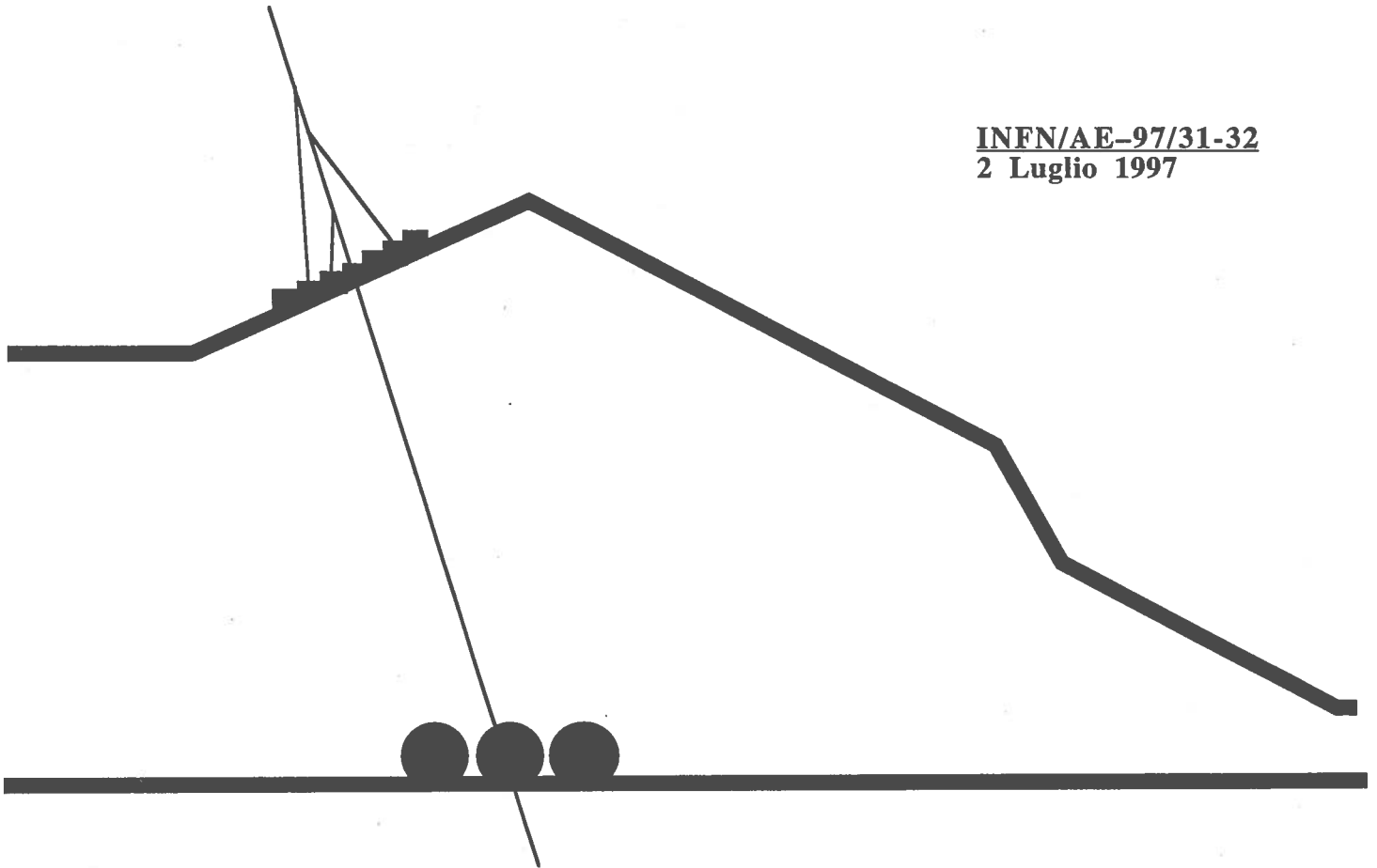


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*Contributions of the LVD and EAS TOP Collaborations to the XXV ICRC  
Durban, South Africa July 28–Aug. 10, 1997*

**INFN – Laboratori Nazionali del Gran Sasso**

*Published by SIS-Pubblicazioni  
dei Laboratori Nazionali di Frascati*



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# THE HIGH ENERGY MUON SPECTRUM IN EXTENSIVE AIR SHOWERS: FIRST DATA FROM LVD AND EAS-TOP AT GRAN SASSO

INFN/AE-97/31  
2 Luglio 1997

## ABSTRACT

Simultaneous measurements of  $N_e$ ,  $N_\mu^{GeV}$  ( $= N_\mu(E_\mu > 1 GeV)$ ) at the surface and  $N_\mu^{TeV}$  ( $= N_\mu(E_\mu > 1.3 TeV)$ ) and  $\Delta E_\mu/\Delta L$  (i.e. muon energy losses per unit of track length) are performed at the Gran Sasso Laboratories by EAS-TOP at the surface (2000 m a.s.l.) and LVD (3400 m w.e. underground) in the energy range of primaries  $2 \cdot 10^{14} - 5 \cdot 10^{15} eV$ . 'VH' (iron-like) and 'light' (proton-like) primary candidates are selected from the shower size ( $N_e$ ) vs. LVD data distributions. In particular, in two ranges of  $N_e$ , 'VH' primaries were selected using large muon number detected by LVD and 'light' primaries using high muon energy losses in the LVD scintillation counters. They are analyzed at the surface in the  $N_e - N_\mu^{GeV}$  domain. The identification is confirmed by their 'location' in the regions of 'high' and 'low' muon number distribution. In particular the experimental points lay around the average predictions from the CORSIKA-HDPM code. The procedure allows thus the identification of the primaries of individual events and the confirmation of the average predictions of the hadronic interaction and cascade model used.

## INTRODUCTION

Main problems in the interpretation of EAS data are given by the difficulties of separating hadronic physics from composition effects, and by the role of the fluctuations intrinsic in the detection technique. A main improvement in such direction is of performing multicomponent observations of EAS and of analyzing a sample, although small, of individual events. This is one of the aims of the EAS-TOP experiment at the Gran Sasso laboratories and its correlated measurements with the detectors operating in the underground laboratories (the main principles of the method are discussed in EAS-TOP Collaboration, 1997a).

The present data include measurements from the electromagnetic ( $N_e$ ) and muon detectors ( $N_\mu^{GeV} = N_\mu(E_\mu > 1 GeV)$ ) of EAS-TOP and the LVD deep underground detector ( $N_\mu^{TeV} = N_\mu(E_\mu > 1.3 TeV)$ ). Events candidate for being originated by 'light' (proton-like) or 'very heavy' (iron-like) primaries are selected from their characteristics in the EAS-TOP ( $N_e$ ) and LVD ( $N_\mu^{TeV}$ ) domain. 'Light' primaries are selected from the high muon energy, indicated by large energy losses in LVD, and relatively small  $N_e$  (indicating high energy/nucleon of the primary). Very heavy primary candidates are selected from high muon multiplicities in a specified shower size interval. Such events are studied at the surface following the  $N_e - N_\mu^{GeV}$  data. It is shown that in both cases, although in different primary energy ranges, they fall on the average expected region for the respective primaries.

## THE DATA AND THE ANALYSIS

EAS-TOP is an EAS array located at 2000 m a.s.l.,  $30^\circ$  above the zenith of the underground Gran Sasso laboratories. Its e.m. detector is made of 35 modules scintillator detectors  $10 m^2$  each spread over an area of  $10^5 m^2$  (Aglietta et al., 1988 and 1993). The shower size ( $N_e$ ) is measured for events internal to the edges of the array, through a fit of the l.d.f. providing also the core location, with accuracy  $\sigma_{N_e}/N_e \approx 10\%$  for  $N_e \geq 2 \cdot 10^5$ .

The muon detector is a  $144 m^2$  tracking module (EAS-TOP Collaboration, 1995).  $N_\mu^{GeV}$  represents the total muon number with  $E_\mu > 1 GeV$ , obtained from the number of muons recorded in the muon detector ( $n_\mu$ ) and the experimental average l.d.f. constructed at the zenith angle of  $25 - 35^\circ$ :

$$N_\mu^{GeV} = k \times n_\mu \times (r/r_0)^{0.75} \times (1 + r/r_0)^{2.5} \text{ (with } r_0 = 400 \text{ m).}$$

An analysis of the  $N_e - N_\mu^{GeV}$  data has been presented (EAS-TOP Collaboration, 1995).

LVD is a large volume of liquid scintillator (Aglietta et al., 1992) interleaved with limited-streamer tubes (Aglietta et al., 1994) in a compact geometry, that combines high tracking capabilities with good energy loss measurements (Aglietta et al., 1997b), located in the underground Gran Sasso laboratories. The final detector will consist of five towers of 304 scintillator counters each. In the present analysis' only one tower is considered (total area  $78 \text{ m}^2$ ).

Due to the lack of information on the EAS core location deep underground,  $N_\mu^{TeV}$  is the detected muon number, and therefore represents a lower limit to the total muon number with  $E_\mu > 1.3 \text{ TeV}$ , and the  $N_e - N_\mu^{TeV}$  relation is affected by the 'geometrical' triggering probability ( $N_\mu^{TeV} \geq 1$ ).

$\Delta E_\mu / \Delta L$  is the muon energy released in the LVD scintillator counters ( $1.5 \times 1 \times 1 \text{ m}^3$  seen by three photomultipliers) normalized to the track length  $\Delta L$  in the scintillators, obtained from the tracking system with accuracy within 1%.

The energy resolution is about 15% for a  $10 \text{ MeV}$  energy release (Aglietta et al., 1992).

The data have been collected in 14200 h of running time between June 1992 and December 1996.

A first set of data comparable with the experimental ones has been simulated by means of the CORSIKA code (HDPM model, version 4.502 Capdevielle et al., 1991) for proton and iron primaries ( $\gamma_p = \gamma_{Fe} = 2.62$ ). The muon propagation in the rock is simulated by means of the MUSIC code (Antonioli et al., 1997). The full response of the detectors is introduced.

## RESULTS AND CONCLUSIONS

The experimental and simulated  $N_e - N_\mu^{GeV}$  and  $N_e - N_\mu^{TeV}$  scatter plots are shown in Figs. 1 and 2. In Fig. 1 the average expectations from the simulations for proton and iron primaries are also shown.

For events with  $N_\mu^{TeV} = 1$  and  $N_e < 2 \cdot 10^5$ , we studied the energy loss distributions inside the LVD counters. We found that the fraction of events giving energy losses  $\Delta E_\mu / \Delta L > 4 \text{ MeV/cm}$  simultaneously in the top and bottom layers of LVD crossed by the track is 0.7% for proton primaries and 0.1% for iron primaries.

On the basis of these considerations, 'VH' and 'light' enriched primary beams are selected by EAS-TOP and LVD respectively through:

- (a) large  $N_\mu^{TeV}$  muon numbers: the effective selection efficiency being not relevant at the moment, we will use the empirical selection of events given by  $N_\mu^{TeV} > 2.3 \text{ Log} N_e - 7.3$  (see dashed line in Fig. 2) for  $N_e > 2 \cdot 10^5$ , whose probability of being due to fluctuations of light primaries is small enough;

- (b) large muon energy losses: in this first approximation, they are fixed at  $\Delta E_\mu / \Delta L > 4 \text{ MeV/cm}$  in the highest and lowest counter crossed by the track inside the detector. Only events with  $N_\mu^{TeV} = 1$  and with  $N_e < 2 \cdot 10^5$  are considered.

The  $N_e - N_\mu^{GeV}$  relations at the EAS-TOP level for such selected events a) and b) are shown in Fig. 3, together with the average expectations from the CORSIKA code. The number of events is small, but they clearly identify regions of large and small muon numbers in the  $N_e - N_\mu^{GeV}$  scatter plot, as expected respectively from 'VH' and 'light' primaries. The probabilities that the  $N_\mu^{GeV} - N_e$  distributions for the selected p-like and Fe-like candidates are sampled from the experimental all data distribution of Fig. 1 are, for both cases, less than 1%.

It is shown that the CORSIKA code reproduces fairly well their average behaviours.

Also by means of the quoted simulation it has been shown that for fixed primaries the fluctuations in the  $GeV$  and  $TeV$  muon numbers ( $N_\mu^{GeV}$  and  $N_\mu^{TeV}$ ), as well as  $\Delta E_\mu / \Delta L$  and  $N_\mu^{GeV}$ , are uncorrelated, thus showing that the observed correlation is not connected with the shower development, but through the EAS primaries.

Of course the statistics is poor, but the identification of different classes of primaries in EAS experiments is of utmost significance for cosmic ray measurements at high energies. The hadronic interaction model, and the cascade code used (CORSIKA-HDPM) are on average verified.

The energy range is now essentially below the knee of the size spectrum. Its extension above

the knee will allow a confirmation of the hadronic physics used to analyze the primary composition in such energy range.

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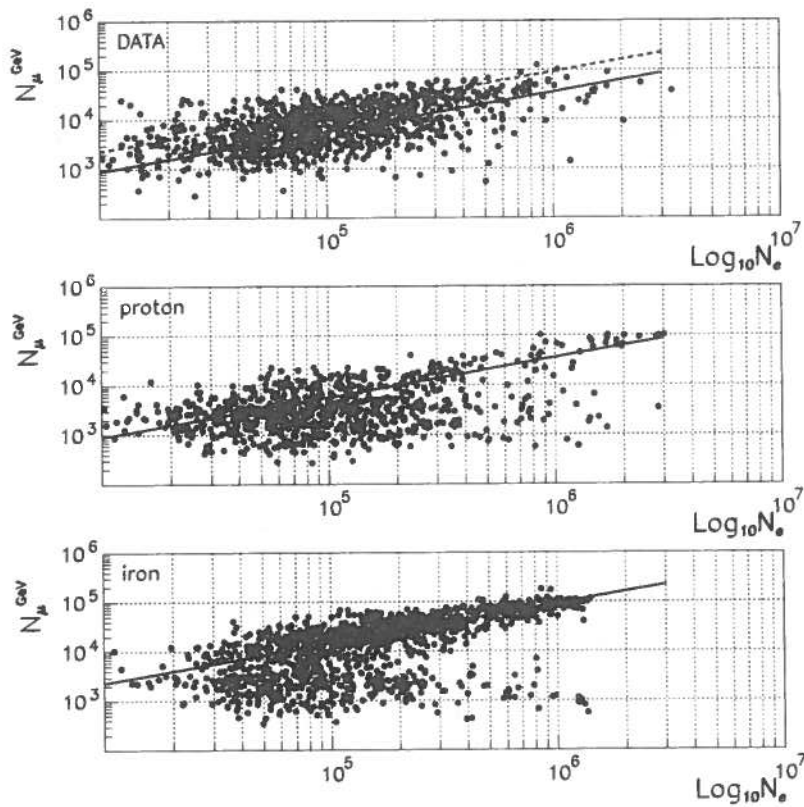


Fig. 1:  $N_{\mu}^{\text{GeV}}$  vs.  $N_e$  for measured events and simulated  $p$  and  $Fe$  primaries. The fits are made without considering events with  $n_{\mu} = 0$ . The fits are also superimposed to experimental data (dashed line:  $Fe$ , solid line:  $p$ ).

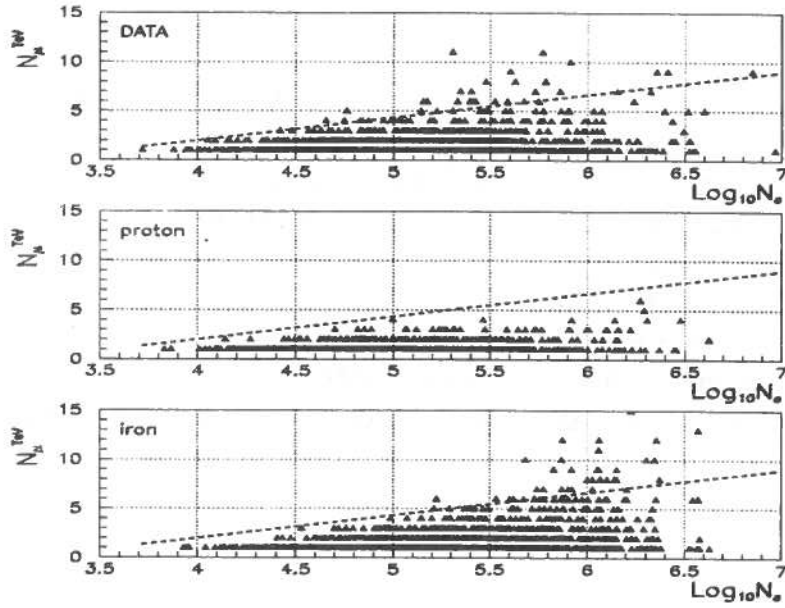


Fig. 2:  $N_{\mu}^{\text{TeV}}$  vs.  $N_e$  for experimental and simulated data. The dashed line represents the cut (a) applied to the data for  $N_e \geq 2 \cdot 10^5$  (see text)

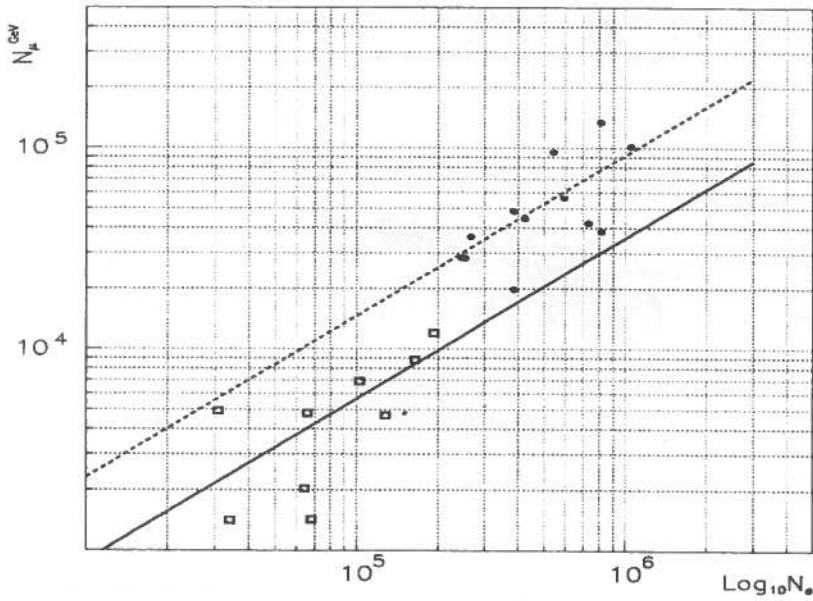


Fig. 3:  $N_{\mu}^{\text{GeV}}$  vs.  $N_e$  for selected 'VH' and 'light' primaries obtained by applying cuts (a) (full circles) and (b) (open squares) (see text). The fits of Fig. 1 obtained from the simulation for Fe (dashed line) and  $p$  primaries (solid line) are also shown.



# LARGE TEV AND GEV MUON MULTIPLICITIES IN EAS: SEPARATION OF P AND VERY HEAVY PRIMARIES AT $10^{15}$ EV

INFN/AE-97/32  
2 Luglio 1997

## ABSTRACT

The method of combining shower size with highest energy muon measurements is introduced as a tool for studying the cosmic ray primary composition at EAS energies ( $E_0 = 10^{14} - 10^{15}$  eV). The shower size is measured through the e.m. detector of EAS-TOP at the surface; information on the muon energy is deduced from the muon energy losses in LVD in the underground Gran Sasso laboratories at a depth of 3000 *m w.e.*. It is shown that the average muon energy losses (and therefore the highest muon energy) increase with shower size. This is expected from a mixed primary composition in our energy range.

## INTRODUCTION

High energy muons are measured in deep underground laboratories for studies of primary composition from the point of view of: a) the muon multiplicities (Bakatanov et al, 1985; Berger et al, 1989; Aglietta et al., 1990; Ahlen et al., 1992); b) the muon multiplicities vs  $N_e$  (Aglietta et al., 1994); c) the muon energies vs  $N_\mu$  (Barnaveli et al., 1987). In the present paper we present first data on measurements of shower size ( $N_e$ ) at the surface and muon energy losses (i.e. muon energies) deep underground.

The shower size is measured through EAS-TOP, the EAS array located on the top of the underground Gran Sasso laboratories. Different mean muon energies are selected in LVD by looking at the increase in the radiative mean energy losses, through the muon energy loss per unit path length,  $dE/dx$ . Low fractional energy losses  $\nu = \Delta E/E$  to charged secondaries are primarily detected in the LVD counters because of their size; pair production is expected to be the dominant source of increasing energy losses. Due to the limited thickness of LVD (some 800-1200  $g\ cm^{-2}$ ), fluctuations play an important role in the single muon energy loss per unit path length distributions. Measurements are largely improved by collecting large samples of muons selected on independent bases, as the depth of traversed rock (Aglietta et al., 1997) or -and this is the present case- as the shower size at surface (Emaldi, 1996). It emerges that the LVD detector is sensitive to the increase of the average muon energy with shower size, and that the measured relation between the average muon energy loss in the LVD detector and shower size measured at the surface by EAS-TOP reflects the "mixed" character of the cosmic ray primary composition.

## DATA ANALYSIS

EAS-TOP (2000 *m a.s.l.*; Campo Imperatore, 30<sup>0</sup> from the vertical of the underground Gran Sasso laboratories) is an apparatus tailored for the detection of several different EAS components (Aglietta et al., 1989). Its e.m. detector is an array of 35 modules, each of area 10  $m^2$ , enclosing an area of  $\sim 10^5 m^2$ . In the present work we consider only internal trigger events, i.e. events with the reconstruction of primary arrival direction, core location and shower size (Aglietta et al., 1993).

LVD, (Bari et al., 1989; Aglietta et al., 1992,1994) located in the underground Gran Sasso laboratories, detects muons passing through by the interactions in the scintillator counters and tracking system. The data reported here come from the first tower of LVD. To avoid instrumental effects and for homogeneity reasons the present work is restricted to high saturation counters (roughly  $\sim 600 \div 700$  MeV of ADC saturation energy). The tracking system provides bidimensional information about an ionizing particle's impact point. Here we considered only muon tracks with at least three impact points observed by the tracking system.

EAS-TOP and LVD are separated by 3000 - 3200 *m w.e.* thickness with a corresponding mean minimum surface energy for a muon to reach LVD from EAS-TOP ranging from  $\sim 1.4$  *TeV* to  $\sim 1.6$  *TeV*. Event coincidence was established off-line, using the absolute time given by atomic clocks with an accuracy better than 1  $\mu s$  (Aglietta et al., 1992).

Present analysis regards the period 1992-1995 of common data taking of the two detectors, with the full EAS-TOP e.m. array and one tower of LVD. By considering only EAS-TOP internal trigger events, we have recorded 3419 events within  $\pm 2 \mu s$  of the coincidence peak, with an expected accidental contamination of 3.5%. By imposing the above mentioned condition on muon track reconstruction in LVD a total number of 2835 muon tracks were retained; each track was individually analyzed. For each muon, every traversed counter (the data sample has a total of 2007 hit counters selected) gives an indication of the energy loss per unit path length  $dE/dx$  through the quantity  $\Delta E/\Delta L$ , where  $\Delta E$  is the energy deposition and  $\Delta L$  is the track length in the traversed counter. The scintillation counters are calibrated exploiting the most probable energy deposition by muons obtained from a detailed Monte Carlo simulation (Kudryavtsev and Ryazhskaya, 1992) and for all the counters the estimated error in energy determination is less than 3% at  $E = 185$  *MeV*. According to the resolution of the tracking system, the error on  $\Delta L$  is then less than 1%.

This quantity  $\Delta E/\Delta L$  is not a proper measure of  $dE/dx$  due to *leakage* effects (the counter thickness is  $\sim 80$  *g cm<sup>-2</sup>*) (Antonioli et al., 1991) and to *contamination* from secondaries generated by the muon outside the counter and penetrating it. In case of multiple muon events, the cross-talk among the muons due to these effects is largely negligible and the influence on  $\langle \Delta E \rangle$  is on average less than 0.1%, i.e. negligible with respect to the effect we have obtained (see below). The influence of both the effects on  $\Delta E/\Delta L$  measurements is found to depend on  $\Delta L$ , decreasing with increasing  $\Delta L$ . The  $\Delta L$  distribution shows a peak at large values of  $\Delta L$  determined by mean arrival zenith angle of muons coming from EAS-TOP ( $29^\circ$ ). We have selected counter traversals with  $\Delta L$  values corresponding to the peak ( $100$  *cm*  $< \Delta L < 130$  *cm*): in this way we minimize leakage and contamination effects (large  $\Delta L$ ) retaining sufficiently high statistics.

## RESULTS AND DISCUSSION

Four shower size intervals were chosen with regard to statistics, namely  $N_e < 10^{4.5}$ ,  $10^{4.5} \leq N_e < 10^{5.0}$ ,  $10^{5.0} \leq N_e < 10^{5.5}$  and  $N_e \geq 10^{5.5}$ .

A comparison among the distributions indicates that the region of 2-4 *MeV/cm* in  $\Delta E/\Delta L$  values (just above the ionization peak) has a weight growing with the size of showers. This is shown in figure 1 where the integral distributions of  $\Delta E/\Delta L$  (fraction  $> \Delta E/\Delta L$ ) are superimposed. The region with the rapid decrease of the distributions corresponds to the ionization peak region in the differential distributions. Distributions go down to zero at  $\sim 6$  *MeV/cm* as an effect of ADC saturation of the counters. Saturation of the coun-

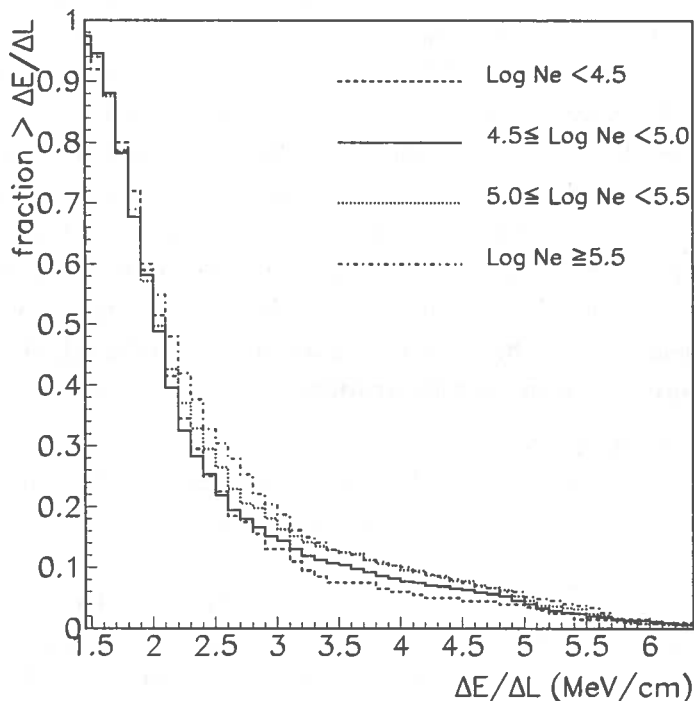


Fig. 1: Integral distributions of  $\Delta E/\Delta L$  values for four different shower size intervals. Note the enhancement of the tails with shower size.

ters occurs in each interval at the rate of 2.1%, 2.5%, 3.4% and 5.2% respectively from the lowest to the highest shower size interval.

The enhancement with shower size of energy deposition per unit path length is also manifest directly in terms of  $\langle \Delta E/\Delta L \rangle$  values; such behaviour is shown in figure 2 where the data are reported ( $\circ$ ) with the statistical errors. Simulation for pure proton ( $\Delta$ ) and pure iron ( $\square$ ) primaries are also reported, where shower development in the atmosphere is obtained from the CORSIKA code (Capdevielle et al., 1992) muon transport in the rock is done with the code described in (Kudryavtsev, 1987) and (Antonioli et al, 1997), and detector simulation is done with GEANT (Brun et al, 1987). Correcting for the ADC saturation of the counters, the enhancement with shower size in  $\langle \Delta E/\Delta L \rangle$  values is

$$\frac{1}{\Delta \log N_e} \cdot \frac{1}{\langle \Delta E/\Delta L \rangle} \Delta \left( \frac{\Delta E}{\Delta L} \right) = (5.9 \pm 0.8 \pm 0.3)\% \quad (1)$$

per decade variation of  $N_e$  at  $N_e \sim 10^5$ , where the first error is statistical and the second systematic (without the saturation correction the result is 5.6% per decade variation of  $N_e$ ).

We conclude that a significant enhancement in  $\langle \Delta E/\Delta L \rangle$  associated with shower size is observed. At our energies mean ionization losses are almost flat with energy (knock-on electrons included); radiative energy losses are then required to account for it. Moreover this enhancement is determined mainly by effects at  $\Delta E/\Delta L$  values immediately larger than those corresponding to the ionization dominance region. These processes then must be dominated by low fractional energy losses  $\nu$  which we expect from direct  $e^+ - e^-$  pair production (Alekseyev and Zatsepin, 1960).

In figure 2 we see also that such a rise in  $\Delta E/\Delta L$  values is not expected in a pure proton composition and this constitutes a simple direct indication that a mixed cosmic ray composition is required in the energy range  $10^{14} - 10^{15}$  eV. This reflects the  $E_0/A$  cut-off at high muon energies.

## CONCLUSIONS

The highest energy muons in EAS are studied by means of the combined EAS-TOP and LVD data:

- measurements are performed in LVD by exploiting the increasing muon energy losses due to direct pair production;
- the mean muon energy loss in LVD per unit path length increases with shower size; the rate is  $(5.9 \pm 0.8 \pm 0.3)\%$  per decade variation of  $N_e$  at  $N_e \sim 10^5$ ;
- the measurement is sensitive to primary composition and

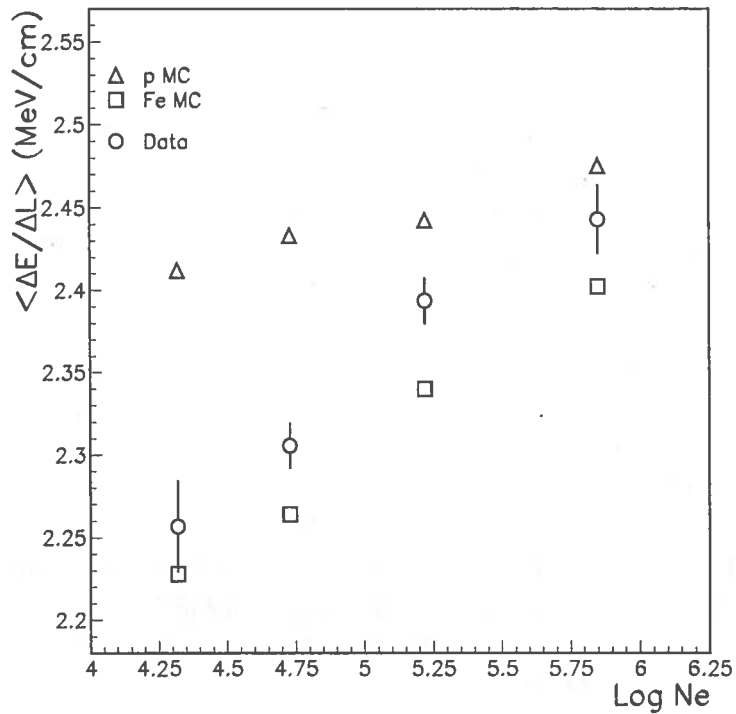


Fig. 2: Values of  $\langle \Delta E/\Delta L \rangle$  from simulations and from data analysis; note that pure proton are quite flat.

- simulations show that this is not compatible with the expectations from a pure proton composition. This suggests that mean energy losses per unit path length are a new significant parameter in the study of the primary cosmic ray composition around the knee.

#### ACKNOWLEDGEMENTS

We wish to thank the staff of the Gran Sasso Laboratory for their aid and collaboration. This work is supported by the Italian Institute for Nuclear Physics (INFN) and in part by the Italian Ministry of University and Scientific-Technological Research (MURST), the Russian Ministry of Science and Technical Policy, the Russian Found of Fundamental Researches (grant 96-02-19007), the US Department of Energy, the US National Science Foundation, the State of Texas under its TATRP program, and Brown University.

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