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Search for dark matter from the centre of the Earth with 8 years of IceCube data

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ABSTRACT: Neutrinos have been proved to be unique messengers in the understanding of fundamental physics processes, and in astrophysical data sets they may provide hints of physics beyond the Standard Model. For example, neutrinos could be the key to discerning between various dark matter models that are based on Weakly Interacting Massive Particles (WIMPs). WIMPs can scatter off standard matter nuclei in the vicinity of massive bodies such as the Sun or the Earth, lose velocity, and be gravitationally trapped in the center of the body. Self-annihilation of dark matter into Standard Model particles may produce an observable flux of neutrinos. For the case of the Earth, an excess of neutrinos coming from the center of the planet could indicate WIMP capture and annihilation at the Earth's core. The IceCube Neutrino Observatory, located at the geographical South Pole, is sensitive to these excess neutrinos. A search has been conducted on 8 years of IceCube data, probing multiple dark matter channels and masses. With this analysis, we show that IceCube has world-leading sensitivity to the spin-independent dark matter-nucleon scattering cross section above a WIMP mass of 100 GeV.

KEYWORDS: Data analysis; Data reduction methods; Neutrino detectors; Particle detectors

[1]Full author list and acknowledgments are available at icecube.wisc.edu.

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1 Introduction

The nature of dark matter (DM) is one of the biggest unknowns of the last century. Astronomical and cosmological evidence indicates that DM constitutes 84% of the total matter density and 31% of the content of the universe [1]. Many models [2] have been proposed to describe it throughout the years. The Weakly Interacting Massive Particle (WIMP) model, where DM is a particle arisen from the super-symmetry extension of the Standard Model (SM) and interacts only weakly, is one of the most probed theoretically and experimentally. WIMPs could scatter off nuclei in the vicinity of the Earth, lose velocity and become gravitationally captured in the center of the planet. Such particles can self-annihilate into SM particles, generating a flux in which neutrinos are among the final products and can be detected by the IceCube Neutrino Observatory at the geographical South Pole. IceCube [3] is a cubic kilometer of instrumented ice at a depth of 1450 m. The Digital Optical Module (DOM) is the fundamental units of detection of IceCube. It hosts a downward-looking photo-multiplier tube (PMT) for light detection. With a grid of 5160 DOMs on 86 strings, IceCube can detect the Cherenkov light produced by the passage of charged particles through the volume. IceCube can detect neutrino induced events with neutrino energy from 5 GeV to 10 PeV.

With this work, we propose a new search for dark matter from the centre of the Earth with 8 years of IceCube data, following a pathfinder analysis [4] carried out with 1 year of data.

2 Dark matter from the center of the Earth

The processes of WIMP capture and self-annihilation are described by:

$$\frac{\mathrm{d}N}{\mathrm{d}t} = C_\mathrm{C} - C_\mathrm{A} N^2, \tag{2.1}$$

where C_C is the capture rate and $\Gamma_\mathrm{A} = C_\mathrm{A} N^2$ is the annihilation rate. The solution of (2.1) is:

$$\Gamma_\mathrm{A} = \frac{C_\mathrm{C}}{2} \tanh^2 \left(\frac{t_\oplus}{\tau}\right), \tag{2.2}$$

where $\tau = (C_C \cdot C_A)^{-1/2}$ is the equilibrium time and $t_\oplus$ is the age of the Earth. Equilibrium is reached when $t_\oplus \gg \tau$ and that is not verified for the case of the Earth. Given the definition of C_A in [5], this means that an assumption on the velocity averaged annihilation cross-section $\langle \sigma_A v \rangle$ must be made. For consistency with the other similar searches, the standard Halo model [5] with a local density value of 0.3 GeV/cm^3 is assumed.

3 Datasets and event selection

The signal for this analysis is up-going events coming from the directions around the centre of the Earth. The main sources of background for this analysis are the so-called *atmospheric muons* and *neutrinos* produced in cosmic ray air showers. Atmospheric muons are down-going events that are mis-reconstructed as up-going and are the most prominent background component. Atmospheric neutrinos can traverse the whole Earth and reach the detector from below, so they are up-going events.

The limited arrival directions of neutrinos from Earth's core do not allow us to estimate the background via scrambling real data, and thus we have to rely on Monte Carlo (MC) simulations. A small sample of data has been used to verify the correct behaviour of simulations. Signal has been simulated with the WimpSim [6, 7] software. Annihilation channels $\chi\chi \to \tau^+\tau^-/W^+W^-/b\,\bar{b}$ in the mass range 10 GeV–10 TeV have been simulated. CORSIKA [8] simulations have been used for atmospheric muons, while atmospheric neutrinos have been simulated via GENIE (up to 100 GeV) and NuGen (from 100 GeV to 10 PeV). Neutrino oscillation [9] has been considered for neutrinos with energy $E < 100$ GeV.

A dedicated event selection has been developed for this analysis. The main goal was to discard the highest possible number of atmospheric muons. This was achieved via veto and quality of the reconstruction cuts and, in the last instance, using a random forest algorithm. The differences between lower and higher energy signal events needed to be addressed by splitting the analysis into a low energy (LE) and high energy (HE) selection, optimised respectively for the DM configurations $\chi\chi \to \tau^+\tau^-$, $m_\chi = 50$ GeV and $\chi\chi \to W^+W^-$, $m_\chi = 1$ TeV. The final selections are >99% neutrino pure.

4 Analysis method and sensitivities

A binned likelihood search has been developed. The Point Spread Function (PDF) is derived from the final selections and is defined for each bin as:

$$\mu_{\text{bin}}(\xi, \overrightarrow{\eta}) = \xi S_{\text{bin}}(\theta, E) + \sum_i \eta_i B_{i,\text{bin}}(\theta, E), \tag{4.1}$$

where $S_{\text{bin}}(\theta, E)$ and $B_{i,\text{bin}}(\theta, E)$ are the 2D zenith-energy distributions for signal and background components representations respectively. ξ is the signal fraction and η_i are the fractions of the various background components.

To account for the statistical uncertainties of the distributions, the effective likelihood developed in [10] has been used. This likelihood can be considered a generalisation of the Poisson likelihood, to which it reduces when the uncertainties are negligible. The likelihood can be expressed for each bin as:

$$\mathcal{L}_{\text{eff}}(\mu|k) = \frac{\beta^{\alpha}\Gamma(k+\alpha)}{k!(1+\beta)^{k+\alpha}\Gamma(\alpha)}, \tag{4.2}$$

where k is the number of observed events. α and β are defined as:

$$\alpha = \frac{\mu^2}{\sigma^2} + 1; \qquad \beta = \frac{\mu}{\sigma^2}. \tag{4.3}$$

The total likelihood is the sum of (4.2) over all the bins. Further checks on the analysis performance using the Poisson likelihood will be performed in the future.

The ratio between the absolute best fit and the best fit found when fixing $\xi = 0$ is the Test Statistic (TS):

$$\text{TS} = \frac{\mathcal{L}(\hat{\xi}, \hat{\vec{\eta}}|k)}{\mathcal{L}(\xi = 0, \hat{\vec{\eta}}|k)}. \tag{4.4}$$

The 90% confidence level (C.L.) sensitivity is computed on 10000 pseudo-experiments and the number of signal events $n_{90\%}$ is found. The latter can be converted to volumetric flux via:

$$\Gamma_{\nu\to\mu} = \frac{n_{90\%}}{t_{\text{live}} V_{\text{eff}}}, \tag{4.5}$$

where t_{live} is the livetime of the experiment and V_{eff} the effective volume. As mentioned in section 2, a value for $\langle\sigma_{\text{A}} v\rangle$ must be assumed, for consistency with other similar works [11, 12], we take $\langle\sigma_{\text{A}} v\rangle = 3 \times 10^{-26}\,\text{cm}^3\,\text{s}^{-1}$. Solving (2.2) analytically, volumetric flux values can be converted into annihilation rate values. The spin-independent DM-nucleon cross-section $\sigma^{\text{SI}}_{\chi N}$ final values can be obtained from the annihilation rate via a tool in the WimpSim package. Sensitivities are computed over all the mass range for both the selections and, for each point, the one giving the best limit is chosen. The switch from the LE to the HE analysis happened for all channels for $m_\chi > 100$ GeV. Sensitivities obtained with the method described are shown in figure 1 and compared with other similar searches performed by ANTARES [11] and SuperKamiokande [12].

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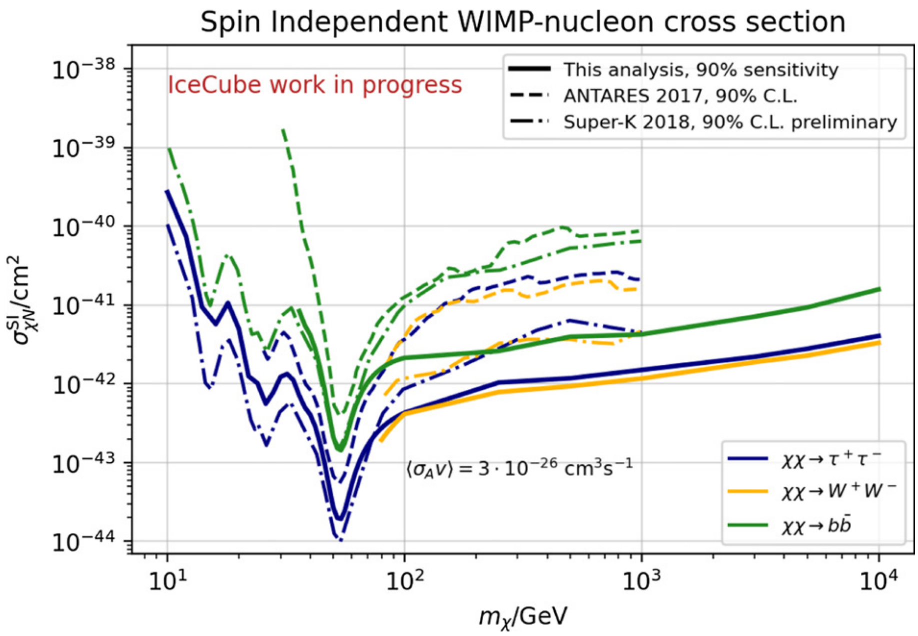

Figure 1. 90% sensitivities on the spin-independent DM-nucleon cross-section for all channels, compared with the most recent limits from ANTARES [11] and SuperKamiokande [12].

5 Conclusions

A 2D binned likelihood analysis searching for dark matter from the centre of the Earth with 8 years of IceCube data has been developed. 90% C.L. sensitivities have been calculated. The analysis shows very competitive sensitivities in comparison with similar searches. In particular, in the region with $m_\chi > 100$ GeV, this work is promising the world's best limits. Further optimisation studies are foreseen and the final results are expected in late 2021.

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