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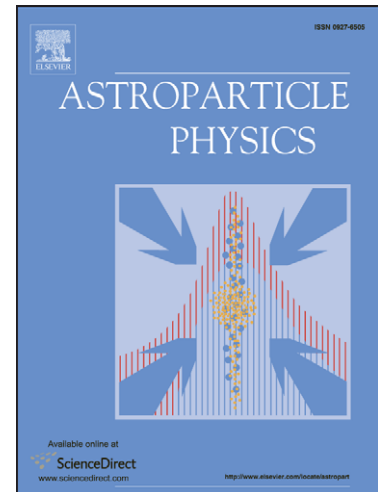
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Abstract

¹ We report on the search for electromagnetic and hadronic showers (“cas-
² cades”) produced by a diffuse flux of extraterrestrial neutrinos in the AMANDA

3 neutrino telescope. Data for this analysis were recorded during 1001 days of
 4 detector livetime in the years 2000 to 2004. The observed event rates are
 5 consistent with the background expectation from atmospheric neutrinos and
 6 muons. An upper limit is derived for the diffuse flux of neutrinos of all fla-
 7 vors assuming a flavor ratio of $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$ at the detection site.
 8 The all-flavor flux of neutrinos with an energy spectrum $\Phi \propto E^{-2}$ is less
 9 than $5.0 \cdot 10^{-7} \text{GeV s}^{-1} \text{sr}^{-1} \text{cm}^{-2}$ at a 90% C.L.. Here, 90% of the simulated
 10 signal would fall within the energy range 40 TeV to 9 PeV. We discuss flux
 11 limits in the context of several specific models of extraterrestrial and prompt
 12 atmospheric neutrino production.

Keywords: neutrinos, cascades

13 1. Introduction

14 The production of high-energy cosmic rays is most likely accompanied
 15 by astrophysical neutrinos [1]. High-energy neutrinos may be produced in
 16 astrophysical sources that accelerate protons and light nuclei and provide a
 17 dense environment of matter and radiation for interactions within or near the
 18 source. Source candidates include supernova remnants and micro-quasars in
 19 our Galaxy, as well as extragalactic sources such as Active Galactic Nuclei
 20 and Gamma-Ray Bursts (for a review, see [2, 3, 4]). For a generic astro-
 21 physical neutrino source, the neutrino flux is expected to be produced with
 22 a flavor ratio $\nu_e : \nu_\mu : \nu_\tau \sim 1 : 2 : 0$. After propagation to Earth, neutrino
 23 flavor mixing generally causes the ratio to be $1 : 1 : 1$ at the detection site [5].
 24 Deviations to this equal partition are expected only for neutrino production
 25 in dense astrophysical environments or strong magnetic fields [6]. Because
 26 of the presence of all neutrino flavors in a cosmic neutrino beam, an ideal
 27 neutrino detector has sensitivity to all neutrino flavors.

28 The primary goal of the AMANDA detector was the search for extrater-
 29 restrial high-energy neutrinos. AMANDA was installed in the Antarctic ice
 30 cap at the geographical South Pole. The detector consisted of 677 optical
 31 modules (OMs) which were arranged in 19 vertical strings. The OMs were
 32 frozen into the ice at depths from 1500 m to 2000 m with a vertical separation
 33 of 20 m for strings 1 to 4 and 10-12 m for the other strings. The resulting
 34 instrumented volume formed a cylindrical geometry of about 200 m diame-
 35 ter and 500 m height. Each OM contained a photomultiplier tube (PMT)
 36 which recorded the Cherenkov light emitted by relativistic charged particles.

37 These particles were mainly high-energy muons produced in cosmic air show-
38 ers as well as muons and other charged particles produced by neutrino-ice
39 interactions in or near the detector volume. Analog signals from the OMs
40 were transmitted to a surface data acquisition system (DAQ) where leading-
41 edge times and amplitudes of the PMT pulses were digitized. The main
42 AMANDA trigger, used here, retained only events with pulses from at least
43 24 OMs recorded within $2.5 \mu\text{s}$.

44 In this paper, we present a search for a diffuse neutrino flux from un-
45 resolved astrophysical sources. Charged-current ν_e and ν_τ interactions, and
46 neutral-current interactions of all three neutrino flavors, will produce electro-
47 magnetic and/or hadronic showers (so-called “cascades”) in the ice. In con-
48 trast, charged-current ν_μ interactions produce a muon track. In AMANDA,
49 electromagnetic and hadronic cascades are indistinguishable, although the
50 average light level produced for a given shower energy is slightly different
51 for each [7]. For cascades, the direction of the incoming neutrino is diffi-
52 cult to reconstruct to better than a few tens of degrees, but the calorimetric
53 properties of the detector allow the energy of these events to be measured to
54 better than 0.2 in the $\log_{10} E$ [8]. In the search for a diffuse high-energy neu-
55 trino flux, exclusion of track-like events eliminates most cosmic ray induced
56 muon events, leaving mostly cascade-like events. An additional advantage
57 in searching for cosmic ν_e and ν_τ compared to ν_μ is the fact that the flux of
58 background atmospheric electron-neutrinos is more than an order of magni-
59 tude lower than the corresponding ν_μ flux and that the fluxes have different
60 energy dependencies. The astrophysical high-energy neutrino sources are ex-
61 pected to have a spectrum of $\sim E^{-2}$ while the atmospheric flux decreases
62 with $\sim E^{-3.7}$.

63 Previous efforts to search for neutrino-induced cascades [9] used data
64 collected in 1997 with the 10-string AMANDA-B10 detector. A further
65 search [8] used data taken in 2000 with the completed 19-string AMANDA
66 detector. Other limits on the diffuse flux of astrophysical muon-neutrinos
67 were derived by searching for track-like events [10] or by searching for events
68 depositing a very large amount of energy [11]. These analyses used data from
69 2000-2003 and 2000-2002, respectively and are briefly discussed in section 4.5
70 below. With five years of data, this paper presents the final AMANDA re-
71 sults on the search for cascades from interactions of astrophysical neutrinos.
72 In 2006, AMANDA was integrated into the IceCube neutrino telescope [12].
73 Data was taken by the combined detector for three years, until AMANDA
74 was decommissioned in 2009.

Year	livetime (days)	Triggered Events	Trigger Rate (Hz)
2000	197	1.37×10^9	80.5
2001	193	2.00×10^9	120.0
2002	204	1.91×10^9	108.4
2003	213	1.86×10^9	101.1
2004	194	1.72×10^9	102.6
Total	1001	8.86×10^9	

Table 1: Effective detector livetime, number of triggered events and trigger rate for the 5 years of data used in the analysis. The year to year trigger rate variations are caused by changed settings of the photomultiplier voltages and discriminator thresholds as well as by modifications of other triggers than the high multiplicity trigger used for the cascade analysis.

75 2. Experimental Data and MC Simulation

76 The experimental data used here were recorded during the austral win-
77 ters (February through November) in the years 2000 through 2004, i.e. they
78 include the previously published year 2000 data of the cascade analysis [8].
79 Only data from periods with a stable operating detector were used for this
80 analysis. This was a total livetime of 1001 days, after correction for DAQ
81 deadtime between events. A total of $8.9 \cdot 10^9$ events were recorded at an
82 average trigger rate of 103 Hz (Table 1). Although the yearly trigger rates
83 in Table 1 differ by up to 20%, the characteristics of the data, taken with
84 the high multiplicity trigger, do not change appreciably. The different re-
85 construction steps will be described in the following section, but one of the
86 essential cascade parameters is used here to illustrate the consistency be-
87 tween the annual data samples. Figure 1 shows the reconstructed energy of
88 cascade candidates for the different years. There are only $\sim 5\%$ differences,
89 which confirms that the data can be used for a combined 5-year analysis.

90 The data are dominated by the background of high-energy muons pro-
91 duced by cosmic ray interactions in the atmosphere. By removing track-like
92 events, most of this atmospheric muon background can be eliminated. Muons
93 may also lose energy by bremsstrahlung, direct pair production and pho-
94 tonuclear interactions. Therefore, a fraction of high-energy muons remain,
95 mainly those that radiate energetic bremsstrahlung photons resembling cas-
96 cade events. Since the atmospheric muon background simulation with the
97 air shower simulation package CORSIKA [13] produces many lower-energy

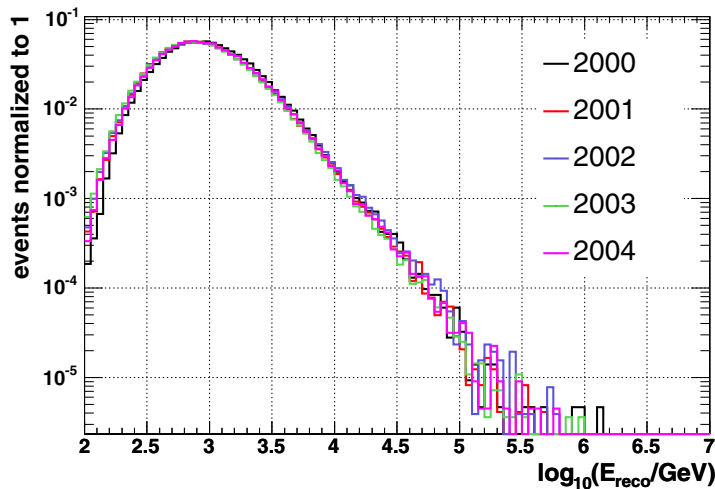


Figure 1: Reconstructed cascade energy for data of different years. For comparison, the curves are normalized to 1.

98 muons that do not radiate bremsstrahlung, computing time constraints made
 99 an optimization necessary to increase the statistics for high energy muons (see
 100 Table 2). The internal energy thresholds of CORSIKA were raised relative
 101 to those used in the standard AMANDA atmospheric muon simulation for
 102 the primary cosmic ray energy, the muon energy evaluated at the surface,
 103 and the energy released into a single secondary cascade near the AMANDA
 104 detector. For simulated events with more than one muon, these thresholds
 105 were applied to the highest energy muon and the secondary cascade which
 106 released the most energy. Two optimized samples were generated. The pa-
 107 rameters of these simulations are summarized in Table 2, along with those of
 108 the standard simulation used in muon-focused AMANDA analyses. Figure 2
 109 shows that the high-energy part of the spectrum is well represented by the
 110 optimized simulations. For the further analysis the second optimized sample
 111 with an equivalent livetime of 4670 days was used compared to 1001 days of
 112 real data.

113 Neutrino events of all flavors (ν_e, ν_μ, ν_τ) with energies between 100 GeV
 114 and 100 PeV were simulated with the neutrino generator code ANIS [14]. A
 115 general-purpose neutrino sample was produced with an E^{-1} spectrum with
 116 the neutrino interaction vertices uniformly distributed throughout the in-

BG sample	$E_{\text{cut}}^{\text{primary}}$	E_{cut}^{μ}	$E_{\text{cut}}^{\text{secondary}}$	Equivalent Livetime
standard	800 GeV	300 GeV	0.5 GeV	15 days
optimized sample 1	3 TeV	1.2 TeV	500 GeV	880 days
optimized sample 2	20 TeV	3.0 TeV	800 GeV	4670 days

Table 2: The atmospheric muon background samples used in this analysis. The equivalent livetime may be compared to the total detector livetime of 1001 days.

117 teraction volume. For this analysis the interaction volume was defined as a
 118 cylinder with a radius of 300 m and a height of ± 300 m from the detector center.
 119 These events were then re-weighted to a hypothetical E^{-2} signal flux, as
 120 well as to several astrophysical neutrino model predictions with other energy
 121 spectra. For astrophysical neutrinos we assume equal flavor for neutrinos and
 122 antineutrinos. The steeper atmospheric neutrino spectrum was simulated by
 123 re-weighting the same events according to the atmospheric flux model [15],
 124 having a power law spectrum $\sim E^{-3.7}$.

125 In the next step of the simulation chain, for all events with final state
 126 muons (atmospheric background muons, signal and atmospheric background
 127 muon-neutrino events), the muons were propagated through the ice using the
 128 Muon Monte Carlo program MMC [16]. In this step the energy loss of muons
 129 due to ionization losses, bremsstrahlung, pair production, and photo-nuclear
 130 interactions is simulated.

131 3. Analysis

132 The goal of the analysis was to identify astrophysical neutrino-induced
 133 cascade events within the large background of atmospheric muon events. The
 134 analysis applied the same reconstruction algorithms to the experimental and
 135 simulated data sets. The algorithms were used already for the previous year
 136 2000 cascade analysis [8]. To a good approximation, cascade events are point-
 137 like Cherenkov light emitters since the longitudinal cascade size of a few meters
 138 is short compared to the typical distance between OMs. Cherenkov light
 139 emission in ice peaks at an angle of 41° relative to the cascade longitudinal
 140 axis, but because of photon scattering in the ice, the directional information
 141 is mostly lost by the time of detection. Unlike cascades, muons typically

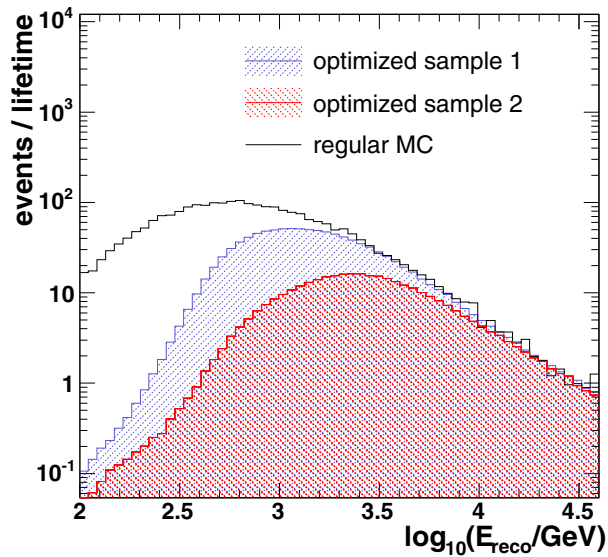


Figure 2: Reconstructed cascade energy for various background Monte Carlo samples. All events shown here have passed the vertex likelihood cut $L_{\text{vertex}} < 7.1$ (see the following section). At high energies, there is good agreement between the standard and the optimized samples.

142 leave long tracks of light along their path through the detector. Most of these
 143 muons can easily be rejected, but a fraction of muon tracks produce large
 144 bremsstrahlung cascades in the detector, leading to a cascade-like pattern of
 145 OM pulses (“hits”). In addition to hits from Cherenkov photons, uncorre-
 146 lated random hits are caused by photomultiplier dark noise and electronics
 147 noise. Non-physics hits are also produced by cross-talk along the cables as
 148 well as in the surface electronics. A hit cleaning procedure removes most of
 149 the random and cross-talk hits prior to event reconstruction [17].

150 3.1. First Reconstruction Steps

151 Most of the nearly 9 billion triggered events are atmospheric muons which
 152 dominate clearly the background. A simple and fast reconstruction algorithm
 153 is needed to reduce the size of the data set. We used a fast ‘first guess’ event
 154 reconstruction with an analytic algorithm to estimate the cascade vertex
 155 position and time from the hit times and hit positions [8]. Two variables
 156 from this reconstruction were then used in the cascade event selection. The

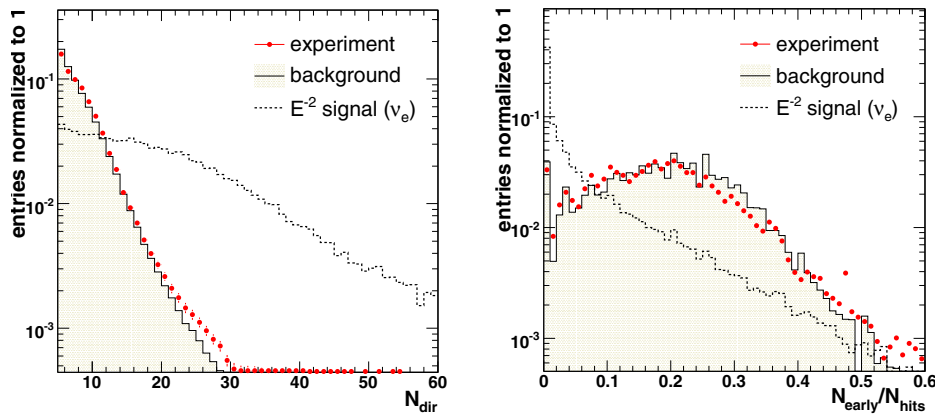


Figure 3: The two variables from a first-guess event reconstruction used in early data reduction for experimental data, signal and background Monte Carlo. Left: The number of direct hits N_{dir} , with time residuals $0 < t_{\text{resid}} < 200 \text{ ns}$. Right: The ratio of early hits ($t_{\text{resid}} < 0$) hits, N_{early} , to the total number of hits, N_{hits} .

157 first variable was the number N_{dir} of direct hits, defined as hits with times
 158 delayed relative to the arrival times expected for unscattered photons from
 159 the reconstructed interaction vertex by less than 200 ns. The second variable
 160 was N_{early} , the number of hits which occurred earlier than the direct hits, that
 161 is hits with 'negative delay' times. The number of early hits should be small
 162 for real cascades, since such hits would violate causality for photons actually
 163 emitted at the cascade vertex position and time. Early hits in cascade events
 164 can only result from random dark noise, or from misreconstruction of the
 165 cascade vertex position. Relative to these incorrectly classified cascades,
 166 hits produced by light emitted farther back along the muon track will be
 167 classified as early hits. Figure 3 shows both variables for the data as well
 168 as for the simulated atmospheric muon background and signal. The cut
 169 values for the background reduction are presented in Table 3 together with
 170 the corresponding efficiencies. The large discrepancies between experimental
 171 data and simulated atmospheric muon background seen in table 3 are less
 172 visible in Fig. 3 due to the normalization. They are mainly caused by the
 173 simplified description of ice properties in the Monte Carlo simulation. The
 174 influence on the systematics error will be discussed in section 4.1.

175 *3.2. Maximum Likelihood Methods*

176 For events remaining after the cuts described above, the cascade ver-
 177 tex and the energy were reconstructed with more sophisticated maximum
 178 likelihood methods [9, 17, 18] which take into account the scattering and
 179 absorption of Cherenkov photons in ice.

180 *3.2.1. Vertex Position Reconstruction*

For the observation of the residual or delay time of photons (t_{res}) as a
 function of the distance d between a hit OM and the reconstructed vertex
 position, a normalized probability density function (PDF) $p(t_{\text{res}}, d)$ was de-
 veloped. This PDF allows to construct the likelihood function:

$$\mathcal{L} = \prod_{\text{hit}=1}^{\text{all hits}} p(t_{\text{res}}, N, d), \quad L = \frac{-\log(\mathcal{L})}{N_{\text{hits}} - N_{\text{free}}}. \quad (1)$$

181 The vertex position and time are reconstructed by minimizing the likelihood
 182 function L in analogy to a reduced χ^2 . N_{hits} is the total number of hits and
 183 $N_{\text{free}} = 4$ is the number of free vertex parameters (3 space coordinates x, y, z
 184 and time t). The resulting vertex resolution is about 4 m in the transverse
 185 coordinates x, y and slightly better in the depth coordinate z .

186 *3.2.2. Energy Reconstruction*

A maximum likelihood method is also used for the energy reconstruc-
 tion. Here, the likelihood is given by the probability to identify special hit
 patterns relevant for cascades. The hit-probability can be expressed by the
 number of expected photo-electrons η as a function of the distance d from
 an isotropically emitting point-like cascade:

$$\eta = I_0 \frac{E}{d} e^{-d/\lambda_{\text{att}}}, \quad (2)$$

187 where $\lambda_{\text{att}} = \sqrt{\lambda_{\text{scat}}^{\text{eff}} \lambda_{\text{abs}}}/3$ is the attenuation length which is ~ 29 m for
 188 Cherenkov wave lengths. For distances larger than the photon scattering
 189 length, $d \gg \lambda_{\text{scat}}$, the information on the direction of the photon vanishes
 190 because of multiple scattering. The scattering of light is then described by
 191 the effective scattering length $\lambda_{\text{scat}}^{\text{eff}}$. The normalization constant I_0 depends
 192 on the OM orientation and the direction of the cascade.

With the expression for the expected number of photo-electrons one can calculate for each OM the probability to observe a hit:

$$P_{\text{hit}}^{\text{casc}} = 1 - P_{\text{nohit}}^{\text{casc}} = 1 - e^{-\eta}, \quad (3)$$

For a realistic definition of the hit probability, one has to add the probability for the detection of noise hits:

$$P_{\text{hit}} = 1 - P_{\text{nohit}} = P_{\text{hit}}^{\text{casc}} + P_{\text{noise}} - P_{\text{hit}}^{\text{casc}} P_{\text{noise}}. \quad (4)$$

A likelihood function can be constructed as a product of the probability functions P_{hit} and P_{nohit} :

$$\mathcal{L} = \prod_{i=1}^{\text{all hit OM}} P_{\text{hit}}(E, d) \prod_{i=1}^{\text{all nohit OM}} P_{\text{nohit}}(E, d), \quad (5)$$

$$L = -\frac{\mathcal{L}}{N_{\text{OM}} - N_{\text{free}}}. \quad (6)$$

193 N_{OM} is the total number of hit OMs and $N_{\text{free}} = 1$ is the number of fit
 194 parameters. The resolution of the energy reconstruction is energy dependent.
 195 In $\log_{10} E$ units it is 0.13 at 100 GeV, rising to 0.22 at 1 PeV.

196 3.3. Selection Criteria for Likelihood Parameters and Vertex Position

The vertex and energy likelihood parameters were used for the further event selection. These variables contain the information about the quality of agreement between the best-fit hypothesis and the event. For the vertex position, the cut value is $L_{\text{vertex}} < 7.1$. Since the cut variable L_{energy} is energy dependent, the cut criterion is:

$$L_{\text{energy}} \leq \begin{cases} 1.1, & \log_{10}(E_{\text{reco}}) \leq 3.9 \\ -0.625 \times \log_{10}(E_{\text{reco}}/\text{GeV}) + 3.54, & \log_{10}(E_{\text{reco}}) > 3.9 \end{cases} \quad (7)$$

197
 198

With the radial distance ρ_{xy} an additional cut variable was introduced which is defined as the distance of the cascade vertex from the central axis of the detector:

$$\rho_{xy} = \sqrt{x_{\text{reco}}^2 + y_{\text{reco}}^2} \quad (8)$$

The radial distance cut is softened in dependence on the cascade energy. For events inside the instrumented AMANDA detector volume of 100 meters radius, the energy cut is fixed to remove misreconstructed atmospheric muons.

For bright cascades (high energies), the background contamination is less severe and the cut is softened with increasing energy:

$$\rho_{xy} \leq \begin{cases} 100 \text{ m}, & \log_{10}(E_{\text{reco}}) \leq 3.1 \text{ TeV} \\ 42.3 \times \log_{10}(E_{\text{reco}}/\text{GeV}) + 43.8 \text{ m}, & \log_{10}(E_{\text{reco}}) > 3.1 \text{ TeV} \end{cases} \quad (9)$$

199

200 These three selection criteria are summarized in Table 3 with the correspond-
201 ing cumulative cut efficiencies for data, background and signal events.

202 3.4. Final Selection Criteria

203 For the final event selection, three cut variables (see Fig. 4) were com-
204 bined into a multivariate quality parameter. The first variable is the vertex
205 likelihood parameter L_{vertex} , which possesses additional discriminative power
206 after the cut shown in Table 3. The second variable ($\Delta\rho_{xy}^{60}$) is the distance
207 in the horizontal $x - y$ plane between vertex positions reconstructed with
208 different hit selection criteria: $\Delta\rho_{xy}^{60} = \sqrt{(x_{\text{reco}} - x_{\text{reco}}^{60})^2 + (y_{\text{reco}} - y_{\text{reco}}^{60})^2}$. In
209 the first vertex reconstruction all hits were included; in the second, hits at a
210 radius of more than 60 m from the first vertex were excluded. For a signal cas-
211 cade event one expects only small differences in vertex position between the
212 two reconstructions. Background muons that reach this stage of the analysis
213 often have a bright bremsstrahlung induced shower. For these events the dif-
214 ference $\Delta\rho_{xy}^{60}$ is typically larger than for signal cascades. The third variable
215 that enters the multivariate quality parameter is $\cos\theta_{\mu}$, where θ_{μ} is the zenith
216 angle obtained by fitting the event to a muon track hypothesis. As can be
217 seen in Fig. 4, the distribution peaks near $\cos\theta_{\mu} = 0$ for neutrino-induced
218 cascades. When roughly spherical cascades are reconstructed as muon tracks
219 in the tall cylindrical AMANDA detector, they appear mainly as horizontal
220 tracks, whereas the atmospheric muon background is downward-going with
221 $\cos\theta_{\mu} > 0$.

We combined the three variables shown in Fig. 4, into one quality variable,
the likelihood ratio:

$$Q_S = \frac{\prod_i p_i^s(x_i)}{\prod_i p_i^s(x_i) + \prod_i p_i^b(x_i)}, \quad (10)$$

222

223 where $0 < Q_S < 1$ and i runs over the three variables $x_i = L_{\text{vertex}}, \Delta\rho_{xy}^{60}(E),$
224 $\cos\theta_{\mu}$. The functions p^s and p^b for signal and background, respectively,
225 represent the probability density functions for the individual variables x_i for
226 background due to atmospheric muons and signal consisting of a flux of ν_e

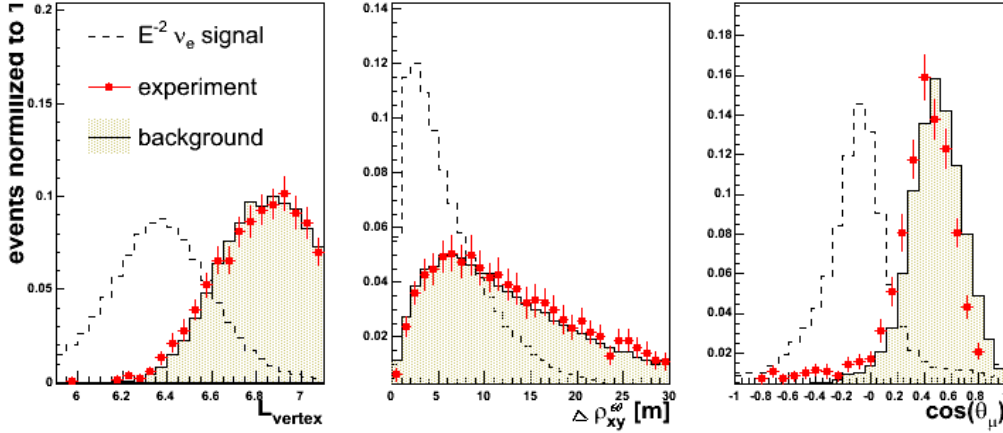


Figure 4: Distributions of three variables which are used to construct the discriminating likelihood parameter Q_S for the experimental data, the background and the signal MC. The left plot shows the vertex likelihood distribution. The plot in the middle shows the $\Delta\rho_{xy}^{60}$ distributions. The plot on the right is the $\cos\theta_\mu$ distribution taken from the iterative muon likelihood reconstruction.

227 with a spectral slope $\Phi(E) \propto E^{-2}$. They are obtained from simulations and
 228 shown in Fig. 4.

229 The distribution of the variable Q_S (Fig. 5a) peaks close to one for the
 230 simulated cascade signal and close to zero for the simulated muon back-
 231 ground (and experimental data). In addition to a cut on Q_S , which does
 232 not fully separate signal from background, the reconstructed cascade energy
 233 E_{reco} (Fig. 5b) was used to further reduce the background.

234 A discrete optimization procedure was used to find the cut values for Q_S
 235 and E_{reco} which maximized the separation of cascades from an E^{-2} neutrino
 236 spectrum from background muons. A two-dimensional grid was formed in the
 237 two variables, with bounds $0.90 < Q_S < 0.99$ and $4.35 < \log_{10}(E_{\text{reco}}/\text{GeV}) <$
 238 6 and step sizes of 0.01 and 0.05 respectively. At each grid point, the sen-
 239 sitivity, defined as the average upper limit for a ν_e flux in the absence of a
 240 signal [19], was calculated. The optimum sensitivity was found with the cuts
 241 $Q_S > 0.92$ and $\log_{10}(E_{\text{reco}}/\text{GeV}) > 4.65$ yielding an average upper limit on
 242 the ν_e flux which will be given in section 4.4.

243 The efficiencies of all applied cuts are summarized in Table 3 for exper-
 244 imental data, the simulated background from atmospheric muons and at-

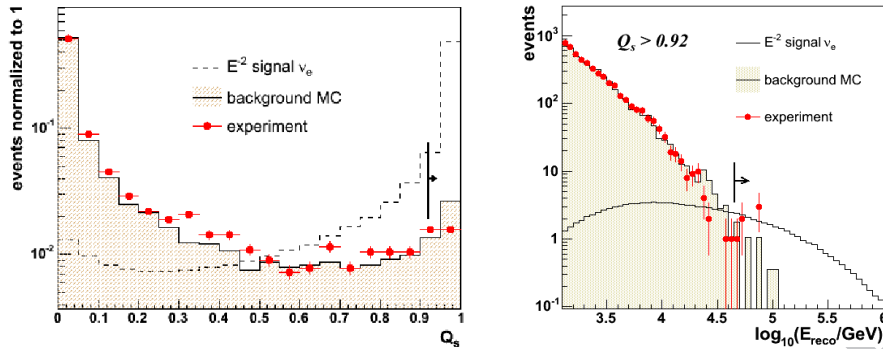


Figure 5: Distributions of the final cut variables Q_S and E_{reco} for the experimental data, for background and signal Monte Carlo. Left (a): The discriminating parameter Q_S . Right (b): The reconstructed cascade energy distribution E_{reco} after application of all quality cuts and a cut on the discriminating parameter $Q_S > 0.92$. The signal Monte Carlo distribution is normalized to the lifetime of 1001 days and a flux $\Phi = 10^{-6} E^{-2} \text{GeV s}^{-1} \text{sr}^{-1} \text{cm}^{-2}$.

245 atmospheric neutrinos, and a hypothetical astrophysical electron-neutrino sig-
 246 nal with a flux of $\Phi = 10^{-6} E^{-2} \text{GeV s}^{-1} \text{sr}^{-1} \text{cm}^{-2}$ used as a benchmark for
 247 an extraterrestrial flux. All selection criteria were developed using only 20%
 248 of the experimental data, sampled evenly throughout the 5 years, and the
 249 remaining 80% were analyzed only after the cuts had been finalized in the
 250 manner described above. This blind analysis technique [20] was adopted to
 251 prevent possible biases in the selection procedure due to statistical fluctua-
 252 tions in the data. The results discussed in the following section were obtained
 253 with the full sample.

254 4. Results

255 4.1. Systematic Uncertainties

256 Several sources of systematic uncertainties must be evaluated and consid-
 257 ered in calculating a limit on the astrophysical neutrino flux. Uncertainties in
 258 the detector parameter description and in the simulation and analysis chain
 259 were studied in detail in [17]. In the following we will discuss the major
 260 sources of systematic uncertainties in this analysis.

261 The detector configuration and trigger conditions changed slightly over
 262 the five year period, resulting in year-to-year variations in the event rate of

Cut Variable	Data	μ^{atm}	ν_e^{atm}	$E^{-2}\nu_e$ Signal
$N_{\text{early}}/N_{\text{hits}} < 0.05$	0.054	0.030	0.53	0.38
$N_{\text{dir}} \geq 8$	0.032	0.015	0.49	0.33
$L_{\text{vertex}} < 7.1$	6.5×10^{-4}	3.7×10^{-4}	0.32	0.24
$L_{\text{energy}}(E)$	1.3×10^{-4}	1.0×10^{-4}	0.27	0.17
$\rho_{xy}(E)$	8.7×10^{-5}	5.9×10^{-5}	0.12	0.10
$Q_S > 0.92$	3.5×10^{-6}	2.1×10^{-6}	0.01	0.08
$\log_{10}(E_{\text{reco}}/\text{GeV}) > 4.65$	4.8×10^{-10}	5.2×10^{-10}	3.0×10^{-5}	0.02

Table 3: The cumulative cut efficiencies for experimental data, several types of background and an $E^{-2}(\nu_e + \bar{\nu}_e)$ signal. The cut variables L_{energy} and ρ_{xy} are energy dependent.

263 about 10% after the different analysis steps. The variation of the optical
 264 module sensitivity as one possible source was investigated in detail for the
 265 years 2001 and 2003. For most of the strings the sensitivity was stable or the
 266 decrease was less than 10%. The efficiency was about 20% lower only for
 267 strings 1-4 in 2003. Since the strings operated with normal efficiency until
 268 the AMANDA shut-down in 2009, photocathode aging can be excluded. The
 269 reasons are changes of the high voltage and signal amplification settings. Av-
 270 eraging the variation in OM sensitivity over the full detector, the systematic
 271 uncertainty was estimated to be 13%.

272 An essential component is the uncertainty in the modeling of photon prop-
 273 agation through the ice. A software package, PHOTONICS [21], was devel-
 274 oped to simulate photon propagation through a turbid, translucent medium,
 275 taking into account the full wavelength and depth dependences of the scat-
 276 tering and absorption parameters. The required optical properties of deep
 277 ice at the South Pole have been measured by the AMANDA collaboration
 278 [22]. The inclusion of the full measured depth and wavelength dependencies
 279 in the photon propagation simulation results in very large lookup tables for
 280 use in the simulation of signal and background event topologies. Because of
 281 the computing time constraints to generate a large muon background sam-
 282 ple, a much simplified simulation model PTD [23] was used in this analysis.
 283 In PTD the ice is divided into horizontal layers of homogeneous ice, such
 284 that each OM only sees a sheet of ice with depth-independent absorption
 285 and scattering properties typical of its own depth. In this approximation,
 286 the simulation propagates photons consequently through homogeneous ice
 287 only and are not subjected to the vertical variations in ice properties. An

288 additional simplification is that all photon scattering is modeled assuming
 289 an average wavelength of 420 nm. To investigate the uncertainty due to the
 290 simplified photon propagation in PTD, lower statistics Monte Carlo samples
 291 were generated using the more realistic PHOTONICS tables. A comparison
 292 of both photon propagation simulations yields uncertainties in event rate due
 293 to the photon propagation with PTD tables of 19% for atmospheric muons,
 294 23% for atmospheric ν_μ and 28% for atmospheric ν_e . For simulated E^{-2}
 295 signal events the uncertainty of 2% is less crucial, since the higher energy of
 296 the signal events confers a certain amount of immunity to the specific optical
 297 properties of the ice. Meanwhile, PHOTONICS is the standard package for
 298 photon propagation in the ice of the AMANDA and IceCube detectors.

299 The reconstruction steps and selection criteria of the analysis (summa-
 300 rized in Table 3) yield different passing rates for data and simulated at-
 301 mospheric muon background. Relaxing the Q_S cut for the background Monte
 302 Carlo sample to $Q_S > 0.83$ results in the same efficiency as for the experi-
 303 mental data. The number of signal events increases by 12%, which is taken
 304 as a measure of the uncertainty in the cut efficiency.

305 Finally, the theoretical uncertainties were considered. For the simulation
 306 of the atmospheric muon background there is uncertainty in the shape of the
 307 energy spectrum. Variations in the spectral energy slopes by $\Delta\gamma = 0.1$, a
 308 value somewhat larger than the current uncertainties [24], change the num-
 309 ber of events passing the energy cut by 5%, which is negligible relative to
 310 the other systematic and statistical uncertainties. Another theoretical un-
 311 certainty comes from the primary atmospheric neutrino flux prediction [25].
 312 This uncertainty was estimated to be less than 20% and does not contribute
 313 significantly to the total theoretical uncertainty, as the atmospheric neutrino
 314 event rate is a very small fraction of the total background rate. The 5%
 315 uncertainty of the neutrino signal is caused by the uncertainty of the neu-
 316 trino cross section at high energies [26]. In Table 4 the contributions to the
 317 systematic uncertainties are summarized and added in quadrature to get the
 318 total value.

319 4.2. Final Event Sample

320 After applying all cuts given in Table 3, six experimental events remain
 321 (see Fig. 5b). For these events the characteristic data and reconstructed
 322 variables are summarized in Table 6. The expected background at this final
 323 analysis level is 6.5 events, mostly from atmospheric muons (6.4 events) with

Systematic Uncertainty	$\Delta N_{\mu^{atm}}$	$\Delta N_{\nu_{\mu}^{atm}}$	$\Delta N_{\nu_e^{atm}}$	$\Delta N(E^{-2}\nu_e \text{ Signal})$
Year-to-year variation	10 %	10 %	10 %	10 %
OM sensitivity	13 %	13 %	13 %	13 %
Cut efficiency	12 %	12 %	12 %	12 %
PTD ice model	19 %	23 %	28 %	2 %
Theoretical uncertainty	5 %	20 %	20 %	5 %
Total	28 %	37 %	40 %	21 %

Table 4: Different contributions to the systematic uncertainties of the number of events for the muon background, the atmospheric and signal neutrinos.

N_{Exp}	$N_{\text{BG}}^{\text{Total}}$	$N_{\mu^{atm}}$	$N_{\nu_{\mu}^{atm}}$	$N_{\nu_e^{atm}}$	$N(E^{-2}\nu_e \text{ Signal})$
6	$6.5_{-2.4}^{+2.5}$	$6.42_{-2.40}^{+2.50}$	0.065 ± 0.023	0.016 ± 0.006	20.9 ± 4.4

Table 5: The number of experimental events remaining after all cuts and the corresponding expected numbers of background and signal events from Monte Carlo simulations. The quoted errors include systematic uncertainties. For the ν_e signal a benchmark flux of $\Phi = 10^{-6} E^{-2} \text{GeV s}^{-1} \text{sr}^{-1} \text{cm}^{-2}$ is assumed.

324 a small component from atmospheric muon neutrinos (0.065) and electron
325 neutrinos (0.016).

326 Also shown in Fig. 5 is the expectation from the benchmark $E^{-2} (\nu_e + \bar{\nu}_e)$
327 signal Monte Carlo simulation. Normalized to the 1001 days of livetime, the
328 final cut yields 20.9 signal ν_e events. Table 5 summarizes the final event
329 numbers. The errors include the systematic uncertainties given in Table 4.
330 Only the number of atmospheric muons has in addition a statistical error
331 since the simulation was limited by statistics. This uncertainty was estimated
332 with the upper and lower bounds for the 68.2% C.L. using the method of
333 Feldman and Cousins [19] to $N_{\mu^{atm}} = 6.4_{-1.5}^{+1.8}$ events.

334 Since no excess over the expected background was observed, an upper
335 limit on the diffuse flux of astrophysical neutrinos was deduced. Following
336 the method of Feldman and Cousins for constructing the confidence belt, the
337 event upper limit before considering systematic uncertainties is $\mu = 4.99$ at
338 90% C.L. A Gaussian systematic error distribution was assumed for both
339 signal and background. For the signal, the width is set to the estimated sys-
340 tematic uncertainty of $\pm 21\%$. Since the error distribution for the background
341 is asymmetric, its peak position is chosen in the center of the uncertainty

Event #	1	2	3	4	5	6
Year	2002	2002	2002	2002	2003	2004
GPS day	179	181	273	285	129	56
V_x , m	14.62	19.08	84.92	1.19	26.59	51.9
V_y , m	111.64	103.72	7.89	125.36	-87.65	101.3
V_z , m	-95.64	-102.52	-48.12	-102.99	-126.70	-108.10
L_{vertex}	6.521	6.360	6.215	6.588	6.818	6.550
$\log_{10} E_{\text{reco}}$, GeV	4.884	4.672	4.895	4.725	4.728	4.867
L_{energy}	0.663	0.591	0.586	0.772	1.089	0.596
$N_{\text{early}}/N_{\text{hits}}$	0.0231	0.0083	0.0001	0.0258	0.0070	0.0041
N_{direct}	23	16	29	30	16	62
N_{hits}	520	485	497	388	282	478
N_{ch}	227	208	267	188	175	208
Q_s	0.948	0.986	0.988	0.951	1.00	0.939

Table 6: The observables and reconstructed variables for the six events which passed all analysis cuts.

342 interval. The systematic uncertainties on the signal and background expect-
343 tations were then included in the calculation of the event upper limit with
344 the software package POLE++ [27]. This results in an event upper limit of
345 6.7 events at 90% confidence level.

346 4.3. AMANDA Effective Area

347 The sensitivity of the AMANDA detector to all three neutrino flavors
348 can be expressed as an effective area. This measure incorporates the neu-
349 trino interaction probability, the detector sensitivity to events, the daughter
350 lepton's range and the efficiency of the selection cuts. Neutrino event rates
351 for any assumed neutrino flux can be computed from the effective area by
352 integrating the flux times the effective area, with respect to energy.

353 Figure 6 shows the neutrino effective area of the AMANDA detector as
354 a function of energy for $(\nu_e + \bar{\nu}_e)$, $(\nu_\mu + \bar{\nu}_\mu)$ and $(\nu_\tau + \bar{\nu}_\tau)$ for the present
355 analysis averaged over 4π steradian. For $\bar{\nu}_e$, the peak around 6.3 PeV is the
356 Glashow resonance, due to resonant production of W^- by neutrinos on atomic
357 electrons. At 100 PeV the effective area reaches $0.3 - 0.8 \text{ m}^2$, depending on
358 the neutrino flavor.

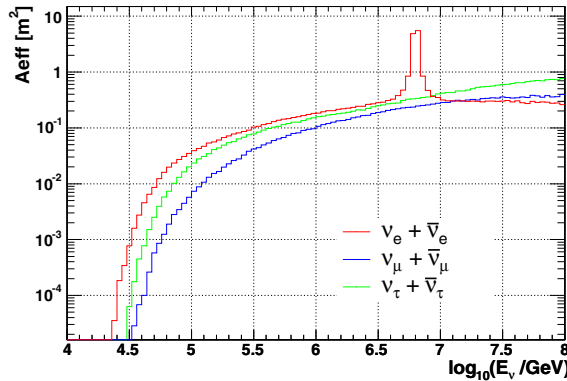


Figure 6: The neutrino effective areas for ν_e , ν_μ and ν_τ as a function of neutrino energy after all selection criteria have been applied.

359 Figure 7 shows the neutrino effective area for different zenith angle (θ)
 360 bands. Neutrino absorption in the Earth reduces the effective area for $\cos \theta <$
 361 0 when $E_\nu \geq 100$ TeV. This also affects the Glashow resonance which is
 362 not visible for upward-going ($\nu_e + \bar{\nu}_e$). Tau neutrinos are not absorbed in
 363 the Earth but instead are regenerated, emerging with lower energies [28].
 364 Because of this, the effective area for upward-going ν_τ does not decrease
 365 with higher energies.

366 4.4. Flux Upper Limit

367 The upper limit of 6.7 events deduced in Section 4.2 was combined with
 368 the effective area to constrain neutrino flux models. For a given model, we
 369 computed the ratio of the event upper limit to the expected neutrino event
 370 rate for that model. If this ratio, the Model Rejection Factor (MRF) [29], is
 371 less than one, the model is ruled out by the data at 90% CL. For example, an
 372 E^{-2} power law total flux of neutrinos of all flavors, $\Phi = 10^{-6} E^{-2} \text{GeV s}^{-1} \text{sr}^{-1} \text{cm}^{-2}$,
 373 distributed equally over all neutrino flavors would produce 7.0 events due
 374 to electron-neutrinos i.e. 1/3 of the value from Table 5, 2.3 due to muon-
 375 neutrinos, and 4.0 due to tau-neutrinos for a total of 13.3 neutrino events.
 376 Comparing these 13.3 events to the experimental limit of 6.7 events, one ob-
 377 tains an MRF of 0.5. Rescaling the model flux by the MRF leads to the flux
 378 upper limit $E^2 \Phi_{90\% \text{CL}} \leq 5.0 \cdot 10^{-7} \text{GeV s}^{-1} \text{sr}^{-1} \text{cm}^{-2}$. For this spectrum, the
 379 central 90% of the ν_e signal events would fall into the energy range 40 TeV

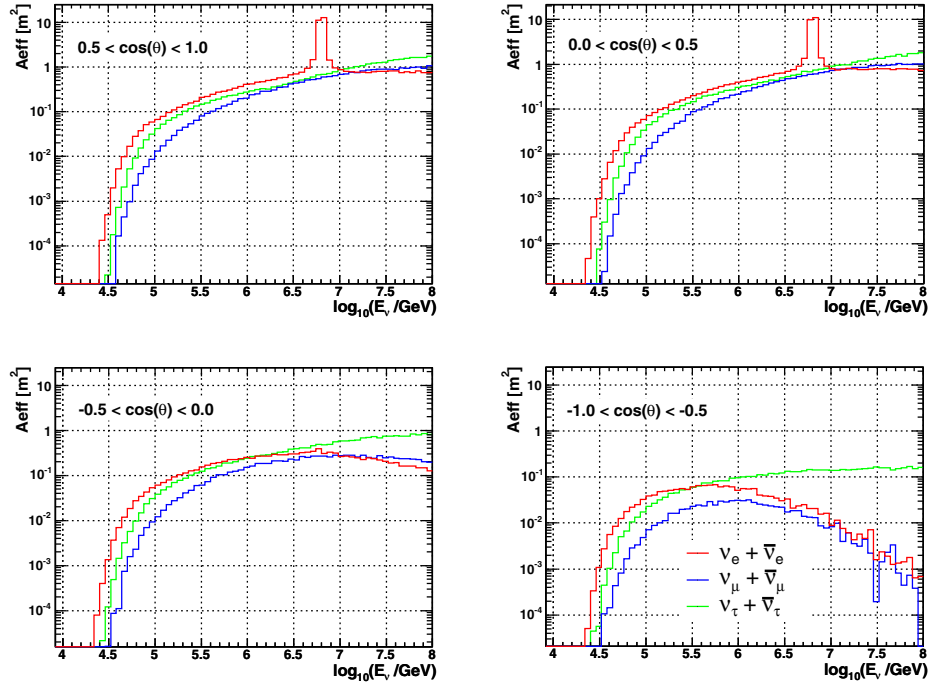


Figure 7: The neutrino effective area for AMANDA as a function of the neutrino energy for four different ranges of the zenith angle. Distributions for electron-, muon- and tau-neutrinos are shown separately. The tau regeneration effect is mainly visible in the two lower plots, which are for up-going neutrinos.

380 to 9 PeV. This upper limit on the total flux assumes a flavor ratio of 1 : 1 : 1
 381 and is equivalent to a limit of $E^2\Phi_{90\%CL} \leq 1.7 \cdot 10^{-7} \text{GeV s}^{-1} \text{sr}^{-1} \text{cm}^{-2}$ on each
 382 individual neutrino flavor. A more conservative upper limit on the flux of
 383 electron neutrinos that does not depend on the assumption of a 1 : 1 : 1
 384 flavor ratio is derived by assuming that the ν_μ and ν_τ fluxes are zero. An
 385 upper limit of $E^2\Phi_{\nu_e} \leq 3.3 \cdot 10^{-7} \text{GeV s}^{-1} \text{sr}^{-1} \text{cm}^{-2}$ at 90% C.L was obtained.

386
 387 Table 7 presents the expected number of events in 1001 days of livetime
 388 and the corresponding MRFs for several models of neutrino production in
 389 astrophysical sources and in the atmosphere. The spectra predicted by these
 390 models are shown in Fig. 8. With the exception of the Waxman-Bahcall
 391 model for neutrino production in GRBs [32], the astrophysical models con-

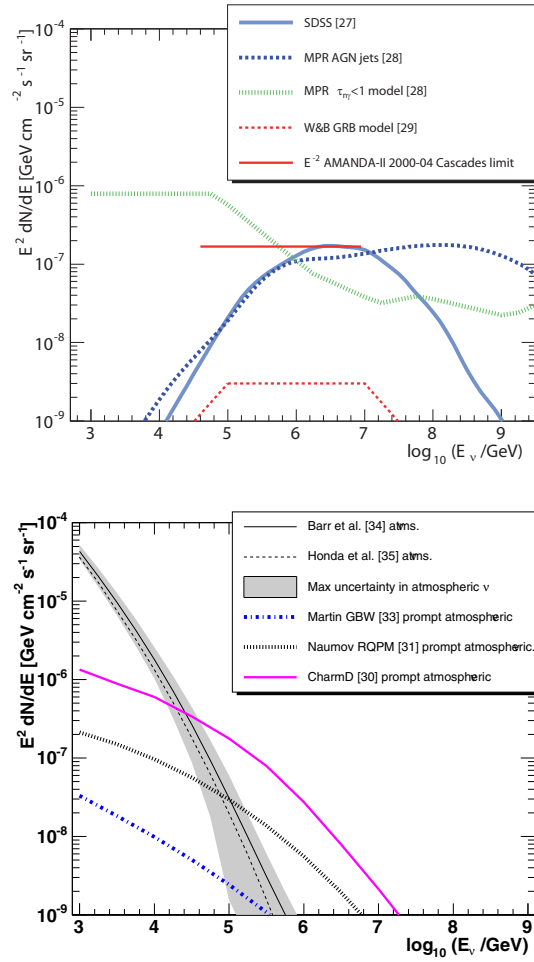


Figure 8: Flux prediction per neutrino flavor. a) For several models of astrophysical neutrino sources. b) For atmospheric neutrinos from pion and kaon decays and due to charm production. Table 7 gives the Model Rejection Factors for the individual models.

392 sider neutrino production in AGN. The model by Mannheim, Protheroe and
 393 Rachen [31] provides an upper bound for AGN sources optically thin to neu-
 394 trons (optical depth $\tau < 1$). Since for this model the MRF is less than one,
 395 our experimental data can exclude this model, with most of the discrimina-
 396 tion power derived from the region below 0.5 PeV. For the other astrophysical
 397 model predictions that were tested [30, 31, 32], the MRFs are greater than

Model	$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$	all-flavors	MRF
$10^{-6} E^{-2}$	6.97	2.32	3.99	13.30	0.50
SDSS (2005) [30]	1.08	0.37	0.60	2.05	2.58
MPR (AGN jet) [31]	1.07	0.50	0.72	2.29	2.29
MPR ($\tau < 1$) [31]	8.52	7.56	2.77	18.85	0.28
WB GRB [32]	0.03	0.02	0.01	0.06	89.50
Charm D [33]	2.06	0.68	-	2.74	1.92
Naumov RQPM [34]	0.42	0.15	-	0.57	9.24
Martin GBW [36]	0.04	0.01	-	0.05	112.34

Table 7: Summary of the expected number of events in 1001 days of lifetime from various astrophysical and atmospheric prompt neutrino models. A flux ratio of 1 : 1 : 1 is assumed. For the event upper limit the estimated value of $\mu_{90\%} = 6.7$ is used which includes all systematic uncertainties.

one, i.e. the AMANDA flux upper limits do not constrain these other models.

This analysis is also sensitive to atmospheric electron- and muon-neutrinos produced in decays of short lived charmed mesons, the so-called prompt neutrinos, which have a harder spectrum than the conventional flux of atmospheric neutrinos. The model with the highest flux prediction that is considered here is based on a non-perturbative calculation for the cross section [33], would result in 2.7 events and is therefore close to being constrained. This model was ruled out by the previous AMANDA diffuse ν_μ study [10]. Other models for prompt neutrino production [34, 36] predict significantly lower event rates and are hence not constrained by our data.

4.5. Comparison with other Results

This five years cascade analysis has an about 60% higher sensitivity than the result published for the year 2000 [8]. The reconstruction algorithms and the selection criteria for cascade-like events were almost identical in both analyses. The five times larger number of triggered events and the considerably higher equivalent live time for the atmospheric muon background sample of about 4700 days allowed to improve the neutrino energy range. In Table 8, the essential parameters are summarized also for other diffuse analyses of the AMANDA and Baikal experiments. Fig. 9 shows the corresponding flux limits and the validity regions in neutrino energy.

The search for a diffuse flux of muon neutrinos [10] was performed for the

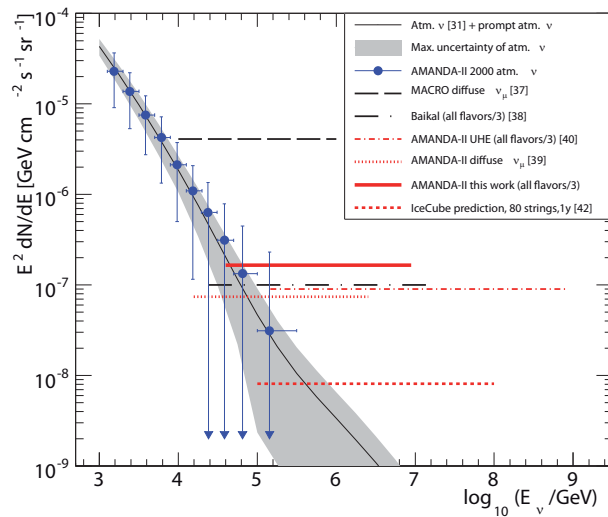


Figure 9: The upper limit on a diffuse neutrino flux from sources with an E^{-2} energy spectrum are shown for muon neutrinos and all-flavor analyses. All-flavor upper limits were divided by three, assuming the flavor ratio at the Earth to be $\nu_e + \bar{\nu}_e : \nu_\mu + \bar{\nu}_\mu : \nu_\tau + \bar{\nu}_\tau \approx 1 : 1 : 1$.

419 years 2000 to 2003. In contrast to the cascade analysis, one searches for up-
 420 going muon tracks in the AMANDA detector resulting from neutrinos which
 421 interact with the rock or the ice below the detector. The essential final
 422 cut parameter is the number of hit optical modules ($N_{\text{ch}} > 100$) which is
 423 equivalent to an energy cut. It allows to separate astrophysical high energy
 424 neutrinos from lower energetic atmospheric neutrinos or misreconstructed
 425 muons which are the main background contributions. Applying this cut,
 426 6 events remain in the data sample in good agreement with the expected
 427 number of 7 atmospheric neutrino events.

428 The focus of the other AMANDA diffuse neutrino analysis was the ultra-
 429 high-energy (UHE) part of the spectrum [11]. For energies above 10^7 GeV ,
 430 the Earth becomes opaque to neutrinos. Therefore, this analysis investi-
 431 gates neutrinos reaching the detector from directions near to the horizon.
 432 At these energies the background of atmospheric neutrinos can be neglected,
 433 but bundles of atmospheric muons can produce enough light in the detector
 434 similar to UHE neutrino events. Monte Carlo studies have shown that OMs

Analysis	ν Flavors	Livetime (days)	Energy Range (PeV)	Sensitivity Limit
Cascades (this analysis)	ν_e, ν_μ, ν_τ	1001	0.040 - 9	$\leq 5.0 \cdot 10^{-7}$
Cascades [8]	ν_e, ν_μ, ν_τ	197	0.050 - 5	$\leq 8.6 \cdot 10^{-7}$
Diffuse ν_μ [10]	ν_μ	807	0.016 - 2.5	$\leq 7.4 \cdot 10^{-8}$
UHE ν [11]	ν_e, ν_μ, ν_τ	457	0.200 - 1000	$\leq 2.7 \cdot 10^{-7}$
Cascades [41] (Baikal exp.)	ν_e, ν_μ, ν_τ	1038	0.020 - 20	$\leq 2.7 \cdot 10^{-7}$

Table 8: Comparison of this cascade analysis with published results from different diffuse analyses of the AMANDA experiment and of the Baikal experiment. The upper limit of the sensitivity is defined as $E^2\Phi \leq \dots$ GeVs⁻¹ sr⁻¹ cm⁻² at 90% C.L..

435 have more single hits for background muon bundles, whereas UHE neutrinos
 436 produce more multiple hits. In this analysis all three neutrino flavors are
 437 considered, which leads to a separation of cascade-like and muon-like events
 438 at higher reconstruction levels. After all selection criteria remain 1 data and
 439 1.3 background events yielding the excellent diffuse all-flavour neutrino flux
 440 limit.

441 The Baikal experiment has published a search for diffuse neutrinos [41]
 442 where data are analyzed taken between 1998 and beginning of 2003. Their
 443 cascade analysis has the advantage that the scattering of Cherenkov photons
 444 is rather small in the water of the Lake Baikal which allows the reconstruction
 445 of the shower direction. This results in an improved background suppression
 446 and in a total all-flavor flux limit which is slightly better than the limit of our
 447 analysis.

448 5. Conclusions

449 A search for neutrino-induced cascades in 1001 days of AMANDA data
 450 yielded a result consistent with cosmic ray induced atmospheric background.
 451 From this non-detection of an excess we derive an upper limit on the diffuse
 452 flux of astrophysical neutrinos with a spectrum $\Phi \propto E^{-2}$, as well as for
 453 other astrophysically motivated spectra. This analysis is sensitive to all three
 454 neutrino flavors. Since neutrino oscillations generally results in an equal flux
 455 of neutrinos of all three flavors at Earth [5], we constrain the total flux of

456 astrophysical neutrinos to $E^2\Phi \leq 5.0 \cdot 10^{-7} \text{ GeVs}^{-1} \text{ sr}^{-1} \text{ cm}^{-2}$ at 90% C.L.
457 for a neutrino energy spanning 40 TeV to 9 PeV.

458 As shown in Fig. 9, the limit from this five year analysis, which is mainly
459 sensitive to ν_e and ν_τ , provides competitive constraints on the flux of electron
460 neutrinos and on the flux of all neutrino flavors. These new results for the
461 limit and for the effective area are more stringent and supersede the older
462 ones based on the data taken in the year 2000.

463 Since 2005 the IceCube neutrino telescope [12] is under construction,
464 which once completed in 2011 will have an instrumented volume of one cu-
465 bic kilometer. The search for a diffuse neutrino flux using the signature of
466 isolated cascades is expected to significantly profit from the larger size and
467 the improved readout technology of IceCube. First results, however not a
468 limit, were presented for the 22 string IceCube data taken in 2007 [42]. For
469 astrophysical neutrinos when a 1-km³yr exposure is reached [43].

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