Low Energy Atmospheric Neutrino Events in MACRO

A. Surdo[1] **for the MACRO Collaboration**
[1] *INFN Sezione di Lecce - Via Arnesano, I-73100 Lecce, Italy*

Abstract

The flux of low energy atmospheric neutrinos ($\overline{E}_\nu \sim 4\ GeV$) has been studied with the MACRO detector at Gran Sasso by detecting ν_μ interactions inside the apparatus, and by upward-going stopping muons. The updated analysis of the data collected until now with the complete apparatus will be presented. The results show a deficit of the measured number of events in an uniform way over the whole zenith angle with respect to Monte Carlo predictions. The deficit and the angular distributions, when interpreted in terms of neutrino oscillations, are consistent with the MACRO results on the much higher energy upward throughgoing muons ($\overline{E}_\nu \sim 100\,GeV$).

1 Introduction:

Recent results (Fukuda, 1998, Ambrosio, 1998a) have confirmed the anomaly in the atmospheric neutrino flux which was previously observed by several underground experiments (Casper, 1991, Fukuda, 1994, Allison, 1997). The suggested explanation for this anomaly is ν_μ disappearance due to neutrino oscillations, with maximum mixing and Δm^2 in the range of a few times 10^{-3} eV^2. The high energy ν_μ events have been deeply investigated by the MACRO experiment (Ronga, 1999). Here we report on the updated analysis (Bernardini, 1998, Spurio, 1998) of low energy ν events.

The MACRO detector (Ahlen, 1993) is a large rectangular box (76.6 m $\times$ 12 m $\times$ 9.3 m) whose active detection elements are planes of streamer tubes for tracking and liquid scintillation counters for fast timing. The lower half of the detector is filled with trays of crushed rock absorber alternating with streamer tube planes, while the upper part is open. The low energy ν_μ flux can be studied by the detection of ν_μ interactions inside the apparatus, and by the detection of upward going muons produced in the rock surrounding it and stopping inside the detector (Fig. 1a). Because of the MACRO geometry, muons induced by neutrinos with the interaction vertex inside the apparatus can be tagged with *time-of-flight* ($T.o.F.$) measurement only for upgoing muons ($IU\mu$=*Internal Upgoing* μ). The downgoing muons with vertex in MACRO ($ID\mu$=*Internal Downgoing* μ) and upward going muons stopping inside the detector ($UGS\mu$ = *Upward Going Stopping* μ) can be identified via topological constraints. Fig. 1b shows the parent neutrino energy distribution for the three event topologies detected by MACRO. The *Internal Upgoing* μ events are produced by parent neutrinos with energy spectrum almost equal to that of the *Internal Downgoing plus Upward Going Stopping* μ events.

2 Internal Upgoing Events (IU):

The data sample used for the Internal Upgoing (IU) events corresponds to an effective live-time of 4.1 years from April, 1994 up to February, 1999. The identification of IU events was based both on topological criteria and $T.o.F.$ measurements. The basic requirement is the presence of at least two scintillator clusters in the upper part of the apparatus (see Fig. 1a) matching a streamer tube track reconstructed in space. A similar request is made in the analysis for the up throughgoing events produced by ν_μ interactions in the rock below the detector (Ambrosio, 1998a).

For IU candidates, the track starting point must be inside the apparatus. To reject fake semi-contained events entering from a detector crack, the extrapolation of the track in the lower part of the detector must cross and not fire at least three streamer tube planes and one scintillation counter.

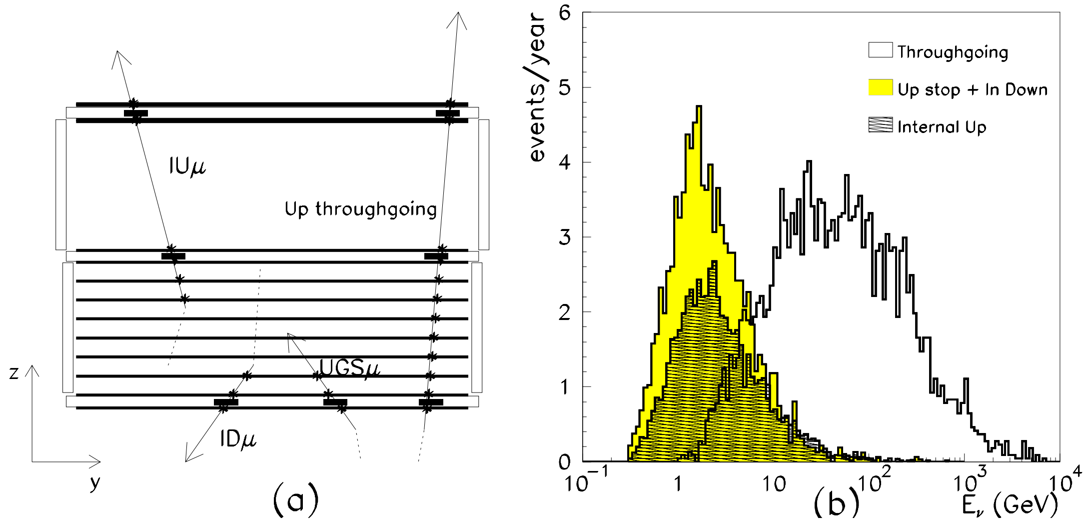

Figure 1: Left: sketch of different event topologies induced by neutrino interaction in or around MACRO. $IU\mu$= Internal Upgoing μ; $ID\mu$= Internal Downgoing μ; $UGS\mu$= Upgoing Stopping μ; Up throughgoing = upward throughgoing μ. In the figure, the stars represent the streamer tube hits, and the black boxes the scintillator hits. The $T.o.F.$ of the particle can be measured for the $IU\mu$ and up throughgoing events. Right: parent neutrino energy distribution for the three ν_μ samples.

The above conditions, tuned on the Monte Carlo simulated events, account for detector inefficiencies and reduce the contribution from upward throughgoing muons which mimic semi-contained muons to less than $\sim 1\%$. The measured $1/\beta$ distribution is shown in Fig. 2. The measured muon velocity βc is calculated with the convention that downgoing muons have 1/β near +1 while upgoing muons have 1/β near -1. It was evaluated that 5 events are due to an uncorrelated background. After the background subtraction, 116 events are classified as IU events.

3 Upgoing Stopping Events (UGS) and Internal Downgoing (ID):

The $UGS + ID$ events are identified via topological constraints, and not with the $T.o.F.$ For this analysis, the effective live-time is $4.1\ y$. The main request for the event selection is the presence of one reconstructed track crossing the bottom layer of the scintillation counters (see Fig. 1a). All the hits along the track must be confined at least one meter inside each wall of a MACRO supermodule. The selection conditions for the event vertex (or μ stop point) in the detector are symmetrical to those for the IU search, and reduce to a negligible level the probability that an atmospheric muon produces a background event. The main difference with respect to the IU analysis (apart from the $T.o.F.$) is that on average fewer streamer tube hits are fired. To reject ambiguous and/or wrongly tracked events which passed the event selection, a scan with the MACRO Event Display was performed. All the real and simulated events which passed the event selection were randomly merged. The accepted events passed a double scan procedure (differences are included in the systematic uncertainty).

The main background source is due to upward going charged particles (mainly pions) induced by interactions of atmospheric muons in the rock around the detector (Ambrosio, 1998b).

4 Comparisons between Data and Monte Carlo:

The expected rates were evaluated with a full Monte Carlo simulation. The events are mainly due to ν_μ

CC, with a contribution from NC and ν_e ($\sim 13\%$ for IU and $\sim 10\%$ for $UGS + ID$). The ν_e and ν_μ were allowed to interact in a volume of rock containing the experimental Hall B and the detector. The rock mass in the generation volume is $169.6\, kton$, while the MACRO mass is $5.3\, kton$. The atmospheric ν flux of the Bartol group (Agrawal, 1996) and the cross sections of Lipari 1995 were used. The detector response has been simulated using GEANT and simulated events are processed in the same analysis chain as the real data. In the simulation, the parameters of the streamer tube and scintillator systems have been chosen in order to reproduce the real average efficiencies. The total theoretical uncertainty on ν flux and cross section at these energies is of the order of 25%. The systematic error is of the order of 10%, arising from the simulation of detector response, data taking conditions, analysis algorithm efficiency, and the mass and acceptance of the detector. With our full MC simulation, the prediction for IU events is $202 \pm 20_{syst} \pm 50_{theor}$, while the observed number of events is $116 \pm 11_{stat}$. The ratio $R = (DATA/MC)_{IU} = 0.57 \pm 0.05_{stat} \pm 0.06_{syst} \pm 0.14_{theor}$. The prediction for $UGS + ID$ events is $274 \pm 27_{syst} \pm 68_{theor}$, while the observed number of events is $193 \pm 14_{stat}$. The ratio $R = (DATA/MC)_{UGS+ID} = 0.71 \pm 0.05_{stat} \pm 0.07_{syst} \pm 0.18_{theor}$. An almost equal number of UGS and ID neutrino induced events are expected in our data sample. Fig. 3 shows the angular distribution of the IU and $UGS + ID$ data samples, with the Monte Carlo predictions.

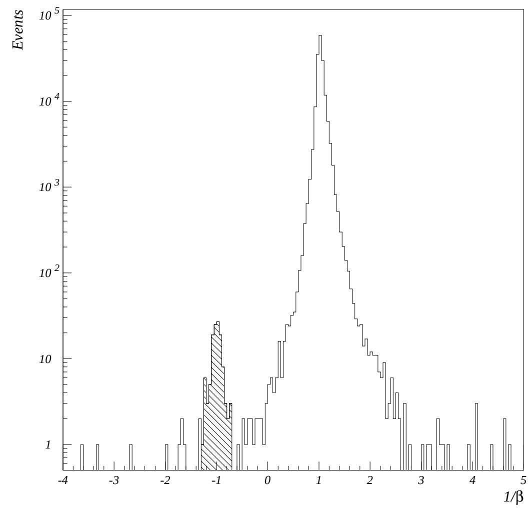

Figure 2: The $1/\beta$ distribution of the detected IU events (dashed area) after all analysis cuts. The remaining $\sim 1.6 \times 10^5$ are downgoing atmospheric stopping muons.

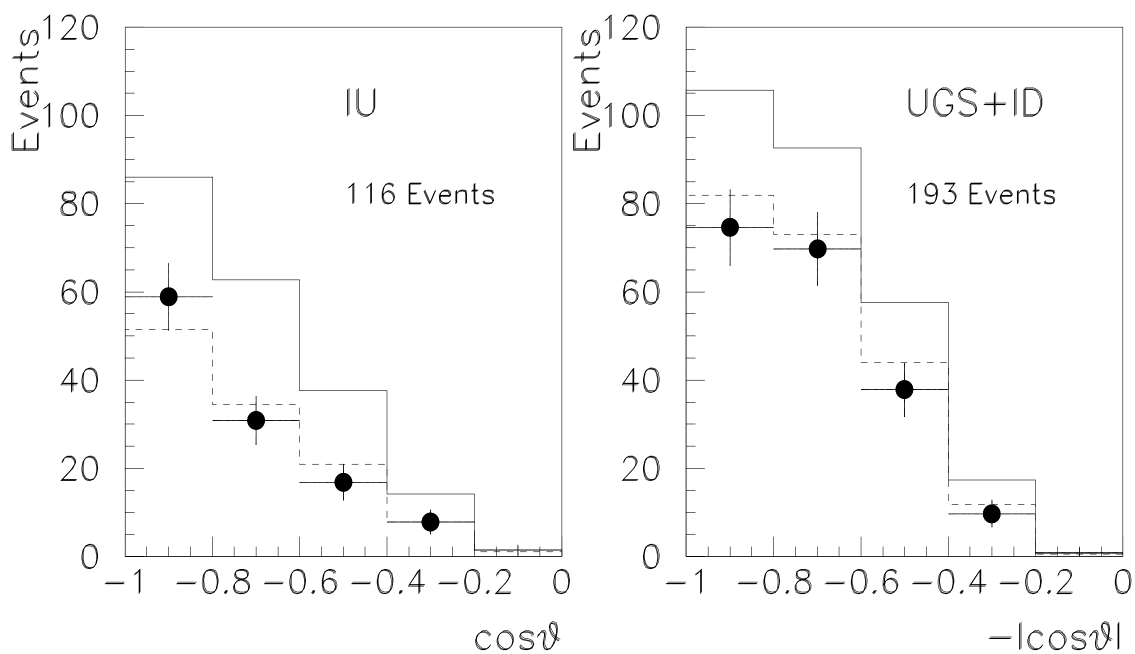

Figure 3: Zenith angle (θ) distribution for IU and $UGS + ID$ events. The background-corrected data points (black points with error bars) are compared with the Monte Carlo expectation assuming no oscillation (full line) and two-flavour oscillation (dashed line) using maximum mixing and $\Delta m^2 = 2.5 \times 10^{-3}\ eV^2$.

The low energy ν_μ samples show a deficit of the measured number of events over the whole angular distribution with respect to the predictions based on the absence of neutrino oscillations. The measured deficit of low-energy events is in agreement with the MACRO results on the throughgoing events (Ambrosio, 1998a, Ronga, 1999), *i.e.* with a model of ν_μ disappearence with $\sin^2 2\theta \simeq 1.0$ and $\Delta m^2 \sim 2.5 \times 10^{-3}\ eV^2$. In fact, the IU and UGS events have crossed the Earth ($L \sim 13000\ km$), and in the energy range of few GeV the flux is reduced by a factor of two for maximum mixing and $\Delta m^2 \sim 10^{-2} \div 10^{-3}\ eV^2$. No flux reduction is expected for ID events ($L \sim 20\ km$).

5 Ratio IU over $UGS + ID$ events:

Due to the large theoretical error arising from the uncertainties on absolute ν flux and cross section, the total number of events has a non negligible probability to be compatible with the no-oscillation hypothesis ($\sim 6.5\%$ for IU and $\sim 14\%$ for $UGS + ID$ events). On the other side, using the ratio between IU and $UGS + ID$ events, the theoretical error coming from neutrino flux and cross section uncertainties almost disappears. A residual 5% due to small differences between the energy spectra of the two samples survives. The systematic uncertainty on the ratio is also reduced to $\sim 6\%$ due to some cancellations. The value of that ratio over the zenith angle distribution obtained from data is shown in Fig. 4, where it is compared with MC expectation. The ratio between the total numbers of detected events is $R = 0.60 \pm 0.07_{stat}$, while $R = 0.74 \pm 0.05_{syst} \pm 0.04_{theor}$ is expected in case of no oscillation. The probability to obtain a ratio at least so far from the expected one is $\sim 6\%$ assuming Bartol as the true parent ν flux and taking into account the not Gaussian shape of the uncertainty on the ratio. In conclusion, the analysis of low energy ν events collected by MACRO shows a preference toward an oscillation model with parameters compatible with those suggested by the upward-throughgoing muon data.

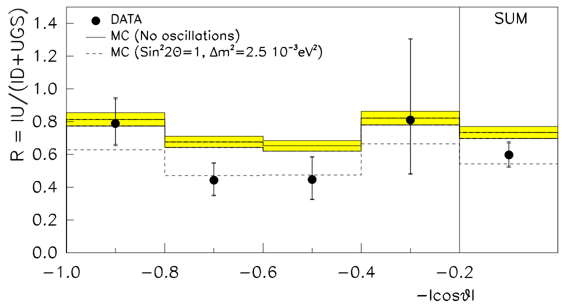

Figure 4: The $cos\theta$ distribution of the ratio between IU and $UGS + ID$ events. The data result is compared with Monte Carlo expectation assuming no oscillation (full line) and two-flavour oscillation (dashed line) using maximum mixing and $\Delta m^2 = 2.5 \times 10^{-3}\ eV^2$.

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