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Search for extraterrestrial point sources of high energy neutrinos with AMANDA-II using data collected in 2000–2002

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The results of a search for point sources of high energy neutrinos in the northern hemisphere using data collected by AMANDA-II in the years 2000, 2001, and 2002 are presented. In particular, a comparison with the single-year result previously published shows that the sensitivity was improved by a factor of 2.2. The muon neutrino flux upper limits on selected candidate sources, corresponding to an E_ν^{-2} neutrino energy spectrum, are included. Sky grids were used to search for possible excesses above the background of cosmic ray induced atmospheric neutrinos. This search reveals no statistically significant excess for the three years considered.

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I. INTRODUCTION

In this communication, we update a previously published search for high energy neutrino point sources from the data collected by AMANDA-II [1] in 2000 [2], using the three-year sample from 2000 to 2002. The sensitivity

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for the detection of point sources has constantly improved in AMANDA-II, starting from 1997 [3] and 1999 data [4], due to both detector performance and analysis technique improvements. The search for possible extraterrestrial high energy neutrinos assumes the signal has a $dN/dE_\nu \propto E_\nu^{-2}$ energy spectrum, as predicted by the Fermi acceleration mechanism. The atmospheric neutrinos which have a much steeper spectrum represent the background in which the signal is searched for.

This analysis, for most aspects similar to that presented and deeply discussed in [2], includes an effective requirement on the minimum energy of the reconstructed events which improves the sensitivity for high energy neutrino detection. Namely the sensitivity for this analysis is ~2.2 times better than previously obtained for the year 2000. This improvement is better than what would be expected from the longer exposure alone in the presence of background.

II. DATA ANALYSIS

The data used for this analysis were collected between the months of February and November in the years 2000, 2001 and 2002 (see Table I).

The experimental sample used in this analysis corresponds to a total of 607 days of live time and contains almost 5.6×10^9 triggers. Starting from 2002, a first level filter is performed at the south pole during data taking. The reduced amount of data is transferred via satellite to the northern hemisphere for analysis. After the application of an iterative maximum-likelihood reconstruction algorithm and the selection of tracks that are likely to be up going [5], about 0.45×10^6 events with reconstructed declination $\delta > -10°$ remain. Since AMANDA-II is located at the south pole, $\delta = 0°$ corresponds to horizontal and $\delta = 90°$ to vertical up-going directions. These events, containing mostly the residual component of atmospheric muons and a contribution of atmospheric neutrinos, were used as the experimental background against which the signal selection is optimized.

To avoid biasing the event selection the data were scrambled by randomizing the reconstructed right ascension (α) of each event. The optimization procedure used in this analysis is similar to that described in [2], the difference being in the choice of observables. Instead of a neural network parameter the number of hit optical modules for each event (number of channels or nch) is used, along with the reconstructed track length in the array and the likelihood ratio between the muon track reconstruction and a muon reconstruction constrained by using an atmospheric muon prior [6]. A full simulation chain, including neutrino absorption in the Earth, neutral current regeneration, muon propagation and detector response for the given data taking periods, is used to simulate point sources of muon neutrinos and antineutrinos [2]. Events are simulated at the center of each 5° band of declination (δ), according to an E_ν^{-2} energy spectrum. The final cuts on these observables and the optimum size of each circular search bin were independently determined for each declination band in order to have the strongest constraint on the signal hypothesis. This corresponds to the best sensitivity, i.e. the average flux upper limit obtained in an ensemble of identical experiments assuming no signal [7]. The resulting zenith-dependent median pointing resolution varies between 1.5° and 2.5°. The true directional information was then restored for the calculation of the limits.

TABLE I. The experimental live time and number of triggered events for each year used in this analysis. The triggered events may vary in different years mostly due to different cleaning procedures, which are mainly affected by the number of stable optical modules during the specific year.

Year	Live time (days)	Triggers
2000	197	1.34×10^9
2001	194	2.04×10^9
2002	216	2.17×10^9

The upper limits of this analysis were calculated using the background n_b measured using the events off source in the corresponding declination band, and the expected number of events, n_s, from a simulated point source of known flux $\Phi(E_\nu)$: $\Phi_{\mathrm{limit}}(E_\nu) = \Phi(E_\nu) \times \mu_{90}(n_{\mathrm{obs}}, n_b)/n_s$. Here n_{obs} is the number of observed events in the given source bin, and μ_{90} is the upper limit on the number of events following the unified ordering prescription of Feldman and Cousins [8]. The three years were analyzed both separately and as combined data samples.

The absolute normalization of the atmospheric neutrino simulation (with the flux from [9]) with respect to the selected experimental events was determined to be 1.03 ± 0.02 (statistical error only). The used flux was compared with several more recent calculations and confirmed that it gives a reasonable representation of the neutrino intensity over the range of energies and angles relevant for AMANDA-II. The response of AMANDA-II is such that most of the atmospheric neutrino signal comes from muon neutrinos and antineutrinos with energies between ~50 GeV and ~100 TeV [10,11]. The intrinsic theoretical uncertainty of the atmospheric neutrino flux in this energy region was taken to be about 30% [12,13], even if above 10 TeV it could be significantly higher. The overall experimental systematic uncertainty in the acceptance was evaluated using the down-going muon flux, and it is ~30% [14]. This includes the detector efficiency and the optical properties of the fiducial ice, needed for the detector simulation, which were determined using down-going muon data and *in situ* calibration lasers [15]. The absolute pointing accuracy, determined with coincident events between the SPASE air shower array [16] and AMANDA-II, is better than 1°, i.e. smaller than the angular resolution.

These systematic uncertainties do not affect significantly the limit calculations [2].

III. RESULTS

Figure 1 shows the calculated sensitivity versus declination for energies above 10 GeV. The event selection used produces a sensitivity which is fairly constant over all declinations. For $0° < \delta < 5°$ $[0 < \sin(\delta) < 0.09]$ the background contamination is 4 times higher than for $\delta > 5°$, and the sensitivity is poorer. For $\delta > 80°$ $[\sin(\delta) > 0.98]$, on the other hand, the solid angle aperture is small and the background evaluation is affected by higher relative statistical fluctuations.

The final three-year sample consists of 646 upward ($\delta > 5°$) reconstructed muons (see Table II). The predicted number of atmospheric neutrinos is 635. In the year 2000 alone, the number of selected events is 306, compared with the 601 (699 for $\delta > 0°$) in Ref. [2]. The difference between the two samples is due to the different choice of observables used for the selection optimization. In particular, the use of the nch observable, which is correlated to the energy released by the muon in the array and, ultimately, to the neutrino energy, selects ~26% higher median energies than those in [2] (from ~700 GeV to ~1 TeV for a single year). This selection is obtained at the price of removing a significant fraction of atmospheric neutrino events: for instance only 221 events in [2] would survive the new selection, 94% of which (i.e. 207) are also found in the new sample from the year 2000.

As shown in Table II the number of events in the final sample ($n_{\rm obs}$) is not the sum of the ones selected in the individual years, because the event selection has been reoptimized with the 3 times larger exposure. The energy cut becomes more stringent with increasing exposure and the median energy of the three-year selected sample is ~1.3 TeV (and extending up to ~100 TeV). Consequently the three-year sample contains ~40% fewer observed events than the sum of single years, but only ~17% of the high energy neutrino signal events are lost.

TABLE II. The number of observed events with $\delta > 5°$ after cut optimization, for each year and the combined three-year sample. The numbers relative to Ref. [2] are compatible with a normalization factor of ~0.86, for the atmospheric neutrino simulation, as quoted in the above reference. The numbers n_p of the predicted atmospheric and signal neutrino events (with signal energy spectrum of $d\Phi_{\nu_\mu}/dE_\nu = 10^{-6} \times E_\nu^{-2}$ cm^{-2} s^{-1} sr^{-1} GeV^{-1}) are also shown.

Year	$n_{\rm obs}$	$n_p(\nu_\mu^{\rm atm})$	$n_p(\nu_\mu^{\rm sig})$
2000 [2]	601	676	133
2000	306	296	111
2001	347	364	115
2002	429	429	131
2000–2002	646	635	297

The detector performance is assessed by the neutrino effective area $A_{\rm eff}^\nu(E_\nu, \delta)$, which contains the neutrino interaction probability, muon propagation, detector response and the analysis selection. It is defined by the relation between the differential neutrino flux $d\Phi_\nu/d\Omega dE_\nu$ and the predicted number of neutrino events $n_p(\nu)$, through the equation

$$n_p(\nu) = T_{\rm live} \cdot \int_\Omega \int_{E_\nu^{\rm min}}^{E_\nu^{\rm max}} A_{\rm eff}^\nu(E_\nu, \delta) \frac{d\Phi_\nu}{d\Omega dE_\nu} d\Omega dE_\nu. \quad (1)$$

Figure 2 shows the muon neutrino effective area as a function of neutrino energy for the three-year optimized selection. The curves are shown for different declinations.

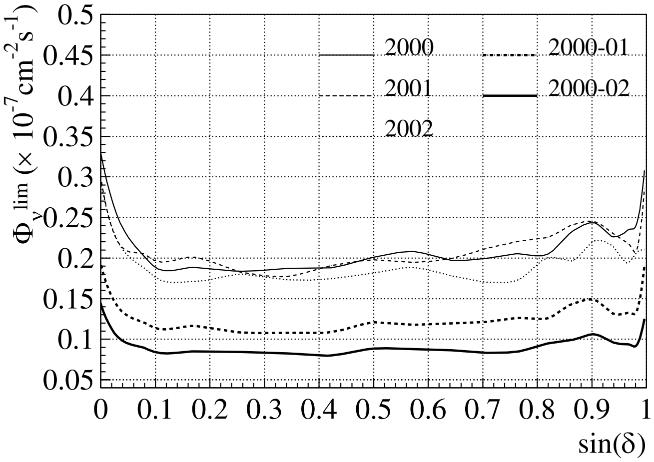

FIG. 1. Sensitivities on the integrated flux above $E_\nu = 10$ GeV as a function of declination and for an E_ν^{-2} energy spectrum. The sensitivities for the years 2000, 2001 and 2002 are compatible with each other, and shown along with the one for 2000–2001 and for the 2000-2002 three-year sample.

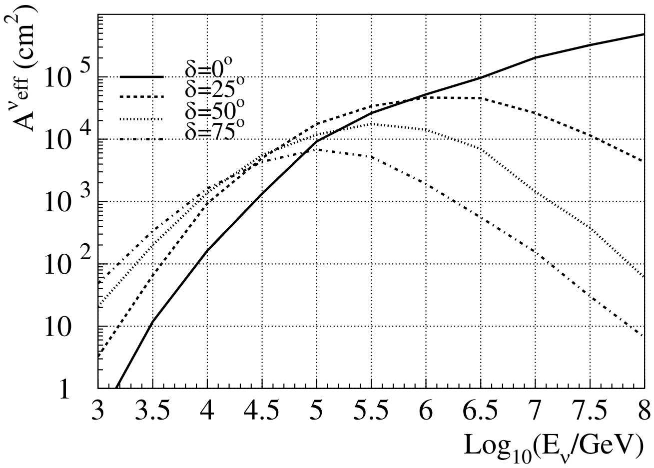

FIG. 2. Muon neutrino effective area as a function of the neutrino energy at different declinations. The effect of neutrino absorption in the Earth is responsible for the effective area decrease at high energies and declinations.

Above 10^6 GeV neutrinos begin to be absorbed by the Earth, except for the events that enter AMANDA-II horizontally. As shown in Table II we expect the present effective area to be smaller than in [2], nevertheless its overall reduction is more enhanced at low energies, where the signal is not expected to be particularly significant.

A binned search for excesses in the $5° < \delta < 85°$ region was performed on the three-year event sample. The search grid contains 290 rectangular bins with declination-dependent width ranging from 5.6° to 8.8°, based on the optimized search bin diameter. The grid is shifted 4 times in δ and α to fully cover boundaries between the bins of the original configuration. A higher number of grid shifts showed no improvement in the average maximum statistical significances on the simulated Poisson-fluctuated signal with intensities comparable to the background. The probability distribution for background fluctuations in the ensemble of bins was evaluated by using 20 000 experimental samples with scrambled α and calculating the highest value of the maximum statistical fluctuation significance over the entire sky.

TABLE III. 90% C.L. upper limits on candidate sources. Results from the present analysis are reported for a comparison with the limits from [2]. Limits are for the assumed E_ν^{-2} spectral shape, integrated above $E_\nu = 10$ GeV, and in units of 10^{-8} cm^{-2} s^{-1} ($\Phi_\nu^{\rm lim}$).

			From [2]			This work		
Candidate	$\delta(°)$	$\alpha(h)$	$n_{\rm obs}$	n_b	$\Phi_\nu^{\rm lim}$	$n_{\rm obs}$	n_b	$\Phi_\nu^{\rm lim}$
TeV Blazars								
Markarian 421	38.2	11.07	3	1.50	3.5	0	1.35	0.34
Markarian 501	39.8	16.90	1	1.57	1.8	3	1.31	1.49
1ES 1426+428	42.7	14.48	1	1.62	1.7	2	1.13	1.16
1ES 2344+514	51.7	23.78	1	1.23	2.0	1	1.25	0.82
1ES 1959+650	65.1	20.00	0	0.93	1.3	0	1.59	0.38
GeV Blazars								
QSO 0528+134	13.4	5.52	1	1.09	2.0	1	1.88	0.57
QSO 0235+164	16.6	2.62	1	1.49	1.7	3	2.15	1.12
QSO 1611+343	34.4	16.24	0	1.29	0.8	0	1.66	0.31
QSO 1633+382	38.2	16.59	1	1.50	1.7	1	1.33	0.75
QSO 0219+428	42.9	2.38	1	1.63	1.6	0	1.15	0.37
QSO 0954+556	55.0	9.87	1	1.66	1.7	2	1.04	1.50
QSO 0716+714	71.3	7.36	2	0.74	4.4	3	0.93	1.91
Microquasars								
SS433	5.0	19.20	0	2.38	0.7	1	2.21	0.55
GRS 1915+105	10.9	19.25	1	0.91	2.2	3	1.84	1.26
GRO J0422+32	32.9	4.36	2	1.31	2.9	2	1.49	1.08
Cygnus X1	35.2	19.97	2	1.34	2.5	0	1.59	0.31
Cygnus X3	41.0	20.54	3	1.69	3.5	1	1.26	0.75
XTE J1118+480	48.0	11.30	1	0.92	2.2	1	1.12	0.80
CI Cam	56.0	4.33	0	1.72	0.8	2	1.05	1.44
LS I +61 303	61.2	2.68	0	0.75	1.5	5	1.67	2.43
SNR, magnetars and miscellaneous								
SGR 1900+14	9.3	19.12	0	0.97	1.0	2	1.78	0.94
Crab Nebula	22.0	5.58	2	1.76	2.4	4	1.86	1.43
Cassiopeia A	58.8	23.39	0	1.01	1.2	2	1.12	1.38
3EG J0450+1105	11.4	4.82	2	0.89	3.2	1	1.83	0.59
M 87	12.4	12.51	0	0.95	1.0	3	1.83	1.24
Geminga	17.9	6.57	3	1.78	3.3	2	2.06	0.81
UHE CR Triplet	20.4	1.28	2	1.84	2.3	0	2.15	0.20
NGC 1275	41.5	3.33	1	1.72	1.6	1	1.14	0.78
Cyg. OB2 region.	41.5	20.54	3	1.72	3.5	1	1.14	0.78

The bin with the most statistically significant excess from the three-year experimental sample is at about $\alpha = 22h$ and $\delta = 21°$, with 10 observed events in the search bin on a background of 2.38 events, estimated from the corresponding declination band. The observed excess has a statistical significance of 1.9×10^{-4} (3.73σ). The chance probability of such an excess, in the ensemble of bins, is 28%.

Table III shows the 90% C.L. neutrino flux limits for northern hemisphere TeV blazars, selected GeV blazars, microquasars, magnetars and selected miscellaneous candidates. The limits are compared with the values from [2]; they are compatible with the average flux upper limit, or sensitivity, of Fig. 1 and the deviations from it are due to statistical fluctuations in the observed sample.

Figure 3 shows the 90% C.L. neutrino flux upper limits in equatorial coordinates. The limits are calculated by scanning the sky and counting the events within the optimized search bins at the given declination. The highest upper limit in the figure corresponds to the previously discussed statistically significant bin. Other high limit spots visible in the figure have statistical significances smaller than 3.4σ.

We analyzed the 2000–2002 data sample collected by the AMANDA-II detector to search for point sources of high energy neutrinos. We performed both a nontargeted

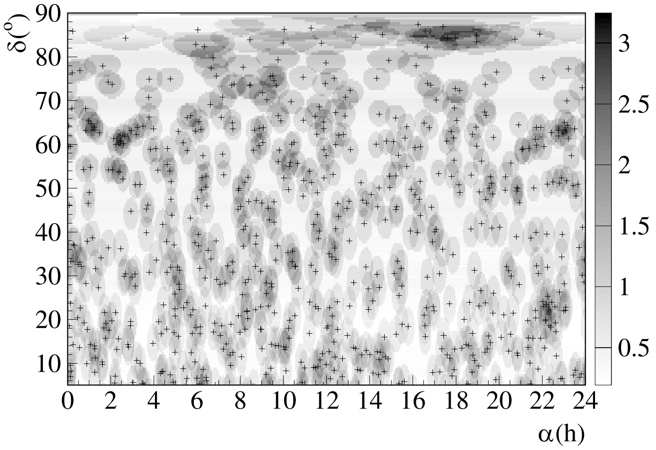

FIG. 3. 2000–2002 upper limits (90% C.L.) on the neutrino flux integrated above 10 GeV in equatorial coordinates for $\delta > 5°$. Limits (scale on right axis) are given in units of $\times 10^{-8}$ cm^{-2} s^{-1} for the assumed E^{-2} spectrum. Systematic uncertainties are not included. The cross symbols represent the observed events.

binned search and a targeted search focusing on known objects that are potential high energy neutrino emitters (as in Ref. [2]). The sensitivity on the neutrino flux integrated above $E_\nu = 10$ GeV is $\sim 9 \times 10^{-9}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. We found no evidence of a significant flux excess above the background. A km-scale experiment, such as IceCube [17], will be able to increase the detection sensitivity by at least a factor of 30 in the same time scale above 1 TeV.

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