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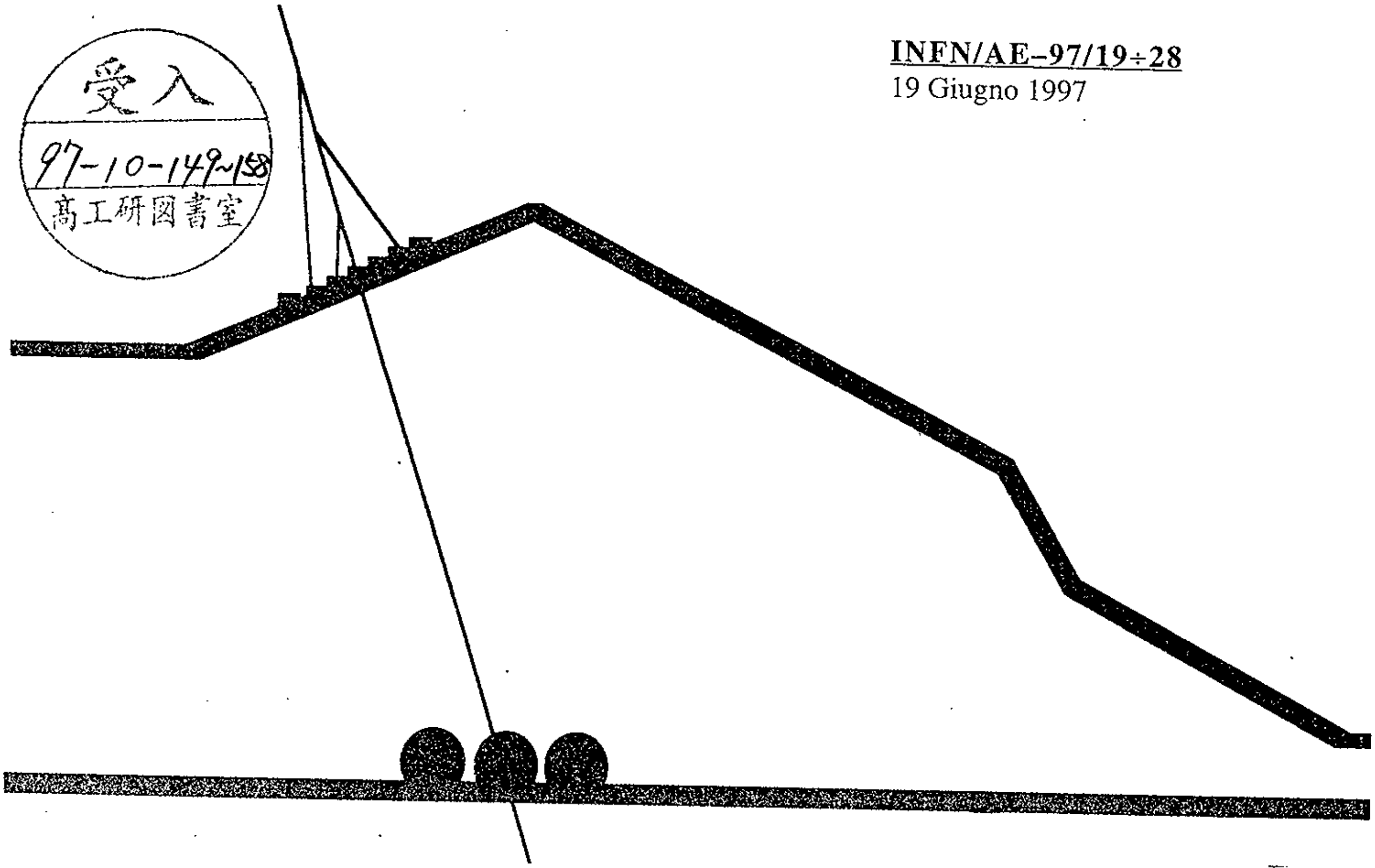

Contributions of the MACRO Collaboration to the 1997 Summer Conferences

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The MACRO Collaboration

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OBSERVATION OF UPGOING CHARGED PARTICLES IN MACRO PRODUCED BY HIGH ENERGY INTERACTIONS OF MUONS

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ABSTRACT

The experimental study of upgoing charged particles produced underground by hard muon scattering has been studied by the MACRO experiment at the Gran Sasso Laboratory. At total of 243 events with an upgoing particle associated with a downgoing muon in a sample of 12.2×10^6 single muons were found. These events may represent a source of background for the measurements of the muon neutrino flux using upward throughgoing and stopping muons. The implications for MACRO as a muon neutrino detector are discussed.

INTRODUCTION

Upgoing particles (which most likely are charged pions) induced by the hard muon scattering on a nucleon N, $\mu + N \rightarrow \mu + \pi^{\pm} + X$, have been detected by the MACRO experiment at the the Gran Sasso depth. These events have never been previously observed in underground experiments. A data taking periods of $1.55\ y$ was considered; during this period, 12.2 10^6 single downgoing muons and 243 events with upgoing charged particles associated with a downgoing muon were detected. The distributions of the pion range, of the emission angles with respect to the muon direction and of the distance between the downgoing muon and the upgoing pion have been measured.

If the downgoing muon is not detected (for example when the μ passes near but not through the detector) the upgoing pion induced by the muon simulates an upgoing neutrino-induced muon. This represents a background for the flux measurement of neutrino-induced upward throughgoing and stopping muons, which is evaluated for our detector in the last section.

MUON-INDUCED UPGOING PARTICLES IN MACRO

The MACRO detector (Ahlen et al., 1993) consists of a large rectangular box divided in six equivalent parts called supermodules, with overall dimensions of $77m \times 12m \times 9m$. The detection elements are planes of limited streamer tubes for particle tracking and liquid scintillation counters for fast timing. The directions of throughgoing particles in the detector are determined by time-of-flight with scintillator. Vertical muons crossing MACRO pass through $\sim 500\ g/cm^2$ of MACRO material (absorber plus active elements), corresponding to a minimum threshold energy of about $1\ GeV$ for muons.

High energy secondaries produced at large angles by muon interactions in the rock or in the concrete below the apparatus are identified using the tracking system. The topology of such events is that of two tracks converging somewhere below the detector, both in the wire and strip projective views of the tracking system (see Figure 1). A dedicated tracking algorithm was developed to reconstruct the upgoing short tracks in events in which a single downgoing muon is already present; for a description of the standard tracking algorithm, see (Ahlen et al., 1993). Any alignment between at least three hits (including the scintillator hit) was considered a track. The minimum pion vertical depth for events reconstructed in such a way is $\sim 30\ g\ cm^{-2}$. Timing information from the scintillation counters is used to identify the direction of the two particles.

Data corresponding to a detector livetime of $1.55\ y$ were analyzed; in this period, 12.2 10^6 single downgoing muons were collected. Upgoing pions induced by downward going muons were searched for in double track events in which one of the two tracks has been reconstructed by the dedicated tracking algorithm. In the most common case (71%) the short track in the event belongs to a second down-

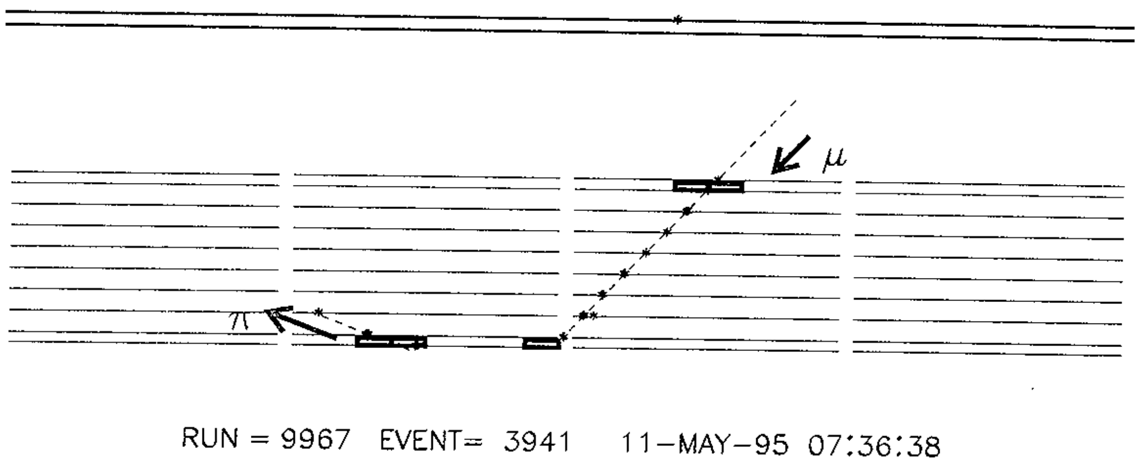

Fig. 1: On-line display of a typical muon interaction in the rock below the apparatus giving rise to an upgoing charged particle. The muon is coming from the lateral wall of the upper part.The rectangular boxes indicate scintillator counters hits and the points are streamer tube hits. The tracks are reconstructed in the wire view of the streamer tubes, and only two supermodules (24m) are shown.

going muon, parallel to the first one. Other cases giving a fake short track are electromagnetic showers of muons inside the detector (17%), bad tracking results (4%), muon interactions occurring inside the detector (5%) and low momentum muons with a curved trajectory (2%). A sample of 243 events with an upgoing track associated with a muon interaction were found. Four of them have both particles tracked by the standard tracking algorithm. The identification relies on the event topology from tracking and on the timing information from scintillator, and was performed using software cuts and a visual scan with the MACRO event display. A selection efficiency $\epsilon_s = (95 \pm 2)\%$ was estimated using a simulated sample of events, as described in the next section.

ANALYSIS OF THE UPGOING PARTICLES

The distributions presented in Figure 2 were obtained using the results of the track fitting procedure from the 243 selected events. They refer to: *(i)* the range of the upgoing particle (total and inside the detector); *(ii)* the scattering angles between the downgoing and the upgoing particles; and *(iii)* the distribution of the radial distance D between the upgoing π and the downgoing μ. The total range of the upgoing particle is calculated from the estimated interaction point (vertex) up to the stopping point inside the detector. The distribution and density of the material inside and around the apparatus as included in the reconstruction programs was used. The vertex lies below the detector, and corresponds to the intersection point of the two reconstructed tracks (see Figure 1) in the two views of the tracking system. If the value of the vertex depth in the two views differs by less than 50 cm, the event is defined as well reconstructed. For the well reconstructed subsample (168/243 events), the total range of upgoing particles is presented in Figure 2a. For the remaining 75 events, the uncertainty on the total range is at least of $\sim 100\ g\ cm^{-2}$.

The partial range of the upgoing particle inside the apparatus is calculated from the entry point up to the stopping point and is presented in Figure 2b (all events were included). Figure 2c shows the measured distribution of the scattering angle $\Delta\alpha$ of the pion with respect to the muon direction in the zenith plane; Figure 2d shows the distribution of the distance D between the muon and the upgoing pion at $z = 89\ cm$, the center of the bottom layer of the scintillator counters. The distributions fall for small D and $\Delta\alpha$ is due to a low reconstruction efficiency. The radial distance between the two tracks is less than 4 m (about one third of the dimension of one MACRO supermodule) in 90% of the cases. The distributions presented in Figure 2 allows to estimate the probability that a muon-induced upgoing pion gives a background event for the ν_μ studies, as discussed in the last section.

The detection of an upgoing pion produced at a certain point below the detector by a downgoing muon depends on the muon angular distribution at the MACRO location, on the emission angles of

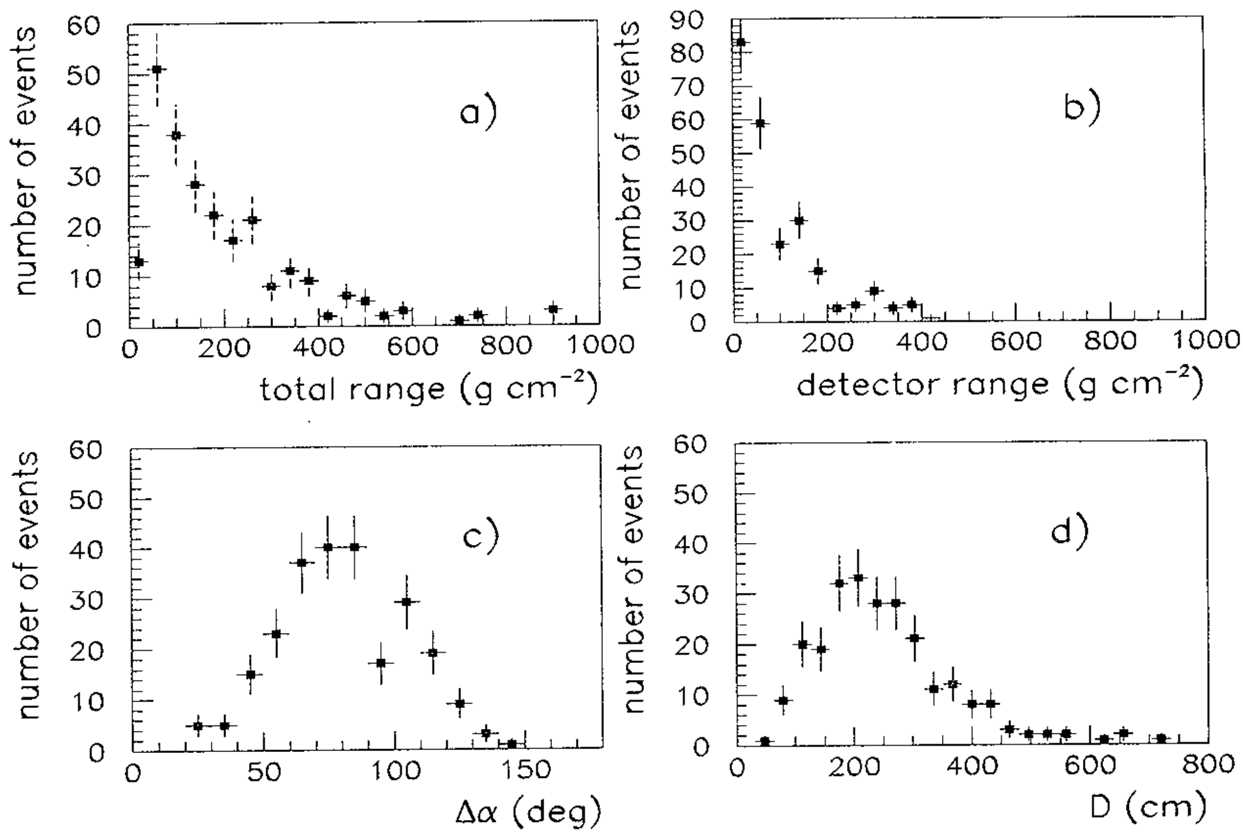

Fig. 2: a) Distribution of the reconstructed total range crossed by upgoing particles with a well reconstructed interaction vertex (168 well reconstructed events). b) Distribution of the reconstructed detector range crossed by the upgoing particles. c) Measured distribution of the $\pi - \mu$ scattering angle $\Delta\alpha$ and d) of the distance D between the downgoing muon and the upgoing pion at the z location of the centre of the bottom layer of scintillation counters. All events were included in b),c) and d).

the pion with respect to the muon and on the pion range. The probability to detect a muon-pion pair in MACRO for different values of these parameters was evaluated using a Monte Carlo. This allows the calculation of the reconstruction efficiency ϵ_r for these events. The probability to detect and reconstruct both the muon and the upgoing pion is less than 5% if the scattering angle $\Delta\alpha < 45^o$ (i.e. when both the pion and the muon are near-horizontal in the MACRO reference frame) (see Figure 2c); the tracking efficiency is small for $D < 100\ cm$ (Figure 2d) because the tracking algorithm do not discriminate the pion and the muon tracks if they are too near. The reconstruction efficiency, for $\Delta\alpha > 45^o$ and averaged over the remaining parameters quoted above, is $\epsilon_r = (21 \pm 2_{stat} \pm 4_{sys})\%$.

From the detected number of events, the selection efficiency ϵ_s and the detection probability ϵ_r, the detector-independent number of upgoing pions per downgoing muon emerging from the floor at the MACRO depth and with a scattering angle in the zenithal plane $\Delta\alpha > 45^o$ was estimated as

$$N_{\pi/\mu} = \frac{243}{(\epsilon_s \times \epsilon_r) \times 12.2\ 10^6} = (10^{+4}_{-2.5})\ 10^{-5}$$

COMPARISON WITH A MODEL OF H.E. MUON INTERACTIONS

Preliminary estimates of pion production by underground muons in MACRO have been made with a stand-alone full simulation with FLUKA (Fassó et al.,1993), interfaced with a simplified version of the apparatus response. The FLUKA code uses a model of hard muon scattering with the muon photonuclear cross sections (Bezrukov and Bugaev, 1981); at the MACRO depth, the cross sections for the average muon energy is $\sigma_\gamma(\overline{E}_\mu = 300\ GeV) \simeq 0.40\ mb$.

To evaluate the number of events in MACRO with an upgoing pion induced from this process by a downgoing muon, the atmospheric muon spectrum at the MACRO location, and the differential yield $Y_{\pi/\mu}$ of charged pions are needed. The measured angular distribution (Ambrosio et al., 1995) of the survived atmospheric muons (after the unfolding of the detector acceptance) was used; the muon energy is extracted between 1 GeV up to 10 TeV following the analytic approximation model (Gaisser, 1990) for the muon energy spectrum at a depth of $h = 3.8\ km.w.e.$. The muons interact randomly below the detector, and the energy spectrum of the upgoing particles from the floor is evaluated. It was found that the charged particle yield is dominated by charged pions; the charged kaon contribution is lower by about one order of magnitude. Protons (and neutrons) have an energy spectrum considerably softer than that of pions. The pion yield decreases sharply with increasing pion kinetic energy. For this reason, we identify the upgoing particles with charged pions. The number of upgoing pions per downgoing muon is calculated integrating the yield $Y_{\pi/\mu}$ of charged pions emerging from the floor over the differential energy and angular distribution. With this calculation, we find $(11.5 \pm 4.5)\ 10^{-5}$. This number agrees well with the experimental value $N_{\pi/\mu} = (10^{+4}_{-2.5})\ 10^{-5}$

BACKGROUND FOR MUON NEUTRINO STUDIES

The flux of atmospheric muon neutrinos $\Phi_{\nu(\mu)}$ at the Gran Sasso location can be inferred from the measurement of upgoing muons. The probability that a downgoing muon misses the apparatus while an upgoing pion is observed, simulating an upgoing muon, was evaluated using a simulation whose input data are the measured distributions corrected for the detector detection probability. Upgoing pions crossing two scintillator planes and at least $200\ g\ cm^{-2}$ of detector material represent the background for the measurement of upward throughgoing muons (Ambrosio et al., 1996). The estimated background rate is $(1.9 \pm 0.5_{stat} \pm 0.4_{sys})\ events/year$ for the upward throughgoing sample for a muon energy threshold of $\sim 400\ MeV$. If the upgoing pion stops inside the *fiducial volume* defined in (Mikheyev, 1994) an upgoing stopping muon is simulated. The estimated background rate is $(5.9 \pm 0.9_{stat} \pm 0.6_{sys})\ events/year$ for the upgoing stopping sample. This background is of the order of $\sim 1\%$ of the upward throughgoing muons and of the order of 8% of the upgoing stopping muons. The quoted background is specifically evaluated for MACRO. The probability to detect the pion and to miss the muon increases for smaller and shallower detectors.

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