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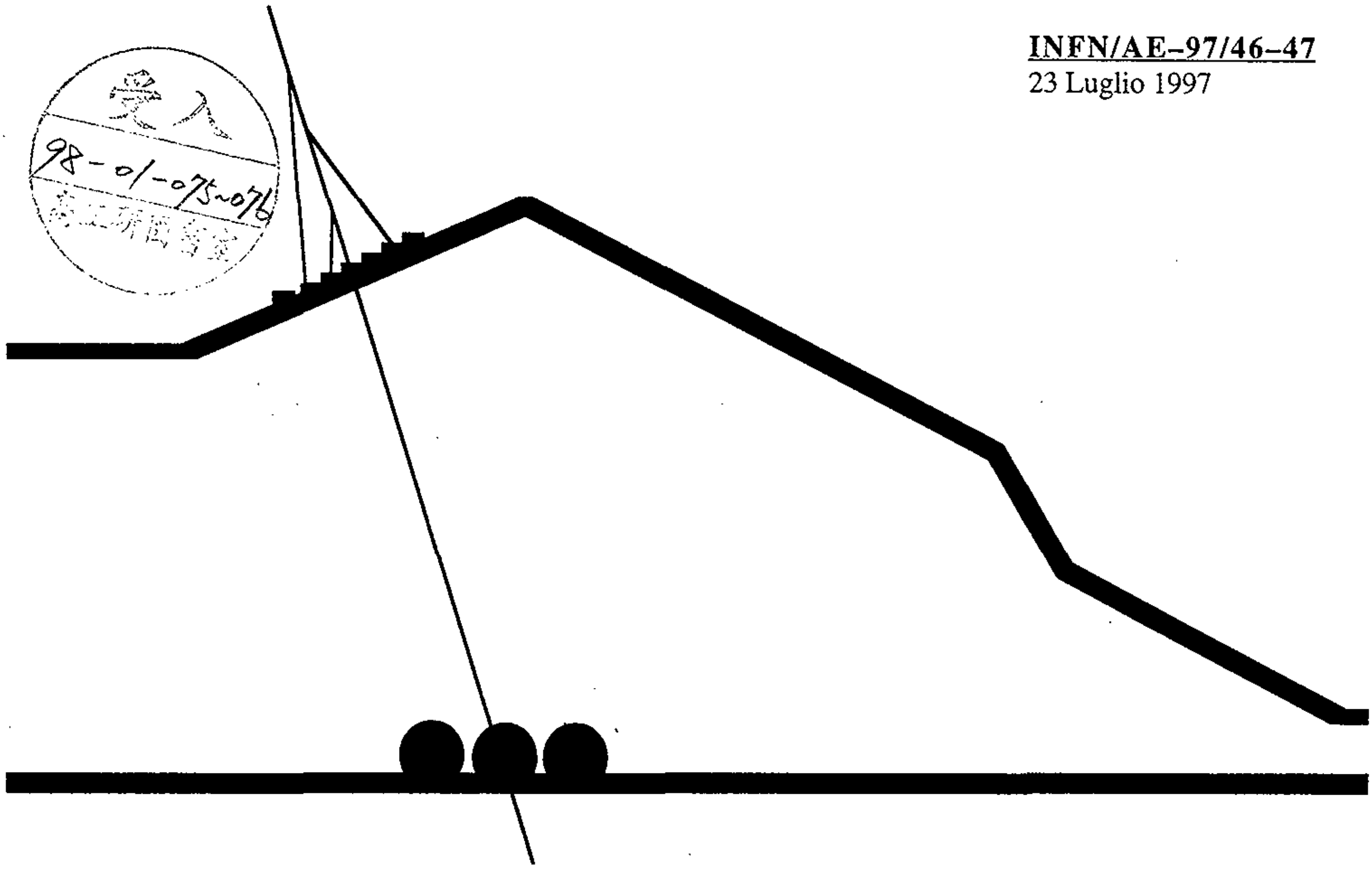

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STUDY OF THE PRIMARY COSMIC RAY COMPOSITION IN THE KNEE REGION WITH EAS-TOP AND MACRO

EAS–TOP and MACRO Collaborations

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ABSTRACT

The rigidity dependent model of the cosmic ray composition at the "knee" is checked by means of the combined EAS–TOP and MACRO data at the Gran Sasso laboratories. Different hadron interaction models provide consistent results with both the muon multiplicity and with the correlated electron and TeV muon data from the two experiments.

INTRODUCTION

The combined measurements of the e.m. component of EAS at the surface and of the high energy muons recorded in deep underground laboratories allow studies of both the cosmic ray primary composition and the interaction models used to interpret the data. Such measurements are performed by the EAS–TOP and MACRO detectors at the Gran Sasso Laboratories. EAS–TOP is the EAS array (enclosed area $A_i = 10^5$ m^2, sensitive area $A_s = 350$ m^2) measuring the shower size (total number of charged particles N_e) at 2000 m a.s.l., while MACRO samples the number of muons (N_μ) at a minimum rock depth of 3100 m w.e. ($A_s = 6 \times 140$ m^2, E_μ^{th}=1.3 TeV). The two detectors are separated by 1100–1300 m of rock and located at a relative zenith angle of $\sim 30°$. Details on the detectors and on their performances and on the analysis of a first sample of coincident data have been presented elsewhere (EAS–TOP and MACRO, 1990, 1993, 1994, 1995). In the present note we present an analysis of the muon multiplicity distributions in different intervals of shower size (below and above the knee) to test the Peters - Zatsepin rigidity dependent model of the knee ($E_k(Z)=Z \cdot E_k(1)$), as e.g. predicted by the rigidity dependent leakage effect from the Galaxy (Peters, 1959 and Zatsepin et al., 1962). Hadron interaction models based on different physical principles are used.

THE DATA

From the technical point of view, we want to stress the combined reconstruction capabilities of the two detectors. They are outlined in Fig. 1 where the differences in the projected arrival directions between the EAS (time-of-flight-technique) and muons (tracking technique) are shown. The distribution widths are compatible with the resolutions of both detectors ($\sim 1°$ each), while the mean values don't show any systematic effect at a level $< 0.05°$. Concerning the physics results, coincident events are selected in the range in which the shower size can be reconstructed by EAS–TOP. Data have been collected during 347.8 live days for a total number of 7889 events in the useful angular window. The number of recorded events is 1310 for $N_e \geq 2.2 \cdot 10^5$ and 226 for $N_e \geq 7 \cdot 10^5$ i.e. the size of the knee as observed at 30° (EAS–TOP collab., 1995), corresponding to about 2200 TeV for primary protons.

RESULTS AND CONCLUSIONS

The results are compared with simulations based on the HEMAS (Forti et al., 1990) and DPMJET (Battistoni et al., 1995 and Ranft, 1995) codes. Full descriptions of the detectors are included following the GEANT code (Brun et al., 1984). In the HEMAS code the interaction model is obtained by the parametrization of the UA5 experimental results at the SPS collider. The DPMJET code is based on the two component Dual Parton Model including the mini–jet production as predicted by the lowest order perturbative QCD, and is therefore a theoretically inspired model. An extrapolation of the low energy data is used for the primary composition (see Table 1), with different hypotheses about the knee: at constant primary energy ($E_k(Z)=E_k(1)$=2200 TeV), and at atomic number scaling energies ($E_k(Z)=Z \cdot E_k(1)$), and $\Delta\gamma = -0.5$. The value of $E_k(1)$ is chosen to reproduce the observed size spectrum, assuming that it is dominated by the lightest mass component.

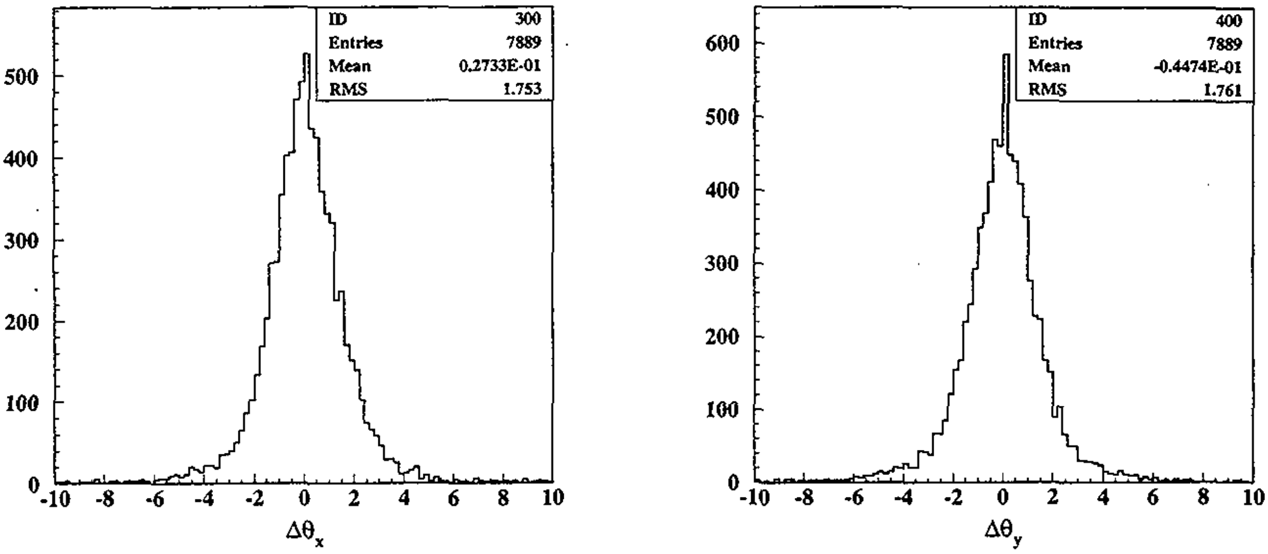

Fig. 1: Distributions of the projected angular difference between the EAS and muon arrival directions measured respectively by EAS–TOP and MACRO.

Table 1: Parameters of the differential spectra $dN/dE = K \cdot (E/GeV)^{-\gamma}$ of the nuclear components of the composition model used.

Mass group	K $(m^2\ s\ sr\ GeV/nucleus)^{-1}$	γ_1	$E_{knee}\ (GeV)$	γ_2
p	$5.57 \cdot 10^4$	2.86	$2.2 \cdot 10^6$	3.36
He	$9.15 \cdot 10^3$	2.68	$4.4 \cdot 10^6$	3.18
CNO	$1.18 \cdot 10^3$	2.56	$1.5 \cdot 10^7$	3.06
Mg-Si	$1.35 \cdot 10^3$	2.63	$2.6 \cdot 10^7$	3.13
Fe	$1.46 \cdot 10^3$	2.63	$5.7 \cdot 10^7$	3.13

The $N_e - N_\mu$ relation for both composition models and interaction codes is shown in Fig. 2. Most significant are the muon multiplicity distributions obtained for shower sizes below and above the knee of the measured size spectrum, and are shown in Figs. 3 and 4. The high multiplicity tail of the muon number distribution is better reproduced by a composition becoming heavier above the knee, as predicted by the rigidity dependent break, for both interaction models. It is interesting to remark that the DPMJET model solves the systematic deviation of the first point in the $N_e - N_\mu$ plot shown in Fig. 2 (relative to $\approx$ 100 TeV primaries). The measurement concerns the average muon multiplicity $< N_\mu^{det} >$ in fixed size windows and is therefore largely independent of the assumed primary spectra (see paper HE 1.2.24 in these proceedings). This means that for higher primary energies ($\geq$ 1000 TeV, where secondary production at low x_F becomes relevant for the TeV muon yield) both models describe the experimental rates; at lower energies (< 100 TeV, where the fragmentation region is dominant) the DPMJET model is more adequate. A recent work (J. Knapp et al., 1996), aiming to compare different interaction models, confirms that around the knee energy the predictions for TeV muons exhibit differences within 10%. We want also to point out that, qualitatively, the relative difference in the shapes of the muon multiplicity distributions for the two hypotheses about the nature of the knee is only marginally dependent on the details of the chosen input spectra, for a wide class of reasonable mixed compositions. Thus the data support a primary composition becoming heavier above the knee,

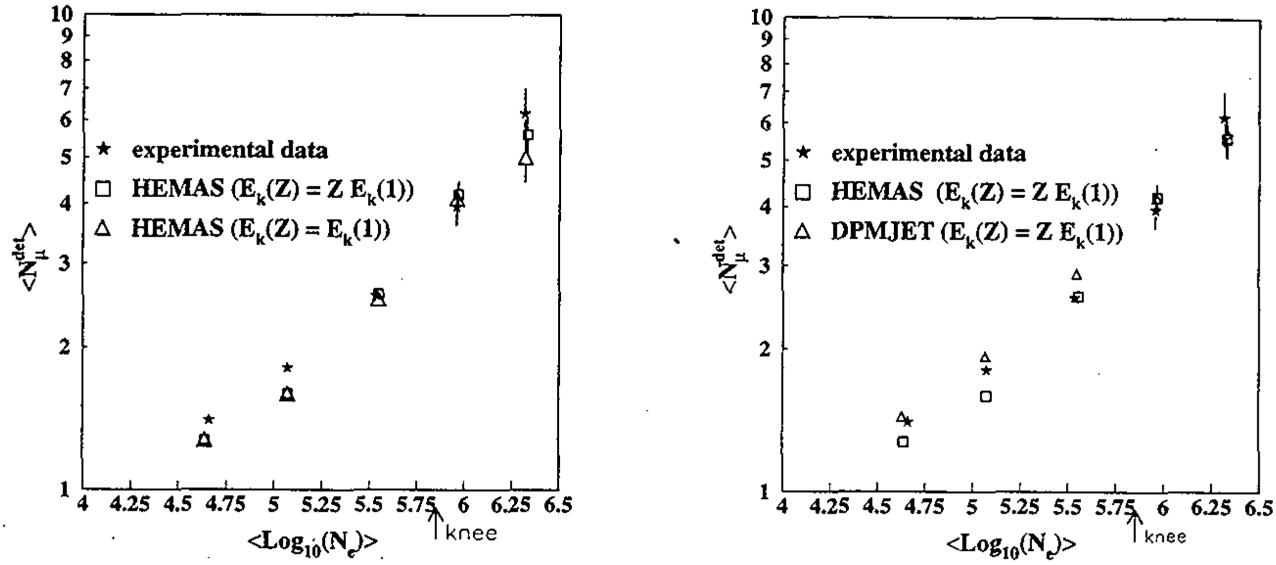

Fig. 2: Correlation between $< N_\mu^{det} >$ and $<Log_{10}N_e>$: comparison between different knee hypotheses (left) and different interaction models (right).

in agreement with the rigidity-dependent model of the knee. We also notice how the analysis of the underground muon fluxes as a function of multiplicity, performed by MACRO alone (Ambrosio et al., 1995 and 1996), is consistent with a rigidity dependent knee. This was first proposed in the frame of the rigidity dependent leakage effect from the Galaxy (P–Z), but other processes can as well be responsible. Different hadron interaction models provide consistent results; this aspect will be further investigated.

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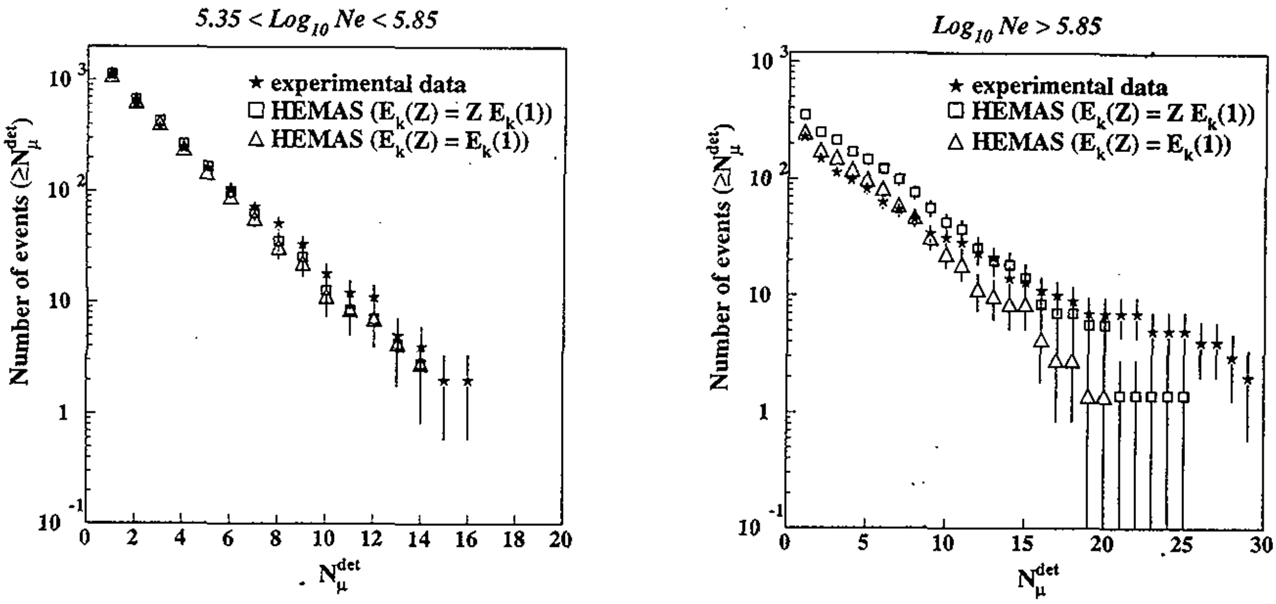

Fig. 3: Measured and expected integral distribution of detected muon multiplicity, for $5.35 \leq Log_{10}N_e \leq 5.85$ *(left), and* $Log_{10}N_e > 5.85$ *(right): comparison between different knee hypotheses.*

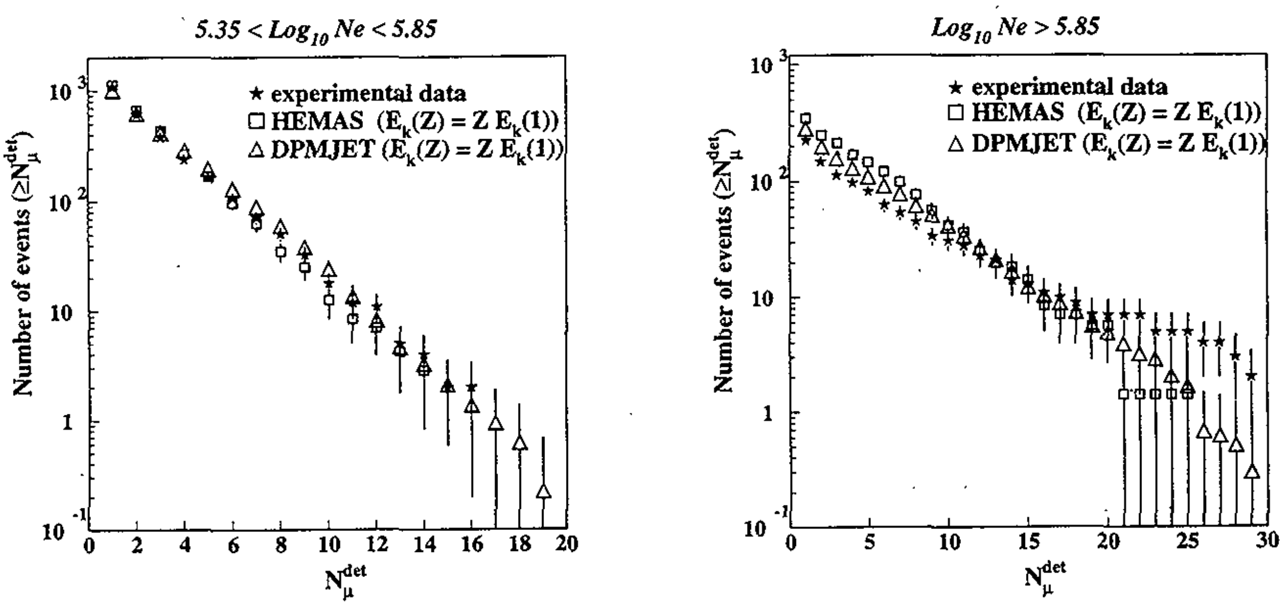

Fig. 4: Measured and expected integral distribution of detected muon multiplicity, for $5.35 \leq Log_{10}N_e \leq 5.85$ *(left), and* $Log_{10}N_e > 5.85$ *(right): comparison between different interaction models.*

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