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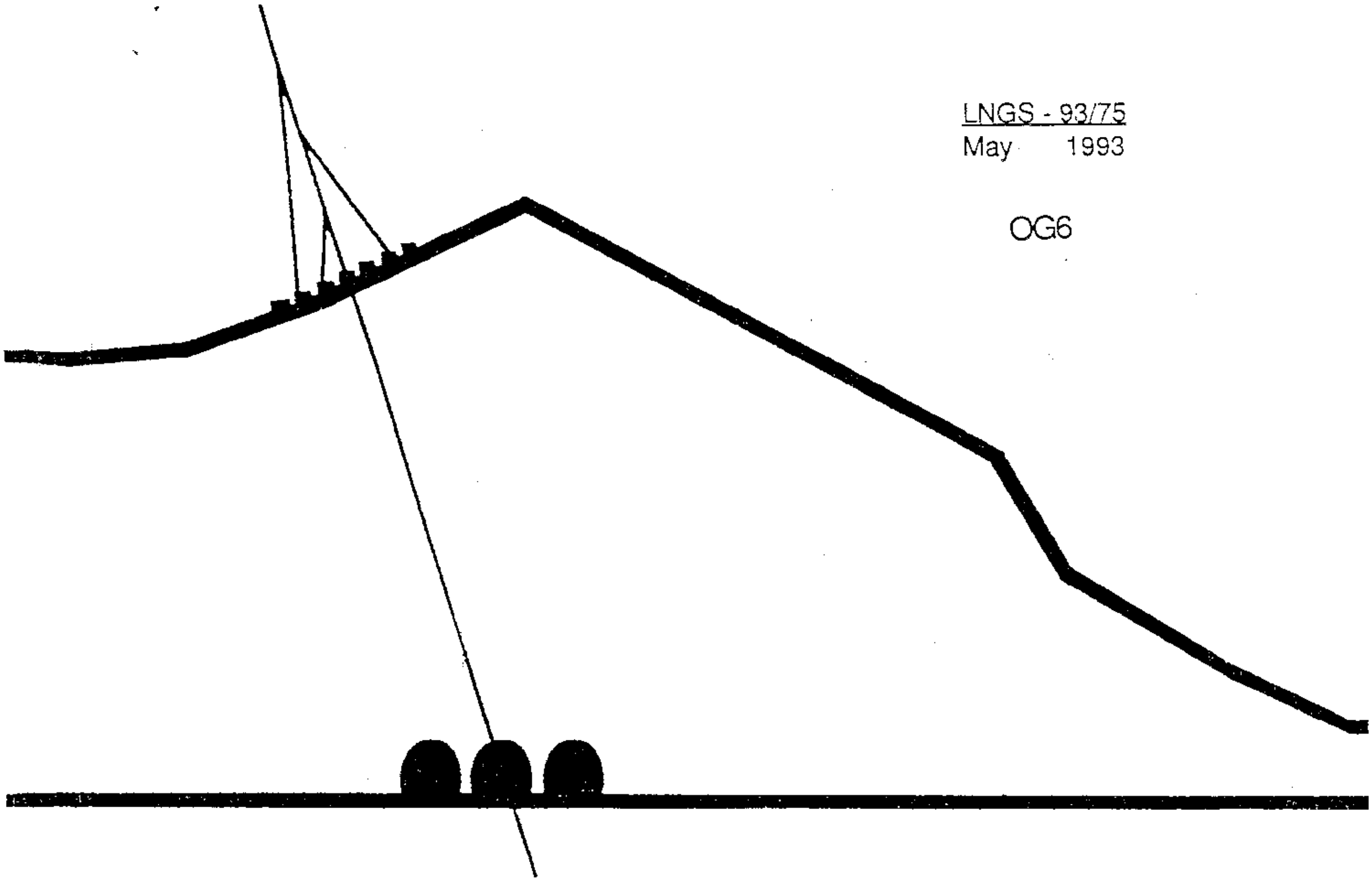

Constraints on the PeV Cosmic Ray Composition and Interaction Models from Coincident EAS-TOP and MACRO Data

CONTRIBUTIONS TO THE 23rd ICRC
The EAS-TOP and MACRO Collaborations

INFN - Laboratori Nazionali del Gran Sasso

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ABSTRACT

An analysis of coincident deep underground muon data and of the electromagnetic (em) component of Extensive Air Showers as measured by the MACRO and EAS-TOP experiments at Gran Sasso is presented. Constraints on the primary cosmic ray composition are obtained.

1. Introduction

The simultaneous measurement of the em shower size and the high-energy muon content in cosmic-ray cascades can provide information on the cosmic-ray primary composition and hadronic interactions as a function of the primary energy. This technique can be used to select events above the 'knee' in the primary spectrum, and provides results that are nearly independent of the assumed energy spectrum, in contrast, e.g. to using underground muon data alone. We discuss the measurements of: a) the em component (N_e) performed at mountain altitude by the em detector of EAS-TOP[1], at Campo Imperatore, 2000 m a.s.l., and b) the TeV muons (N_μ) deep underground, by MACRO[2], in Hall B of the Gran Sasso National Laboratory, with an average rock thickness of 3200 mwe separating the two. First results on the combined operation and resolutions of the two detectors have been published in ref. [3]. Descriptions of the two detectors and of the coincidence technique are reported in ref. [4], together with a preliminary analysis of primary composition (where a simplified simulation was used). A first analysis of the muon multiplicity distribution as detected by MACRO alone is reported in ref. [5]. We present here the first quantitative constraints, allowed by the statistics of the analyzed data, on the primary composition and parameters of the interaction model deduced by comparison of the coincident data with full simulations of cascades in the atmosphere, muon transport in the rock, and detector responses.

2. The Correlated Data

Four runs have been performed with the detectors operating in coincidence:

a) 1989: 46.1 days live time, 347 events, 87 internal, 1 SM of MACRO and 22 modules of EAS-TOP, higher energy threshold[3]; b) 1990: 96.3 days live time, 7644 events, 582 high-energy internal, 2 SM of MACRO and 29 modules of EAS-TOP[4]; c) 1992: 172 days live time, $\sim$ 42,000 events, 6 SM of MACRO and 29 modules of EAS-TOP; d) 1992-1993: 75 days live time, $\sim$21,000 events, 6 SM of MACRO and 35 modules of EAS-TOP. The data under discussion are from data set b. (Data sets c and d are under analysis, and the results will be presented at the Conference).

In the sample of coincident internal events the expected accidental background is approximately 3 events out of 582. In fact two events were rejected due to their large misalignment of reconstructed directions ($>50^\circ$). To extend the analysis to the lower energy range 10 - 100 TeV for the same data set, a fiducial area has been selected inside EAS-TOP, and the statistics of the muon events pointing to this region without having triggered the EAS-TOP array (anticoincident, or AC events) are studied.

3. The Simulation

The physics generator is taken from ref. [6], based on a parameterization of a proton-proton and proton-antiproton hadronic interaction model according to collider results up to $\sqrt{s}$=900 GeV, with the inclusion of nuclear target effects extracted from data at lower energy. A measurement of the muon decoherence function performed by MACRO[7] has provided a test of this generator, rejecting other simplified models.

A full Monte Carlo simulation is performed, including the generation of muons and hadrons with $E \geq 1$ TeV, and gamma-rays. The contribution to N_e from gamma-rays, and from hadrons with $E \leq 1$ TeV, is calculated by sampling from a pre-constructed conversion table based on the EGS4 and GEANT codes that takes into account the transition effect in the EAS detectors. The lateral distribution function is taken from the experimental EAS-TOP data. Muons are propagated down to the MACRO depth by means of a full transport routine. The sampling area is twice the effective one for EAS-TOP, and 30 times greater than the effective horizontal area for MACRO. Simulated data are then analyzed by means of the same reconstruction procedure used for physical events.

The analysis of the coincidence experiment is performed by first constraining the simulated N_e spectrum for EAS-TOP alone to agree with that measured by the surface array. Two different approaches have therefore been followed:

a) the simulation of pure nuclear species (A=1,4,14,27 and 56) with statistical samples equivalent to the experimental one. For each species, an energy spectrum is obtained from the corresponding EAS-TOP size spectrum using an N_e-E_0 conversion table. This table is deduced from the same cascade model described above. Thus the simulations for pure species are compatible "by construction" with the EAS-TOP data alone[8]. The resulting energy spectra therefore differ from each other, and from the existing all-particle spectra. (For example, the differential energy spectrum utilized for p primaries is, in units of $m^{-2}s^{-1}sr^{-1}GeV^{-1}$: $1.53\times10^5\ E^{-2.88}$ for $E<1.68\times10^6$ GeV and $1.30\times10^7\ E^{-3.19}$ above, and that for Fe primaries is: $3.23\times10^6\ E^{-2.99}$ for $E<3.54\times10^6$ GeV and $4.50\times10^8\ E^{-3.32}$ above.) With this approach, we try to understand the behavior of the cascade model and obtain an indication of the average primary mass.

b) the extrapolation of the nuclear spectra, as measured in direct experiments[9] at lower energies, up to the knee region. The resulting spectrum and composition for $10^5 < N_e < 10^{5.5}$ gives a size spectrum consistent with the one measured by EAS-TOP alone[8]. In the following we shall refer to this model as Σ. Again the simulated sample has the same statistics as the experimental one.

4. Comparison of the Measured and Simulated Data

For the coincident events the comparison of measured and simulated quantities are shown in Figs. 1 - 3, namely, the distributions of: a) N_e (Fig. 1); b) N_μ (Fig. 2); c) $<N_\mu>$ vs. N_e (Fig. 3), i.e. average number of detected muons in fixed intervals of N_e as a function of N_e. This is the relevant plot for composition studies. Only a few pure species are shown for the sake of clarity, together with the result from the Σ model in the relevant energy range. The distributions of Figs. 1 and 2 show absolute numbers of events, all for the same total live time. The coincident muon multiplicity distributions of Fig. 2 cannot be compared directly with those discussed by MACRO alone, either from the point of view of the data (since the energy range is different from MACRO alone), or the analysis (since MACRO normalizes to the all-particle energy spectrum).

5. Discussion

a) From the point of view of the coincidence rate the pure proton composition constructed in the manner described above appears to be inconsistent with experimental rates over the entire N_e range, while a better agreement can be obtained with a heavier composition ($<A> \geq 4$), and in particular in the range $10^5 < N_e < 10^{5.5}$, with the Σ model.

b) In the range $10^5 < N_e < 10^{5.5}$, $<N_\mu>$ is inconsistent with the pure proton composition, while it is in agreement with the Σ model.

c) For $N_e < 10^5$, where the $<N_\mu>$ vs. N_e distribution is not sensitive to the primary composition (see Fig. 3), the measured and simulated values of $<N_\mu>$ are in good agreement. In this energy range the absolute coincident event rate and the rate of AC events are underestimated by the Σ model by $\sim$ 30% and 36%, respectively. This effect is under investigation and could be indicative of a lack of protons in the model. Greater statistics are required for a more detailed analysis.

d) For $N_e > 10^{5.5}$ (i.e. above the knee) a tendency to a larger $<N_\mu>$ with respect to the simulation of pure primary protons is seen. In particular these events are in the tail of the measured N_μ distribution ($N_\mu \geq 16$) in Fig. 2. In a high-statistics simulation of the region $N_e > 10^6$, we find that the fraction of events with $N_\mu \geq 16$ is 1.6% for a pure proton composition, and 19% for pure iron. The experimental value is 3 out of 11 events. The probability for a pure proton beam to give at least 3 events with $N_\mu \geq 16$ is 6×10^{-4}.

6. Conclusions

a) The extrapolation of direct measurements of cosmic ray spectra fits, within the experimental errors, the measured value of $<N_\mu> / N_e$ and coincidence rates in the range $10^5 < N_e < 10^{5.5}$, below the knee of the primary spectrum.

b) A pure proton composition is not consistent with the higher energy data ($E_0 > 10^{16}$ eV). In order to reach consistency within 2σ the number of TeV muons produced in the UHE interaction model would have to be increased by about 30%, especially in the lower energy region. This would exceed the muon production rates in all the models discussed in ref. [10].

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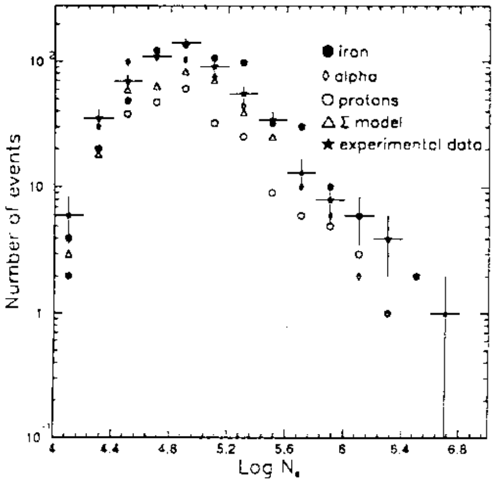

Figure 1. Measured and expected shower size spectrum.

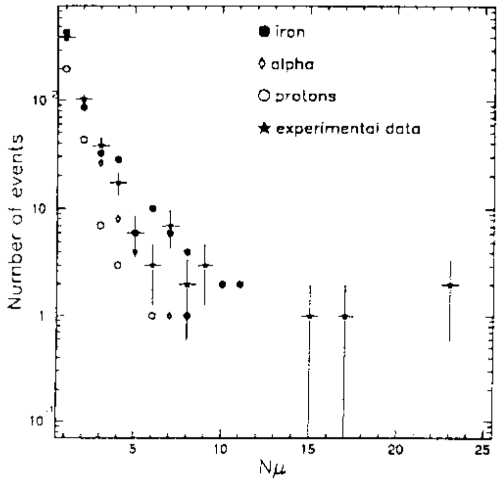

Figure 2. Measured and expected muon multiplicity distributions.

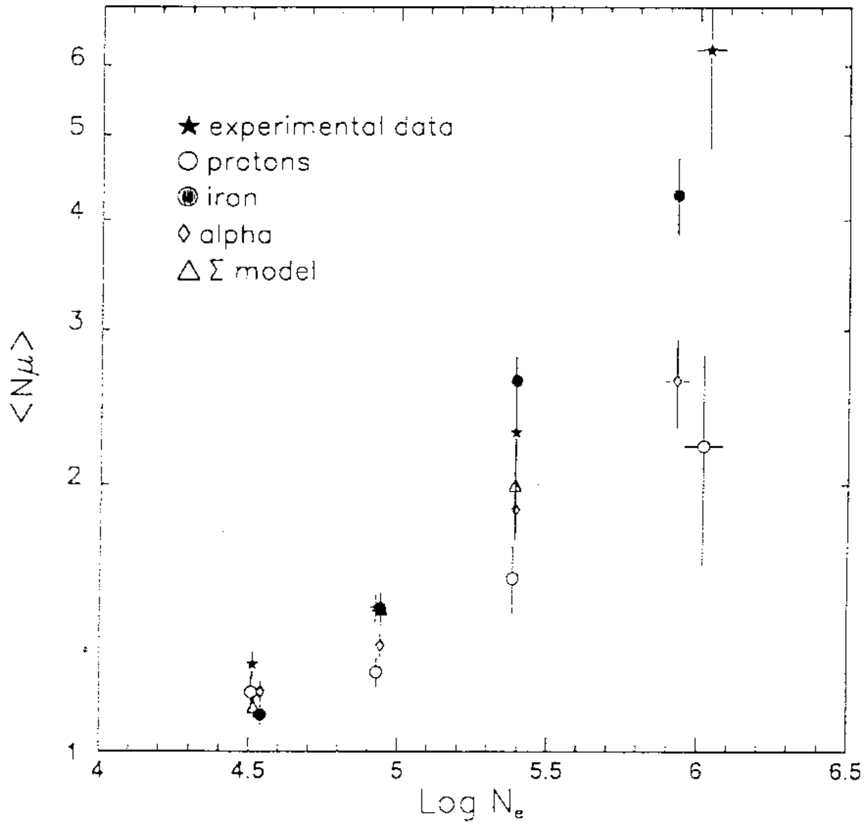

Figure 3. Correlation between $<N_\mu>$ and N_e for experimental, pure species models, and the Σ model in the relevant energy range.

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