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MACRO results on atmospheric neutrino oscillations

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Abstract. The final results of the MACRO experiment on atmospheric neutrino oscillations are presented. The data concern different event topologies with average neutrino energies of ~ 3 and ~ 50 GeV. Multiple Coulomb Scattering of the high energy muons was used to estimate the neutrino energy of each event. The angular distributions, the L/E_ν distribution, the particle ratios and the absolute fluxes all favour $\nu_\mu \to \nu_\tau$ oscillations with maximal mixing and $\Delta m^2 = 0.0023\,\mathrm{eV}^2$. A discussion is made on the Monte Carlos used for the atmospheric neutrino flux.

PACS. 13.15.+g ν interactions – 14.60.Pq ν mixing – 96.40.De CR composition energy spectra – 96.40.Tv ν and μ.

1 Introduction

MACRO was a large area multipurpose underground detector [1] designed to search for rare events and rare phenomena in the penetrating cosmic radiation. It was located in Hall B of the underground Gran Sasso Lab at an average rock overburden of 3700 m.w.e.; it started data taking with part of the apparatus in 1989; it was completed in 1995 and was running in its final configuration until the end of 2000. The detector had global dimensions of $76.6 \times 12 \times 9.3\,\mathrm{m}^3$ and provided a total acceptance to an isotropic flux of particles of $\sim 10,000\,\mathrm{m}^2\,\mathrm{sr}$; vertically it was divided into a lower part, which contained 10 horizontal layers of streamer tubes, 7 of rock absorbers and 2 layers of liquid scintillators, and an upper part which contained the electronics and was covered by 1 layer of scintillators and 4 layers of streamer tubes. The sides were covered with 1 vertical layer of scintillators and 6 of limited streamer tubes.
MACRO detected upgoing ν_μ's via charged current interactions, $\nu_\mu \to \mu$; upgoing muons were identified with the streamer tube system (for tracking) and the scintillator system (for time-of-flight measurement). The events measured and expected for the three measured topologies, deviate from Monte Carlo expectations without oscillations, Fig. 1; the deviations and the L/E_ν distribution point to the same $\nu_\mu \to \nu_\tau$ oscillation scenario [2]-[8], Fig. 2.

2 Atmospheric neutrinos: Monte Carlos

The measured data of Fig. 1 were compared with different MC simulations. In the past we used the neutrino flux computed by the Bartol96 group [9] and the GRV94 parton distribution. For the low energy channels the cross sections by P. Lipari *et al.* were used; the propagation of muons to the detector used the energy loss calculation by Lohmann *et al.* The total systematic uncertainty in the predicted flux of upthroughgoing muons, was estimated at $\pm 17\,\%$; this is mainly a scale error that does not change the shape of the angular distribution. The detector was simulated using GEANT. A similar MC (Honda96) was used by the SuperK Collaboration [10,11].
Recently new improved MC predictions were made available by the Honda [11] and Fluka [12] groups. They include three dimensional calculations of hadron production and decays and of neutrino interactions, improved hadronic model and new fits of the primary cosmic ray flux. The two MCs yield predictions for the non oscillated and oscillated ν_μ fluxes equal to within few % [8]. The shapes of the angular distributions for oscillated and non oscillated Bartol96, new Fluka and new Honda fluxes are the same to within few %. The absolute values of our upthroughgoing muon data are about $20-30\%$ above those predicted by the new Fluka and Honda MCs, Fig. 3. This situation is also true for the new SuperK data [10]. The high energy ν_μ data thus suggest that the new Honda and Fluka predictions should be raised, probably because of the used CR fit. The inclusion of the new ATTIC Collaboration measurements of primary CRs seems to lead to the old energy dependence of $E^{-2.71}$ [13]. Thus one may assume that the Bartol96 MC could still be used for the prediction of the absolute flux. It should be noted that the evidence for neutrino oscillations rests mainly with the shape of the angular distribution and this is the same in all MCs.

3 MACRO results on atmospheric neutrinos

The *upthroughgoing muons* come from ν_μ interactions in the rock below the detector; the ν_μ's have a median energy $\overline{E}_\nu \sim 50$ GeV; muons with $E_\mu > 1\,\mathrm{GeV}$ cross the whole

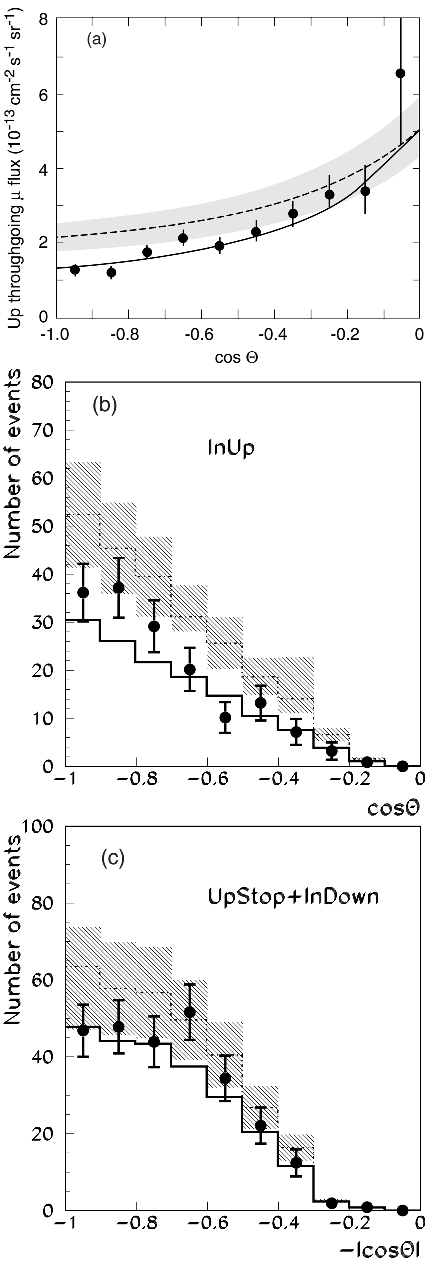

Fig. 1. Zenith distributions for the MACRO data (*black points*) for **a** upthroughgoing, **b** semicontained and **c** upstopping muons + down semicontained. The dashed lines are the no-oscillation Bartol96 MC predictions (*with scale error bands*); the solid lines refer to $\nu_\mu \rightarrow \nu_\tau$ oscillations with maximal mixing and $\Delta m^2 = 2.3 \cdot 10^{-3}$ eV^2

detector. A large number of possible systematic effects and backgrounds that could affect the measurements were studied, [3,8]. The data, Fig. 1a, deviate in shape and in absolute value from the Bartol96 MC non oscillated predictions.

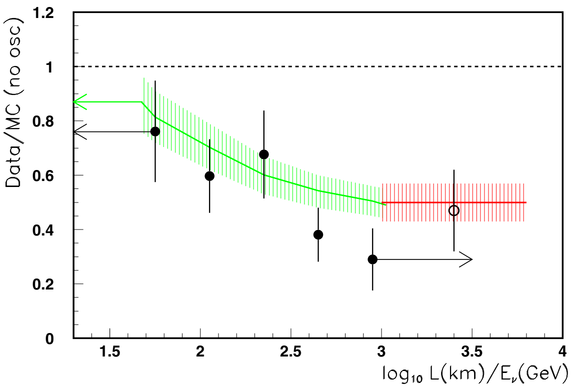

Fig. 2. Ratio (Data/MC Bartol96) as a function of the estimated L/E_ν for the upthrougoing muon sample (*black circles*) and the semicontained up-μ (*open circle*). The horizontal dashed line at Data/MC=1 is the expectation for no oscillations

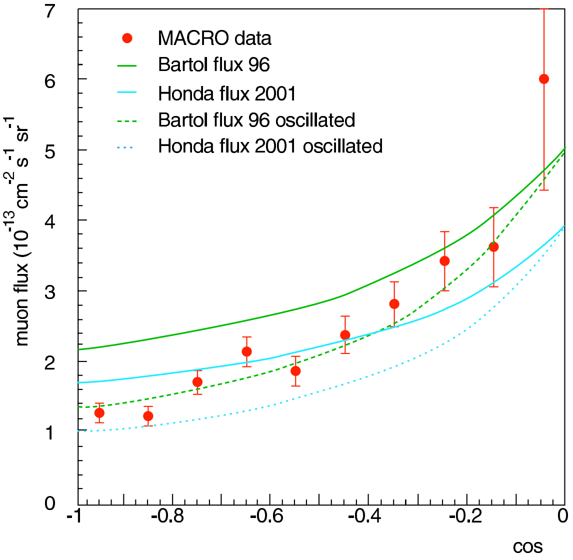

Fig. 3. Comparison of our measurements with the Bartol96 and the new Honda 2001 oscillated and non oscillated fluxes

$\nu_\mu \rightarrow \nu_\tau$ versus $\nu_\mu \rightarrow \nu_s$. Matter effects would produce a different total number and a different zenith angle distribution of upthroughgoing muons. The ratio R_1 = Vertical/Horizontal = $N(-1 < cos\theta < -0.7)/N(-0.4 < cos\theta < 0)$ was used to test the $\nu_\mu \rightarrow \nu_s$ oscillation hypothesis versus $\nu_\mu \rightarrow \nu_\tau$ [2,6,8]. The $\nu_\mu \rightarrow \nu_s$ oscillations (with any mixing) are excluded at about 99.8% c.l. with respect to $\nu_\mu \rightarrow \nu_\tau$ oscillations with maximal mixing [8].

Oscillation probability as a function of the ratio L/E_ν. E_ν was estimated by measuring the muon energy, E_μ, by means of the muon Multiple Coulomb Scattering (MCS) in the rock absorbers in the lower MACRO. The space resolution achieved is $\simeq$ 3 mm. For each muon, seven variables were given in input to a Neural Network (NN) trained to estimate muon energies with MC events of known input energy crossing the detector at different zenith angles. The distribution of the ratio $R = (Data/MC_{noosc})$ obtained by this analysis is plotted in Fig. 2 as a function of (L/E_ν) [7]. Notice that the data extend from $(L/E_\nu) \sim 30$ km/GeV to 5000 km/GeV.

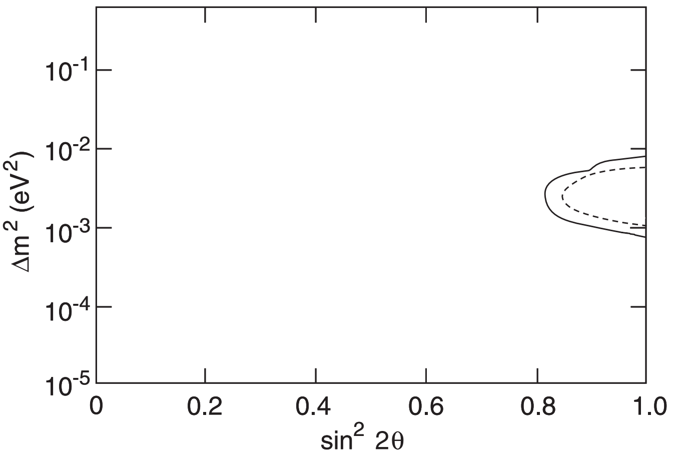

Fig. 4. Interpolated qualitative 90% C.L. contour plots of the allowed regions in the $\Delta m^2 - \sin^2 2\theta$ plane for the MACRO data using only the ratios R_1, R_2, R_3 (*outer continuous line*) and using also the absolute values assuming the validity of the Bartol96 fluxes (*dotted line*)

The *Internal Upgoing* (IU) muons come from ~ 4 GeV ν_μ's interacting in the lower apparatus. Compared to the no-oscillation prediction there is a reduction in the flux of these events, without distortion in the shape of the zenith distribution, Fig. 1b. The MC predictions for no oscillations in Fig. 1b and 1c are the dashed lines with a 21 % systematic band. At these energies the Bartol96, the new Honda and Fluka MCs agree well also in absolute values.

The *Upstopping* (UGS) muons are due to ~ 3 GeV ν_μ's interacting below the detector and yielding upgoing muons stopping in the detector. The *Semicontained Downgoing* (ID) muons are due to ν_μ-induced downgoing muon tracks with vertex in the lower MACRO. The two types of events are identified by topological criteria; the lack of time information prevents to distinguish the two sub-samples. The upgoing ν_μ's should all have oscillated completely, while the downgoing ν_μ do not. The zenith distribution shows, as expected, a uniform deficit of about 25 % of the measured number of events with respect to the no-oscillation prediction, Fig. 1c [5,8].

4 Determination of the oscillation parameters

In the past, in order to determine the oscillation parameters, MACRO made fits to the shape of the upthroughgoing muon distribution and to the absolute flux compared to the Bartol96 MC prediction. The other data were only used to verify the consistency and to make checks. The result was $\Delta m^2 = 0.0025$ eV^2 and maximal mixing. Later also the L/E_ν distribution was considered.

In order to reduce the effects of possible systematic uncertainties in the MCs (to about 6%) we now use the following three independent ratios [8].

(i) High Energy Data: zenith distribution ratio: $R_1 = N_{vert}/N_{hor}$
(ii) High Energy Data, neutrino energy measurement ratio: $R_2 = N_{low}/N_{high}$
(iii) Low Energy Data: Ratio $R_3 = (Data/MC)_{IU}/(Data/MC)_{ID+UGS}$.

The no oscillation hypothesis has a probability $P \sim 3 \cdot 10^{-7}$ and is thus ruled out by $\sim 5\sigma$. The formula used for combining independent probabilities is $P = P_1P_2P_3(1 - \ln P_1P_2P_3 + 1/2(\ln P_1P_2P_3)^2)$ [14]. By fitting the three ratios to the $\nu_\mu \to \nu_\tau$ oscillation formulae we obtain $\sin^2 2\vartheta = 1$, $\Delta m^2 = 2.3 \cdot 10^{-3}$ eV^2 and the allowed region indicated by the solid line in Fig. 4.
Assuming the validity of the Bartol96 flux we may also add the information on the absolute flux values of the

(iv) high energy data (systematic scale error of $\gtrsim$17%) $R_4 = N_{meas}/N_{MCBartol}$.
(v) low energy semicontained muons, with a systematic scale error of 21%, $R_5 \simeq N_{meas}/N_{MCBartol}$.

These informations reduce the area of the allowed region in the $\Delta m^2 - \sin^2 2\theta$ plane, as indicated by the dashed line in Fig. 4. The limit lines represent smoothed interpolations and are qualitative.

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