of interest for neutrino telescopes, the expression for the capture rate when the scattering

off electrons is the dominant process becomes [71]

$$C = A \left(\frac{10^3 \text{GeV}}{m_\chi} \right)^2 \left(\frac{\sigma_e}{10^{-40} \text{cm}^2} \right). \quad (2.7)$$

A detection or non-observation of a signal from the Sun can be used to measure or place limits on the parameter σ_e , the WIMP-electron scattering cross section.

Searches focusing on celestial bodies offer the advantage of proximity, resulting in a large flux at the detector from a relatively small amount of collisions at the source, and the advantage of low backgrounds: at neutrino energies expected from WIMP annihilation processes, GeV - TeV, the background from objects such as the Sun is low, making the signal easily identifiable. The only other production mechanism for neutrinos in this energy range comes from neutrinos produced by scatterings of cosmic rays with the Sun's atmosphere [72]. The predicted flux of neutrinos produced by WIMP annihilations in a compact object such as the Sun is subject to considerable uncertainties. Processes influencing neutrino transport, such as neutrino oscillations and neutrino interactions within the dense medium composing the object have their associated uncertainty: a detailed discussion of the magnitude of the uncertainties caused by the error bands in the measured neutrino oscillation parameters and the cross sections for neutrino interactions can be found in [73]. The mean velocity dispersion and the local density of the WIMP halo are necessary inputs for the computation of the capture rate, and thus for the neutrino flux resulting from annihilations. Uncertainties in the composition of the target, i.e. the exact abundances of elements composing the Sun, also influence the capture rate of WIMPs.

The second main target of indirect searches for dark matter with neutrino telescopes is the Galactic Centre. To estimate the flux of SM particles produced from WIMP pair annihilations in galactic objects such as DSphs and the Milky Way halo, a necessary input is the density of the dark matter halo, which for most objects remains largely unconstrained, with both cuspy and cored density profiles producing a similar agreement when fitted to observed rotational velocities of gravitationally-bound objects. Cuspy profiles are defined as having rapidly growing densities towards the centre of the galaxy, whereas cored objects have a constant density, a "core", in the inner few kpc. In general, observations of velocity dispersions of galactic objects result in better fits for cored profiles, whereas numerical simulations of dark matter halos prefer cuspy profiles. In addition, the presence of substructure can boost the flux substantially, and the amount of substructure

present in halos is difficult to measure as the gravitational lensing effect from smaller substructures and the amount of baryonic matter emitting visible light is extremely small. The flux of SM particles emitted from annihilations in DM halos is dependent on the J-factor, defined as

$$\mathcal{J} = \int_{\Delta\Omega} \int_{\text{l.o.s.}} \rho^2(\theta, l) dl d\Omega. \quad (2.8)$$

The squared density profile is integrated along the line of sight, l.o.s., and the solid angle it subtends in the sky, $\Delta\Omega$. The profile is squared as two DM particles participate in a pair-annihilation process. For decays of DM particles, the flux of SM particles depends on the D-factor, defined as

$$\mathcal{D} = \int_{\Delta\Omega} \int_{\text{l.o.s.}} \rho(\theta, l) dl d\Omega. \quad (2.9)$$

For sources that cover a large solid angle in the sky such as the Galactic Centre, the emission profile is less diffuse in the case of annihilations, where the flux depends on the integral of the squared density profile, which grows rapidly closer to the centre of the object. The flux of neutrinos emitted can be expressed as

$$\frac{d^2\Phi_\nu}{dE_\nu dt} = \frac{1}{4\pi} \frac{1}{2} \frac{\langle\sigma v\rangle}{m_{\text{WIMP}}^2} \frac{dN_\nu}{dE_\nu} \mathcal{J}. \quad (2.10)$$

The flux depends on the WIMP mass, m_{WIMP} , the J-factor, the neutrino spectrum produced from a single annihilation event, $\frac{dN_\nu}{dE_\nu}$, and the thermally-averaged annihilation cross section, $\langle\sigma v\rangle$, the parameter being constrained/measured in indirect searches for dark matter. The dark matter velocity distribution is approximated by a Maxwell-Boltzmann distribution in the standard halo model, as favored by recent simulations [74]. The above expression is valid for velocity-independent cross sections: a velocity dependence of the cross section will result in localised effects, where the cross section, and thus the rate of annihilations, will depend on the rotational velocity of WIMPs. Furthermore, averaging over the velocity of dark matter particles is necessary as the functional dependence of the dark matter annihilation cross section on the particle velocity is not known. Thirdly, possible enhancements to the cross section such as Sommerfeld enhancements are not considered, which could boost the annihilation flux by orders of magnitude [75]. This enhancement arises as an increase in the cross section at low particle velocities, arising from light mediators creating long-range attractive forces between particles. The expression above is also modified if dark matter particles are Dirac particles, the 1/2 factor which avoids double counting particles and anti-particles disappears if the particles are of Dirac

nature. Finally, when considering model realisations of the dark matter particle, usually the novel particle is coupled to the Standard Model through multiple channels. The limits derived for a certain channel using this equation always assume a 100% branching ratio to that channel. Constraints are thus weakened for particles annihilating through multiple channels.

Another source of uncertainty in these searches is the computation of the neutrino spectrum: for larger dark matter masses, $> \text{TeV}/c^2$, particles are produced with energies above those that can be measured with precision at colliders. The dynamics of showering and hadronisation processes of the daughter particles are largely unconstrained at these energies. Furthermore, particles with energies above the weak scale of a few hundred GeV emit weak gauge bosons: the full range of diagrams of possible interactions that could produce these bosons is not implemented in Monte Carlo generators such as PYTHIA at the time of writing, so different methods are employed by authors computing SM particle spectra from WIMP annihilations to include these interactions. This causes small differences in the predicted spectra by different publications [76–78]. In the case of WIMPs interacting with the SM via some unknown mediator, the mediator can open additional decay channels or modify the kinematics of SM particle production in the annihilation cascade, altering the resulting SM particle spectra. A more detailed discussion on the impact of the spectrum computation on the constraining power in indirect detection experiments is provided in a dedicated section in the Results chapter.

Neutrino telescopes can place competitive limits on the thermally-averaged annihilation cross section, especially at higher masses above 10 TeV where absorption of γ rays starts to suppress the flux. Experiments such as ANTARES and IceCube have placed competitive limits on the annihilation cross section by searching for a signal from the Galactic Centre in the past: IceCube is limited by the poor visibility of the Galactic Centre, whereas ANTARES has been limited by its size. KM3NeT hopes to surpass these experiments in terms of sensitivity to dark matter annihilation from this source due to the excellent visibility of the source, combined with the eventual large size of the detector, comparable to IceCube. The current status of the constraints imposed by neutrino telescopes is presented alongside leading γ -ray limits in the Results section of this thesis, in Fig. 5.2.

2.3.4 Modern claims of dark matter particle detection

In the recent years, multiple experiments have reported possible observations of particle dark matter interactions with the SM, although further probes with more sensitive detectors seemed to have refuted those claims. Furthermore, the detection claims have often not been compatible with one another. Claims of sterile neutrino detection come from probes of different astrophysical objects, yet with the same instrument: the 3.5 keV excess detected in X-rays when observing galaxy clusters [79], Andromeda galaxy [80], and the Galactic Centre [81], all observed with the XMM-Newton instrument. Further observations of other objects and more rigorous reanalysis of the data have since cast doubt on the validity of this claim [82].

Claims of the detection of WIMP dark matter have been reported, two of which have received significant attention in the community. The most famous modern claim for dark matter comes from the DAMA/LIBRA experiment [60], mentioned previously. The annual modulation in event counts due to the Earth's motion has been observed at the experiment. Other experiments have seen hints of a detection, although with less than 5σ significance: the CoGeNT germanium crystal detector [83], the CRESST-II cryogenic crystal detector [84] and the CDMS-II Ge-Si crystal detector [85]. The COSINE-100 and ANAIS-112 experiments, the next generation detectors built in order to confirm the DAMA/LIBRA signal, have failed to do so, even though the same target material and detection techniques are used. Null signals in next generation crystal detectors seem to be in conflict with detection claims of the previous generation of crystal detectors, and liquid xenon and argon detectors further exclude the best fit signal region of these experiments by orders of magnitude.

The second claim of WIMP dark matter detection consists of the Galactic gamma ray excess (GCE) [86], an excess of γ -ray radiation in the Galactic Centre detected with the Fermi telescope that cannot be explained with known sources and astrophysical processes. As discussed in the cited paper, the γ -ray emission from the innermost regions of the Milky Way can be explained by a self-annihilating WIMP, with a mass $m_{\text{WIMP}} \sim 25 - 30 \text{ GeV}/c^2$ and an annihilation cross section at the order of magnitude of the thermal cross section, distributed following a cuspy density profile. Furthermore, follow-up studies that attempt to apply a mask to remove emission from known point sources seem to indicate that an excess still remains [87]. However, numerous publications refute this claim: one

publication argues that the excess disappears when using templates for the stellar galactic and nuclear bulges in the fit, indicating that astrophysical emission in these regions better fits the observed data [88]. Authors in [89] are able to fully account for the emission when considering a population of unresolved millisecond pulsars. Moreover, the results of their statistical analysis indicates that a spatial clustering of photons indicative of a population of point sources is responsible for the excess, in contrast to earlier claims of a spatially smooth excess. Finally, the possibility that the emission originates from the supermassive black hole in the centre of the Galaxy has also been considered in literature [90]. To this day, a scientific consensus on the origin of the excess has not been reached - future studies with more sensitive instruments and with multiple messengers, along with developments in the understanding of the source population and emission mechanisms of objects in the innermost regions of the Milky Way could resolve the origin of this excess.

3

Neutrino detection and the KM3NeT detector

This chapter provides an introduction to neutrinos and their properties: their interactions with the environment and the phenomenon of neutrino oscillations. The physics probed with neutrino detection is described, which includes the determination of neutrino oscillation properties, neutrino astronomy, and the indirect detection of dark matter. This is followed up with a detailed description of KM3NeT, the neutrino detector used in this work to look for neutrinos produced by dark matter annihilations.

3.1 Neutrino production and detection

Neutrino telescopes such as KM3NeT can detect neutrinos produced by different phenomena. At the energies relevant for KM3NeT (GeV-PeV range) the three main categories they can be divided into are: atmospheric neutrinos, produced by interactions of cosmic rays in the atmosphere; cosmic neutrinos, produced at cosmic accelerators, and neutrinos produced by dark matter annihilations. Neutrinos do not carry electric charge and do not interact electromagnetically with the surrounding environment. The detection thus proceeds indirectly, by observing the products of neutrino scatterings off nucleons in and around the detector active volume. These ultra-relativistic scattering products will then emit detectable Čerenkov radiation. As neutrinos only interact via the weak interaction and have a very small scattering cross section, the probability of neutrinos interacting in

the vicinity of the detector is very low, hence the need for a large volume detector such as KM3NeT. Furthermore, over a given distance a neutrino will oscillate in flavour: the neutrino flavour produced by some process may not be the same flavour detected at the detector, due to the inequality of the mass and flavour eigenstates.

3.1.1 Production of neutrinos detected in KM3NeT

Atmospheric neutrinos are produced in hadronic interactions of cosmic rays in the atmosphere. In the energy range from GeV energies up to tens of TeV, they constitute the most abundant neutrino flux detected by neutrino telescopes such as KM3NeT. The long path lengths of atmospheric neutrinos travelling through the Earth can be used in oscillation studies. The primary science goal of the KM3NeT/ORCA detector is the determination of the neutrino mass hierarchy and the measurement of oscillation parameters, the θ_{23} mixing angle and the atmospheric squared mass difference, ΔM^2 . Interactions of cosmic rays in the atmosphere produce charged pions and kaons. The charged pions predominantly decay to muons, with a 99.9% branching ratio, producing neutrinos in the following processes:

$$\begin{aligned}\pi^\pm &\rightarrow \mu^\pm + \nu_\mu(\bar{\nu}_\mu) \\ \mu^\pm &\rightarrow e^\pm + \nu_e(\bar{\nu}_e) + \bar{\nu}_\mu(\nu_\mu)\end{aligned}\tag{3.1}$$

On the other hand, kaons have three relevant decay channels that produce a significant amount of neutrinos and muons:

$$\begin{aligned}K^\pm &\rightarrow \pi^\pm \rightarrow \mu^\pm + \nu_\mu(\bar{\nu}_\mu) \rightarrow e^\pm + \nu_e(\bar{\nu}_e) + \bar{\nu}_\mu(\nu_\mu) + \nu_\mu(\bar{\nu}_\mu) \\ &\rightarrow \pi^0 + e^\pm + \nu_e(\bar{\nu}_e) \\ &\rightarrow \pi^0 + \mu^\pm + \nu_\mu(\bar{\nu}_\mu)\end{aligned}\tag{3.2}$$

Each decay channel contributes a branching ratio of 63.6%, 5.1% and 3.4%, respectively. The remaining kaons decay to pairs or triplets of pions - the charged pions then follow the same decay chain as shown in Equation 3.1. The atmospheric neutrino flux produced in

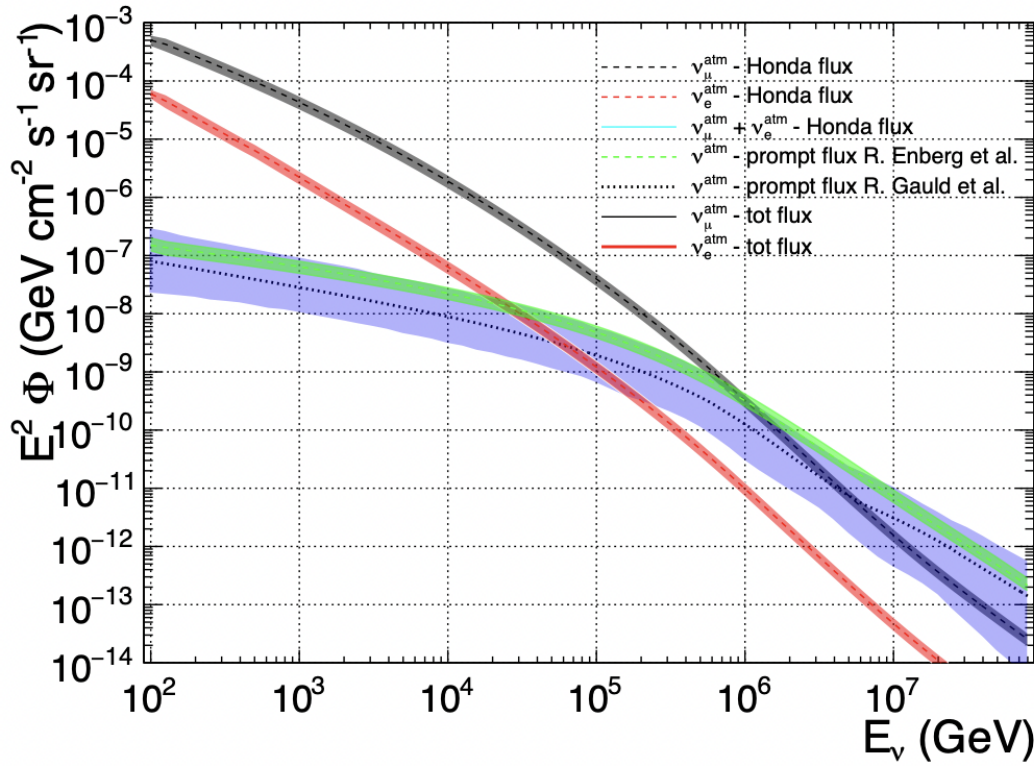


FIGURE 3.1: The atmospheric neutrino flux components as a function of the neutrino energy. The width of the colored bands around the lines quantifies the uncertainties of each component of the flux. Taken from [91].

these interactions is referred to as the *conventional* atmospheric neutrino flux. At higher energies, interactions of cosmic rays with the atmosphere produce heavy hadrons, which promptly decay to high energy neutrinos. This component of the flux is referred to as the *prompt* atmospheric neutrino flux. It becomes dominant at energies above 1 PeV. A plot of the components of the atmospheric neutrino flux is seen in Fig. 3.1.

KM3NeT also aims at detecting neutrinos emitted by the same cosmic accelerators that produce high energy cosmic rays, the exact origin of which is still unknown. Neutrinos provide an excellent avenue for the determination of the origin of cosmic ray acceleration, as they are not deflected by magnetic fields nor absorbed in dense environments. The cosmic ray spectrum exhibits certain features, a few breaks in the spectrum, named the *knee*, *second knee*, and the *ankle*, hinting at different origins at different energies. Cosmic rays up to the second knee are believed to be of Galactic origin, produced in supernova remnants and accelerated via diffusive shock acceleration [92, 93]. Cosmic rays at energies higher than the ankle region are thought to be of extragalactic origin, produced in extreme environments such as gamma-ray bursts or active galactic nuclei [94]. Neutrinos can be

produced from the interactions of the cosmic rays with surrounding matter or photon fields, referred to as the *hadronic* scenario. The interactions with the surrounding medium result in the production of pions, which results in the production of both neutrinos and γ rays. The *leptonic* scenario refers to processes initiated by electrons such as synchrotron radiation which only produce γ rays. Therefore, the detection of astrophysical neutrinos provides very valuable information on the production mechanism of cosmic rays and γ rays. The total neutrino flux from all astrophysical sources has been detected by the IceCube collaboration, it is referred to as the diffuse astrophysical neutrino flux [95]. In addition, several point sources have been identified by the same collaboration with a convincing degree of certainty [96]. Finally, the experiment also recently reported the observation of neutrinos from the Galactic Plane [97]. An additional component to the astrophysical neutrino flux are cosmogenic neutrinos, i.e. neutrinos produced in the interactions of ultra high energy cosmic rays with the cosmic microwave background. This flux is guaranteed to exist but it is yet to be detected with a convincing degree of certainty. As of the time of writing of this thesis, the KM3NeT collaboration has published the detection of the highest energy neutrino so far, reported in [98]. The exact origin of the event is unknown: the landscape of the measured astrophysical fluxes and cosmogenic and diffuse models is shown in Fig. 3.2.

A further possible source of neutrinos at neutrino telescopes consists of neutrinos produced by annihilations of dark matter particles, described in detail in the previous chapter.

3.1.2 Neutrino oscillations

The modern theory of neutrino oscillations begun in the 1960s with the hypothesis of two flavour mixing [99]. The mixing occurs as the flavour eigenstates are a quantum superposition of the mass eigenstates, where the transition from the flavour to the mass basis is described with the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix:

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{11} & U_{12} & U_{13} \\ U_{21} & U_{22} & U_{23} \\ U_{31} & U_{32} & U_{33} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}.$$

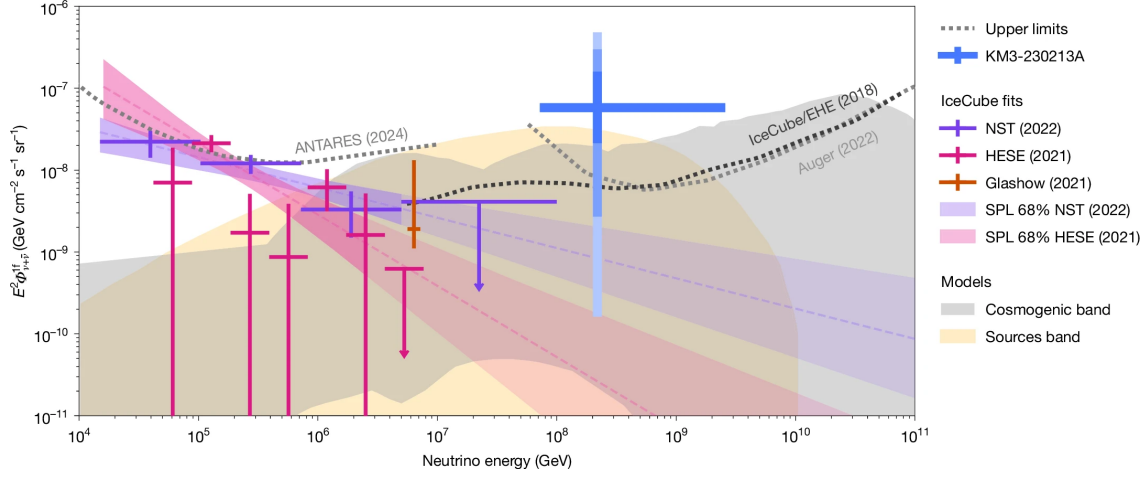


FIGURE 3.2: The astrophysical neutrino fluxes measured by IceCube are shown as purple and pink crosses, with the corresponding 1σ single power law best fits shown as shaded regions of the same colour. The blue cross represents the flux required in order to account for the observation of the KM3NeT very high energy event. The grey and black dotted lines represent upper limits by IceCube, Auger and ANTARES. The yellow band represents a model prediction of the diffuse flux due to known astrophysical sources, while the grey band represents model predictions for the cosmogenic neutrino flux. Taken from [98].

The PMNS matrix can be parametrised in terms of three mixing angles, θ_{ij} , and a complex phase, δ_{CP} , which accounts for possible CP violation in the leptonic sector. The probability of a neutrino of energy E to oscillate from flavour α to flavour β after travelling some distance L can be expressed as

$$P_{\nu_\alpha \rightarrow \nu_\beta} = \sum_{i,j} U_{\alpha,i}^* U_{\beta,i} U_{\alpha,j} U_{\beta,j}^* \exp\left(i \frac{\Delta m_{ij}^2 L}{2E}\right). \quad (3.3)$$

As can be seen, the oscillation probability depends on the terms of the PMNS matrix, which in turn depend on the mixing angles and δ_{CP} , and the mass-squared difference of the neutrino masses. The neutrino mass hierarchy remains an open question in neutrino physics, offering two solutions: the so-called normal ordering, where the two lightest states have a small mass difference (~ 10 meV) and the third state has a larger difference (~ 50 meV), or the inverted ordering, where the two heavier states are separated by a

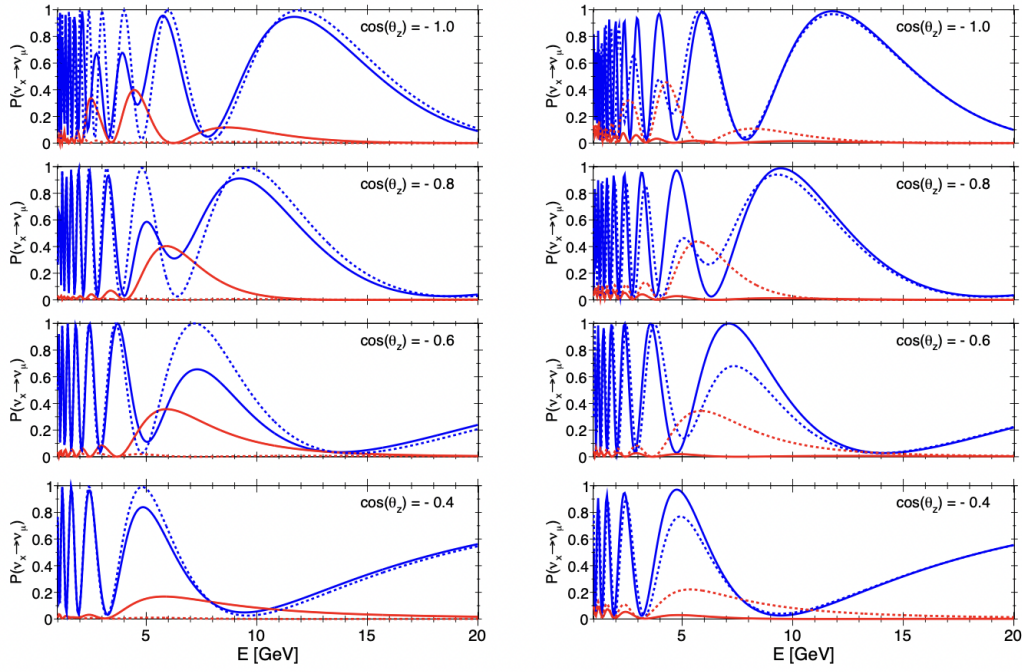


FIGURE 3.3: The oscillation probabilities $\nu_\mu \rightarrow \nu_\mu$ (blue) and $\nu_e \rightarrow \nu_\mu$ (red) for different zenith angles, shown as a function of the neutrino energy, for normal (full lines) and inverted (dashed lines) ordering. The plots in left column represent the oscillation probabilities of neutrinos; the ones in the right column represent oscillation probabilities of anti-neutrinos. Taken from [91].

small mass difference. The precise measurements of oscillation parameters and the determination of the mass hierarchy are the goal of neutrino oscillation experiments, which can be divided into reactor, accelerator, solar and atmospheric neutrino experiments. Based on the path length, neutrino energy and the involved neutrino flavours, the experiments are sensitive to different mixing parameters. Observations of atmospheric neutrinos in detectors such as KM3NeT are sensitive to the mixing angle θ_{23} and the Δm_{31}^2 mass squared splitting, in addition to the neutrino mass ordering, due to an enhancement of $\nu_\mu \rightarrow \nu_e$ ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$) transitions caused by matter-induced modifications of oscillation probabilities for the case of normal (inverted) ordering. Experiments such as KM3NeT cannot distinguish between neutrinos and anti-neutrinos on an event basis, but differences in the atmospheric fluxes of neutrinos and anti-neutrinos and in their interaction cross sections result in differences in the event rate at certain energies and zenith angles, which can be exploited to determine the mass ordering. An example plot showing the oscillation probabilities of muon neutrinos and electron neutrinos transitioning to muon neutrinos at different zenith angles is shown in Fig. 3.3.

3.1.3 Types of interactions

In the energy regime of the KM3NeT detector, at GeV energies and above, the vast majority of detected neutrino interactions consists of deep inelastic scatterings on quarks composing the nuclei of atoms in the sea. Neutrinos can exchange a $W^\pm$ or Z^0 boson with the target in the scattering process: when the interaction involves a charged boson, it is referred to as a charged current interaction, the other case being neutral current interactions. The cross sections for the two interactions differ: approximately $\sim 1/3$ of the neutrino interactions are neutral current scatterings, the remaining $\sim 2/3$ are charged current scatterings [100]. The neutrino transfers approximately $1/3$ of its energy to a quark in a neutral current scattering, whereas in charged current scatterings the neutrino transfers almost all of its energy to the outgoing lepton [100]. The light signature produced from the interaction differs for the two types of interactions, and the interaction products of charged current interactions is different depending on the neutrino flavour.

Electron neutrinos interacting via the charged current interaction produce a highly energetic electron, which in turn induces a cascade of electron-positron pairs and bremsstrahlung photons. The resulting light emission is approximately spherically symmetric, with small elongation in the direction of the leading primary electron produced in the scattering [101]. This allows for a pointing resolution on the order of a few of degrees for this type of event [91]. For scatterings occurring within the detector volume, the energy deposition is contained within the detector, resulting in an energy resolution at the percent level [91].

The product of the charged current scattering of a muon neutrino is a highly relativistic muon, which in turn has a much larger range in water compared to its lighter lepton counterpart. The reconstruction of the neutrino direction from the light profile of the produced muon assumes that the outgoing lepton is produced collinearly. At the energies observed by KM3NeT, the average angle between the incident neutrino and the outgoing muon can be approximated as [102]

$$\langle \theta \rangle \leq \frac{0.7^\circ}{(E_\nu/1\text{TeV})^{0.7}}. \quad (3.4)$$

At TeV energies and above, this allows for a pointing accuracy below one degree. The energy loss of the muon can be parametrised with a simplified formula as [103]

$$\frac{dE}{dX} = -\alpha - \beta E, \quad (3.5)$$

where $\alpha = 2.0 \times 10^{-6} \text{ TeV cm}^2/\text{g}$ is an ionisation term, considered constant at this energy regime, as is $\beta = 4.2 \times 10^{-6} \text{ cm}^2/\text{g}$, a term encoding energy losses due to brehmsstrahlung, electron-positron pair production and photonuclear effects. The muon range, defined as the distance the particle travels before its energy drops below some threshold value E_{th} , can then be defined as

$$\lambda = \frac{1}{\beta} \ln \left(\frac{\alpha + \beta E}{\alpha + \beta E_{\text{th}}} \right). \quad (3.6)$$

At TeV energies and above, this range is in the order of kilometers. Therefore, the muon can traverse the entire volume of the detector unimpeded. Furthermore, muons produced outside of the detector volume can reach the detector and leave a detectable signature.

Along its trajectory, the muon emits a cone of Čerenkov light. This phenomenon occurs when a charged particle travels with a velocity larger than the speed of light in that medium, inducing a polarisation in the atoms which is asymmetric in the direction of motion of the particle. The resulting effect is seen as a cone of Čerenkov light emitted along the direction of motion of the charged particle. The opening angle of the emission, the Čerenkov angle, is given as

$$\theta_{Ch} = \frac{1}{\beta n}. \quad (3.7)$$

At neutrino energies detectable with the KM3NeT instruments, particles are ultra-relativistic ($\beta \sim 1$), and the average refractive index of water is $n \sim 1.35$, resulting in a cone angle of 42° . The predictability of the emission and the long path lengths of the muons traversing through the detector allow for an excellent angular resolution for these types of events.

Tau neutrinos scattering by the exchange of a $W^\pm$ boson produce a highly relativistic tau lepton, which results in a characteristic emission profile due to the short-lived nature of the lepton. The tau lepton decays to a muon with a branching ratio of $\sim 17\%$, resulting in the elongated emission profile characteristic for muons traversing the detector. The remaining relevant decay channels into electrons or hadrons produce a shower at the point of decay. At energies above $\sim \text{PeV}$, the separation between the initial shower producing

the tau lepton and the secondary shower from the decay of the tau lepton is large enough such that the two showers can be distinguished, resulting in a double “bang” signature unique to this class of events.

In the case of neutral current interactions, the light emission produced by the scattering is the same for all three types of neutrinos. The incident neutrino exchanges a Z^0 boson with a target nucleon, resulting in a hadronic cascade, which leaves a localised light deposition, similar in shape to the electromagnetic cascade induced by electron neutrinos.

3.2 The KM3NeT detectors

The KM3NeT experiment consists of two detectors located in the Mediterranean sea [91]. The KM3NeT/ARCA detector is situated 100 kilometers off the coast of Sicily, near Portopalo di Capo Passero, anchored to the seabed at a depth of 3500 m. The design accomodates the detection of neutrinos of TeV energies and above, with the goal of the detection of the diffuse astrophysical neutrino flux, and the identification of individual point sources of high energy neutrinos. The KM3NeT/ORCA detector is located 40 kilometers off the coast of Toulon, France, installed at the seabed at 2500m depth. The spacing of the detector components is optimised for the studies of the atmospheric neutrino flux, with the goal of the precise determination of the neutrino oscillation parameters, and the neutrino mass ordering.

The research carried out in this thesis was conducted with data collected with the KM3NeT/ARCA detector, so this chapter will focus on the description of this detector. The detection principle, the components participating in the neutrino detection, and the data acquisition architecture are identical for the two detectors, only the spacing of the components differs between the two, allowing for a different sensitivity in neutrino energy.

3.2.1 Detector components

As stated previously, the KM3NeT/ARCA and KM3NeT/ORCA detectors are composed of the same elements, only differing in their spacing. Photomultiplier tubes (PMTs) detect the Čerenkov light of the products of the neutrino scatterings. The PMTs are 3''

Hamamatsu R12199-02 tubes [104]. The photocathode releases free electrons via the photoelectric effect, which then pass through 10 dynode stages where the signal gets amplified before reaching the anode, where the current pulse is read out. In order to obtain a gain of 3×10^6 , a high voltage is required at the order of 900-1300 V [104]. More information on the measured wavelength-dependent quantum efficiency, transit time spread, dark count rate and other PMT properties can be found in a dedicated publication [104].

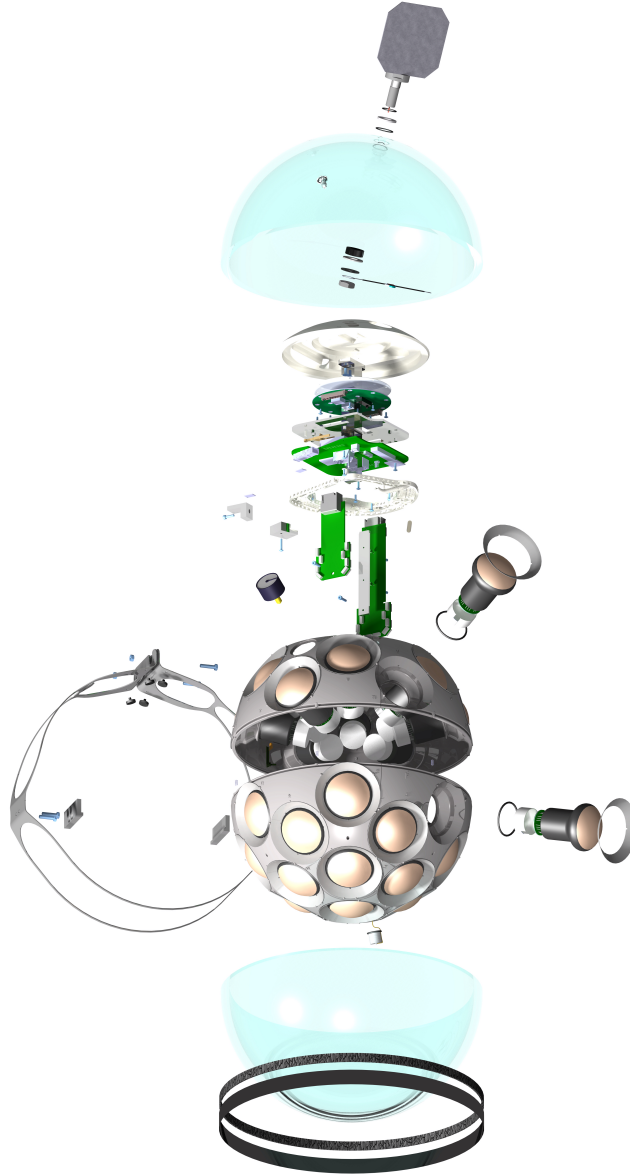


FIGURE 3.4: A blown-up view of the KM3NeT digital optical module, highlighting all the components contained within.

The PMTs themselves are grouped into digital optical modules (DOMs) [105], pressure

resistant spheres housing 31 PMTs. The multi-PMT approach results in a near 4π solid angle coverage, and provides additional information on the photon arrival direction compared to the single-PMT DOM used in KM3NeT's predecessor, ANTARES. The DOM is also equipped with time, position and orientation calibration sensors. The sensors and PMTs are connected to an electronic board named the Central Logic Board (CLB) [106]. This board processes information read out by individual sensors and maintains communication with the on-shore station. There are 32 individual time-to-digital converters (TDCs) in order to record the timing pulse of each PMT and the positioning sensor. The all-data-to-shore concept is followed, where all the data collected offshore is digitised and sent to the onshore control station without any reduction. Triggers and selection algorithms are applied at the on-shore station, in order to reduce the data and form events for reconstruction [107].

The DOMs are grouped into detection units (DUs), string-like structures anchored to the seabed, and held afloat by buoys, the two of which keep the DU taut [108]. The DUs are arranged in a circular configuration on the seabed, resulting in a detector of a cylindrical shape. The spacing between DOMs on a DU is different at the two sites: for KM3NeT/ORCA, this spacing is 9 metres, whereas for KM3NeT/ARCA it is 36 metres. Furthermore, the spacing between the DUs themselves is different for the two detectors: for KM3NeT/ORCA, this spacing is on average about 20 metres, whereas for KM3NeT/ARCA it is 95 metres on average. As the extension of the light emission by the particles produced from the neutrino scatterings depends on the energy, the different separations between detector components result in a different sensitivity window in energy.

The KM3NeT detector is currently undergoing construction, but its modular structure allows for data taking to proceed with partially constructed detector configurations. The KM3NeT/ORCA detector currently consists of 24 DUs, whereas the KM3NeT/ARCA detector consists of 33 DUs. The current expectation envisions both detectors to be completed by 2030. The finished detector will be composed of two building blocks with 115 DUs each. The proposed layout of the full ARCA detector is shown in Fig. 3.5. The analyses reported in this thesis correspond to the data recorded with the ARCA detector between the years 2021 and 2023, when the detector was consisting of 8, 19 and 21 DUs.

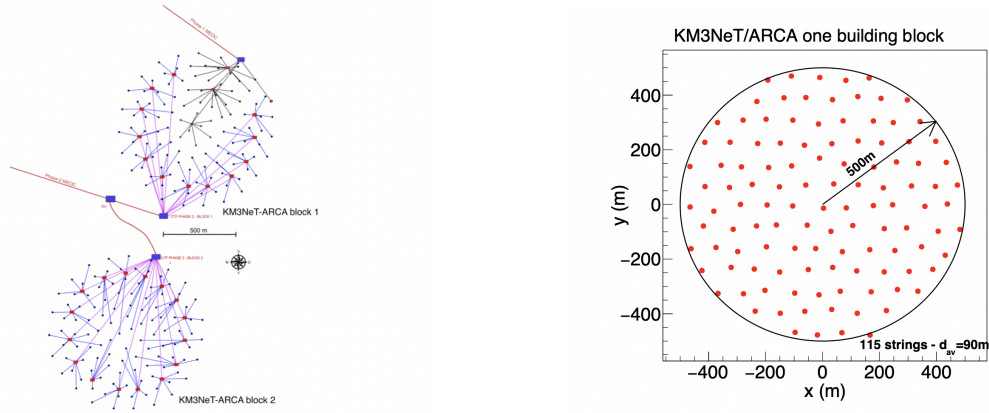


FIGURE 3.5: Left: the proposed layout of the full ARCA detector on the seabed; right: the layout of one building block. Taken from [91].

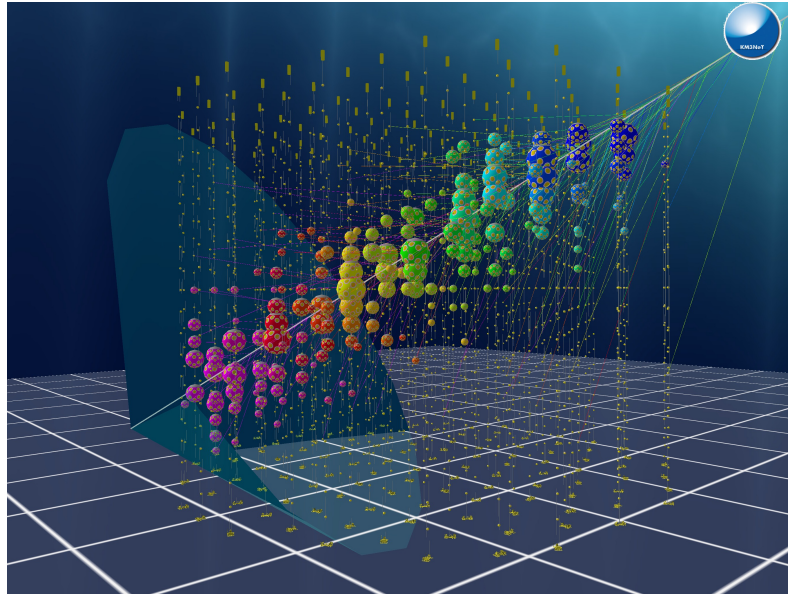


FIGURE 3.6: An event display visualising a muon traversing the detector. The Čerenkov light cone is shown as a shade of blue. The blobs denote the optical modules with registered hits, and the blob colours encode the time at which the hits were registered: the DOMs in the top right corner, visualised in blue, recorded hits at the earliest time, whereas the DOMs in magenta, seen in the bottom left, recorded hits at the latest time.

3.2.2 Event topologies in KM3NeT

The photon emission resulting from the interactions of different neutrino flavours described in the previous section produce different event topologies in KM3NeT. The elongated light emission profile produced by a muon traversing the detector is referred to as a "track-like" event. Due to the superior pointing accuracy for these types of events, this event topology offers the best prospects for identifying a neutrino source, such as the Milky Way dark

matter halo. The analyses in this thesis are conducted on track-like events. The angular resolution of this class of events is limited by the kinematic angle, the scattering angle between the incoming neutrino and the outgoing muon. At the energies relevant for this analysis ($E_\nu > 1 \text{ TeV}$), this is not a limiting factor. Due to its unique signature compared to interactions of other flavours and currents, track-like events should predominantly be composed solely of muon neutrino events, interacting via the charged-current interaction.

On the other hand, the electromagnetic cascades induced by electron neutrino charged-current events are indistinguishable from the cascades induced by neutral current events. Therefore, these events are grouped together into one type of event, referred to as "shower-like" events. Due to the fact that the energy deposition of shower-like events is contained within the detector active volume, this class of events offers the best energy resolution. For the case of track-like events, the muon has most likely been produced outside the detector active volume, and traverses the entire volume of the detector without decaying. Therefore, the light produced during the entire lifetime of the muon is not recorded by the detection instruments. On the other hand, shower-like events disperse their energy on short scales, and the light emission is contained within the detector volume and recorded by the detection instruments. This class of event is therefore useful in searches which profit from superior energy resolutions, such as the search for neutrinos produced by direct annihilations of dark matter into neutrinos, resulting in a line-like spectrum. For shower-like events, this spectral feature is preserved, and can be used to distinguish the neutrinos produced by dark matter from background events.

3.3 Background events in KM3NeT

In searches for high-energy neutrinos from astrophysical or dark matter origins, signal events are outnumbered by background events by several orders of magnitude. Background can be categorised into two types: optical and physical. Optical background can be produced by the internal noise of the photon detection and amplification detector components or by photon sources in the sea emitting radiation at similar wavelengths as the Čerenkov radiation of leptons produced in neutrino scatterings. Physical background is produced by ultra-relativistic particles traversing the detector: atmospheric muons and neutrinos. A short overview of each source of noise and background follows, the rejection of which will be described in more detail in the chapter describing the analysis method.

Noise from detector components results in a charge readout in the PMTs. The components of the PMT, such as its dynodes, undergo spontaneous emission of electrons, which produce a current pulse in the readout. The DOM itself is composed of many structural components, some of which may contain traces of radioactive elements, adding to the dark current noise detected with the PMTs.

The most prevalent radioactive element present in the sea composing the active volume of KM3NeT is potassium, specifically the ^{40}K isotope. One kilogram of seawater contains 400 mg of potassium, of which 0.012% consists of the radioactive isotope, a total of 0.05 mg in a kilogram of water. The isotope has a half-life of $1.25 \cdot 10^9$ years, decaying mainly via the β -decay into ^{40}Cl . This process produces a highly energetic electron, with an energy exceeding the threshold for Čerenkov emission, thereby producing background radiation that is detected by the PMTs. Despite the long half-life, the background is significant, due to the enormous volume encompassed by the detectors: a rate of 7-8 kHz is observed in all the PMTs. This source of background can be removed by looking at coincidences between multiple PMTs on the same DOM: a single decay produces photons that are detected by multiple PMTs on the same DOM, the simultaneous detection of these photons at the same time can be used to reject these events [109]. Furthermore, the timing coincidence can be exploited to perform time calibrations of PMTs in the same DOM [109].

Another source of background to consider is bioluminescence. Living organisms such as plankton and bacteria produce light in the blue portion of the spectrum, as the light is absorbed the least in this end of the spectrum. This directly coincides in wavelength with Čerenkov radiation emitted by neutrino scattering products. This source of background increases in certain months of the season, but the small living organisms are uniformly distributed in space and emit a steady, low rate of radiation.

The sources of background present in the sea, and the above described dark currents, form an easily reducible source of background, as the location of the detected photons is random. The ultra-relativistic products of neutrino scatterings will produce signals in multiple DOMs, across multiple PMTs, whereas the backgrounds described above will not produce coincidences across different DOMs in the detector.

The physical background consists of ultra-relativistic particles produced in the Earth's atmosphere. Particles of interest that reach KM3NeT are atmospheric neutrinos and atmospheric muons. Both are produced by cosmic rays interactions in the atmosphere,

described in Section 3.1.1. Muons will impinge on the detector from directions above the horizon, some of which will arrive in bundles, as air showers produced by cosmic rays can produce a cluster of muons that can reach the detector. The directionality and multiplicity of atmospheric muons can be exploited in order to distinguish them from neutrinos and reject them. Atmospheric neutrinos will leave the same light signatures in the detector as astrophysical neutrinos or neutrinos produced by dark matter annihilation processes, and thus form an irreducible background. Therefore, an accurate modeling of the atmospheric muon and atmospheric neutrino flux is important for a precise simulation of the background in the detector, in order to optimise the event selection to reject atmospheric muons and to distinguish signal events from atmospheric neutrinos. The uncertainty in the prediction of the atmospheric neutrino flux is at the order of $\sim 30\%$ in the energy range relevant for KM3NeT [110]. The uncertainties originate from the uncertainties in the interaction cross sections, and due to uncertainties in hadronic models, which govern how cosmic ray particles interact, and how the subsequent interaction products decay and impart energies to secondaries. The atmospheric muon flux is not well understood at the time of writing of this thesis: experiments using the most updated hadronic interaction models and measured cosmic ray fluxes as inputs see a deficit of muons in simulations compared to the data [111]. This deficit reaches up to 40% when measured in the KM3NeT detectors [112]. Hadronic interaction models are extracted from accelerator measurements at $\sim$ TeV centre-of-mass energies. Recent studies have shown that the muon puzzle tension could be alleviated [113], following observations of enhanced strangeness production by the ALICE collaboration, which could be explained by alternative hadronisation mechanisms [114]. Future measurements in LHC will place further constraints on hadronic interaction models at high energies, which will reduce the uncertainty on both the atmospheric neutrino and muon flux.

3.4 Detector simulation, reconstruction and calibration

This section presents a brief overview of the simulation chain in KM3NeT, detailing the procedure followed to obtain light signatures in KM3NeT, starting from an incident flux at the detector surface. What follows is a description of the reconstruction of the event observables, such as the event direction, energy and interaction vertex, from the observed light signals at the PMTs. Finally, an overview of the position and orientation calibration

in KM3NeT is given, as this topic formed a significant portion of the work conducted during the course of this PhD.

3.4.1 Detector simulation

The detector simulation proceeds in three distinct steps, after which the output files do not differ from files one obtains from data taking.

Firstly, events corresponding to scatterings of neutrinos with nuclei composing the seawater are generated on some imaginary surface surrounding the detector, referred to as the can. Secondly, the scattering products are propagated through the seawater, generating Čerenkov light, which in turn results in an electrical signal at the individual PMTs. In this step, light absorption and reflection are taken into account, as are the internal properties of the PMTs, such as their quantum efficiency. This simulation step results in a myriad of electrical signals at individual PMTs, each with its characteristic time stamp. Triggering algorithms are applied to this data, discerning causally connected PMT hits and rejecting noise caused by dark currents, bioluminescence or radioactivity.

3.4.1.1 Event generation

Neutrinos are generated with an internal software named *gSeaGen* [115], a GENIE-based [116] framework developed to extend the validity of the methods of GENIE, a Monte Carlo based event generator, to PeV energies. Three different volumes can be distinguished: the instrumented volume, containing the light detection elements; the can volume, the surface on which the light is generated, and the interaction volume, the volume within which interactions are generated. The can volume is usually defined such that it is larger in dimension (radius and height) than the instrumented volume by five times the attenuation length of photons in water, thus ensuring that any photons produced by these particles that could possibly reach the detector are simulated. The interaction volume, in the case of shower-like events, is equal to the can volume. For the case of track-like events, the interaction volume is defined by the maximum muon range in seawater, computed via Eq. 3.6.

The rate of neutrinos incident on the detector is very high, but of these only a very small fraction actually interact. Therefore, the simulation proceeds by forcing every incident

neutrino to interact, assigning a generation weight to each generated neutrino. This generation weight takes into account how the events were generated, i.e. with what spectrum, the probability of Earth absorption, the interaction cross section and more [115]. One can then simulate a physical flux at the detector by multiplying the generation weight by the flux:

$$w_{\text{event}} = w_{\text{gen}} \times \Phi(\theta, E). \quad (3.8)$$

Given an event energy and zenith angle, one multiplies the generation weights of the simulated neutrino events in KM3NeT by the Honda flux [117] at this energy and zenith angle, thus obtaining the correct number of atmospheric neutrino events incident at the detector, scaling for a certain data taking period.

Muons are generated in KM3NeT with an internal software named MUPAGE [118], given some muon flux model. The software generates muon bundles at certain water depths and zenith angles based on parameteric formulas, allowing for fast MC generation. The parametric formulas were tuned on CORSIKA [119], a software that simulates the interaction of cosmic rays in the atmosphere and propagates the secondaries down to sea level, accounting for interactions, decays and energy loss processes of the secondaries. In order to save computational time, muons are simulated for some fraction of the detector livetime, and are given an appropriate generation weight to upscale the number of events to the entirety of the detector livetime. This procedure is possible since muons do not exhibit a significant time variation, and they are the most dominant source of background, with millions of muons impinging on the detector per year. Therefore, one can simulate a portion of this flux and still have sufficient statistics for conducting analyses.

3.4.1.2 Light propagation

The propagation of light and its detection involves considerations of a number of physical processes, outlined below.

1. Processes leading to the emission of light, that is the Čerenkov radiation emitted by a particle traversing the detector medium, energy losses, radiative processes, hadronic interactions

2. The scattering and absorption of light in the medium
3. The response of the PMTs to the light incident on the PMT surface

Two approaches are followed in order to propagate the light, based on the energy on the primary particle: in KM3NeT/ORCA, low energy events with energies below 500 GeV are simulated with *KM3Sim* [120], a *GEANT4* [121] based software which sequentially propagates particles through the detector volume and calculates the emission magnitude and direction at each step. Due to the size of the detector, this method becomes computationally too intensive at higher energies, therefore a second approach is followed. A custom package named *JSirene* calculates the hit distribution of PMTs in the detector, based on the particle energy and direction, using pre-computed tabulated probability distributions which take into account absorption and scattering of light, and the efficiency of the PMTs.

3.4.1.3 Triggering algorithms

In order to faithfully reproduce the observed data, in this stage of the simulation a random noise simulation is added to the data, with a frequency corresponding to ^{40}K decays in seawater. Since there are variations in these rates, a run-by-run approach is followed: the data taking is divided into runs, data taking periods of 6 hours. Simulations are conducted per run, simulating the noise conditions observed during that run. What follows is a hierarchical application of triggers, each of which is designed to remove a certain portion of the noise detected by the PMTs.

The first trigger applied is the so-called L0 trigger, which is applied off-shore: only hits registering above 0.3 photoelectrons are sent to shore, where the time over threshold (ToT), the time during which the signal is above the described threshold, is stored. The L1 triggers is applied subsequently: this trigger requires the coincidence of two or more L0 hits from different PMTs placed on the same optical module, within a given time window, defined as 10 ns. Finally, an L2 trigger is applied, exploiting the spatial information of the hit PMTs, requiring a minimum angular separation between hit PMTs.

Dedicated track and shower triggering algorithms are applied afterwards, exploiting the information of the expected emission profiles of the two topologies. The track algorithm is named *3D muon*: this algorithm considers causally connected L2 hits - hits

are causally connected when their separation in time matches what is expected from a particle travelling the distance between the hit DOMs at a speed close to the speed of light. The causally connected hits within a cylinder of a given radius, which is dependent on the water absorption properties, are then grouped into an event: a number of different central cylinder axes are tested, in order to test the potential track directions. The *3D shower* algorithm applies a logic similar to the *3D muon* algorithm, with the exception that the expectation of the emission profile is spherical, instead of cylindrical. The sphere radius is then again dependent on the water properties. Hits that trigger the algorithms are saved, along with all the hits in the detector within a time window of the triggered hits, and the event reconstruction is applied to them.

3.4.2 Event reconstruction

The output of the trigger algorithm is a reduced ROOT [122] file containing triggered events for a given run or set of runs. The format of these files is equivalent for simulations and real data, therefore the methods described in this section are applicable both to simulated and real data.

3.4.2.1 Track reconstruction

The goal of the track reconstruction is to provide an estimate of the arrival direction, position of the interaction vertex and energy of the particle. The input for the track reconstruction are the amplitudes and times of each current pulse detected by individual PMTs. A muon track is described by five parameters: its direction, time, and position along the trajectory. The reconstruction proceeds through a maximum-likelihood fit, after initial constraints for the track are provided as a result of pre-fit procedures. A key variable which is computed at a given time t_0 for some muon position and direction is the expected arrival time of the emitted Čerenkov photon to some DOM. In order to reduce the dimensionality of the problem, a coordinate system is defined where the particle travels along the z-axis, and crosses $z = 0$ at a time t_0 and coordinates x_0, y_0 . The expected arrival time on the PMT denoted with index j is [123]

$$\hat{t}_i = t_0 + \frac{z_j}{c} + \tan(\theta_c) \frac{\rho_j}{c}. \quad (3.9)$$

The arrival time depends on the shortest distance between the muon and the PMT, $\rho_j = \sqrt{(x_j - x_0)^2 + (y_j - y_0)^2}$, the distance from the PMT to the $z = 0$ plane, and the Čerenkov angle, θ_c . This variable is compared to the measured arrival time of the photon to the DOM, and the difference between the expectation and measurement is named the time residual. The goal of the reconstruction is to find a track which minimises these residuals for triggered hits in the event.

The first step in the reconstruction is a linear pre-fit, which solves the Equation 3.9 after a selection of causally connected hits, in order to remove outliers caused by radioactivity, bioluminescence, and strongly scattered photons. The most likely track parameters are obtained via a minimisation of the χ^2 , repeating the procedure for each hit in the event:

$$\chi^2 = \sum_i^{\text{hits}} \frac{(t_i - \hat{t}_i)^2}{\sigma_i^2}. \quad (3.10)$$

The parameters t_i and σ_i denote the measured time and the time resolution of PMT i , and $\hat{t}_i$ is the expected arrival time for this PMT, obtained via Equation 3.9. The procedure is repeated for different track directions, with a grid angle of one degree, and the output of this stage are the 12 most likely directions.

What follows is a likelihood maximisation procedure, using the Levenberg-Marquardt method [124] to fit all five parameters of the particle trajectory simultaneously. The registered signal of each PMT can be described by a probability density function (PDF) dependent on the distance of closest approach of the particle to PMT i , ρ_i , the orientation of the PMT, described with angles θ and ϕ , and the time residual, Δt_i , the difference between the expected arrival time, expressed via equation 3.9, and the measured one. The likelihood equation can then be expressed as

$$\mathcal{L} = \prod_i^{\text{hits}} \frac{\delta P}{\delta t}(\rho_i, \theta, \phi, \Delta t_i). \quad (3.11)$$

The PDFs are calculated by taking into account the scattering and absorption of photons in the seawater, energy losses of the particle such as Bremsstrahlung radiation, the background from radioactivity, the quantum efficiencies of the PMTs, their angular acceptance and transit time spread. For the full configuration of the KM3NeT/ARCA detector, a reconstruction resolution better than 0.1° is achieved for events above 100 TeV

[123]. At energies below 1 TeV, the reconstruction resolution is limited by the kinematic angle, the scattering angle between the neutrino and produced muon [123]. The vertex reconstruction proceeds after the estimation of the trajectory, by back tracking the initial hits of the particle trajectory. Having obtained the event trajectory, the particle energy fit is performed next. The spatial distribution of the hit and non-hit PMTs in the vicinity of the trajectory are used in combination with the above described PDFs, comparing the hit probability with the measured presence or absence of a hit on that PMT.

3.4.2.2 Shower reconstruction

The shower reconstruction follows a similar approach to the track reconstruction, where an initial fit is conducted in order to provide adequate initial conditions for the subsequent minimisation.

The initial fit consists of a determination of the shower vertex position. Firstly, a coincidence conditional is applied by demanding that only hits within 20 ns on the same DOM are considered. In order to further suppress any possible influence of hits caused by background from radioactivity or bioluminescence, a significance is computed for each hit by the use of an M-estimator:

$$M = \sum_{\text{hits}} \sqrt{1 + (t_i - \hat{t}_i)^2}$$

$$\hat{t}_i = t_0 + \frac{n}{c} r_i. \quad (3.12)$$

The time of the hit t_i , the expected hit time of a spherical wave front $\hat{t}_i$ and its velocity $\frac{c}{n}$ are used to determine the significance. A minimisation is then performed to find the starting position and time of the shower, given the initial starting position as the center of gravity of the hits.

The vertex is used as a starting point for a direction fit, where the direction and energy are fitted using a maximisation procedure, testing 12 initial isotropic starting directions. The likelihood is then evaluated from the probabilities of observing a hit on a PMT, and the resulting measured or absent hit on that PMT. The reconstruction results in an

angular resolution at the level of a few degrees, and a resolution in energy below 10% above TeV energies.

3.4.3 Calibration of KM3NeT

3.4.3.1 Time calibration

An accurate reconstruction of a particle trajectory on a sub-degree level requires timing precision at the nanosecond level, as the resolution depends on the measurement of the arrival time of the Cherenkov light on the PMTs. Time calibration in KM3NeT is achieved at different scales: the synchronisation of PMTs in the same DOM (intra-DOM calibration) the calibration of different DOMs on the same DU (inter-DOM calibration) and the synchronisation of all the DUs with an on-shore clock distribution time system. Calibration can proceed in-situ, utilising well-defined periodic signals in order to compute the calibration constants of the elements in the detector, or with the usage of dedicated time synchronisation technology placed in the detector.

In a single DOM, the PMTs are calibrated from measurements of ^{40}K decays. The decays may cause a hit in multiple PMTs, which can be used to derive the time-offset between PMTs. The distribution of the hit time difference of a pair of PMTs is expected to be Gaussian, with a mean equal to the transit time difference between the PMTs, and the width being related to the PMT transit time spreads. The coincidence rate of a pair of PMTs, and the spread caused by the spatial distribution of decaying ^{40}K particles are determined from Geant4-based Monte Carlo simulations. The coincidence rate is then parametrised as a function of their angular separation, and the hit time distributions of all possible pairs of PMTs in a DOM are fitted simultaneously, deriving the PMT time offsets and transit time spreads.

The inter-DOM calibration aims at determining the propagation time of the clock broadcast signal between DOMs. The calibration is performed with the use of optical beacons present in the DOMs. Two different kinds of sources of short-pulsed light, the laser beacons and the nanobeacons [125], are utilised as cross-checks of the time calibration between DOMs. Studies have been conducted in order to understand the optical pulse

shape, and the timing of the emission is controlled via an on-shore clock signal broadcast. The timing measurement of the nanobeacon pulses allows for the synchronisation of individual optical modules.

The aforementioned clock broadcast system is implemented through the White-Rabbit protocol [126]. This protocol allows for a synchronisation of two devices connected via an optical cable: in the case of KM3NeT, this broadcast from shore is splitted to all off-shore nodes at the bases of each DU. The inter-DU calibration is based on the measurement of the Round-Trip-Time of the synchronisation signal from the master clock on-shore to each DU. The measurement must take into account delays caused by the different paths taken by each signal to reach each DU base and the chromatic dispersion in the fibers. A chromatic dispersion occurs due to the fact that the on-shore signal is emitted at a different frequency compared to the returning signal emitted by the DU base CLBs. The inter-DU calibration can be verified using the reconstruction of muon tracks, similar to the verification of the inter-DOM calibration. The outlied calibration procedure results in DOMs on different DUs being synchronised with an accuracy of a few nanoseconds [127].

3.4.3.2 Position calibration

The KM3NeT detector is placed in the deep sea, where it is affected by sea currents which cause the DUs to sway. The accurate reconstruction of particle trajectories requires the precise knowledge of the position of each detector element registering light from the particles. The predicted angular resolution of the full ARCA detector, better than 0.1° , requires the knowledge of the positioning of each detector element at a precision level of 20 centimetres [128].

The positioning system utilises piezo-electric acoustic sensors, housed within each DOM and at the bases of each DU. The sensors detect acoustic signals produced by emitters placed in tripod structures anchored to the sea bed. The emitters send signals approximately once per minute at a specific frequency recognised by the acoustic data filter in the piezo sensors. The output of the detected signal is a time-of-arrival measurement, and an emitter identifier.

The measured time of arrival of the sensor is converted into a best estimate of a time of emission. An acoustic event is triggered if enough sensors record a time of emission

within a time window. What follows is a fitting procedure, taking as input a set of acoustic events within a time period of 10 minutes, during which the detector is assumed not to move significantly. The fit produces as output an estimate of the detector geometry at that moment in time. The detector geometry is described by a set of fixed parameters, such as the anchor positions of the DUs, the height of each DOM with respect to the base, the position of the piezo sensor at the base of the DU, the emitter positions, and a set of dynamic parameters: two tilt angles and their second order corrections, a stretching factor which describes the stretching of the ropes due to the tilt, and the time of emission of each ping. The fit finds the best set of dynamic parameters by means of a χ^2 minimisation, computed as the sum of the differences between the measured and expected time of arrival of the signals on the sensors, derived from the best-fit geometry. The fit is performed every 10 minutes, and the dynamic positioning of the detector is implemented in the event reconstruction to account for the displacement of the detection elements. A precision below 10 centimetres [128] is reported when checking the agreement with muon track calibrations, described in more detail in the final section of this chapter.

3.4.3.3 Orientation calibration

Sea currents and movements of the detection elements result in twists and tilts of the DUs, which alter the pointing directions of the PMTs in DOMs. In order to preserve the accuracy of the event reconstruction, a knowledge of the orientation of the optical modules should be known within 3 degrees [128]. The relative orientation of the optical modules is achieved with compasses and accelerometers, which measure the Earth's magnetic field and gravitational acceleration in three directions. The measurements taken in the sea are converted from Cartesian coordinates to a yaw (ϕ), pitch (θ) and roll (ψ). The pitch and roll angles define the tilt of the device with respect to the horizontal position, whereas the yaw defines the orientation with respect to the magnetic North. Given some accelerometer measurement, A_x, A_y, A_z , and magnetometer values H_x, H_y, H_z , the pitch and roll can be defined as

$$\theta = \text{atan2} \left(A_x, \sqrt{A_y^2 + A_z^2} \right)$$

$$\psi = \text{atan2}(-A_y, -A_z).$$

In the horizontal system, the yaw can be computed from the magnetometer measurements:

$$\phi = \text{atan2}(-H_y, H_x).$$

If the system is tilted, “unpitching” and “unrolling” must be performed on the magnetic field measurements, H , to align to the horizontal system:

$$H_{\text{hor}} = C^{-1}B^{-1}H,$$

where C and B are the pitch and roll rotation matrices. The yaw is then computed from the horizontal components and the pitch and roll as

$$\phi = \text{atan2}(-H_{y,\text{hor}}, H_{x,\text{hor}}).$$

The field measurements in each direction need to be corrected for the internal offsets of the devices, and for potential gains of the accelerometers, which can vary up to $\pm 11\%$. The accelerometers onboard the KM3NeT optical modules have an offset spread of ~ 100 mg, g being the Earth’s gravitational acceleration. Uncorrected for, such offsets could result in an error of up to 5° for measurements in the horizontal system, and an additional 3° error for tilts at 10° . Uncorrected gains result in an error of 1° in the horizontal system, and an additional 1° in a system that is tilted by 10° . In order to correct for the internal offsets and gains of the devices, the devices are calibrated in a lab before they are placed in optical modules and integrated into the detector. The calibration is performed by placing the devices on a rotating gyro-gimbal. The devices are rotated around the x,y and z axes, repeated again for an inverse placement of the device, and two rotations with an incline of 45° with respect to the z-axis, for a total of 8 rotations. The rotations result in readings of both devices forming a sphere in the $[A_x, A_y, A_z]$ and $[H_x, H_y, H_z]$ coordinate system. The deviation of the sphere centre from the origin of the coordinate system reveals the internal offset of the device, whereas the deviation of the sphere radius from the value of the Earth’s gravitational acceleration reveals the gain of the accelerometer. The measured gains and offsets are saved in a database, allowing for a simple retrieval of the data when the devices are taking data in the sea.

The calibration of the DU twists proceeds by fitting compass data in a time window of 10 minutes. The fit function is a polynomial expressed in terms of quaternions, values

which describe the rotation of the compass and accelerometer measurements around some principle axis $\hat{u}$. The fit minimises a χ^2 , given as the square of the smallest angle between the measured and modelled quaternion of all DOMs within a DU. The above described procedure shows an agreement within a few degrees [129] when cross-checked with the muon track calibration method.

3.4.3.4 In-situ calibrations with atmospheric muons

The above described calibration methods can be verified with additional calibrations using atmospheric muon events [130]. The reconstruction of atmospheric muon tracks can be used to calibrate the relative time offsets between DUs, and their position and orientation, referred to as the track quality method. It relies on the fact that the reconstruction likelihood depends on the hit properties, thus also on the relative position, orientation, and timing of each registered hit. The calibration parameters are varied one at a time, and the likelihood is maximised for a range of values around the optimal value obtained from the conventional calibration. The optimum calibration parameters are the ones which maximise the variable $Q = \mathcal{L}/n_{\text{hits}}$, the ratio of the likelihood and the number of hits used in the reconstruction.

An additional in-situ inter-DOM time calibration method has been developed as an additional cross-check, exploiting hit time residuals [129]. The method consists of selecting events with at least 7 DOMs registering L1 hits. An iteration over DOMs then commences, excluding one DOM from the track reconstruction each time. One can then compare the measured hit time of the excluded DOM to the expected hit time of the reconstructed track, obtaining a time residual. This residual distribution is then compared to Monte Carlo simulations of the same procedure, and the time offset is obtained by maximising the agreement between data and Monte Carlo distributions bin-by-bin.

The performance of the calibration can be evaluated by observing the Moon and Sun shadow in cosmic rays [131]. Namely, cosmic rays are blocked by nearby celestial objects, causing a deficit of events in the direction of these objects. The width of the shadow and its deviation from the origin, the expected centre of the object, can be evaluated by conducting the analysis in coordinates centred at the celestial object. The deficit of cosmic rays in angular bins is described as a bi-dimensional Gaussian. The width of the shadow is a measure of the angular resolution, defined as the standard deviation of the

bi-dimensional Gaussian. In order to fit it, the objects are assumed to be centred at the origin, and a fit is performed to obtain the most likely value of the parameter. The amplitude of the shadow and the track density, the muon density as a function of zenith, expressed as a polynomial function, are fitted along with the shadow width. In order to fit the displacement of the shadow with respect to the expectation, the shadow width is fixed to a value obtained from MC simulation. The displacement of the shadow with respect to the expectation represents the absolute pointing error. This error is evaluated by fitting the shadow centre, along with the above mentioned parameters describing the shadow amplitude and muon track density. The angular resolution, estimated from the shadow width, is reported as $\sigma_{res} = 0.53^\circ$, while the displacement of the shadows with respect to the expectation is reported as being at the order of $\mathcal{O}(0.1^\circ)$ [131]. The Moon and Sun shadows are detected with a significance of 4.2σ and 6.2σ , respectively [131].

4

Analysis methods

The following chapter describes the methodology followed in order to search for dark matter in the data sets of the KM3NeT detector. The chapter is divided into sections which aim to sequentially explain the steps followed in order to reach the final results. Firstly, a description of how the data is selected is provided in Sec. 4.1 - from the selection of data taking periods, referred to as runs from hereon, to the selection of individual events based on their reconstructed quantities. In Sec. 4.2 the methodology followed to obtain the probability density functions of the signal (neutrinos from WIMP annihilations) and the background (atmospheric muons and neutrinos) is described. Sec. 4.3 describes the unbinned likelihood methodology followed in order to measure a potential signal or obtain a limit on the number of signal events that can be rejected with some confidence in the data samples. Sec. 4.4 describes how the limit on the number of signal events is converted to a limit on the incoming flux, and thus the WIMP self-annihilation cross section. Section 4.5 describes an alternative methodology used in order to derive the sensitivity and upper limit to the WIMP annihilation cross section for the purpose of combining limits from different experiments, including γ -ray observatories. Finally, Section 4.6 describes the methodology employed in order to search for dark matter in the Sun.

4.1 Data and event selection

4.1.1 Run selection

The previous chapter described how data is recorded in KM3NeT and how hits are causally selected in order to form an event, i.e. a collection of causally connected hits, which are then reconstructed with dedicated track and shower reconstruction algorithms. The events are grouped into data taking runs - one run is defined as a 6 hour time period of data taking. Data is thus processed run-by-run, allowing for precise simulations of the detector conditions during each of these runs, and for efficient parallelisation of the processing. The mean PMT rates are measured per run and simulated accordingly, along with the detector calibration providing the best fit.

Runs with unfavourable data taking conditions are rejected prior to their further processing. This includes periods of downtime due to the installation of new detector components, calibration runs, runs with technical issues such as sparking PMTs or non-responsive DOMs, runs with extremely high bioluminescence or runs that do not pass run quality criteria. Run criteria are set to monitor certain data quality variables, in order to identify runs for which the data quality variables are unstable, or below or above a certain threshold. Some of the data quality variables monitored and their threshold values within which runs are accepted are:

- The livetime of the run, defined as the sum of all the timeslices received on shore. Acceptance region: $[1200, 60000]$ s
- The number of missing time slices, defined as the difference between the run livetime computed as the difference between the end and start time of the run, and the livetime computed as the sum of all the time slices received on shore. Threshold < 100
- The trigger rate, i.e. the amount of event triggers per second. Acceptance region: $[0.05, 50]$ Hz
- UDP packet loss, which is a measure of the average amount of frames without packet loss. Acceptance region $[0.95, 1.05]$.

- High rate veto, calculated as the average fraction of time with a PMT in the high rate veto state, a state in which the PMT rate is above a certain threshold and its data is rejected. Acceptance region: $[0.0, 0.5]$
- Mean rate - the mean rate on a PMT during the data taking period. Acceptance region: $[4500, 15000]$ Hz
- Data acquisition defects: wrong run setups or crashes of the data acquisition system
- Calibration defects: missing calibrations for certain runs
- Data processing defects: runs for which errors were encountered in processing due to corrupted metadata, failures in reconstruction, etc.
- Analysis defects: runs for which an unusually high data-MC disagreement has been observed

Run quality plots have been produced for one configuration used in this analysis, the ARCA detector with 21 DUs, and are shown in Fig. 4.1. The panel on the left of the

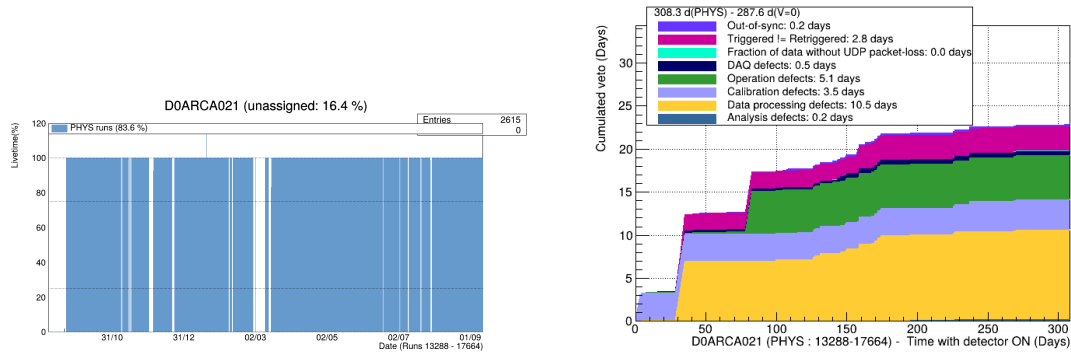


FIGURE 4.1: The run selection status during the data taking of the ARCA21 detector. The plot on the left shows which runs were selected as physics runs, runs passing the selection criteria which are then used in physics analyses such as the dark matter search conducted in this work. The plot on the right shows the amount of livetime lost due to different veto criteria.

Figure illustrates the selected runs as a function of time- physics runs (referred to PHYS runs in the Figure) are runs passing all quality criteria which are used in subsequent physics analyses. The plot on the right shows the cumulated veto, i.e. the amount of time lost due to different veto criteria explained above.

Configuration	analysed period	effective livetime [days]	number of selected events
ARCA8	26.09.2021 - 01.06.2022	210	647
ARCA19	10.06.2022 - 12.09.2022	52	517
ARCA21	22.09.2022 - 11.09.2023	289	914

TABLE 4.1: The data taking period, the effective livetime and the number of selected events of each data set after the application of a quality run selection and an event selection as described in the text. The detector configuration is defined as the number of active detector units, as indicated by the number ending the ARCA acronym.

4.1.2 The data samples used

The work presented in this thesis has been conducted on the data of the KM3NeT/ARCA detector in the period between September 2021 and September 2023. Two sea operations were conducted during this time period, during which additional detection units have been installed. Therefore, the data sample and the simulated data can be divided into three time periods. The event selection was optimised separately for each of them, and signal and background expectations are computed separately for each period. The first one will be referred to as ARCA8 from hereon. This period refers to data taken between September 2021 and June 2022, during which 8 DUs were taking data. The sea operation in June 2022 increased the number of DUs to 19, and this second period lasted until September 2022, referred to as ARCA19. The sea operation in September added two new DUs to the detector, hence the period between September 2022 and September 2023 will be referred to as ARCA21. Table 4.1 contains information on the data taking period, the effective livetime and the selected number of events after the application of an event selection for the three configurations. The sea operation in September 2023 increased the number of DUs to 28, but at the time of writing of this thesis this data is not available for analysis due to unexpected timing calibration issues.

4.1.3 Event selection

Runs passing the run quality criteria are processed further to create lighter files to be used in physics analyses. The analysis conducted in this thesis is performed on such files, labelled Data Summary Tapes (DSTs), where different data taking runs are grouped together into larger time periods. Furthermore, in order to speed up the processing, hit information is not present in the DSTs. Only the reconstructed variables of the best reconstructed track and shower are stored in this file format. The best reconstructed

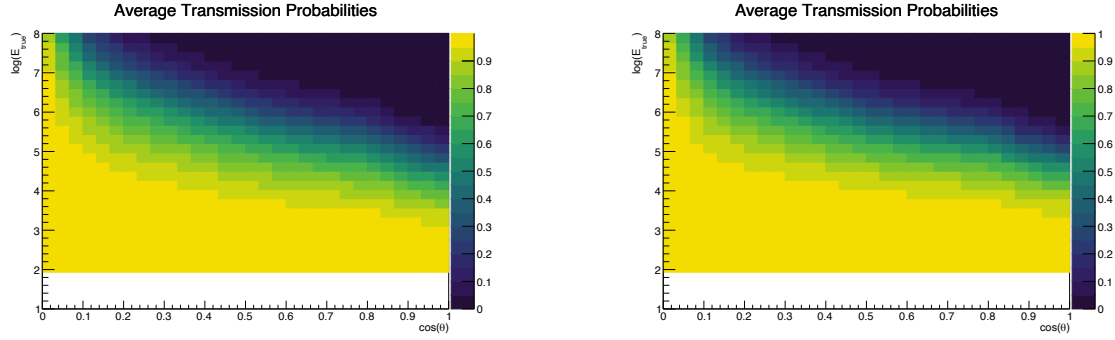


FIGURE 4.2: The transmission probability of muon neutrinos (left) and antineutrinos (right) as a function of the logarithm of the neutrino energy, and the cosine of the zenith angle.

track and shower are defined as the solutions which maximise the likelihood for each of the hypotheses.

The work conducted in this thesis focuses on track events, from charged current scatterings of muon neutrinos. As stated previously, due to the large path length of relativistic muons passing through the detector, the incoming direction of this class of events can be determined with a high accuracy. The main source of background for this class of events are atmospheric muons: the amount of atmospheric muons detected by KM3NeT is orders of magnitude larger than the amount of atmospheric neutrinos, as only a small fraction of the neutrinos interact in the vicinity in the detector and produce a lepton which leaves a detectable trail of light. In order to remove these muons, only events with reconstructed directions below the horizon are considered, referred to as upgoing events from hereon. Upgoing events traverse the Earth prior to arriving at the detector. Atmospheric muons are thus absorbed by the Earth, while neutrinos up to $\sim \text{TeV}$ energies have a negligible probability of absorption. The transmission probability of neutrinos as a function of their true energy and zenith angle is shown in Fig. 4.2, for muon neutrinos and antineutrinos. As seen in the Figure, the phenomenon of absorption only affects through-going signal events at the largest WIMP masses tested ($100 \text{ TeV}/c^2$), for most masses tested it has a negligible effect.

A significant portion of atmospheric muons are reconstructed inaccurately, with upgoing reconstructed directions. This is illustrated in Fig 4.4, where the distribution of the BDT score, described in the following paragraph, is shown after the application of the initial selection requiring an upgoing reconstructed track direction. As seen in the

Figure, after this condition is applied the bulk of the sample still consists of misreconstructed muons. Therefore, conditions on reconstruction variables that reflect the quality of the reconstruction procedure must be placed in order to remove the remainder of atmospheric muons. Additional features are computed when creating DSTs in order to better characterise the event properties. Firstly, features which test how well the best-fit track solution converges: the number of prefit track solutions within one degree from the best reconstructed track, the number of downgoing/upgoing tracks, the zenith spread of the prefit tracks. Secondly, features which test further the compatibility with the Čerenkov cone emission hypothesis are computed, comparing the time residuals of hits with respect to the best-fit track solution. These features include: the distance between the closest and furthest hit from the interaction vertex having a time residual below 15 nanoseconds, the number of such hits within 100 metres of the vertex compared to the total number of such hits, the number of hits with a small time residual for both the track and shower hypothesis.

The above described variables and features are provided as input to a Boosted Decision Tree (BDT) algorithm, a machine learning method aimed at classifying events based on the input features of the population, in this case reconstructed events in KM3NeT. Before the algorithm is described in more detail, the goals and methods employed in using it will be introduced. BDTs are used in order to classify reconstructed events, specifically to identify well reconstructed neutrinos and to reject atmospheric muons. To achieve this, the algorithm is provided with training data and the signal to search for: in this case, simulated neutrinos with reconstructed angular errors smaller than one degree was the target class of events we were trying to isolate from the rest of the population. The algorithm iteratively trains on the training data until it obtains a classifier model, which takes input features of the event and produces a score between -1 and 1 based on the event features. A score close to 1 signifies a high probability of the event belonging to the signal class.

The classification procedure of a decision tree learning algorithm consists of a recursive splitting of the input data based on the provided features until reaching the terminal node, where a probability of belonging to a class is assigned based on the input features of the event. The splitting of the data is performed with the aim of minimising entropy - each split should maximise the separability of the two classes we are trying to identify. Tree boosting refers to the grouping of many decision trees into a classifier by the means of

iterative creation of trees - each created tree is given a weight based on its accuracy, and the output of the ensemble of trees is the weighted sum of all the tree outputs. The iteration proceeds until the *loss function* is minimised. The loss function quantifies the distance between the truth and the classifier output after each step. Different methods can be employed to iteratively add trees until the loss function is minimised; in this work the technique of gradient boosting was employed. This technique involves the use of gradient descent, a process where the gradient of the loss function with respect to the current prediction is computed: this gradient is then minimised in the following step, and the process is repeated until a given accuracy is reached.

Boosted decision trees were utilised in the event selection of the ARCA19 and ARCA21 samples. For the ARCA8 sample, the event selection consisted of conditions on reconstructed event variables, as machine learning-based methods were still under development at the time. The variables offering the largest separability between muons and neutrinos include the reconstructed track length, the estimated angular error in reconstruction, and the track likelihood (the likelihood value obtained from the likelihood maximisation in the track reconstruction). A plot of the distributions of the above mentioned reconstruction variables is shown in Fig. 4.3 for data events and the MC expectation in the ARCA8 detector. A plot of the BDT score distributions in the ARCA19 and ARCA21 detector is shown in Fig. 4.4.

In order to determine the threshold value for each selection variable after the cut, the following is considered:

- The resulting muon contamination in the sample
- The neutrino efficiency
- The agreement between data and simulations
- The quality of the event reconstruction

Muon contamination refers to the percentage of the background sample consisting of atmospheric muons after the application of the selection. Cut values which minimise the muon contamination are searched for. The neutrino efficiency refers to the ratio of the number of neutrinos surviving the selection and the number of neutrinos prior to the application of the selection. Event selections should aim to maximise this variable, as

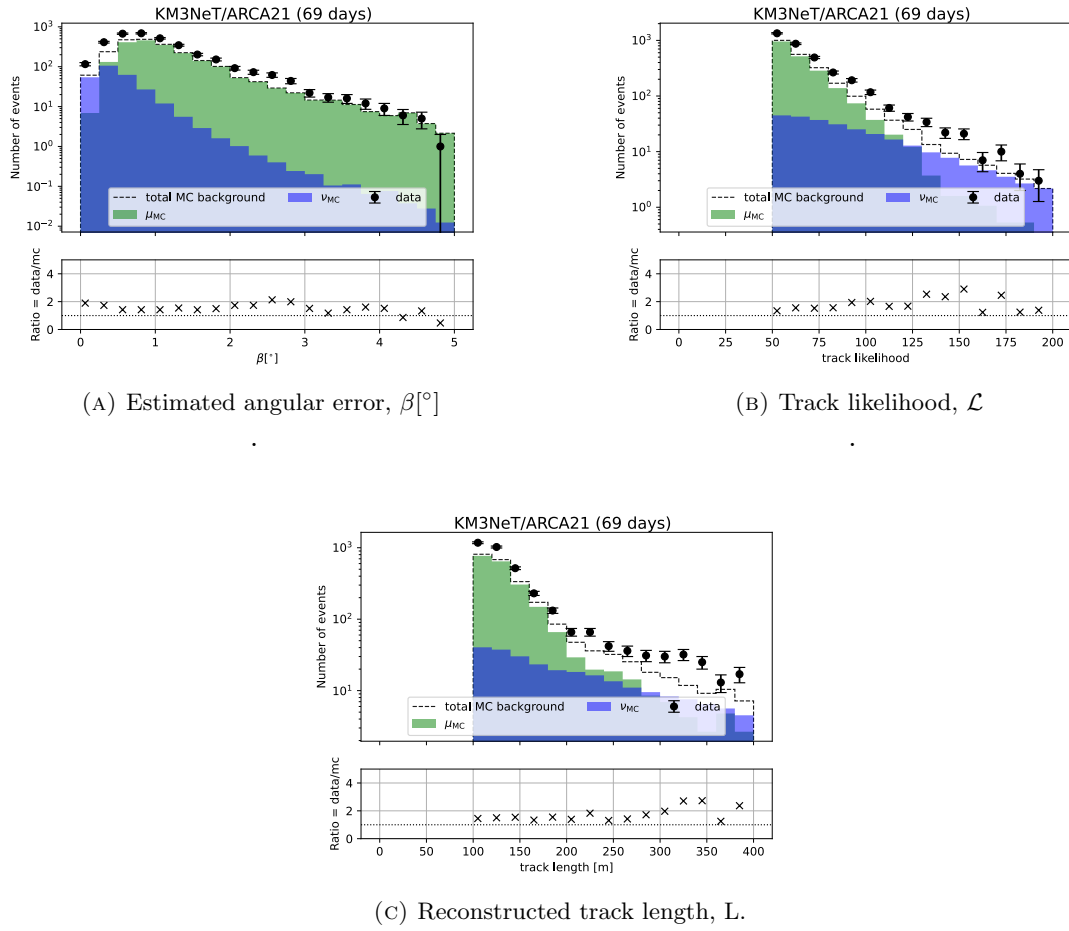


FIGURE 4.3: Distributions of reconstruction variables used in the ARCA8 selection, shown for data events and the atmospheric muon and neutrino simulation.

this variable indicates the amount of signal neutrinos, neutrinos produced by dark matter annihilations, surviving the selection. The agreement between data and simulations is also considered - extreme cut values which may provide superior discrimination of neutrinos from atmospheric muons are rejected if the agreement between data and simulations deteriorates significantly. Finally, the quality of the event reconstruction is also considered. Measures of the quality of reconstruction include the angular and energy resolution. Improvements in resolutions imply that the signal and background expectations provide a more accurate representation of reality, resulting in a superior discrimination of the signal neutrinos from dark matter annihilations. The angular distribution of signal events will be less dispersed around the source centre with improving angular resolution, and the reconstructed energy distribution will more closely resemble the expected distributions of true energy.

The event selection is applied to each configuration in stages. In the first stage, cuts

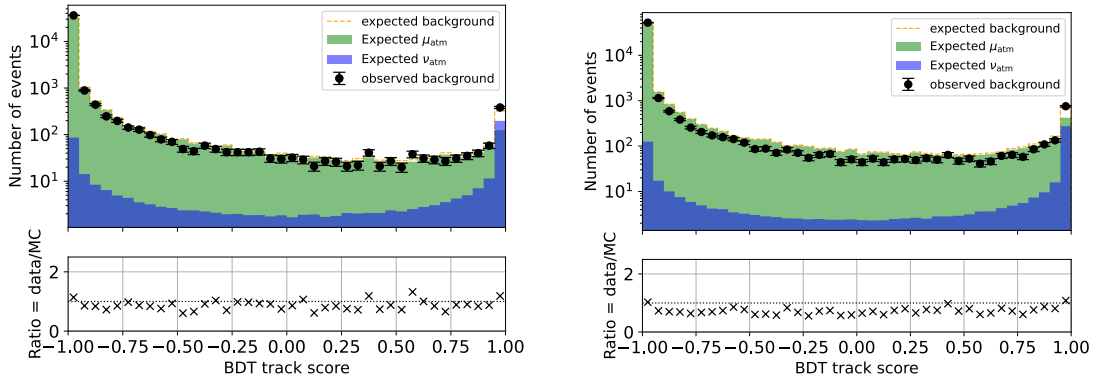


FIGURE 4.4: BDT score distributions of data events and the MC background expectation prior to the application of the final event selection, shown for the ARCA19 detector (left) and ARCA21 (right). Black dots indicate data events, the atmospheric muon simulation is shown in green, the atmospheric neutrino simulation in blue and the dashed line indicates the total number of simulated background events. The ratio plot compares the number of data events in each bin to the total number of expected background events from simulations. The final selection places a cut on the BDT score at 0.95, for both the ARCA19 and ARCA21 detectors.

that will be referred to as anti-noise cuts are applied first. This selection applies loose conditions on reconstruction variables in order to remove noise events, events induced by electrical noise recorded by the PMTs - ^{40}K decays, PMT dark currents and other sources of noise. A common anti-noise selection is applied to all three detector configurations, requiring a minimum number of hits and a minimum track likelihood, which removes all the simulated noise events in each configuration:

$$\mathcal{L}_{\text{track}} > 50 \ \&\& \ N_{\text{hits}} > 20. \quad (4.1)$$

An additional condition is then applied on the resulting data sample, cleared of noise events: the reconstructed event direction is required to be upgoing. Two different sources are studied in this thesis: dark matter is searched for in the direction of the Galactic Centre and the Sun. The Galactic Centre stays below the horizon for $\sim 70\%$ of the calendar year, while the Sun stays below for half of the time, at the geographic location of ARCA. The upgoing sample is further analysed to improve the sample quality. The discrimination power of reconstructed variables is tested by computing quantiles of the atmospheric muon and neutrino simulations, estimating which cut values would remove a certain percentage of atmospheric muons, what is the resulting amount of atmospheric neutrinos surviving this cut, and what is the resulting agreement between data and MC

Configuration	muon contamination	selection efficiency [1 TeV/ c^2]	selection efficiency [100 TeV/ c^2]
ARCA8	60.2%	41.2%	49.2%
ARCA19	27.2%	68.8%	77.2%
ARCA21	43.3%	73.9%	80.7%

TABLE 4.2: The muon contamination and selection efficiencies for WIMP masses of 1 TeV/ c^2 (column 3) and 100 TeV/ c^2 (column 4) for the muon annihilation channel are shown for the three ARCA configurations analysed. The selection efficiency is defined as the ratio between the selected muon neutrino signal events after the application of the final selection and the number of muon neutrino signal events detected after the application of an upgoing, anti-noise selection only.

after the cut placement. This procedure identifies potential variables to be used in the event selection. Different cut thresholds are then applied to these variables, in order to compute the resulting muon contamination, neutrino efficiency, data-MC agreement, and detector resolutions. The amount of signal neutrinos surviving the cut for different signal hypotheses is also considered: since we are testing a wide range of possible WIMP masses, certain selections will achieve a larger neutrino purity, at the expense of the rejection of a lot of low energy events which are difficult to reconstruct accurately. Therefore, such selections result in superior sensitivities to neutrinos produced by annihilations of WIMPs with a large mass, but are not adequate for neutrinos produced by lower mass WIMPs, as these selections will reject most of the signal. Therefore, the event selection is optimised for each signal hypothesis independently in order to maximise the sensitivity of the data set to the signal that is searched for. Table 4.2 shows the achieved muon contamination and selection efficiency of signal events.

The achieved quality of reconstruction with the final selection applied to the ARCA21 sample is visualised in Fig. 4.5. As seen in the plot on the left, a sub-degree angular resolution is achieved above 1 TeV. The slight worsening of the resolution at higher energies has been consistently observed with all data samples, but since it occurs above the energy range considered in this analysis (only masses $m_{\text{WIMP}} < 100\text{TeV}/c^2$ are considered), it has not been thoroughly investigated in this work. For this subset of high energy events, the energy resolution also degrades, with an underestimation of event energies becoming more pronounced above 100 TeV.

4.1.4 Selection efficiency: effective areas and acceptances

The methods described in the previous section try to maximise the purity of the event sample, clearing it of atmospheric muons that were reconstructed as upgoing. An increase

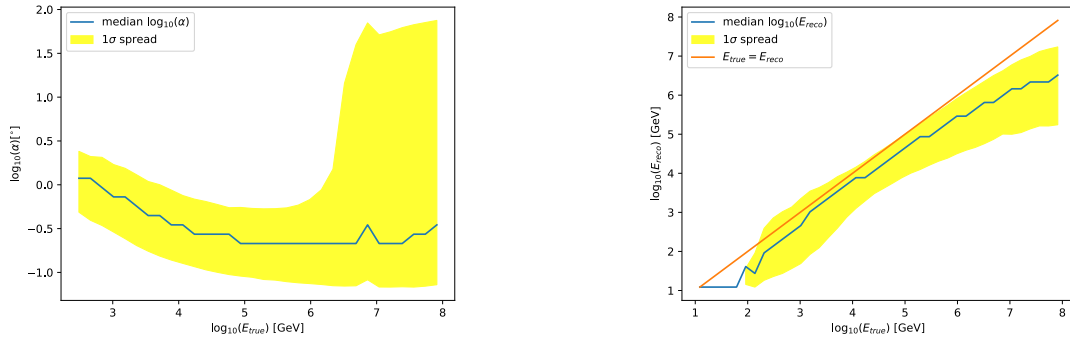


FIGURE 4.5: The angular resolution achieved with the final selection for the ARCA21 data sample is shown on the left: the x-axis shows the logarithm of true energy, while the y-axis shows the logarithm of the angular error in degrees. The median of the angular error in each bin is plotted as a blue line, while the yellow shaded region indicates the 1σ spread. The plot on the right shows the logarithm of the true energy on x-axis, and the logarithm of the reconstructed energy on the y-axis. The median reconstructed energy in each true energy bin is plotted as a blue line, with the corresponding spread shown in shaded yellow. The orange line indicating $E_{true} = E_{reco}$ is shown for comparison.

in the strictness of the event selection will remove muons more rigorously, but a certain portion of signal neutrinos will also be removed. Two observables are computed in order to measure this effect: the detector effective area and acceptance. The detector effective area represents the area equivalent of a 100% efficient detector. It is computed from simulations as the ratio between the number of selected events after the application of the event selection and the total simulated neutrino flux. In practice, it is computed using the generation weight, used also to reweight events to a certain flux, as seen in Eq. 3.8. The effective area is computed for each flavour separately, expecting the largest effective area for muon neutrino events, as the event selection is designed to select well-reconstructed tracks. The quantity is binned in energy and declination. The detection efficiency of events grows rapidly with energy due to the increase in the neutrino interaction cross section with energy and the greater detection efficiency at higher energies due to the larger amount of light emitted. Due to the varying visibility of different declinations at the geographical position of KM3NeT/ARCA, the effective area also varies with the declination of events. The effective area for the declination of the Galactic Centre is shown for different detector configurations in Fig. 4.6.

The effective area of each neutrino flavour is used in the calculation of the signal acceptance, a measure of a detector sensitivity to a certain energy spectrum. It is computed by convolving the effective area with the predicted signal spectrum, i.e. the spectrum of

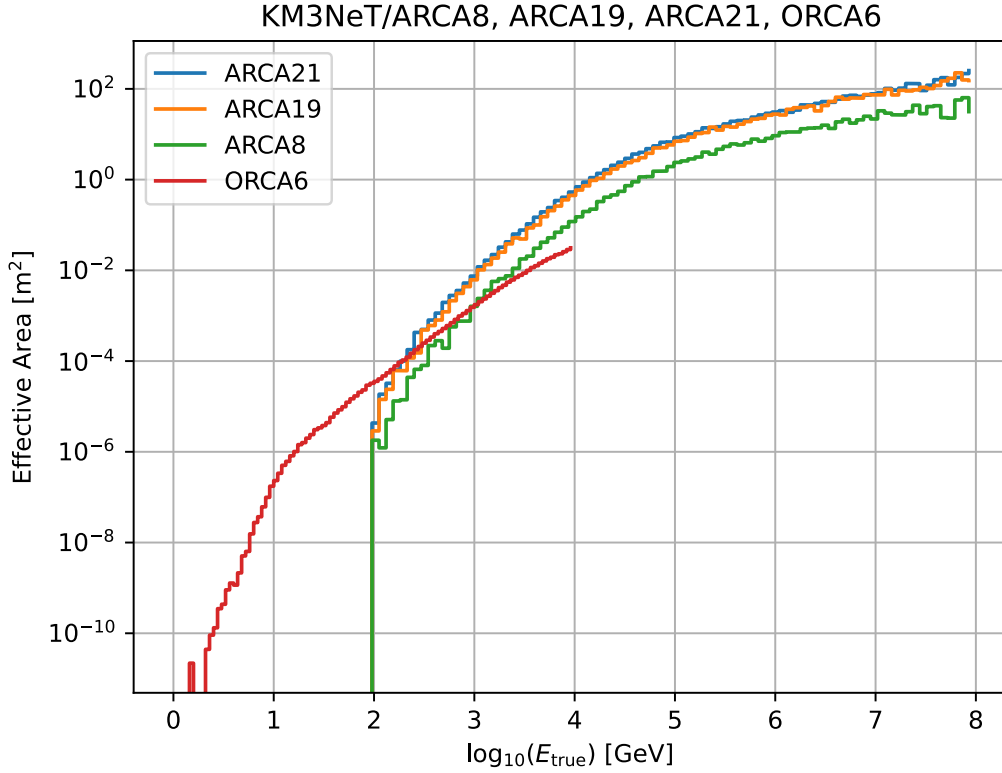


FIGURE 4.6: The muon neutrino effective area, binned in energy, for different detector configurations, at the declination of the Galactic Centre, $\delta = -29.01^\circ$.

neutrinos from dark matter annihilations:

$$\text{Acc}_d = \frac{\int_{E_{\text{th}}}^{m_{\text{WIMP}}} A_{\text{eff}_d}(E_\nu, \delta) \frac{dN}{dE} dE_\nu}{\int_{E_{\text{th}}}^{m_{\text{WIMP}}} \frac{dN}{dE} dE_\nu}. \quad (4.2)$$

The subscript d will be used to denote a specific detector configuration throughout this chapter (ARCA8, ARCA19, ARCA21). The quantity E_{th} represents the threshold energy, the minimum energy that can be detected with the instrumentation, defined as 100 GeV in ARCA. In the case of multiple neutrino flavours, the total acceptance is computed with the following formula:

$$\text{Acc}_d = \frac{\sum_{e,\mu,\tau} \int_{E_{\text{th}}}^{m_{\text{WIMP}}} A_{\text{eff}_{i,d}}(E_\nu, \delta) \frac{dN_i}{dE} dE_\nu}{\sum_{e,\mu,\tau} \int_{E_{\text{th}}}^{m_{\text{WIMP}}} \frac{dN_i}{dE} dE_\nu}. \quad (4.3)$$

The index i denotes the neutrino flavour. Given some flux of neutrinos produced by annihilations in the Galactic Centre, the number of neutrinos detected in the detector will be equal to

$$N_d = \Phi \cdot T_d \cdot \text{Acc}_d. \quad (4.4)$$

T_d is the effective livetime of the configuration d . The flux is obtained through the expression in Eq. 2.10; it depends on the thermally-averaged pair annihilation cross section, the J-factor integral, the squared WIMP mass and the integrated spectrum.

In the case of analyses on multiple detector configurations, the expression in Eq 4.4 can be used to determine the relative amount of signal expected in each detector configuration. Given some input flux, the number of events depends on the signal acceptance and livetime of the configuration d . By measuring these two quantities, one can estimate which data set will measure the largest amount of a potential signal flux.

4.2 Signal and background modelling

In an unbinned likelihood analysis, signal and background models are created from the available neutrino simulations and data events for a given data taking period. These models are required for the creation of fake data sets and for the evaluation of signal and background likelihoods. This section describes the methodology followed to obtain signal and background models that are then used in the likelihood analysis.

The separation of signal neutrinos originating from WIMP annihilations from the atmospheric background is achieved using two reconstructed event observables: the direction and energy of the event. Neutrinos produced in WIMP annihilations in the Milky Way will arrive to the Earth from the densest region of the dark matter halo, the Galactic Centre. The emission will not be point-like, as it originates from a spatially extended spherical halo. The flux is modelled using an emission profile, i.e. a distribution quantifying the probability of neutrino emission as a function of the distance to the source centre. The distribution of background events in space and energy can be estimated from MC simulations of the atmospheric neutrino and atmospheric muon flux, or inferred directly from data, following a blinding strategy. In this work, background distributions computed from blinded data are used.

4.2.1 Background estimation method

Background events (atmospheric muons and neutrinos) are produced almost isotropically in the atmosphere, but they do not appear isotropic in the detector. The selection of only

upgoing events implies that at any given time, approximately half of the sky is inaccessible. Combined with the effect of the Earth's rotation, this will result in certain declinations being within the detector's field of view more often than others at the geographical position of KM3NeT/ARCA in the south of Italy. The right ascension distribution of detected background events is uniform, as such it is not required in order to accurately describe the spatial behaviour of the atmospheric background. In the blinding procedure, this coordinate is obtained by sampling a random value in the allowed range of angles, $[0 - 2\pi]$, while the rest of the event information is obtained from the data events. The randomisation of right ascension values ensures that any signal events in the data set are displaced from their original direction.

The probability density function of the atmospheric background is parametrised as a 2D function of the reconstructed energy and declination of data events. The choice of a joint distribution comes from the fact that the declination distribution changes from bin to bin when binned in energy. At lower energies certain incoming angles result in events not passing through the entirety of the detector and leaving a very small fraction of visible light. At higher energies, an event coming from the same direction may be detected, as the amount of light emission is greater. On the other hand, very high energy events have a non-negligible probability of being absorbed by the Earth, with vertically upgoing events having the highest probability, as the path they have to traverse through the Earth is the largest (see Fig. 4.2). The probability density function of the atmospheric background in the ARCA21 detector is plotted in Fig. 4.7. Two distributions are shown

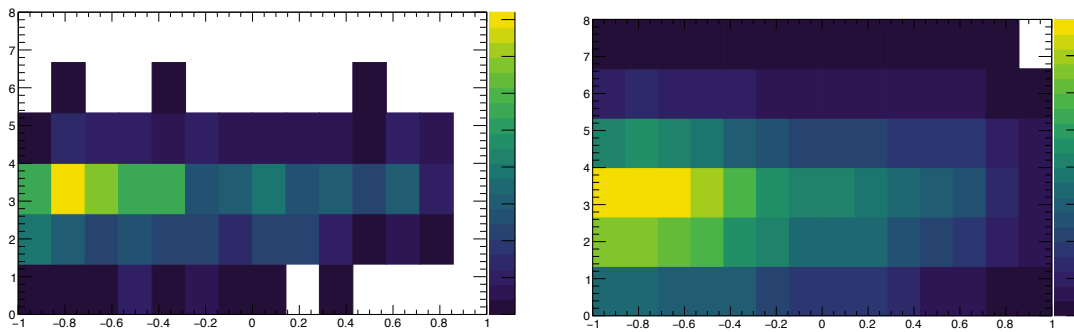


FIGURE 4.7: The background distributions in the ARCA21 detector, showing the sine of the declination angle on the x-axis, and $\log_{10}(E_{\text{reco}})$ on the y-axis. The distribution on the left is obtained by binning the data detected throughout the lifetime of ARCA21. The distribution on the right is obtained after a smoothing procedure has been applied to the distribution on the left, described in more detail in the main text.

in the figure: the distribution on the left is obtained from data, after the event selection has been applied. The sine of the declination of the events is on the x-axis, while the y axis is $\log_{10}(E_{\text{reco}}/\text{GeV})$. The sine is used in order to ensure uniform binning in solid angle. The distribution on the right is obtained by smoothing the histogram on the left. A smoothing using Gaussian kernel density estimation is applied in order to obtain the new distribution, representing the background probability in different bins in declination and reconstructed energy. Kernel density estimation is a procedure in which the value of some function $f(x)$ at a point $f(x_i)$ is evaluated as a sum of contributions from points across the phase space, using a kernel function to represent the relation between points - Gaussian kernels utilise Gaussian functions as the kernel. The smoothing is applied in order to ensure a correct minimisation of the likelihood: problems were encountered in the computation of the minimum likelihood when distributions with many empty bins are used. More details on the minimisation procedure, the problems faced and the specific solutions employed to fix them will be described in Sec. 4.3 which gives an overview of the likelihood analysis.

4.2.2 Neutrino spectra from WIMP annihilations in the Galactic Centre

The neutrino spectra resulting from a pair annihilation of two WIMP particles is estimated with PYTHIA, an MC event generator used to simulate particle collisions. At the time of writing of this thesis, the neutrino spectra computations available in the literature used versions of PYTHIA that did not incorporate the full range of possible interactions producing on-shell electroweak bosons. Two different computations of the neutrino spectra were used in this work. Comparisons were conducted to evaluate the impact of the different approaches to the computation of the final state neutrinos. The differences arise in how the initial states produced from WIMP annihilations, produced with a virtuality scale $\mu \sim m_{\text{WIMP}}$, with $\mu \gg q_w$ being above the electroweak scale, q_w , are evolved up to the electroweak scale q_w , beyond which MC generators such as PYTHIA include the full scale of interactions.

The first approach, known as the poor particle physicist cookbook for dark matter indirect detection (PPPC4DMID, abbreviated to PPC in the text) [76], uses PYTHIA to generate annihilation spectra and augments them with leading-order electroweak corrections. The corrections are computed using leading-order electroweak splitting functions

derived in the collinear approximation and added analytically by convoluting the initial spectra from PYTHIA [132]. In contrast, the approach followed in the BRW publication [77] performs an evolution of fragmentation functions using the DGLAP (Dokshitzer, Gribov, Lipatov, Altarelli, and Parisi) equations. These equations track how particles split into other particles as a function of energy, accounting for additional radiation due to electroweak effects at high energies. It includes triple gauge couplings, and the dynamic modeling of EW showers, accounting for cascading effects of the emission of multiple EW bosons. The evolution is performed from the DM mass scale down to the electroweak scale, at which point the massive gauge bosons are integrated out, and Pythia is used only for the low-scale evolution. In order to evolve the DGLAP equations, the authors assumed the EW bosons to be massless, which would neglect kinematic suppression of EW boson emission at energies around the electroweak scale, resulting in an overprediction of final states at low energies. Therefore, each calculation has its advantages and drawbacks and each may be more accurate in a certain regime of energies. In this work, both calculations are used to compute the expected energy distributions of neutrinos in the detector, and the resulting differences in the two predictions are used to quantify the theoretical uncertainties in the determination of the neutrino spectra. The results are reported using the PPPC spectra, whereas the BRW calculation is used as a check in order to constrain the impact of the spectrum choice on the sensitivity to the WIMP pair-annihilation cross section.

A comparison of the PPPC and BRW muon neutrino spectra per annihilation, after accounting for neutrino oscillations on the way to the surface of the Earth, is shown in Fig. 4.8. In the plot on the left of the Figure, the muon neutrino spectrum for WIMP annihilations to muons is shown: almost no differences are seen, for both example WIMP masses. On the other hand, significant differences are seen in the plot on the right displaying the spectra resulting from annihilations to neutrinos. For annihilations to neutrinos, a $1/3$ branching ratio to each neutrino flavour is assumed from hereon. The differences in the PPPC and BRW spectra are caused by the methodology used to incorporate electroweak corrections, specifically at lower energies, while at higher energies the PPPC method of convoluting initial PYTHIA spectra causes a broadening of the line-like feature seen close to the WIMP mass. This channel is the only channel for which a non-negligible difference is observed in the spectra predictions. The impact of these differences depends on the energy response of the detector: if the energy response is such that these differences can

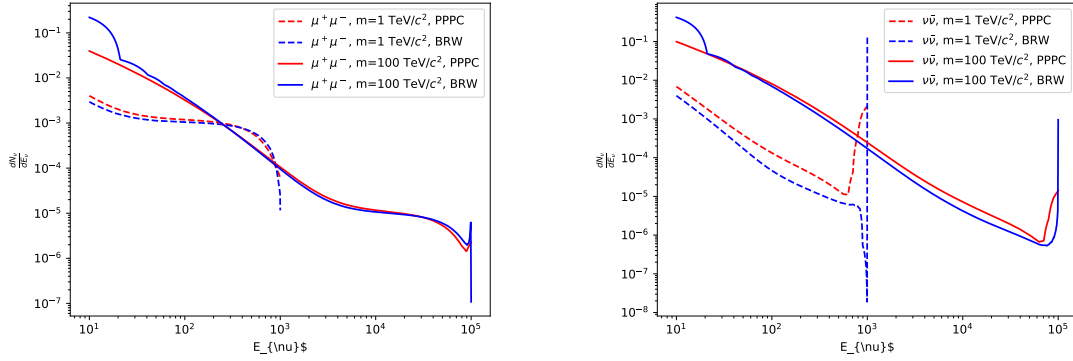


FIGURE 4.8: The spectrum of muon neutrinos per annihilation is shown for two different WIMP masses, for WIMPs annihilating to muons on the left, and to neutrinos on the right. The red curves show the PPC spectra, while the blue curves show the BRW spectra. Oscillations on the way to the Earth surface are taken into account.

be resolved in the reconstructed energy distributions, the two spectrum predictions will yield different signal responses.

In this work, numerous signal hypotheses are tested, varying the WIMP mass and annihilation channel and producing the resulting signal responses of the detector. For the purposes of saving computational time, five representative channels were chosen as the search targets. A plot of the muon neutrino spectrum at the Earth surface, accounting for neutrino oscillations, for each channel available in the PPC tool is shown for two masses, $1 \text{ TeV}/c^2$ and $100 \text{ TeV}/c^2$, in Fig. 4.9. A clear trend is seen, especially at higher

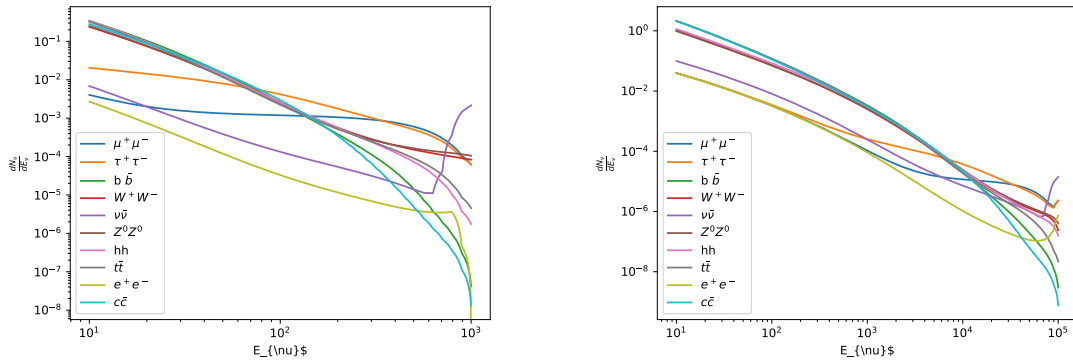


FIGURE 4.9: The muon neutrino spectrum per annihilation for WIMPs of two masses, $1 \text{ TeV}/c^2$ (left) and $100 \text{ TeV}/c^2$ (right), annihilating to different primaries. Neutrino oscillations on the way from the source to the Earth surface are accounted for.

masses when electroweak corrections become more relevant: the energy distributions for different families of particles become more similar. In particular, the spectrum for annihilations to different bosons - W^+W^- , Z^0Z^0 , hh have a very similar shape across the

energy range relevant for KM3NeT. Secondly, the spectrum for annihilations to the three different types of leptons is similar, with some disparity close to the mass of the parent particle - annihilations to the heaviest lepton ($\tau^+\tau^-$) produce the largest amount of high energy neutrinos, while the opposite is true for the lightest lepton (e^+e^-). Different types of quarks exhibit the similar behaviour, with annihilations to top quarks yielding the largest amount of high energy neutrinos. Finally, annihilations to the three neutrino types produce a unique spectrum shape, with a distinct rise in the spectrum at the WIMP mass. The five representative annihilation channels considered as search targets are: one bosonic channel (W^+W^-), two leptonic channels ($\tau^+\tau^-$, $\mu^+\mu^-$), one hadronic channel ($b\bar{b}$) and the neutrino channel. This choice assures the coverage of a wide range of realistic WIMP models. For instance, if the true WIMP model results in annihilations to Z^0Z^0 , the choice of channels covers this possibility as the W^+W^- spectrum is extremely similar. Among the five considered channels, the W^+W^- channel is expected to yield the highest detection significance.

4.2.3 Spatial distribution of WIMP particles in the Milky Way halo

In order to determine the spatial distribution of signal events, a halo profile for the Milky Way must be assumed to quantify the amount of dark matter particles present along a given line of sight. A well motivated choice of density profile parametrisation includes the Zhao family of profiles, described as a function of the centre of the galaxy, r :

$$\rho_{\text{WIMP}} = \frac{\rho_0}{\left(\delta + \frac{r}{r_s}\right)^\gamma \cdot \left[1 + \left(\frac{r}{r_s}\right)^\alpha\right]^{\frac{\beta-\gamma}{\alpha}}}, \quad (4.5)$$

where ρ_0 is the normalisation density and r_s the scale radius. Measurements of velocity dispersions of halo tracers in the outermost region of the halo, circular velocity measurements of star forming regions at intermediate radii, and terminal velocity measurements within the Solar circle are used in order to perform a fit of the mass density profile [133]. The fit is performed for a given choice of profile shape, i.e. for a given set of $\alpha, \beta, \gamma, \delta$. In this work, the results are reported using a cuspy density profile to model the mass density of the Milky Way halo, the Navarro-Frenk-White (NFW) profile. In order to evaluate the impact of the choice of density profile on the limits to the WIMP annihilation cross section, a study was conducted computing limits for a cored profile, the Burkert profile.

The shape parameter values for each of these profiles is obtained from fits in [133], these values are listed in Table 4.3.

Parameters	NFW	Burkert
$(\alpha, \beta, \gamma, \delta)$	(1,3,1,0)	(2,3,1,1)
ρ_0 [GeV/cm ³]	0.471	0.487
r_s [kpc]	16.1	9.26

TABLE 4.3: Shape and scale parameters of density profiles used in this work in order to model the mass density of WIMPs in the Milky Way. Taken from [133].

4.2.4 Signal probability density functions

The first step in constructing the signal probability density function is the computation of the detector angular error distribution. It is obtained from simulations of neutrino events, reweighting events of all flavours passing the event selection to the predicted spectrum resulting from WIMP annihilations using Eq. 3.8. The angular response function will differ depending on the input spectrum: for the lowest masses investigated, low energy neutrinos produced by annihilations of low mass WIMPs will be more difficult to reconstruct than the high energy neutrinos produced in annihilations of high mass WIMPs. The dependence of the detector angular precision on the neutrino energy is due to the amount of light emitted: the higher the energy, the larger is the amount of emitted light, and thus the amount of PMTs with detected hits. Therefore, the two variables used in the discrimination of the dark matter signal from the atmospheric background are correlated. As such, a 2D distribution of the angular distance from the source centre and the true energy will be used as the signal model in order to generate signal events. When signal events are generated with some true energy E_{true} , an energy matrix $E_{\text{true}} - E_{\text{reco}}$ is used to convert the true quantity to the reconstructed value. The distribution evaluating signal probabilities evaluates the probability based on the reconstructed energy of events. The following paragraph will reference the angular error distribution as being binned in reconstructed energy, as the paragraph describes the procedure utilised to arrive to the signal probability distribution.

In this analysis, a very extended source is studied - the observer is located within the extension of the source itself, the Milky Way halo. The incoming direction of the neutrino comes from a large region of the sky, additionally smeared by the angular reconstruction error. The angular error distribution as a function of $\log_{10}(\alpha)$ [°] is shown for different

reconstructed energy bins in Fig. 4.10a. In order to model the Milky Way halo, a spherical profile is assumed, which allows for the emission profile to be modelled in one dimension, as a function of the angular distance from the source centre. The smearing of the angular error distribution with the source emission profile results in a distribution $\frac{dP}{d\alpha}$, which gives the fraction of events reconstructed at a certain angle, α , away from the centre of the source. This distribution is binned in 10 bins in $\log_{10}(E/\text{GeV})$, showing a behaviour as described previously, with events in lower energy bins found at larger angles on average, due to the worsening of the angular reconstruction at lower energies. This 2D distribution, binned in true energy, is used for the generation of mock signal events in the likelihood analysis, after it has been normalised such that the sum of the bin counts, multiplied by the bin widths, is equal to 1. An example of such a distribution is shown in Fig. 4.10b, where the signal angle distribution is parametrised as a function of $\log_{10}(\alpha)$ [°].

The distribution quantifying the probability for an event to be a signal event is obtained by a rescaling of the above described $\frac{dP}{d\alpha}$ distribution, binned in reconstructed energy. The methods described below are applied sequentially, bin by bin for each bin in E_{reco} . In order to correctly evaluate the probability for an event to belong to the signal hypothesis, the binned distribution must be rescaled by a solid angle factor, quantifying the amount of solid angle of the sky covered by that bin. Bins close to the source centre cover a very small portion of the sky, and thus the probability for an event to be found in such a small patch in the sky is extremely small, due to the small solid angle. Each bin is rescaled by the inverse of the area of the sky covered by that bin, obtaining the distribution $\frac{dP}{d\Omega}$:

$$\frac{dP}{d\Omega} = \frac{dP}{d\alpha} \cdot \frac{d\Omega}{d\alpha}, \quad (4.6)$$

where the Jacobian of the solid angle with respect to one angle α is obtained by expressing the solid angle element in spherical coordinates, and integrating over one of the angles due to the assumption of spherical symmetry:

$$d\Omega = \int_0^{2\pi} d\phi \sin(\alpha) d\alpha \quad (4.7)$$

$$\frac{d\Omega}{d\alpha} = 2\pi \sin(\alpha) \quad (4.8)$$

After the rescaling of the distribution, a plateau must be set to the bins at very small angles. This manual setting of the plateau is required due to the lack of events reconstructed

with such a small angular error. Without the setting of the plateau, events reconstructed very close to the source could be assigned a signal probability equal to zero, due to empty bins at small angles. This behaviour is not physical: any events reconstructed at a distance smaller than the angular scale that the detector can resolve should be given the same probability. Therefore, this plateau is set by performing a Gaussian fit to the distributions after they have been rescaled by the solid angle factor. The plateau is set up to the fitted peak, after which the distribution is normalised by N , the sum of the bin contents, bin widths, and the solid angle factor of the bin:

$$N = \sum_{N_{\text{bins}}} \frac{d\Omega}{d\alpha} \cdot \frac{dP}{d\Omega}(i) \cdot \Delta\alpha(i).$$

The signal probability distribution, rescaled by the solid angle size of bins, after the manual setting of the plateau and the subsequent normalisation is shown in Fig. 4.10c, where the angle is expressed as $\log_{10}(\alpha)$ [°].

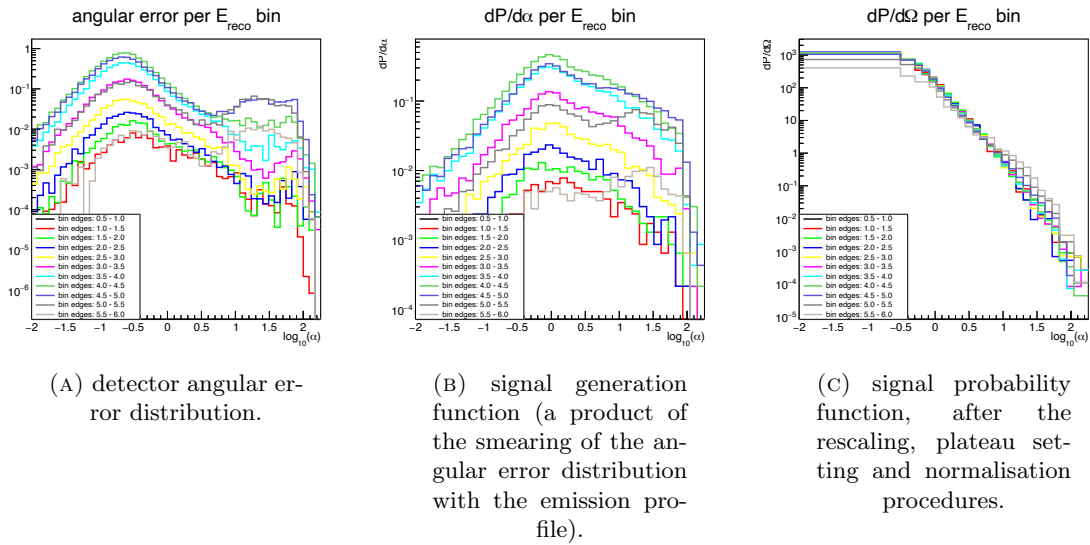


FIGURE 4.10: The angular distributions of signal events in different bins in reconstructed energy, $\log_{10}(E_{\text{reco}})$.

4.3 Unbinned likelihood analysis

The likelihood analysis aims to determine the sensitivity of the instrument to signal events, quantified as the number of signal events that can be rejected as belonging to the data set with 90 percent confidence, n_{90} . One can also define a discovery potential, the number of events needed in order to claim a detection of a certain significance. Following a

frequentist approach [134], the rejection power of a hypothesis evaluated on a given data set is obtained through the following procedure:

1. Creation of pseudo-experiments
2. Minimisation of likelihood
3. Computation of the test statistic
4. Computation of integrals of the test statistic distribution in order to determine n_{90}

Each of the steps followed to obtain the final sensitivity to the number of signal events will be described in detail in the following sections.

4.3.1 Pseudo-experiment creation

In order to test the discriminating power of KM3NeT to neutrinos from dark matter annihilations, a statistical test is performed by creating many mock data sets, with a varying amount of signal events injected. A total of 10^4 data sets containing only background events are created: the number of background events in the sample is obtained from a Poisson distribution with the mean set to the number of detected events during that time period. This number is obtained from the real data, as the absolute number of background events in the MC simulations does not match exactly what is measured in the data (see for example Fig. 4.3 to see the magnitude of the discrepancy). As mentioned earlier, the distribution shown in the plot on the left in Fig. 4.7 is used for the generation of declinations and reconstructed energies of mock background events, while the right ascension is sampled from a uniform distribution in the range from 0 to 2π .

A total of 10^3 pseudo-experiments are created for each number of signal events injected, up to 20 signal events. The signal coordinates and true energies are sampled from the distribution shown in the middle plot in Fig. 4.10. The sampling of the distribution results in a generated angular distance from the source centre: spherical symmetry is employed to transform this value into a declination and right ascension, by sampling a random point from a circle at the given angular distance from the source. Uncertainties in reconstruction are also applied in the generation of signal energies: the energy estimate has its associated uncertainty, repeated measurements of a particle of a given true energy

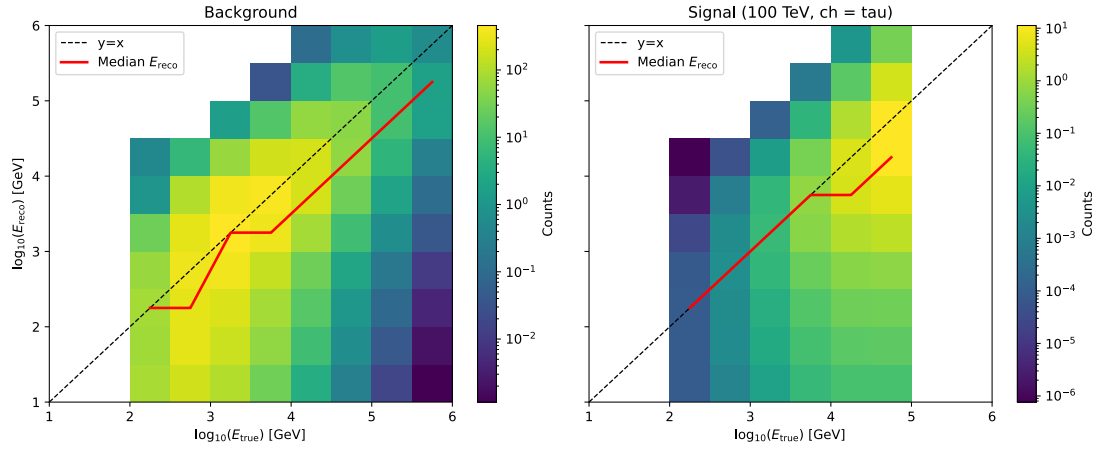


FIGURE 4.11: The 2D distribution of the true and reconstructed energies for the simulation of background events (left), and signal events, for the hypothesis of a 100 TeV/ c^2 WIMP annihilating to taus (right). The red solid line indicates the median E_{reco} value for each true energy bin, while the black dashed line indicates $x = y$, plotted to indicate where the histogram should be most populated, if the reconstruction is unbiased.

will result in a spread of measured reconstructed energies. To account for this, a 2D energy matrix, a distribution of true and reconstructed energies of events is created. For signal events, the distribution used in the generation of coordinates and energies generates the true energies of events, and the energy matrix transforms the generated true value to a reconstructed, measured value. The same approach cannot be followed for background events, as these are generated from blinded data. Instead, the generated reconstructed energy is used in order to evaluate the most likely true energy that would result in the measured energy, obtained from the energy matrix. This true energy is then inputted into the energy matrix again, in order to obtain a new reconstructed energy. This procedure is intended to encapsulate the energy reconstruction uncertainties which would result in a range of values upon repeated measurements of a true quantity. The two-dimensional energy matrices used to account for energy reconstruction uncertainties are shown for background events and one signal hypothesis in Fig. 4.11.

The number of signal events present in each mock data sample is subject to Poisson fluctuations and uncertainties on the signal acceptance of the detector. The uncertainty on the signal acceptance, the total number of detected events given some input flux, is estimated by conducting simulations with modified water properties and PMT efficiencies. These two parameters are not known exactly, and could thus exert an influence on the number of detected events. The absorption length of water in the simulations was altered by $\pm 10\%$, as were the PMT efficiencies, following measurements made in ANTARES [135].

The water absorption length exerted the largest influence on the number of detected events, exhibiting a small dependence on energy, with an increase in the variation in the number of detected events at the highest energies. In this work, this uncertainty was taken to be an average value across the whole energy range, equal to 30%. This uncertainty, along with the uncertainty due to Poisson fluctuations, can be modelled in two ways:

1. Event smearing: variation of the number of signal events injected into fake data sets, by sampling from Gaussian and Poisson distributions
2. Test statistic smearing: the number of injected signal events is kept fixed, performing a smearing on the resulting TS distributions afterwards

Method 1 will be described in more detail here, while method 2 will be described in more detail in the section discussing the computation of the TS, in Sec. 4.3.3. The variation of a given number of signal events in method 1 starts with the construction of a Gaussian function, with a mean set to the number of signal events originally intended to be injected, and the spread is set to the value of the systematic uncertainty, $\sigma = 0.3 \cdot n_{sg}$. A value is sampled from this distribution, representing the modulated number of signal events due to the influence of uncertainties on water properties. This value is then used as a mean of a Poisson function, from which an integer is sampled: counting experiments will measure a different number of events if repeated multiple times with the same exposure due to counting fluctuations, modelled appropriately with a Poisson function. The value sampled from the Poisson function represents the final number of signal events to be injected in the sample. The number of background events in each sample is Poisson fluctuated separately.

In this work, multiple data samples of the ARCA detector are analysed together. As the detector grew in size, its neutrino detection efficiency and the reconstruction performance improved, thus motivating the use of separate generation functions for each detector to generate signal and background events, adding a "configuration" label to the event vector. In order to determine how many signal events should be injected into each sample, the relative signal fraction in each sample is computed using the expression shown in Eq. 4.4. Given some signal fraction for each configuration, multinomial sampling is used to determine the number of signal events in each of the configurations by computing

cumulative probabilities for collections of samples:

$$\begin{aligned} C_{d_1} &= f_{d_1} \\ C_{d_2} &= f_{d_1} + f_{d_2} \\ C_{d_3} &= f_{d_1} + f_{d_2} + f_{d_3}, \end{aligned} \tag{4.9}$$

where f_{d_n} is the proportion of the total signal in sample n , computed as a product of the signal acceptance and livetime of the sample following Eq. 4.4 and dropping the flux out of the equation, since this factor is equal for each sample (the same flux is attempted to be measured with each sample, it is constant in time). What follows is a sequential generation of random numbers: for each signal event injected, the range within which the random number, r , falls in determines which sample the event belongs to:

$$\begin{aligned} r < C_{d_1} &\rightarrow d_1 \\ C_{d_1} < r < C_{d_2} &\rightarrow d_2 \\ C_{d_2} < r < C_{d_3} &\rightarrow d_3 \end{aligned}$$

4.3.2 Likelihood evaluation

Mock data samples containing events from the three ARCA configurations are then evaluated with an unbinned likelihood. The distribution on the right in Fig. 4.7 is used to evaluate the probability of an event being a background event given its declination and reconstructed energy, while the distribution on the right in Fig 4.10 is used to evaluate the probability of an event being signal, given its angular distance from the source centre and reconstructed energy. The signal and background probability distributions are created separately for each of the ARCA8, ARCA19 and ARCA21 detector configurations: the configuration label in the event vector is used in order to know which probability distributions to use in the likelihood evaluation on an event-by-event basis. An extended, unbinned, negative log likelihood is used:

$$\log(\mathcal{L}) = - \sum_d \sum_{i=0}^{N_d} \log[f_d \cdot n_{\text{sg}} \cdot \mathcal{S}^d(\alpha_i, E_i) + (N_d - f_d \cdot n_{\text{sg}}) \cdot B^d(\alpha_i, E_i)] - N_t. \tag{4.10}$$

The sum with index d runs over the different detector configurations, while the sum over i runs over the total number of events for that sample, N_d . The parameter f_d

represents the relative signal fraction present in data sample d , the same factor that is used to determine the number of signal events injected into the data sample of each configuration following Eq. 4.9. The symbols $\mathcal{S}^d(\alpha_i, E_i)$ and $B^d(\alpha_i, E_i)$ denote the signal and background probabilities of event i belonging to configuration d , having coordinates α_i and reconstructed energy E_i . The parameter n_{sg} is the total number of signal events present in the combined data sample of all configurations; this is the parameter being varied in order to minimise the likelihood. Finally, the total number of events present in all configurations, N_t , is subtracted from the likelihood once the minimised logarithmic sum is computed.

In this work, the *TMinuit* minimiser from ROOT is utilised to minimise the likelihood of each mock data sample. As stated previously, background distributions are smoothed out in order to remove empty bins and ensure correct behaviour of the minimiser algorithm. The problem encountered when using distributions with empty bins can be understood by examining Eq. 4.10: in the case of an event having coordinates or, more often, energies for which the background probability is zero, $B^d(\alpha_i, E_i) = 0$, event i pulls the parameter of interest n_{sg} to larger values: as the factor $(N_d - n_{sg})$ is being multiplied by $B^d = 0$, any value of n_{sg} can increase the value of the likelihood for this particular iteration, for this event i . In the case of only a few events out of ~ 1000 in a sample having zero background probabilities, the correct minimum likelihood can still be found, as the few events will influence a small effect on the fitted n_{sg} . But, as seen in the plots of the background distributions obtained from data, the detector livetimes are very small, and the number of data events present in each configuration is not large ($\mathcal{O}(100 - 1000)$). Thus the distributions have many empty bins, and a substantial number of events would be assigned a zero background probability.

The first preliminary check conducted to evaluate the performance of the minimiser is shown in Fig. 4.12. This Figure shows the fraction of times the minimum number of signal events is fitted to the mock data sets, as a function of the number of signal events injected into the data sets. As can be seen by the first data point, the background hypothesis is returned as the best fit of the likelihood roughly half of the times for mock data sets containing solely background events. The minimisation procedure is further evaluated by checking the best fit points for different numbers of injected signal events. This is visualised in Fig. 4.14. The figure shows the best fit number of signal events returned by the likelihood for data sets with a varying number of signal events injected. In this plot,

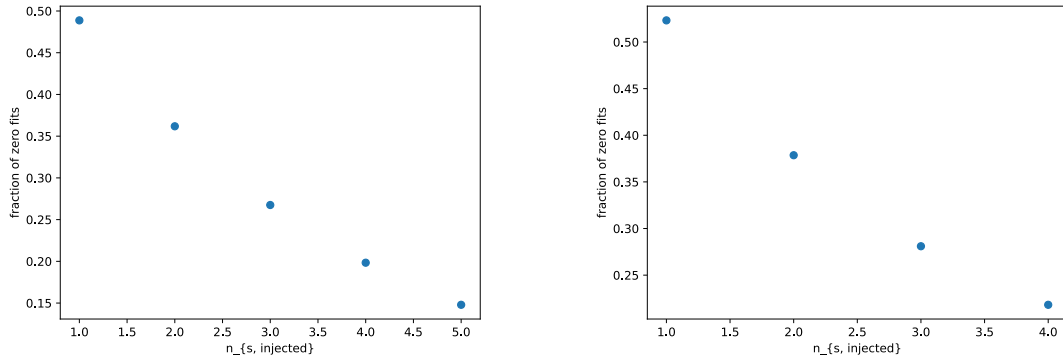


FIGURE 4.12: The fraction of times the minimum number of signal events is fitted to the mock data sets, shown as a function of the number of signal events injected into the data sets. On the left is the result obtained using the second method of accounting for systematics, test statistic smearing, while the right figure shows the result obtained using the event smearing method.

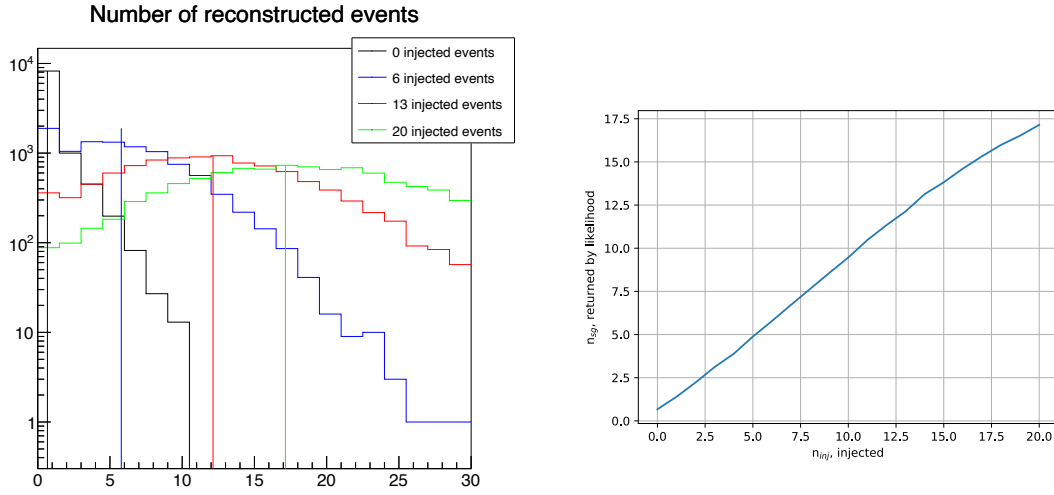


FIGURE 4.13: Left: the number of fitted events for different numbers of injected signal events. Right: the mean of the best fit number of events for each injected number of signal events. In this plot, the event smearing smearing method is used to account for systematics.

systematic uncertainties are accounted for using the method of event smearing, method 1. The minimiser accurately fits the number of signal events, with the event smearing causing a widening of the distributions. In method 2 of smearing the test statistic distributions, the number of injected signal events is kept fixed, which is why the minimiser is even more accurate in determining the best fit point. This is visualised in Fig. 4.13: the distributions on the left of the plot show a much smaller spread, as expected. This method does not introduce a smearing until the test statistic is computed, which is when the two methods begin converging and yielding equivalent results, as seen in the following section.

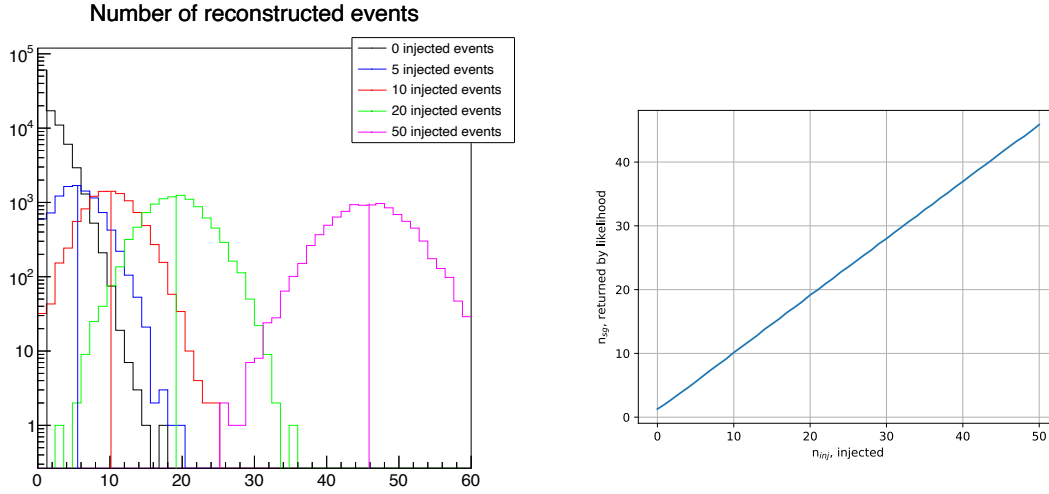


FIGURE 4.14: Left: the number of fitted events for different numbers of injected signal events. Right: the mean of the best fit number of events for each injected number of signal events. In this plot, the test statistic smearing method is used to account for systematics.

4.3.3 Test statistic computation

In order to evaluate the significance of a fitted signal, the test statistic is computed. The test statistic is defined as the likelihood ratio between the minimised likelihood and the likelihood of the pure background hypothesis:

$$\log(\text{TS}) = \log \left(\frac{\mathcal{L}(n_{\text{sg}}^{\text{max}})}{\mathcal{L}(n_{\text{sg}} = 0)} \right). \quad (4.11)$$

This ratio identifies the significance of a detection by comparing it to the likelihood of the null hypothesis, of having zero signal events in the sample. As stated previously, many mock data sets are created for a varying number of signal events injected into the samples. The output of the pseudo-experiment algorithms are TS distributions, 10^4 values of the TS for pure background mock data sets, 10^3 values for each injected number of signal events.

In this work, a bounded minimiser is used in the likelihood minimisation: a lower bound of 10^{-3} is set to the fit parameter n_{sg} . Therefore, in the cases when the likelihood minimum is below the bound, $n_{\text{sg}}^{\text{max}} < 10^{-3}$, when the pure background hypothesis is most likely, the computed minimised likelihood will not be the true minimum of the likelihood. This results in negative values of the log of the test statistic, as

$|\mathcal{L}(n_{\text{sg}} = 0)| > |\mathcal{L}(n_{\text{sg}}^{\text{max}} = 10^{-3})|$. Furthermore, a pileup of very small negative values of

the test statistic occurs in the TS distributions - even in the cases with injected signal, a lot of pseudo-experiments will still be fitted with the number of signal events equal to the lower bound, resulting in many small negative values. The construction of confidence intervals and the evaluation of the sensitivity on the number of signal events requires the computation of quantiles of the TS distributions. The pileup of TS values at small negative values makes the computation of quantiles of the TS distributions more difficult. In order to evaluate quantiles more accurately, the log of the TS distribution is computed. To compute the logarithm of the above described negative values, the TS values are shifted such that they are positive. The minimum negative value of the pure background TS distribution is found, labelled C . After this value has been found, the pure background TS distribution and the distribution for each number of injected signal events is shifted as follows:

$$TS_{\text{new}} = \log_{10}(TS + C). \quad (4.12)$$

As stated in Sec. 4.3.1 when discussing the creation of mock data, two different approaches can be followed to account for the effect of systematic uncertainties and counting fluctuations on the number of detected signal events. The approach of event smearing was described in the previous sections. In this paragraph, the methodology of test statistic smearing will be described, referred to as method 2 in the text. This method consists of a smearing of the TS distributions for each number of injected signal events. The smearing of the TS distributions is performed by sampling from Poissonian and Gaussian distributions. A convolution of the TS distribution for some number of injected signal events n_{sg} with a Poisson function is applied as follows:

$$P(TS(\mu)) = \sum_{n_{sg}} P(TS(n_{sg})) \cdot \mathcal{P}(\mu, n_{sg}), \quad (4.13)$$

where the factor $\mathcal{P}(\mu, n_{sg})$ is the Poisson probability to detect n_{sg} events given some mean μ . TS distributions are thus computed for each μ , spaced in intervals of 0.05 up to the maximum number of injected signal events. The systematic uncertainty on the number of detected signal events is added by means of a Gaussian smearing of the resulting distributions. Therefore, the output of the TS distribution transformation algorithms are smeared distributions of the shifted test statistic, visualised in Fig 4.15 for both the methodologies used to account for the systematic uncertainty in the detected number of signal events. The figure will be discussed in more detail in the following section, when

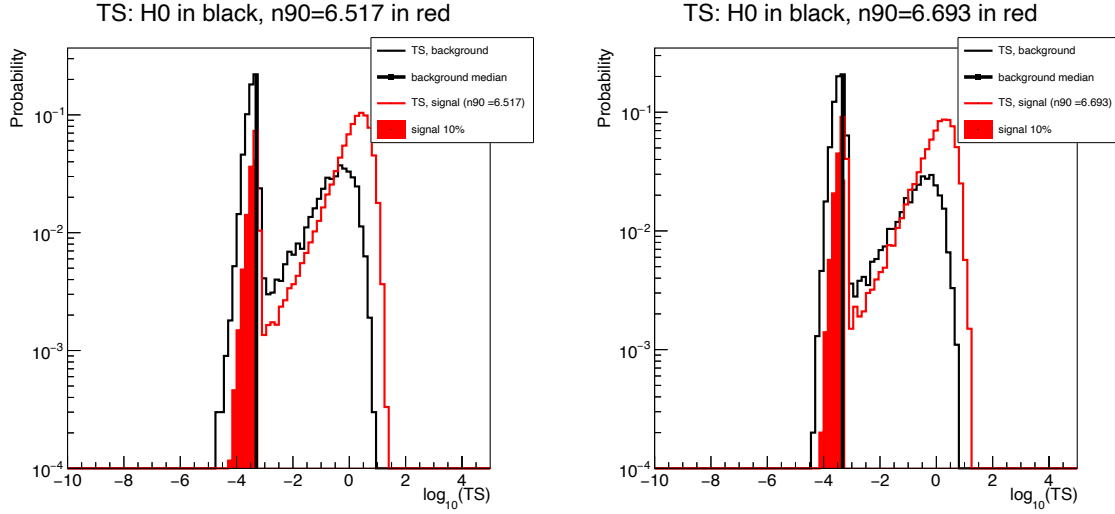


FIGURE 4.15: The transformed test statistic distributions, shown on the left for the test statistic smearing method of accounting for systematics, and on the right for the event smearing method. The histogram in black shows the transformed TS values of mock background data sets, while the red histogram shows the TS values of the mock data sets with a number of signal events injected equal to the 90% C.L. rejection power. The shaded region indicates the false negatives, equaling 10% of the total integral of the distribution.

discussing how the sensitivity to the number of signal events is described.

4.3.4 Number of signal events sensitivity

As described previously, the TS is a measure of the significance of an observation, encoding the deviation of some observation of signal events and the null hypothesis, consisting solely of background events. Confidence intervals can be constructed from TS distributions in order to exclude a portion of the parameter space of the parameter governing the amount of signal present in the data sample at the given confidence. In this work, this parameter is the thermally-averaged WIMP pair annihilation cross section, $\langle\sigma v\rangle$. Equivalently, the distributions can be used in order to define a discovery region, i.e. a threshold TS value above which discovery at some confidence level can be claimed.

A sensitivity is defined as the upper limit on the number of events that would be obtained in the case that the data follows the average behaviour of mock background samples. Sensitivities are computed for a given confidence level (C.L.): when attempting to reject a signal hypothesis, a confidence level signifies the amount of trials in which one would reject the signal, given the average behaviour of the background. The frequentist approach is followed in this work: the sensitivity is computed comparing TS distributions

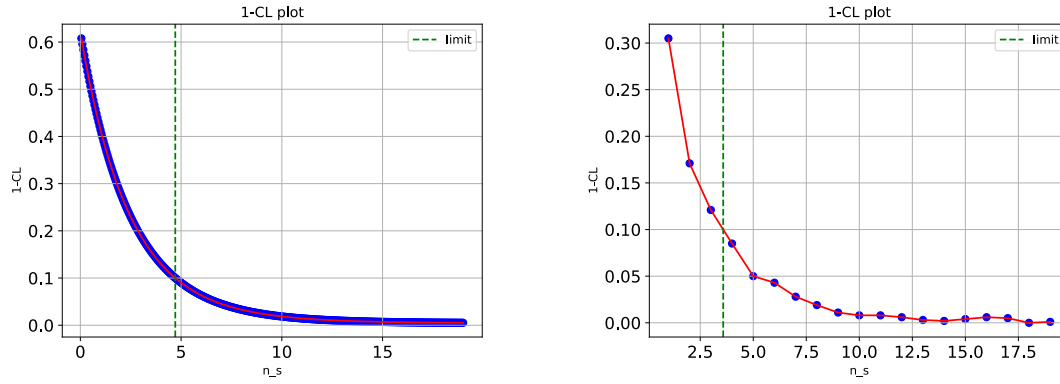


FIGURE 4.16: The integral of the TS distributions at the median of the background TS distribution, for TS distributions with different number of signal events injected. The point at which $y = 0.1$ is interpolated, this number of events is taken as the sensitivity at 90% C.L. The figure on the left shows the plot for the TS smearing method of accounting for systematics, while the plot on the right represents the results for the event smearing method. Both plots are shown for the signal hypothesis of a $1 \text{ TeV}/c^2$ WIMP annihilating to neutrinos.

of a given number of injected signal events to the median of the pure background TS distribution. A confidence level commonly used in the field is 90%: a sensitivity to the number of signal events at this confidence level implies that for this number of injected signal events, the computed TS would be smaller than the average TS of the background ten percent of the time. We would falsely identify this data sample as containing solely background events ten percent of the time. A visualisation of the computation of the sensitivity is shown in Fig. 4.15. The transformed TS of mock background data sets is shown in black, while the TS distribution in red belongs to mock data sets with number of events injected approximately equal to the sensitivity in the number of events, indicated in the titles of the two figures. The first sharp peak in the distributions corresponds to cases when the minimum value was fitted to the number of signal events. The extended tail of TS values are cases when a non-zero signal was fitted to the data sets. The shaded region of the red histogram indicates false negatives, the 10% of cases when the TS value is below the median of the background TS distribution. The figure on the left corresponds to the TS obtained using the TS smearing method to account for the systematics, while the figure on the right accounts for systematics using the event smearing method. In order to find the number of signal events at the desired rejection power, the TS integrals for different number of injected signal events at the median of the background are computed and sorted into a ROOT TGraph, an interpolative object that allows for the computation of the sensitivity at an exact rejection point, as visualised in Fig. 4.16. Once the sensitivity

has been obtained, the upper limit can be computed after the unblinding of the data, assigning the measured right ascension coordinates to the events. The TS is computed from the real data and transformed following the same procedures used in the computation of the sensitivity - the same constant C is used to shift the data TS as was used in the computation of the sensitivity. The resulting final TS value is compared to the results obtained in pseudo-experiments: if the TS of the unblinded data is lower than the median TS of mock background data sets, this implies that the data sample is even less likely to contain signal than was measured on average in mock background data sets. In order to remain conservative, the upper limit is set equal to the sensitivity for such cases. If the observed TS is larger than the median of the pure background TS distribution, this implies that the data sample may contain some amount of signal, or atmospheric background events that are mistakenly fitted as being signal events. In such cases, the upper limit is computed by finding the number of signal events for which the integral of the TS distribution is equal to 10% at the value of the observed TS. The procedure is identical to the procedure used to compute the sensitivity, with the exception that TS distributions with injected signal are now compared to the observed TS, instead of the median of the pure background TS distribution.

In the case of an observed test statistic that differs significantly from the pure background values obtained in pseudo-experiments, this would indicate an observation of signal. The discovery potential can be computed from the TS distributions obtained from mock data sets: a discovery potential at a given confidence provides a measure of the signal strength that one could measure with that confidence. It is computed by determining the threshold TS value from the TS distribution of the background hypothesis: for instance, for a 5σ discovery, the TS value is found for which the probability to encounter a higher TS value from pure background samples is $2.87 \cdot 10^{-7}$. This number is a measure of the false positive rate, the probability that a TS value larger than the threshold comes from a data set consisting of solely background events. The discovery potential is then computed as the number of signal events for which the median of its TS distribution lies at the threshold TS value.

The above described likelihood methodology, from the creation of pseudo-data to the likelihood and TS evaluation and the computation of the sensitivity to the number of signal events, is followed for each parameter choice. When testing multiple independent hypotheses on one data set, a trial factor is applied to account for the look-elsewhere

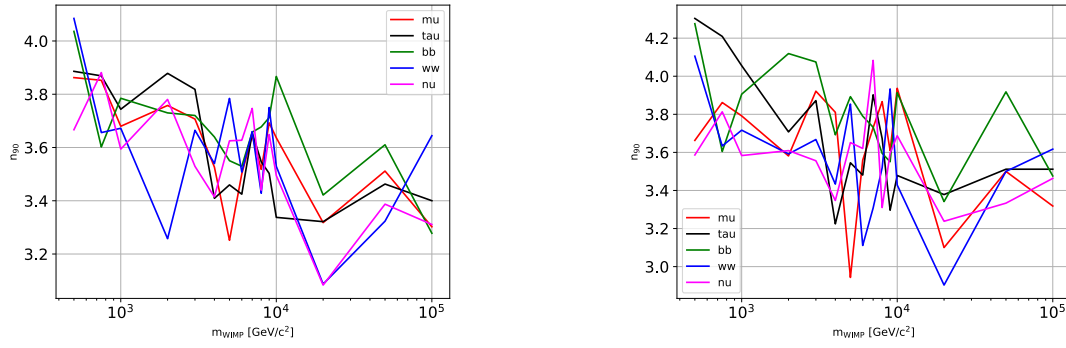


FIGURE 4.17: Number of signal events that can be rejected for different signal hypotheses: the x-axis shows the dark matter mass, while the different colours indicate different WIMP annihilation channels. The plot on the left shows the limit obtained using the method of smearing TS distributions to account for the effect of systematic uncertainties on the number of detected events, while the result on the right is obtained by smearing the injected number of signal events.

effect: the probability of obtaining some statistically significant detection increases with the number of independent hypotheses one tests on the data. However, in this particular case trial factors are not applied, as the tested signal hypotheses are not independent from one another. Firstly, the signal is expected to be emitted from the same region of the sky for each signal hypothesis, ignoring some very small differences in the dispersion of the signal depending on the WIMP mass (at lower WIMP masses the angular response worsens so the expected signal is slightly more diffuse). The energy distributions for each signal hypothesis may look slightly different, but these differences are minuscule after the distribution is smeared by the detector energy reconstruction error. Furthermore, the spatial coordinates of events have the most discriminating power in distinguishing signal from background - any event reconstructed at a very large distance from the Galactic Centre will be assigned a negligible signal probability, even if it is a very high energy event, for example $E \sim \mathcal{O}(10 - 100 \text{ TeV})$, with a reconstructed energy that seems to indicate production from a pair annihilation of WIMPs of a large mass. Therefore, even though each signal hypothesis tested has a slightly different energy distribution, due to the fact that the bulk of the signal/background discriminating power lies in the reconstructed direction of the neutrinos, the signal hypotheses are very correlated, and the trial factor is close to one.

An example plot of the rejection power achieved with the KM3NeT ARCA8/19/21 samples is shown in Fig. 4.17. As seen in the Figure, the sensitivity on the number of signal events will in general be the lowest for the largest WIMP masses tested, as the

energetic signal neutrino events produced in these WIMP annihilations have energies that are rarely observed in background events. Fluctuations in the sensitivities are seen at many points of the parameter space: such fluctuations are expected, their magnitude is within the expected fluctuations caused by statistical uncertainties.

4.4 Computation of the dark matter cross section limit

The output of the likelihood algorithms is a sensitivity to the number of signal events that can be rejected as belonging to the data sample(s) with 90 percent confidence, for each tested signal hypothesis. A sensitivity to the number of signal events can be converted to a sensitivity to the signal flux using Eq. 4.4, provided that the signal acceptance, computed with Eq. 4.2, and the data taking livetime is known. The factor N_d in Eq. 4.4 is replaced by the sensitivity to the number of events. The data taking livetime is obtained as the total livetime of the detector after the application of the run selection, which discards runs according to the criteria described in Sec. 4.1.1. Finally, the acceptance is computed for all neutrino flavours following Eq. 4.3.

The flux sensitivity represents the largest neutrino flux produced by WIMP pair annihilations that can be rejected with 90 percent confidence with the data samples used. It is once again computed for each signal hypothesis independently. In general, the flux sensitivity will be the lowest at the largest masses, due to the energy dependence of the effective area, and the subsequent increase in the signal acceptance with the WIMP mass. Additionally, the improvement in the number of events sensitivity also contributes to lower flux sensitivities at larger WIMP masses. The integrated flux sensitivity to neutrinos produced by WIMP annihilations in the Sun is shown in Fig. 4.18. The sensitivity is shown as a function of the WIMP mass for the three annihilation channels considered in the Sun analysis, comparing the sensitivity obtained in this work to the sensitivity obtained in previous works with the low energy detector, KM3NeT/ORCA.

The flux sensitivity can be converted to a sensitivity on the thermally averaged WIMP pair annihilation cross section following Eq. 2.10. The sensitivity to the cross section is computed for each signal hypothesis independently, and the sensitivity is usually visualised as a function of the WIMP mass, for a particular annihilation channel. The shape of this curve will differ from the flux sensitivity curve: due to the $1/m_{WIMP}^2$ factor in Eq. 2.10,

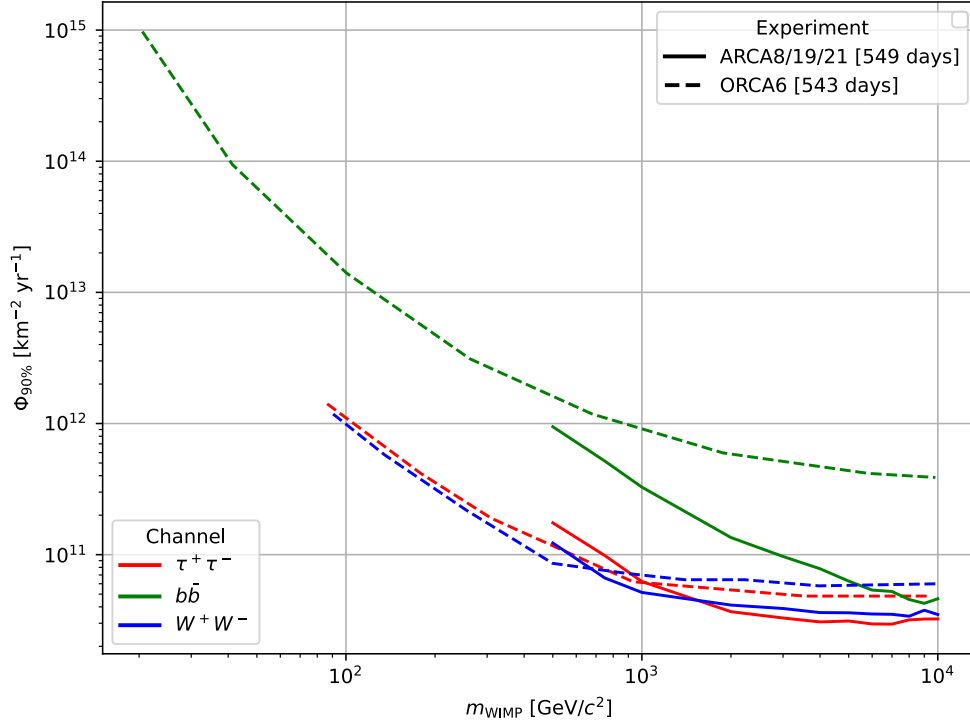


FIGURE 4.18: Flux sensitivity to neutrinos produced by WIMP annihilations in the Sun.

for the largest WIMP masses this factor worsens the limit. The resulting curve will have a U-shape, such that KM3NeT/ARCA offers the best sensitivities in the mass range $\mathcal{O}(\text{TeV}/c^2 - 10\text{TeV}/c^2)$.

In order to compute the cross section sensitivity, the integration of the WIMP mass density along the line of sight and solid angle must be performed. In this work, the integrals are computed using the CLUMPY software [136]. Results are computed for two representative density profiles, one cored and one cuspy profile following the Zhao parametrisation, using the shape and scale parameters shown in Table 4.3. The two sets of results will serve as a measure of the theoretical uncertainties associated with the sensitivity: if the density profile of the Milky way is in reality more cored, the less restrictive sensitivity obtained for the Burkert profile would be a more accurate estimation of the rejection power of the data set. On the other hand, in the case of a confirmation of a cuspy nature of the Milky Way halo, the more optimistic sensitivity obtained with the NFW profile would be more accurate.

4.5 Likelihood combination with γ -ray telescopes

This section describes an alternative approach to combining multiple data sets in order to compute a common sensitivity [137]. The previously described method of evaluating an unbinned likelihood on the combined data requires the knowledge of event-by-event data of each sample that is being combined. In the case of data samples of multiple experiments, this is not always possible as experiments are reluctant to share event-by-event data and instrument responses. Instead, the method described in this section relies on the computation of the likelihood of each data set separately.

This method does not rely on the minimisation of the likelihood. Instead, given some real or mock data sample, the likelihood is evaluated for some arbitrary number of signal events n_{sg} , thus obtaining a 2D array of $(n_{sg}, \mathcal{L}(n_{sg}))$ values. This 2D array is then converted into likelihood values as a function of the parameter of interest, the thermally averaged WIMP pair annihilation cross section, $\langle\sigma v\rangle$. The number of signal events used to compute the likelihood value is converted into $\langle\sigma v\rangle$ as described in the previous section, by combining Equations 4.4 and 2.10. The likelihood values $\mathcal{L}(\langle\sigma v\rangle)$ are each divided by the likelihood of the null hypothesis:

$$TS(\langle\sigma v\rangle) = -2 \log \left(\frac{\mathcal{L}(\langle\sigma v\rangle)}{\mathcal{L}(\langle\sigma v\rangle = 0)} \right). \quad (4.14)$$

Therefore, a curve of the test statistic as a function of the parameter of interest is the end result of the methodology evaluated on one data set. Examples of this curve are shown in Fig. 4.19, discussed in more detail in the final paragraph of this section, once the methodology used in order to extract a limit from this plot has been explained.

In order to compute the sensitivity to the annihilation cross section for some rejection power, many mock data sets containing solely background events are created. The test statistic curve is evaluated for each data set. Wilks' theorem [138] is assumed in order to compute the sensitivities of individual data sets. The theorem states that the distribution of the test statistic asymptotically approaches a χ^2 distribution with n degrees of freedom as the sample size grows to infinity. The degrees of freedom are determined from the difference in the dimensionality of the signal and null hypothesis: the signal hypothesis has one additional parameter (n_{sg}) with respect to the null hypothesis, therefore the TS curve will follow a χ^2 distribution with one degree of freedom. This assumption allows

for the construction of confidence intervals, as integrals of χ^2 distributions for different confidence levels are well-known quantities. For example, for one degree of freedom, the following equality holds assuming a one-sided limit:

$$\int_0^{2.71} \chi_1^2 = 0.95. \quad (4.15)$$

Therefore, the value of the parameter of interest, $\langle\sigma v\rangle$, which can be rejected with 95% confidence, is equal to the value for which the test statistic is equal to 2.71:

$$TS(\langle\sigma v\rangle_{95\%C.L.}) = 2.71.$$

The sensitivity is then evaluated for each mock data set individually, and the final sensitivity is computed as the mean of the sensitivities of all the individual mock data sets. The averaging smooths out statistical fluctuations which happen at the level of individual data sets. Statistical uncertainty bands are also computed using the mock data sets. The uncertainty bands are computed by finding the corresponding 1σ and 2σ quantiles of the distribution of sensitivities obtained with individual data sets. In order to compute the upper limit, the same procedure is followed as for the computation of sensitivities. The TS curve, $TS(\langle\sigma v\rangle)$, is computed for the real data, and the limit on the cross section is found by finding the value for which the TS is equal to 2.71.

The above described methodology is used to obtain the sensitivities and limits for one individual data taking period / experiment. In order to compute a combined limit for multiple experiments or different detector configurations of ARCA, the individual TS curves are multiplied by one another and the limit is evaluated on the new TS curve. This methodology is particularly appealing due to the simplicity of sharing data between different experiments: all the sensitive information such as the detector efficiency, the point spread function and the event-by-event data itself is processed by individual experiments, after which the results combination is performed via the sharing of $TS(\langle\sigma v\rangle)$ values. As long as the same parameter is being measured or constrained, this methodology allows for the combination of TS curves computed for different search targets. As stated in Sec. 2.3.3.2, the primary search targets of γ -ray experiments in dark matter searches are dwarf spheroidal galaxies. An observation or a lack of an observation of signal events in these objects results in a measurement or limit on the same parameter, $\langle\sigma v\rangle$, as the same WIMP annihilation process is responsible for the production of γ rays in dwarf spheroidal

galaxies as for the production of neutrinos in the Milky Way. Therefore, this method can be used to:

- Produce a combined limit from multiple data sets studying the same target - for example, the ARCA8, ARCA19 and ARCA21 samples in which signal is searched for in the Galactic Centre
- Produce a combined limit for different dwarf spheroidal galaxies observed with the same γ -ray observatory
- Combine limits obtained for different search targets across different experiments

In this work, this method was utilised in order to validate results obtained with the frequentist approach to computing the limits. A preliminary study was conducted using the TS curves obtained with the observation of multiple dwarf spheroidal galaxies with the MAGIC γ -ray telescope: the study revealed that this method has great potential in improving the existing limits on the WIMP pair annihilation cross section in regions of the parameter space where γ -ray telescopes have less constraining power: for the case of WIMPs annihilating to neutrinos, and for the annihilations to heavier leptons ($\mu^+\mu^-$, $\tau^+\tau^-$) at large WIMP masses ($m > 10 \text{ TeV}/c^2$). For the case of hadronic channels, the spectrum of neutrinos is created via secondary interactions, which produce neutrinos of lower energies, resulting in softer spectra when compared to leptonic and the neutrino channel. As the neutrino interaction cross section rapidly decreases with decreasing energy, the signal acceptance for hadronic channels is substantially lower, and neutrino telescopes do not have significant constraining power for hadronic annihilation channels.

An example plot showing the TS curves as a function of the parameter of interest for the individual ARCA configurations and the combined TS curve is shown in Fig 4.19. The red curve in the figure is the product of the values of the curves obtained from individual detectors, from this red curve the combined limit from all detectors is extracted. Fluctuations are observed in the curves in the plot, as the likelihood is computed at a large number of points in the parameter space, on a single mock data set. The fluctuations do not have a large effect on the final sensitivities obtained in this method, as the sensitivities are obtained from a large number of such computed curves for a given signal hypothesis.

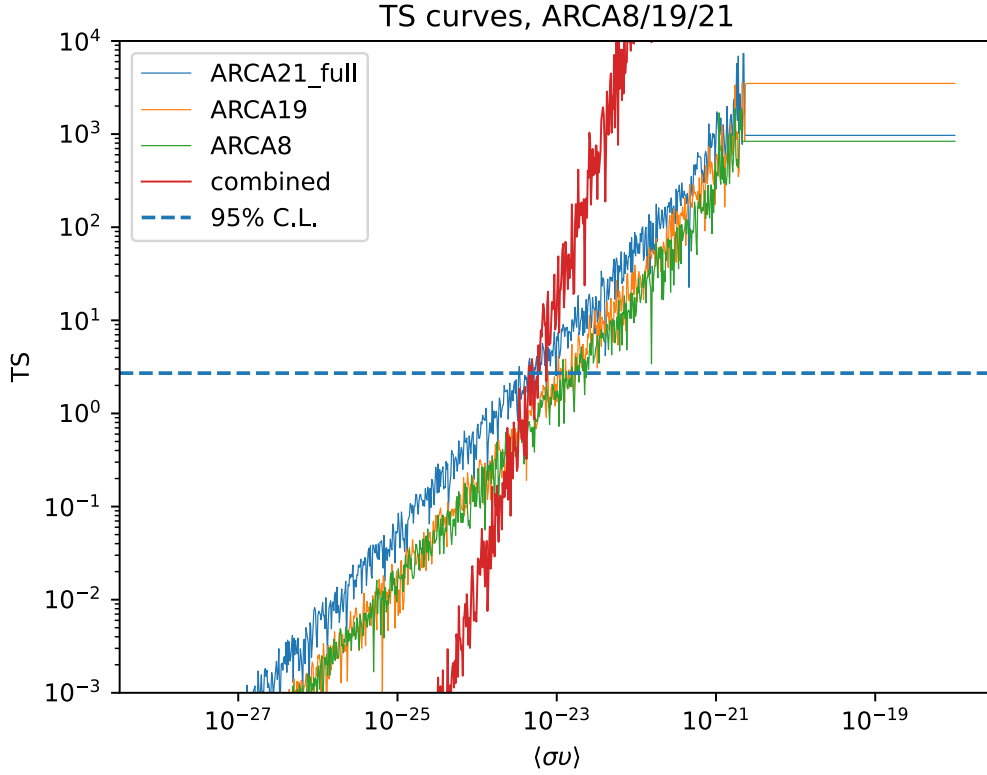


FIGURE 4.19: The computed test statistic as a function of the parameter of interest, shown for individual data sets denoting different ARCA configurations. The combined curve is shown in red. The example is shown for a $600 \text{ GeV}/c^2$ WIMP annihilating to muons.

4.6 Searching for dark matter in the Sun

The same unbinned likelihood methodology that was described in Sec. 4.3 was employed to search for dark matter in the Sun. Some differences arise in considerations of how to model the signal flux produced at the source. Firstly, one must account for the fact that WIMP annihilations and the subsequent particle interactions are occurring in a dense medium. Secondly, the Sun is moving in the equatorial coordinate system, such that certain quantities depending on the incoming direction of particles, for example the effective area, must account for the motion of the Sun.

4.6.1 Neutrino spectra from WIMP annihilations in the Sun

The Sun is a dense medium, affecting both the secondary processes resulting in the production of neutrinos, and the propagation of the produced neutrinos. Secondary processes

such as hadronisation and showering proceed unimpeded in sparse environments such as the Galactic Centre. In the Sun, one must account for the probability that the produced particles interact with the surrounding environment before they can shower or hadronise. In the case of leptons, taus will promptly decay and produce neutrinos before they can lose a significant portion of energy due to interactions [139]. On the other hand, muons will interact with the environment and lose all their energy before they can decay [139]. Top quarks will decay before interacting, while other quarks will promptly hadronise. If the lifetime of the produced hadron, τ_{dec} , is much shorter than the interaction time, τ_{int} , the hadron decays prior to any energy losses. If the decay and interaction times are comparable, interactions and decays are simulated. The decay products and the interaction products are weighted by the probability of each process:

$$p_{\text{dec}} = \frac{\tau_{\text{int}}}{\gamma\tau_{\text{dec}} + \tau_{\text{int}}} \quad p_{\text{int}} = \frac{\gamma\tau_{\text{dec}}}{\tau_{\text{int}} + \gamma\tau_{\text{dec}}}. \quad (4.16)$$

The two probabilities are comparable for hadrons composed of b and c quarks, while for hadrons composed of up, down and strange quarks, the interaction time is orders of magnitude lower, such that the hadrons lose all energy before they decay [73].

The propagation of neutrinos is also altered compared to sparse environments such as the Galactic Centre. Firstly, matter effects alter the oscillation probabilities with respect to oscillations in vacuum. Secondly, neutrinos above a certain energy have a non-negligible probability to interact with matter. The interaction length of neutrinos can be expressed as

$$\lambda_{\text{int}}(E_\nu) = [n_N \sigma^{CC}(E_\nu) + n_N \sigma^{NC}(E_\nu)]^{-1}, \quad (4.17)$$

where n_N is the nucleon density of the medium, and σ^{CC} and σ^{NC} are the neutrino-nucleon charged-current and neutral-current cross sections. Neutrino-electron interactions can be neglected as they are subdominant [140]. Above a few TeV, the Sun core becomes opaque to neutrinos, as the interaction length drops below the radius of the Sun core. For this reason, a saturation effect occurs when testing WIMP hypotheses for masses above this energy threshold: the neutrino spectrum resulting from an annihilation of a 20 TeV/ c^2 WIMP to taus looks the same as the spectrum of a 5 TeV/ c^2 WIMP, as the high energy neutrinos produced by the higher mass WIMP get absorbed.

4.6.2 Implementation of a moving source

The Sun is a specific source in the sense that it does not remain motionless in equatorial coordinates. One must account for this when computing the signal efficiency of the data set. The effective area is computed as a two-dimensional distribution, a function of event energy and declination. The effective area in different declination bins is then summed as a weighted average, weighting each declination bin according to the fractional amount of time the Sun spent in that declination bin during the data taking period. This weighted average is then multiplied by the spectrum and integrated through the energy range in order to obtain an estimate of the signal acceptance. A plot showing the signal acceptance for the three channels of interest is shown in Fig. 4.20.

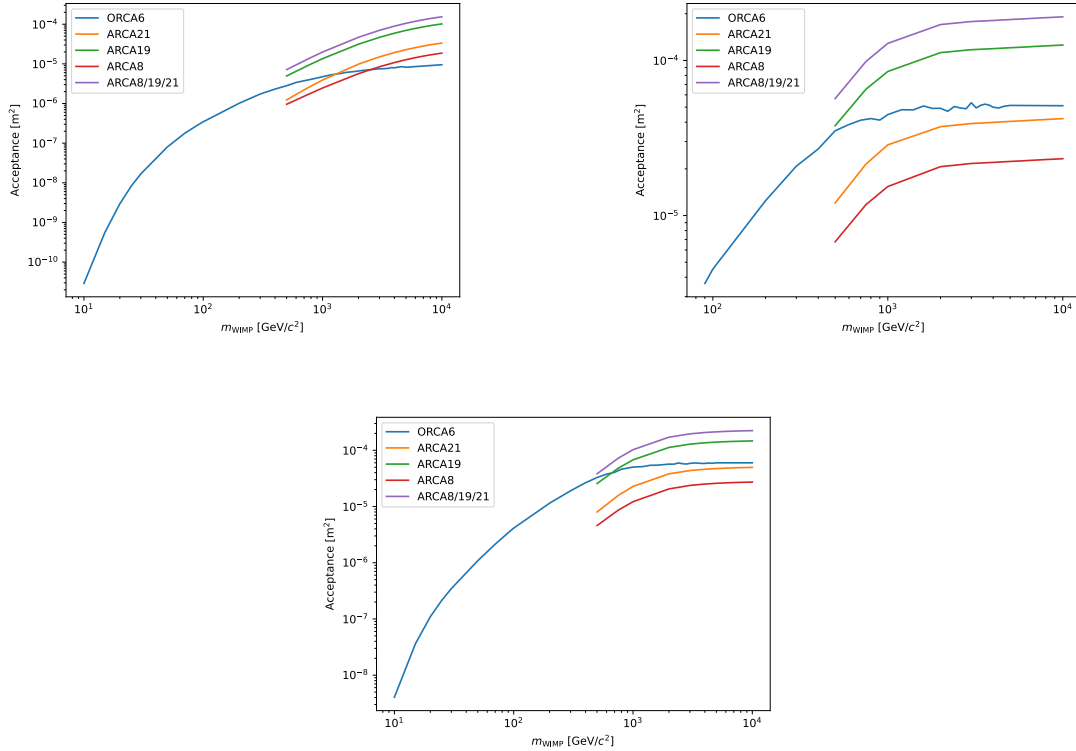


FIGURE 4.20: The integrated signal acceptance for WIMPs in the Sun annihilating to $b\bar{b}$ (left), W^+W^- (middle), and $\tau^+\tau^-$ (bottom), shown as a function of the WIMP mass. The plots show acceptances of the three configurations used in this analysis, ARCA8, 19, and 21, and the acceptance of ORCA6, the data set on which this analysis was performed previously.

The unbinned likelihood analysis proceeds in the same manner as for the Galactic Centre, with the exception that source positions need to be generated. A plot of the Sun path, expressed as a function of the sine of the declination, during the data taking

of each of the three data sets considered in this work is shown in Fig. 4.21. As seen in

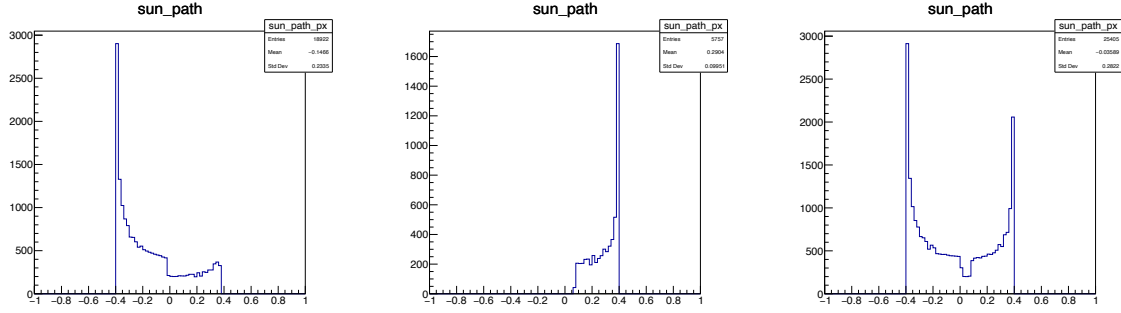


FIGURE 4.21: The sun path shown as a function of $\sin(\delta)$ for the ARCA8 data set (left), ARCA19 (middle) and ARCA21 (right).

Table 4.1, ARCA8 took data during the autumn, winter and spring- hence why the sun path distribution is asymmetrical, as there is no data during the summer months when the Sun appears more at positive declinations. The situation for ARCA19 is the opposite, as this detector only recorded data during the summer. Finally, the ARCA21 detector took data throughout a calendar year, resulting in a nearly symmetric distribution. Since source positions are time-dependent, they are generated according to the following procedure:

1. Generation of event coordinates
2. Generation of event times, based on a $\delta - t$ distribution of events
3. Generation of the Sun declination from the event times, using a $\delta_{Sun} - t$ distribution
4. Generation of Sun right ascensions: following the blinding policy, this is set as a random number between 0 and 2π

Both the event coordinates and source coordinates are saved in the event vector, which allows for the computation of the angular distance from the source, α , needed for the computation of signal probabilities. Once data is unblinded, the Sun position must be computed at the time that each data event is recorded. The probability evaluation then proceeds in the same way, comparing coordinates of data events to the position of the Sun at that time.

5

Results

In this chapter, the results obtained throughout the course of my PhD are presented. Firstly, the results of the search for dark matter in the Galactic Centre with the unbinned likelihood approach are reported. This is followed by a section describing the efforts made to unify and combine the data sets of KM3NeT and its predecessor, ANTARES, and the resulting improvement in the reported upper limits. The results obtained by the method of combining likelihood curves are reported in the following section. What follows is a section discussing the impact of the chosen dark matter inputs: a study was conducted to investigate the variation in the upper limits when different neutrino spectrum computations and different dark matter density profiles are used. A report of the studies conducted in order to assess the impact of systematic uncertainties on the constraining power of KM3NeT to the parameters of interest are reported next. Lastly, the sensitivities to dark matter in the Sun are reported in the final section of this chapter.

5.1 Unbinned likelihood search with the ARCA8/19/21 data

The event samples of ARCA8, ARCA19 and ARCA21 have been extensively described in Sec. 4.1, both the run selection and the methodology used to select well-reconstructed neutrinos and to filter out the downgoing atmospheric muons. This collection of samples, referred to as ARCA8/19/21, is used throughout the different analyses reported in this chapter. The likelihood methodology described in Sec. 4.3 was applied to the samples: firstly on mock data sets in order to estimate the sensitivity of KM3NeT to the WIMP

pair-annihilation cross section, after which the TS of the unblinded data was computed. No significant excess above the background was found for any of the signal hypotheses tested. Therefore, upper limits on the thermally-averaged cross section were placed for each signal hypothesis. The upper limits are shown as a function of the WIMP mass for each channel tested in Fig. 5.1. The figure shows the upper limits from KM3NeT's predecessor, ANTARES, for reference. The upper limit shown in orange is obtained using

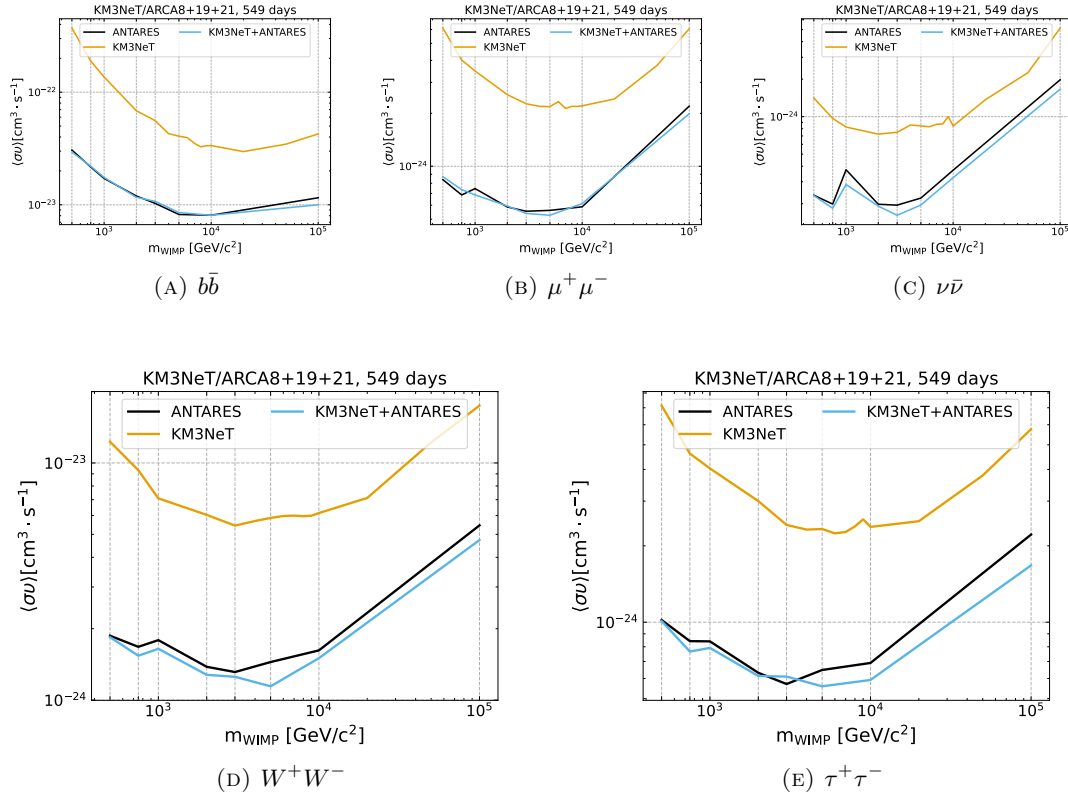


FIGURE 5.1: Comparison of upper limits on the thermally-averaged WIMP pair-annihilation cross section obtained with the ARCA8/19/21 data set and the ANTARES data set. Shown in black are limits obtained in using the full ANTARES 4532 day data set. The orange line is the ARCA8/19/21 limit obtained in this work, while blue line shows the limit obtained when combining ANTARES and KM3NeT data.

the data set of ARCA8/19/21 and the methodology described in the previous chapter. The ANTARES limits were recomputed using the software tools developed during the course of this thesis. The signal and background responses were recomputed, and the resulting sensitivities are shown with the blue line. Finally, the KM3NeT and ANTARES data sets were merged and an analysis was conducted on the combined data set, resulting in a small improvement in the sensitivities as seen by the teal line.

The upper limits are compared to other experiments in the field in Fig. 5.2 [141–146]. The other neutrino telescopes in the figure, IceCube and ANTARES, utilise a very

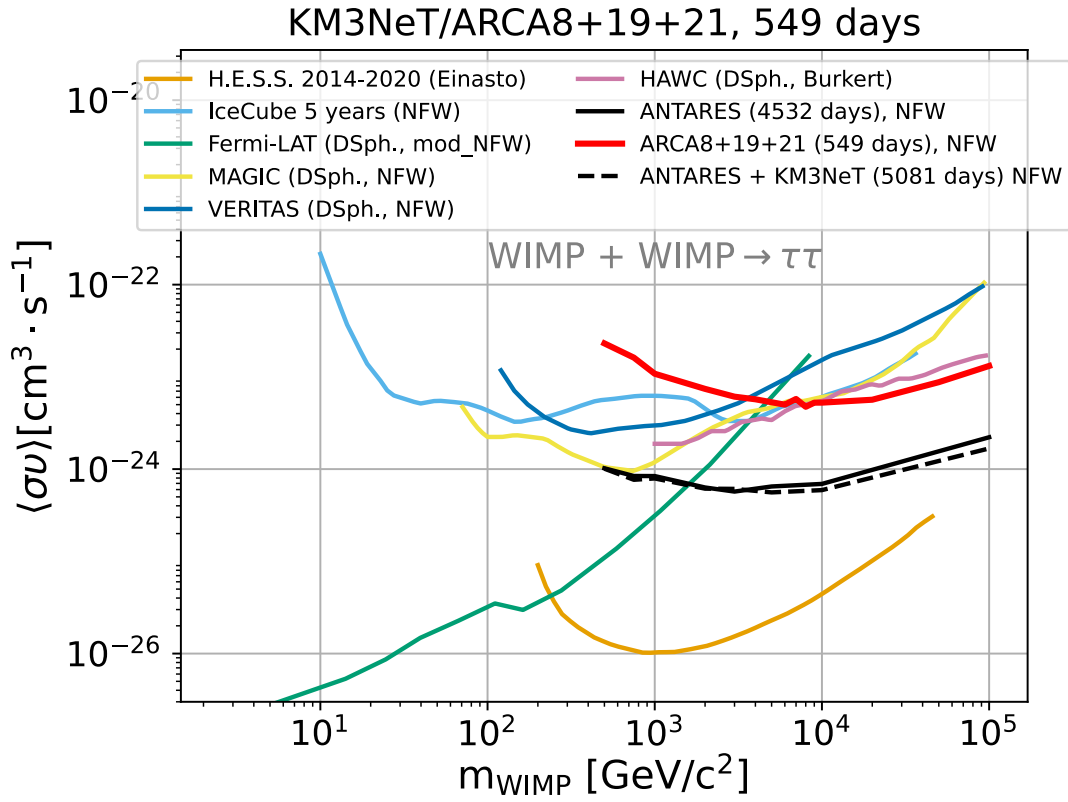


FIGURE 5.2: The limit on the WIMP pair-annihilation cross section for annihilation to tauons obtained with the KM3NeT dataset is shown in red, as a function of the WIMP mass. The updated ANTARES limit is shown in black. The black dashed line is the sensitivity obtained with the combined KM3NeT and ANTARES data. The plot also contains the latest limits by neutrino and γ -ray observatories conducting indirect dark matter searches [141–146]. The legend also indicates the density profile used in order to compute the result, and the sources studied (DSph. indicates dwarf spheroidal galaxies).

similar methodology in order to obtain a limit on this parameter: both detectors look for neutrinos from WIMPs annihilating in the Galactic Centre, using the same spectrum prediction and density profile parametrisation in order to compute the signal expectation and upper limits. This allows for a direct comparison of results. The IceCube experiment, despite having a larger detection volume and longer livetime, performs at a similar level as the neutrino telescopes in the Mediterranean, due to the position of the Galactic Centre in the Southern sky. The sky is above the horizon from the viewpoint of IceCube, resulting in signal neutrinos arriving to the detector from downgoing directions, the same directions from which the largest source of background, atmospheric muons, are arriving. Therefore, the rejection of background and isolation of signal events is more difficult for signal events arriving from the direction of the Galactic Centre. For the Mediterranean neutrino telescopes KM3NeT and ANTARES, the Galactic Centre remains visible, below

the horizon, for $\sim 75\%$ of the observation time, making it easier to reject muons by requiring events to be reconstructed with upgoing directions. IceCube has to utilise more restrictive selection methods: for example, track events are required to have vertices inside the detector volume (referred to as starting events), which ensures the detected muon was produced by a neutrino interacting in the detector volume, rather than a cosmic ray interacting with the atmosphere. Furthermore, cascade-like events are utilised, since their event topology differs from the light signatures produced by atmospheric muons traversing the detector.

KM3NeT's predecessor, ANTARES, has a smaller detection volume (12 detection lines), but a much longer observation time, with an effective livetime of 4532 days. However, KM3NeT has improved in certain design aspects and software with respect to ANTARES. Firstly, one of the most important differences between the two detectors is the light detection technology: KM3NeT employs optical modules with 31 smaller PMTs in one module, whereas the ANTARES optical module contains one large PMT. The advantages of the KM3NeT design are numerous: the larger number of PMTs offers superior determination of the direction the light was emitted from, in particular it allows for some directional information when only one optical module detected light [105]. The multi-PMT design is also more resilient against technical failures, as the failure of a PMT does not impact the detection capability of the detector when the optical module has other functional PMTs still detecting light. The light detection efficiency is an important consideration, as the ANTARES detector's light collection efficiency decreased with time due to the effect of sedimentation on the optical modules. In terms of analysis methodology, certain improvements were made in different areas: firstly, the use of machine learning in event selections has not been utilised in the ANTARES dark matter searches. Furthermore, improvements were made in the signal/background modelling: previous ANTARES analyses decoupled the detector angular and energy responses from one another. As explained in Sec. 4.2.4, the angular response of the detector differs in each reconstructed energy bin. Furthermore, the shape of the declination distribution of background events differs for each energy bin. Therefore, coupling the spatial and energy variable in the generation functions and probability functions is a more accurate way to model the signal and background events. Due to all of these improvements, the results obtained with KM3NeT are comparable to the ANTARES upper limits, despite the large difference in the livetime (factor ~ 8.6).

Finally, the results obtained with KM3NeT are also compared to results obtained with γ -ray telescopes. In the mass region where KM3NeT/ARCA is sensitive, the results from H.E.S.S. lead the field. This observatory dedicated a significant amount of observation time observing the Galactic Centre, with their null observations resulting in leading upper limits in the field for certain channels. At lower masses, results from other imaging atmospheric Čerenkov telescopes are relevant: MAGIC, HAWC and VERITAS. These telescopes obtain limits by studying dwarf spheroidal galaxies, which contain a smaller amount of dark matter with respect to the Galactic Centre but offer the advantage of a negligible background from the γ -ray emission in astrophysical processes. At the lowest masses in the GeV range, the space-based Fermi-LAT instrument is the most sensitive to WIMP annihilation signals.

5.2 Impact of the choice of dark matter inputs: spectrum and density profile

As described in Sec. 2.3.3.3, indirect dark matter searches in the Galactic Centre require the prior knowledge of the mass density profile of the Milky Way halo, along with the neutrino spectrum produced in a pair-annihilation process. The mass density profile is difficult to estimate in the innermost regions of the galaxy, and the computation of the neutrino spectrum suffers from uncertainties when considering processes at high energies ($> \text{TeV}$), for which the relevant processes have not been well constrained in accelerators. Therefore, in order to quantify these uncertainties, different theoretical inputs were used in this work in order to estimate their impact on the constraining power of the parameter of interest, $\langle\sigma v\rangle$.

To evaluate the impact of the choice of spectrum computation, the Bauer-Rodd-Webber (BRW) calculation [77] is used in order to compute the signal expectation at the detector and to compute the signal acceptance. Any change in the signal response will alter how the signal is generated when creating mock data sets, and how the likelihood is evaluated. For instance, if one of the spectrum computations predicts a softer neutrino spectrum, this will have a twofold effect: firstly, the events will be reconstructed at lower energies, where there is a larger portion of background events. Secondly, a softer spectrum will result in a worsening of the angular response, as the angular resolution worsens at

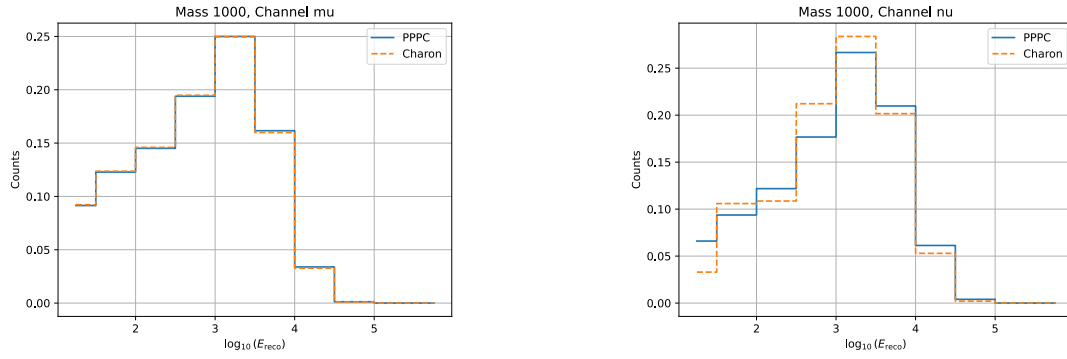


FIGURE 5.3: The energy response of the ARCA21 detector to signal events weighted with PPC (blue solid line) and BRW spectra (orange dotted lines). The plot on the left shows the energy distribution for 1 TeV/ c^2 WIMPs annihilating to muons; on the right the annihilation to neutrinos is shown.

lower energies. Both of these effects would result in a worsening in the sensitivity on the number of signal events. On the other hand, a softer spectrum would result in a lower signal acceptance: the acceptance directly influences the flux sensitivity, and thus the annihilation cross section sensitivity, through Eq. 4.4.

The comparison of the different inputs has been shown in Fig. 4.8, where the spectrum prediction is shown for both PPC and BRW, for a number of different signal hypotheses. Significant differences are only seen in the neutrino channel, so this is the only channel for which the spectrum input is expected to have a large impact on the resulting sensitivities. The ARCA21 energy response for the two different spectrum computations is shown in Fig. 5.3. As expected from the initial inspection of the differences in the two spectrum computations, the largest difference in the energy distributions is seen for the neutrino channel. A comparison of the angular distributions obtained using the two spectrum computations is shown in Fig 5.4. A comparison of the differential acceptances for a given mass is shown for two channels in Fig 5.5. The integrated signal acceptance for all the masses tested in this work is shown for the two spectra in Fig. 5.6. As expected from the preliminary comparisons of the spectra, the impact of the spectrum choice is negligible for all channels with the exception of the neutrino channel, where a larger acceptance value is obtained when using BRW spectra. Differences are most pronounced in the neutrino channel due to the differences in how the spectra are computed: in PPC, electroweak radiative processes are numerically summed at leading order, convoluting the initial spectra from PYTHIA, thus artificially smearing out the peak close to the dark matter mass. In the BRW paper, the spectrum from the dark matter mass down to the weak scale is

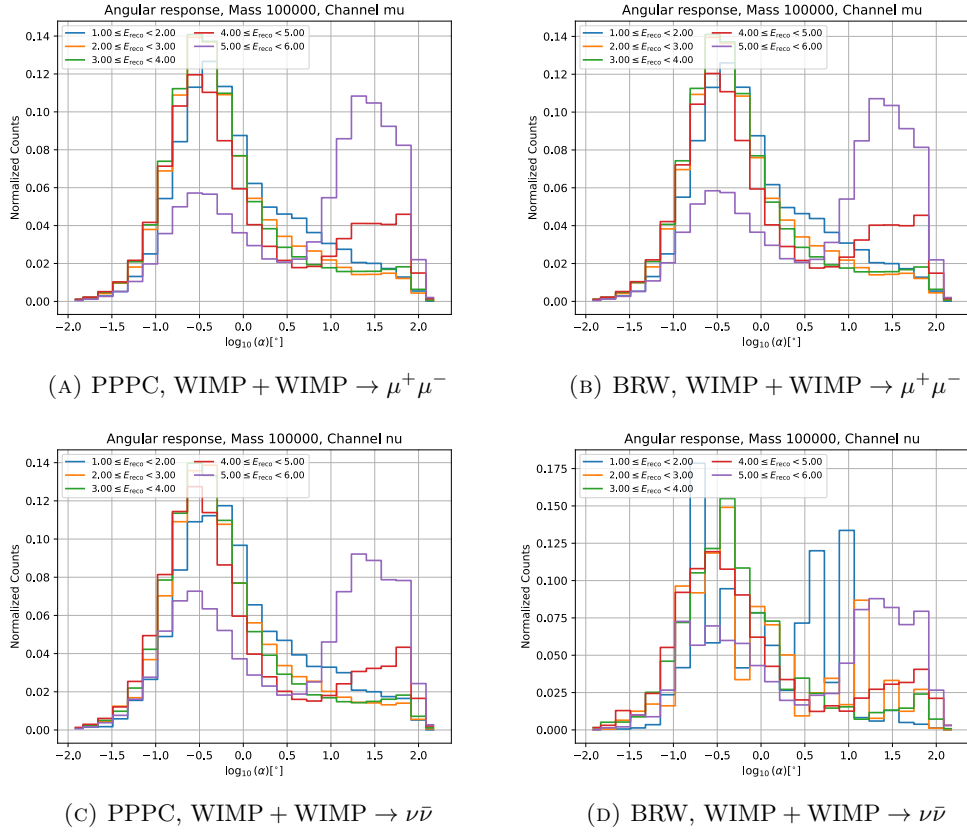


FIGURE 5.4: Angular response of the ARCA21 detector for annihilations of 100 TeV/c^2 WIMPs in different bins of reconstructed energy. On the left are shown the angular distributions weighted with PPC spectra, on the right the distributions are weighted with the BRW spectra. Annihilations to muons are assumed in the top row, whereas annihilations to neutrinos are assumed for the bottom row.

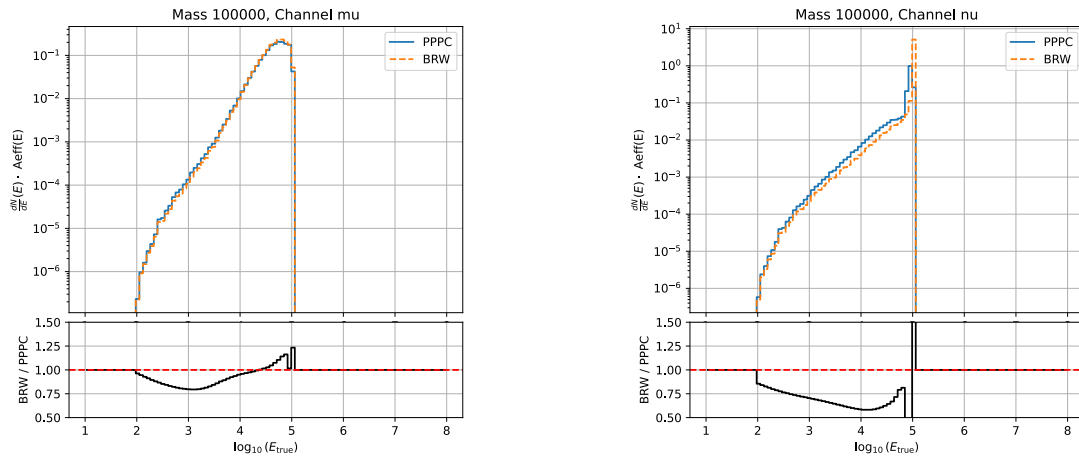


FIGURE 5.5: The differential acceptance as a function of true energy for a signal hypothesis of a 100 TeV/c^2 WIMP annihilating to muons (left) and neutrinos (right), shown for the two spectra. The ratio plot on the bottom indicates the ratio of acceptances per bin.

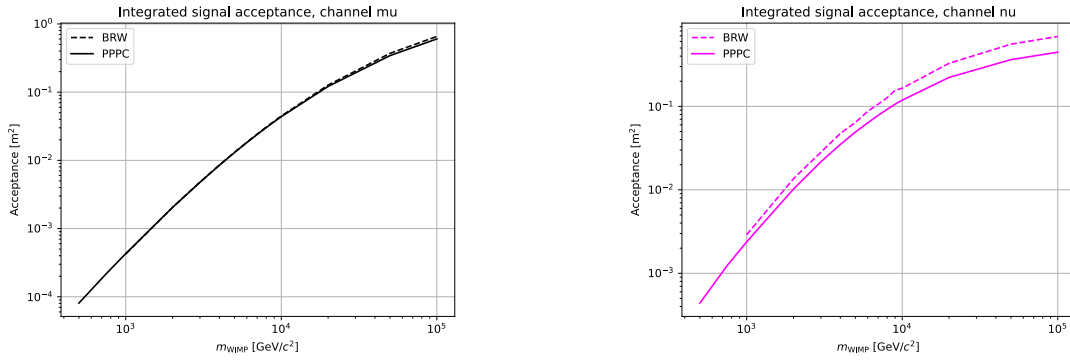


FIGURE 5.6: The integrated acceptance as a function of the WIMP mass for a signal hypothesis of WIMPs annihilating to muons (left) and neutrinos (right), shown for the two spectra.

computed by evolving the fragmentation functions to compute the full energy distribution after radiation. A recent publication [78] has provided a fully consistent treatment across the parameter space by using the latest versions of PYTHIA, enhanced with a shower algorithm that accounts for helicities of particles, trilinear and off-shell couplings, all built into the shower algorithm and not resummed as in the other publications. The publication includes a detailed discussion on how the differences in the computation of the EW radiation affects different annihilation channels: differences are minimal close to the dark matter mass, however at the low energy tail the different publications diverge. In KM3NeT/ARCA, the high energy part of the spectrum is measured for all WIMP masses tested. The low energy tail where large differences in spectrum computations are seen are below the threshold of observation.

In order to estimate the impact of these effects on the sensitivity, the unbinned likelihood analysis was repeated, using the BRW spectra to create the distributions that generate signal event coordinates and energies, and evaluate signal probabilities. The analysis was conducted on a singular data set, ARCA21, in order to save computing power- significant processing time is needed to create signal models in all the available data sets, and the execution of the likelihood framework is significantly slower when multiple data sets are included and the total number of events considered is larger. The sensitivity to the number of signal events obtained with the PPC and BRW spectra is shown in Fig 5.7. As seen in the Figure, an equivalent limit on the number of signal events is obtained when using the two spectra. The minute differences in the spectra are not large enough to be reflected in the detector response and to impact the signal event generation and likelihood evaluation. The sensitivities to the WIMP pair-annihilation cross section obtained with

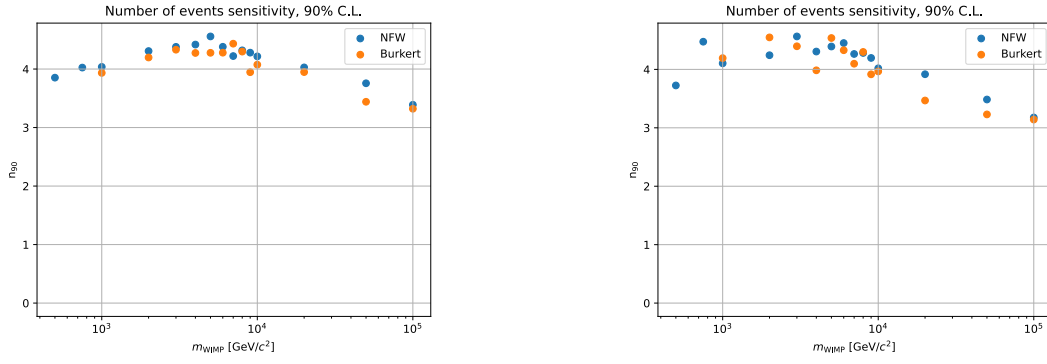


FIGURE 5.7: The sensitivity to the number of signal events as a function of the WIMP mass, shown for the muon channel on the left, and the neutrino channel on the right for the two spectra being compared.

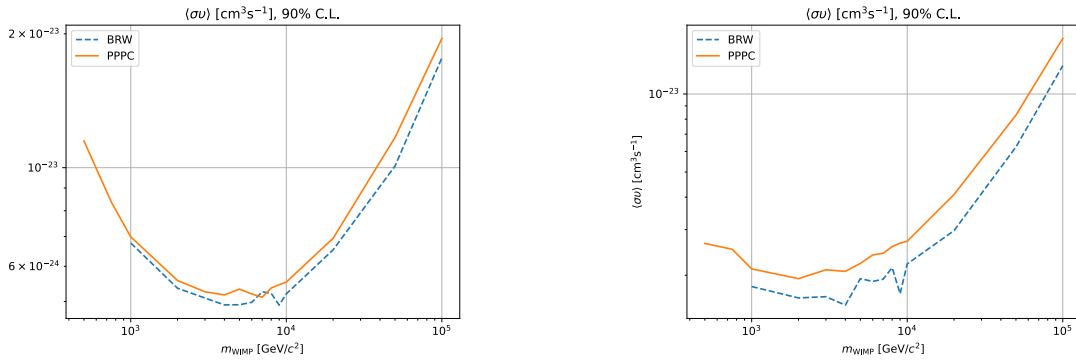


FIGURE 5.8: The sensitivity to the thermally-averaged WIMP pair-annihilation cross section as a function of the WIMP mass, shown for the muon channel on the left, and the neutrino channel on the right for the two spectra being compared.

the two spectra are shown in Fig. 5.8 for the muon and neutrino channel. As the number of events sensitivities are equal across the scanned parameter space, the differences in the sensitivities are driven by the differences in the integrated acceptance, hence why the impact of the spectrum choice is the largest for the neutrino channel.

The results reported in previous sections of this chapter were all obtained using a cuspy density profile, the NFW profile. As stated previously, a cored density profile, in this instance the Burkert profile, will be used in order to evaluate the impact of this quantity on the limit on the WIMP annihilation cross section. The parameters of the density profiles used to model the mass density of the halo has been provided in Table 4.3. The Burkert profile has an extended core of constant density in the centre of the Galaxy, making the emission more diffuse. The extent of the emission is quantified with the variable $\frac{dJ_{int}}{d\alpha_{int}}$, the rate of the change of the integral of the J-factor with respect to the integration angle. This one-dimensional quantity was projected in galactic coordinates in

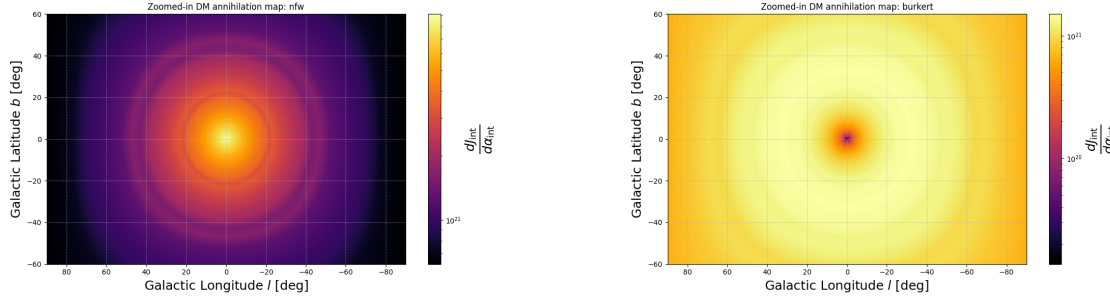


FIGURE 5.9: A projection of the rate of change of the J-factor integral as a function of the angular distance to the centre of the Galaxy onto a 2D grid in Galactic coordinates.

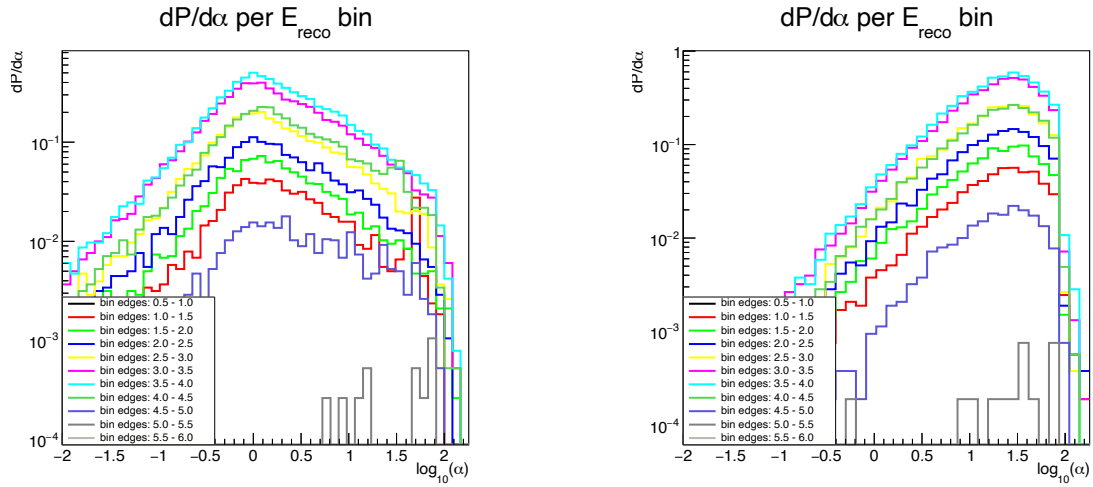


FIGURE 5.10: The distributions used to generate the logarithm of the angular distance to the source, $\log_{10}(\alpha)$, for a 1000 TeV/ c^2 WIMP annihilating to muons. The different colors indicate different energy bins in $\log_{10}(E_{reco})$, projections in each energy bin are shown. On the left, the angular response function was smeared with the NFW emission profile, on the right with the Burkert profile.

order to visualise the emission profile of the flux in Fig. 5.9. As can be seen in the Figure, the cuspy density profile results in more point-like emission, while the constant density core of the Burkert profile results in a more extended emission profile. Furthermore, due to the constant density core, the emission is weaker in the centre of the Galaxy, and rises towards the edge of the core. This is purely a geometric effect, as the line of sight distance increases with the angular distance from the source, and the integral of the squared density is integrating over a larger line of sight, considering more matter. The effect of the spatial extension of the source on the distributions used to generate signal coordinates is shown in Fig. 5.10. As seen in the Figure, due to the shape of the Burkert profile, signal events will be generated at larger angular distances away from the source when the Burkert profile is assumed. As the signal events are more dispersed, a much larger quantity of signal events is needed in order to be distinguished from the background. In other words,

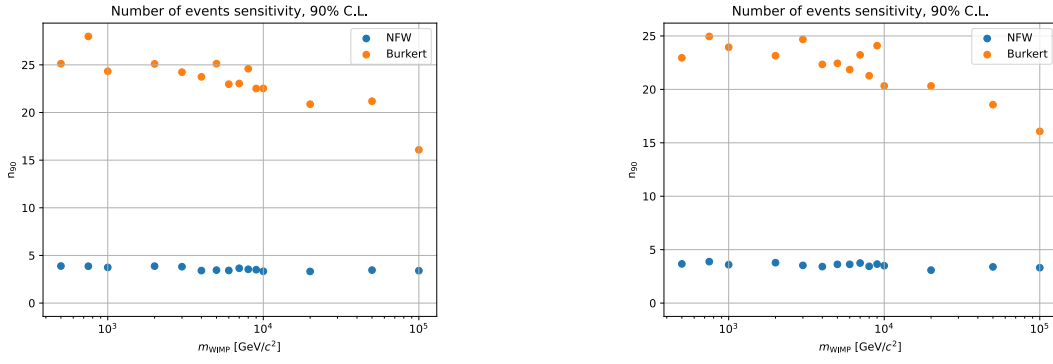


FIGURE 5.11: The number of signal events that can be rejected with 90% confidence as a function of the WIMP mass, shown for the tau annihilation channel on the left, and the neutrino channel on the right. The orange points are obtained assuming the Burkert density profile, while the blue dots assume a NFW density profile.

the more extended emission profile will result in a larger limit on the number of signal events that can be rejected with 90% confidence. This is confirmed in Fig. 5.11, where the sensitivity to the number of signal events is plotted for the two density profiles. The more extended emission profile results in a factor 5 worse sensitivity to the number of signal events. The second quantity influenced by the choice of the density profile is the integral of the J-factor, directly scaling the neutrino flux in Eq. 2.10. The integrated J-factor values obtained with the two density profiles are reported in Table 5.1.

NFW	Burkert
$1.76 \cdot 10^{23}$	$8.77 \cdot 10^{22}$

TABLE 5.1: Full sky J-factor integrals obtained for the two density profiles considered in this work.

The final sensitivities to the WIMP annihilation cross section obtained for the Burkert profile are compared to the results previously obtained using the NFW profile in Fig. 5.12. An order of magnitude difference in the sensitivities is observed across the parameter space, for all channel and mass scenarios. This is due to the two reasons outlined above: the more diffuse emission profile results in a sensitivity to the number of events that is five times larger, while the J-factor integral is two times smaller, resulting in an order of magnitude worsening of the cross section sensitivities. This parameter is therefore the largest source of uncertainty in computing cross section limits by searching for a flux of secondary particles from the Milky Way halo. The actual limit on the annihilation cross section lies somewhere in-between the two lines, but until a more precise determination of the density profile is achieved, the precise limit cannot be determined. Instead, limits

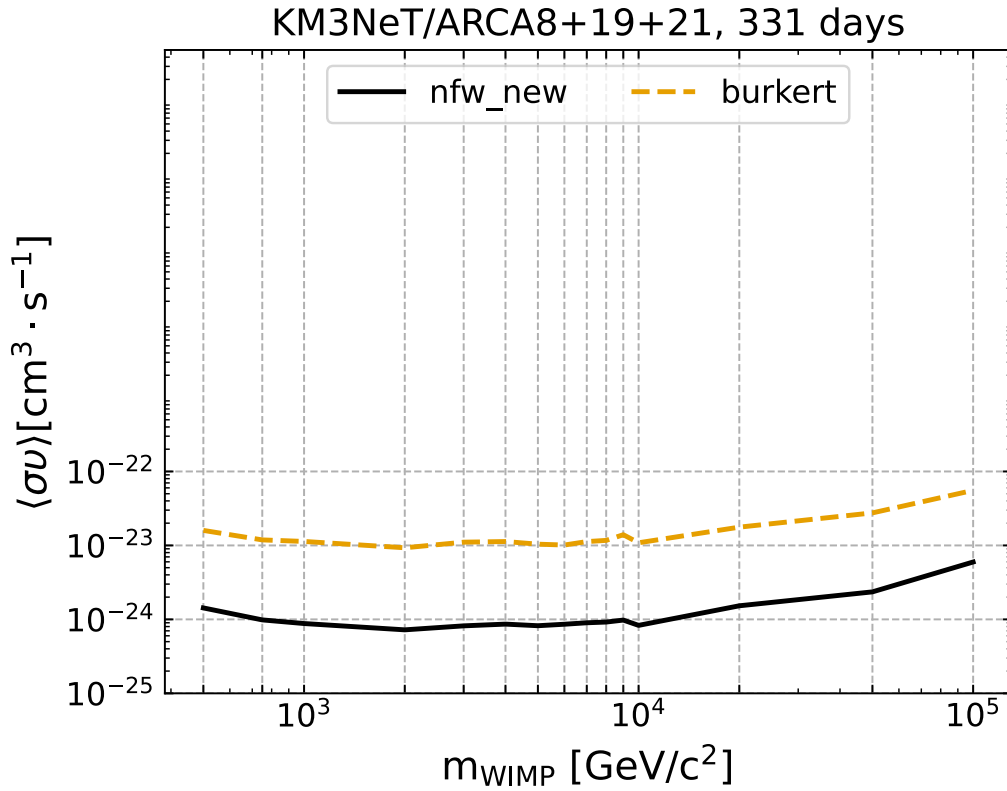


FIGURE 5.12: Sensitivities to the WIMP annihilation cross section for the neutrino channel as a function of the WIMP mass, shown for the neutrino annihilation channel. The sensitivity shown in orange assumes a Burkert density profile, while the black line assumes an NFW profile.

for different families of profiles are usually reported, in order to provide context to the constraining power of the limits.

5.3 Systematic studies

Unconstrained detector properties are a class of systematic uncertainties affecting all analyses conducted with the data of that detector. The main detector uncertainties in KM3NeT are the water absorption length and the quantum efficiencies of the PMTs. These quantities, if not known exactly, can affect the number of detected photons on the PMTs, and the measurements of event observables, such as its energy and track length. In order to evaluate the impact of these uncertainties, neutrino simulations with modified water properties and quantum efficiencies have been created by analysts in the Collaboration, modifying the water absorption length and quantum efficiencies by $\pm 10\%$. A total of four modified neutrino simulations of a portion of the total ARCA21 livetime

were analysed in this work. In order to evaluate the impact of these modifications of the simulation, event distributions in certain variables are created first. In order to evaluate the impact on the constraining power of KM3NeT to the WIMP annihilation cross section, signal and background response functions are created for the modified simulations, and the likelihood analysis is repeated, using the signal and background responses obtained from modified simulations. Finally, these results are compared to the sensitivities obtained when the nominal neutrino simulation is used in the creation of the signal and background response. In this section, event distributions will often contain a ratio plot. The ratios are always computed with the nominal number of events in the numerator, and the number obtained from the modified simulations in the denominator:

$$R = \frac{n_{\text{nominal}}}{n_{\text{modified}}}.$$

A comparison of the event distributions of certain variables was conducted at two different cut levels. Firstly, the distributions were compared at the upgoing level, applying only the anti-noise selection (Eq 4.1) and a cut on the reconstructed directions, requiring the events to be coming from below the horizon. The resulting reconstructed energy, zenith, track length and the number of hits distributions are shown for the nominal neutrino simulations and four modified simulations in Fig. 5.13. In this work, a stricter event selection is usually applied in order to reduce the muon contamination and improve the detector response. Therefore, the impact of systematic uncertainties should be evaluated at an equivalent cut level. At the time of writing, due to time constraints it was not possible to train a BDT and compute scores for all the modified neutrino simulations. Instead, the track length, beta and the ratio of the likelihood and the number of hits are used in order to reach a cut level with an equivalent muon contamination. A comparison of the event distributions at this cut level are shown in Fig. 5.14.

The signal response for the different neutrino simulations is shown in Fig. 5.15, while the background response is shown in Fig. 5.16. In general, no big changes in the shape of the distributions are observed. The main differences are that simulations with a larger water absorption length and a larger quantum efficiency of PMTs result in a larger number of detected events. Both of these modifications result in more charge produced at the PMTs for a particle of a given energy passing through the detector, as expected. On the other hand, simulations with a reduced absorption length produce less light at

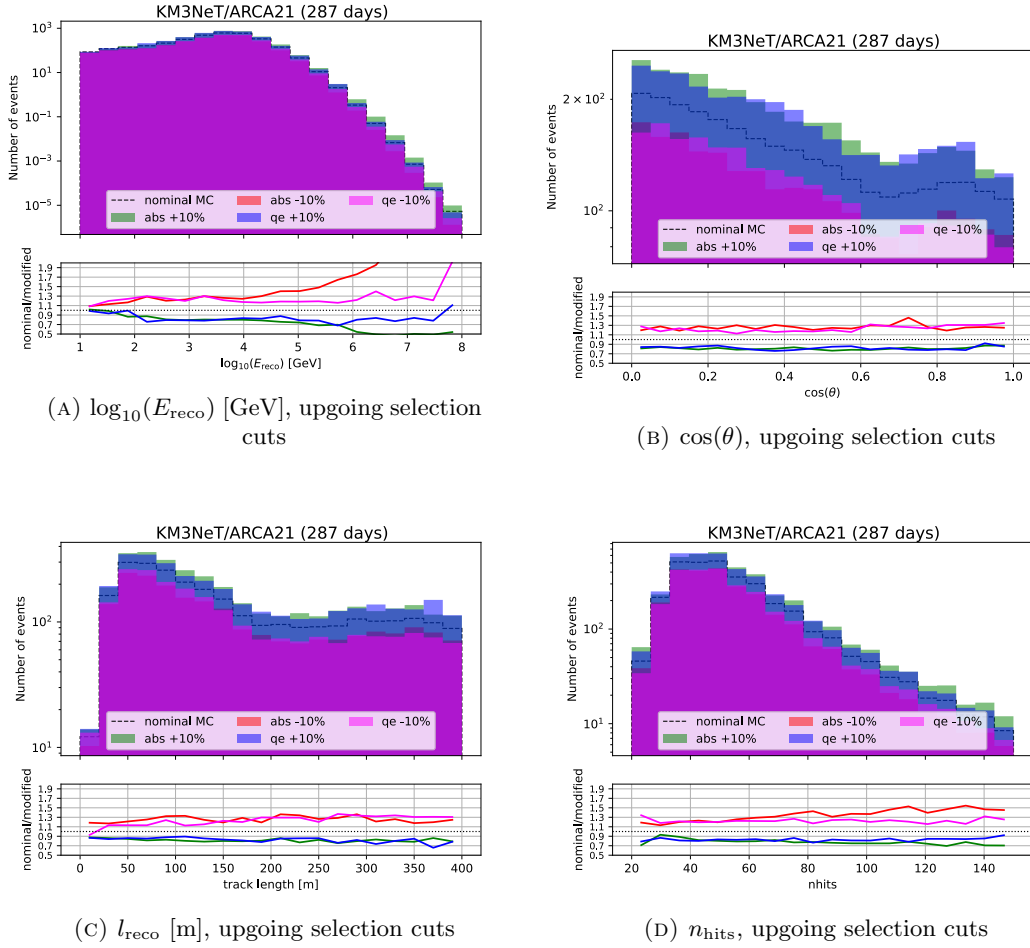


FIGURE 5.13: The event distributions of the reconstructed energy, zenith, track length and number of hits, shown for the nominal neutrino simulation and the four modified neutrino simulations. In the figure legend, the tag “abs $\pm 10\%$ ” refers to simulations with modified water absorption lengths, and “qe $\pm 10\%$ ” refers to simulations with modified PMT quantum efficiencies.

the PMTs, and the simulation with a reduced PMT quantum efficiency produces less charge for a given amount of light. Thus, the reduced number of detected events for these simulations is also expected. One surprising feature is observed in the background energy distribution: a deficit in the final bin for all modified neutrino simulations is observed, the cause of which is unknown.

The integrated signal acceptances obtained with the nominal and modified neutrino simulations are shown in Fig. 5.17. The acceptances are shown for four channels, across which the same behaviour is observed: simulations with an increased absorption length and PMT efficiency have a larger acceptance, due to the fact that the effective area is larger. Following the same logic as outlined in the paragraph above, such a behaviour is expected.

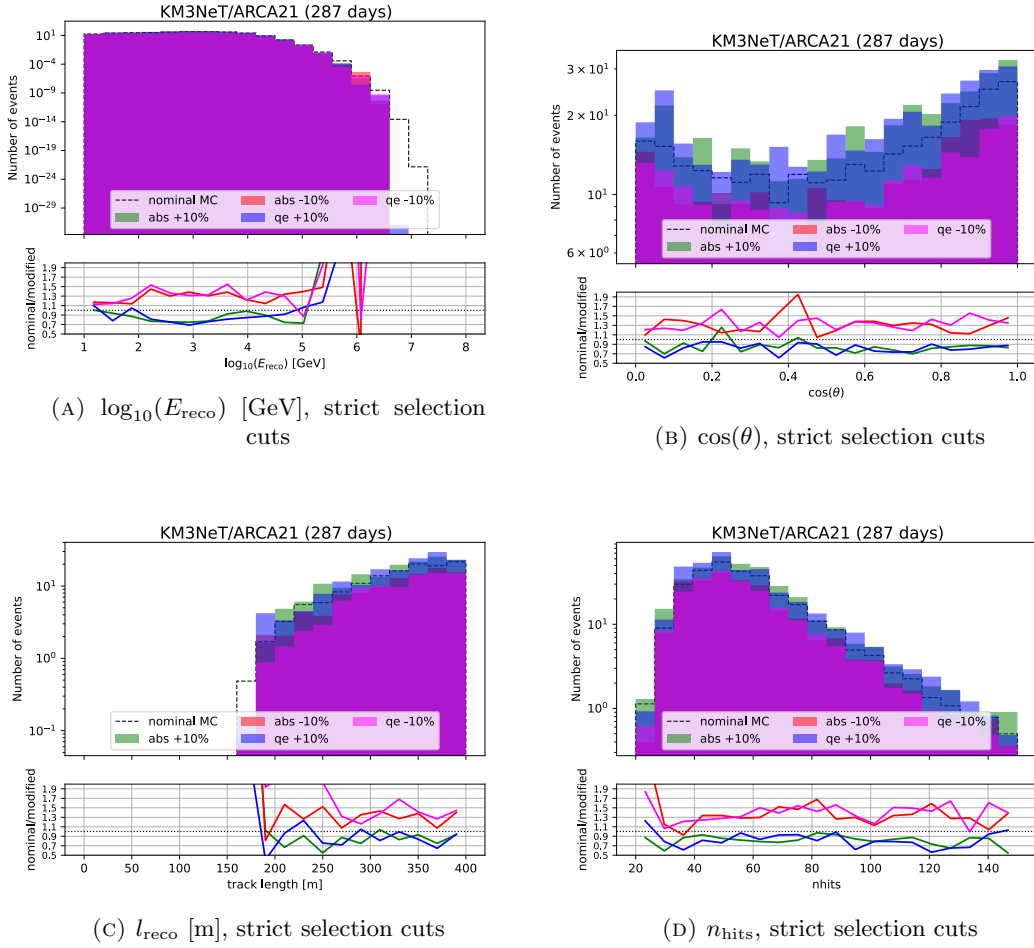


FIGURE 5.14: The event distributions of the reconstructed energy, zenith, track length and number of hits, shown for the nominal neutrino simulation and the four modified neutrino simulations. In the figure legend, “abs $\pm 10\%$ ” refers to simulations with modified water absorption lengths, and “qe $\pm 10\%$ ” refers to simulations with modified PMT quantum efficiencies.

Finally, the unbinned likelihood analysis was conducted in order to compute the sensitivities to the thermally-averaged WIMP pair-annihilation cross section. As there were no glaring differences in terms of how the signal response and acceptance was modified for different channels, the sensitivity was computed for one representative channel, in order to check the effect of modified simulations. The likelihood analysis was conducted as follows: for each modified simulation, the signal and the background generation functions obtained from the modified simulation were used to generate event directions and energies. To evaluate the likelihood, the signal and background probability distributions obtained from the nominal MC simulation were used. This attempts to emulate the situation where the nominal absorption length is incorrect: the generation functions are generating the

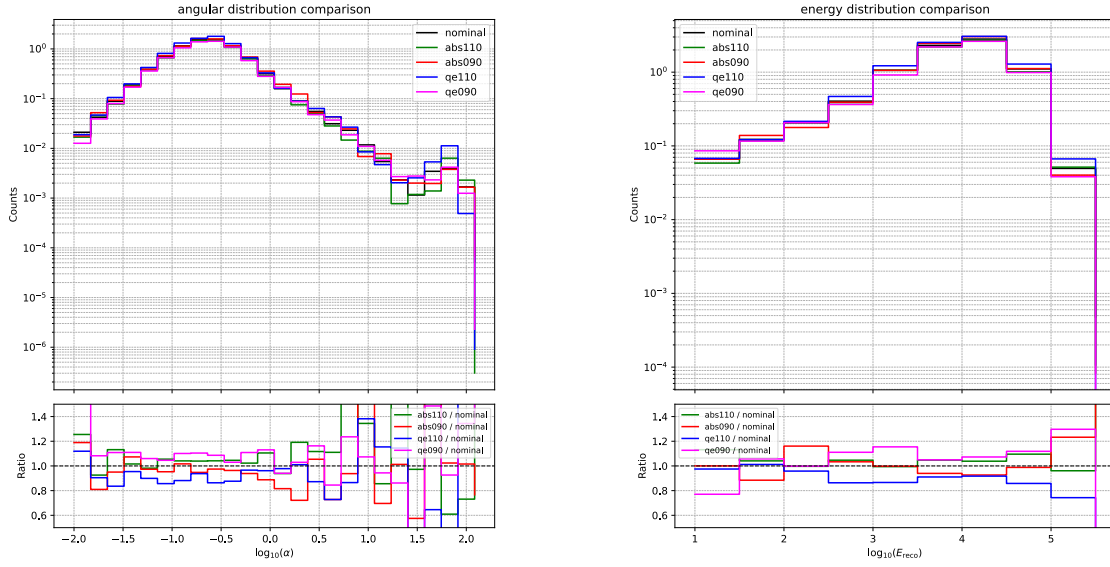


FIGURE 5.15: The signal angular and energy response for the nominal and modified neutrino simulations, shown for a 100 TeV/ c^2 WIMP annihilating to muons.

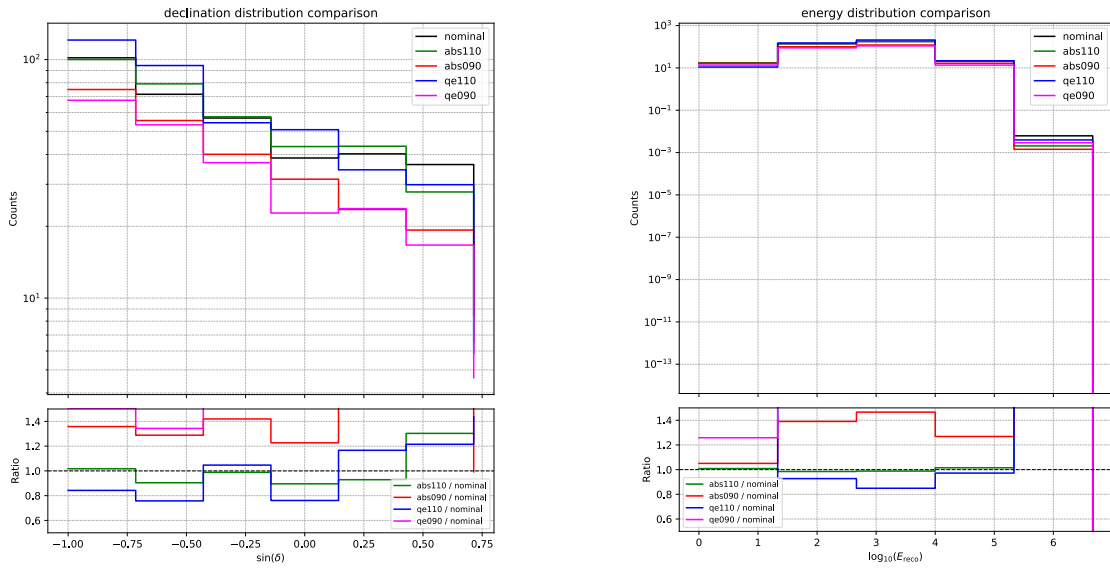


FIGURE 5.16: The background declination and energy distribution for the nominal and modified neutrino simulations. Since only neutrinos were simulated with modified water and PMT properties, these plots show only neutrinos, neglecting muons that pass the selection.

events using the modified, in this scenario true, absorption length. However, the likelihood is evaluated with the nominal, incorrect absorption length. Finally, for comparison purposes, the likelihood analysis was also conducted on the nominal MC sample, using two different approaches: in the first approach, no smearing to the generated number of signal events is applied. The second approach smears the number of signal events according to the methods described in Sec. 4.3.1. The nominal MC sample is used as a

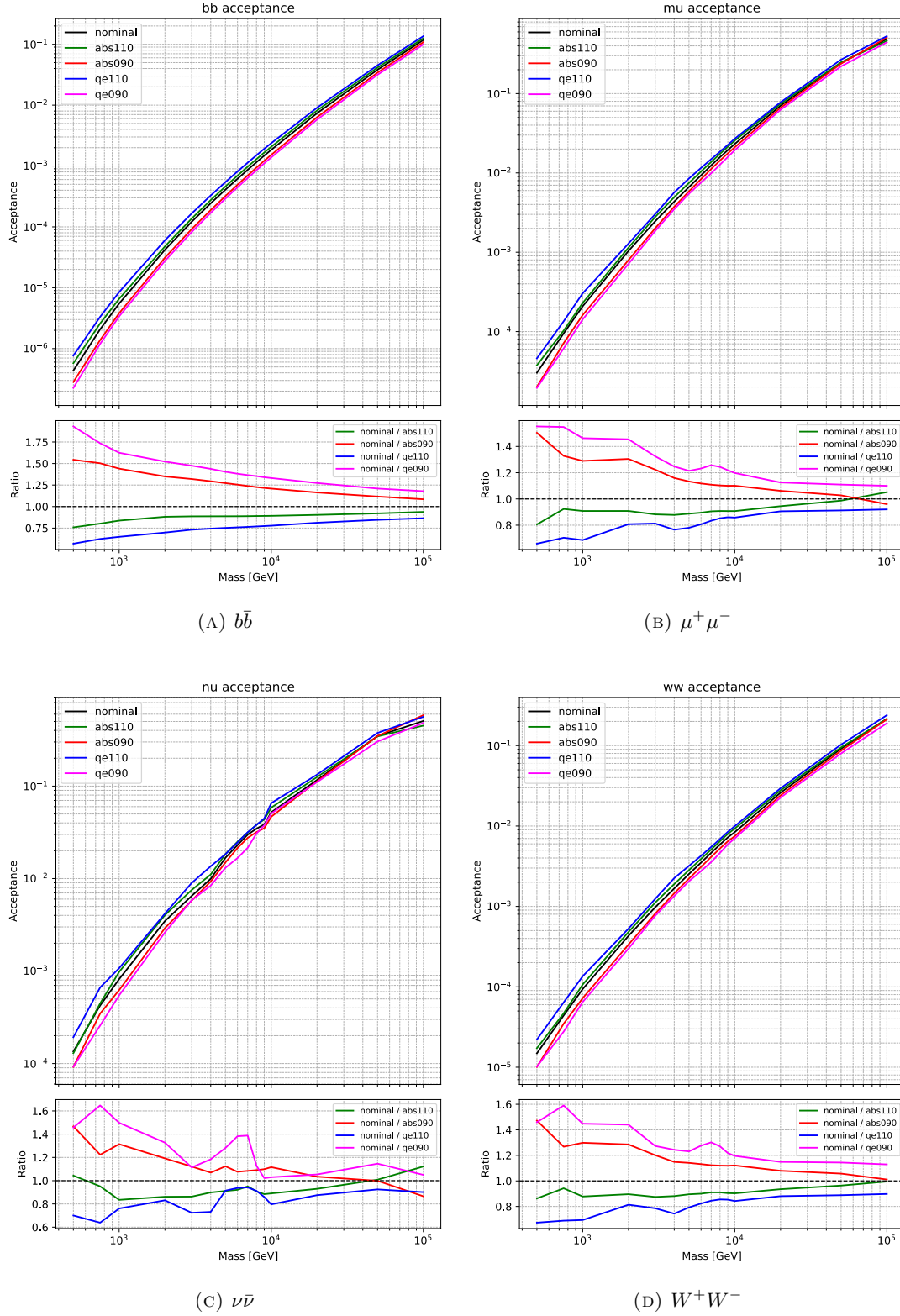


FIGURE 5.17: The integrated signal acceptances, shown as a function of the WIMP mass, for four annihilation channels. The figure compares the acceptances obtained with the nominal neutrino simulation and the modified simulations. In the figure legend, “abs $\pm 10\%$ ” refers to simulations with modified water absorption lengths, and “qe $\pm 10\%$ ” refers to simulations with modified PMT quantum efficiencies.

benchmark, to see what are the sensitivities in the case where the detector systematics are perfectly known. The results with the nominal MC sample where a smearing on the injected number of signal events is applied are also computed. This result is computed to check if the methods applied to account for detector systematics match the offset in sensitivities observed when using the modified MC simulations.

The final results are shown as a function of the WIMP mass for the nominal and modified neutrino simulations for the muon annihilation channel in Fig. 5.18. The re-

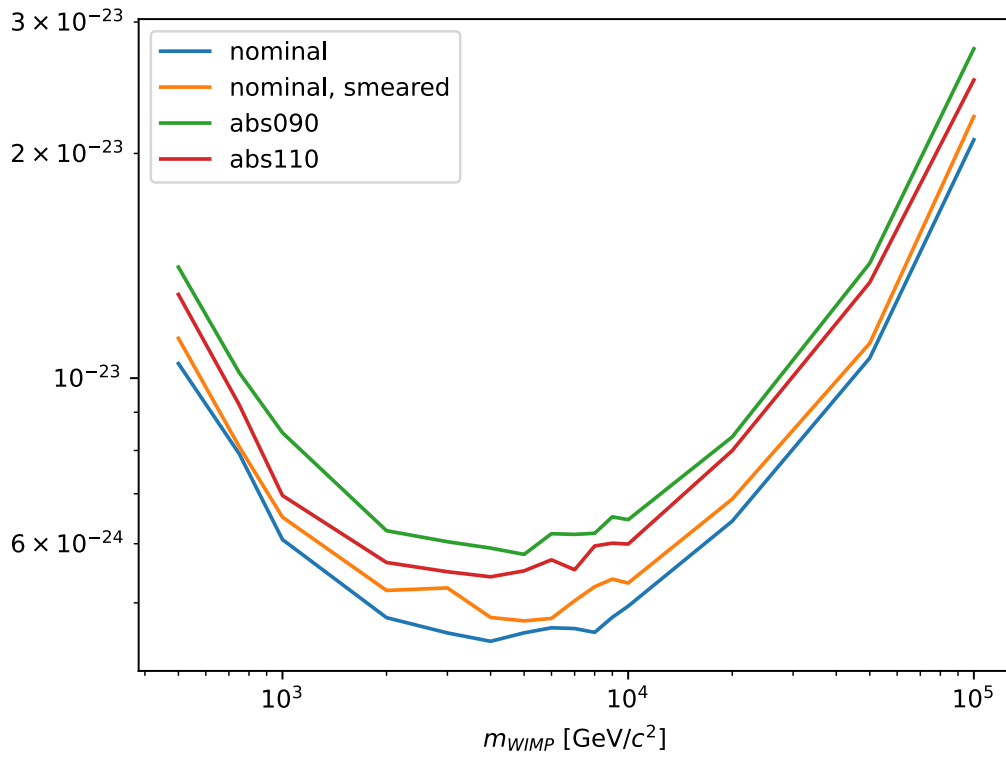


FIGURE 5.18: Sensitivities to the WIMP pair-annihilation cross section as a function of the dark matter mass, assuming annihilation to muons. The red and green line show the sensitivities obtained when simulations with modified absorption lengths are used to generate mock data sets. The blue line shows the results obtained with the nominal simulation, while the orange line also shows sensitivities obtained with the nominal simulation, but with the TS distributions smeared by a 30% Gaussian to account for the effect of systematic uncertainties on the detected number of signal events.

sults show some expected trends: for simulations with a shorter water absorption length, the effective area, and thus the signal acceptance, is lower, hence the sensitivity to the WIMP annihilation cross section is less constraining across the parameter space. On the other hand, the simulation with a larger water absorption length results in a larger signal acceptance. However, due to the fact that the modified simulations are used in the

signal and background generation, but the nominal MC is used in the likelihood evaluation, the sensitivity to the number of events is slightly worse, hence the improvement in the sensitivities is not exactly equal to the increase in the acceptance. The signal and background generation functions, created with the modified simulation, may create more events in certain energy bins than is predicted by the nominal simulation. This mismatch in the generation and probability functions results in a slight worsening in the sensitivity to the number of events. Finally, the results obtained with the nominal simulation reveal the impact of the smearing method on the number of events. The offset between the sensitivity obtained with the nominal simulation without accounting for the systematic uncertainty in the number of events, and the sensitivity obtained using the nominal simulation and accounting for the uncertainty, closely matches the observed change in sensitivity when a modified simulation is used. Thus, the methods used to account for systematic uncertainties seem to accurately account for their effects.

5.4 Likelihood combination with γ -ray experiments

The method described in Sec. 4.5 has been developed within the KM3NeT software framework in order to combine results with γ -ray observatories in the future. In order for this tool to be used, a unification of analysis inputs was conducted: common WIMP masses and channels were chosen, the same spectral computations used to model the γ -ray and neutrino spectra, and to model the Milky Way halo. Efforts are being conducted in order to contact the relevant personnel at the MAGIC telescope to proceed with the results combination at the moment of writing of this thesis. However, the tools have been prepared and verified for future analysers to pursue this topic. In this work, the tools developed were used as an alternate method to compute sensitivities and limits to the WIMP pair-annihilation cross section for individual and the combined data sets of KM3NeT. Therefore, the results reported in this section are used to verify the consistency of the unbinned method.

The methodology used to arrive to a constraint on the WIMP pair-annihilation cross section have been extensively described in Sec. 4.5, with a visual demonstration of the method in Fig. 4.19. The final upper limits and sensitivities obtained for the combination of the ARCA8, ARCA19 and ARCA21 data sets using this methodology are shown in Fig. 5.19. The plot displays the upper limits (solid lines) and sensitivities (dashed lines)

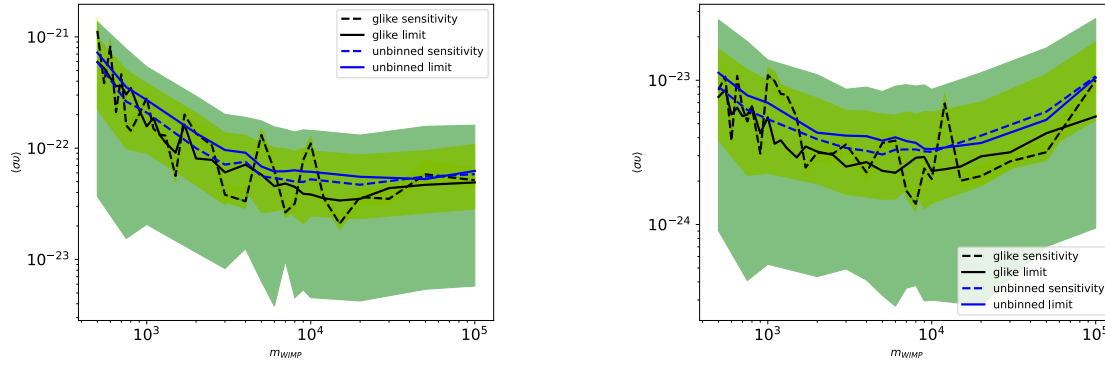


FIGURE 5.19: The upper limits and sensitivities at 95% C.L. on the WIMP annihilation cross section for the $b\bar{b}$ (left) and $\mu^+\mu^-$ (right) annihilation channel, shown as a function of the WIMP mass. The blue solid and dashed lines indicate the limits and sensitivities obtained with the unbinned method, while the black solid and dashed lines indicate the limits and sensitivities obtained with the likelihood combination method. The green bands indicate the 1σ and 2σ statistical uncertainties on the limit obtained with the unbinned method.

obtained with the approach of combining likelihood curves and with the unbinned method. The 1σ and 2σ statistical uncertainty bands obtained in the unbinned approach are also plotted. The limits and sensitivities of both approaches are reported at 95% C.L. in this plot, as this is the convention in the software framework of combining likelihood curves. A good agreement is seen in the results obtained with both methods, with small deviations at certain points in the parameter space. Such deviations are expected by statistical fluctuations, as they are well within the statistical uncertainty bands. The sensitivities obtained with the method of combining likelihood curves exhibit more instabilities, due to the fact that the number of samples generated for each point in the parameter space is smaller: only 300 mock data realisations are created in this method, in comparison to 10^4 realisations for each number of signal events generated in the unbinned method. However, despite the statistical fluctuations, the two methods yield equivalent results. Future studies will combine these results with the sensitivities and limits from γ -ray observatories.

5.5 Dark matter in the Sun

An unbinned likelihood analysis was also conducted searching for dark matter annihilations in the Sun, using spectrum models from [77], implemented within a framework to account for neutrino transport in [73]. As explained in the previous chapters, the neutrino

spectrum resulting from WIMP annihilations in the Sun has a cutoff at a few TeV, due to neutrino absorption. Therefore, the ARCA detector is not well suited for this search. The low energy counterpart, ORCA, has more constraining power due to its superior efficiency at lower energies ($< \text{TeV}$). A study was still conducted using the ARCA data sets used so far in this work: in the future, analysers can combine the prepared ARCA samples, the signal and background responses, with the ORCA data samples. Combining the data can result in a significant improvement in the range of energies where both detectors have comparable sensitivities.

A previous analysis [147] searching for dark matter in the Sun using 543 days of the ORCA detector with 6 detection units is used as a benchmark to compare the results to. One important difference with respect to that analysis is the choice of tools for the computation of the neutrino spectra: the previous analysis used *WimpSim* [148], a tool that uses different methods to compute the initial spectrum and to model the neutrino transport through the Sun. All the results in the field use this spectrum computation tool in their analyses, thus it is important to understand the differences of this spectrum calculation with respect to the computation used in this work [73]. At production, the *WimpSim* calculation does not account for electroweak corrections, relevant at energy scales probed in this work ($> 100 \text{ GeV}$). In terms of neutrino transport, authors in [73], whose results are used in this work, use an integro-differential equation approach in order to transport neutrinos through the solar matter, in contrast to the Monte Carlo based transport implemented in *WimpSim*. A comparison of the neutrino spectra at Earth, after accounting for neutrino transport and oscillations, is shown for the two spectra computations in Fig. 5.20. As seen in the Figure, despite the differences in the methodol-

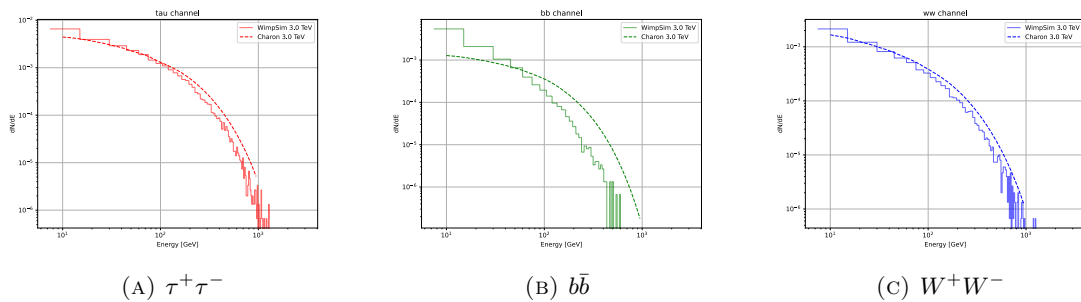


FIGURE 5.20: Comparison of neutrino spectra at Earth obtained using the two different spectrum computations available in the literature, shown for three WIMP annihilation channels at a WIMP mass $m_{\text{WIMP}} = 3 \text{ TeV}/c^2$.

ogy, the two spectrum computations predict similar energy distributions of neutrinos at

Earth. However, electroweak processes affect the hadronic channel, $b\bar{b}$, the most, with a significant increase in the number of high energy neutrinos predicted in [73].

In order to further understand the differences between the two spectra and their impact on the constraining power of our parameter of interest, the signal acceptance is compared to the acceptance obtained in the ORCA6 analysis using *WimpSim* in Fig 5.21. The

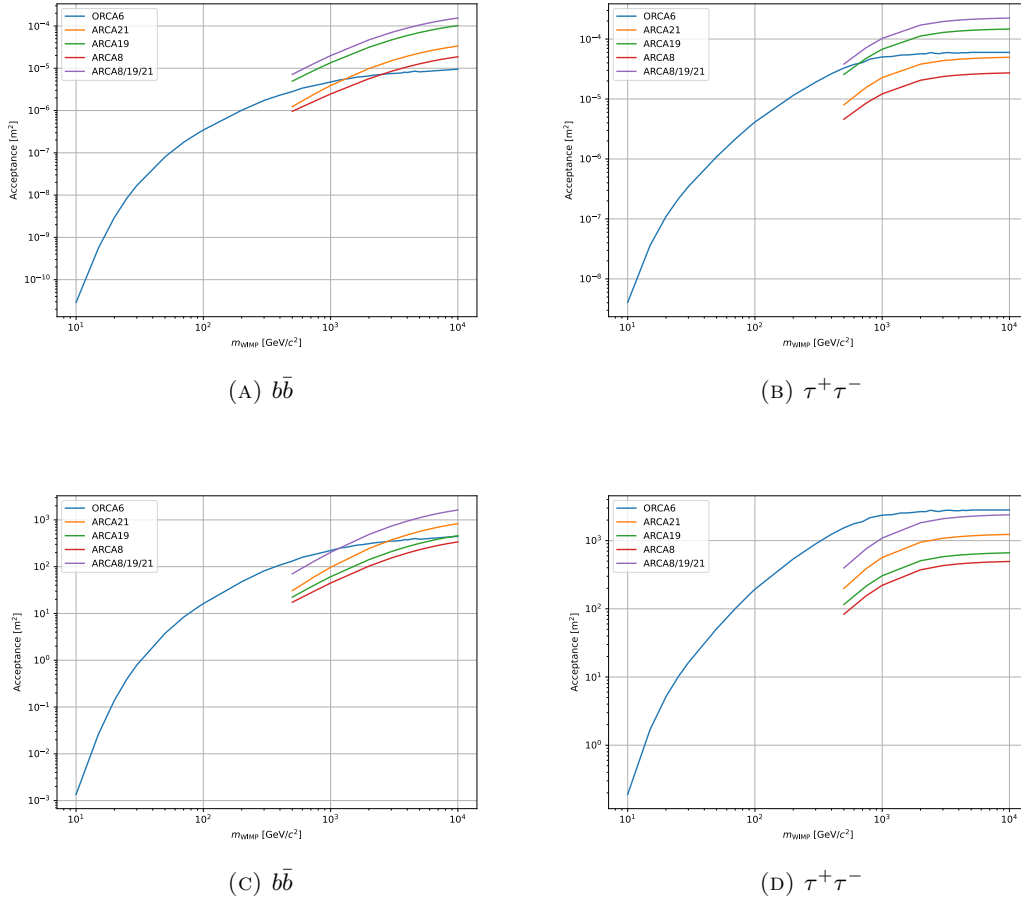


FIGURE 5.21: The integrated signal acceptances are shown as a function of the WIMP mass for two annihilation channels in the top row. The bottom row compares the acceptance multiplied by the livetime of the sample.

Figure shows the integrated acceptances as a function of the WIMP mass in the top row, whereas in the bottom row the acceptance is multiplied by the livetime of the sample, with the combined curve computed as a sum of the products of the individual acceptances and livetimes. In the top row of the Figure, the difference between the ARCA and ORCA acceptances is more pronounced for the $b\bar{b}$ channel relative to the $\tau^+\tau^-$ channel, due to the harder spectrum used. Furthermore, the curves in the bottom row of the Figure indicate that the acceptances and livetimes of the combined ARCA sample and the ORCA sample

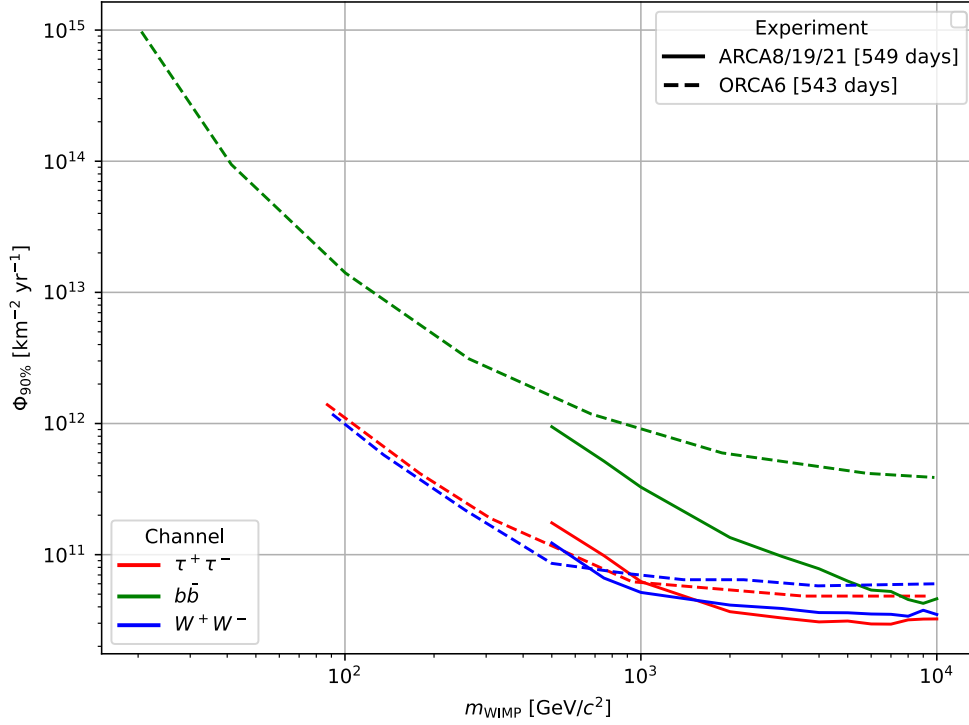


FIGURE 5.22: Flux sensitivity at 90% C.L. for neutrinos produced by WIMP annihilations in the Sun. Shown on the plot is the sensitivity obtained in this work, and the sensitivity obtained in the previous analysis on the ORCA6 data set.

are very comparable, leading to the conclusion that the sensitivities will be close to equal, too.

The flux sensitivities obtained in this work and the previous ORCA6 analysis are compared in Fig. 5.22. As can be seen, an improvement at WIMP masses above $1 \text{ TeV}/c^2$ is seen for the W^+W^- and $\tau^+\tau^-$ channels, while for the $b\bar{b}$ channel an improvement is seen across the mass range, due to the harder spectrum used in this work relative to the spectrum used in the ORCA6 analysis. The equations 2.5 and 2.6 are then used in combination with Eq. A.1 in order to convert the flux sensitivities into sensitivities on the WIMP-nucleon scattering cross section, assuming the equilibrium relation $\Gamma = C/2$, a reasonable assumption for the Sun [69]. The spin-dependent and spin-independent WIMP-nucleon scattering cross section sensitivities obtained in this work are compared to the ORCA6 result in Fig. 5.23, as a function of the WIMP mass, for all three annihilation channels considered. In general, the relative difference in the results should remain the same whether one compares spin-dependent and spin-independent cross sections. From

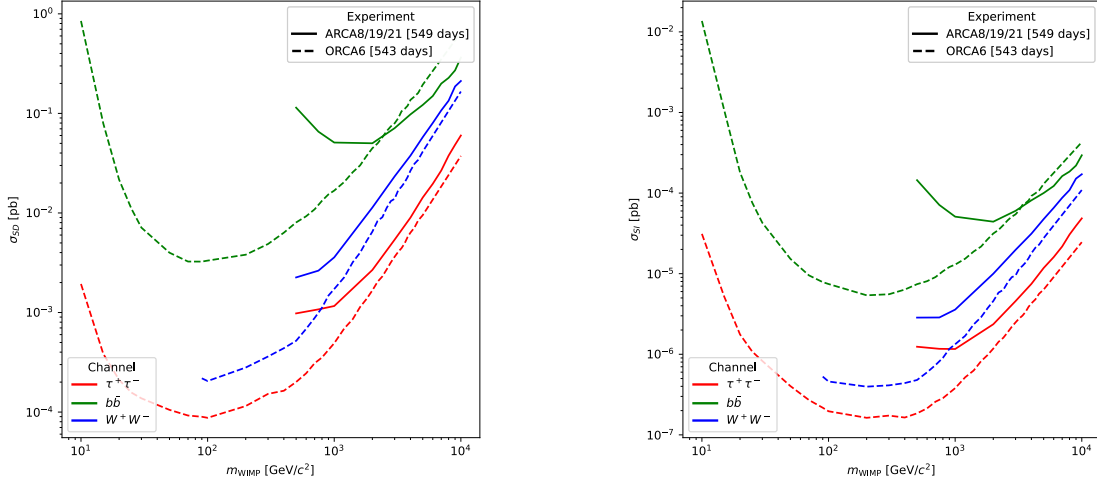


FIGURE 5.23: The spin-dependent (left) and spin-independent(right) WIMP-nucleon scattering cross section sensitivities, shown as a function of the WIMP mass for the three channels considered. The results of this work are shown as solid lines, while the results obtained in the previous analysis with the ORCA6 data set are shown as dashed lines.

the equations A.1, 2.5 and 2.6 it follows that the conversion of flux sensitivities only depends on properties of the Sun, the dark matter halo and the WIMP particle. This analysis used the same inputs to model the Sun and the Milky Way halo as the previous ORCA6 analysis, hence the relative difference between the fluxes should be preserved when comparing cross sections. This is not what is observed, indicating a difference in the scaling factors that convert flux sensitivities to cross section sensitivities. These scaling factors are referred to in the literature as the spin-dependent and spin-independent conversion factors. The conversion factors are equal to

$$\begin{aligned}
 K_{SD} &= \frac{8\pi D^2 \cdot m_{\text{WIMP}} \cdot v}{A_{SD} \cdot \rho_\chi \cdot S(m_\chi/m_H) \cdot \int_{E_{th}}^{m_{\text{WIMP}}} \frac{dN}{dE} dE} \\
 K_{SI} &= \frac{8\pi D^2 \cdot m_{\text{WIMP}} \cdot v}{A_{SI} \cdot \rho_\chi \cdot \sum_i \phi_i f_i F_i(m_\chi) \frac{S(m_\chi/m_{N_i})}{m_{N_i}} \cdot \int_{E_{th}}^{m_{\text{WIMP}}} \frac{dN}{dE} dE},
 \end{aligned} \tag{5.1}$$

where the terms have the same meaning as in Equations A.1, 2.5 and 2.6. These quantities are compared in Fig. 5.24. As seen in the Figure, there is a clear difference in the conversion factors: this difference can be accounted for by the fact that the spectrum used is different, and the energy range over which the spectrum is integrated differs too: in ARCA, the neutrino detection threshold, E_{th} in Eq. 5.1 is 100 GeV, whereas this threshold is 1 GeV in ORCA. Therefore, the spectrum integral will be larger for in the ORCA analysis, reducing the conversion factors.

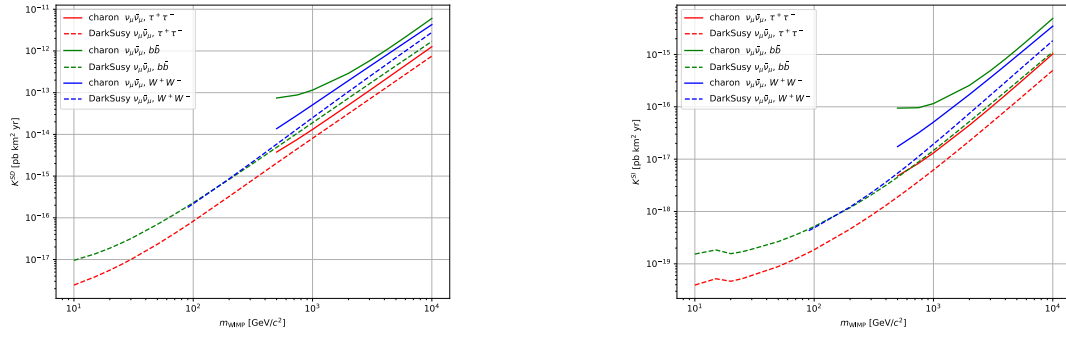


FIGURE 5.24: The spin-dependent (left) and spin-independent (right) conversion factors, shown as a function of the WIMP mass for the three channels considered. The results of this work are shown as solid lines, while the results obtained in the previous analysis with the ORCA6 data set are shown as dashed lines.

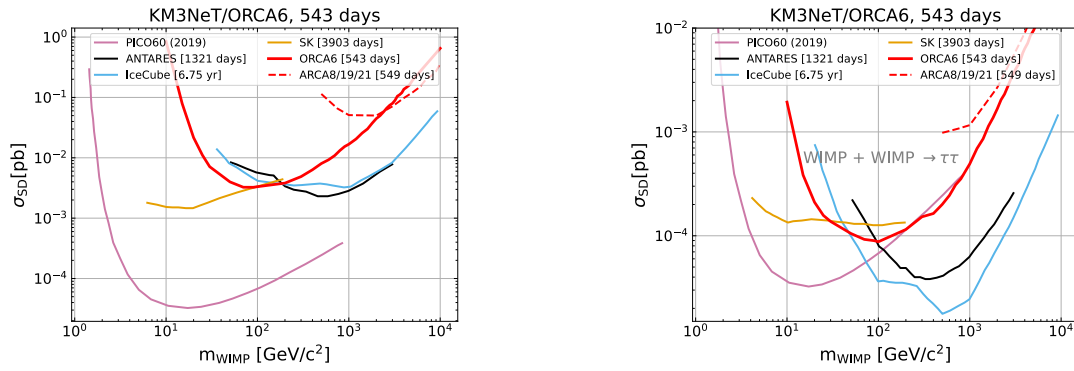


FIGURE 5.25: Sensitivities to the spin-dependent WIMP-nucleon scattering cross section as a function of the WIMP mass obtained in this work are compared to upper limits from the ORCA6 analysis and the upper limits of other experiments in the field [147, 149–152].

The spin-dependent sensitivities computed in this work are placed in context to other experiments in the field in Fig. 5.25, showing results for the $b\bar{b}$ (left) and the $\tau^+\tau^-$ (right) annihilation channels. As seen in the Figure, competitive results are obtained, both with the ARCA data set used in this work, and the ORCA data set used in the previous analysis. The IceCube result [150] remains more constraining, due to its larger livetime, and the efficiency of low-energy neutrino detection of the DeepCore sub-detector. The result of KM3NeT’s predecessor, ANTARES [149], remains more constraining with respect to the KM3NeT results, due to the accumulated livetime. The result from Super-Kamiokande [151] probes the parameter space at lower masses compared to KM3NeT, due to the denser detector configuration allowing for efficient neutrino detection at ($\sim$ GeV) energies. The PICO60 result [152] is a result obtained from a direct detection experiment: this class of experiments attempts to directly observe the WIMP-nucleon scattering in the detector. Therefore, no assumption of equilibrium between annihilation and capture is

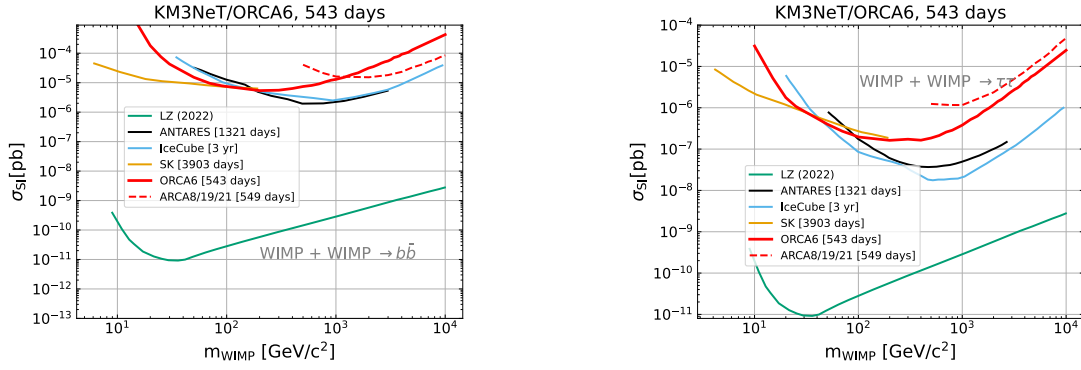


FIGURE 5.26: Sensitivities to the spin-independent WIMP-nucleon scattering cross section as a function of the WIMP mass obtained in this work are compared to upper limits from the ORCA6 analysis and the upper limits of other experiments in the field [147, 149, 151, 154, 155].

needed, and the cross section limit obtained does not depend on the annihilation process depleting the amount of dark matter in the Sun. Hence, the result is independent of the annihilation channel, the same line is plotted in both figures. In general, direct detection experiments can place much more competitive limits to the WIMP-nucleon scattering cross section in comparison to indirect detection experiments, due to their detection efficiency and excellent background rejection. However, in the case of spin-dependent scattering, WIMPs only scatter off nuclei with net spin, which are in general scarce in the most common detection media of direct detection experiments: Xe, Ar, Ge. The incoming WIMP particles scatter off trace materials present in the medium, hence the effective volume of a direct detection detector is much smaller for this type of interaction. Therefore, neutrino telescopes have the potential to lead the field in constraints on spin-dependent WIMP-nucleon scattering processes. A discussion on the classes of models constrained by placing a limit on this parameter can be found in Ref. [153].

The spin-independent sensitivities are compared as a function of the WIMP mass in Fig. 5.26. As already mentioned in this section, the relative difference in the limits between the indirect detection experiments remains approximately the same as for the spin-dependent case. For this class of interactions the spin-independent sensitivities from the direct detection experiment LZ [155] are orders of magnitude more constraining, as the WIMPs can scatter off all nuclei composing the detection medium. However, it is important to note that a detection of a scattering in a direct detection experiment is not a confirmation of the existence of dark matter, as these experiments do not have

the pointing accuracy to confirm the arrival direction of the particle. In order to confirm its astrophysical origin, the particle must also be detected indirectly, from regions of space where a large quantity of dark matter annihilations are predicted to occur, such as the Sun ¹. Therefore, even though the indirect detection limits are orders of magnitude weaker, the search is important in order to confirm the astrophysical origin of a weakly interacting particle detected in a direct detection experiment. A large amount of observation time would be needed to confirm the signal with current generation of neutrino telescopes. However, next generation neutrino detectors with increased detection volumes could confirm this signal.

Finally, the sensitivity to the WIMP-electron scattering cross section is also computed, assuming annihilations to tauons. The sensitivities are plotted as a function of the WIMP mass in Fig. 5.27. The results are plotted along with the limit obtained from IceCube public data in [71]. It is worth noting that the IceCube limits are not official results from the IceCube collaboration. The limit was obtained by the means of a χ^2 analysis, comparing the observed and expected number of events in a binned distribution of the angular distance of events to the Sun. The WIMP-electron scattering process is difficult to constrain in direct detection experiments. Indirect detection experiments can put more stringent constraints on the scattering cross section. Therefore, as the number of detection units increases and the livetime accumulates, KM3NeT will push the constraints on this parameter beyond existing limits in the literature.

¹Attempts to reconstruct directions of particles in direct detection experiments have already been tested [156], and new prototypes with updated technologies are being tested [157]. The trade-off in these experiments is the active volume: they need to utilise gaseous media at low pressure in order for the tracks to be long enough to provide directional information.

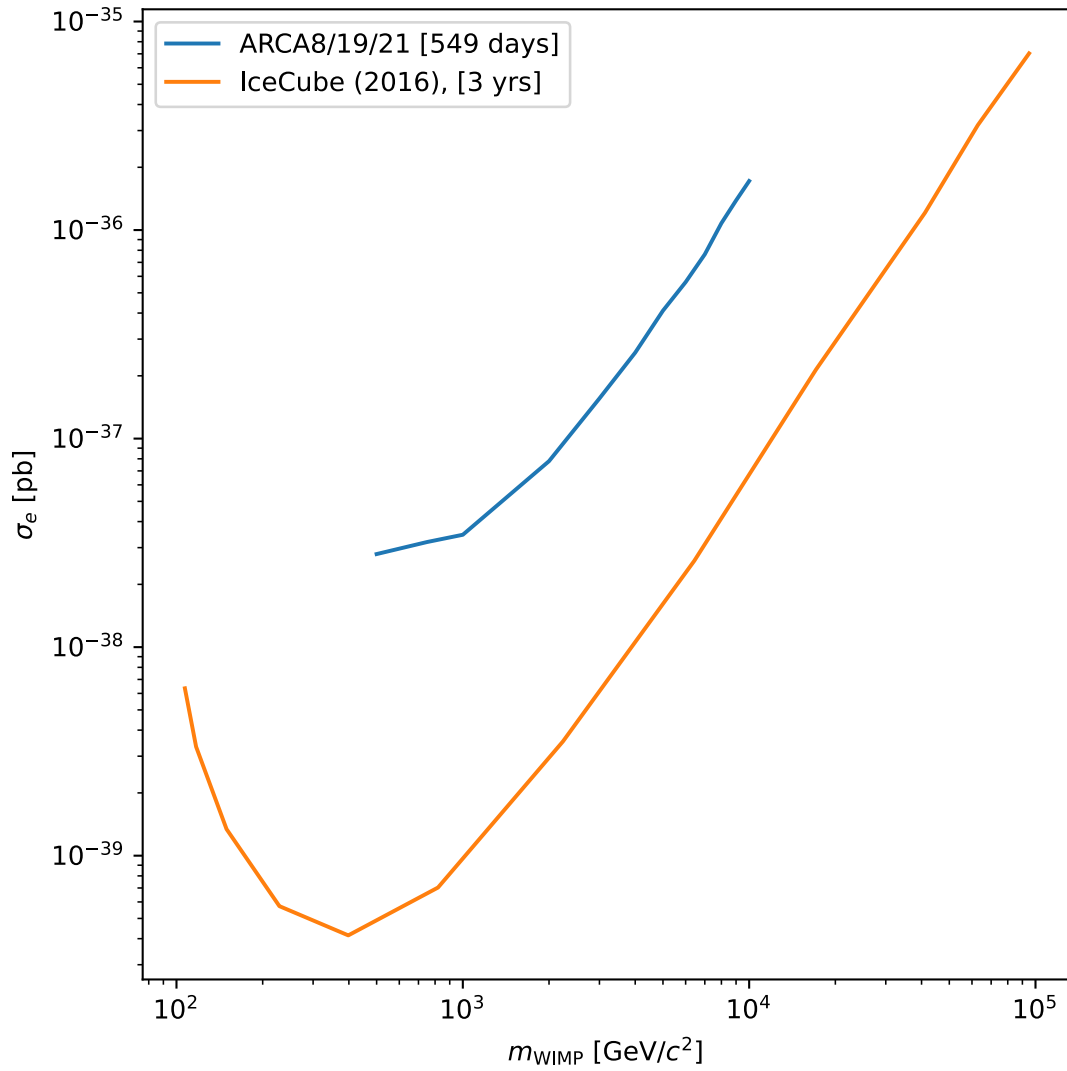


FIGURE 5.27: The sensitivity to the WIMP-electron cross section as a function of the WIMP mass, assuming annihilations to taus. The sensitivities are compared to upper limits obtained from IceCube public data in [71].

6

Conclusions

The search for dark matter is an ongoing pursuit in the fields of particle physics and astrophysics. So far, the gravitational influence of dark matter has been detected at various scales, from the rotation curves of individual galaxies, to the observations of large scale structure in the Universe. However, the particle nature of dark matter is yet to be confirmed. Experimental approaches to detect the dark matter particle consist of attempts to produce dark matter particles at colliders, to observe its scattering with SM particles, and to observe the products of its self-annihilation or decay. The three approaches to the problem are complementary, since the detection of a novel particle through one approach is not sufficient to identify it as dark matter. This is because dark matter searches rely on incomplete evidence, such as missing energy in collider events, or nuclear recoils and secondary particles that could have alternative astrophysical explanations. Only the simultaneous detection using different detection strategies can provide robust evidence of the existence of the dark matter particle.

The theoretical landscape of possible candidates is vast. Cosmological bounds place limits on the possible mass range of the dark matter candidate particle. These bounds can be evaded, assuming a more complex dark sector or an alternate production mechanism in the early Universe. This thesis focuses on minimal extensions of the SM sector, of which WIMPs are the primary candidate particle for dark matter. Indirect detection experiments can probe the parameter space of weakly interacting massive particles, probing masses in the $\text{GeV}/c^2 - \text{TeV}/c^2$ range, and self-interaction strengths at the order of weakly interacting particles.

Neutrino telescopes are examples of indirect detection experiments. The possibility of detecting the products of dark matter self-interactions as neutrinos became a reality at the onset of the 21st century, as large volume neutrino telescopes began probing the relevant regions of the parameter space. Searches with neutrino telescopes are complementary to searches with γ -ray observatories: they allow for the probing of certain annihilation channels that γ -ray telescopes are not as sensitive to, such as the neutrino channel. Furthermore, due to the absorption of γ rays at high energies, neutrino telescopes can provide more robust limits for larger dark matter masses ($> 10 \text{ TeV}/c^2$). Finally, certain search targets are difficult to observe in γ rays, but could potentially produce a significant secondary particle flux due to dark matter annihilations. A signal of dark matter in γ rays from the Galactic Centre is difficult to observe due to the abundant emission of γ rays from astrophysical processes. A flux of secondary particles is also expected to be produced in compact celestial bodies, such as the Sun. Any γ rays produced in such a source are absorbed before they reach the Sun's surface, but the neutrinos produced can travel unimpeded to the Earth and be detected.

This thesis presented the latest results of dark matter searches with the KM3NeT experiment. Dark matter was searched for in the Galactic Centre and the Sun. The results obtained were studied considering several effects on the constraining power: the uncertainties due to the theoretical inputs, related to the modelling of the Milky Way halo and the computation of the neutrino spectrum. The effect of systematic uncertainties related to the knowledge of the detector medium and PMT efficiencies was also computed. Finally, an alternative method to calculate the limit on the WIMP pair-annihilation cross section was presented, which allows for a fast and efficient combination of results from different experiments, studying different search targets. Each of these results will be summarised in a dedicated section in this chapter.

6.1 Search for dark matter in the Galactic Centre

The latest available data sets of the KM3NeT/ARCA detector have been analysed in search for neutrinos produced by dark matter annihilations in the Milky Way halo. The predicted incoming directions of the signal neutrinos were obtained by assuming a cuspy, spherical density profile for the Milky Way halo. This emission template was then smeared with the detector angular error, obtained from neutrino simulations of the detector. The

signal energy distribution was obtained by reweighting the neutrino simulation with the neutrino spectrum resulting from a single WIMP pair annihilation. The atmospheric background during each data taking period was inferred from the data, shuffling the events in right ascension in accordance with the KM3NeT blinding policy. These signal and background models were used as inputs for an unbinned likelihood analysis. The log likelihood ratio of the best fit and null hypotheses was computed in order to derive a limit on the number of signal events that can be rejected with 90% confidence, following the Neyman approach. The sensitivity to the number of signal events was converted into a sensitivity on the neutrino flux, from which the constraint on the WIMP pair-annihilation cross section was derived. Upon unblinding, no significant excess over the background was observed, leading to the setting of upper limits on the parameter of interest, across a range of WIMP masses and possible annihilation channels. With just over 549 days of livetime, the results are already competitive and at the same order of magnitude as experiments with a much larger livetime, such as IceCube and ANTARES. This is mainly due to the position of the KM3NeT detector in the Mediterranean, allowing for an excellent visibility of the Galactic Centre, when compared to IceCube. Improvements in the detector design, such as the multi-PMT optical modules, along with improvements in the analysis techniques, primarily the use of machine learning in the event selection, further improve the limits of KM3NeT with respect to results in the literature, such as ANTARES.

6.2 Impact of uncertainties

The derived limits on the WIMP pair-annihilation cross section have their associated uncertainties, which can be divided into two categories: uncertainties in the theoretical inputs, such as the mass density profile of the Milky Way halo and the computation of the neutrino spectrum, and uncertainties due to unconstrained detector properties, such as the absorption length of water and the quantum efficiencies of the PMTs.

The density profile of the Milky Way halo is not very well constrained, due to the difficulty of determining rotational velocities in the inner regions of the Milky Way. The dependence of the halo mass on the radius in the innermost region of the Milky Way is not very well known, with both cuspy and cored density profiles producing the same level of agreement when fitted to rotational velocity data. Therefore, in order to understand the impact of this uncertainty, the search for dark matter was conducted using both families

of profiles to model the mass density of the Milky Way. Cuspy profiles should result in more stringent limits, as the mass density is more concentrated towards the centre of the Galaxy, resulting in emission that is close to being point-like. On the other hand, in cored density profiles the emission is more diffuse, due to the presence of the constant density core. This should result in less stringent limits on the WIMP annihilation cross section. This behaviour is exactly observed when conducting the analysis with cored and cuspy density profiles on the ARCA8/19/21 data set. The study found that the limits are an order of magnitude less stringent for cored density profiles.

The second source of uncertainty in the theoretical inputs is related to the computation of the neutrino spectrum. This analysis probes masses well above the energy scale accessible in terrestrial laboratories, therefore the subsequent processes occurring after the initial annihilation of WIMPs into SM particles are not very well understood. Multiple computations of the neutrino and γ -ray spectra exist in the literature, each publication following its own approach to model the high-energy processes. The influence of the spectrum choice on the limits on the WIMP annihilation cross section was computed by using different spectra computations available in literature to model the signal response. The analysis concluded that the impact of the spectrum choice is not nearly as large as the choice of density profile. The largest differences in the derived sensitivities are observed for the neutrino channel, due to the fact that the shape of the energy distributions differs the most between the two spectrum computations.

The second class of uncertainties is related to the imprecise knowledge of detector properties. The two uncertainties with the largest influence on the number of detected events are the uncertainty on the water absorption length, and the uncertainty on the quantum efficiencies of the PMTs. These uncertainties affect the number of detected events in the detector, but also the measurements of event observables, such as the particle energy and track length. In order to investigate the impact of these uncertainties, neutrino event simulations with modified absorption lengths and PMT efficiencies were created for the ARCA21 data set, modifying the water absorption length and PMT efficiencies by $\pm 10\%$, for a total of four different modified simulations. The impact of changing these quantities was first assessed in the event distributions of measured observables, such as the event reconstructed energy and direction, the angular error, the track length and the goodness-of-fit of the track reconstruction. No significant change in the shape of the distributions was observed, only a change in the absolute number of events detected. The

unbinned likelihood analysis was then conducted for four different cases: in two cases, modified simulations with the water absorption length set to $\pm 10\%$ of the nominal value were used in order to generate the signal and background events in mock data sets. The probability distributions obtained from the nominal simulations were used to evaluate the event probabilities. This choice is equivalent to the situation where the nominal value of the parameter is not the true value, but is assumed as such. For the two remaining cases, the unbinned likelihood analysis is conducted using the nominal simulation for both the generation of mock data, and the evaluation of signal and background probabilities. In one case, no smearing is applied to the injected number of signal events, whereas in the other case this smearing is applied, in order to account for the effect of the detector uncertainties. The study concluded that the impact of these uncertainties is significant, mostly due to the effect on the detector efficiency. The impact on the efficiency varies as a function of energy, changing by 20 – 40% across the energy range analysed in this work. The methodology of smearing the event numbers seems to degrade the sensitivities by a similar amount as the degradation observed when using simulations with modified water properties, indicating that the methodology used in this work to account for detector uncertainties is adequate.

6.3 Results combination with γ -ray experiments

An alternate methodology developed in the γ -ray community to combine the constraints on the WIMP annihilation cross section with multiple data sets [137] was introduced within KM3NeT. This methodology is used in γ -ray observatories to combine the limits obtained by studying different sources, with different instruments. The method does not require the sharing of event-by-event information between experiments, thus making the sharing of data between experiments easier. For the purposes of developing this method, the theoretical inputs used for the modelling of the signal response had to be unified across the different experiments. This included the computation of the signal response for additional signal hypotheses, expanding the search to more masses and channels. The sensitivities obtained for individual detector configurations and the combined sensitivities obtained with this method closely match the results obtained with the unbinned likelihood methodology, thus verifying both approaches to computing limits. Future analysers will

share the outputs created in this work with analysers in γ -ray observatories, thus obtaining the first combined limits of γ -ray and neutrino observatories.

6.4 Dark matter in the Sun

A second possible source of neutrinos produced by WIMP annihilations was considered in this work, the Sun. This target is ideal for dark matter searches as the only astrophysical background from the Sun in this energy range are solar atmospheric neutrinos [72]. A detection of neutrinos from the Sun in this energy range ($> \mathcal{O}(100\text{GeV})$) would be a robust confirmation of the existence of dark matter. In this work, a novel computation of the neutrino spectrum from the Sun is used, improving on previous spectrum computations in the literature by including electroweak corrections. The same ARCA8/19/21 data set as in the Galactic Centre search was analysed in search of neutrinos from dark matter annihilations in the Sun. Preliminary studies indicate that the ARCA detector has similar capabilities in studying this source as KM3NeT/ORCA. The limited livetime of the partial detector configurations hinders the result, as the limit is still not as competitive as the limits from IceCube, or the limits of ANTARES. In the context of the cross section being spin-dependent, the limits from indirect detection experiments are the most constraining in the field above $m_{\text{WIMP}} > 1 \text{ TeV}/c^2$, due to the limited effective volume of direct detection experiments for this class of interactions. Finally, limits on the WIMP-electron scattering cross section were also computed. This process is yet another process that is difficult to constrain in direct detection experiments, hence why it is important to recast the flux limits and to set limits on this parameter when conducting indirect searches towards the Sun. Future studies of this source could greatly benefit from the combination of data sets, as both KM3NeT detectors have a similar sensitivity to the flux of neutrinos from dark matter annihilations in the Sun. The limits could thus be improved significantly by combining the data sets, following the approach developed to combine the data of ARCA8/19/21.

A

Summary

Motivación para buscar materia oscura

El descubrimiento de la materia oscura se remonta a la década de 1930, cuando Fritz Zwicky comparó la cantidad de masa luminosa en el cúmulo de galaxias de Coma con la masa estimada a partir de las velocidades rotacionales observadas de los objetos ligados. El resultado apuntó a una gran cantidad de materia no luminosa presente en el sistema, a la que se refirió como “materia oscura”. En los años 70, Vera Rubin y Kent Ford estudiaron las velocidades de rotación de las estrellas en la galaxia de Andrómeda. El estudio reveló una cantidad significativa de masa presente a grandes distancias del centro de la galaxia, indicando la existencia de un halo extendido de materia oscura. Las observaciones del Bullet Cluster aportaron más evidencia de la existencia de una forma de masa faltante. Este sistema comprende dos cúmulos de galaxias en interacción, observados en rayos X en los años 90. Las medidas en rayos X revelaron temperaturas extremadamente altas en el sistema, mientras que la reconstrucción por lente gravitacional débil mostró un desplazamiento entre el grueso de la masa de los sistemas y el gas bariónico caliente. Estas dos observaciones indican que la masa bariónica fue ralentizada cuando los cúmulos colisionaron, mientras que la materia oscura atravesó sin impedimentos.

También hay pruebas de materia oscura a escalas cosmológicas. El Fondo Cósmico de Microondas (CMB) es una forma de radiación emitida durante la época de recombinación en el universo temprano. Las fluctuaciones de temperatura en el CMB han sido mapeadas

con precisión y analizadas estadísticamente, cuantificando las pequeñas anisotropías mediante un espectro de potencia. La forma del espectro depende del contenido de materia y energía del universo en el momento de la recombinación. Como la materia oscura no se acopla a los fotones, no oscila como el plasma fotón-bariónico, pero profundiza los pozos gravitacionales, incrementando así la amplitud de las oscilaciones. Además, las anisotropías en el CMB son semillas para las galaxias observadas en el universo tardío. Al comparar simulaciones numéricas de formación de estructuras con observaciones del agrupamiento de galaxias según el corrimiento al rojo, se reveló que se necesita algún tipo de materia fría y sin presión para formar las estructuras observadas.

Candidatos a materia oscura

Las explicaciones al problema de la masa faltante pueden dividirse en tres categorías: teorías de gravitación modificada, candidatos de materia bariónica y materia no bariónica.

Las teorías de gravitación modificada intentan modificar las leyes newtonianas de la gravedad a gran escala, motivadas por el hecho de que estas leyes podrían fallar en regímenes de aceleraciones muy pequeñas. Existen varias teorías, cada una con descripciones matemáticas diferentes para ese régimen. La teoría TeVeS (tensor-vector-escalares) es una teoría relativista que modifica las ecuaciones de la relatividad general añadiendo un campo vectorial temporal, $\mathcal{U}_\mu$, y un campo escalar, ϕ , además del métrico de Einstein. La teoría tiene éxito explicando ciertas dinámicas galácticas, pero falla a escalas mayores: no puede explicar la dinámica de cúmulos como el Bullet Cluster, ni caracterizar el espectro de potencia del CMB.

La materia bariónica ha sido históricamente investigada como posible solución al problema de la masa faltante. Sin embargo, las observaciones del CMB indican que la mayoría de la materia debe ser una forma fría y no bariónica. Esto excluye objetos compactos astrofísicos masivos (MACHOs), como enanas marrones, planetas o agujeros negros convencionales. Una clase de objetos compactos que ha recibido atención recientemente son los agujeros negros primordiales (PBH), que se habrían formado en el universo temprano a partir de fluctuaciones de la densidad. Estas teorías sugieren que se formaron antes de la recombinación, actuando como pozos potenciales sin presión durante ese período, lo cual concuerda con las observaciones del CMB. Los PBH pueden buscarse mediante sus efectos en la dinámica de objetos orbitales en la Vía Láctea o por fotones emitidos

por acreción. Actualmente podrían componer gran parte de la masa faltante observada, aunque la fracción permitida depende de su masa y distribución.

Hay numerosos candidatos no bariónicos para la materia oscura. Según la velocidad de los candidatos en el momento de desacoplamiento en el universo temprano, se clasifican en fría, cálida y caliente. Las partículas de materia oscura fría son no relativistas en el desacoplamiento, mientras que las cálidas o calientes sí lo son. Esto afecta el modo de formación de estructuras: en candidatas cálidas o calientes la formación es de arriba abajo (estructuras grandes primero), mientras que con materia oscura fría se da un escenario de abajo arriba (se forman primero halos pequeños, luego estructuras mayores). El Universo observable sigue el escenario de abajo arriba, indicando que la materia oscura es fría. Otro aspecto importante es el mecanismo de producción de las partículas: pueden producirse térmicamente o mediante otros procesos. En la producción térmica (freeze-out), las partículas estaban en equilibrio con el plasma barión-fotón hasta que la temperatura bajó por debajo de su masa, tras lo cual su densidad se congeló. Este mecanismo se permite dentro de un cierto rango de masas; fuera de él se requieren modelos más complejos.

Las partículas masivas de interacción débil (WIMPs) tienen masas en el rango de GeV-TeV/ c^2 y podrían reproducir la densidad relictas observada mediante freeze-out, siempre que la interacción sea del orden de la fuerza débil (el “milagro WIMP”). Diversas extensiones del Modelo Estándar predicen WIMPs. En la supersimetría, cada fermión del SM tiene un compañero bosónico, y viceversa. Esta teoría ofrece candidatos de materia oscura, resuelve el problema de jerarquía y explica la masa del Higgs. Las teorías con paridad R generan una partícula supersimétrica estable, eléctricamente neutra e interactuando débilmente: un WIMP.

Las teorías con dimensiones extra, como las dimensiones extra universales, también generan candidatos WIMP estables por simetrías discretas no rotas asociadas a las dimensiones adicionales.

Además del freeze-out, existen otros mecanismos de producción. En escenarios de freeze-in, la materia oscura interactúa muy débilmente con el SM y nunca alcanza equilibrio térmico. Las partículas SM incrementan lentamente la densidad de materia oscura hasta que la temperatura baja del umbral de producción y la abundancia relictas se congela. Los neutrinos estériles son un ejemplo de candidato producido así. Finalmente,

los axiones merecen mención: son candidatos viables, aún no restringidos por observaciones, y además resuelven el problema CP fuerte. Se producen por el mecanismo de “misalignment” en el universo temprano, generando un condensado frío de axiones.

Búsquedas de materia oscura

En este trabajo se realiza una búsqueda de WIMPs en los datos de KM3NeT. Por lo tanto, en esta sección se describirá una visión general de los métodos experimentales utilizados para detectar WIMPs.

En búsquedas en colisionadores, se producen WIMPs en colisiones de partículas del SM y se detecta su escape mediante momento transversal faltante. En las búsquedas *Mono-X*, *Mono-V* and *Mono-Higgs*, el WIMP se produce junto a otro producto del SM detectado, y se infiere el momento faltante. Otra técnica busca resonancias, donde la partícula WIMP decae rápidamente en un par de estados del SM, produciendo picos en distribuciones de masas invariantes. La tercera técnica explora partículas de vida larga que decaen alejadas del vértice de interacción, buscando leptones desplazados, vértices desplazados o gran cantidad de momento faltante. Hasta ahora no se ha observado ninguna señal de materia oscura en colisionadores.

En Detección directa, se detecta el retroceso de núcleos al colisionar con WIMPs. La energía transferida se convierte en luz de centelleo, ionización o fonones. Detectores de xenón líquido como XENONnT, LUX-ZEPLIN o PandaX-4kT usan cámaras de proyección de tiempo de fase dual; detectores de argón líquido como DarkSide-20k emplean una estrategia similar. Detectores de germanio (SuperCDMS) usan ionización y fonones. Detectores de yoduro de sodio como DAMA/LIBRA, ANAIS-112 o COSINE-100 detectan centelleo en múltiples cristales. El experimento DAMA/LIBRA afirmó una detección significativa, pero fue refutada por generaciones más sensibles.

En detección indirecta, se buscan productos del SM generados por aniquilaciones o decaimientos de WIMPs: rayos cósmicos, γ rays o neutrinos. En los detectores de rayos cósmicos, se intenta detectar un exceso de antipartículas por encima del fondo esperado de procesos astrofísicos. Estas búsquedas no son direccionales, ya que los rayos cósmicos son desviados por el campo magnético galáctico. En las búsquedas de rayos γ y neutrinos, se utiliza la dirección de la partícula entrante para determinar si fue producida por WIMPs o

por algún proceso astrofísico de fondo. Las búsquedas de productos del Modelo Estándar se realizan hacia las direcciones de objetos que contienen grandes cantidades de materia oscura en comparación con el fondo astrofísico: para experimentos de rayos γ , esto incluye galaxias enanas esferoidales y el Centro Galáctico. Para los telescopios de neutrinos, los objetivos de búsqueda incluyen el halo de la Vía Láctea y objetos compactos cercanos donde la materia oscura se acumula con el tiempo, como el Sol y el núcleo de la Tierra. Para cualquier objetivo de búsqueda, el flujo de productos del Modelo Estándar en la Tierra es igual a:

$$\frac{d^2\Phi}{dE dt} = \frac{\Gamma}{4\pi D^2} \frac{dN}{dE}, \quad (\text{A.1})$$

Γ es la tasa de aniquilación, D la distancia y $\frac{dN}{dE}$ el espectro secundario. La tasa de aniquilación dependerá de la densidad numérica de WIMPs y de la probabilidad de que la aniquilación ocurra, expresada como una sección eficaz de aniquilación promediada térmicamente, $\langle\sigma v\rangle$. Este parámetro se mide o se limita en las búsquedas indirectas de materia oscura. Para WIMPs que se aniquilan en el halo de la Vía Láctea o en galaxias enanas esferoidales, la cantidad de productos secundarios en la Tierra es igual a:

$$\frac{d^2\Phi_\nu}{dE_\nu dt} = \frac{1}{4\pi} \frac{1}{2} \frac{\langle\sigma v\rangle}{m_{\text{WIMP}}^2} \frac{dN_\nu}{dE_\nu} \mathcal{J}, \quad (\text{A.2})$$

donde $\mathcal{J}$ es la integral de densidad al cuadrado a lo largo de la línea de visión y el ángulo sólido. En el caso de búsquedas en objetos compactos, los WIMPs se acumulan en el centro del objeto debido a dispersión repetida con los núcleos que componen el núcleo del objeto. Estas partículas quedan atrapadas gravitacionalmente, se hunden hacia el centro y se aniquilan a una tasa dada, la cual aumenta a medida que aumenta la densidad numérica de WIMPs. Dado suficiente tiempo, se alcanza el equilibrio entre la captura y la aniquilación: este es el caso para los WIMPs que se dispersan en el Sol. Por lo tanto, la tasa de aniquilación y la tasa de captura son iguales, lo que permite una medida o una restricción sobre el parámetro que gobierna la tasa de captura, la sección eficaz de dispersión WIMP-nucleón.

Detección de neutrinos y el detector KM3NeT

Los neutrinos son partículas eléctricamente neutras, que sólo interactúan con el medio ambiente a través de la interacción débil. La detección se realiza de forma indirecta,

detectando los productos de dispersión de neutrinos sobre nucleones mediante su radiación Čerenkov. En esta tesis se analizan neutrinos con energías a escala de GeV y superiores. A estas energías, los neutrinos detectados pueden ser producidos por diferentes fenómenos: neutrinos atmosféricos, producidos por interacciones de rayos cósmicos con la atmósfera; neutrinos cósmicos o astrofísicos, producidos en aceleradores cósmicos como los blazares. Finalmente, el tercer posible escenario de producción de neutrinos de alta energía es el objeto de estudio de esta tesis: neutrinos producidos por aniquilaciones de materia oscura.

Producción y propagación

Los neutrinos atmosféricos se producen en interacciones hadrónicas de rayos cósmicos en la atmósfera, que generan piones y kaones cargados, los cuales luego decaen produciendo neutrinos. A energías más altas, se producen hadrones más pesados que decaen rápidamente en neutrinos de alta energía. Los neutrinos astrofísicos se producen en aceleradores cósmicos, sitios donde se asume que los rayos cósmicos también son acelerados a las energías observadas. El espectro de rayos cósmicos presenta características que indican diferentes poblaciones de fuentes. Hasta cierta energía, la mayoría de los rayos cósmicos son de origen galáctico, producidos por ejemplo en remanentes de supernova. A energías más altas, se cree que son de origen extragaláctico. Fuentes potenciales incluyen estallidos de rayos γ y núcleos galácticos activos. Finalmente, los neutrinos cosmogénicos se producen por interacciones de rayos cósmicos con el fondo cósmico de microondas (CMB). La colaboración IceCube ha detectado el flujo difuso astrofísico, el flujo proveniente de una fuente puntual identificada como un blazar, y el flujo del plano galáctico. La colaboración KM3NeT ha detectado recientemente el neutrino de mayor energía hasta la fecha, cuyo origen aún se debate.

Los neutrinos que se propagan desde su sitio de producción hasta la Tierra oscilan en sabor durante la propagación. La mezcla de sabores de neutrinos ocurre porque los estados propios de sabor son una superposición de los estados propios de masa. La matriz de mezcla puede parametrizarse en términos de ángulos de mezcla, θ_{ij} , y una fase de violación CP δ_{CP} . La probabilidad de oscilar de un sabor a otro depende de estos términos, de la diferencia de masa al cuadrado entre los estados de masa, y de la relación entre la distancia recorrida y la energía del neutrino. Las diferencias de masa al cuadrado pueden ordenarse según el orden normal o el orden invertido, dependiendo de si los dos

estados más ligeros tienen una diferencia de masa pequeña y el tercer estado una grande, o viceversa. El detector de bajas energías de KM3NeT, KM3NeT/ORCA, fue construido con el propósito de determinar la jerarquía de masas neutrinas y medir con precisión el ángulo de mezcla θ_{23} y la diferencia de masa al cuadrado Δm_{31} .

Interacciones de neutrinos

A energías de GeV y superiores, los neutrinos interactúan mediante dispersión profundamente inelástica sobre quarks que componen el medio del detector, el mar. Pueden intercambiar un bosón W^+/W^- , referido como interacción de corriente cargada (CC), o un bosón Z_0 , referido como interacción de corriente neutra (NC).

En interacciones de corriente cargada, se producen leptones asociados al neutrino padre. Los electrones producidos en interacciones CC de neutrinos electrónicos inducen una cascada de pares electrón-positrón y fotones de frenado (bremsstrahlung). La emisión resultante es esférica y ligeramente elongada en la dirección del electrón primario, permitiendo una resolución angular de unos pocos grados. La deposición de energía ocurre en escalas de longitud cortas, de modo que toda la luz producida en las interacciones subsecuentes puede detectarse, resultando en una resolución energética a nivel porcentual. Esta geometría de emisión esférica se denomina evento tipo "shower" (cascada).

Los neutrinos muónicos que interactúan vía CC producen un muón altamente relativista. El muón tiene un rango grande, de modo que puede atravesar todo el detector y salir sin impedimentos. A lo largo de su trayectoria, el muón emite un cono de luz Čerenkov. El ángulo de apertura en agua a las energías observadas en KM3NeT es aproximadamente 42° . La luz se emite a lo largo de toda la traza al atravesar el volumen del detector, denominándose eventos tipo "track" (traza). Para eventos tipo traza, se pueden lograr resoluciones angulares subgrado.

Los neutrinos tau que interactúan vía CC producen un leptón tau, que decae rápidamente. El leptón tau puede decaer a un muón, resultando en una señal tipo traza. Otros canales de decaimiento, como a electrones o hadrones, producen una cascada (shower) en el punto de decaimiento.

Las interacciones de corriente neutra inducen una cascada hadrónica en el núcleo blanco, mientras que el neutrino dispersado sale del detector sin dejar rastro. Sin embargo,

la cascada hadrónica produce una deposición localizada de luz similar a la topología tipo cascada producida por cascadas electromagnéticas de electrones energéticos.

El detector KM3NeT

El experimento KM3NeT consiste en dos detectores ubicados en el fondo del mar Mediterráneo. El detector KM3NeT/ARCA está situado a 100 kilómetros de la costa de Sicilia, cerca de Portopalo di Capo Passero, a una profundidad de 3500 m. El diseño permite la detección de neutrinos con energías de TeV y superiores, orientado a detectar el flujo difuso astrofísico y a identificar fuentes puntuales de neutrinos. El detector KM3NeT/ORCA está ubicado a 40 kilómetros de la costa de Toulon, Francia, a una profundidad de 2500 m. Este detector está diseñado para detectar neutrinos en energías de GeV, orientado a medir parámetros de oscilación neutrina y determinar el ordenamiento de masas de los neutrinos. Los estudios realizados en esta tesis se efectuaron con los datos de KM3NeT/ARCA, por lo que este detector será descrito con más detalle. Sin embargo, los componentes de detección y la arquitectura de adquisición de datos son idénticos; sólo difiere el espaciamiento de los elementos del detector, lo que permite una sensibilidad a diferentes energías.

La luz Čerenkov emitida por los productos de interacción es detectada por tubos fotomultiplicadores (PMTs) de 3", organizados en módulos ópticos digitales (DOMs), esferas resistentes a la presión que contienen 31 PMTs. Los DOMs también contienen sensores de calibración de tiempo, posición y orientación. Convertidores tiempo-a-digital para cada PMT registran el pulso temporal de cada PMT, enviando los datos a tierra, donde se aplican algoritmos de disparo sobre los datos crudos. Los DOMs se agrupan en unidades de detección (DUs), estructuras tipo cuerda ancladas al fondo marino y sujetas por boyas. Las DUs se disponen en círculo sobre el fondo marino. El espaciamiento entre DOMs y DUs difiere entre los detectores ARCA y ORCA, resultando en diferentes sensibilidades energéticas. En ARCA, las DUs están más separadas, al igual que los DOMs en una cuerda, lo que resulta en una sensibilidad a energías mayores comparado con ORCA. Al momento de escribir, el detector ARCA consta de 33 DUs, mientras que ORCA de 24. El detector ARCA completo constará de dos bloques constructores, cada uno compuesto por 115 DUs, mientras que ORCA contará con un bloque constructor de 115 DUs. Los análisis reportados en esta tesis se realizaron con datos del detector ARCA

entre los años 2021 y 2023, cuando el detector contaba con 8, 19 y 21 DUs. Los análisis se realizaron con eventos tipo traza, que ofrecen una resolución espacial superior.

Eventos de fondo en KM3NeT

Los eventos producidos en fuentes cósmicas, como neutrinos astrofísicos producidos en blazares o neutrinos producidos en aniquilaciones de materia oscura, son superados en número por los eventos de fondo por órdenes de magnitud. Los eventos de fondo pueden clasificarse en fondo óptico y fondo físico.

El fondo óptico es producido por el ruido interno de los componentes de detección de fotones o por fuentes de fotones en el mar, como los decaimientos del isótopo ^{40}K . Estos decaimientos producen un fondo constante e isotrópico del orden de 7-8 kHz. Una segunda fuente de fondo óptico es la bioluminiscencia, que aumenta en ciertos meses de la temporada. El fondo óptico es fácilmente eliminado de los datos, ya que los fotones son detectados desde direcciones aleatorias.

El fondo físico consiste en partículas producidas por reacciones de rayos cósmicos con la atmósfera terrestre: muones y neutrinos atmosféricos. Los muones llegan desde direcciones por encima del horizonte y son la fuente más numerosa de fondo. Para eliminarlos, se requiere que los eventos se reconstruyan como provenientes desde debajo del horizonte, atravesando la Tierra. La Tierra se usa así como un escudo contra los muones atmosféricos. Sin embargo, los neutrinos atmosféricos pueden atravesar el núcleo terrestre, y sus productos de interacción dejarán las mismas señales electromagnéticas en los detectores que los productos de interacción de los neutrinos señal. Por lo tanto, se requieren modelos precisos del fondo de neutrinos atmosféricos para modelarlos correctamente y separarlos de los neutrinos señal.

Simulación, reconstrucción y calibración del detector

La simulación de neutrinos en KM3NeT se realiza en tres pasos. Primero, los eventos se generan en una superficie imaginaria que rodea al detector, llamada volumen de interacción. En el detector real, la tasa de neutrinos incidentes es muy alta, pero sólo una pequeña fracción de ellos interactúa dentro del volumen de interacción. En las simulaciones, cada neutrino es forzado a interactuar, asignando un peso de generación que

codifica la probabilidad de interacción, la probabilidad de absorción en la Tierra, y el espectro con el que fueron generados. Luego, los neutrinos pueden ser reponderados para obtener la tasa en el detector para ese flujo. Los eventos de muones atmosféricos también se generan en alguna superficie, usando fórmulas paramétricas que describen el flujo de muones a ciertas profundidades y ángulos cenitales en el agua. Los muones se simulan para una fracción del tiempo vivo y el número correcto se obtiene reescalando por la razón entre el tiempo vivo total y el simulado.

La propagación de la luz considera: los procesos que llevan a la emisión de luz —radiación Čerenkov, pérdidas energéticas, procesos radiativos, interacciones hadrónicas—; la dispersión y absorción de la luz; la respuesta de los PMTs a la luz incidente. A energías menores a 500 GeV, la generación de luz es manejada por un software basado en *Geant4* que propaga partículas secuencialmente a través del detector y calcula la emisión y trayectoria en cada paso. A energías mayores, se usa un paquete personalizado que calcula la distribución de impactos en los PMTs basado en la energía y dirección de la partícula, usando funciones de densidad de probabilidad precomputadas que consideran dispersión, absorción y eficiencia del PMT.

La salida de la etapa de generación de luz en la simulación es idéntica a la salida producida por datos crudos en el mar. Por tanto, se aplican los mismos algoritmos de disparo. Primero, se aplica un disparo nivel 0 (L0) costa afuera: sólo los impactos que superan 0.3 fotoelectrones son enviados a tierra. El disparo siguiente L1 requiere impactos coincidentes en PMTs colocados en el mismo módulo óptico. El disparo L2 requiere una separación angular mínima entre PMTs impactados. Luego, se aplican algoritmos dedicados para eventos tipo traza y tipo cascada, explotando los perfiles de emisión esperados de ambas topologías.

La reconstrucción de eventos procede con eventos que pasan los disparos tipo traza y cascada. La reconstrucción de trazas estima la dirección de llegada y la energía de la partícula, y el vértice de interacción, dada la amplitud y tiempos de cada pulso registrado. Primero se realiza un preajuste χ^2 , luego se aplica un ajuste de máxima verosimilitud que ajusta simultáneamente todos los parámetros de la trayectoria. La reconstrucción de cascadas sigue un enfoque similar: se realiza un ajuste inicial para proporcionar condiciones iniciales para el ajuste de verosimilitud posterior.

Para que la reconstrucción logre una resolución angular subgrado en trazas y una resolución energética a nivel porcentual en cascadas, es necesaria una calibración precisa del detector. La calibración temporal se aplica jerárquicamente. Primero, los PMTs en un mismo DOM se calibran con mediciones de decaimientos de ^{40}K en el agua de mar. Se considera la separación angular entre PMTs, y las distribuciones de tiempos de impactos de todos los pares posibles de PMTs en un DOM se ajustan simultáneamente. Los DOMs en una DU se calibran con el uso de balizas ópticas presentes en los DOMs, permitiendo la sincronización de DOMs vecinos. Finalmente, las DUs se calibran usando un sistema de transmisión de reloj, mediante el protocolo White-Rabbit.

Los elementos de detección también se ven afectados por corrientes marinas, requiriendo calibración precisa de posición y orientación. Receptores acústicos en cada DOM y en la base de la DU detectan señales acústicas producidas por emisores ubicados en el fondo marino. El tiempo de llegada en cada receptor se convierte en una estimación del tiempo de emisión, tras lo cual se realiza un procedimiento de ajuste para estimar la geometría exacta del detector.

La orientación de cada DU se realiza con acelerómetros y magnetómetros presentes en cada DOM. Las lecturas se convierten a un sistema de coordenadas usando el norte magnético y la dirección vertical —donde la aceleración gravitatoria es máxima— como puntos de referencia. Para que las lecturas sean precisas, los dispositivos se calibran previamente en laboratorio para ganancias y offset. Las ganancias y offsets medidos se aplican a las medidas brutas, y luego se realiza una minimización χ^2 para determinar el giro de la DU alrededor de algún eje principal.

Finalmente, las calibraciones pueden verificarse usando trazas de muones atmosféricos, conocido como el método de calidad de trazas. La reconstrucción se realiza primero con los tiempos, posiciones y orientaciones nominales del detector, luego se varían los parámetros de calibración uno a uno manteniendo fija la traza. Los parámetros de calibración óptimos son aquellos que maximizan la razón de verosimilitud por número de impactos. El desempeño de la calibración puede evaluarse observando la sombra de la Luna y el Sol en los rayos cósmicos, ya que estos objetos bloquean los rayos cósmicos entrantes. Así, debe observarse un déficit de muones atmosféricos en las posiciones de los objetos celestes. El ancho de la sombra mide la resolución angular, mientras que el desplazamiento de la sombra respecto a la posición esperada mide el error absoluto de apuntado.

Métodos de análisis

Datos y selección de eventos, eficiencia de detección

El primer paso en la búsqueda de materia oscura en los datos de KM3NeT es la selección de corridas de toma de datos y la selección de eventos bien reconstruidos. Una corrida de toma de datos es un periodo ininterrumpido de seis horas de adquisición. Las corridas se evalúan según sus condiciones de toma de datos, verificando la tasa media de disparo, la cantidad de segmentos de tiempo faltantes, cualquier defecto en calibración, procesamiento o adquisición de datos.

Tras definir la selección de corridas, se aplica una selección de eventos sobre las corridas seleccionadas. En este análisis, se seleccionan eventos tipo traza con direcciones reconstruidas ascendentes. Primero, para eliminar ruido, se requiere un número mínimo de impactos y una buena verosimilitud de traza. Segundo, para eliminar la mayor parte de los muones atmosféricos, se exige que los eventos estén reconstruidos como ascendentes. Sin embargo, una porción significativa de muones atmosféricos permanece en la muestra, con direcciones reconstruidas como ascendentes. Por ello, se aplican cortes de calidad que buscan seleccionar eventos bien reconstruidos. Se entrena un BDT usando parámetros reconstruidos de la traza como características, definiendo como señal neutrinos muónicos con resolución angular menor a un grado. Se determina un corte en la puntuación BDT que minimiza la contaminación de muones manteniendo la eficiencia de detección lo más alta posible.

La eficiencia de detección de un detector se cuantifica mediante un área efectiva, equivalente al área de un detector 100% eficiente, calculada como la razón entre eventos seleccionados y el flujo total simulado de neutrinos. Esta área está binned en energía y declinación. El área efectiva en un bin de declinación dado se usa para calcular la aceptación de señal, una convolución del área efectiva con el espectro de señal predicho. Esta cantidad, junto con el tiempo vivo del detector, determina la cantidad de eventos detectados en una muestra de datos para un flujo dado.

Modelado de señal y fondo

La búsqueda de neutrinos provenientes de aniquilaciones de materia oscura se realiza mediante un análisis de máxima verosimilitud sin binning, usando las direcciones y energías medidas de los eventos para distinguir señal de fondo. Los eventos de fondo tienen dependencia en declinación, debido a la visibilidad variable causada por la rotación terrestre. La ascensión recta de eventos de fondo es una distribución uniforme, por lo que esta variable es superflua para caracterizar el fondo. La declinación medida y las energías reconstruidas de los eventos de datos se usan para generar eventos de fondo y evaluar la verosimilitud del fondo, mientras que la ascensión recta de eventos de fondo se genera aleatoriamente, siguiendo un procedimiento de cegamiento.

Para modelar los neutrinos de señal, se requiere una predicción precisa del espectro de neutrinos producido en una aniquilación de WIMP. Para ello se usan paquetes externos. Estos paquetes usan PYTHIA, un generador Monte Carlo de colisiones de partículas, complementado con correcciones electrodébiles a energías por encima de la escala electrodébil. Se producen predicciones de espectro para múltiples realizaciones del WIMP: en este trabajo, se buscan WIMPs en el rango de masa $500\text{GeV}/c^2 - 100\text{TeV}/c^2$, aniquilando en cinco canales: $\mu^+\mu^-$, $\tau^+\tau^-$, $b\bar{b}$, W^+W^- , $\nu\bar{\nu}$. Para determinar la cantidad de aniquilaciones en una dirección dada, se debe definir un perfil de densidad del halo. En este análisis, se usan un modelo cuspy de ejemplo y un perfil cored de ejemplo. Luego, los espectros se usan para determinar la distribución energética de eventos de señal en el detector, mientras que el factor J se combina con la respuesta angular del detector para determinar las direcciones entrantes de eventos señal, definidas en función de la separación angular al centro de la fuente. Esta distribución conjunta se usa para generar coordenadas y energías de eventos señal, reescalando la distribución de probabilidad por el tamaño del ángulo sólido de cada bin angular.

Análisis de máxima verosimilitud sin binning

El objetivo del análisis de máxima verosimilitud sin binning es determinar el número de eventos que pueden detectarse o rechazarse con cierta confianza. Para estimar esto, se crean muchos conjuntos de datos, variando la cantidad de eventos señal inyectados en cada conjunto. La verosimilitud se minimiza para cada conjunto, ajustando el número

de eventos señal presente en la muestra. El estadístico de prueba (TS) se define como la razón entre la verosimilitud minimizada y la verosimilitud de la hipótesis de sólo fondo.

Los valores del TS se agrupan en distribuciones según la cantidad de eventos señal inyectados. La sensibilidad al número de eventos señal que puede rechazarse a un nivel de confianza dado se estima calculando primero la mediana de la distribución del TS para muestras de sólo fondo. Luego, las distribuciones con señal inyectada se comparan con esta mediana: para un nivel de confianza del 90%, la distribución con integral igual al 10% en la mediana del fondo representa el número de eventos señal para los cuales la muestra se caracteriza erróneamente como sólo fondo el 10% de las veces. En caso de descubrimiento, para un nivel dado, por ejemplo 5σ , se calcula el TS de la distribución de fondo en ese cuantíl. El número de eventos señal para el cual la mediana está por encima de este valor representa el número de eventos señal necesarios para un descubrimiento a 5σ .

La sensibilidad al número de eventos señal se usa para determinar la sensibilidad al flujo de señal, dividiendo la sensibilidad en número de eventos por la aceptación y tiempo vivo de la muestra. La sensibilidad al flujo se convierte en sensibilidad a la sección eficaz de aniquilación termalmente promediada del par WIMP según la Ec. A.2. Una vez que se abre la información (unblinding), el análisis se repite sobre los datos reales. Si el TS de los datos está por debajo de la mediana del fondo, se establecen límites superiores a las sensibilidades. Si el TS de los datos está por encima de la mediana del fondo, se recalcula el límite superior del número de eventos señal, usando el TS de los datos en lugar de la mediana del fondo para determinar el número de eventos con integral igual al 10%.

Combinación de verosimilitudes con experimentos de γ -ray

Se exploró un método alternativo para calcular sensibilidades y límites, con el objetivo de combinar resultados con observatorios de rayos γ . El método busca combinar límites sin compartir información sensible como respuestas instrumentales o información evento a evento. Lo que se comparte entre experimentos es la curva del estadístico de prueba: se crean un cierto número de conjuntos de datos sólo con fondo, y para cada conjunto se calcula el TS en varios puntos del espacio de parámetros. En lugar de minimizar la verosimilitud, se calcula $TS(n_{sg})$, y esta distribución se transforma en $TS(\langle\sigma v\rangle)$ usando la aceptación de señal y el tiempo vivo para convertir entre ambos. El límite se estima

asumiendo el teorema de Wilks, que establece que una distribución de TS asintóticamente tiende a una χ^2 con n grados de libertad a medida que el tamaño de la muestra crece al infinito. Para un grado de libertad, se alcanza un 95% de confianza en 2.71. Por tanto, el valor de $\langle\sigma v\rangle$ para el cual la curva TS es igual a 2.71 es la sensibilidad para ese conjunto de datos individual. La sensibilidad final se determina como la mediana de todas las sensibilidades. Para combinar múltiples muestras, se multiplican las curvas TS entre sí, y luego se evalúa la sensibilidad en el producto. El límite se obtiene siguiendo el mismo procedimiento, pero calculando la curva TS para los datos reales.

Materia oscura en el Sol

Las aniquilaciones de materia oscura en el Sol ocurren en un medio denso, por lo que se consideran efectos adicionales en el cálculo del espectro de neutrinos. Se debe determinar si una partícula producida decae o hadroniza antes o después de perder una cantidad significativa de energía por interacciones. Además, se debe considerar la probabilidad de absorción de neutrinos producidos, junto con las oscilaciones modificadas debido a efectos de materia.

El Sol se considera una fuente puntual. Por lo tanto, la función de respuesta del instrumento describe adecuadamente la distribución de las direcciones de llegada de eventos señal respecto a la posición solar. Las distribuciones energéticas de eventos señal se obtienen reponderando las simulaciones con los espectros de neutrinos. El análisis sin binning procede igual que para el Centro Galáctico, con una excepción: la fuente se mueve en el cielo. Por ello, se deben tener en cuenta los tiempos de evento para comparar las direcciones del evento con la posición solar en ese momento. La aceptación de señal también se calcula considerando el tiempo que el Sol pasa en cada bin de declinación. La sensibilidad al flujo se convierte en sensibilidad a la sección eficaz de dispersión WIMP-nucleón con la fórmula:

$$\sigma_{SD/SI} = \Phi_{90\%} \cdot K_{SD/SI}. \quad (\text{A.3})$$

Donde $K_{SD/SI}$ es un factor de conversión que considera la distancia Tierra-Sol, la densidad local del halo, la distribución de velocidades, las abundancias de elementos y los diferentes factores de supresión que afectan la dispersión. Se asume que la dispersión es completamente dependiente o independiente del espín, por lo que se reportan dos límites.

Resultados y discusión

Se analizaron las muestras de datos ARCA8, ARCA19 y ARCA21 en la búsqueda de materia oscura en el Centro Galáctico. La selección de eventos se optimizó para obtener las mejores sensibilidades posibles, tras lo cual se abrió la información (unblinding). No se observó un exceso significativo por encima del fondo, resultando en límites superiores sobre el parámetro $\langle\sigma v\rangle$ en función de la masa del WIMP, para los cinco canales de aniquilación considerados. Se analizó en combinación con los datos de KM3NeT el legado de datos de su predecesor, ANTARES, resultando en una mejora con respecto al resultado de ANTARES del orden del 20% para las mayores masas de WIMP. Los límites superiores se situaron en contexto con otros experimentos de detección indirecta en el campo, como se muestra en la Fig. A.1. Los límites obtenidos son competitivos para las mayores masas

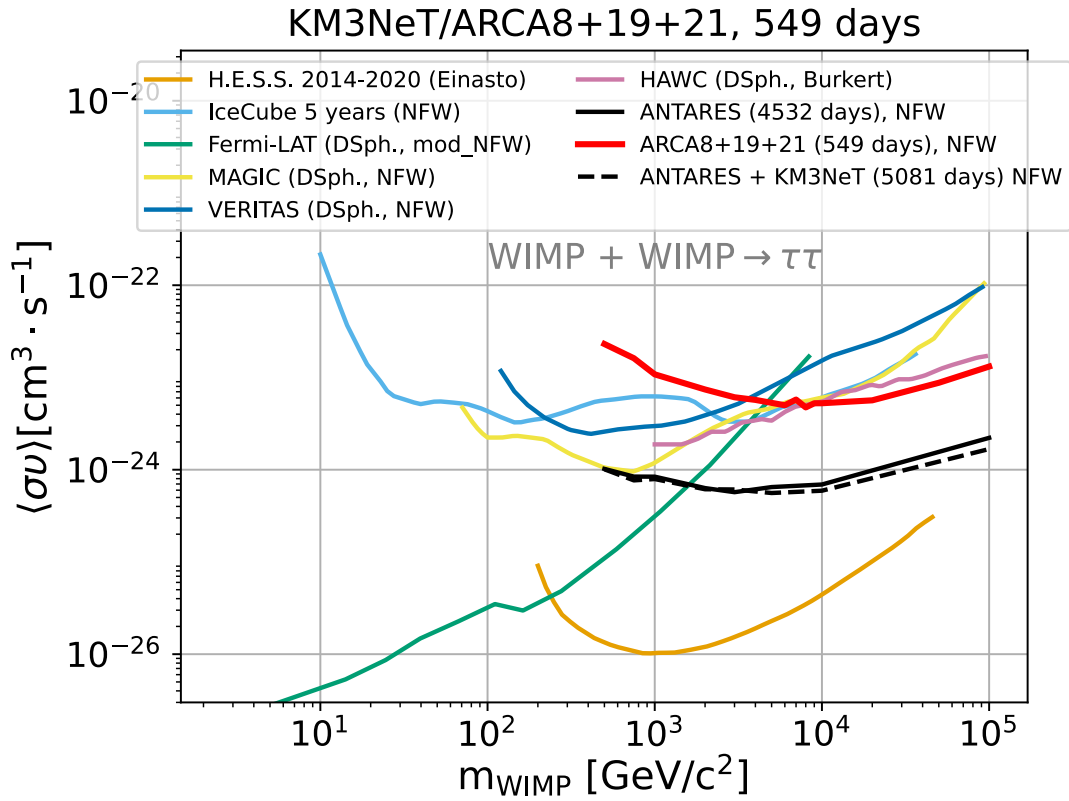


FIGURE A.1: El límite sobre la sección eficaz de aniquilación de pares de WIMP para la aniquilación en tauones obtenido con el conjunto de datos de KM3NeT se muestra en rojo, como función de la masa del WIMP. El límite actualizado de ANTARES se muestra en negro. La línea negra discontinua corresponde a la sensibilidad obtenida con la combinación de datos de KM3NeT y ANTARES. El gráfico también contiene los límites más recientes de observatorios de neutrinos y rayos γ que realizan búsquedas indirectas de materia oscura [141–146]. La leyenda indica también el perfil de densidad usado para calcular el resultado y las fuentes estudiadas (DSph. indica galaxias enanas esferoidales).

de WIMP, para las cuales los observatorios de rayos γ tienen dificultades para observar fotones debido a efectos de absorción.

Se analizaron las incertidumbres de los resultados obtenidos. Primero, se investigó el efecto de las incertidumbres de modelado. Se varió el espectro de entrada usando un cálculo diferente que incorpora las correcciones electrodébiles de forma distinta. No se observaron cambios significativos en las sensibilidades. Luego, se varió el perfil de densidad: se usó el perfil de Burkert, un perfil más extendido, para calcular el factor J y modelar la señal. La extensión del perfil resulta en una emisión más dispersa y un integral del factor J menor, produciendo sensibilidades hasta un orden de magnitud peores. La comparación de sensibilidades se muestra en la Fig. A.2.

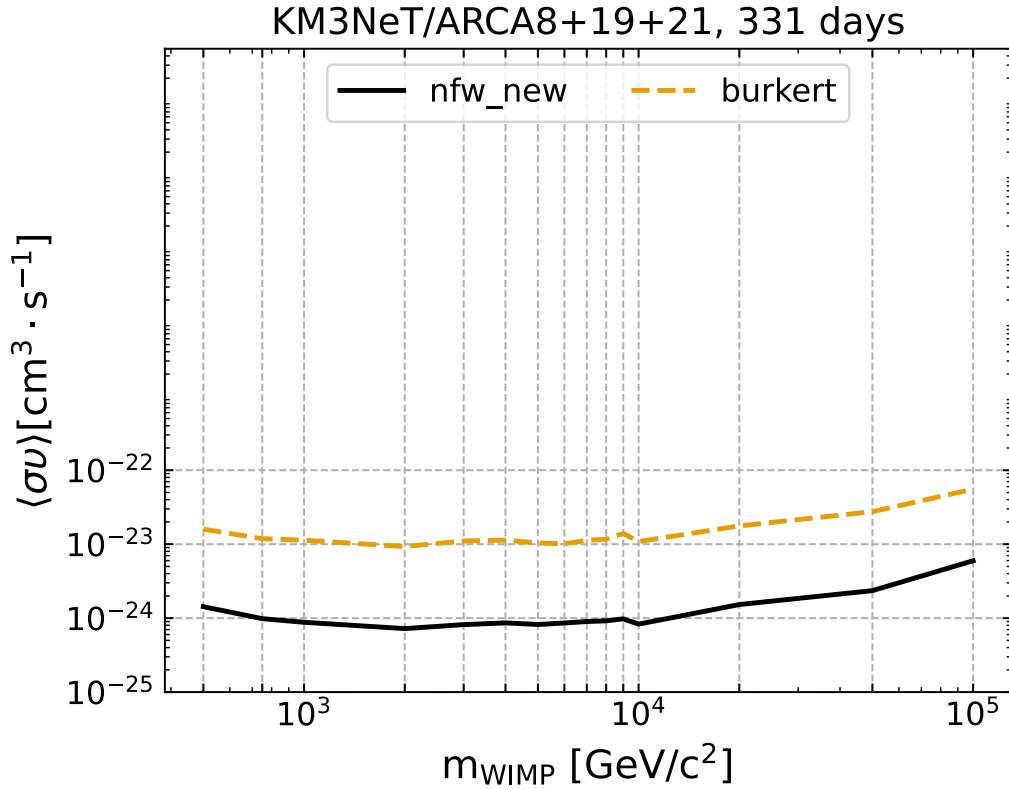


FIGURE A.2: Sensibilidades a la sección eficaz de aniquilación de WIMP para el canal neutrino en función de la masa del WIMP, mostradas para el canal de aniquilación a neutrinos. La sensibilidad en naranja asume un perfil de densidad Burkert, mientras que la línea negra asume un perfil NFW.

A continuación, se investigó el efecto de las incertidumbres relacionadas con el detector. Se usaron simulaciones con propiedades del agua y eficiencias de PMT modificadas para crear expectativas de fondo modificadas, y se realizó el análisis de verosimilitud con estos

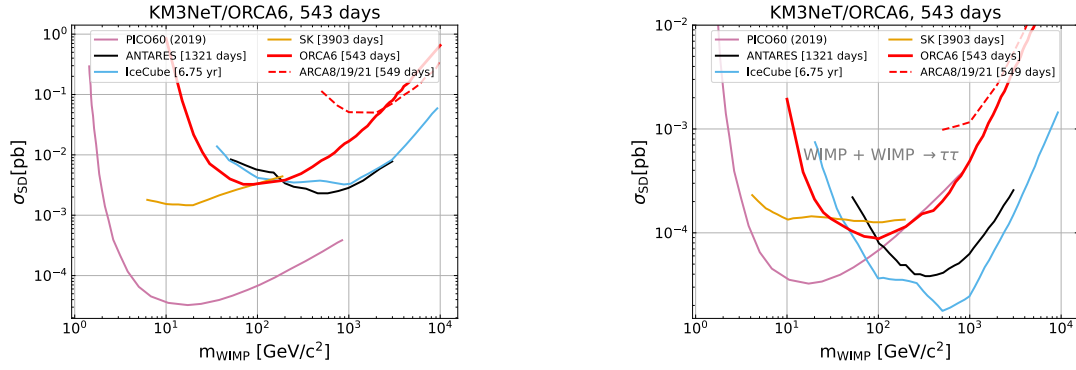


FIGURE A.3: Sensibilidades a la sección eficaz de dispersión WIMP-nucleón dependiente del espín en función de la masa del WIMP obtenidas en este trabajo comparadas con límites superiores del análisis ORCA6 y otros experimentos en el campo [147, 149–152].

ingredientes modificados. La variación en los resultados fue similar al empeoramiento observado cuando se aplica nuestro método para contabilizar incertidumbres del detector, validando el enfoque usado para incluir estas incertidumbres.

El método de combinación de verosimilitudes no se ha usado aún para combinar resultados con observatorios de rayos γ , debido a limitaciones de tiempo (como escribir 17 resúmenes distintos de esta tesis). Sin embargo, se calcularon las primeras sensibilidades y límites superiores, que coinciden estrechamente con las sensibilidades obtenidas en el análisis sin binning, validando ambos enfoques.

Los conjuntos de datos ARCA8, 19 y 21 también se analizaron en busca de materia oscura en el Sol. No se observó exceso sobre el fondo, resultando en límites superiores sobre la sección eficaz de dispersión WIMP-nucleón en función de la masa del WIMP, para tres canales de aniquilación. Los resultados se compararon con otros experimentos en el campo: en el caso de dispersión independiente del espín, los experimentos de detección directa son órdenes de magnitud más sensibles. Para escenarios dependientes del espín, los límites obtenidos son competitivos, ya que el volumen efectivo de núcleos con espín neto en experimentos de detección directa es significativamente menor. Los límites dependientes del espín se colocan en contexto con otros experimentos en la Fig. A.3. Finalmente, las sensibilidades al flujo también se reinterpretaron como sensibilidades a la sección eficaz de dispersión WIMP-electrón, un proceso difícil de estimar en experimentos terrestres. Debido a su mayor tamaño y tiempo vivo, se obtienen límites significativamente mejores con el detector IceCube para este parámetro.

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