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Study of neutrino induced upgoing muon energy

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Abstract: An estimate of the energy of neutrino-induced muons in MACRO is provided by a multiple Coulomb scattering measurement. The MACRO original upward-muon data sample has been subdivided according to the reconstructed muon energy. The results are interpreted in terms of neutrino oscillation

1. Introduction

MACRO[1] can be used as a neutrino detector by measuring neutrino induced muon events. From the study of the upgoing muon deficit and from the distortion of the relative angular distribution, MACRO provided evidence for neutrino oscillations[2]. The oscillation probability depends on the ratio L_ν/E_ν, where L_ν is the distance travelled by neutrinos inside the earth and E_ν is the neutrino energy: an estimate of this ratio is fundamental for any oscillation analysis. For high energy muons L_ν is properly measured using the reconstructed zenith angle of the tracked muon. As far as the E_ν is concerned, part of the neutrino energy is carried out by the hadronic component produced in the rock below the detector while the energy carried out by the muon is degraded in the propagation up to the detector level. Nevertheless, Monte Carlo simulations show that the muon energy at the detector level still preserves information about the original neutrino energy.

Since MACRO is not equipped with a magnet, the only way to infer the muon energy is through the multiple Coulomb scattering (MCS) of muons in the $\simeq 25$ radiation lengths (X^o) of detector. We use the streamer tube system[1], which provides the muon coordinates on a projected view. The other complementary view of the tracking system ("strip" view) cannot be used for this purpose since the space resolution is too poor. In MACRO, a muon crossing the whole apparatus has $X/X^o \simeq 25/\cos\theta$ and $y \simeq 480/\cos\theta$ cm, giving, on the vertical, $\sigma_x^{MS} \simeq 10$ cm/E(GeV). The muon energy estimate can be performed up to a saturation point, occurring when σ_x^{MS} is comparable with the detector space resolution

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σ_x. The MACRO streamer tube system, with a cross section of (3×3) cm^2, provides $\sigma_x\simeq1$ cm: the muon energy estimate through MCS is possible up to $\simeq$ 10 GeV/$\sqrt{cos\theta}$.

A first energy estimate has been presented in[5], where the feasibility of this approach was shown. The deflection of the muons inside the detector depends on the muon energy and was measured using the digital information of the limited streamer tube system. The measured event rate vs. L_ν/E_ν is in good agreement with the expectations, assuming neutrino oscillations with Δm^2=2.5$\times10^{-3}eV^2$ and $\sin^2 2\theta$=1. Since the interesting energy region for atmospheric neutrino oscillation studies spans from $\simeq$ 1 GeV up to some tens of GeV, it is important to improve the detector space resolution to push the saturation point as high as possible. We improved the MACRO space resolution exploiting the TDCs of the MACRO QTP system[3] to operate the limited streamer tubes in drift mode. The QTP system is equipped with a 6.6 MHz clock which corresponds to a TDC bin size of ΔT=150 ns. Although the MACRO streamer tubes, operated in drift mode, can reach a space resolution as good as $\sigma\simeq250\mu$m[4], in MACRO the main limitation comes from the TDC bin size. The expected ultimate resolution is $\sigma\simeq V_{drift}\times\Delta T/\sqrt{12}\simeq$2mm, where $V_{drift}\simeq$ 4 cm/μs is the drift velocity.

Since the QTP electronics was designed for slow monopole analysis, in order to fully understand the performance of the QTP TDCs in this context and to perform an absolute energy calibration, we made two tests at CERN PS-T9 and SPS-X7 beams. A slice of the MACRO detector was reproduced in detail: absorbers made of rock excavated in the Gran Sasso tunnel, like those of MACRO, were used. Following the MACRO geometry, the tracking was performed by 14 limited streamer tube chambers, operated with the MACRO gas mixture (He(73%)/n-pentane(27%)). The experimental setup was exposed to muons with energy ranging from 1 GeV up to 100 GeV. Each QTP-TDC time was converted into drift circles inside the chambers. The distribution of the residuals of the fitted tracks showed a $\sigma\simeq$ 2 mm, demonstrating the successful use of the QTP-TDCs to operate the streamer tube system in drift mode. In order to implement this technique in the MACRO data, we used more than $15{\cdot}10^6$ downgoing muons to align the wire positions with an iterative software procedure. After the alignment, a resolution of $\sigma\simeq$ 3 mm was obtained. This is a factor 3.5 better than the standard resolution of the streamer tube system used in digital mode (Fig. 1). The distribution of the MACRO downgoing muon residuals is shown in Fig. 1 (black circles) together with the GMACRO simulation (continuous line). In the same plot we superimposed the residuals distribution obtained with streamer tubes in digital mode (dashed line). The difference between the resolution obtained at test beam ($\sigma\simeq$ 2 mm) with respect to that obtained with MACRO

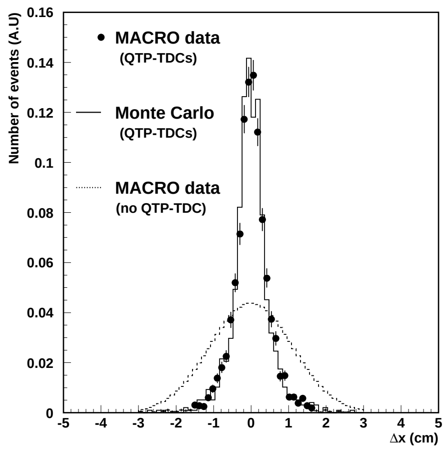

Figure 1: *Distribution of the residuals for MACRO data (histogram) and for simulated data (black circles). The dashed histogram shows the streamer tube resolution used in digital mode.*

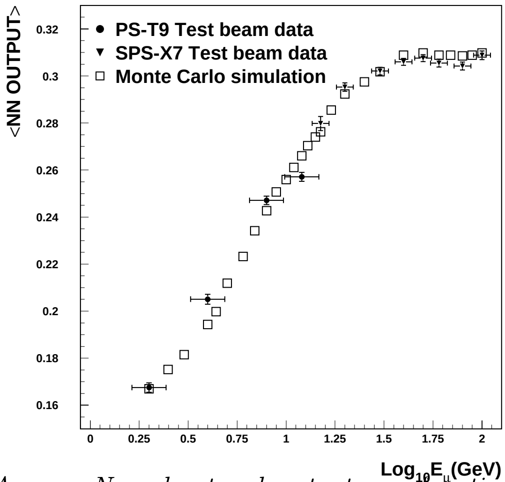

Figure 2: *Average Neural network output as a function of the muon energy*

data ($\sigma \simeq 3$ mm), comes from systematic effects such as the presence of δ rays produced in the rock absorbers causing earlier stops to QTP-TDCs.

2. Muon energy estimate and data analysis

For the muon energy estimate we followed a neural network (NN) approach. We chose JETNET 3.0, a standard package with a multilayer perceptron architecture and with back-propagation updating. The NN has been configured with 7 input variables, related to the multiple scattering, 1 hidden layer and we chose the Manhattan upgrading function. The NN was trained using a set of Monte Carlo events with known input energy, crossing the detector at different zenith angles. In Fig. 2 we show the average output of the NN as a function of the residual muon energy before entering the detector. The output of the NN increases with the muon residual energy up to $E_\mu \simeq 40$ GeV, ($E_\nu \simeq 200$ GeV). For the analysis, we used the whole sample of upgoing muon events collected with the upper part of MACRO (Attico) running, for a total live time of 5.5 years. We considered upgoing muons selected by the TOF system and the muon tracks reconstructed with the standard MACRO tracking. We then selected hits belonging to the track and made of a single fired tube, to associate unambiguously the QTP-TDC time information. Spurious background hits have been avoided by requiring a time window of 2 μs around the trigger time. Finally, we selected events with at least four streamer tube planes with valid QTP-TDC data. After the selection cuts 348 events survived, giving an efficiency of about 50%.

We used the information provided by the neural network to separate the upgoing muons into different energy regions and to study therein the oscillation effects. We studied the zenith angle distributions of the upgoing muon events in four regions with different muon energy, selected according to the NN output. The same selection has been applied to simulated events. To make a comparison between real data and Monte Carlo expectations, we performed a full simulation chain by using the Bartol neutrino flux and the GRV94 DIS parton distributions [7]. The propagation of the muons from the interaction point up to the

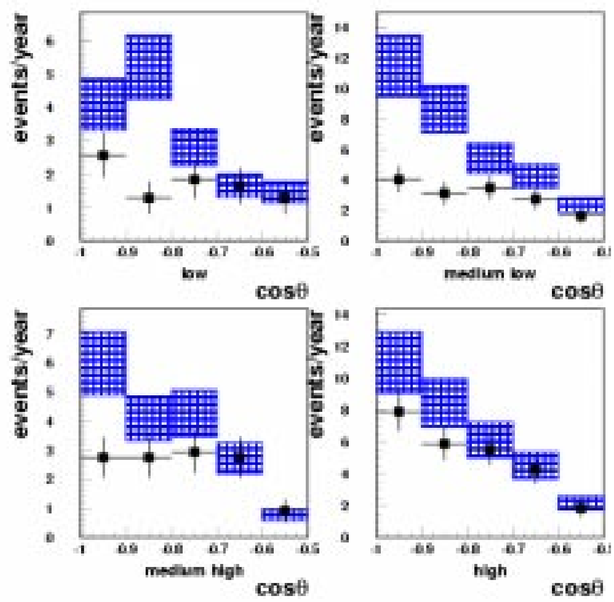

Figure 3: *Zenith angle distributions for upward going muons in four energy windows (black squares). Rectangular boxes show the Monte Carlo expectation with the no-oscillation hypothesis (statistical errors plus 17% systematic uncertainty on the overall flux).*

detector has been done using the FLUKA99 package[8], while the muon simulation inside the detector was performed with GMACRO (the GEANT 3.21 based detector simulation).

Should the upgoing muon deficit and the angular distribution distortion (with respect to the Monte Carlo expectation) pointed out by MACRO come from neutrino oscillations with parameters $\Delta m^2 = \mathcal{O}(10^{-3}\ eV^2)$ and $\sin^2 2\theta \simeq 1$, such deficit and such angular distribution distortion would not manifest at all neutrino energies. The effect is expected to be stronger at low neutrino energies (E$\leq$ 10 GeV) and to disappear at higher energies (E$\geq$100 GeV). We used the NN to separate four different neutrino energy regions whose median energy is respectively 12 GeV (low), 20 GeV (medium-low), 50 GeV (medium high) and 102 GeV (high). In Fig. 3 we show the zenith angle distributions of the upgoing muon events in the four energy regions selected compared to the expectations of Monte Carlo simulation, assuming the no-oscillation hypothesis. It is evident that at low energy a strong disagreement between data and Monte Carlo (no-oscillation hypothesis) is present, while the agreement is restored with increasing neutrino energy. The corresponding χ^2-probabilities for the no-oscillation hypothesis in these four windows are respectively 1.8% (low), 16.8% (medium-low), 26.9% (medium-high) and 87.7% (high): the χ^2/DoF values are clearly running with the neutrino energy, spanning from 13.7/5 to 1.8/5. The χ^2 has been computed using only the angular shape. Finally, we tried to get information on the ratio L_ν/E_ν. The output of the NN was calibrated on an *event by event* basis to have a linear response as a function of $log_{10}(L_\nu/E_\nu)$. The ratio of DATA/ Monte Carlo(no oscillation) as a function of $log_{10}(L_\nu/E_\nu)$, is plotted in Fig. 4: a good agreement is found with the oscillation probability function we expect with the parameters quoted above.

3. Conclusions

The sample of upward through-going muons measured by MACRO has been analyzed in terms of neutrino oscillations using multiple Coulomb scattering to infer muon energy. The improvement of the space resolution obtained by exploiting the QTP electronics extended the muon residual energy reconstruction up to $\simeq$ 40 GeV. Two dedicated runs at the CERN PS-T9 and SPS-X7 beams allowed us to check the MACRO QTP-TDCs

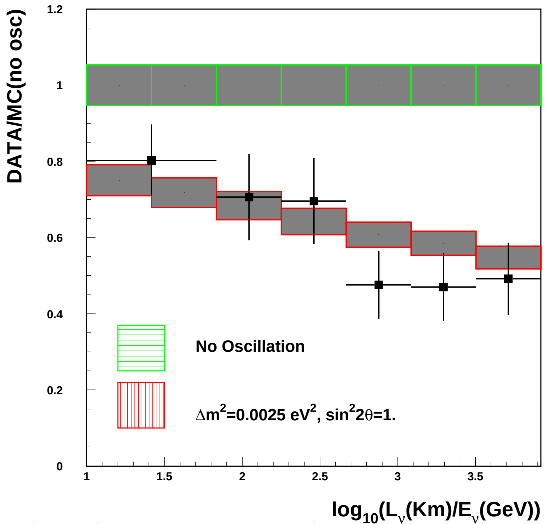

Figure 4: *Data/MC (without oscillation) as a function of the ratio L_ν/E_ν.*

and showed the feasibility of operating the limited streamer tubes in drift mode. The angular distribution of the upward going muon sample has been subdivided into four energy windows, showing the energy trend expected from the neutrino oscillation hypothesis. Moreover, we performed a study in terms of L_ν/E_ν. Also in this case, the observed transition from 1 to 0.5 in the ratio of data to Monte Carlo prediction is the one expected from the neutrino oscillation hypothesis with oscillation parameters $\Delta m^2 = \mathcal{O}(10^{-3}\ eV^2)$ and $\sin^2 2\theta$=1.

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