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Search for dark matter towards the Sun with the KM3NeT/ORCA6 neutrino telescope

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Dark matter is acknowledged to exist at different scales in the Universe. Cosmological observations strongly suggest that approximately 25% of the overall energy density of the Universe is attributed to dark matter, while roughly 5% is composed of baryonic matter. Since the neutrinos produced in pair-annihilation or decay of weakly interacting massive particles (WIMPs) could be observed by neutrino telescopes, these instruments provide an important complementarity in the quest for detecting dark matter signals. An excess of signal could be observed in regions where dark matter might accumulate, e.g., the Sun. The KM3NeT telescope is composed of two detectors, namely, ARCA (Astroparticle Research with Cosmics in the Abyss) and ORCA (Oscillation Research with Cosmics in the Abyss). The energy threshold of the latter is $\sim$ 1 GeV. Given the fact that neutrinos above 1 TeV are typically absorbed before they can escape from the Sun, the energy range of the KM3NeT/ORCA detector is optimal for the search of dark matter signals coming from our star. In this contribution, the search for WIMP annihilation signals coming from the Sun is presented. An unbinned likelihood method is used to discriminate the signal from the background in a 543-day livetime sample of data collected with the 6 first detection units of the ORCA detector. The limits on the neutrino flux and on the spin-dependent and spin-independent cross sections are given for three different annihilation channels. No evidence for a dark matter signal over the expected background has been found.

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1. Introduction

Dark matter is one of the most intriguing puzzles in the modern particle physics picture. Cosmological and astrophysical observations, including the anisotropies in the cosmic microwave background radiation and the rotational velocities of galaxies, provide a solid evidence of the existence of dark matter. In particular, it is predicted that only 5% of the total energy density of the Universe belongs to baryonic matter, while 25% is attributed to dark matter, and the remaining 70%, to dark energy. A common hypothesis postulates that dark matter is made of weakly interacting massive particles (WIMPs).

While direct search experiments are designed to search for the collision of a dark matter particle with a nucleus, indirect search experiments aim to detect the neutrinos produced in a WIMP pair-annihilations. Since the average energy density of dark matter in the Galactic Halo at the location of the Sun is about $0.3\,\text{GeV}/\text{cm}^3$, it is preferable to search for a signal of dark matter annihilations in places where dark matter might accumulate. Some of the most promising candidates are the Sun [1], the Earth and the Galactic Centre.

As the Sun is moving in the Milky Way, a wind of dark matter particles permeates through it. Even if most of these particles cross the Sun without interacting, a fraction of them collides with the nuclei present in it. If the collision is hard enough, the dark matter particle may lose a significant amount of energy and therefore remain gravitationally trapped in the Sun. This will increase the dark matter density in our star, which makes WIMP pair-annihilations more likely to happen.

The expected flux of neutrinos at the Earth surface due to WIMP pair-annihilations in the Sun is given by the following expression:

$$\frac{\mathrm{d}\Phi}{\mathrm{d}E} = \frac{\Gamma}{4\pi D_{\text{SE}}^2}\frac{\mathrm{d}N}{\mathrm{d}E}\,, \tag{1}$$

being $\frac{\mathrm{d}N}{\mathrm{d}E}$ the so-called neutrino yield – i.e. the number of neutrinos per unit of energy that are emitted in one annihilation–, D_{SE} the distance from the Sun to the Earth and Γ the annihilation rate of WIMP particles in the Sun.

The annihilation rate is strongly correlated with the capture rate, C_r. In particular, the following relationship can be established:

$$\Gamma = \frac{1}{2}C_r \tanh^2\left(\frac{t}{t_\odot}\right)\,, \tag{2}$$

being $t_\odot$ a characteristic time of the Sun, and t its lifetime. A situation of equilibrium is often assumed, which implies that $t/t_\odot \gg 1$ and, consequently:

$$\Gamma = \frac{1}{2}C_r\,. \tag{3}$$

The capture rate of dark matter in the Sun is related to the WIMP-nucleon scattering cross section, which can be spin-dependent (σ^{SD}) or spin-independent (σ^{SI}). Therefore, a relationship between the WIMP-nucleon cross section and the flux of neutrinos can be established:

$$\sigma^{\text{SD,SI}} = K^{\text{SD,SI}}\Phi_{\nu+\bar{\nu}}\,, \tag{4}$$

where K is the so-called conversion factor, which is computed using the software package DarkSUSY [2] in this analysis. The conversion factor contains information about the WIMP pair-annihilation channel, the mass of the WIMP and the energy threshold of the detector.

2. The KM3NeT neutrino telescope

KM3NeT [3] is a neutrino research infrastructure under construction at the bottom of the Mediterranean Sea, which consits of two different detectors: the KM3NeT/ARCA (Astroparticle Research with Cosmics in the Abyss) detector, located off-shore Sicily, Italy, and the KM3NeT/ORCA [4] (Oscillation Research with Cosmics in the Abyss) detector, located off-shore Toulon, France. The former has been designed to detect high-energy neutrinos, which makes it best suited for astronomy and astrophysics research in the TeV−PeV energy range. ORCA is optimised for the detection of atmospheric neutrinos with the primary goal of measuring neutrino properties like the oscillation parameters and the neutrino mass ordering. For this reason, the ORCA detector is optimised at lower energies, ranging from 1 GeV to 1 TeV.

Both the ARCA and ORCA detectors are composed of Digital Optical Modules (DOMs) [5], arranged in vertical strings called Detection Units (DUs), which have a segmented photo-sensitive area provided by 31 photomultiplier tubes (PMTs) housed in a 17" glass sphere. The Cherenkov light induced by the ultra-relativistic charged particles produced in the neutrino interactions nearby the detector can produce signals (*hits*) in the PMTs.

On its final configuration, the ARCA (ORCA) detector will be composed of 230 (115) detection units. The dataset analysed in this work has been taken with the 6 DUs configuration of the ORCA detector, referred to as ORCA6, in the period from January 2020 to November 2021.

3. Methods

In this work, the dataset of ORCA6 is analysed to search WIMP pair-annihilation signals coming from the Sun. After rejecting the runs that do not survive the quality checks, the sample analysed has a total livetime of 543 days.

Three WIMP annihilation channels are explored as benchmarks:

$$\text{WIMP} + \text{WIMP} \rightarrow \tau^+\tau^- \,, W^+W^- \,, b\bar{b} \,. \tag{5}$$

The yields for these annihilation modes are computed by the PYTHIA-based program WimpSim [6].

Based on the event topology, events can be classified as *shower-like* or *track-like*. On the one hand, shower-like events are produced in all neutral current neutrino interactions, as well as in charged current ν_e and ν_τ interactions. They exhibit the characteristic formation of electromagnetic and hadronic showers, wherein a significant fraction of energy is promptly dissipated. On the other hand, track-like events arise mostly from charged current ν_μ interactions. These events are distinguished by the generation of a leading muon. Being a charged particle, the muon's path through the detector materialises as a substantial emission of Cherenkov light, that produce signals in the photosensors used for the reconstruction of the neutrino direction and energy.

The analysis presented in this contribution is optimised on the selection of the track-like events, exhibiting a better angular reconstruction than the shower-like events. In addition, a set of cuts is used to reject background, mainly composed of atmospheric muons and atmospheric neutrinos, as well as to optimise the sensitivity on the flux of neutrinos. A first set of quality cuts is applied on data to reject badly reconstructed events and to reduce muon contamination, ensuring good agreement between data and Monte Carlo. In a second step, the set of cuts on β (the estimated error in the reconstructed muon track direction), the total number of detected hits in the event, and the track likelihood (the likelihood of the track reconstruction algorithm) that optimise the sensitivity on the neutrino flux, is searched for.

The analysis method is based on the generation of pseudo-experiments (PEs), each of them consisting of a skymap populated with n_b background events and n_s injected signal events. Then, an unbinned likelihood analysis is performed over the skymaps to determine the most likely number of signal events within them. The ingredients of the likelihood fuction are the point spread function (PSF), which is the probability distribution of the angular distance to the Sun, and the probability density function (PDF), which is a two-dimensional probability distribution of the number of hits and the β parameter. The corresponding signal distributions are built from Monte Carlo simulations, weighting the events by the WIMP pair-annihilation spectra. The background PDF and PSF distributions are built from the scrambled data.

The likelihood function is expressed as

$$\ln \mathcal{L}(n_s) = \sum_{i=1}^{N_{\text{tot}}} \ln \left[n_s \mathcal{S} \left(\Psi_{\odot,i}, \beta_i, N_{\text{hits},i} \right) + n_b \mathcal{B} \left(\Psi_{\odot,i}, \beta_i, N_{\text{hits},i} \right) \right] - (n_s + n_b) \,, \tag{6}$$

where $\mathcal{S}$ and $\mathcal{B}$ denote the signal and background probability density functions, $\Psi_\odot$ denotes the angular distance to the Sun and $N_{\text{tot}} = n_s + n_b$ is the total number of events in the skymap. In order to reduce the computation time, for each skymap only the events inside a 30° cone around the position of the Sun are computed in the likelihood. The events outside this cone are treated as background: $\mathcal{S} = 0$ and $\mathcal{B} = 1$.

For each pseudo-experiment, the likelihood function is maximised with respect to n_s. The test statistic (TS) is calculated as

$$\text{TS} = \log_{10} \left(\frac{\mathcal{L}(\hat{n}_s)}{\mathcal{L}(0)} \right) \,, \tag{7}$$

where $\hat{n}_s$ is the number of signal events that maximises the likelihood. $\mathcal{L}(0)$ corresponds to the likelihood of the hypothesis that all the events originate from the atmospheric background, i.e., the null hypothesis.

A Poissonian smearing is performed over the TS distributions in order to simulate statistical fluctuations. In addition to this, a 15% Gaussian smearing is applied to include the systematic uncertainties in the number of detected events. This value was obtained by simulating events with a modified absorption length of photons: the variability in this factor had the greatest impact on the quantity of detected events. The smearings are performed as follows:

$$P(\text{TS}|\mu) = \sum_{i=0}^{n_{\text{inj}}^{\text{max}}} P(\text{TS}|i) \int_{\mu-4\sigma_\mu}^{\mu+4\sigma_\mu} P(i|\bar{\mu}) G(\bar{\mu}|\mu, \sigma_\mu) d\bar{\mu} \,. \tag{8}$$

Following the Neyman approach [7], an average upper limit on the number of signal events, n_s, is computed comparing each signal $P(\text{TS})$ distribution with the median of the background TS distribution. The sensitivity, n_{90}, is defined as the 90% CL upper limit for a measurement equal to the median of the background TS distribution. The sensitivity on the flux is obtained as

WIMP mass range	β	N_{hits}	Track likelihood
$10\,\text{GeV} < m_\chi < 300\,\text{GeV}$	$< 1°$	> 20	> 120
$300\,\text{GeV} < m_\chi < 10\,\text{TeV}$	$< 1°$	> 20	> 60

Table 1: Sets of cuts that optimise the sensitivity on the neutrino flux for the $\tau^+\tau^-$ channel and the W^+W^- channel.

WIMP mass range	β	N_{hits}	Track likelihood
$10\,\text{GeV} < m_\chi < 300\,\text{GeV}$	$< 1°$	> 40	> 120
$300\,\text{GeV} < m_\chi < 10\,\text{TeV}$	$< 0.9°$	> 20	> 80

Table 2: Sets of cuts that optimise the sensitivity on the neutrino flux for the $b\bar{b}$ channel.

$$\Phi^{90}_{\nu+\bar{\nu}} = \frac{n_{90}}{Acc \times T}, \tag{9}$$

being Acc the detector acceptance to the signal, and T the livetime of the dataset. The acceptance is computed as

$$Acc = \int_{E_{\text{th}}}^{M_{\text{WIMP}}} A_{\text{eff}}(E)\,\frac{\mathrm{d}N}{\mathrm{d}E}\mathrm{d}E\,. \tag{10}$$

Here $\frac{\mathrm{d}N}{\mathrm{d}E}$ is the spectrum given by WimpSim, E_{th} is the energy threshold (1 GeV for ORCA) and $M_{\text{WIMP}} \in (10\,\text{GeV}, 10\,\text{TeV})$ is the mass of the WIMP. A_{eff} denotes the effective area of the detector, defined as the surface of an ideal detector with an efficiency of 100%. This quantity can only be obtained from the simulation, as the ratio between detected events and generated events.

Table 1 shows the combination of cuts that optimises the sensitivity for the $\tau^+\tau^-$ and W^+W^- annihilation channels, while Table 2 shows the same for the $b\bar{b}$ channel.

Finally, Equation 4 is used to obtain the sensitivities on the cross sections for the spin-dependent and the spin-independent interactions.

4. Results

The KM3NeT/ORCA6 dataset has been analysed to search for dark matter in the Sun, considering WIMP masses in the range from 10 GeV to 10 TeV. After the analysis of the 543 days of livetime, the TS values obtained from this dataset are compatible with the background hypothesis for all combinations of WIMP masses and annihilation channels.

Figure 1 shows the 90% CL upper limits on the neutrino flux for the three channels explored. As neutrinos with energies above 1 TeV are absorbed before they can escape from the Sun, the spectra of the WIMP pair-annihilation for masses ranging from 1 TeV to 10 TeV are highly correlated. For this reason, the limit on the flux tends to flatten for masses in the TeV scale.

Figures 2 and 3 show the 90% CL upper limits on the spin-dependent and the spin-independent cross sections, obtained using the conversion factors (see Equation 4).

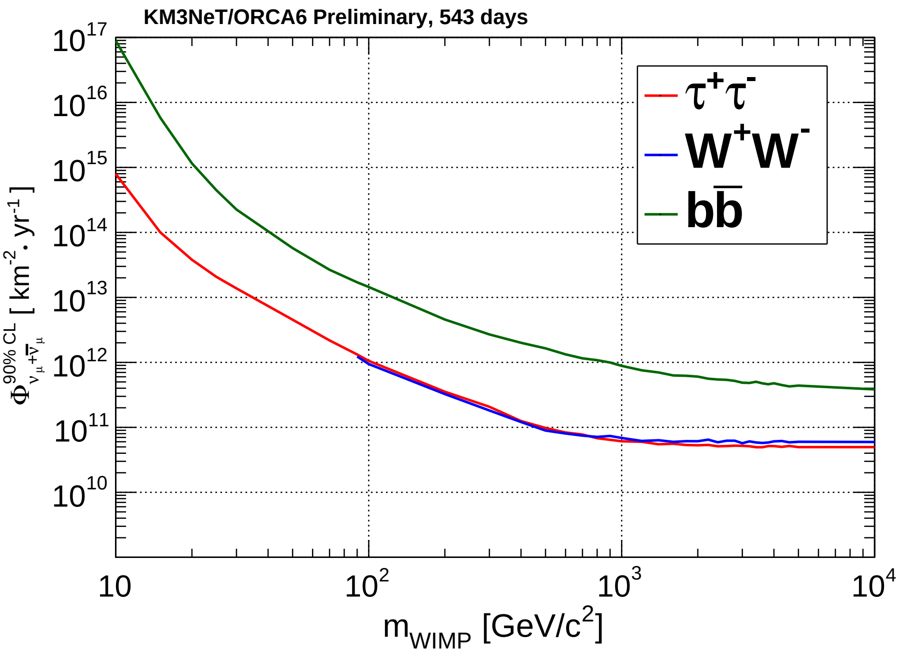

Figure 1: The 90% CL upper limits on the flux of neutrinos as a function of the WIMP mass for each of the three annihilation channels.

5. Conclusions

In this contribution, the initial findings of dark matter annihilation searches from the Sun using 543 days of data collected with the KM3NeT/ORCA detector in its 6 DUs configuration are presented. The KM3NeT/ORCA detector offers extensive coverage of the WIMP mass parameter space, namely from 1 GeV to 1 TeV. The signal has been searched for using an unbinned likelihood method in three different annihilation channels ($\tau^+\tau^-$, W^+W^- and $b\bar{b}$). As no dark matter signal has been found in the data over the expected background, limits on the neutrino flux, and on the spin-dependent and the spin-independent cross sections have been established. This detector has already achieved competitive results during its early construction phase, even outperforming its predecessor, ANTARES [13], in some specific regions of the parameter space.

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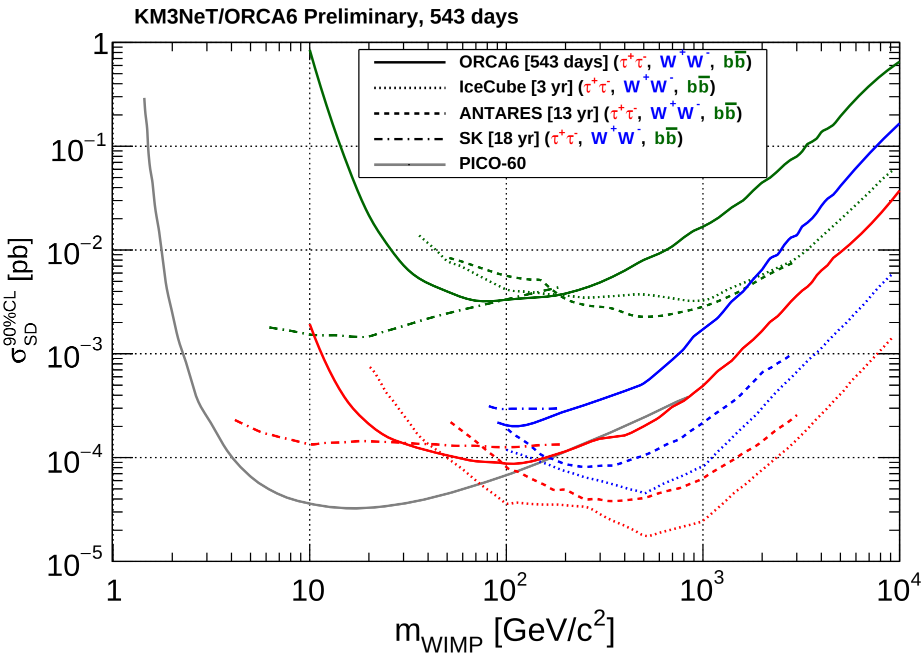

Figure 2: The 90% CL upper limits on the spin-dependent WIMP-nucleon cross section as a function of the WIMP mass for each of the three annihilation channels. The full lines show the results obtained in this analysis, whereas the other lines show the upper limits obtained by IceCube [8], ANTARES [9], Super-Kamiokande [10] and PICO-60 [11] (shown as a full line).

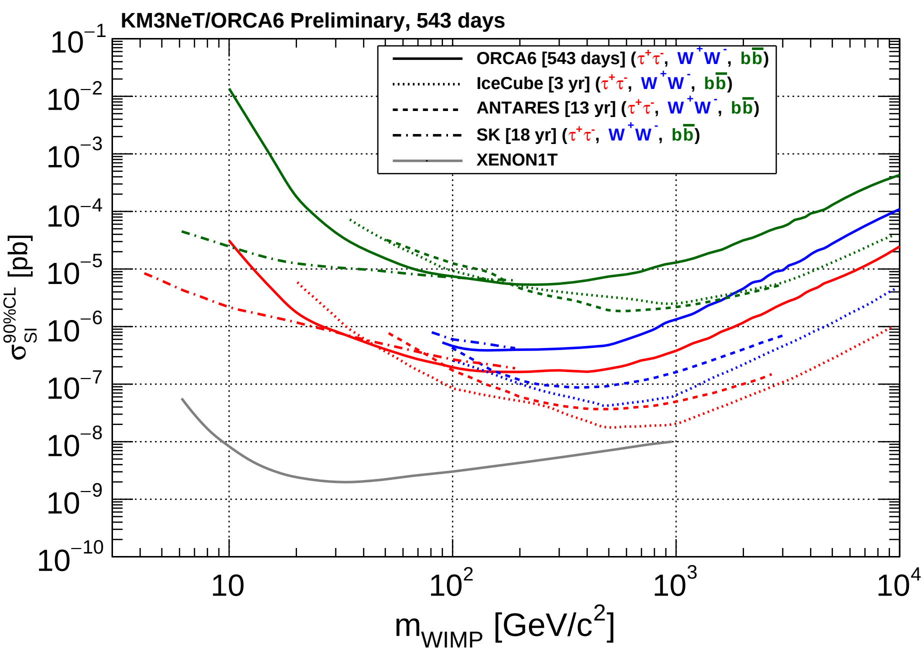

Figure 3: The 90% CL upper limits on the spin-independent WIMP-nucleon cross section as a function of the WIMP mass for each of the three annihilation channels. The full lines show the results obtained in this analysis, whereas the other lines show the upper limits obtained by IceCube [8], ANTARES [9], Super-Kamiokande [10] and XENON1T [12] (shown as a full line) .

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