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Search for neutralino dark matter with the AMANDA neutrino telescope

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Abstract: If non-baryonic dark matter exists in the form of neutralinos, a neutrino flux is expected from the decay of neutralino pair annihilation products inside heavy celestial bodies. Data taken with the AMANDA neutrino telescope located at the South Pole can be used in a search for this indirect dark matter signal. We present the results from searches for neutralinos accumulated in the Sun using AMANDA data from 2001, and improved new limits on the flux of muons from 50–250 GeV/c^2 neutralino annihilations in the Earth obtained with data from 2001–2003.

Introduction

Cosmological observations have suggested the presence of non-baryonic dark matter on all distance scales. The WMAP results [1] confirmed our current understanding of the Universe, summarized 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 neutral electroweak and Higgs bosons mix into a 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, 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 will 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 atmospheric neutrino flux. In this paper we present the results of searches with the Antarctic Muon And Neutrino Detector Array (AMANDA) for neutralino dark matter accumulated in the Earth (2001–2003 data set) and the Sun (2001 data set). We also discuss current improvements and preliminary results from ongoing analyses on higher statistics data samples accumulated during recent years.

The AMANDA detector [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 $500\,\mathrm{m}$ high and $200\,\mathrm{m}$ wide detector was completed in 2000 and totals 677 light sensitive devices distributed on 19 strings. The detector is triggered when at least 24 detector modules are hit within a sliding $2.5\,\mu\mathrm{s}$ window. Since 2001 an additional, lower multiplicity, trigger (referred to as *string trigger*) is operational that exploits not only temporal information but also the space topology of the hit pattern. This lowers the energy threshold of the detector and is especially beneficial for the sensitivity to neutralinos with $m_\chi < 200\,\mathrm{GeV}/c^2$.

Reconstruction of muons, with their long range, offers the angular resolution required to reject the background produced by cosmic ray interactions with the atmosphere and search for a neutralino-induced signal, which, due to the geographic location of AMANDA, yields vertical upward-going (Earth) or near horizontal (Sun) tracks in the instrumented volume. Indeed, it is possible to eliminate the dominant background, downward-going atmo-

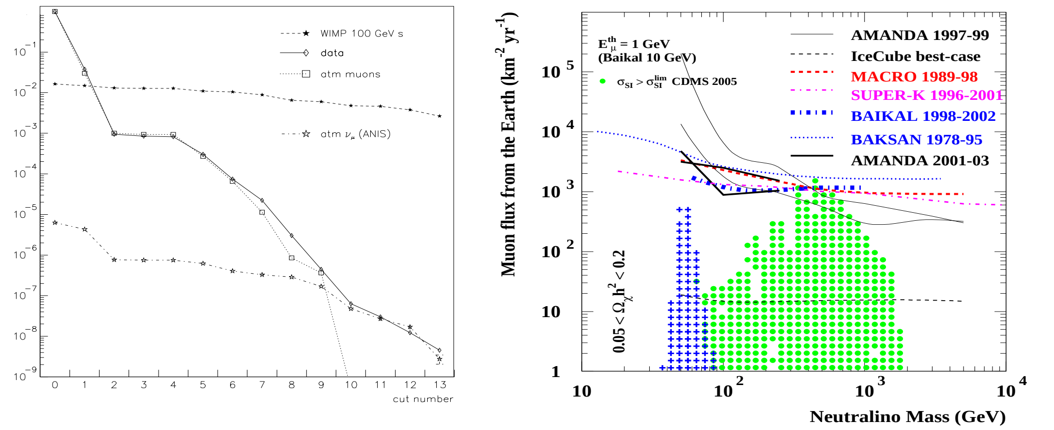

Figure 1: (a) Detection efficiencies relative to trigger level for the different filter levels in an Earth neutralino analysis ($m_\chi = 100\,\mathrm{GeV}/c^2$, soft spectrum) for 2001–2003 data. (b) As a function of neutralino mass, the 90% CL upper limit on the muon flux from hard (bottom) and soft (top) neutralino annihilations in the center of the Earth compared to the limits of other indirect experiments [9] and the sensitivity estimated for a best-case IceCube scenario [10]. Markers show predictions for cosmologically relevant MSSM models, the dots represent parameter space excluded by CDMS [11].

spheric muons. However, upward-going and horizontal atmospheric neutrinos will always contaminate the final, selected data sample.

Signal and background simulation

We have used the DARKSUSY program [5] to generate dark matter induced events for seven neutralino masses m_χ between $50\,\mathrm{GeV}/c^2$ and $5000\,\mathrm{GeV}/c^2$, and two annihilation channels for each mass: the W^+W^- channel produces a hard neutrino energy spectrum ($\tau^+\tau^-$ for $m_\chi < m_W$), 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 ANIS [7] with energies between 10 GeV and 325 TeV and zenith angles above 80°.

Search for low mass neutralinos in the center of the Earth

A neutralino-induced signal from the center of the Earth is searched for in AMANDA data collected between 2001 and 2003, with a total effective livetime of 688.0 days. This search focuses on improving the sensitivity for low mass neutralinos, with $m_\chi \leq 250\,\mathrm{GeV}/c^2$, and includes events triggered with the string trigger. The complete data set of 5.3×10^9 events is divided in a 20% subsample, used for optimisation of the selection procedure, and a remaining 80% sample, on which the selection is applied and final results calculated. Detector data are used as background for the optimisation, and compared to simulated background events to verify the understanding of the background and the simulation. The simulated atmospheric muon sample contains 3.6×10^7 triggered events (equivalent to an effective livetime of 4.5 days). The sample of atmospheric neutrinos totals 2.4×10^5 events, which corresponds to 2.5×10^4 triggers when scaled to the livetime of the data sample used for calculation of the final results.

The characteristics of the signal differs depending on the neutralino model under study. Hence, the selection criteria are tuned separately for each neutralino model. Between 2001 and 2002 the detector was upgraded and the trigger settings changed slightly. The event selection is therefore developed separately for 2001.

First, we reduce the total background by selecting events with upward-going signature. Then the data are tested against reconstruction criteria to remove events unlikely to be correctly reconstructed. After this, the search is limited to the events with reconstructed angle differing less than 40° from straight upward-going. At this level (cut number 4 in Fig. 1a), the sample is still dominated by misreconstructed atmospheric muon events, more

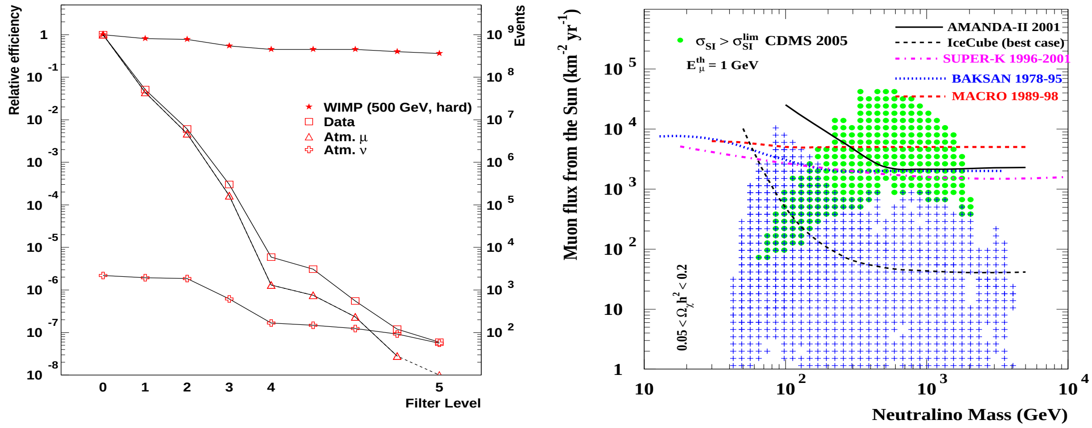

Figure 2: (a) Detection efficiencies relative to trigger level for the different filter levels in a Sun neutralino analysis ($m_\chi = 500\,\mathrm{GeV}/c^2$, hard spectrum) for 2001 data. (b) As a function of neutralino mass, the 90% CL upper limit on the muon flux from hard neutralino annihilations in the center of the Sun compared to limits of other indirect experiments [9] and the sensitivity estimated for a best-case IceCube scenario [10]. Markers show predictions for cosmologically relevant MSSM models, the dots represent parameter space excluded by CDMS [11].

than 10^3 times more abundant than the atmospheric neutrino background. The background is then further reduced by a series of sequential cuts on reconstruction quality parameters and energy parameters.

After about ten cuts (depending on mass and annihilation channel), the data sample is dominated by atmospheric neutrinos. All of the data from the three years are combined at this analysis level, and the final selection is applied on the three years together. With no significant excess of vertical tracks observed, the final selection on reconstructed zenith angle is optimised for the average lowest possible 90% confidence level upper limit on the muon flux. From the number of observed events and the amount of estimated background in the final angular search bin, we infer the 90% confidence level upper limit on the number of signal events for each of the considered neutralino models. 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.

Search for neutralino annihilations in the Sun

The data collected in 2001 is also used for the search for solar neutralinos and corresponds to 143.7 days of effective livetime. The total event sample contains 8.7×10^8 events, but does *not* include events triggered only by the string trigger. In contrast to the neutralino search in the Earth, the background level can be reliably obtained from randomization of the azimuthal angle. 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 as seen from the South Pole. This analysis was only possible after completion of the full detector, whose $200\,\mathrm{m}$ diameter size provides enough lever arm for robust reconstruction of horizontal tracks.

A similar analysis strategy as in previous section is adopted. First, events are selected with well-reconstructed horizontal or upward-going tracks. The remaining events are then 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, see Fig. 2a. Finally, these are removed by cuts on observables related to reconstruction quality.

There is no sign of a significant excess of tracks from the direction of the Sun in the final data sample. The background in the final search bin around the Sun is 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 upper limits on the muon flux coming from annihilations in the Sun for each considered neutralino mass [12], as shown in Fig. 2b.

Discussion and outlook

Figures 1b and 2b present the AMANDA upper limits on the muon flux from neutralino annihilations in the Earth and the Sun (only hard channel) respectively, together with the results from other indirect searches [9]. Limits have been rescaled to a common muon threshold of $1\,\mathrm{GeV}$ 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 the previously published AMANDA results from searches for neutralinos in the Earth [8] the analysis of 2001–2003 data benefits from the larger detector volume and the addition of the string trigger with its lower energy threshold. This makes it possible to improve the sensitivity especially for low energy Earth neutralino models; for masses above $250\,\mathrm{GeV}/c^2$ the effect is expected to be less pronounced. The new limits on the neutralino-induced muon flux are up to a factor 60 stronger than our earlier result.

A similar improvement (with respect to [12]) is expected for the solar neutralino analysis of 2001–2003 data, thanks to the increased detector exposure, improved reconstruction techniques and the string trigger. A preliminary analysis shows a factor 10–100 improvement of the effective volume at early analysis level for low energy models, mainly due to the inclusion of the string triggered events.

The neutralino searches will be continued on a larger set of AMANDA data from 2000–2006. Since 2007 AMANDA is embedded as a high-granularity subdetector of the IceCube neutrino telescope, currently under construction. This offers additional opportunities for the dark matter searches, as described in [10].

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