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Search for Relativistic Magnetic Monopoles with the AMANDA-II Detector

H. WISSING[1] FOR THE ICECUBE COLLABORATION[⋆]
[1] *III Physikalisches Institut, RWTH Aachen University, D-52056 Aachen, Germany*
[⋆] *see special section of these proceedings*
hwissing@physik.rwth-aachen.de

Abstract: Cherenkov emissions of magnetic charges moving through matter will exceed those of electric charges by several orders of magnitude. The AMANDA neutrino telescope is therefore capable of efficiently detecting relativistic magnetic monopoles that pass through its sensitive volume. We present the to date most stringent limit on the flux of relativistic magnetic monopoles based on the analysis of one year of data taken with AMANDA-II.

Introduction

The existence of magnetic monopoles is mandatory in a large class of Grand Unified Theories. Predicted monopole masses range from 10^8 to 10^{17} GeV, depending on the symmetry group and unification scale of the underlying theory [1]. The monopole magnetic charge will be an integer multiple of the *Dirac Charge* $g_D = e/(2\alpha)$, where e is the electric elementary charge and $\alpha = 1/137$ is the fine structure constant. Since magnetic monopoles are topologically stable, they should still be present in today's universe and can be searched for in cosmic radiation. Once created, monopoles can efficiently be accelerated by large scale magnetic fields. Monopoles with masses below $\sim 10^{14}$ GeV are expected be relativistic [2] and neutrino telescopes could detect their direct Cherenkov emissions. The number of Cherenkov photons N_γ emitted per path length dx and photon wavelength $d\lambda$ radiated from a monopole with magnetic charge g passing through matter with index of refraction n is [3]

$$\frac{dN_\gamma}{dx d\lambda} = \frac{2\pi\alpha}{\lambda^2}\left(\frac{gn}{e}\right)^2\left(1 - \frac{1}{\beta^2 n^2}\right), \quad (1)$$

where β is the speed of the monopole as a fraction of the speed of light in vacuum. The Cherenkov light intensity in ice radiated from a relativistic magnetic monopole carrying one Dirac charge is enhanced by factor $(g_D \cdot n/e)^2 = 8300$ compared to the intensity radiated from a particle with electric charge e and the same speed.

Search Strategy

The AMANDA-II neutrino telescope consists of 677 light sensitive optical modules (OMs) embedded in the ice under the geographic South Pole at depths between 1500 and 2000 meters. Each OM contains a photomultiplier tube (PMT) and supporting electronics enclosed in a transparent pressure sphere. The OMs are deployed on 19 vertical strings arranged in three concentric circles (see Figure 1). The inner ten strings are read out electrically via coaxial or twisted-pair cables, while the outermost strings use optical fiber transmission. For each triggered event, leading and trailing edges of up to eight PMT pulses and one peak amplitude can be recorded per OM. AMANDA-II has been

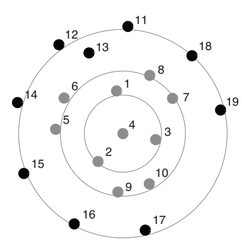

Figure 1: Arrangement of the 19 strings of the AMANDA-II detector in the horizontal plane.

taking data since the beginning of the year 2000.

This analysis concerns data taken between February and November 2000.

We have simulated the detector response to relativistic magnetic monopoles carrying one Dirac Charge with four different speeds: $\beta = v/c = 0.76, 0.8, 0.9,$ and 1.0. Down-going atmospheric muons, which form the principal background to this search, were simulated with the air-shower simulation package CORSIKA [4]. Following a "blind" analysis procedure, the data selection chain is optimized on simulated data, and only a subset of 20% of the experimental data is used to verify the simulation of the detector response. This 20% is later discarded, and the developed selection criteria applied to the remaining 80% of the data. The blinded data comprise about 154 days of livetime, after correction for dead-time and rejection of periods of low data quality.

A relativistic magnetic monopole passing through the detector's sensitive volume will stand out as an extremely bright event relative to the atmospheric muon background. Observables that provide a measure of the light yield in the detector are the number of OMs hit during an event, the total number of pulses (or *hits*) recorded, the fraction of OMs which registered only a single hit (as opposed to those which recorded multiple hits), and the sum of the recorded PMT pulse amplitudes. These observables are used to reject the bulk of low energy atmospheric muons, either as one-dimensional cut parameters or as input to a discriminant analysis [5].

Up-going Monopoles

Magnetic monopoles with masses in excess of 10^{11} GeV can cross the entire earth and enter the detector from below [6]. The search for up-going relativistic magnetic monopoles is in principle background free, since up-going charged leptons induced by atmospheric neutrinos from the northern hemisphere will produce significantly less Cherenkov light than would magnetic monopoles. However, track reconstruction algorithms sometimes fail to identify large atmospheric muon bundles as down-going, and those misreconstructed events will remain as residual background. Figure 2 shows the zenith angle distribution of reconstructed particle tracks obtained from an iterative

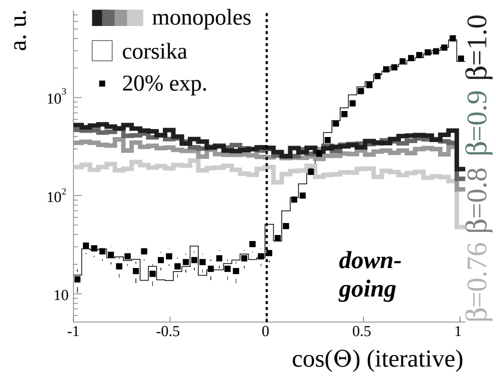

Figure 2: Cosine of the reconstructed zenith angle for simulated atmospheric muon background (light black histogram), 20% experimental data (black markers), and simulated monopole signal (heavy grey histograms). Each of the four grey histograms corresponds to one of the simulated monopole speeds from $\beta = 0.76$ (lightest grey) to $\beta = 1.0$ (darkest grey). A zenith angle of $\Theta = 0°$ corresponds to vertically down-going.

likelihood reconstruction [7] for simulated signal and background as well as for 20% of the experimental data. For the up-going monopole search we reject all events for which the reconstructed zenith angle is smaller than 90 degrees. The background of misreconstructed atmospheric muon bundles is rejected by a final cut on the sum of PMT pulse amplitudes (ΣADC). At this level of the analysis, an excellent simulation of the OM response to large amounts of light is required. This involves an accurate modeling of the sensitivity of individual OMs as well as the probability with which OMs *"overflow"*, *i.e.*, record more than eight hits during one event (in which case a fraction of the hits is discarded by the data acquisition system). These requirements dictate that we use the amplitude sum of only a subset of OMs as final cut parameter, including only those OMs for which the detector simulation provides an exact description. This is the case for the OMs which are read out via fiber optics and which are located at depths below 1630 m. The fiber OMs have a substantially better time and double pulse resolution than the electronically read-out OMs. Thereby the simulation of their response to multiple photons is more reli-

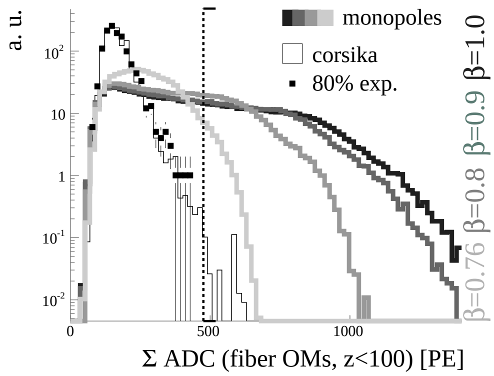

Figure 3: Sum of the PMT pulse amplitudes measured in the outer strings below a depth of 1630 m. The final cut (dashed line) requires the amplitude sum to be bigger than 476 photo electrons.

able. Using only this subset of OMs does not affect sensitivity, since the fiber OMs are attached to the outer nine strings of the array and define the surface area of the detector. Rather, the obtained flux limit improves as a result of the reduced systematic error.

Figure 3 shows the distribution of the final cut parameter. The exact value of the final cut is determined by optimizing the *sensitivity* of the analysis, *i.e.*, the cut is placed where we expect to obtain the most stringent flux limit [8]. The background simulation predicts 0.23 events from misreconstructed atmospheric muons to remain in the 80% data set. After unblinding the data, no events are observed.

The 90% C. L. flux limits in units of 10^{-16}cm^{-2}s^{-1}sr^{-1} obtained for monopoles with various speeds β are listed in Table 1.

The limits are valid for monopoles with masses greater than 10^{11} GeV. A systematic uncertainty of 20% in both background rate and signal efficiency is incorporated into the calculation of the confidence belts according to [9].

β	0.76	0.8	0.9	1.0
$\Phi_{90\%C.L.}$	8.6	0.66	0.42	0.37

Table 1: 90% C. L. upper limits in units of 10^{-16}cm^{-2}s^{-1}sr^{-1} on the flux of relativistic magnetic monopoles with masses $> 10^{11}$ GeV.

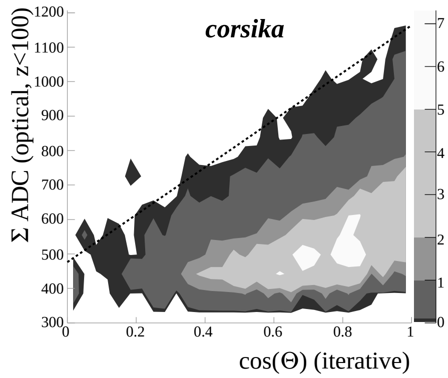

Figure 4: Expected background from atmospheric muons in the $\cos(\Theta) - \Sigma ADC$ plane before placing the final cut (dashed line).

Down-going Monopoles

The search for down-going magnetic monopoles is subject to a much higher background rate. In order to preserve sensitivity over 4π sr, we use linear combinations of the reconstructed zenith angle and observables that are sensitive to the light deposition in the detector as cut parameters. The coefficients of each observable are found by a discriminant analysis. This optimization naturally results in cuts that require a greater light deposition for vertical tracks (smaller zenith angles), while the requirement is relaxed towards the horizon.

The final cut parameter for the down-going monopole search is a linear combination of the cosine of the reconstructed zenith angle ($\cos\Theta$) and the sum of pulse amplitudes recorded by the OMs on the outer strings at depths below 1630 m (ΣADC). Figure 4 shows the expected distribution of background events in the $\cos(\Theta) - \Sigma ADC$ plane. The final cut parameter is shown in Figure 5. Like in the up-going monopole search, the final cut is optimized such that we expect to obtain the most stringent limit. The background simulation predicts 2.6 events to remain in the experimental data set, and three events are observed after unblinding the data. The limits on relativistic monopoles with various speeds obtained from this observation are listed below (Table 2). The limits are valid for monopoles with masses greater than 10^8 GeV. Systematic uncertainties are accounted for according to [9].

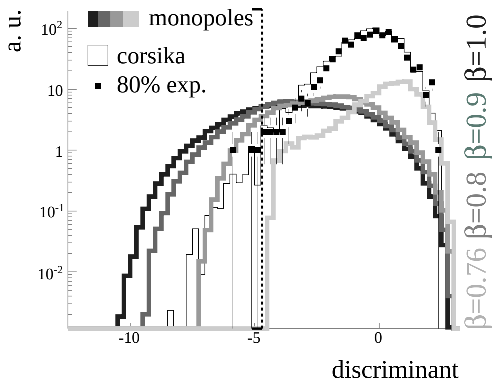

Figure 5: Final cut parameter (obtained from a discriminant analysis using $\cos(\Theta)$ and ΣADC as input observables) for the unblinded 80% experimental data (black markers), expected atmospheric muon background (black histogram), and simulated monopole signal (grey heavy histograms). The dashed black line marks the final cut.

β	0.8	0.9	1.0
$\Phi_{90\% C.L.}$	16.33	4.1	2.8

Table 2: 90% C. L. upper limits in units of 10^{-16}cm^{-2}s^{-1}sr^{-1} on the flux of relativistic magnetic monopoles with masses greater than 10^8 GeV.

Conclusions

The analysis of data taken with the AMANDA-II neutrino telescope during the year 2000 permits constraint of the flux of relativistic magnetic monopoles with speeds $\beta = v/c > 0.76$. For monopole speeds greater than $\beta = 0.8$ and monopole masses greater than $\sim 10^{11}$ GeV, the flux limit is presently the most stringent experimental limit. The search for lighter monopoles is possible, but less sensitive. With the analysis of one year of AMANDA data, the flux of magnetic monopoles with masses as low as 10^8 GeV and speeds close to $\beta = 0.8$ can be constrained to a level below the Parker Bound [10]. Figure 5 shows the flux limits set by AMANDA compared to those set by some other experiments.

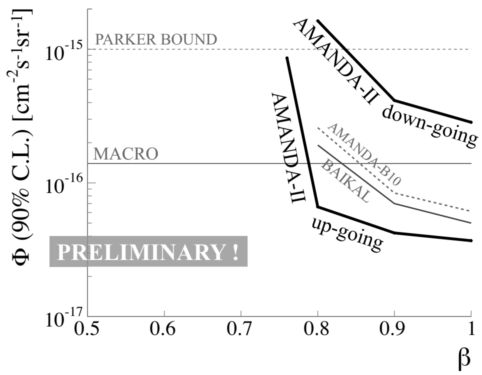

Figure 6: Limits on the flux of relativistic magnetic monopoles set AMANDA-II (this work), by MACRO [11], and by BAIKAL [12].

Acknowledgments

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