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Results on high-energy atmospheric neutrino oscillations with MACRO

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Abstract. The MACRO detector has measured 809 upward through-going muons induced by neutrinos of mean energy around 50 GeV from Mar. 1989 to 19 Dec. 2000 when the acquisition was stopped. Results on neutrino oscillations are shown favoring a $\nu_\mu \to \nu_\tau$ scenario with maximal mixing and $\Delta m^2 \sim 2.5 \cdot 10^{-3}$ eV^2 versus either no oscillations and $\nu_\mu \to \nu_{sterile}$ oscillations.

1 Neutrino measurement in MACRO and neutrino oscillation analysis

The MACRO detector, located in the Gran Sasso Laboratories, has a minimum rock overburden of 3150 hg/cm^2 which reduces the atmospheric muon flux by a factor of $\sim 5 \cdot 10^5$. MACRO's dimensions are 76.6 m $\times$12 m $\times$9.3 m. The lower 4.8 m high part is filled with rock absorber, which sets a minimum threshold for vertical muons of 1 GeV, alternating with 10 streamer tube layers used for tracking. The upper part is open and contains electronic racks covered by 4 streamer planes. There are 2 horizontal layers of liquid scintillators, at the bottom and at the top of the lower part, and a third horizontal layer in the upper part. All vertical walls are covered by scintillators. The time information provided by scintillator counters singles out the flight direction by the time-of-flight technique with a time resolution of ~ 600 ps. About 50% of tracks cross 3 scintillator counters with consequent redundancy in time measurement.

The neutrino oscillations have been studied using three neutrino event topologies in MACRO. Here we present the results of the high energy upward throughgoing events (median neutrino energy ~ 50 GeV) (Ahlen, 1995) induced by neutrinos in the rock below the detector. The results concern the whole MACRO data set, but we stress that we are still working on a global reanalysis of the whole data set in order to reduce further our experimental error. Final results will be presented in a future paper. The analysis of lower energy topologies (median neutrino energy ~ 4 GeV) are described in Ambrosio (2000) and Spurio (2001). A study based on multiple scattering to infer neutrino energy is in Sioli (2001) and neutrino astronomy results are in Perrone (2001).

Data were collected during the running period since March 1989 to April 1994 with the detector under construction and during the full detector run which lasted until Dec. 2000, when the acquisition was stopped (live time 5.52 yrs). Since the total live time normalized to the full configuration is 6.16 yrs, the statistics is largely dominated by the full detector run. This analysis of a data sample of more than 40 million atmospheric muons has achieved a rejection factor of the order 10^{-7} against the backgrounds caused by showering events and radioactivity in coincidence with muons. The main cut is the requirement that the position of a muon hit along a scintillator counter evaluated from timing agrees within ± 70 cm with that from streamer tube tracking.

A background induced by low-energy up-going particles (mainly pions) induced by undetected down-going muons in the rock surrounding the detector has been determined (Ambrosio, 1998). A cut requiring > 200 g/cm^2 of material crossed in the lower part of MACRO reduces it to the level of 1%. We exclude a region in azimuth angle from $-30°$ to $120°$ for horizontal up-going muons ($\cos\theta > -0.1$) due to insufficient rock overburden. For muons crossing 3 scintillator boxes a linear fit of the times as a function of the path length is performed and a cut is applied on the χ^2. Further minor cuts are applied to events crossing 2 counters.

In our convention, muons traveling downwards have the inverse of the velocity in units of the speed of light ($1/\beta = c\Delta t/L$, with Δt the time of flight and L the path length) around 1. On the other hand, upward-going muons have $1/\beta \sim -1$. We select upward-going muons requiring $-1.25 \leq 1/\beta \leq -0.75$. The $1/\beta$ distribution for the sample collected with the full detector is shown in Fig. 1. Based on the events outside the up-going muon peak we estimate a background due to incorrect β measurement of 22.5 events. We estimate that 14.2 up-going particles due to atmospheric

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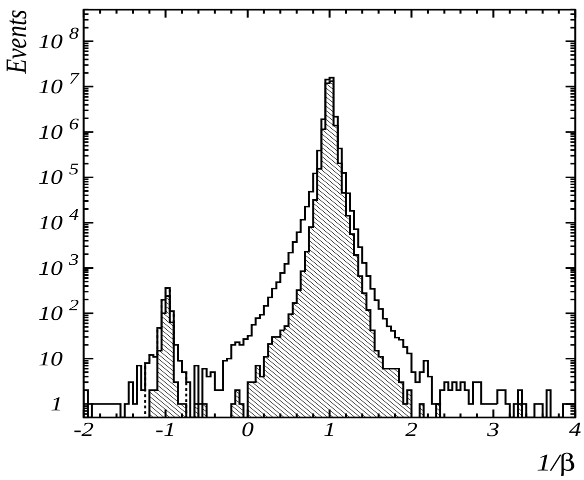

Fig. 1. $1/\beta$ distribution for the full detector run. The shaded area concerns events crossing 3 scintillator boxes. Two vertical dotted lines show the range $-1.25 < 1/\beta < -0.75$. There are $\sim 35.4 \cdot 10^6$ downgoing μs and 782 events in the upgoing μ $1/\beta$ range.

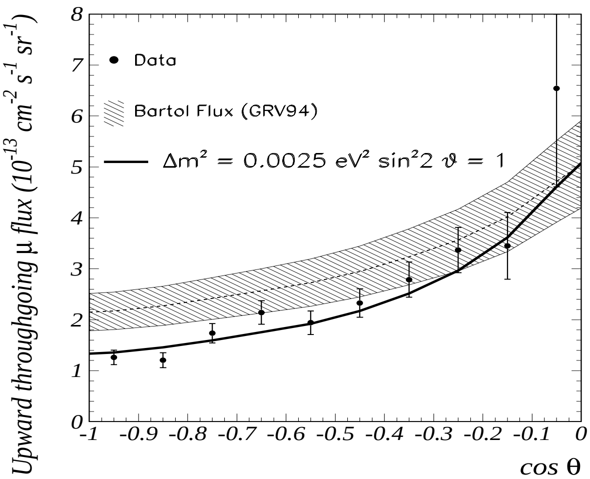

Fig. 2. Zenith distribution of the up-going muon flux ($E_\mu > 1$ GeV). The data sample is made of 809 events (background subtracted), the expected events are 1122.3 ± 190.7. Their ratio is $0.721 \pm 0.026_{stat} \pm 0.043_{sys} \pm 0.123_{th}$. Dots show the measured flux with the statistical and systematic errors in quadrature. The shaded area shows the theoretical error band of $\pm 17\%$ on the normalization of the Bartol flux (Agrawal, 1996) for no oscillations. The dashed line shows the prediction for an oscillated flux with $\sin^2 2\theta = 1$ and $\Delta m^2 = 0.0025$ eV^2.

muon interactions (Ambrosio, 1998) survive our cuts. Moreover 17 events are the result of neutrino interactions in the bottom scintillator layer, hence we exclude them from this analysis. We find 863 events with $-1.25 \leq 1/\beta \leq -0.75$, and 809 when subtracting the backgrounds.

The upward-going muon simulation is obtained using the Bartol group neutrino flux (Agrawal, 1996) and the GRV94 deep inelastic parton distributions (Glück, 1995), which increase the predicted flux by 1% with respect to the Morfin and Tung set S_1 (Morfin, 1991) we used in the past. For the low energy channels (quasi-elastic and 1π production) we use the cross sections in Lipari (1995). The muon propagation in the rock to the detector is performed using the energy loss calculated in Lohmann (1985) for standard rock. The estimated total systematic uncertainty on the predicted up-going muon flux is $\pm 17\%$, which affects mainly the normalization of the flux, not the shape of the angular distribution. The same cuts applied to the data are used for the simulated events and finally 1122 are selected. The ratio data/simulation is $0.721 \pm 0.026_{stat} \pm 0.043_{sys} \pm 0.123_{th}$. In Fig. 2 the measured and expected zenith angle distributions of the flux for up-going muons of energy $E_\mu > 1$ GeV are shown. A noticeable deficit of events in the region around the vertical can be noticed.

We have tested the shape of the angular distribution (10 bins) with the hypothesis of no neutrino oscillations normalizing the prediction to the data. The χ^2/d.o.f. is 25.9/9 and the resulting probability is 0.2%. In the hypothesis of two-family $\nu_\mu \rightarrow \nu_\tau$ oscillations the minimum χ^2 is 7.1 outside the physical region ($\sin^2 2\theta \in [0, 1]$). In the physical region we find $\chi^2_{min} = 9.7/9$ d.o.f. ($P = 37\%$) for maximum mixing and $\Delta m^2 \sim 0.0025$ eV^2. Combining the probabilities from the 2 independent tests on the zenith shape of the flux and on the total number of events (Roe, 1992), the maximum probability is 66% for $\Delta m^2 \sim 0.0024$ eV^2 and maximum mixing. Figure 3 shows the angular distribution of the ratio of measured and expected fluxes in the no oscillation hypothesis. The solid line is the ratio between the oscillated expected flux (for maximum mixing and $\Delta m^2 = 0.0025$ eV^2) and the no oscillated one.

As a cross-check, we have considered the events which cross 3 counters detected with the full configuration (shaded area in Fig. 1). The zenith distribution of the flux for the 3 box events reveals a deficit around the vertical as the one in Fig. 2. The $\chi^2/d.o.f.$ for the shape test and no oscillations is 9.4/7 (P = 22.8%) and for $\nu_\mu \rightarrow \nu_\tau$ oscillations with maximum mixing and $\Delta m^2 \sim 0.0025$ eV^2 we have $\chi^2/d.o.f. = 3.7/7$ (P = 81.5%).

The 90$\%$ c.l. regions, computed using the prescription in Feldman (1998), are shown in Fig. 4 for the test on the shape of the zenith distribution and the combined test of shape and total number of events. We stress that the region singled out by the shape analysis is independent of variations of the normalization of neutrino fluxes, which is the most relevant error in theoretical estimates. As a matter of fact, the angular distribution of the flux is known at the percent level (see Sec. 2). MACRO 90% c.l. regions are smaller than the Super-Kamiokande (SK) (Fukuda, 1999) one for throughgoing muons due to the different average energy thresholds (1.5 GeV for MACRO and ~ 6 GeV for SK). Given the lower threshold, the reduction seen by MACRO at the vertical is expected to be larger than the one in SK for the oscillation parameters in the allowed regions. Moreover the MACRO

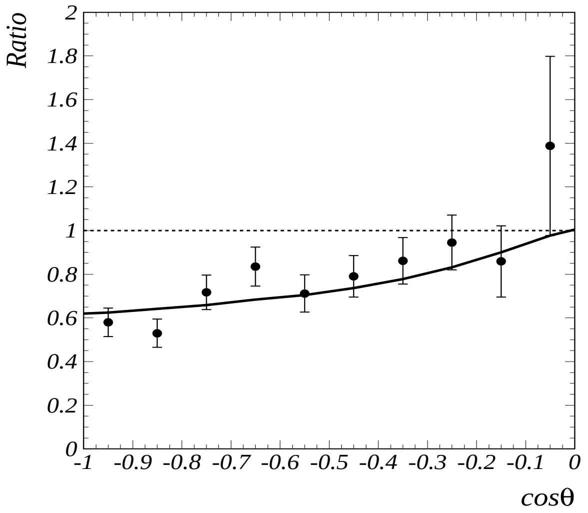

Fig. 3. Zenith distribution of the ratio of measured up-going muon flux in Fig. 2 over the expected one with no oscillations (dots with statistical and systematic errors in quadrature). The $\pm 17\%$ error on the normalization of the prediction is not shown. The solid line is the ratio between oscillated and no oscillated predicted fluxes. The dotted line corresponds to no oscillations.

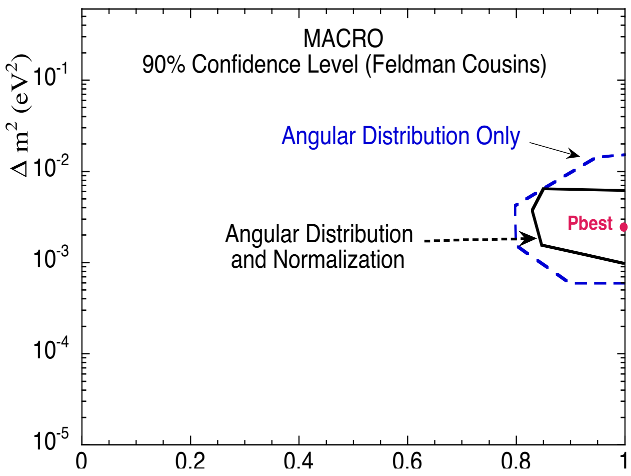

Fig. 4. MACRO 90% c.l. regions computed testing the shape of the angular distribution and this one combined with the total number of events (dashed line). Regions are computed as prescribed in Feldman (1998).

region is smaller due to the different methods used to compute the contour plots and because the absolute minimum is for $\sin^2 2\theta > 1$.

2 Matter effects. $\nu_\mu \rightarrow \nu_\tau$ against $\nu_\mu \rightarrow \nu_{sterile}$

Scenarios including a fourth light sterile neutrino could explain the 3 different experimental indications on Δm^2 coming from atmospheric neutrinos (Ahlen, 1995; Fukuda, 1999), from LSND (Athanassopoulos, 1998) and from solar neutrinos (Bahcall, 2000). Matter effects are relevant for $E_\nu/|\Delta m^2| \geq 10^3$ GeV/eV^2 (Akhmedov, 1993), hence for the high energy sample. Matter effects due to the difference between the weak interaction effective potential for muon neutrinos with respect to sterile neutrinos (which have null potential) produce different zenith angular distributions and total number of up-going muons. In Fig. 5 the reduction factors with respect to the no oscillation hypothesis for $\nu_\mu \rightarrow \nu_{sterile}$ and $\nu_\mu \rightarrow \nu_\tau$ (maximum mixing) are shown as an example for 2 values of Δm^2.

We have tested the two-family $\nu_\mu \rightarrow \nu_{sterile}$ hypothesis using the shape of the zenith distribution (Ambrosio, 2001). The best χ^2 is 20.1 (9 d.o.f.) and the combined best probability of the angular distribution and total number of event tests is 8% for maximum mixing and $\Delta m^2 = 0.006$ eV^2. A more powerful test was suggested (Lipari, 1998) and it is obtained by dividing the angular distribution into 2 bins instead of 10 because the difference between $\nu_\mu \rightarrow \nu_{sterile}$ and the $\nu_\mu \rightarrow \nu_\tau$ hypotheses is maximized. Moreover, while the χ^2 is not sensitive to the sign variations, the ratio is. Nevertheless, a possible drawback with respect to the χ^2 test is that some features of the angular distribution could be lost. In order to understand which binning of the ratio of events maximizes the power of the test we have used a simulation of many 'MACRO equivalent' experiments varying the binning. In Fig. 6 we show the ratio which has been chosen as the events with $\cos\theta < -0.7$ over those with $\cos\theta > -0.4$. In doing this ratio, most of the theoretical errors on neutrino flux and cross section affecting the ratio cancel. The error comes from a 3% contribution due to uncertainties on the kaon/pion fraction produced in the atmospheric showers and from a 2% of uncertainty on the cross sections due to the different energy distributions of almost vertical and horizontal events. Another error comes from seasonal variations of the atmosphere, which are not exactly taken into account in upward-going neutrino simulations, and to the fact that the flux is computed using the standard United State atmosphere (Agrawal, 1996). This implies that changes of the atmosphere with latitude and with temperature, which cause variations in particle yields due to decays and interactions, are not properly included. We notice that high energy atmospheric muon rates observed by MACRO at $42°$ North latitude change by $\pm 1.5\%$ between winter and summer (Ambrosio, 1997), while AMANDA at the South Pole has observed variations of $\pm 10\%$ (Bouchta, 1999). The evaluation of the seasonal variations in the atmospheric neutrinos producing upward-going muons in experiments is a more difficult task than for atmospheric muons because the atmosphere should be known at almost all latitudes and at various heights. A very preliminary evaluation gives an error due to seasonal variations on the ratio of vertical/horizontal ν events of about $\pm 2.5\%$. We estimate a total theoretical error of $\leq 5\%$.

The systematic experimental error on the ratio is 4.6% due to analysis cuts and detector efficiencies. Combining the ex-

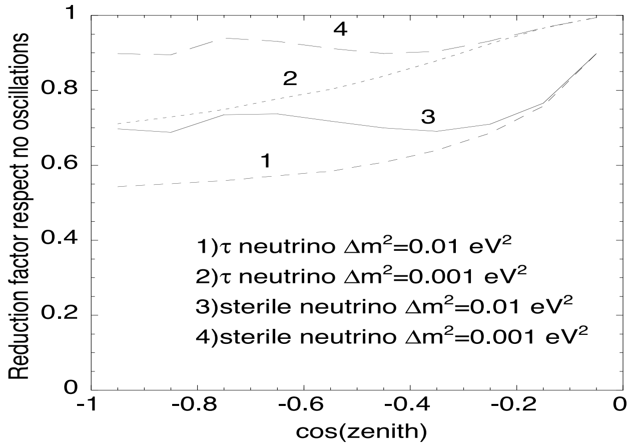

Fig. 5. Reduction factors respect to no oscillations as a function of the cosine of the zenith for maximum mixing and $\Delta m^2 = 0.01$ and 0.001 eV^2 for $\nu_\mu \to \nu_\tau$ and $\nu_\mu \to \nu_{sterile}$.

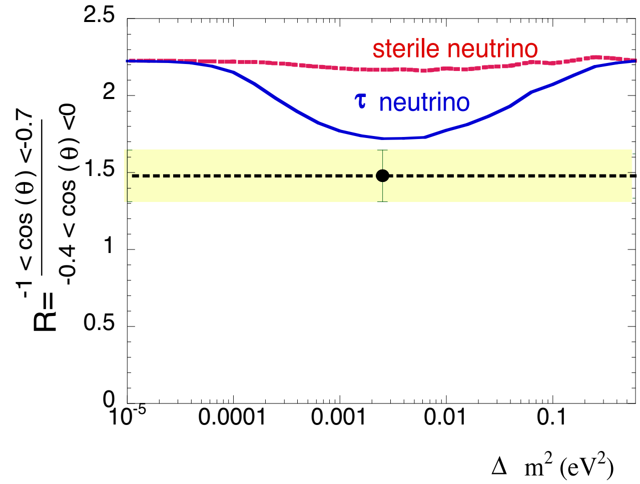

Fig. 6. Ratio of events with $-1 < \cos\theta < -0.7$ to those with $-0.4 < \cos\theta < 0$ as a function of Δm^2 and $\sin^2 2\theta = 1$. The dashed line guides the eye for the experimental value represented by a dot with statistical and systematic error. The solid line is for $\nu_\mu \to \nu_\tau$ and the dotted one for $\nu_\mu \to \nu_{sterile}$.

perimental and theoretical errors in quadrature we obtain the conservative estimation of 7%.

There are 305 events with $\cos\theta \le -0.7$ and 206 with $\cos\theta \ge -0.4$ and the ratio is $R_{meas} = 1.48 \pm 0.13_{stat} \pm 0.10_{sys}$. The minimum expected value of the ratio for $\nu_\mu \to \nu_\tau$ is $R_{\tau_{min}} = 1.72$ for $\Delta m^2 = 0.0025$ eV^2 and for $\nu_\mu \to \nu_{sterile}$ is $R_{sterile_{min}} = 2.16$ for about the same value of Δm^2 (even if, as can be seen in Fig. 6, the dependence of the ratio for sterile neutrino oscillations on Δm^2 is quite flat) both for $\sin^2 2\theta = 1$. The ratio does not have a Gaussian distribution, while the errors reported here are calculated for Gaussians so they should be considered as a crude indication of the statistical significance. The corresponding 1-sided maximum probabilities P_{best} to find a value of $R_{\tau_{min}}$ smaller than R_{exp} in the hypothesis that the true value is $R_{\tau_{min}} = 1.72$ is $P_{best_\tau} = 9.4\%$. In the case of the sterile neutrino it is $P_{best_{sterile}} = 0.06\%$. Hence the ratio of the probabilities is $P_{best_\tau}/P_{best_{sterile}} = 157$ so that $\nu_\mu \to \nu_{sterile}$ oscillations (for any mixing) are excluded at $\sim 99\%$ c.l. compared to the $\nu_\mu \to \nu_\tau$ channel with maximum mixing. In the calculations we have correctly included the non Gaussian distribution of the ratio. Similar results from SK have been published in Fukuda (2000).

3 Conclusions

MACRO data consistently favor $\nu_\mu \to \nu_\tau$ oscillations and a maximum probability of 37% is obtained for maximum mixing and $\Delta m^2 \sim 0.0025$ eV^2 for the high energy sample. Using a test based on the ratio of almost vertical/horizontal events we show that MACRO disfavors $\nu_\mu \to \nu_{sterile}$ oscillations at 99% c.l. with respect to the parameter space point corresponding to the maximum probability for $\nu_\mu \to \nu_\tau$.

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