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Search for neutralino dark matter with the AMANDA neutrino detector

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Data taken with the AMANDA high energy neutrino telescope can be used in a search for an indirect dark matter signal. This paper presents current results from searches for neutralinos accumulated in the Earth and the Sun, using data from 1997-1999 and 2001 respectively. We also discuss future improvements for higher statistics data samples collected during recent years.

1. Introduction

Cosmological observations have long suggested the presence of non-baryonic dark matter on all distance scales. The WMAP results [1] confirmed our current understanding of the Universe, summarised in the concordance model. In this model the Universe contains about 23% non-baryonic cold dark matter, but nothing is predicted about the nature of this dark matter.

A massive, weakly interacting and stable particle appears in Minimally Supersymmetric extensions to the Standard Model that assume R-parity conservation. Indeed, the supersymmetric partners of the electroweak neutral Standard Model bosons mix into an interesting dark matter candidate, the neutralino, whose mass is expected in the GeV-TeV range [2].

On their trajectory through the Universe these particles will scatter weakly on normal matter and lose energy. Eventually, the dark matter particles will be trapped in the gravitational field of heavy celestial objects, like the Earth and the Sun [3]. The particles accumulated in the center of these bodies can annihilate pairwise. The neutrinos produced in the decays of the Standard Model annihilation products can then be detected with a high energy neutrino detector as an excess over the expected atmospheric neutrino flux.

In this paper we present the results of searches with the AMANDA detector for neutralino dark matter accumulated in the Earth (1997-1999 data set) and the Sun (2001 data set). We also summarize current techniques that continue these efforts on higher statistics data samples accumulated during recent years.

The Antarctic Muon And Neutrino Detector Array [4] at the South Pole uses the polar ice cap as a Cherenkov medium for the detection of relativistic charged leptons produced in high energy neutrino interactions with nuclei. The detector was constructed between 1996 and 2000. Now totaling 677 light sensitive devices distributed on 19 strings, the detector is triggered when at least 24 detector modules are hit within a sliding 2.5 μs window. Before 2000, the detector configuration consisted of between 10 and 13 strings and consequently a lower multiplicity trigger condition was able to cope with the high rate of events produced by cosmic ray interactions with the atmosphere.

Reconstruction of muons, with their long range, offers the angular resolution required to reject the atmospheric background and search for a neutralino-induced signal, which, due to the geographic location of AMANDA, yields vertical upward-going (Earth) or horizontal (Sun) tracks in the instrumented volume. Indeed, it is possible to eliminate the dominant background, downward-going atmospheric muons. However, upward-going atmospheric neutrinos will always contaminate the final, selected data sample.

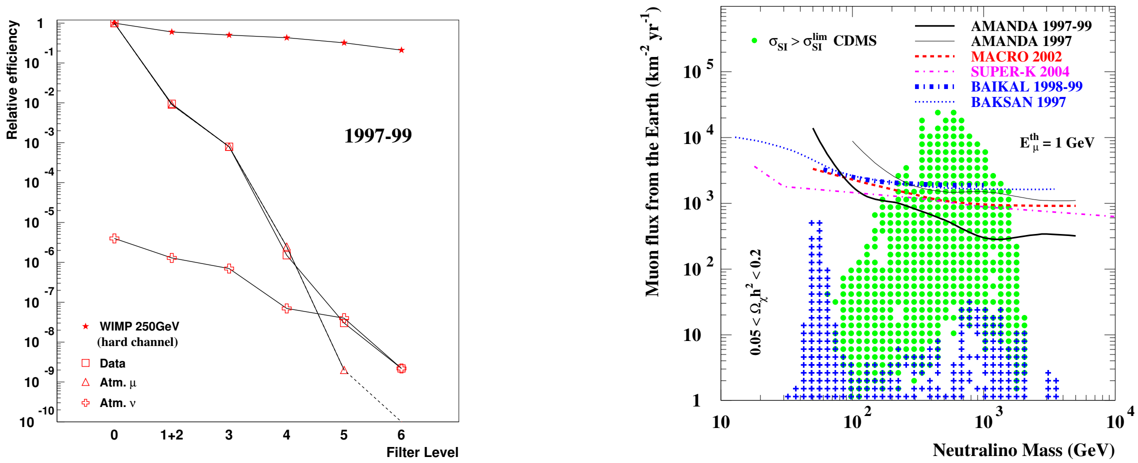

Figure 1. (a) Detection efficiencies relative to trigger level for the different filter levels in the terrestrial neutralino analysis (m_χ=250 GeV, hard spectrum) for 1997-1999 data, neutralino signal, atmospheric muons and neutrinos. (b) As a function of neutralino mass, the 90% confidence level upper limit on the muon flux coming from hard neutralino annihilations in the center of the Earth compared to our results from 1997 data [9] and other indirect experiments [10]. Markers show predictions for cosmologically relevant MSSM models, the dots represent parameter space excluded by CDMS [11].

2. Signal and background simulation

We have used the DARKSUSY program [5] to generate dark matter induced events for seven neutralino masses between 50 GeV and 5000 GeV, and two annihilation channels for each mass: the W^+W^- channel produces a hard neutrino energy spectrum ($\tau^+\tau^-$ for a 50 GeV neutralino), while $b\bar{b}$ yields a soft spectrum. The cosmic ray showers in the atmosphere, in which downward-going muons are created, are generated with CORSIKA [6] with a primary spectral index of γ=2.7 and energies between 600 GeV and 10^{11} GeV. The atmospheric neutrinos are produced with NUSIM [7] with energies between 10 GeV and 10^8 GeV and zenith angles above 80°.

3. Search for neutralino annihilations in the center of the Earth

A neutralino-induced signal from the center of the Earth was searched for in AMANDA data collected between 1997 and 1999, with a total effective livetime of 536.3 days. To reduce the risk of experimenter bias, the complete data set of 5.0×10^9 events was divided in a 20% subsample, used for optimisation of the selection procedure, and a remaining 80% sample, on which the selection was applied and final results calculated. Similarly, the sets of simulated events were divided in two samples: the first for use in the selection optimisation and the second for the selection efficiency calculations. The simulated atmospheric muon sample contains 4.2×10^9 triggered events (equivalent to an effective livetime of 649.6 days). The sample of atmospheric neutrinos totals 1.2×10^8 events, which corresponds to 2.2×10^4 triggers when scaled to the livetime of the analysis.

First, we try to suppress the dominant atmospheric muon background which is about 10^6 times more abundant than the atmospheric neutrino background. This is partially done by selecting the events that are reconstructed as upward-going and that satisfy a cut correlated with reconstruction quality ("filter level 3"). However, only a 10^{-3} reduction of the atmospheric muons is obtained this way (Fig. 1a) and more elaborate selection criteria are needed to reject downward-going muon tracks misreconstructed as upward-going. Depending on the detector configuration and the neutralino model under study, the characteristics of the signal differ, which influences selection efficiencies significantly at this point. Therefore, all further cuts are fine-tuned separately for each neutralino model and year of data taking. At filter level 4, a neural network is trained using between 8 and 10

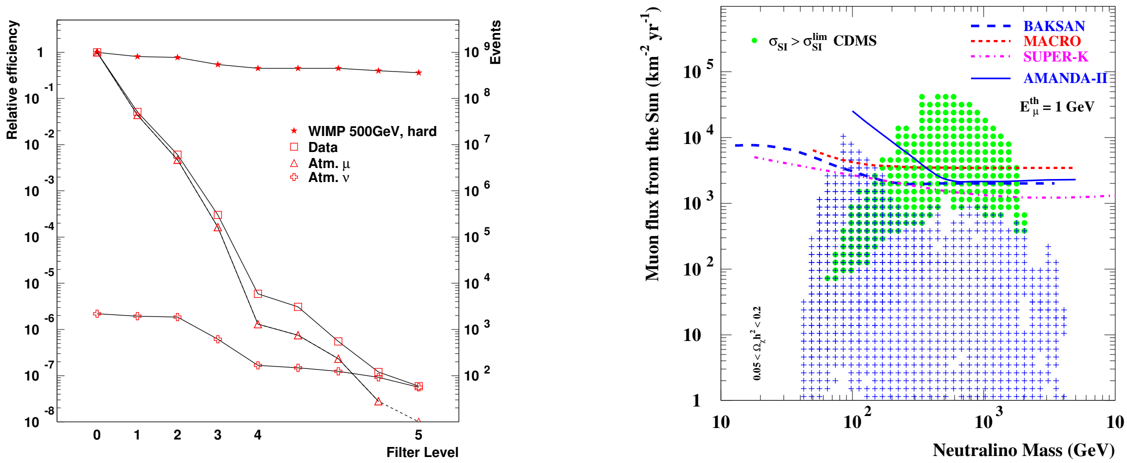

Figure 2. (a) Detection efficiencies relative to trigger level for the different filter levels in the solar neutralino analysis (m_χ=500 GeV, hard spectrum) for 2001 data, neutralino signal, atmospheric muons and neutrinos. (b) As a function of neutralino mass, the 90% confidence level upper limit on the muon flux coming from hard neutralino annihilations in the center of the Sun compared to other indirect experiments [10]. Markers show predictions for cosmologically relevant MSSM models, the dots represent parameter space excluded by CDMS [11].

input observables, reaching another 10^{-3} reduction. Filter level 5 cuts sequentially on observables, with the goal of removing downward-going muons that resemble signal events.

At filter level 5 the data sample is dominated by atmospheric neutrinos (see Fig. 1a). With no significant excess of vertical tracks observed, the final selection on reconstructed zenith angle (filter level 6) was optimised for the average lowest possible 90% confidence level upper limits on the muon flux. From the number of observed events and the amount of (simulated) background in the final angular search bin, we infer the 90% confidence level upper limit on the number of signal events. Combined with the effective volume at the final cut level and the livetime of the collected data, this yields an upper limit on the neutrino-to-muon conversion rate, which can then be related to the muon flux [8] (see Fig. 1b).

4. Search for neutralino annihilations in the Sun

The AMANDA data used in the search for solar neutralinos consists of 8.7×10^8 events, corresponding to 143.7 days of effective livetime, collected in 2001. In contrast to the search in Section 3, reducing the risk of experimenter bias in this analysis can be achieved by randomizing the azimuthal angles of the data. The advantage of this procedure is that it allows the use of the full data set for cut optimisation. The azimuthal angles are restored once the optimisation is finalised and results are calculated. The simulated atmospheric background sample at trigger level totals 1.6×10^8 muons (equivalent to 32.5 days of effective livetime) and 1.9×10^4 neutrinos.

The solar neutralino analysis suffers the same backgrounds as the terrestrial neutralinos, but the signal is expected from a direction near the horizon, due to the trajectory of the Sun at the South Pole. This analysis was only possible after completion of the AMANDA-II detector, whose 200 m diameter size provides enough lever arm for robust reconstruction of horizontal tracks.

We adopted a similar analysis strategy as in Section 3. First, we select events with well-reconstructed horizontal tracks (filter level 1-3). The remaining events are passed through a neural network that was trained separately for the neutralino models under study and used data as background (filter level 4). Although a data reduction of $\sim 10^{-5}$ compared to trigger level is achieved, the data sample is still dominated by misreconstructed downward-going muons. As shown in Fig. 2a, they are removed with extra cuts on observables related to reconstruction quality (filter level 5).

There was no sign of a significant excess of tracks from the direction of the Sun in the final data sample. The expected background in the final search bin around the Sun was estimated from off-source data in the same declination band, which eliminates the effects of uncertainties in background simulation. Combining this with the number of observed events, the effective volume and the detector livetime, we obtain 90% confidence level limits on the muon flux coming from annihilations in the Sun for each considered neutralino mass [12], as shown in Fig. 2b.

5. Discussion and outlook

Figures 1b and 2b present the AMANDA limits on the muon flux from neutralino annihilations into W^+W^- (hard channel) in the Earth and the Sun respectively, together with the results from other indirect searches. Limits have been rescaled to a common muon threshold of 1 GeV using the known energy spectrum of the neutralinos. Also shown are the cosmologically relevant MSSM models allowed (crosses) and disfavoured (dots) by the direct search from CDMS [11]. Compared to our search for a terrestrial neutralino signal in 1997 AMANDA data [9], the limit has been improved by a factor which is more than that expected from additional statistics alone. This is due mainly to the separate cut optimization for each neutralino mass, which exploits the characteristic muon energy spectrum of each model.

In 2001 an extra trigger was installed that lowered the energy threshold of the detector. This trigger takes into account spatio-temporal correlations in the event hit pattern. A preliminary analysis with data taken in 2001 and 2002 shows an improvement of a factor of about 5 in the effective volume in the search for 50 GeV neutralinos (soft annihilation channel) from the Earth with respect to the analysis presented in this note. We are currently performing searches for a dark matter signal both from the Earth and the Sun with data taken from 2000 and later. The increased detector exposure combined with improved reconstruction techniques and the new trigger setting will result in improved limits from these analyses (note that a 4-year exposure alone would already give an improvement of a factor of two).

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