

Search for Dark Matter in the Sun with the ANTARES Neutrino Telescope in the CMSSM and mUED frameworks

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Abstract

ANTARES is the first neutrino telescope in the sea. It consists of a three-dimensional array of 885 photomultipliers to collect the Cherenkov light induced by relativistic muons produced in CC interactions of high energy neutrinos. One of the main scientific goals of the experiment is the search for dark matter. We present here the analysis of data taken during 2007 and 2008 to look for a WIMP signal in the Sun. WIMPs are one of the most popular scenarios to explain the dark matter content of the Universe. They would accumulate in massive objects like the Sun or the Galactic Center and their self-annihilation would produce (directly or indirectly) high energy neutrinos detectable by neutrino telescopes. Contrary to other indirect searches (like with gamma rays or positrons), the search for neutrinos in the Sun is free from other astrophysical contributions, so the interpretation of a potential signal in terms of dark matter is much more robust.

Keywords:

dark matter, neutrino telescopes, WIMP, neutralino, CMSSM, Kaluza-Klein

1. Introduction

One of the most relevant questions in physics is the nature of dark matter. Since the first hints about this issue were pointed out by Zwicky in 1933 [1], a rich set of experimental proofs have been obtained to confirm the fact that most of the matter in the Universe is non-luminous. These proofs include the observations of WMAP [2], the results on the Big Bang Nucleosynthesis [3], the rotation curves of galaxies [4] and the studies of highly

red-shifted Ia supernovae [5]. The conclusion is that our Universe is made of 73% of dark energy and 27% of matter. Moreover, most of the matter (about 80%) is non-baryonic, whose nature is unknown. We know that this non-barionic component cannot be dominated by neutrinos, since they travel at relativistic velocities and therefore they cannot explain the structure of the Universe observed today. Consequently, the candidates for explaining most of dark matter are not in the Standard Model. There are several models to explain such particles. One of the most accepted candidates come from Weakly-Interacting Massive Particles (WIMPs), following the requirements of having an interaction cross-section of the order of that for weak interactions (to reproduce the right relic density) and being massive (to account of the gravitational effects). They also have to be stable. Among the frameworks which are able to provide such particles we will study here two of the most popular ones: SuperSymmetry (SUSY) and Universal Extra Dimensions (UED). In particular, we have considered two constrained versions: CMSSM [6] and mUED [7]. The candidate particles in each case are the neutralino and the lightest Kaluza-Klein particle. Their stability is explained by the conservation of the R-parity in the case of SUSY and KK-parity in the case of UED.

The potential detection of WIMPs in neutrino telescopes is based on the hypothesis that they would accumulate in massive objects like the Sun, the Galactic Center or the Earth due to the loss of energy through elastic scattering. If they are Majorana particles they would self-annihilate and produce secondaries which in turn would yield high energy neutrinos detectable by neutrino telescopes. For the case of Kaluza-Klein particles, direct production of neutrinos is also possible. In the analysis presented here we focus on the Sun. This is very advantageous since a potential detection of high energy neutrinos from the Sun direction would be a very clean signal of dark matter. In contrast to other indirect searches, there would not be other astrophysical explanations, as it happens for instance, when an excess of gammas or positrons is detected, for which other astrophysical scenarios have to be taken into account.

The analysis presented here is a binned search in the data taken by the ANTARES neutrino telescope during 2007 and 2008.

2. The ANTARES neutrino telescope

ANTARES [8] is the largest neutrino telescope in the Northern hemisphere. It is located at (42° 48' N, 6° 10' E) at a depth of 2475 m in the Mediterranean Sea, 42 km off-shore Toulon, France. It consists of 885 10-inch photomultipliers (PMTs) distributed over 12 vertical lines together forming a three-dimensional array. Each PMT is housed in a pressure-resistant glass sphere (Optical Module, OM), together with a gel for optical coupling and a mu-metal cage to attenuate the Earth's magnetic field. The OMs are arranged in triplets (storeys) for a better rejection of the optical background. There are 25 storeys per line except for one of the lines which has only 20 storeys, since the upper part of this line contains devices for acoustic detection tests. The PMTs are pointing 45° downward for a better detection of upgoing events. The length of the lines is 450 m and the horizontal distance between neighbouring lines is 60-75 m. There is also an additional line with devices aimed to monitor the environment (sea current velocity, pressure, temperature, salinity, etc.)

The detection principle is as follows. When a high energy neutrino interacts via a charged current (CC) interaction close or inside the detector (in the water or in the rock below), a relativistic muon is produced. This muon induces Cherenkov light when travelling through the water, which is detected by the photomultipliers. The information of the time [9] and position is used in order to reconstruct the direction of the muon and therefore the direction of the neutrino¹. The track of the muon is reconstructed with a robust fitting algorithm based on a χ^2 test which uses the position and time of the hits [10]. It gives an angular resolution of ~ 2 degrees at energies of tens of GeV. The χ^2 provided by the fit algorithm is used for the selection of well reconstructed tracks, as explained in Section 4.

3. Data and Monte Carlo simulation

In this analysis we have used data taken in 2007 and 2008. During 2007, there were only 5 lines connected. In May 2008 the detector was completed. There were three different configurations: 9, 10 and 12 lines (since May

¹ There are other possible signatures, not used in this analysis: CC interactions of electron and tau neutrinos as well as the NC interactions of all flavours, produce shower events, which, given the granularity of the detector, are seen as point sources of light.

2008). The number of active days was 185.5 and 189.8 for 2007 and 2008, respectively. The un-filtered data are dominated by the background from atmospheric muons, produced by the interaction of cosmic rays in the atmosphere. Most of this background is avoided by accepting only up-going events (since muons cannot traverse the Earth) but a fraction of them are mis-reconstructed as up going. The other source of background is due to atmospheric neutrinos, i.e. neutrinos produced in the interactions of cosmic rays in the atmosphere. In this case, the neutrinos can traverse the Earth, so it is an irreducible background which is discriminated using the fact that this is a diffuse flux, while the signal we are looking for is peaked in the Sun's direction. In Fig. 1 we show a comparison between data and simulation of these two types of backgrounds. It is important to note that the estimation of the background used in the analysis comes directly from scrambled data, in order to reduce the effect of systematic uncertainties associated with the efficiency of the detector and the assumed flux.

In order to simulate the signal, the WimpSim package is used [11]. This program allows for a computation of the neutrino flux arriving at the Earth for different annihilation channels. The main physical processes are taken into account (interactions in the Sun, regeneration of tau leptons, oscillations in the propagation, etc.) Once the neutrino flux is computed for the channels we are interested in, we can weight the events according to the branching ratios of the model under study. As already mentioned, the two frameworks we have considered here are CMSSM and mUED. The main channels for our detector are W^+W^- , $b\bar{b}$ and $\tau\bar{\tau}$ for CMSSM and $c\bar{c}$, $b\bar{b}$, $\tau\bar{\tau}$, $t\bar{t}$ and $\nu\bar{\nu}$ for mUED. In addition to the incoming flux, we have to estimate, through simulation, the response of the detector, i.e. the effective area, which relates this flux with the number of detected events for a given set of cuts.

4. Cut optimization

As mentioned above, we have followed a binned search strategy, i.e. we compare the number of events observed in a cone around the Sun direction with the expected background, looking for an excess which cannot be accounted by this background. Since the neutrino annihilation takes place in the core of the Sun (which has a size much smaller than the angular resolution of the detector), it can be considered as a point source. The optimization of the cuts is done following a blinding policy. In our case, we optimize the

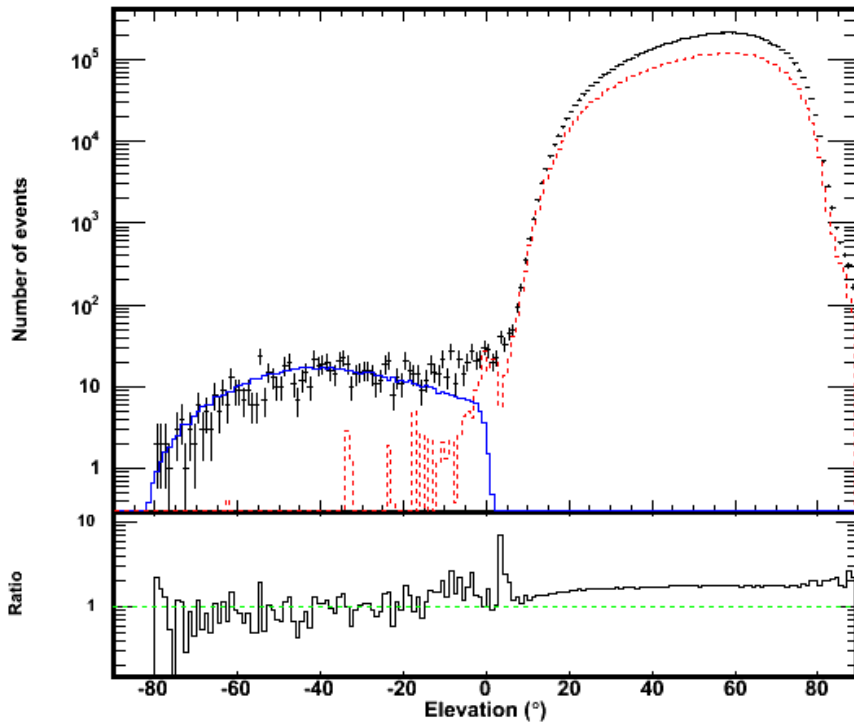


Figure 1: Comparison between data and simulation: elevation of events. The distributions show the simulated atmospheric muons (red), the simulated atmospheric upgoing-neutrinos (blue), and the reconstructed data (black). The ratio of data over simulation is shown below the corresponding plot.

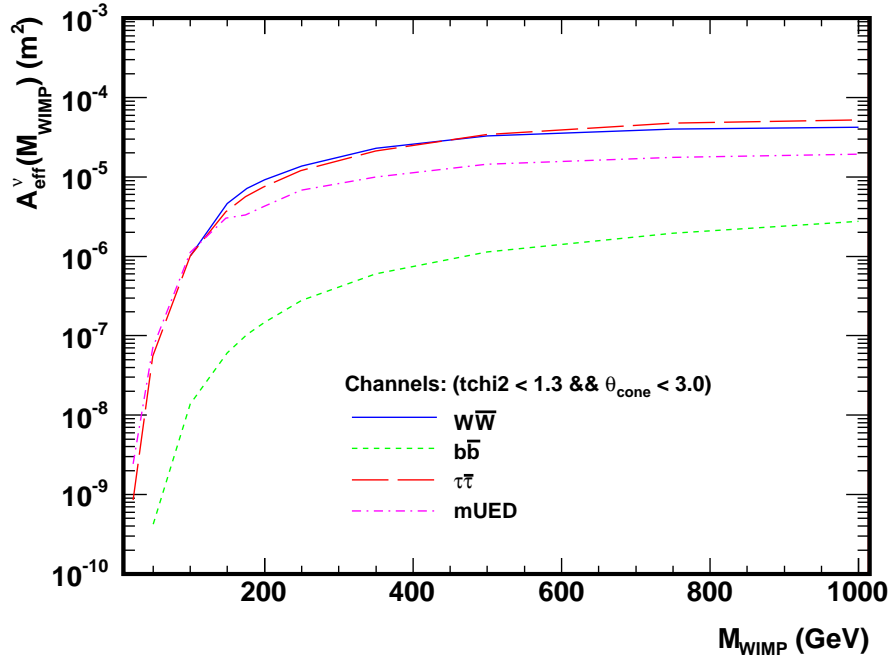


Figure 2: Normalized effective area for different WIMP masses.

selection cuts, the search cone size and the quality parameter χ^2 in order to minimize the average upper limit [12]:

$$\bar{\phi}_\nu^{90\%} = \frac{\bar{\mu}^{90\%}}{A_{\text{eff}}(M_{\text{WIMP}}) \times T_{\text{eff}}}, \quad (1)$$

where $\bar{\mu}^{90\%}$ is the average limit in the number of events, $A_{\text{eff}}(M_{\text{WIMP}})$ is the effective area and T_{eff} is the active time. The effective area for the cuts $\chi_t^2 < 1.4$ and $\Psi < 3^\circ$ is shown in Fig. 2. It includes the Sun visibility (i.e. how much time the Sun is below the horizon) and the bin efficiency (i.e. how much signal is kept in the search cone).

5. Results

The average upper limits expected for different models are shown in Fig. 3 as a function of the WIMP mass. For the case of CMSSM there is a wide

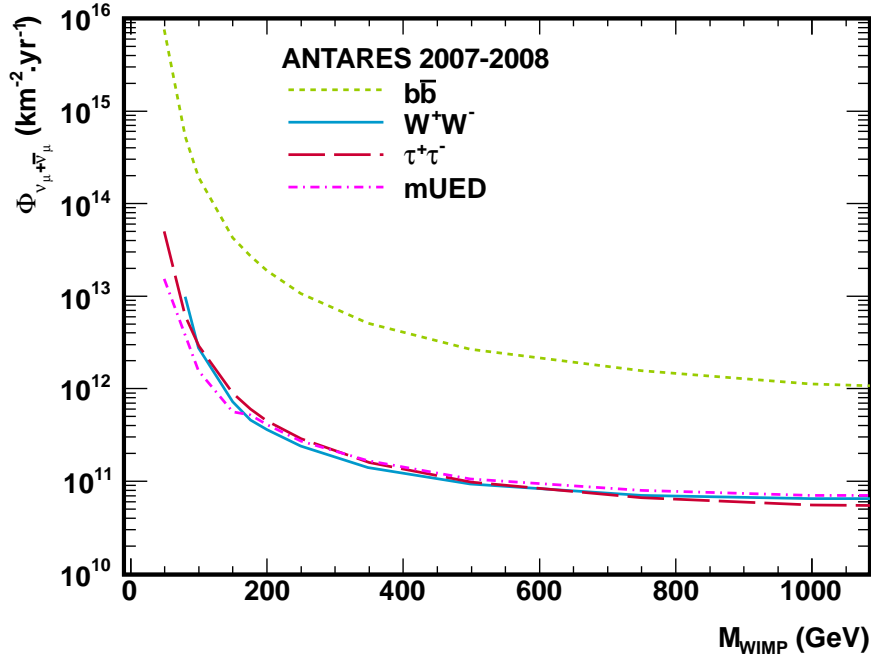


Figure 3: Sensitivity in the neutrino flux as a function of the WIMP mass. (Preliminary).

spread in the branching ratios for the different models inside the framework. Therefore, they are presented separately for the main channels (W^+W^- , $\tau\bar{\tau}$, $b\bar{b}$). The first two channels offer the best limits since the amount of neutrinos produced in these channels is higher. The spread for the mUED framework is smaller, so we present the sensitivity for one particular realization. In this case, the signal is dominated by the $\tau\bar{\tau}$ channel, which explains why we obtain similar limits to the corresponding channel in CMSSM.

These limits can be used to constrain the cross section of interaction between neutralinos or KK particles and protons, in particular for the spin dependent part. The differential neutrino flux is related to the annihilation cross section Γ by

$$\frac{d\phi_\nu}{dE_\nu} = \frac{\Gamma}{4\pi d^2} \frac{dN_\nu}{dE_\nu}, \quad (2)$$

where d is the distance Sun-Earth and dN_ν/dE_ν is the differential number

of neutrino events for each channel. If we assume that equilibrium between capture and annihilation has been reached in the Sun, we can write (for definition of C_{\otimes} see Eq. 4)

$$\Gamma \simeq \frac{C_{\otimes}}{2}. \quad (3)$$

On the other hand, the capture rate is related to the spin-dependent scattering cross-section between a WIMP and a proton as

$$C_{\otimes} \simeq 3.35 \times 10^{18} \text{s}^{-1} \times \left(\frac{\rho_{\text{local}}}{0.3 \text{ GeV} \cdot \text{cm}^{-3}} \right) \times \left(\frac{270 \text{ km} \cdot \text{s}^{-1}}{v_{\text{local}}} \right) \times \left(\frac{\sigma_{H,SD}}{10^{-6} \text{ pb}} \right) \times \left(\frac{\text{TeV}}{M_{\text{WIMP}}} \right)^2, \quad (4)$$

where $\rho_{\text{local}} = 0.3 \text{ GeV} \cdot \text{cm}^{-3}$ is the local density of WIMPs, $v_{\text{local}} = 270 \text{ km} \cdot \text{s}^{-1}$ is the local mean velocity of WIMPs assuming a Maxwell-Boltzmann velocity distribution,

M_{WIMP} is the mass of the dark matter particle and $\sigma_{H,SD}$ is the spin-dependent scattering cross-section between a WIMP and a proton.

We have also used the package SuperBayes [13] and a modified version of it [14] in order to scan the available parameter space of the CMSSM and mUED models, which are also plotted. It can be seen that neutrino telescopes like ANTARES offer the best limits for spin-dependent cross-section.

6. Conclusions

We have presented the sensitivity of the search for neutralinos in the Sun with the ANTARES telescope. We have used data of 2007 and 2008, when the detector configuration had 5 lines (2007) and 10, 9 or 12 (2008). We have studied two frameworks, CMSSM and mUED, and the average limits on the neutrino flux and the expected limits for the spin dependent cross section of the interaction of WIMPs with protons.

Acknowledgements

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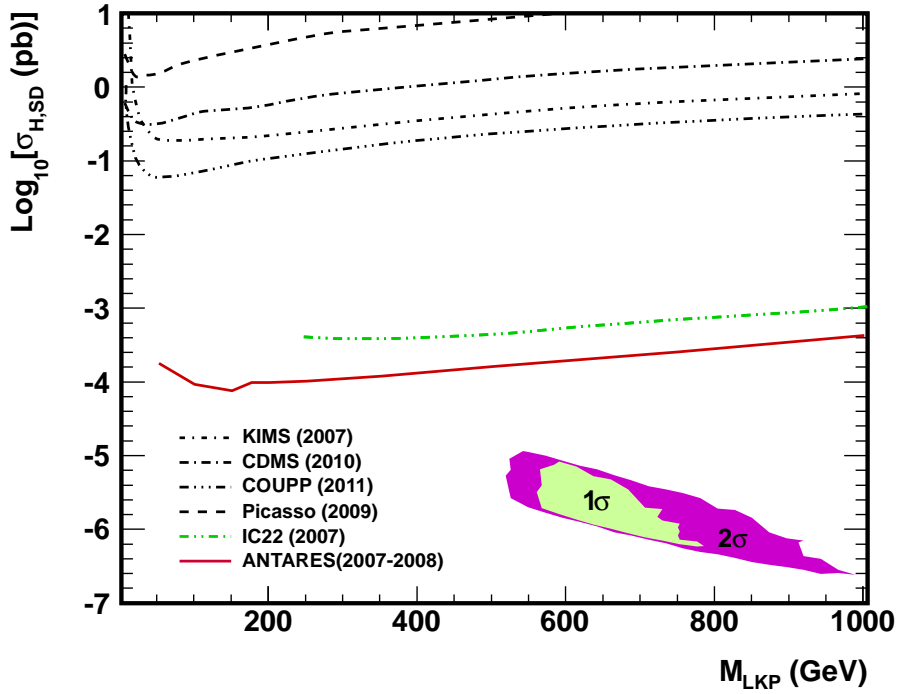
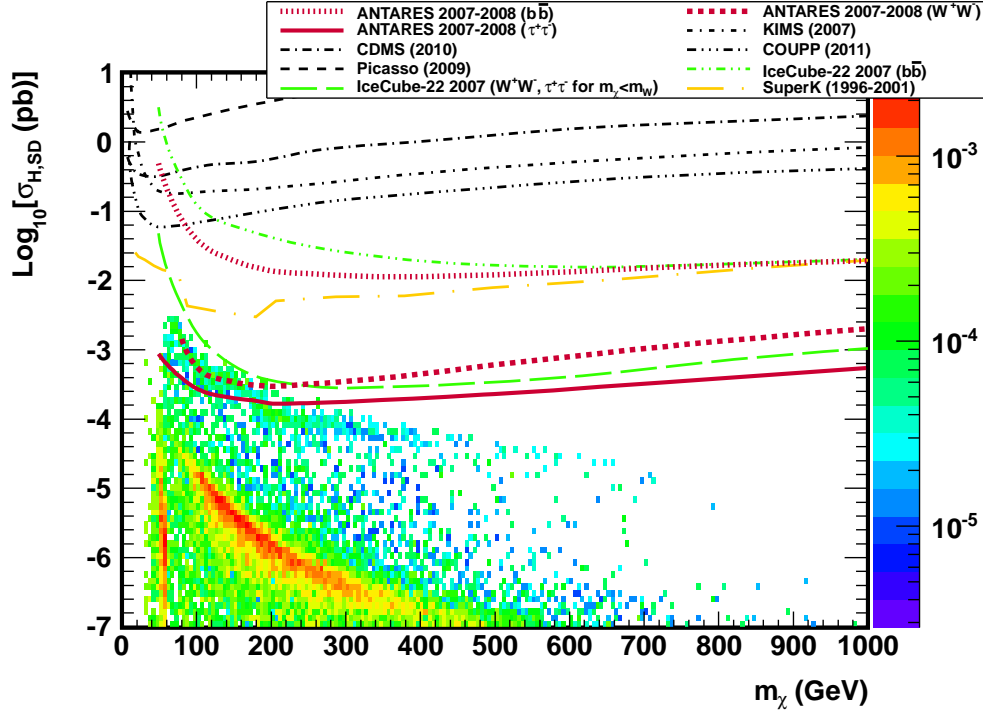


Figure 4: Experimental limits in the spin-dependent cross-section $\bar{\sigma}_{H,SD}$ compared to the theoretical parameter space allowed by the experimental constraints. The upper plot corresponds to the CMSSM model. The bottom plot corresponds to the mUED model, where the light and dark areas correspond to the one and two sigma exclusion regions, respectively. (Preliminary).