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Neutrino astronomy with MACRO

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Abstract.

High energy neutrinos from astrophysical sources can be detected as upward-going muons produced in charged-current interactions with the matter surrounding the detector. We present the results of a search for either a diffuse astrophysical neutrino flux or a point-like source of neutrinos in the sample of upward-going muons gathered by MACRO. We find no evidence for either type of signal. The muon flux upper limit for the diffuse signal has been set at the level of $1.5\times10^{-14}\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$.

1 Neutrino astronomy: overview and motivation

High energy neutrinos in the range from 100 GeV up to 10^7 GeV are expected from a wide class of galactic and extragalactic astrophysical objects. Neutrino production requires the existence of hadronic processes and is generally described in the picture of the so-called *beam dump model* (Gaisser, 1995): high energy protons accelerated in proximity of compact objects by shocks waves or plasma turbulence interact with photons or target matter surrounding the source, producing pions. Neutrinos of electron and muon flavors originate from decay of charged pions, as well as from decay of generated muons. In the same hadronic chains, high energy γ-rays are expected to be produced through neutral pion decay. Like γ-rays, neutrinos can travel undeflected through the Universe. Neutrinos however are much less absorbed than photons and thus make a more powerful *tool* for astronomy searches. Many of the candidate sources of neutrinos (binary systems, supernovae remnants, AGNs, GRBs etc) have already been recognized as gamma rays emitters at energies higher than 100 GeV: this provides an important hint to neutrino astronomy, even if the observed γ-ray energies are not high enough to exclude the electromagnetic production mechanisms, such as synchrotron or inverse Compton processes. In this scenario, the detection of high energy neutrinos would open a new field of research, complementary to γ-ray astronomy and essential in order to investigate the inner structure of the most interesting cosmic objects.

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2 MACRO as a neutrino telescope

MACRO, located at the Gran Sasso Laboratories (Italy), was a large area multipurpose underground detector, formed by a rectangular box whose global dimensions were $76.6 \times 12 \times 9.3$ m^3 (Ahlen, 1995). The lower half of the apparatus was filled with rock absorber alternating with streamer tube planes for particle tracking; liquid scintillator layers, placed at the bottom, the center, the top and all around the detector provided time information for discriminating the direction of incoming particles. The large acceptance ($\sim 10^4$ m^2 sr for an isotropic flux), the good shielding of the site (the rate of cosmic ray muons is $\sim 10^{-6}$ times the surface rate), the fast timing (time resolution ~ 0.5 ns) and the good pointing capability (intrinsic angular resolution $\sim 0.5^o$) made MACRO suitable for working as a neutrino *telescope*.

The events induced by astrophysical neutrinos are expected to have a mean energy in the TeV range and above. Therefore, we employed the simulation tool developed in Bottai, 2001 for correctly handling the propagation of high energy muons up to the PeV energy region. It has been conceived to replace the muon transport software modules implemented in the package GEANT (Geant, 1994) used in the detector simulation program. Moreover, the detector response at high energy has been tested taking special care in verifying the reliability of the scintillator counter response by means of a dedicated calibration procedure. In fact, the information of the energy released in the scintillators by crossing particles is decisive for selecting a data sample of high energy events.

3 Search for a diffuse flux

Here we present the results of a search for a signal of diffuse neutrino flux from the whole sky by using the energy released in the MACRO scintillators. In particular this analysis aims to select a sample of very high energy upward-going muons, since at neutrino energies above some tens of TeV the predicted neutrino fluxes from astrophysical sources start to dominate the atmospheric neutrino background. The simulation of the upward-going muon events has been obtained by using the model by Stecker *et al.* (Stecker, 1991) for the photopion production of neutrinos in AGN core. Neutrino propagation through the Earth has been performed by solving the kinetic equation for the transport of neutrinos in dense media, following the approach suggested in Naumov, 1999. The deep inelastic cross sections have been calculated adopting the set of parton density functions provided by the CTEQ group [CTEQ3-DIS] (PDFLIB, 1997). The muon propagation in the rock surrounding the detector has been evaluated using the analytical formulas given in Lohmann, 1985 and Bottai, 2001. Following the analytical distributions, we have simulated a sample of 13305 upward-going muon events on the surface of a box containing the detector plus an additional layer of surrounding rock to take into account the shower entering the detector. By normalizing to the expected rate from the model by Stecker (4.45 events/year on the surface of this box) it gives a simulation equivalent time $T_{eq} = 2988.5$ years. Of these 13305 muon events, 7547 events reach the active detector hitting at least two scintillators in different layers. This was the minimum requirement to define an ”event”.

We adopt the following notation: taking as a reference the upper counter which measures the time T_1, the time of flight $\Delta T = T_2 - T_1$ is positive if the particle travels downward and it is negative if the particle travels upwards. Two or more adjacent scintillator hits on the same layer, at a maximum distance of 1 m and fired within a time window of 2 ns, form a *scintillator cluster*. Any association between a cluster and a single hit, as well as between two different clusters (provided that they are located on different layers) defines a *scintillator track* whose length is the geometrical distance between the positions of the center of each cluster. If a *cluster* contains more than one counter, its center is calculated by averaging the hit positions weighted with the released energy. For each *scintillator track*, we can then define the quantity $1/\beta = c\Delta T/L$ (L is the track length and c the speed of light) which in the above convention takes the value +1 for downward-going particles and -1 in the opposite case. The number of scintillator tracks associated to each event can be very large when the shower is very intense.

3.1 High energy event selection

The plot of Fig. 1 shows the distribution of the total energy released in the scintillators by the overall sample of simulated events (solid line) and by selected samples with initial energy greater than 1 TeV (dashed line), 10 TeV (dotted line) and 100 TeV (dash-dotted line). By initial energy we mean the energy of the muons when they enter the detector. Figure 1 shows how the initial energy and the released energy are correlated. Moreover, the degree of correlation becomes more and more marked with increasing energy, as expected from a theoretical calculation. The histogram in Fig. 1 results from the combined action of two processes, the increase with energy of the muon energy losses and the rapid decrease of the muon flux. The most perceptible maximum is then dominated by the high number of low energy particles mainly interacting through ionization while the second “bump” is populated by few high energy particles mainly interacting through radiative processes with large energy release. Figure 2 shows the effect of requiring more and more stringent conditions: at least one scintillator with a released energy greater than 500 MeV is fired in the event (light shaded area); at least two scintillators each one with a released energy greater than 500 MeV are fired in the event, with the further requirement that the geometrical distance between the associated hits is less than 1 m (dark shaded area); the above condition with the additional requirement of at least another scintillator with a released energy greater than 500 MeV placed on a different layer (black shaded area). Hereafter we will refer to the last condition as **cutE**. The value of 500 MeV has been chosen in order not to exceed the range of reliability of the scintillator response. A local large deposit of energy is very likely to occur as a result of a discrete radiative interaction, so that, as it can be seen from Fig. 2, the imposed cuts work in the direction of selecting the events contained in the “bump”. In order to discriminate the direction of the incoming events an algorithm based on the time-of-flight technique has been developed. The algorithm calculates the mean time associated with each scintillator layer involved in the event by averaging the scintillator times weighted with the corresponding released energy. After this, for any incoming event topology, it requires time coherence between at least two different layers. The condition by which an event is reconstructed as an upward-going muon will be called **cutD**. By imposing the described cuts 422 of 13305 upward-going muon events survived in the AGNs simulated sample.

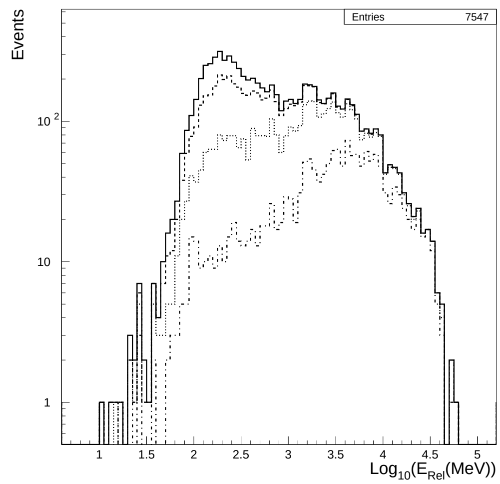

Fig. 1. The distribution of the total energy released in the scintillators by the overall sample of events (solid line) and by selected samples with initial energy greater than 1 TeV (dashed line), 10 TeV (dotted line) and 100 TeV (dash-dotted line).

3.2 Data analysis and results

The data used for this analysis were collected in the period from April 1994 to February 2000 (5.1 years, including efficiencies). After imposing the energy cut (**cutE**) and the direction cut (**cutD**) described in the previous section, 97 events overall survive. Further cuts have been decided in order to ensure the quality of timing information and improve the selection capability.

For each event, we define: *itot* as the number of scintilla-

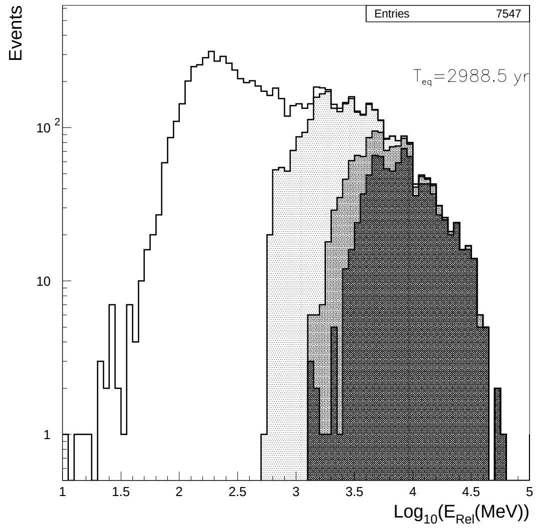

Fig. 2. The effect of more and more stringent cuts on the distribution of the total energy released in the scintillators (see text for comments). The black shaded area refers to **cutE**.

tor tracks whose length is greater than 2.5 m; *iup* as the number of scintillator tracks which verify the condition $-1.25 \leq 1/\beta \leq -0.75$; *idown* as the number of scintillator tracks which verify the condition $0.75 \leq 1/\beta \leq 1.25$.

The new set of analysis cuts can be summarized as below: **cutS** $\rightarrow$ a condition imposed to require enough statistics of scintillators tracks in order to have a significative evidence for an upward-going event. This is obtained by combining the following conditions, derived and tuned by Monte Carlo study: $itot > 20$ and $iup/itot > 0.3$ and $idown/iup < 0.1$. **cutQ** $\rightarrow$ a quality condition imposed in order to eliminate those events for which the scintillator timing is not guaranteed. This condition cannot be applied to the simulated data which don't reproduce this kind of inefficiency. Only one event finally survives the overall set of mentioned cuts. The simulated events have been processed in the same analysis chain as the data by correcting with a factor which takes into account the inefficiency related to the **cutQ**.

The results are summarized in Table 1. The only event found in the data sample is compatible with the signal expected from the atmospheric neutrino background. More details about the simulation of atmospheric neutrinos are in Montaruli, 2001. Moreover, the contribution due to neutrinos from the semileptonic decay of charmed hadrons (prompt neutrinos) has been estimated to stay within few percent of the conventional background signal, at least in the energy range in which this analysis is sensitive.

	Rate of survived events in 5.1 y
Atmospheric (MC)	0.94 ±0.51
Agn (MC)	0.43 ±0.03
DATA	1

Table 1. Expected rate of events surviving the overall set of cuts in 5.1 years of MACRO running. The data, the atmospheric background and the AGN neutrino flux [according to the model by Stecker *et al.* (Stecker, 1991)] are included in the table. Only the statistical errors of the simulation have been considered

3.3 The upper limit

The analyzed data show no evidence of a possible excess due to a diffuse neutrino flux from AGNs in the frame of the model by Stecker *et al.* The analysis presented here has been used to set a muon flux upper limit which can be calculated at a given confidence level, e.g. 90% c.l., as follows:

$$F_{\mu}^{L} = \frac{\text{Upper limit}(90\% c.l.)}{\epsilon \times \int Area(\Omega) d\Omega \times T_l} \qquad (1)$$

where the numerator is calculated from the number of measured events (1 event) in comparison with the expected background (0.94 event), according to the recent unified approach (Feldman, 1998). ϵ is the fraction of simulated AGNs events which survive the analysis cuts, $Area(\Omega)$ is the geometrical area seen by the diffuse flux as a function of the solid angle Ω (the integral extends to the lower Earth hemisphere) and $T_l = 5.1$ years is the considered MACRO running time. With these values the muon flux upper limit becomes:

$$\boxed{F_{\mu}^{L}(90\%\, c.l.) = 1.5 \times 10^{-14} \mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}} \qquad (2)$$

This limit can be finally converted into a (differential) neutrino flux upper limit. In order to compare our results with the upper limits given by other experiments, it is convenient to assume a power law spectrum with spectral index 2 for the initial neutrino flux. We have then weighted the number of survived events with the ratio between this spectrum and the spectrum calculated by Stecker. With these hypotheses, the neutrino flux upper limit from this analysis is $E^2 \cdot F_{\nu}^{L} = 4.1\ \times 10^{-6}\,\mathrm{GeV}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$. Actually, this value must be carefully handled because it is strongly affected by model assumptions (initial spectrum, neutrino cross sections and muon energy losses). Here, it has been estimated for comparison purposes. Figure 3 shows some theoretical predictions of neutrino fluxes from astrophysical sources and upper limits obtained by current experiments.

4 Search for point-like sources

Here we present the updated search for astrophysical point-like sources by using the direction information provided by the streamer tracking system [see (Ambrosio, 2001) for details on this analysis]. The results shown here concern the running period from March 1989 to April 1994 (when the detector was under construction) and the successive full detector running period which lasted until December 2000, when the acquisition was stopped. The total live time normalized to the full configuration is 6.16 years. We evaluate the background due to atmospheric neutrinos randomly mixing (for 100 times) the local angles of upward-going events with their times and smearing them by $\pm 10^{\circ}$ in order to avoid repetitions. We have considered the case of a possible detection of an unknown source represented by an excess of events clustered inside cones of half widths 1.5°, 3° and 5°. Hence we have looked at the number of events falling inside these cones around the direction of each of the 1356 measured events. We find 110 clusters of ≥ 4 muons inside 3° around a given

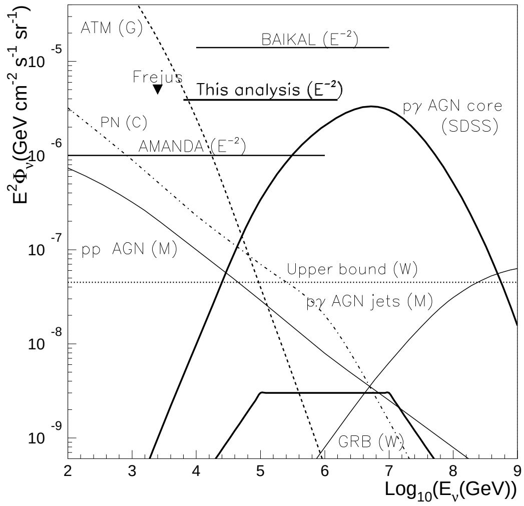

Fig. 3. Diffuse fluxes of $\nu_\mu + \bar{\nu}_\mu$ from AGNs and GRBs according to many predictions. SDSS: (Stecker, 1991); M: (Mannheim, 1995) W: (Waxman, 1997). The dashed curve refers to the angle average atmospheric neutrino flux (Gaisser, 1995); the dash-dotted line refers to the flux of prompt neutrinos according to one of the highest predictions given in Costa, 2001; the dotted line is the theoretical upper bound to neutrino flux from astrophysical sources as calculated in Waxman, 1997. Some current experimental upper limits are also shown: AMANDA (Halzen, 2000), Frejus (Rhode, 1996) and BAIKAL (Balkanov, 2000).

muon (including the event itself), to be compared with 107.8 expected from the background of atmospheric neutrinos. For our search among known point-sources, we have considered several existing catalogues and between them we have selected 42 sources we consider interesting (some AGNs are included in this list). We find no statistically significant excess from any of the considered sources with respect to the atmospheric neutrino background. For the 42 selected sources we find 12 sources with ≥ 2 events in a search cone of 3° to be compared to 14.3 sources expected from the simulation. The 90% c.l. muon and neutrino flux limits are shown in Fig. 4. The upper limits are calculated according to Feldman, 1998 and are valid for muon energies > 1 GeV. At very high energy the effective area can decrease due to electromagnetic showers. As a consequence, the analysis efficiency can decrease too, due to high track multiplicities for high energy events. From Monte Carlo studies, the detector average effective area begins to decrease for $E_\mu > 1$ TeV and it is about 20% (42%) lower at 10 TeV (100 TeV) than at 10 GeV. The limits are calculated for a neutrino spectrum with index = 2.1, taking into account the effect of the absorption of muon neutrinos in the Earth and the collection efficiency of the search half-cone of 3° for the expected signal. The limits lie in the range between $10^{-15} \div 10^{-13}\mathrm{cm}^{-2}\mathrm{s}^{-1}$; *e.g.* for MKN421 the limit is $3.48 \times 10^{-14}\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

5 Conclusions

We presented the results of a search for a signal of the diffuse neutrino flux from the whole sky by analyzing a sample of high energy events. One high energy upward-going candidate was selected which still remains compatible with the expected atmospheric neutrino background. The analyzed data have been used to set a muon and neutrino flux upper limit comparable with the recent results given by other experiments. Then we have shown the updated results on the search for point-like neutrino sources. No positive signal has been detected. The upper limits have been compared with the results obtained by other experiments.

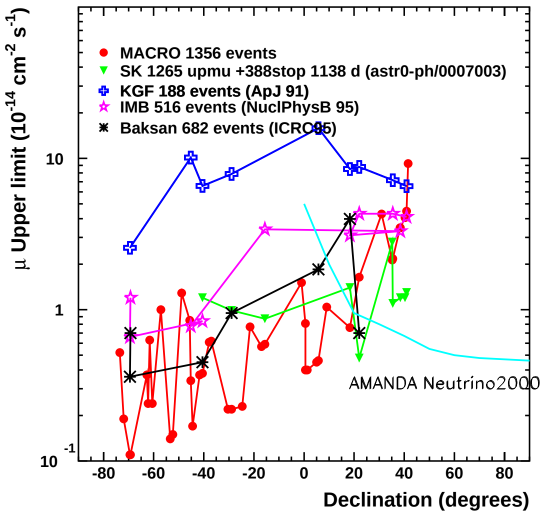

Fig. 4. MACRO 90% c.l. upward-going muon flux limits as a function of the declination of 42 selected sources (full dots). Other experiments limit for some sources are shown. All symbols are linked by solid lines to guide the eyes. The limits from AMANDA (Andres, 2000) cannot be directly compared to other experiments in this plot due to the much higher energy threshold.

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