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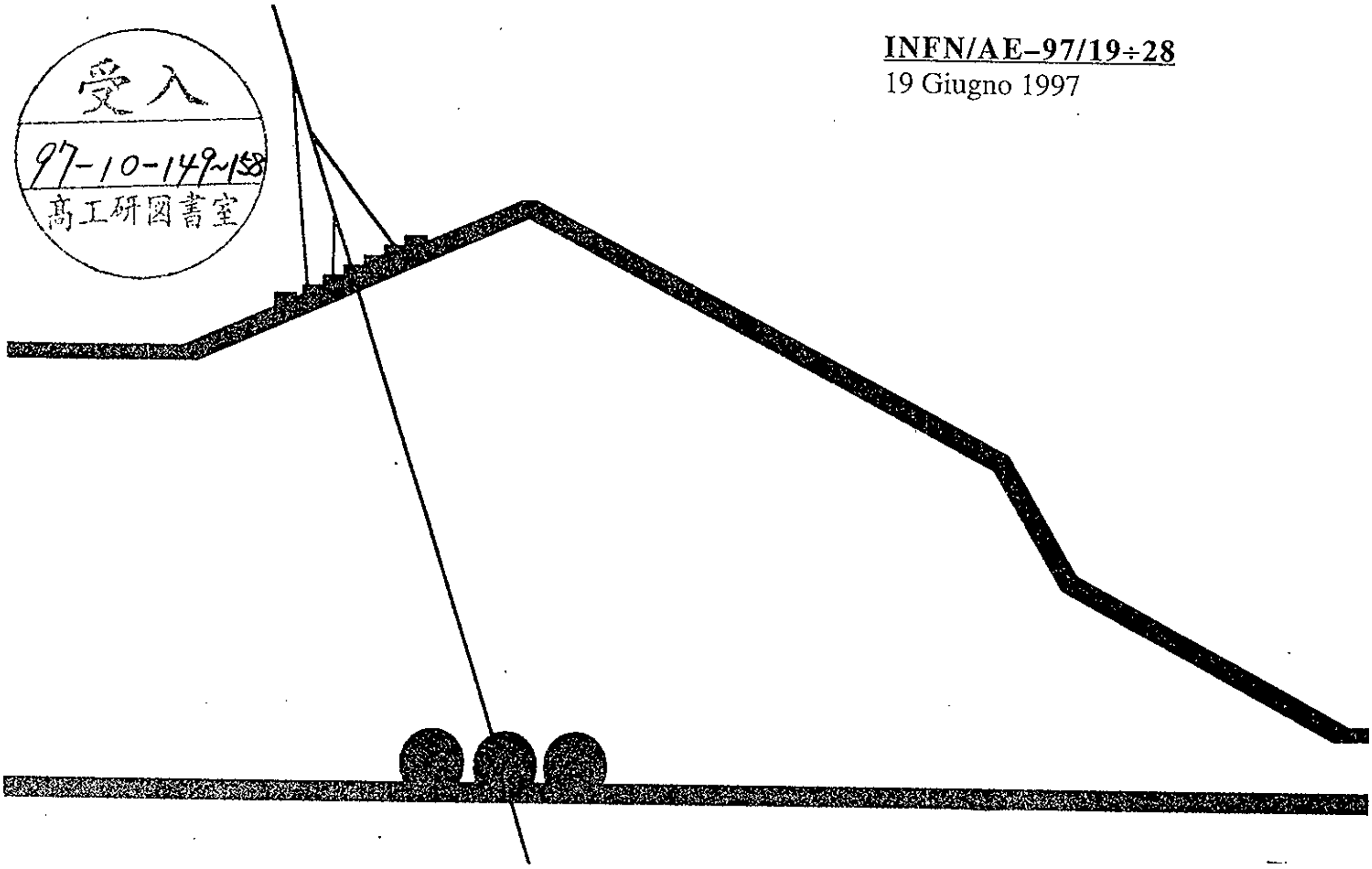

Contributions of the MACRO Collaboration to the 1997 Summer Conferences

INFN – Laboratori Nazionali del Gran Sasso

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The MACRO Collaboration

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THE MEASUREMENT OF THE ATMOSPHERIC MUON NEUTRINO FLUX USING MACRO

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ABSTRACT

The flux of muon neutrinos in the $1 - 1000\ GeV$ range has been measured with the MACRO underground detector. The measurement has been performed by means of the time-of-flight method to separate upward-going muons coming from neutrino interactions in the surrounding rock from downward-going muons coming directly from cosmic ray cascades. The data collected since March 1989 up to November 1996 are summarized. The zenith angular dependence of the measured upward-going muon flux is compared with the expected one assuming the Bartol atmospheric neutrino flux. Also upward-going muons generated inside the detector have been detected.

INTRODUCTION

Atmospheric neutrinos are produced in the cascade originated in the atmosphere by cosmic rays. A lower than expected ratio between atmospheric ν_μ and ν_e contained events has been measured by water Čerenkov experiments. This result has been seen as a clue of ν oscillation and the interest about precise measurements of the atmospheric neutrino flux increased in the last years.

The flux of ν_μ can be inferred from measurements of upward-going muons with underground detectors. The MACRO experiment (Ahlen et al., 1993), located in the Gran Sasso laboratory, is a proper tool for this measurement. The apparatus consists of 6 supermodules and has overall dimensions of $12 \times 77 \times 9\ m^3$. The bottom is filled with crushed rock absorber while the top is hollow (see Figure 1). The detection elements for muons are limited streamer chambers for tracking and liquid scintillator counters for fast timing. The intrinsic angular resolution is better than $0.5°$ and the time resolution is about $500\ ps$ for a single scintillator counter.

In MACRO the upward-going muon events due to interactions of ν_μ appear with three different topologies which are shown in Figure 1. Here we present the analysis of upward-throughgoing muon events, that is muons with enough energy ($E_\mu > 1\ GeV$) to cross the apparatus, produced in the rock outside the detector by ν_μ. The data collected in the period March 1989 - June 1993, when only lower parts of the apparatus were operative, have been already published (Ahlen et al., 1995). Now we present the data taken with the entire apparatus since April 1994 through November 1996 (life-time ~ 2.2 years). The statistics of the new data set is ~ 4 times higher than the previous one and the time measurement is better because the upper scintillator layers are now in data acquisition giving us three time measurements for throughgoing muons. Some preliminary results on partially contained muons produced by ν interactions (mean ν energy $\sim 2\ GeV$)

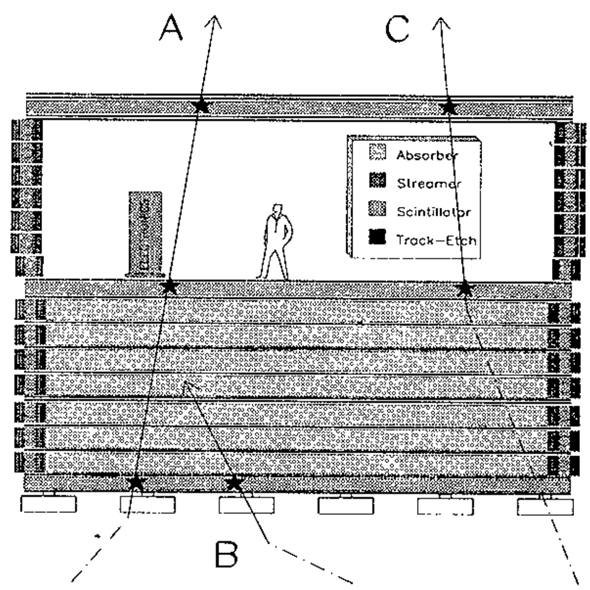

*Fig. 1: Cross section of the apparatus and topology of the upward-travelling tracks : (**A**) throughgoing, (**B**) stopping and (**C**) partially contained muons.*

inside the apparatus are also reported.

ANALYSIS PROCEDURE

The search for upward-going tracks is fully automated and based on the time-of-flight method. The fraction β of the light speed c is given by the following formula :

$$\frac{1}{\beta} = \frac{c \times (T_1 - T_2)}{L}, \quad (1)$$

where T_1 and T_2 are the times measured in the lower and in the higher scintillator planes, respectively, and L is the track length between the two scintillators. When the track hits three scintillator counters the time information is redundant and the β value can be calculated by means of a linear fit.

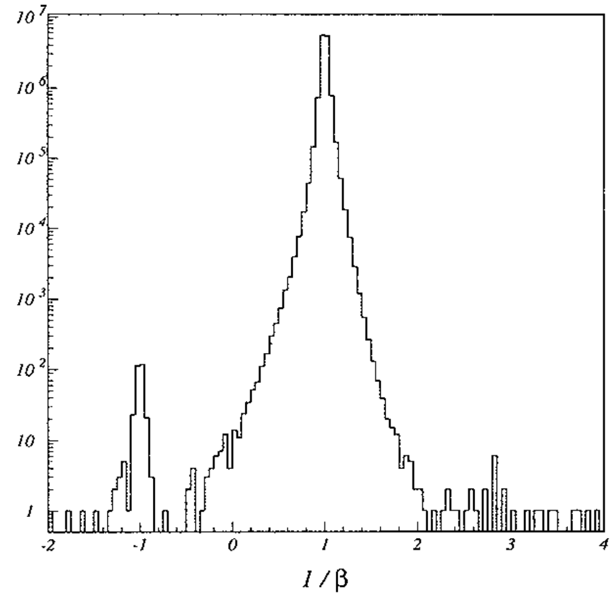

Fig. 2: $1/\beta$ distribution for throughgoing muons after the analysis cuts.

Looking at the $1/\beta$ value it is possible to get a rejection factor higher than the 10^6 necessary to separate a neutrino signal from muons directly produced by cosmic rays. In fact $1/\beta \simeq +1$ for particles going down through the detector and $1/\beta \simeq -1$ for upgoing particles. Some cuts have been used to remove background connected with radioactivity, stopping particles, multiple muons, showers and so on. A minimum path length (2.5 m) assures that the time of flight is sufficiently larger than the time resolution of the scintillator system. Furthermore the geometrical agreement between streamer track and scintillator hits is required. An angular cut for nearly horizontal tracks has been necessary because the shape of the mountain permits cosmic ray muons to reach the detector from below in a well defined azimuth angle range. Furthermore a cut requiring the crossing of at least 200 g/cm^2 of material in the apparatus has been introduced to reduce the background discussed in another talk of this conference (Spurio et al., 1997) due to charged upgoing particles produced at large angles by downgoing muons. A contamination of $\sim$ 1.5 % is expected to survive this cut.

The $1/\beta$ distribution after all cuts is shown in Figure 2. Two well separated peaks indicate the signals from above and from below. In the range $-1.25 < 1/\beta < -0.75$, 286 upward-going muons are present, including an estimated background of $\sim$ 4 events and the 1.5 % contamination previously quoted.

A new algorithm to search for partially contained tracks has been implemented. It is based on time-of-flight and on the check of the confinement of the interaction vertex in the detector. As a preliminary result 56 events have been found in the same data set here analyzed for throughgoing muons. In Figure 3 one of these events is shown. On the basis of Monte Carlo simulation $\sim$ 89 % of them are expected to come from ν_μ charged current and $\sim$ 11 % from ν_e and neutral current interactions.

SIMULATION

The simulation of the upward-going muon events has been performed assuming the Bartol neutrino flux (Frati et al., 1993; Agrawal et al., 1996), the muon energy loss calculated by Lohmann et al. (1985) for standard rock and the ν cross-section calculated by means of the Morfin and Tung parton distribution set S_1 (Morfin and Tung, 1991). The total error on the expected flux of muons at the detector due to uncertainties on these three quantities is ± 17 %.

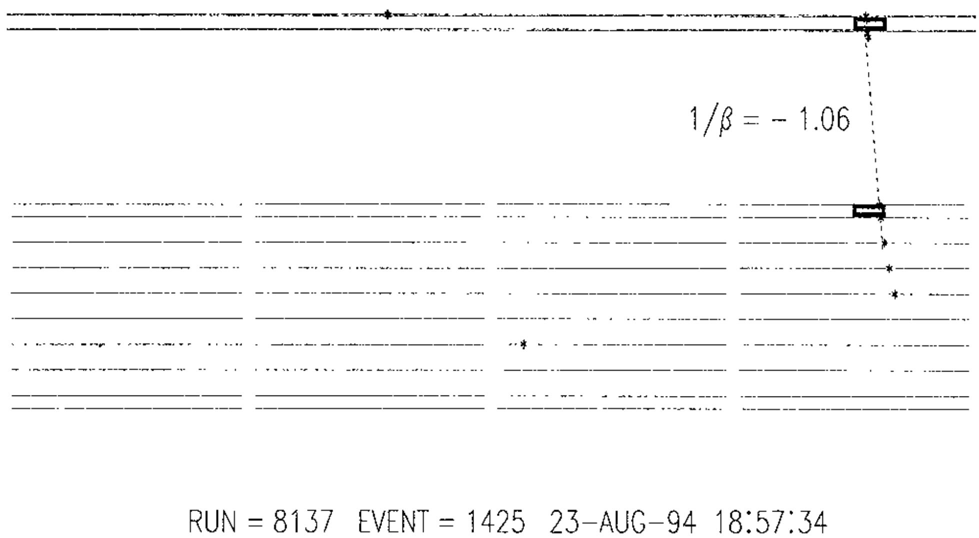

Fig. 3: An event with an upgoing muon generated by a neutrino interaction inside the apparatus. The rectangular boxes and the points indicate, respectively, scintillator counter and streamer tube hits. Only two supermodules of the apparatus are shown in one projective view.

The complete simulation of ν interaction and μ propagation in the rock surrounding MACRO has been implemented. The results of this new simulation do not differ from those of an older simulation in which the upgoing muons are simulated directly on the detector surface, in agreement with the analytically computed μ rate.

The apparatus and the data acquisition are fully reproduced in a GEANT (Brun et al., 1987) based Monte Carlo program and the simulated data are processed by means of the same automated analysis chain used for real data.

CONCLUSIONS

After the background subtraction the observed upward-throughgoing muons are $277 \pm 17_{stat} \pm 22_{syst}$. The 8 % systematic error is the sum of all acceptance errors and it has been evaluated by a thorough study of the downgoing muon sample. The expected number of events is $371 \pm 63_{theor}$. The ratio between observation and expectation is $0.75 \pm 0.05_{stat} \pm 0.06_{syst} \pm 0.13_{theor}$. Figure 4 shows the zenith angle distribution of the measured flux of upgoing muons compared with the expected one assuming an energy threshold of 1 GeV. Excluding the horizontal bin ($-0.1 < \cos\theta_{zenith}$) because of a possible contamination due to large angle scattering of downgoing

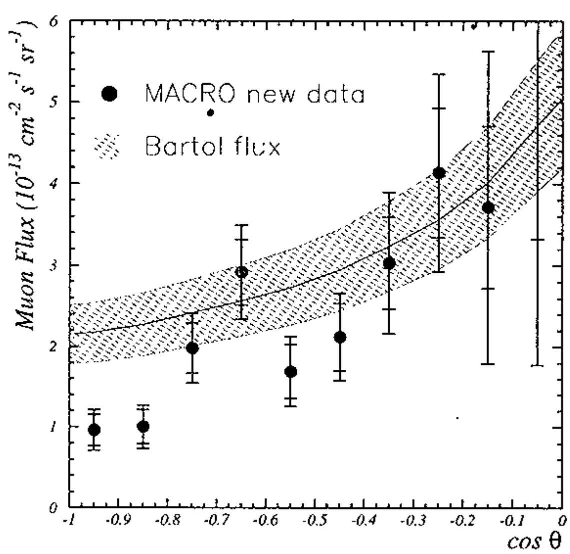

Fig. 4: Zenith distribution of the measured upgoing muon flux compared with the simulated one ($E_\mu > 1$ GeV). Data : April 1994 - November 1996.

muons, the experimental points have been fitted with the expected flux assuming the normalization factor as a free parameter. The normalization factor results to be 0.75 with a χ^2 probability $\sim$ 0.3 % (no ν oscillation assumed).

Taking into account also the published data (Ahlen et al., 1995) the results are not different. The ratio of the totals is $0.74 \pm 0.04_{stat} \pm 0.06_{syst} \pm 0.12_{theor}$. In Figure 5 the zenith angle distribution is shown for the entire MACRO data sample. The sum of the older and newer MACRO data does not modify significantly the shape of the observed flux.

We have to conclude that the total number of measured ν-induced muons may be compatible (8 % C. L.) with the expected number but the flux angular shape does not match the expectation. The deficit lies mainly in the vertical bins ($\cos\theta_{zenith} < -0.8$) just where the study of downgoing tracks reduces the uncertanties about the detector acceptance and efficiency. All checks performed on the downward-going muon data set confirm the accuracy of the claimed systematic errors. Different analysis approachs have been tested with the same results. On the other hand the distributions inferred from the $\nu_\mu \to \nu_\tau$ oscillation do not increase significantly the agreement between observed and calculated fluxes. More investigations about such a peculiar shape are necessary.

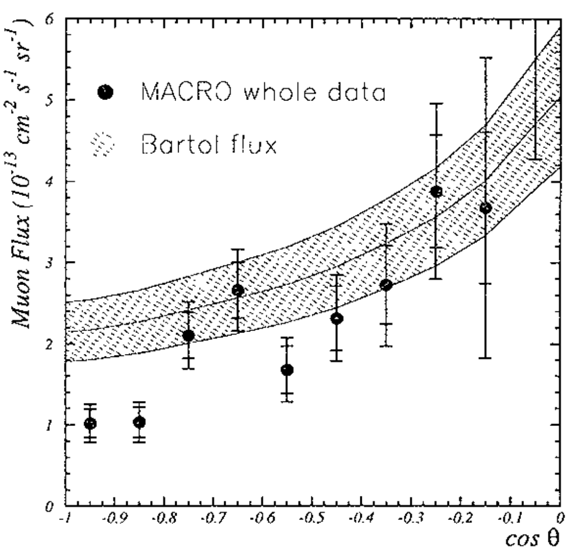

Fig. 5: Zenith distribution of the measured upgoing muon flux compared with the simulated one ($E_\mu > 1$ GeV). Data : March 1989 - November 1996.

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