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SUPPLEMENTS

MULTIPLE MUONS AND PRIMARY COSMIC COMPOSITION STUDIES WITH MACRO

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The analysis of multiple muon events collected with one MACRO supermodule and two supermodules is described. Muon pair separation distributions as corrected for the bias of the finite detector size are presented. Muon multiplicity distributions are compared with two primary cosmic ray composition models.

1. INTRODUCTION

The main bulk of data about the elemental composition of cosmic rays comes from direct measurements with balloons and satellites. These experiments measure the absolute abundances of different nuclei and the energy spectra of the primary species up to energies of about 100 TeV, due to the steeply falling spectrum. In the ultra high energy region $E_0 > 100$ TeV, where the "all-particle" energy spectrum shows an abrupt steepening at about 3000 TeV ("knee region"), very little is known about composition. At present the only way to study this energy region is to obtain information indirectly from the analysis of the properties of secondary particles produced in the atmospheric cascade, i.e. measurements of the extensive air showers and/or study of the penetrating component of the secondaries, the high energy muons. The rates of coincident multiple muons of different multiplicities measured in deep underground experiments are sensitive to the chemical composition and energy spectrum of the primary cosmic ray nuclei, above a threshold determined by the rock overburden ($\sim$ 50 TeV at Gran Sasso). The sensitivity to composition arises from the fact that, above a certain energy, light incident particles (i.e. protons) are less effective in producing multiple muons than heavy nuclei possessing the same total energy per nucleus. With underground detectors, the energy and type of a primary cannot be determined on an event by event basis, but information on the mass composition can be obtained by comparing measured muon multiplicity distributions with those calculated with an accurate Monte Carlo simulation using trial models of the primary spectrum and composition.

Deep underground muons are the decay products of high energy mesons produced in the early stages of the hadronic cascade in the atmosphere. They mostly belong to the kinematical region of high rapidity (fragmentation region), which is is not easily accessed by experiments at Colliders. The transverse momentum distribution of the energetic secondaries largely determines the fraction of muons above threshold that hit the detector. The spatial separation of underground muon pairs is therefore basically sensitive to the hadronic interaction mechanism. If the muon lateral distribution is known and the detector is large, the bias due to the finite size of the apparatus can be corrected.

The MACRO detector, located in the hall B of the Gran Sasso National Laboratory (with a minimum and average rock overburden of 3200 and 3700 m.w.e. respectively) has dimensions of 72 m $\times$ 12 m $\times$ 9 m. It has a modular structure whose basic block is a "supermodule" of 12 $\times$ 12 $\times$ 4.8 m^3, equipped with streamer tube chambers, liquid scintillator tanks and track-etch plastics. A detailed description of the experimental apparatus is given elsewhere.[1] MACRO is well suited for high statistics studies of muon bundles for which, at the Gran Sasso depth, the mean lateral separation is about 6 m. About 10^7 events will be collected per year with the full-sized detector, thus allowing to perform an unbiased study of multiple muon physics at high muon multiplicities and large separations.

In this paper we present an analysis of multiple muon events collected with one supermodule and two supermodules operating.

2. DATA SELECTION AND EVENT ANALYSIS

Muons are reconstructed separately on wire and strip views. Alignment of at least 4 hits in different planes is required to define a track. Two independent projected multiplicities, N_W and N_S, in the wire and strip views, are obtained for each event. In most cases it is possible to associate tracks in the two views to reconstruct the muon tracks in three-dimensional space. 94% of muon pairs in all events having any multiplicity are unambiguously associated.

The rate of reconstructed single muons with $N_W = N_S = 1$ was 116 ± 2 h^{-1} for one supermodule and 235 ± 2 h^{-1} with two supermodules. To eliminate runs with possible technical problems, the runs selected for the present analysis were those with a rate of reconstructed single muon events of at least 100 h^{-1} for one supermodule and 200 h^{-1} for two supermodules, total live time ≥ 1 h and dead time fraction $< 5\%$. We also required that the zenith angle of the muon bundles be less than 60°. The fraction of events surviving this cut was $\sim 94\%$.

The true multiplicity of muons traversing the detector can be different for any given event from the N_W and N_S multiplicities reconstructed from the tracking algorithm, for various reasons, such as a geometrical superposition of two or more tracks in a view.

A fraction of events was visually scanned in order to solve possible ambiguities. A range of different multiplicities was assigned to complicated events (mainly events with showers) when the true multiplicity could not be unambiguously determined. This was done giving an equal fractional weight to each possible multiplicity within the range defined by the scanner. All events with $N_W > 5$ or $N_S > 5$ were scanned. The remaining events were scanned on a sampling basis. In this analysis a total of about 5000 events were scanned.

Fig. 1 shows the multimuon rates for the one supermodule and two supermodule event samples. Only statistical errors, inclusive of scanning uncertainties, are reported in this figure. The systematic error, evaluated with a partial double scanning, turns out to be of the same order as the statistical one. The increase of acceptance from one to two supermodules is clearly reflected in increase of muon rates and access to higher multiplicities. Fig. 2 shows the distributions of the separation between muon pair for each data sample, normalized one to the other in the range between 0 and 4 m. The distributions differ in the region of higher separations, reflecting the doubling of detector acceptance.

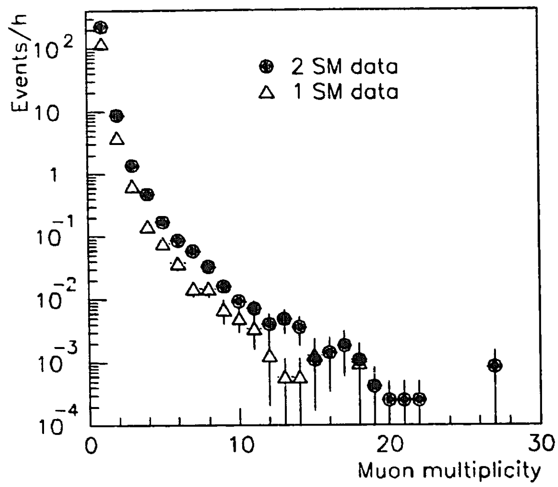

Figure 1
Distribution of multimuon rates as a function of multiplicity for the one supermodule and two supermodule samples. Only statistical errors, inclusive of scanning uncertainties, are shown.

3. COMPARISON WITH MONTE CARLO PREDICTIONS

The interpretation of deep underground muon data requires a simulation including the primary hadronic interaction model, the air shower development and the propagation of muons through the rock. Simulations for an infinite size detector have already been developed by different authors.[2,3] The results of these calculations are expressed in terms of parameterized for-

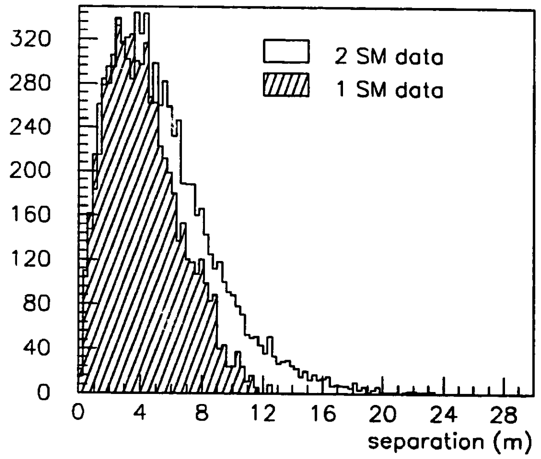

Figure 2
Distributions of muon pair separation in double muon muon events for the one supermodule and two supermodule samples.

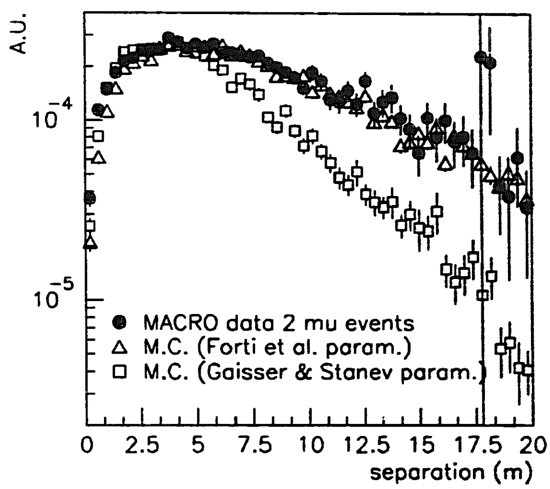

Figure 3
Comparison between the muon pair separation distribution of the data and Monte Carlo predictions. The Monte Carlo predictions refers to the Constant Mass Composition model.[5]

mulas. These formulas describe the main features of the muon bundles, i.e., their lateral distance and multiplicity distributions as a function of the characteristics of the primary (mass, energy and direction) and of the rock depth. These parameterizations can be used in Monte Carlo simulation programs in order to obtain predictions of multimuon data in the actual detector.

We have undertaken a full Monte Carlo simulation with the following features: i) a physics generator including both the parameterizations of hadronic interaction and the characteristics (energy spectrum and elemental composition) of the primary cosmic radiation; ii) an accurate description of the rock depth distribution around the MACRO detector.

The result of our Monte Carlo simulation, using the two hadronic interaction models of Ref. 2 and 3, are compared, in Fig. 3, with the experimental muon pair separation distributions, corrected for the effect of the finite detector size. The muon separation distributions of the one supermodule and two supermodules data samples turn out to be indistiguishable after the correction procedure, when compared in the common interval (0 - 12 m). This fact constitues a strong validity check for the analysis method.[4] Different primary composition models do not exhibit detectable differences as far as muon separation of events with low multiplicity (double or triple muon events) is concerned. Fig. 3 shows that our data are in agreement with the model of Forti et al.[3], which incorporate the most recent hadronic collider data and the available measurements of nucleus-nucleus interactions from fixed target experiments. In the simulation presented hereafter we therefore adopted this model.

To simulate the events inside the apparatus we have used a GEANT[6] based simulation program describing the experimental apparatus in all its details (geometry and detector response) and producing data of the same format as for real events. These data have been processed using the standard offline chain of analysis, which permits an evaluation of both the MACRO acceptance and the reconstruction program efficiency.

We have compared our experimental rates of multimuons with two trial compositions given in literature: the Maryland composition[7] ("heavy") and a Low Energy Composition (LEC)[8] with a proton enhanced component ("light"), as adjusted to give the same all-particle spectrum.[9] It is helpful to know the window of primary energies explored by the detection of multiple muons. The mean primary energy for $N_\mu \geq 2$ is $\sim$ 320 TeV for the "light" and $\sim$ 480 TeV for the "heavy" model. The corresponding value for events with $\geq$ 6 muons is $\sim$ 5500 TeV for both compositions. Therefore the measurements presented in this analysis are sensitive to composition below and above the "knee".

The results of our full Monte Carlo simulation, using the "light" and "heavy" composition models, are shown in Fig. 4, compared with the experimental data for two supermodules. The Monte Carlo predictions are normalized to the same number of events of multiplicity 2 or greater as experimentally observed, in order to reduce possible systematic biases. Error bars on the data points of Fig. 4 represent statistical errors, inclusive of scanning uncertainties. The errors on the Monte Carlo predictions include systematic uncertainties. The systematic error sources that we have considered are: i) uncertainties on the hadronic interaction model; ii) electronic inefficiency and noise in the streamer tube system; and iii) uncertainty in the knowledge of the map of the rock around MACRO. The resulting systematic error turns out to be dependent on muon multiplicity and ranges from $\sim$ 10% for $N_\mu \geq 1$ to $\sim$ 30% for $N_\mu \geq 20$.

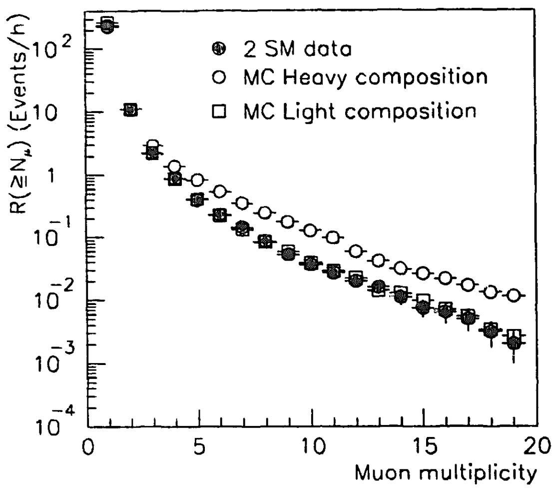

Figure 4
Comparison between the integral multiplicity distributions of two supermodule data and Monte Carlo predictions. The Monte Carlo predictions for the "heavy" and "light" composition models include systematic uncertainties.

4. CONCLUSIONS

The general features of multiple muon physics in MACRO are reasonably understood and reproduced by Monte Carlo simulation. The size of the detector allows the comprehension of the muon lateral distribution, which is essential to analyze the muon multiplicity distribution to study the primary cosmic ray composition. The MACRO muon multiplicity shows good sensitivity to the study of cosmic ray composition at high energy. The comparison with two trial composition models shows a better agreement with the "light" composition. The data sample with larger statistics to be collected with the full apparatus will allow to confirm this result and, eventually, to obtain more definite conclusions.

† For the author list see G. Giacomelli, *Search for gravitational collapse with the MACRO detector*, this volume.

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