V

Neutrino Oscillations at High Energy by MACRO

Abstract

We present updated results of the measurement of upward-going muons produced by neutrino interactions in the rock below the MACRO detector. These data support MACRO's previously published results. They favor a neutrino oscillation explanation of the atmospheric neutrino anomaly.

1   Introduction:

The interest in precise measurements of the flux of neutrinos produced in cosmic ray cascades in the atmosphere has been growing over the last years due to the anomaly in the ratio of contained muon neutrino to electron neutrino interactions. The past observations of Kamiokande, IMB and Soudan 2 are now confirmed by those of SuperKamiokande, MACRO and Soudan2 (with higher statistics) and the anomaly finds explanation in the scenario of ν_μ oscillation (Fukuda 1998a). The effects of neutrino oscillations have to appear also in higher energy ranges. The flux of muon neutrinos in the energy region from a few GeV up to a few TeV can be inferred from measurements of upward throughgoing muons (Ahlen 1995,Ambrosio 1998b,Hatakeyama 1998, Fukuda 1998b). As a consequence of oscillations, the flux of upward throughgoing muons should be affected both in the absolute number of events and in the shape of the zenith angle distribution, with relatively fewer observed events near the vertical than near the horizontal due to the longer path length of neutrinos from production to observation.

Here an update of the measurement of the high energy muon neutrino flux is presented. The new data are in agreement with the old data. The MACRO low energy data are presented in another paper at this conference (Surdo 1999).

2   Upward Throughgoing Muons:

The MACRO detector is described elsewhere (Ahlen 1993, Ambrosio 1998b). Active elements are streamer tube chambers used for tracking and liquid scintillator counters used for the time measurement. The direction that muons travel through MACRO is determined by the time-of-flight between two different layers of scintillator counters. The measured muon velocity is calculated with the convention that muons going down through the detector are expected to have $1/\beta$ near +1 while muons going up through the detector are expected to have $1/\beta$ near -1.

Several cuts are imposed to remove backgrounds caused by radioactivity or showering events which may result in bad time reconstruction. The most important cut requires that the position of a muon hit in each scintillator as determined from the timing within the scintillator counter agrees within ±70 cm with the position indicated by the streamer tube track.

When a muon hits 3 scintillator layers, there is redundancy in the time measurement and $1/\beta$ is calculated from a linear fit of the times as a function of the pathlength. Tracks with a poor fit are rejected. Other minor cuts are applied for the tracks with only two layers of scintillator hit.

It has been observed that downgoing muons which pass near or through MACRO may produce low-energy, upgoing particles. These could appear to be neutrino-induced upward throughgoing muons if the down-going muon misses the detector (Ambrosio 1998a). In order to reduce this background, we impose a cut requiring that each upgoing muon must cross at least 200 g/cm^2 of material in the bottom half of the detector. Finally, a large number of nearly horizontal ($\cos\theta > -0.1$), but upgoing muons have been observed coming from azimuth angles corresponding to a direction containing a cliff in the mountain where the overburden is insufficient to remove nearly horizontal, downgoing muons which have scattered in the mountain and appear
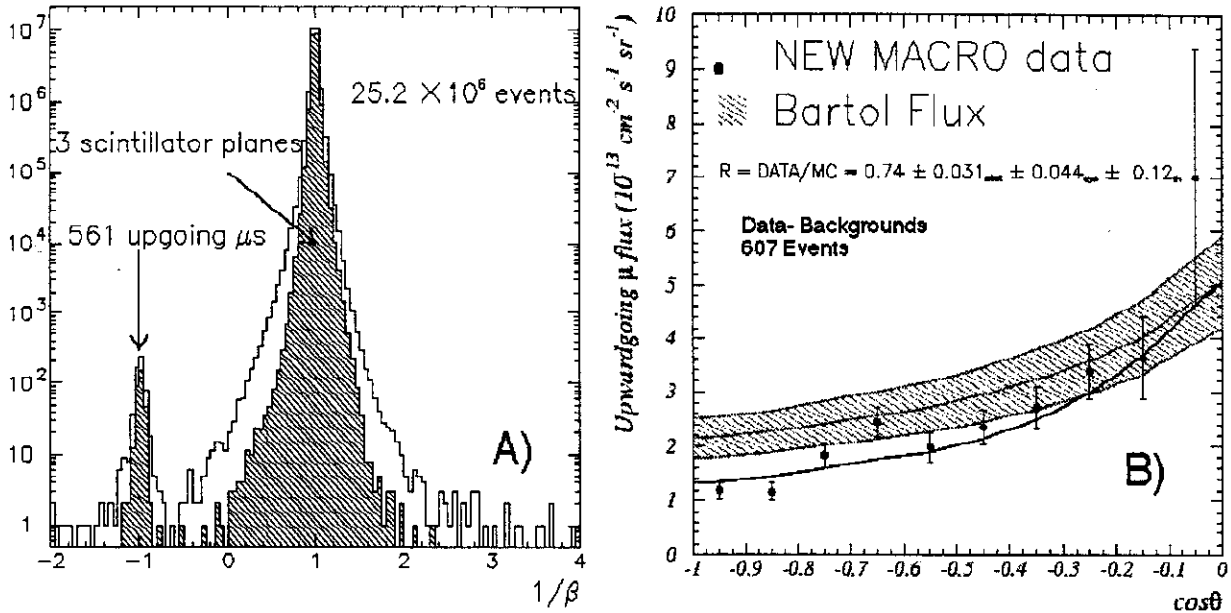
Figure 1: A) Distribution of $1/\beta$ for the full detector data set. A clear peak of upward muons is evident centered at $1/\beta = -1$. The widths of the distributions for upgoing and downgoing muons are consistent. The shaded part of the distribution is for the subset of events where three scintillator layers were hit. B) Zenith distribution of flux of upward throughgoing muons with energy greater than 1 GeV for data and Monte Carlo for the combined MACRO data. The shaded region shows the expectation for no oscillations and includes the 17% uncertainty in the expectation. The lower line shows the prediction for an oscillated flux with $\sin^2 2\theta = 1$ and $\Delta m^2 = 0.0025$ eV^2

as upgoing. We exclude this region from both our observation and Monte-Carlo calculation of the upgoing events.

Figure 1A) shows the $1/\beta$ distribution for the throughgoing data from the full detector running. A clear peak of upgoing muons is evident centered on $1/\beta = -1$.

There are 561 events in the range $-1.25 < 1/\beta < -0.75$ which we define as upgoing muons for this data set. We combine these data with the previously published data (Ahlen, 1995) for a total of 642 upgoing events. Based on events outside the upgoing muon peak, we estimate there are 12.5 ± 6 background events in the total data set. In addition to these events, we estimate that there are 10.5 ± 4 events which result from upgoing charged particles produced by downgoing muons in the rock near MACRO. Finally, it is estimated that 12 ± 4 events are the result of interactions of neutrinos in the very bottom layer of MACRO scintillators. Hence, removing the backgrounds, the observed number of upgoing throughgoing muons integrated over all zenith angles is 607.

In the upgoing muon simulation we have used the neutrino flux computed by the Bartol group (Agrawal 1996). The cross-sections for the neutrino interactions have been calculated using the GRV94 (Glück,1995) parton distributions set, which varies by +1% respect to the Morfin and Tung parton distribution that we have used in the past. We estimate a systematic error of 9% on the upgoing muon flux due to uncertainties in the cross section including low-energy effects (Lipari 1995). The propagation of muons to the detector has been done using the energy loss calculation (Lohmann 1985) for standard rock. The total systematic uncertainty on the expected flux of muons adding the errors from neutrino flux, cross-section and muon propagation in quadrature is $\pm 17\%$. This theoretical error in the prediction is mainly a scale error that doesn't change the shape of the angular distribution. The number of events expected integrated over all zenith angles is 824.6, giving a ratio of the observed number of events to the expectation of 0.74 ± 0.031(stat) ± 0.044(systematic) ± 0.12(theoretical).
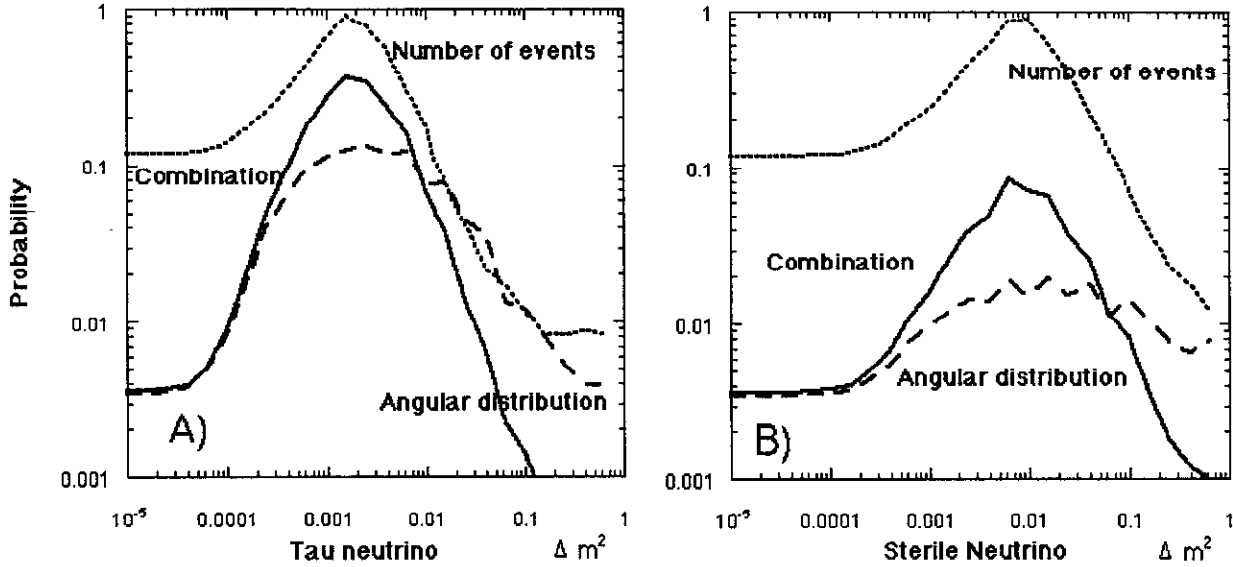
Figure 2: Probabilities for maximum mixing and oscillations $\nu_\mu \to \nu_\tau$ (Fig 2 A) or oscillations $\nu_\mu \to$ sterile neutrino (Fig 2 B). The 3 lines corresponds to the probability from the total number of events (dotted line), the probability from the chi-square of the angular distribution with data and prediction normalized (dashed line) and to the combination of the two independent probabilities (continous line).

Figure 1 B) shows the zenith angle distribution of the measured flux of upgoing muons with energy greater than 1 GeV for all MACRO data compared to the Monte Carlo expectation for no oscillations and with a $\nu_\mu \to \nu_\tau$ oscillated flux with $\sin^2 2\theta = 1$ and $\Delta m^2 = 0.0025$ eV^2 (dashed line).

The shape of the angular distribution has been tested with the hypothesis of no oscillation excluding the last bin near the horizontal and normalizing data and predictions. The χ^2 is 22.9, for 8 degrees of freedom (probability of 0.35% for a shape at least this different from the expectation). We have considered also oscillations $\nu_\mu \to \nu_\tau$. The best χ^2 in the physical region of the oscillations parameters is 12.5 for Δm^2 around $0.0025 eV^2$ and maximum mixing (the best χ^2 is 10.6 , outside the physical region for an unphysical value of $\sin^2 2\theta = 1.5$).

To test the oscillation hypothesis, we calculate the independent probability for obtaining the number of events observed and the angular distribution for various oscillation parameters. They are reported for $\sin^2 2\theta = 1$ in Figure 2 A) for $\nu_\mu \to \nu_\tau$ oscillations. It is notable that the value of Δm^2 suggested from the shape of the angular distribution is similar to the value necessary in order to obtain the observed reduction in the total number of events in the hypothesis of maximum mixing. Figure 2 B) shows the same quantities for sterile neutrinos oscillations (Akhmedov 1993,Liu 1998).

Figure 3 A) shows probability contours for oscillation parameters using the combination of probability for the number of events and χ^2 of the angular distribution. The maximum of the probability is 36.6% for oscillations $\nu_\mu \to \nu_\tau$. The best probability for oscillations into sterile neutrinos is 8.4%. The probability for no oscillation is 0.36%.

Figure 3 B) shows the confidence regions at the 90% and 99% confidence levels based on application of the Monte Carlo prescription in (Feldman 1998). We plot also the sensitivity of the experiment. The sensitivity is the 90% contour which would result from the preceding prescription when the data are equal to the Monte Carlo prediction at the best-fit point.
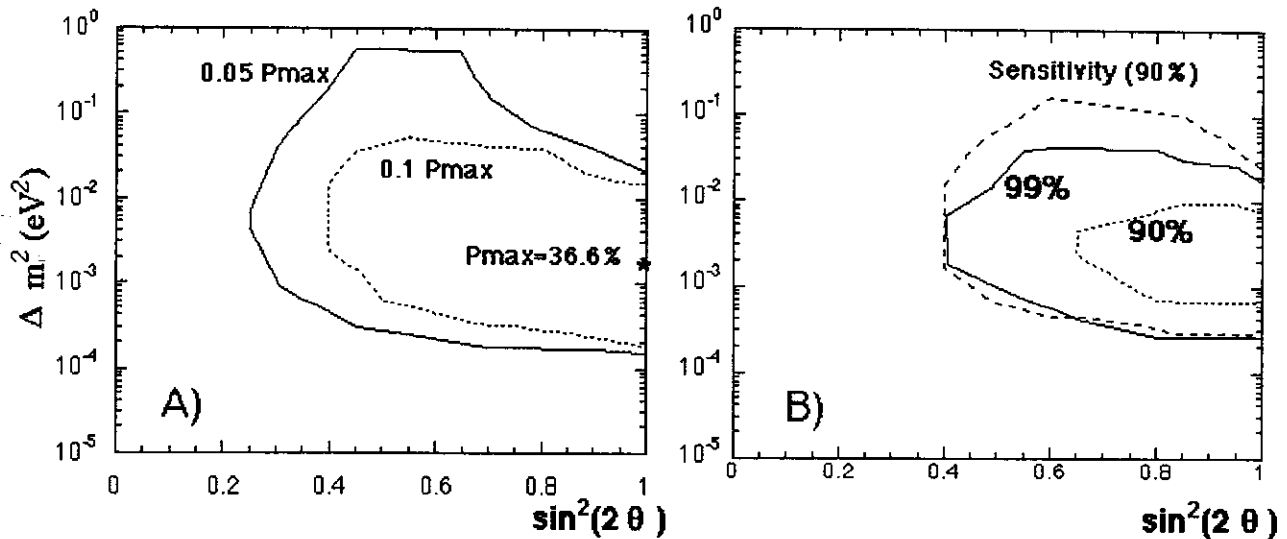
Figure 3: A) Probability contours for oscillation parameters for $\nu_\mu \rightarrow \nu_\tau$ oscillations based on the combined probabilities of zenith shape and number of events tests. The best probability in the physical region is 36.6% and iso-probability contours are shown for 10% and 5% of this value (i.e. 3.6% and 1.8%). B) Confidence regions at the 90% and 99% levels calculated according to Feldman 1998. Since the best probability is outside the physical region the confidence interval regions are smaller than the ones expected from the sensitivity of the experiment.

3   Conclusions:

The upgoing throughgoing muon data set is in favor of $\nu_\mu \rightarrow \nu_\tau$ oscillation with parameters similar to those observed by Superkamiokande with a probability of 36.6% against the 0.36% for the no oscillation hypothesis. The probability of oscillations from the angular distributions only is 13%. The probabilities are higher than the ones of the old data (Ambrosio 1998b). The neutrino sterile oscillation hypothesis is slightly disfavored.

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