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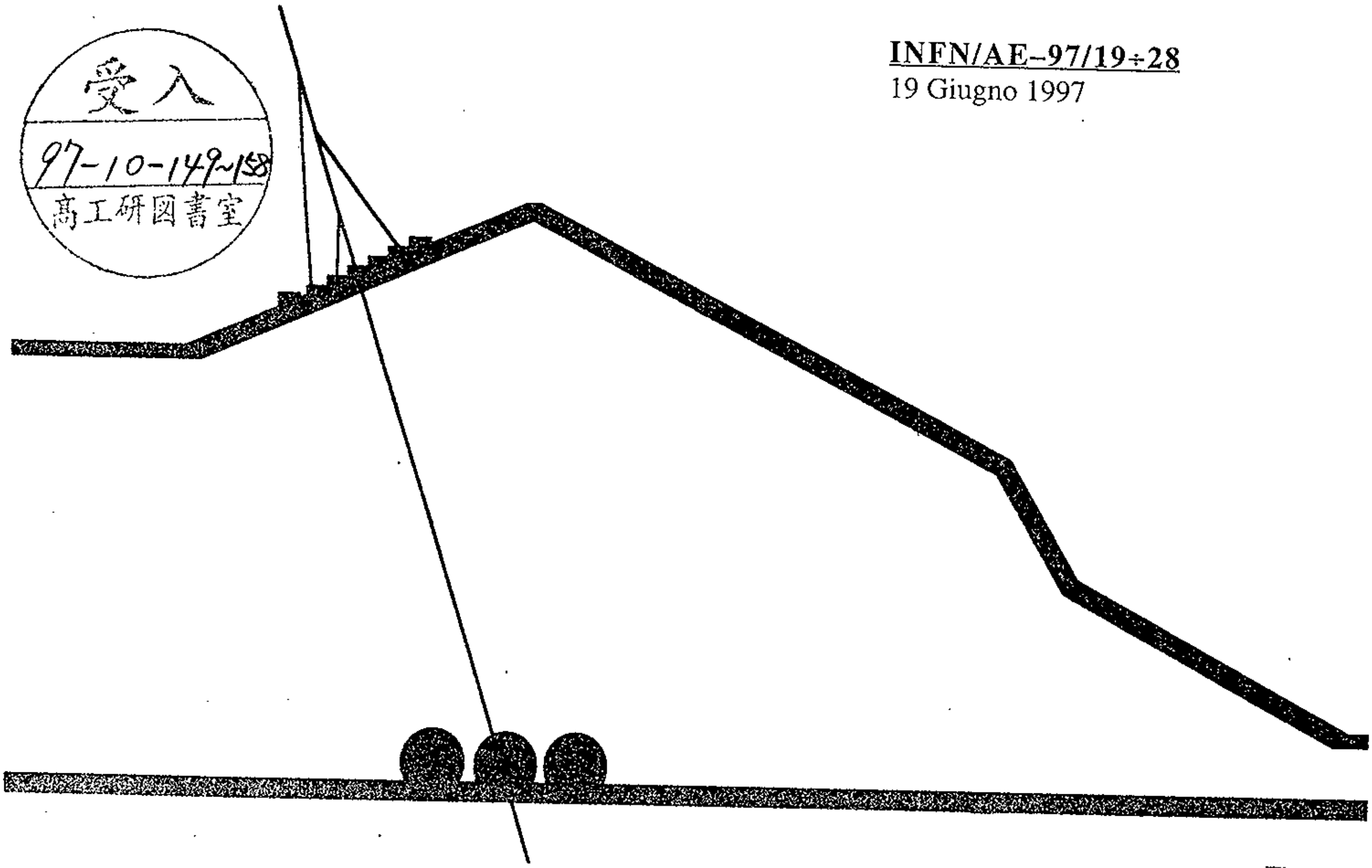

Contributions of the MACRO Collaboration to the 1997 Summer Conferences

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The MACRO Collaboration

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AN IMPROVED ANALYSIS OF THE UNDERGROUND MUON DECOHERENCE OBSERVED IN MACRO

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ABSTRACT

A sample of 350,000 muon pairs observed by MACRO at a depth larger than 3100 hg/cm^2 has been analyzed and the muon lateral distribution has been compared to the predictions of the HEMAS Monte Carlo code. The analysis includes the evaluation of the detector/analysis features affecting the decoherence curve and the measurement of the detector-independent muon lateral distribution at the Gran Sasso depth. The analysis has been performed with improved methods which reduce possible systematic effects. The results and their implications for cosmic ray physics and hadronic interaction models are presented.

INTRODUCTION

The validity of any result on cosmic ray (CR) composition obtained with indirect measurements depends on the reliability range of the Monte Carlo tools used to simulate the primary CR interaction and the shower development in the atmosphere. Moreover, when dealing with direct measurements performed at energies higher than a few tens of TeV, the simulation of the primary CR interaction inside the detector is required to reconstruct the primary CR energy.

The knowledge of the hadronic interaction features is therefore crucial for any experiment studying CR at UHE. The identification of variables sensitive to the details of the hadronic interaction features and the comparison of real data with the Monte Carlo codes play therefore important roles. The MACRO experiment (Ahlen et al., 1993a) performed a detailed study of the cosmic ray composition (Ambrosio et al., 1997) using the HEMAS code (Forti, 1990) to simulate the interaction of primary cosmic rays in the atmosphere. A few years ago, it was pointed out that this code could produce too much P_t (Gaisser, 1993). This hypothesis has been recently restated (Soudan2, 1997). We are going to show in this paper that, despite these theoretical speculations, the HEMAS code properly reproduces the feature of the muon pair separation distribution (decoherence function), a distribution which is very sensitive to the P_t modeling in the Monte Carlo hadronic interaction code (Figure 1). A first attempt to measure the decoherence function with MACRO was performed in MACRO (Ahlen et al., 1992 and 1993b). We present at this conference an improved analysis, in which two different analysis methods were used. The comparison of real data with the Monte Carlo prediction has been performed with special care to avoid possible systematic effects. Moreover, in the present analysis a larger statistical sample is used.

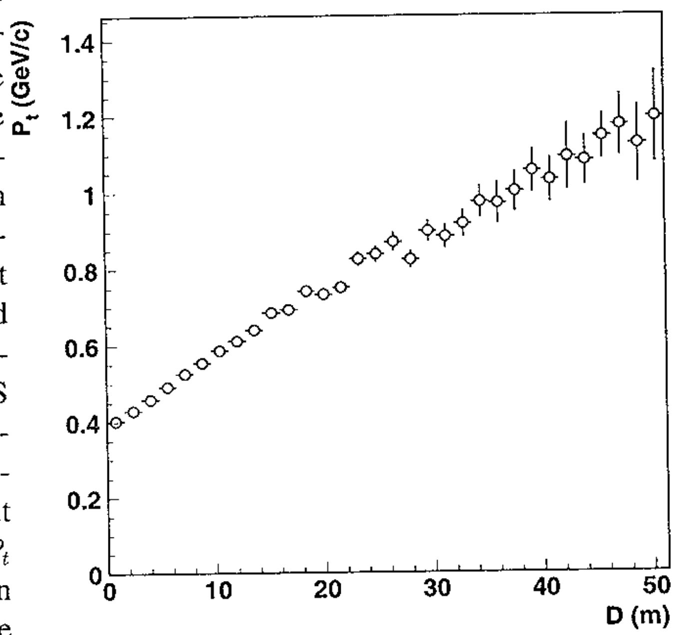

Fig. 1: Average muon parent P_t as a function of the distance between muon pairs at Gran Sasso depth, as computed with the HEMAS code.

DATA ANALYSIS

Apparatus effects cause an unavoidable distortion of the decoherence function. Although MACRO is a large area underground experiment (the largest presently running), the finite size of the detector still has to be accounted for. Although muon pairs with separation D$\simeq$ 70 m can be detected, the apparatus acceptance decreases with the pair distance. Moreover, in a projective apparatus like MACRO the efficiency for unambiguously reconstructing and associating a track in three dimensions has to be evaluated with care. A detailed simulation is therefore required to take into account all these experimental effects. To fulfill the requirements quoted above, we simulated our detector using the GEANT package. Monte Carlo and real data are processed using the same analysis chain. We simulated the interaction of approximately $3.6 \cdot 10^8$ primaries in the atmosphere, using the HEMAS code, according to the MACRO favoured composition model (Ambrosio et al., 1997) inferred by muon multiplicity distribution studies. Folding simulated data with detector simulation is a delicate step. In order to save as much data as possible and to avoid any systematic effects, we used the variance reduction technique (Battistoni et al., 1997), obtaining a sample of $\simeq$1,100,000 simulated muon pairs. Selected runs were used in the real data analysis: we processed about 250,000 muon bundle events ($\simeq$520,000 muon pairs) observed during $\simeq$7000 h of live time. Some cuts have been applied on both the real and the simulated data so that we selected:

- only tracks reconstructed in the wire and strip views, unambiguously associated;
- only "clean" events ($\leq$45 streamer tube fired outside of the tracks);
- only bundles whose average zenith angle is smaller than 60°, to be consistent with the mountain map used in the Monte Carlo;
- only parallel tracks, to reduce the important source of background coming from locally produced hadrons through muon photonuclear processes.

To enforce the cut on the "clean" topologies, we computed the ratio R between the number of streamer tube (ST) wires fired and the number of ST wires expected to be fired, considering the track direction. We accepted only tracks with R$\geq$0.75. Each pair of the bundle has been then weighted with the factor $\frac{2}{n_\mu(n_\mu-1)}$, where n_μ is the number of tracks in the bundle which survived the cuts. After the cuts we have about 350,000 real and 690,000 simulated pairs. We analyzed both the real and the Monte Carlo data with the same software programs (detector dependent curve comparison). Figure 2 shows the comparison between the HEMAS model and the real data. Muon pairs as far as $\simeq$ 70m apart are successfully measured by MACRO; a nice agreement with the Monte Carlo prediction is evident, showing the HEMAS capability in reproducing CR features deep underground. To obtain the muon lateral distribution at the Gran Sasso depths, we evaluated the detection/selection efficiency $\epsilon = \epsilon(D,\theta,\phi)$ by comparing the number of muon pairs in input to the GMACRO simulator and the number of pairs surviving the cuts quoted above, in each bin of (D,θ,ϕ).

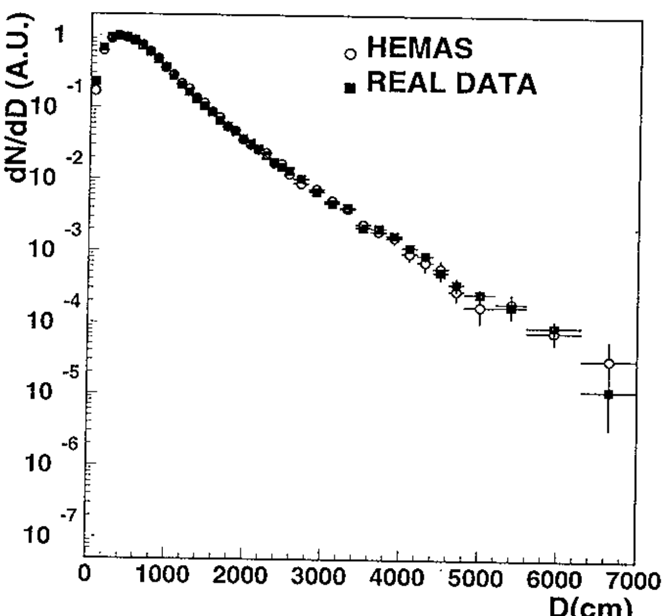

Fig. 2: Decoherence distribution obtained using the detector dependent method (see text), compared to Monte Carlo expectation.

A first attempt to compute $\epsilon(D,\theta,\phi)$ was performed (Ahlen et al., 1992, 1993b) using just muon pairs. This approach overestimated the detection/selection efficiency at small muon separation, because the selection probability of a muon pair is affected by the presence of the other tracks in the bundle ("shadowing effect"). In the present approach, we considered muon bundles generated by HEMAS, following a realistic multiplicity distribution. Then we computed $\epsilon(D,\theta,\phi)$ for each pair. The "shadowing effect", due to multiple tracks, is therefore accounted for. Corrected real data are finally compared directly with the HEMAS simulation. The unfolding procedure requires very high Monte Carlo statistics, so the unfolding is possible only for separation D$\leq$ 50 meters. Figure 3 shows the comparison between Monte Carlo and real data.

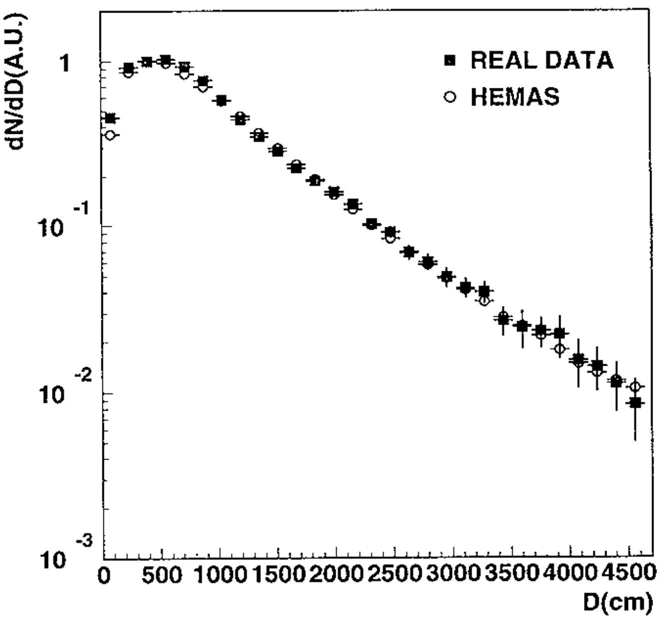

Fig. 3: Decoherence distribution obtained using the detector independent method (see text), compared to Monte Carlo expectation (HEMAS code and MACRO FIT composition model).

A good agreement is evident looking at the plot, confirming the capability of the HEMAS model in reproducing real data features. Further checks on the reliability of the HEMAS hadronic interaction model have been performed, comparing real data and Monte Carlo decoherence in different rock depth and cosθ windows. As an example, we show in Figure 4 the decoherence function in the ranges $0.9 \leq \cos\theta \leq 1.0$ and $0.7 \leq \cos\theta \leq 0.8$, for 3750 $hg/cm^2 \leq$ depth $\leq$ 4150 hg / cm^2. Figure 5 shows the average distance between muon pairs <D>, as a function of cosθ (upper plot) and as a function of the rock depth (lower plot). <D> is found to decrease with cosθ: this is a geometrical effect. Muon pairs originated at larger θ come from primary CR interacting farther from the detector: muons go through larger atmosphere depth before reaching the apparatus. Since muons are divergent, the resulting separation is wider. Deeper depth selection reflects in higher muon energy selection. Since the muon parent meson energy increases roughly linearly with the centre of mass energy $\sqrt{s}$ (while their $<P_t>$ increases with $\sqrt{s}$ only logarithmically), their angular separation, $\psi \simeq P_t/$P, tends to become smaller and therefore the muon separation is less. The agreement between real data and Monte Carlo is satisfactory, confirming the HEMAS capability in reproducing real data in both rock depth and cosθ windows.

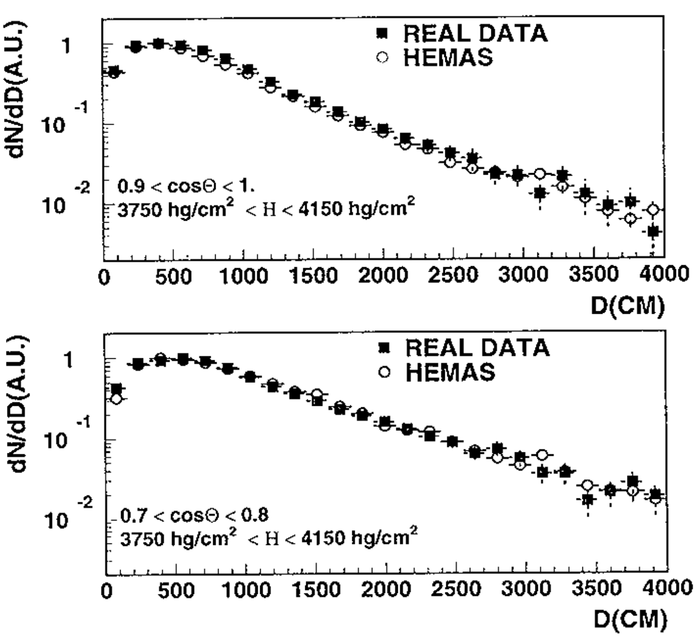

Fig. 4: Detector independent decoherence distribution in the ranges $0.9 \leq cos\theta \leq 1.$, $0.7 \leq cos\theta \leq 0.8$, for 3750 $hg/cm^2 \leq$ depth $\leq$ 4150 hg/cm^2.

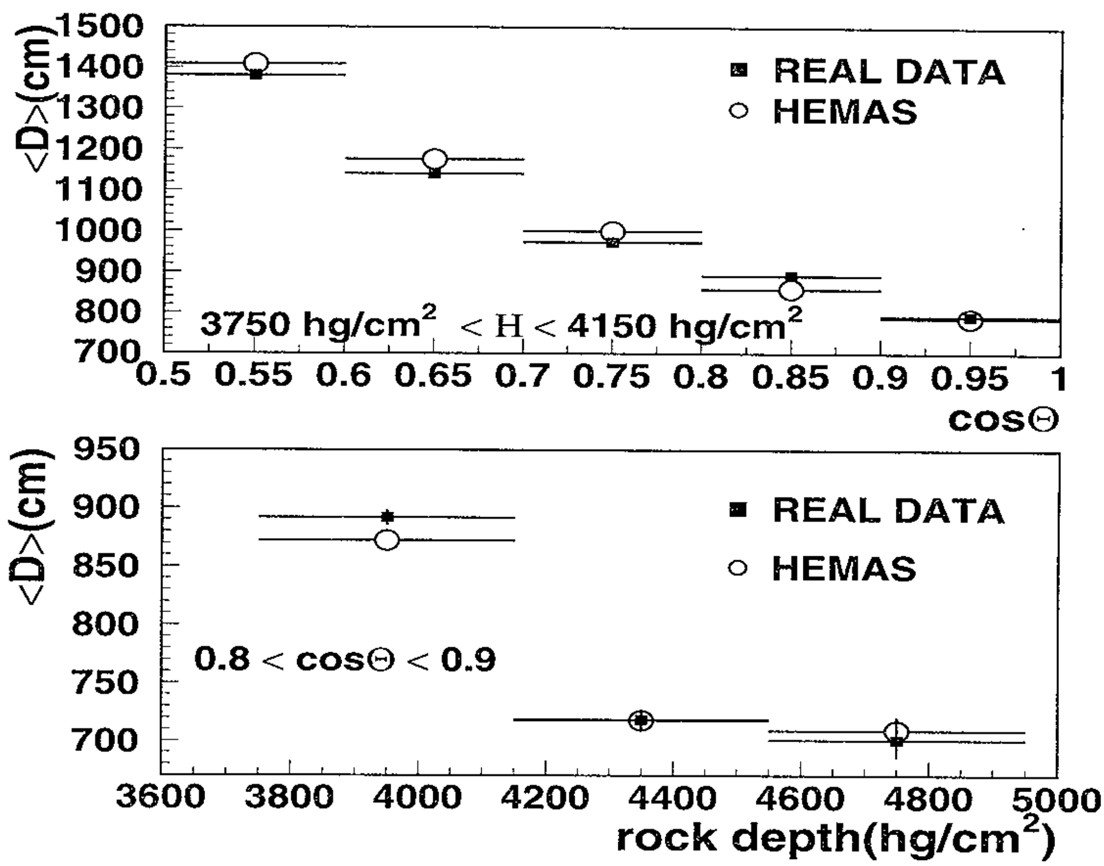

Fig. 5: Average distance between muon pairs <D>, as a function of cosθ and rock depth.

CONCLUSION

We verified that the HEMAS code reproduces the separation distribution of real data. This result has been verified by selecting both cosθ and rock windows. We stress that the study of the decoherence function is an important tool to verify the capability of the Monte Carlo codes in correctly reproducing muon bundle features deep underground. As far as the decoherence is concerned the HEMAS code gives satisfactory results and this makes us confident in using this code for primary CR composition studies.

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