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# Study of primary interactions with multiple muons in MACRO

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The MACRO underground experiment has started a systematic experimental study of the structure of a very high multiplicity event sample, with the aim of gaining a better understanding of the features of the high energy showers. We present here two new analyses: a) the analysis of the distribution of the separation between pairs of high multiplicity muons("decoherence" function); b) the search for clusters of muons within high multiplicity events. The first results are discussed together with a comparison between the real data and the Monte Carlo predictions.

## 1. Introduction

The primary aim of the study of multiple muon events underground is the measurement of primary composition by means of the analysis of the event fluxes as a function of multiplicity. The results obtained by the large area MACRO experiment at Gran Sasso are presented at this conference[1]. A description of the detector and of its performance can be found in ref. [2]. Since we are dealing with indirect measurements, it is important to identify as many experimental observables as possible which can help in the validation of the simulation models, in particular of those aspects affecting the development of the hadronic shower in the atmosphere. MACRO has already published an analysis of muon decoherence [3], which confirmed the substantial validity of the extrapolations obtained from experiments at colliders as a tool to understand the main features of the cosmic ray cascades. Recently, new different analyses have been started. We quote the "decorrelation" function[4], the search for muon clusters[5] and the search for delayed muons in a shower[6]. Not only these measurements provide additional validation in view of composition studies, but they can also give interesting information on the spatial and time structure of the hadronic shower in the atmosphere. In this talk we will focuse on the decoherence distribution in high multiplicity events and on the search for muon clusters.

*For the complete list of the Collaboration see the paper "Search for neutrinos from the Sun and Earth with the MACRO detector" at these proceedings.

## 2. The decoherence function

The already quoted analysis of muon separation (decoherence) in MACRO is dominated by low multiplicity events. As shown in ref. [7], these events mostly belong to a primary energy region below a few hundreds of TeV. A selection of high multiplicity events, corresponds instead to a preferential selection of primaries produced in the 1000 TeV range, and over; these events may be studied with the aim of probing the interaction model at a different scale. Using the selection criteria already described in ref. [1, 3], we have collected a sample of 2580 events with reconstructed multiplicity $N_\mu \geq 8$, from data taken with completed lower MACRO.

In a detector using projective views, like MACRO, it's not always possible to associate in space unambiguosly all the reconstructed tracks in high multiplicity events, using standard tracking algorithms. Therefore, an unbiased analysis can be performed, for the moment, only in one projective view. Real data have been compared with the HEMAS Monte Carlo predictions[9] for two extreme composition models. The "Heavy" model[8], disfavoured by the MACRO composition analysis, predicts a fast increase of $< A >$ with energy. The "Light"[8] model belongs to a class of model predicting a limited increase of $< A >$ with energy. In Fig. 1 we show the projected separation distribution of all independent muon pairs, for the $N_\mu \geq 8$ event sample, as compared with the HEMAS Monte Carlo with the two composition models quoted above. We con-


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firm the capability of the HEMAS simulation in reproducing the spatial event features also at high energy.

## 3. Search for clusters in high multiplicty muon events

On the basis of the phenomelogical work reported in ref. [5], we have also searched for higher order effects in the lateral distribution, by looking for cluster of muons inside the same high multiplicity event. The search for clusters has also been performed on one projected view, making use of an association algorithm described in ref. [5], derived from the jet–defining algorithm adopted in collider experiments. We define the observable

$$\chi_{ij} = (N_i N_j)^{0.25} \cdot R_{ij}, \qquad (1)$$

where $N_i$ and $N_j$ are the multiplicity concentrated in the clusters and $R_{ij}$=$|X_i$-$X_j|$ is the projected distance between the two multiplicity-weighted cluster centers. We then use an iterative procedure: for each pair of particles $i$ and $j$ in the bundle, we compute the corresponding $\chi_{ij}$. The pair with the smallest $\chi_{ij}$ is grouped in a pseudo-particle of multiplicity

$$N_k = N_i + N_j \qquad (2)$$

and position

$$X_k = [N_i \cdot X_i + N_j \cdot X_j]/(N_i + N_J). \qquad (3)$$

The process of "grouping" goes on using the new set of particles and pseudoparticles, until all the pairs have a $\chi_{ij}$ greater than a fixed $\chi_{cut}$. It has to be noted that, according to our definition, an event with no multiple cluster structure is classified as $N_{cluster} = 1$. Furthermore, a cluster can be defined even by a single muon; the value of $\chi_{cut}$ is somewhat related to the maximum spatial dimension of a cluster and to the separation between different clusters. Although it has been pointed out[5] that the cluster effect is also related to some hadronic interaction features as jets production, we expect that the observation of clusters is mainly correlated to the $P_\perp/x_F \cdot h_{production}$ fluctuations in the shower, and so may appear as fluctuations of the muon lateral distribution. Therefore we expect such a measurement to be also composition dependent. In fact, as shown in ref. [9], for a given functional behaviour of the uncorrelated later distribution function of muons, the average separation (and the higher order moments) are mass dependent through a function of $E/A$. Fig. 2 shows the fraction of the reconstructed number of clusters as a function of $\chi_{cut}$, as compared to the simulation results obtained, in the case of the "Light" and "Heavy" composition models, using the HEMAS interaction model.

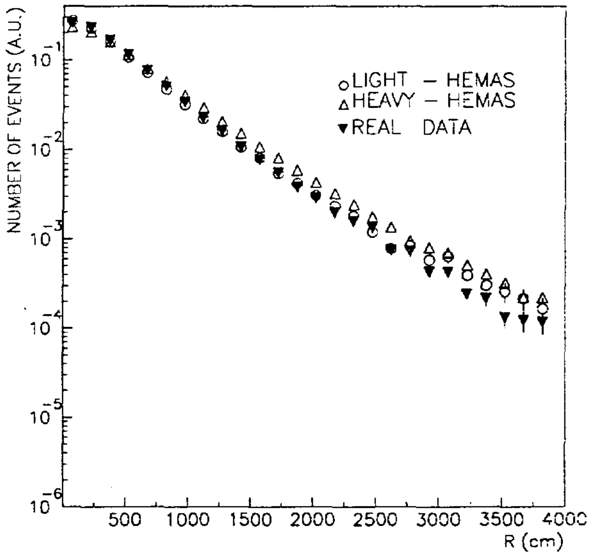


Figure 1. *Distribution of muon pair separation in the wire projected view, for $N_\mu \geq 8$ events, compared to Monte Carlo expectations for different composition models.*

The difference between extreme composition models is noticeable. We have to remind here that in such a plot the points are closely correlated, hence a meaningful statistical comparison can be performed only at a fixed $\chi_{cut}$ value. Monte Carlo simulation obtained using the "Heavy" model is not able to reproduce the real data. An improvement of the agreement is found when using a Monte Carlo obtained with the "Light" model. In Table 1 we report the fraction of measured clusters for $\chi_{cut}$ = 900 cm in the real data and in the simulations obtained using HEMAS with three different composition models. Finally, Fig. 3 shows the comparison between the fraction of

| Fraction of events with | HEMAS Heavy | HEMAS MACRO | HEMAS Light | Exp. data |
|---|---|---|---|---|
| 1 cluster | 0.128 ± 0.005 | 0.203 ± 0.009 | 0.236 ±0.012 | 0.200± 0.009 |
| 2 clusters | 0.468 ± 0.010 | 0.494 ± 0.016 | 0.465 ±0.019 | 0.512± 0.017 |
| 3 clusters | 0.316 ± 0.008 | 0.243 ± 0.010 | 0.242 ±0.013 | 0.234± 0.010 |

Table 1
*Fraction of events with 1, 2 and 3 clusters in experimental and simulated data for different composition models and for $\chi_{cut}$ =900 cm. Quoted errors are statistical only.*

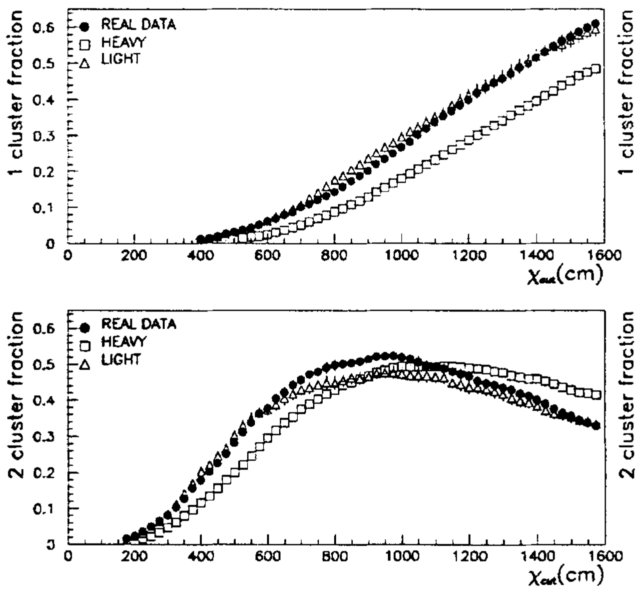


Figure 2. *Fraction of events with 1 and 2 clusters, as measured in a sample of $N_\mu \geq 8$ events, as compared to Monte Carlo expectations for different composition models.*

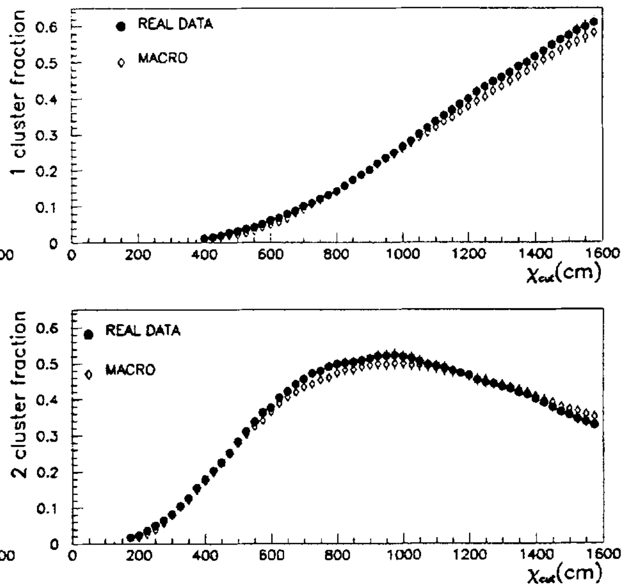


Figure 3. *Fraction of events with 1 and 2 clusters in the real data and in the Monte Carlo simulation obtained using the MACRO fit[1].*

events with 1 and 2 cluster in the real data and in the Monte Carlo obtained using the MACRO fit[1]. A good agreement between real data and Monte Carlo is evident at any $\chi_{cut}$ value, confirming thus the result obtained with the direct fit procedure[1].

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