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Latest Results on Searches for Dark Matter from IceCube

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Construction of the IceCube neutrino observatory was completed in early 2011, including a low-energy in-fill extension. This DeepCore sub-detector offers exciting opportunities for neutrino physics in the energy range of 10 GeV to 1 TeV. IceCube searches indirectly for dark matter via neutrinos from dark matter self-annihilations and has a high discovery potential through striking signatures. We report on the latest results from searches for dark matter self-annihilations in the Milky Way and nearby Galaxy clusters, as well as the search for signals from the Sun and Earth. Furthermore, a formalism for quickly and directly comparing event-level IceCube data with arbitrary annihilation spectra in detailed model scans, considering not only total event counts, but also event directions and energy estimators, is presented. We show an application of this formalism to both model exclusion and parameter estimation in models of supersymmetry.

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1. Introduction

While the presence of dark matter (DM) in the universe has been inferred through its gravitational interactions, it has yet to be directly or indirectly observed. One of the most promising and experimentally accessible candidates for DM are so-called Weakly Interacting Massive Particles (WIMPs). In current models, WIMPs are predicted to have a mass in the range of a few tens of GeV to a few TeV. Neutrino telescopes, such as IceCube, can be used in the search for WIMPs and their underlying fundamental properties. IceCube searches for decaying or self-annihilating DM in galaxy halos and thereby can probe its livetime, or self-annihilation cross section ($\langle\sigma_A v\rangle$) [1]. Additionally, IceCube can test the WIMP-nucleon scattering cross section ($\sigma_{\chi,p}$) by looking for neutrino signals from self-annihilating DM captured in large celestial bodies [2], like the Sun or the Earth.

Here, new sensitivities are presented for the searches for DM candidates in the Sun with IceCube in its 79-string configuration. This detector configuration includes for the first time IceCube's low energy extension DeepCore, allowing for two significant additions compared to previous work. Firstly, we extend the search to the southern sky, doubling the livetime of the analysis for low WIMP mass searches. Secondly, DeepCore's improved low energy detection threshold makes it possible to search for WIMP masses as low as 20 GeV. We discuss novel analysis techniques and compare the resulting sensitivities with the latest IceCube results from a multi-year search for DM annihilations in the Sun with the AMANDA-II and IceCube detectors [3].

For a comprehensive description of the analyses and latest limits from IceCube on $\langle\sigma_A v\rangle$ from the Galactic Center and Halo, the reader is referred to references [4, 5]. IceCube search strategies for self-annihilating DM in dwarf galaxies surrounding the Milky Way and nearby Galaxy clusters are discussed in reference [6].

A formalism for quickly and directly comparing event-level IceCube data with arbitrary annihilation spectra in detailed model scans has recently been published [7], including a global fit to all existing constraints, together with IceCube data. The full likelihood of each experimental result, including IceCube, is combined to give confidence intervals and Bayesian credible intervals on SUSY parameters.

2. The IceCube detector

The IceCube Neutrino Telescope [8] records Cherenkov light in the ice from relativistic charged particles created in neutrino interactions in the vicinity of the detector. By recording the arrival times and intensities of these photons with optical sensors, the direction and energy of the muon and parent neutrino can be reconstructed. IceCube instruments 1 km^3 of glacial ice at the South Pole with 5160 Digital Optical Modules (DOMs) on 86 strings deployed between depths of 1450 m and 2450 m. The analysis discussed here uses data taken with the 79-string configuration of IceCube. In this configuration six more densely instrumented strings are included in the center of the array, optimized for the detection of low energy particles. Together with the seven surrounding standard IceCube strings they form the DeepCore subarray [9].

3. Solar Dark Matter searches with IceCube

In the Minimal Supersymmetric Standard Model [10], the WIMP can take the form of the lightest neutralino, χ, while in the framework of universal extra dimensions [11] it would be the lightest Kaluza-Klein particle (LKP). Whatever their underlying physics, WIMPs may be swept up by the Sun and become gravitationally bound by scattering weakly on solar nucleons. Over time, this leads to an accumulation of DM at the center of the Sun, exceeding the mean Galactic density significantly. Self-annihilation to standard model particles may result in a flux of high energy neutrinos with an energy spectrum depending on the annihilation channel and WIMP mass, and can be searched for as a point-like source by IceCube.

In this analysis we study two selected WIMP annihilation channels: annihilations into $b\bar{b}$ and W^+W^- ($\tau^+\tau^-$ below $m_\chi < 80.4$ GeV), resulting in a rather soft and hard neutrino spectrum, respectively. The dominant background for this work consists of muons and neutrinos created in cosmic ray interactions in the Earth's atmosphere. Additional background is solar atmospheric neutrinos. These originate in cosmic ray interactions in the atmosphere of the Sun and are calculated to the order of 1 event in the final data set.

We search for signal neutrinos originating from a wide range of potential WIMP masses (m_χ), reaching from 20 GeV to 5 TeV. Within this m_χ-range, signal events can have very different event topologies. To accommodate all expected event topologies within one single analysis, the full dataset is split into three independent non-overlapping event selections; first into two seasonal data streams, 'summer' and 'winter', when the Sun is above and below the horizon, respectively. The 'winter' dataset comprises two samples. The first sample ('winter high-energy' event selection, WH) has no particular track-containment requirement and aims to select upward-going muon tracks. The second sample ('winter low-energy' event selection, WL) is a low energy sample, with focus on starting or fully contained neutrino-induced muon tracks inside DeepCore. The 'summer' sample ('summer low-energy' event selection, SL) is a dedicated low energy event sample that uses the surrounding IceCube strings as an active muon veto in order to select starting neutrino-induced events within DeepCore.

Events triggering the detector are processed and filtered on-line at the South Pole IceCube lab. First, all events undergo calibration, pulse extraction and noise-hit cleaning. Photon arrival times and intensities at the DOMs are calculated and then fitted with a muon track hypothesis. Physics filters are applied to enhance the content of signal-like muon events above the dominant atmospheric muon background. Within this first selection step, the dataset is split into the two seasonal streams, where September 22nd 2010 and March 22nd 2011 mark the beginning and ending dates of selection SL.

We proceed first with a description of the additional 'winter' cut selections: In the 'winter' selections, events are required to have a successful track likelihood reconstruction with a zenith angle between 85° and 120° and a minimum multiplicity of 7 DOMs and 2 strings. The track-fit quality parameter (defined as the muon track-fit log-likelihood value divided by the number of degrees of freedom) is demanded to be less than 22. We require direct hits with an observed hit time residual of less than 150 ns and an average spread of hits in z-direction larger than -25 m. These criteria are relaxed for contained events, which have more than eight hit DOMs inside the DeepCore fiducial volume and more than four times as many hit DOMs inside DeepCore than outside. This

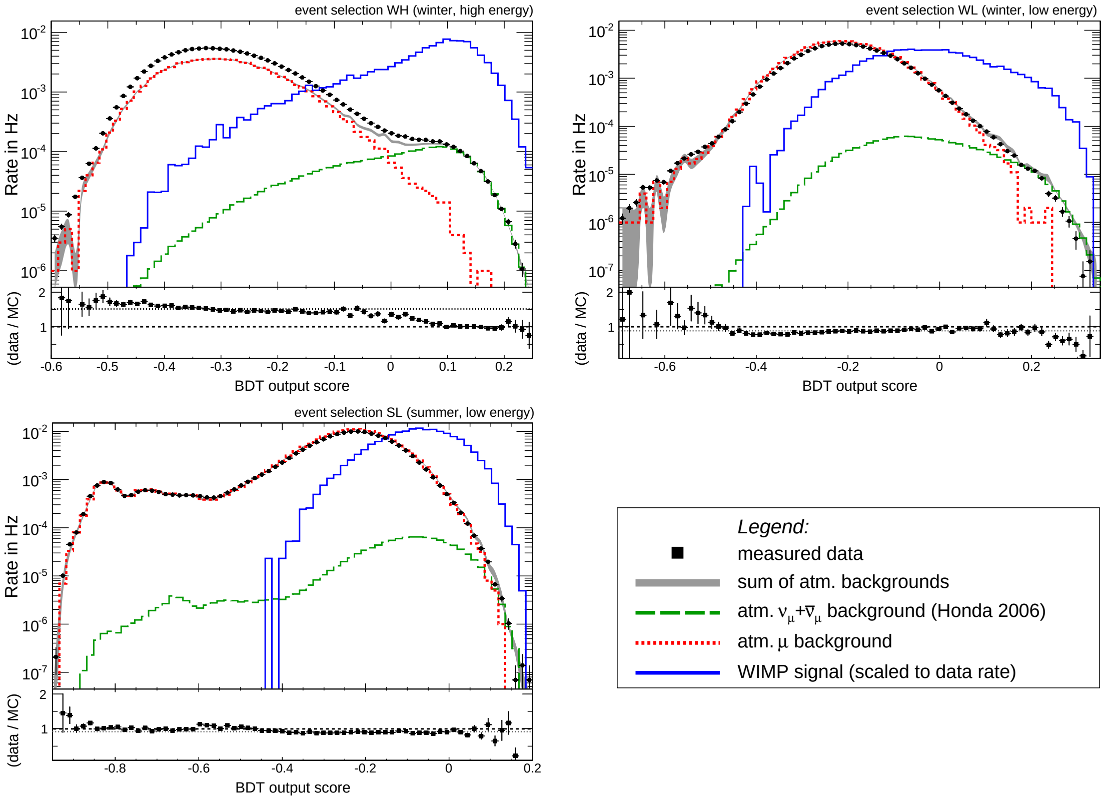

Figure 1: BDT output distributions for the winter ‘high energy’ (top left), the winter ‘low energy’ (top right) and the summer (bottom left) selections. For illustration a 1 TeV ‘hard’ WIMP signal is shown for selection WH and a 50 GeV ‘hard’ WIMP signal for selections WL and SL.

data reduction is followed by additional processing, including an estimate of the angular uncertainty of the muon track fit. It is possible that signal neutrinos arrive in coincidence with an atmospheric background event. In order to retain such signal events, a set of topological criteria are applied to ‘split’ these combined hit patterns into distinct sub-events. These sub-events are then processed as above, and undergo all subsequent event selection in their own right. The winter dataset is then divided into event samples WH and WL. For events to be included in event selection WL, we demand that the number of hit DOMs inside DeepCore be larger than outside. Additionally, the number of outside hits must be less than seven. This ensures that events with a long lever arm and therefore good angular resolution are assigned to the complement sample. Events that do not fulfill this criterion undergo a series of additional, stricter cuts on the same variables as in the initial event selection. Here, we demand higher hit DOM and string multiplicities for the selected events as expected for TeV-energy muon tracks. In this context we remove events with an estimated angular uncertainty of the reconstructed track of more than 10 degrees. ‘Low energy’ events, conversely, undergo a veto cut, removing events with hits in the 10 uppermost layers of DOMs on the regular (non-DeepCore) strings. Additionally, the cut on the estimated angular uncertainty is relaxed (25 degrees) to reflect the broadened signal point spread function at low energies. For event selection SL the cuts additional to the filter stage are different, as the dominant background is well-reconstructed down-going muons penetrating the detector. To reduce this background, we

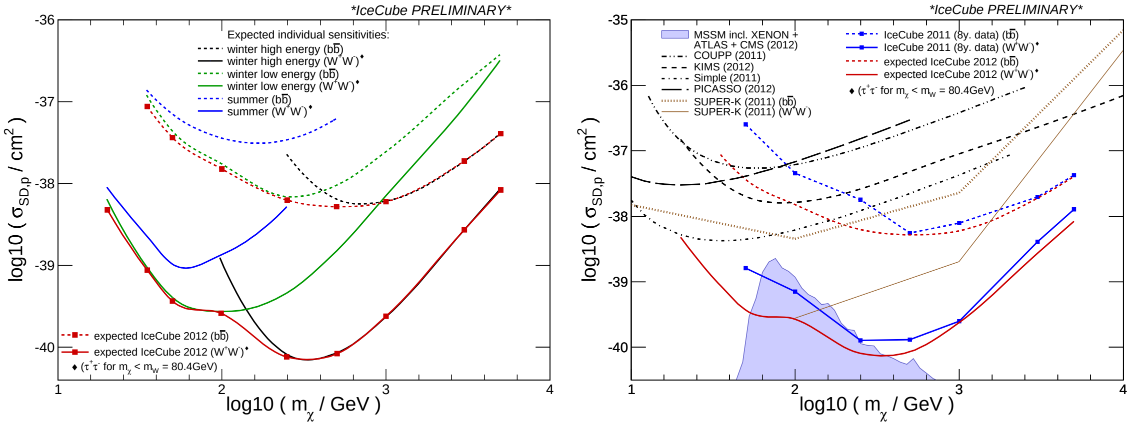

Figure 2: 90% CL sensitivities on $\sigma_{SD,p}$ for hard and soft annihilation channels over a range of WIMP masses. Systematic uncertainties are not included. The figure on the left shows individual sensitivities from event selections WH, WL, SL and the combined multi-dataset sensitivity. The figure on the right compares the multi-dataset sensitivity with the latest IceCube limits and results from other experiments. The shaded region represents an allowed MSSM parameter space taking into account recent accelerator, cosmological and direct DM search constraints.

focus only on low energy signal content with a reconstructed neutrino interaction vertex inside the DeepCore fiducial volume. Selecting only these events, cuts are placed on the zenith angle of the reconstruction ($65^\circ < \Theta_{LLH} < 100^\circ$), the hit multiplicity criteria (more than ten hit DOMs and three hit strings) and the vertical extension of the event (less than 400 m). Additionally, we impose a 14 DOM layer top veto and a tight hit-time containment criterion to reject down-going events. The hit-time criterion demands that the first hit in the veto region must be later than the fourth hit within the fiducial region.

The final background reduction utilizes one Boosted Decision Tree (BDT) for each dataset. For training and testing an independent, high statistics set of signal simulations is used, and discarded afterwards. This multivariate analysis is data driven for backgrounds and uses one month of experimental data recorded when the Sun was not within the analysis region. Through an iterative process, individual variables were removed and added and the BDT's performance evaluated, until we arrived at a final set of 14 variables in selection WH and ten in selections WL and SL. All input distributions for simulated backgrounds and data are in good agreement. The variables picked for selection WH describe both the quality of the track reconstruction and the time evolution of the pattern of hit DOMs and spatial positions within the detector. This is used to separate true up-going muon-like events from mis-reconstructed atmospheric muons. In the low energy selections WL and SL, track quality parameters yield less separation power. In this context the final BDT input observables mainly describe the degree of containment and the vertical and lateral extension of the event within the detector. One exception is the likelihood ratio between a starting track hypothesis and an infinite muon track. The BDT output distributions of all selections are shown in Fig. 1 for observed data, atmospheric backgrounds and a representative WIMP signal. All selections have very good agreement between data and simulations at high BDT score values (very signal like events). This region is largely dominated by atmospheric neutrino events for both winter selections. Such a clear identification of neutrino candidate events within the signal like region is more challenging within the down-going event selection SL. The cut on the BDT score is optimized for each event selection to minimize the model rejection factor, MRF, in the final likelihood analysis. The latter is based on the space angle Ψ between the reconstructed tracks and the position of the Sun. The distribution of Ψ observed in the final event samples is used to define a likelihood-ratio test statistics, which permits the calculation of the confidence interval for the mean number of signal events compatible with the observed data at the 90% C.L. The full study is detailed in Ref. [3]. Under the assumption of no signal, we derive the sensitivities for all three data samples. As the datasets are independent, we can combine them in a statistically suitable way in one likelihood analysis, weighting each by the respective livetime and effective volume. Figure 2 shows the resulting IceCube 79-string sensitivities to the spin-dependent WIMP-proton scattering cross-section, $\sigma_{SD,p}$, for the combined data set and the three individual subsets and compares the combined sensitivity with the current best IceCube limit from 2011 [3] and other experimental limits. The calculation of $\sigma_{SD,p}$ assumes a standard DM halo with a local density of 0.3 GeV/cm^3 and a Maxwellian WIMP velocity distribution with an RMS velocity of 270 km/s.

4. Summary and Conclusions

We have presented a new analysis to search for DM annihilations in the Sun with the IceCube telescope. This search is sensitive for DM candidates in the mass range of 20 GeV to 5 TeV. Furthermore, we have accessed the southern sky for the first time by incorporating strong vetos against the large atmospheric muon background. This has been accomplished through effective integration of the DeepCore sub-array into the analysis. We have given final sensitivities on the spin-dependent WIMP-proton cross-section significantly below the to date most stringent limits. Recently, the analysis was applied to the full IceCube 79-string experimental data set and no significant excess of events from the direction of the Sun were observed. All observed distributions are consistent with the background-only hypothesis. A publication including these new limits (90% CL) and detailed discussions on the effect of different sources of systematic uncertainties is in preparation.

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