ELSEVIER
Astroparticle Physics 9 (1998) 185-192
Astroparticle Physics

The high energy muon spectrum in Extensive Air Showers: first data from LVD and EAS-TOP at Gran Sasso

LVD and EAS-TOP Collaborations

M. Aglietta[p], B. Alessandro[p], B. Alpat[m], E.D. Alyea[g], P. Antonioli[a], F. Arneodo[e,r],
G. Badino[p], G. Bari[a], M. Basile[a], V.S. Berezinsky[j], L. Bergamasco[p], F. Bersani[a],
M. Bertaina[p], R. Bertoni[p], G. Bonoli[a], A. Bosco[b], G. Bruni[a], A. Campos Fauth[c],
G. Cara Romeo[a], C. Castagnoli[p], A. Castellina[p], A. Chiavassa[p], J.A. Chinellato[c],
L. Cifarelli[a,1], F. Cindolo[a], G. Cini Castagnoli[p], G. Conforto[q], A. Contin[a], V.L. Dadykin[j],
A. De Silva[b], M. Deutsch[h], B. D'Ettorre Piazzoli[s], G. Di Sciascio[s], P. Dominici[q],
L.G. Dos Santos[c], L. Emaldi[a], R.I. Enikeev[j], F.L. Fabbri[d], W. Fulgione[p], P. Galeotti[p],
C. Ghetti[a], P.L. Ghia[p], P. Giusti[a], R. Granella[p], F. Grianti[a], G. Guidi[q], E.S. Hafen[h],
P. Haridas[h], G. Iacobucci[a], M. Iacovacci[s], N. Inoue[n], E. Kemp[c], F.F. Khalchukov[j],
E.V. Korolkova[j], P.V. Korchaguin[j], V.B. Korchaguin[j], V.A. Kudryavtsev[j], K. Lau[f],
A. Lima de Godoi[c], M.L. Luvisetto[a], G. Maccarrone[d], A.S. Malguin[j], G. Mannocchi[p],
R. Mantovani[q], T. Massam[a], B. Mayes[f], A. Megna[q], N. Mengotti Silva[c], C. Morello[p],
J. Moromisato[i], R. Nania[a], G. Navarra[p], H. Nogima[c], L. Panaro[p], L. Periale[p], A. Pesci[a],
P. Picchi[p], L. Pinsky[f], I.A. Pless[h], J. Pyrlik[f], V.G. Ryasny[j], O.G. Ryazhskaya[j],
O. Saavedra[p], K. Saitoh[o], S. Santini[q], G. Sartorelli[a], M. Selvi[a], N. Taborgna[e],
V.P. Talochkin[j], J. Tang[h], G.C. Trinchero[p], S. Tsuji[k], A. Turtelli[c], I. Uman[m], P. Vallania[p],
S. Vernetto[p], F. Vetrano[q], C. Vigorito[p], E. von Goeler[i], L. Votano[d], T. Wada[k],
R. Weinstein[f], M. Widgoff[b], V.F. Yakushev[j], I. Yamamoto[ℓ], G.T. Zatsepin[j], A. Zichichi[a]

[a] *University of Bologna and INFN-Bologna, Bologna, Italy*
[b] *Brown University, Providence, USA*
[c] *University of Campinas, Campinas, Brazil*
[d] *INFN-LNF, Frascati, Italy*
[e] *INFN-LNGS, Assergi, Italy*
[f] *University of Houston, Houston, USA*
[g] *Indiana University, Bloomington, USA*
[h] *Massachusetts Institute of Technology, Cambridge, USA*
[i] *Northeastern University, Boston, USA*
[j] *Institute for Nuclear Research, Russian Academy of Sciences, Moscow, Russian Federation*
[k] *Okayama University, Okayama, Japan*
[ℓ] *Okayama University of Science, Okayama, Japan*
[m] *University of Perugia and INFN-Perugia, Perugia, Italy*
[n] *Saitama University, Saitama, Japan*

PII S0927-6505(98)00024-3

[o] *Ashikaga Institute of Technology, Ashikaga, Japan*
[p] *Institute of Cosmo-Geophysics, CNR, University of Torino and INFN-Torino, Torino, Italy*
[q] *University of Urbino and INFN-Firenze, Italy*
[r] *University of l'Aquila, Italy*
[s] *University of Napoli and INFN-Napoli, Napoli, Italy*

Received 26 February 1997; revised 31 March 1998; accepted 8 May 1998

Abstract

We present evidence for a dependence of the average deep underground muon energies on shower size in the coincident EAS-TOP and LVD data at the Gran Sasso laboratories. The measured relation agrees with a mixed chemical composition of the cosmic ray primary spectrum at energies around 10^{15} eV.

---

1. Introduction

A main task in the study of cosmic rays above 10^{14} eV from ground based observation consists of the separation of primary composition from high energy interaction effects. This task is made difficult by the lack of direct knowledge of the high energy hadron interaction properties in this energy region.

Measurements on high energy secondaries (or on their decay products, as e.g. muons) represent important tools for such purpose since they are produced in the first interactions and therefore not subject to the processes of cascade development. Moreover, their energy distribution in the high energy tail is subject to the kinematical cutoff $E_s^{max} < E_0/A$ which makes this observable sensitive to the primary composition. This sensitivity is most effectively displayed when muon energy is correlated to shower size measurements. In fact, the shower size (total electron number N_e) represents the observable which is best related to the primary energy E_0 (although through the primary mass A and an interaction-cascade model): $N_e = \alpha(A) \cdot E_0^{\beta(A)}$.

Measurements of the high energy muon numbers in deep underground observatories have been exploited uncorrelated [1-4] or correlated [5] with the EAS (Extensive Air Shower) shower size data. The selection of high energy muons to select high energy/nucleon primaries has been introduced in [1] and discussed in correlation with surface measurements in [6]. But the whole muon energy distribution and therefore its mean value as a function of shower size is sensitive to the primary composition. This is shown in Fig. 1 where the mean muon energies at the depth of 3000 m w.e. (LVD depth) as obtained from the CORSIKA code [7] and muon propagation in the rock [8,9] are displayed for different primaries and shower sizes.

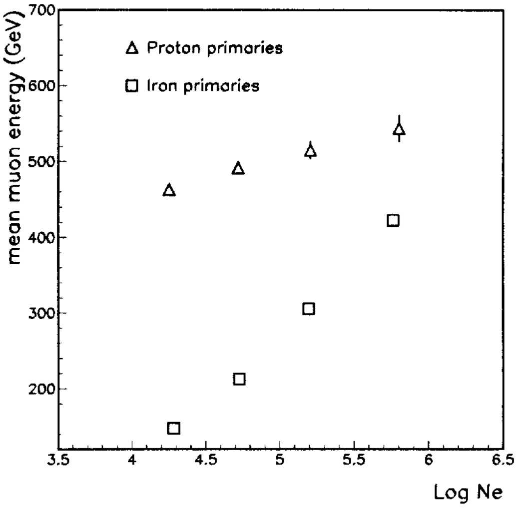

Fig. 1. Expected mean muon energy at LVD level (3000 m w.e. depth) as a function of shower size N_e at EAS-TOP level (2000 m a.s.l.), for different primaries, i.e. protons (p) and iron nuclei (Fe). We sample over a spectral index $\gamma = 2.7$ between $1. \cdot 10^{14}$ eV and $1. \cdot 10^{16}$ eV for proton primaries and between $2.1 \cdot 10^{14}$ eV and $1.4 \cdot 10^{16}$ eV for iron nuclei. The shower sizes plotted correspond to the shower size bins used in the data analysis.

Muon energies for $E_\mu > 300$ GeV in large surface installations can be measured, e.g., (a) through the increase of the number of radiative energy losses mainly

---

[1] Now at University of Salerno and INFN-Salerno, Italy.

due to the effect of direct pair production [10]. The effect of bremsstrahlung and photonuclear interactions is catastrophic and therefore happens infrequently in the detector; (b) through the transition radiation processes.

Effect (a) has been exploited to measure the different mean muon energies for different detected muon numbers (singles and multiples) deep underground [11] as well as to estimate the muon spectrum parameters at great depths [12], and detectors based on effect (b) have been developed [13,14].

In this paper different mean muon energies are studied in LVD by looking at the increase in the radiative energy losses: low fractional energy losses $\nu = \Delta E/E$ are detected in LVD counters because of their size (see below); also in this case 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 distributions. The measurement can be improved either by summing up the contributions of several muons of similar energy, as suggested in [15], or by studying the mean energies of muon classes selected on independent bases as the depth of traversed rock [16] or as shower size at the surface [17].

In this paper we follow the latter approach to perform the first measurement closely related to the mean muon energy vs shower size as shown in Fig. 1. It emerges then 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. Such information is combined with other EAS parameters [18], providing a cross check of the interaction model used for the data analysis.

2. Detectors

EAS-TOP (at 2000 m a.s.l.) is an apparatus tailored for the detection of several different EAS components [19], i.e., the electromagnetic (e.m.), hadron, muon, Cherenkov light and radio emission. The e.m. detector, used for the measurement of shower size N_e, is an array of 35 modules of scintillator, each of area 10 m^2, distributed over an area of $\sim 10^5$ m^2. In the present work we consider only internal trigger events, i.e. events in which the maximum number of particles is detected by an inner module and at least seven counters fired. For such events, primary arrival direction, core location and shower size are reconstructed with accuracies $\Delta\vartheta = 0.5°$, $\Delta r \leq 10$ m and $\Delta N_e/N_e \leq 20\%$ for $N_e \geq 10^5$. A detailed discussion of the EAS-TOP e.m. reconstruction techniques and accuracies is given in [20].

LVD, in the underground Gran Sasso laboratories at 960 m a.s.l., 3000 m w.e. of minimum rock overburden, is designed [21] for multi-purpose studies from neutrino astrophysics [22] to cosmic rays. The detailed characteristics of the detector are described in [22,23]. The data reported here come from the first tower of LVD, containing 38 modules, corresponding to a total volume of $13 \times 6 \times 12$ m^3. Every module contains eight 1.2 t liquid scintillator ($\rho = 0.8$ g cm^{-3}) counters of dimensions $1 \times 1 \times 1.5$ m^3. Each counter is viewed by three photomultipliers. The dividers of the photomultipliers are set to give two different ADC saturation energies, roughly ~ 340 MeV and ~ 680 MeV, depending on the location of the counter. Counters not exposed directly to the rock (i.e., shielded by other counters) have the lower ADC saturation energy in order to optimize energy resolution in the detection of secondary products from neutrino interactions. To avoid instrumental effects and for homogeneity reasons, the present work is restricted to high saturation counters.

The tracking system is made of L-shaped tracking detectors. Each module supports one of these detectors, attached to the bottom (horizontal element) and to one vertical side (vertical element). Each element contains two staggered layers of limited streamer tubes. On one side (and parallel to), and on the other side (and perpendicular to), the streamer tube wires, 4 cm wide pickup strips provide bidimensional information about the ionizing particle's impact point. The staggered double layers of streamer tubes and their orthogonal readout strips yield an effective strip width of 2 cm with no dead space, high overall tracking efficiency and an angular resolution better than 4 mrad. In the present analysis we consider only muon tracks with at least three impact points observed by the tracking system.

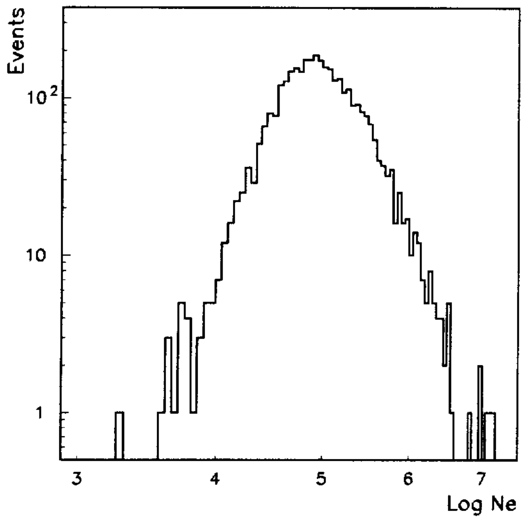

Fig. 2. Shower size distribution of EAS-TOP-LVD time correlated events with *internal* trigger (see text) at EAS-TOP.

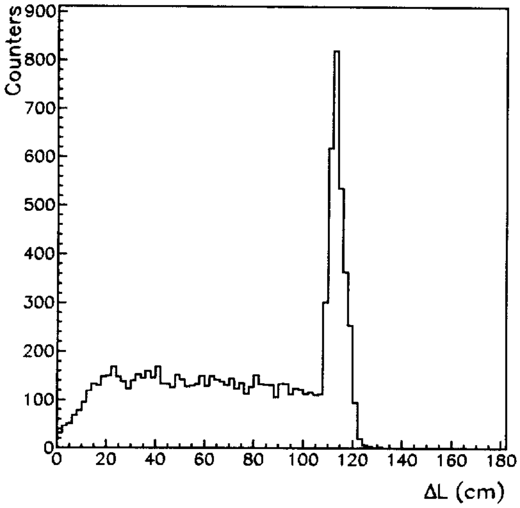

Fig. 3. Distribution of track lengths in each scintillation counter in LVD for muons belonging to EAS-TOP time correlated events.

3. Data and analysis

EAS-TOP and LVD are separated by a rock thickness ranging from 1100 up to 1200 m, depending on the angle ($\langle\vartheta\rangle \sim 29^\circ$) corresponding to 3000-3200 m w.e. (equivalent water thickness). The corresponding mean minimum surface energy for a muon to reach LVD from EAS-TOP ranges from ~ 1.4 TeV to ~ 1.6 TeV. Event coincidence was established off-line, using the absolute time given by atomic clocks with an accuracy better than 1 μs; details on this procedure can be found in [24]. 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 LVD tower. The entire data sample was accumulated during roughly 400 days of total live time with common operation of the two detectors. By considering only EAS-TOP internal trigger events, 3419 events within ± 2 μs of the coincidence peak have been recorded, with an expected accidental contamination of 3.5%. In Fig. 2, the distribution of shower size (N_e) as measured by EAS-TOP for the internal trigger coincidence events is shown.

By imposing the above-mentioned condition on muon track reconstruction in LVD a total number of 2835 muon tracks were retained including tracks from single and multiple muon events. Each muon track was individually analyzed, looking at the energy deposition ΔE in every scintillation counter traversed by it. Counters hit by more than one muon ($< 0.1\%$) are disregarded. To account for the different lengths ΔL in a counter the quantity $\Delta E/\Delta L$ has been used instead of ΔE. The length ΔL in each counter is geometrically derived once the precise counter position is known and the track reconstruction is given.

For each muon, every traversed counter gives an indication of the energy loss per unit path length dE/dx through the quantity $\Delta E/\Delta L$. This quantity $\Delta E/\Delta L$ is not a strict measurement of dE/dx [25], due to *leakage* effects (the counter thickness is ~ 80 g cm^{-2}) [26] and to *contamination* from secondaries generated by the muon outside the counter (for example in the steel just above it) and penetrating it. In case of multiple muon events, the cross-talk among the muons due to these effects is largely negligible as secondaries are generated at very small angles while the mean distance between the muons is large (~ 5 m). An upper limit to the cross-talk has been obtained by studying the energy released in a tank not traversed, but close to a muon track. The influence on $\langle\Delta E\rangle$ is on average less than 0.1%, i.e. negligible with respect to the effect we will show in Fig. 7.

The influence of both leakage and contamination effects on $\Delta E/\Delta L$ measurements is found to depend strongly on ΔL, decreasing with increasing ΔL. Fig. 3 shows the ΔL distribution for the entire data sample.

The narrow peak in the ΔL distribution is geomet-

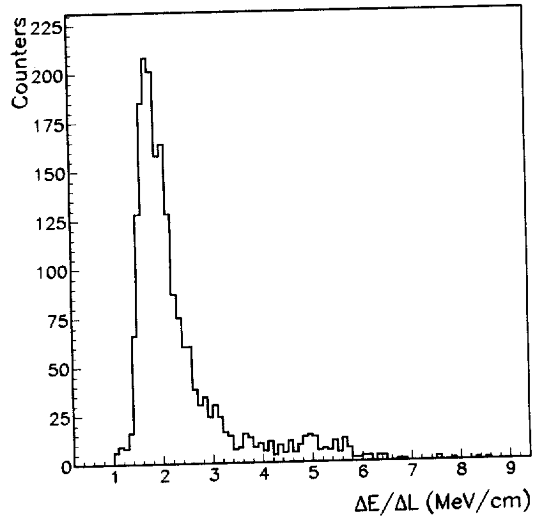

Fig. 4. Distribution of energy depositions in LVD scintillators per unit muon track length for time correlated events. Cuts are discussed in the text.

rically determined by the good parallelism of muon tracks and its position by the mean arrival zenith angle of muons pointing to the EAS-TOP direction ($\vartheta = 29^o$). At such zenith angle most of the counters are hit on both horizontal faces, giving similar ΔL values. Counter traversals with ΔL values corresponding to the peak have been selected (100 cm $< \Delta L <$ 130 cm). A sufficiently high statistics is thus retained and leakage and contamination effects are minimized (large ΔL).

This requirement also minimizes the errors in the determination of ΔL; in fact, as only horizontal faces of the counters are hit, small inaccuracies in the knowledge of the tank position have no effect on ΔL. According to the angular resolution of the tracking system, the error in ΔL is then less than 1%.

The scintillation counters are calibrated exploiting the most probable energy deposition by muons as obtained from a detailed Monte Carlo simulation [27]. The calibration procedure is renewed periodically and for all the counters the estimated error in energy determination is less than 3% at E = 185 MeV.

4. Results and discussion

Fig. 4 shows the $\Delta E/\Delta L$ distribution for the whole sample of correlated events once the cuts discussed in the previous section are applied. The data sample has a total of 2007 hit counters selected.

Fig. 5 reports distributions of $\Delta E/\Delta L$ in different ranges of EAS size. Four shower size intervals were chosen with regard to statistics, namely $N_e < 10^{4.5}$ (Fig. 5a), $10^{4.5} \leq N_e < 10^{5.0}$ (Fig. 5b), $10^{5.0} \leq N_e < 10^{5.5}$ (Fig. 5c) and $N_e \geq 10^{5.5}$ (Fig. 5d). A comparison among the distributions indicates that the region of 2–4 MeV/cm in $\Delta E/\Delta L$ values (i.e., values just above the ionization peak) has a growing weight with the size of showers. Saturation of the counters 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.

This behaviour is evident in Fig. 6, where the integral distributions of $\Delta E/\Delta L$ for the four shower size intervals are superimposed. They are presented in terms of fraction of counters (subscript c) with $\Delta E_c/\Delta L_c > \Delta E/\Delta L$ as a function of $\Delta E/\Delta L$. The region with the rapid decrease of the distributions corresponds to the ionization peak region in the differential distributions. A systematic enhancement with shower size in the region around 2–4 MeV/cm in $\Delta E/\Delta L$ values is present, at $\Delta E/\Delta L$ values slightly larger than those of the region with ionization dominance.

The effect of increase with shower size of energy deposition per unit path length is also manifest directly in terms of $\langle \Delta E/\Delta L\rangle$ values. Fig. 7 reports the $\langle \Delta E/\Delta L\rangle$ values for the four shower size intervals (Data from saturated counters are included without any correction). The arrows indicate the value of $\langle \Delta E/\Delta L\rangle$ for all muons compatible with the EAS-TOP solid angle, for the same set of high ADC saturation counters and with the same cuts on the tracks and on ΔL but without requiring any time coincidence.

The systematic enhancement of $\langle \Delta E/\Delta L\rangle$ with size of shower is significant at more than 5σ level (and its constancy is rejected with a χ^2/d.o.f. value of 48.1/3). All of the data points lie above the average $\Delta E/\Delta L$ value for uncorrelated muons. Including a correction for the ADC saturation of the counters, the enhancement with shower size in $\langle \Delta E/\Delta L\rangle$ values is

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

per decade variation of N_e at $N_e \sim 10^5$, where the first

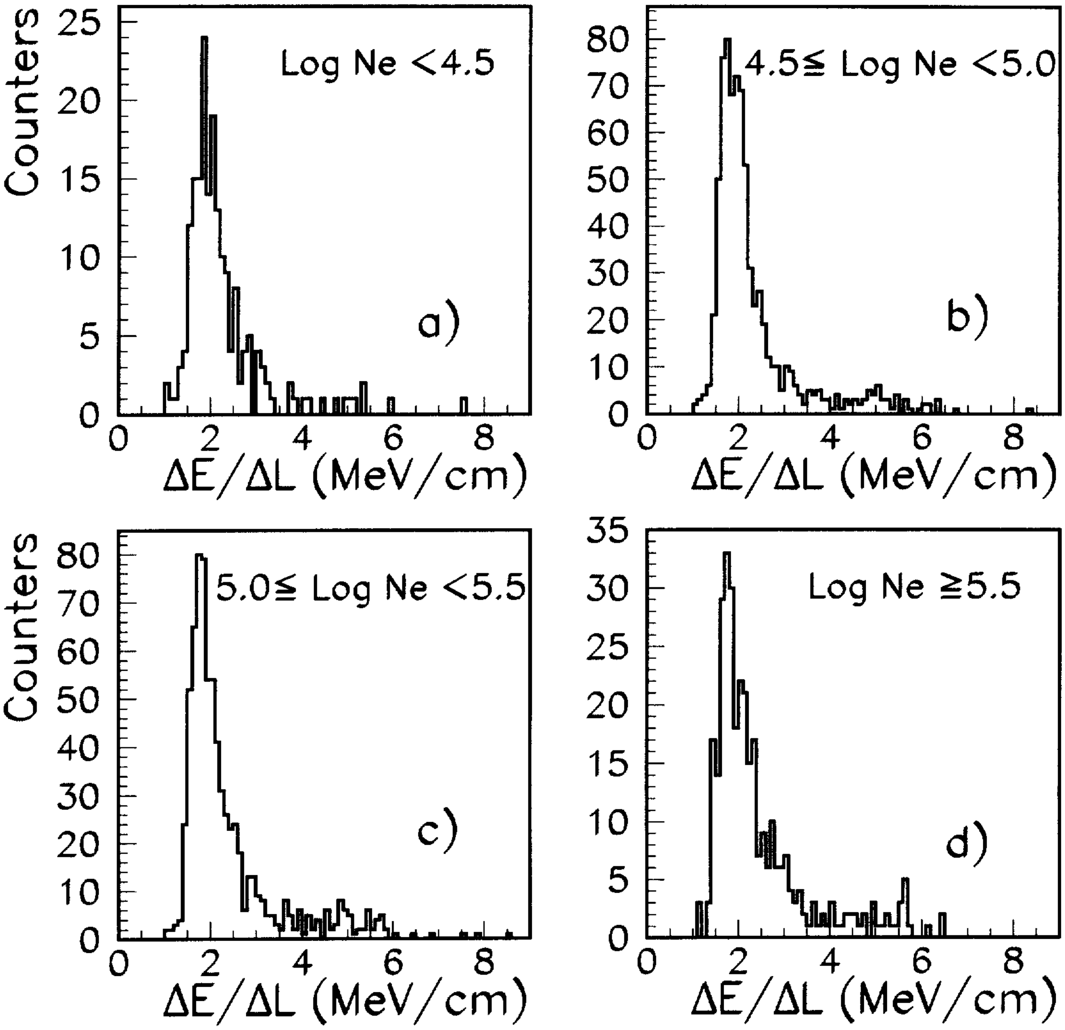

Fig. 5. Distributions of energy deposition per unit track length in LVD scintillators for muons time correlated with EAS-TOP shower events, with shower size *Ne* belonging to four different intervals (a)–(d). Saturation occurs in each interval at the rate of 2.1%, 2.5%, 3.4% and 5.2%, respectively, for intervals (a), (b), (c) and (d).

error is statistical and the second systematic (without the saturation correction the result is 5.6% per decade variation of N_e).

With cross reference to Figs. 6, 7 we conclude that: (1) a significant enhancement in $\langle \Delta E/\Delta L \rangle$ associated with shower size is observed; (2) this enhancement is determined mainly by effects at $\Delta E/\Delta L$ values immediately larger than those corresponding to the ionization dominance region.

Point (1) implies that processes distinct from ionization are acting here (at our energies mean ionization losses are almost flat with energy, knock-on electrons included). Point (2) implies that these processes must be dominated by low fractional energy losses ν as we expect from direct e^+–e^- pair production.

The relationship between mean muon energy losses in LVD counters and the electromagnetic shower size has been calculated by using a full Monte Carlo simulation including the generation and development of the shower in atmosphere (CORSIKA HDPM code [7]) and the propagation of muons in the rock (MUSIC code [8,9]), as well the GEANT [28]

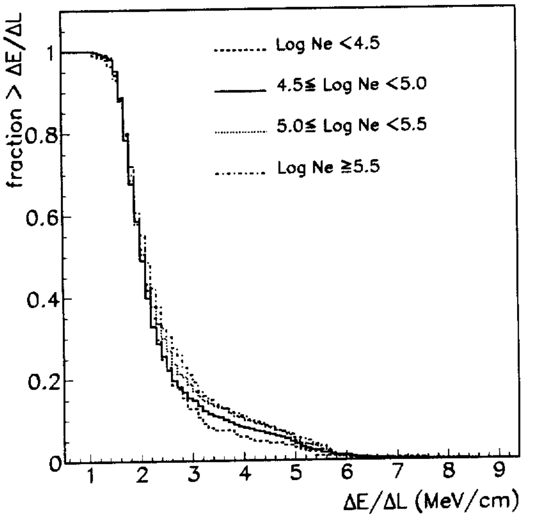

Fig. 6. Fraction of LVD counters with energy deposition per unit muon track length inside the counter $\Delta E_c/\Delta L_c > \Delta E/\Delta L$ for four different shower size intervals at EAS-TOP. Events are time correlated between EAS-TOP and LVD. Note the systematic enhancement of the tails with shower size.

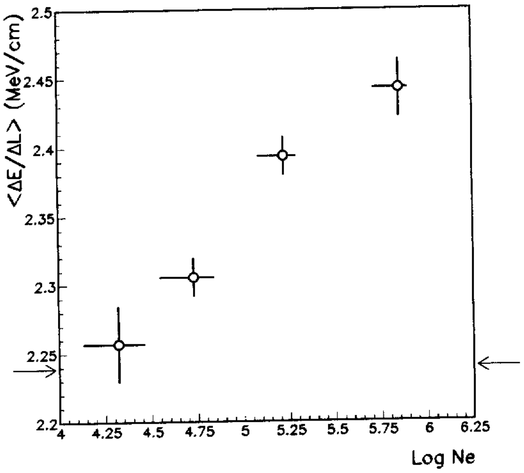

Fig. 7. Mean energy depositions per unit track length inside LVD counters (see text for the cuts) as a function of shower size N_e of time correlated EAS-TOP events. Errors are statistical. The arrows give the corresponding $\langle \Delta E/\Delta L \rangle$ value for LVD-alone events for muons coming from the EAS-TOP solid angle, using the same cuts as for time correlated events. No corrections for saturation are made.

simulation of both surface and underground detector response (which includes efficiency and reconstruction accuracies). We used the sampling technique discussed in [29]. Fig. 8 shows the results of the calculations for proton and iron primaries compared with the data. Systematics in the comparison between data and Monte Carlo results are within ~ 1–2% on $\langle \Delta E/\Delta L \rangle$ values. The predictions for proton primaries are compatible with an almost flat behaviour whereas for iron primaries a clear rise of $\langle \Delta E/\Delta L \rangle$ with size N_e is expected. The presence of an heavy component is thus required; the correlations shower size-muon dE/dx underground are composition sensitive at energies around the "knee". We checked that simulations of pure protons and irons with a different spectral index ($\gamma = 2.62$) give no appreciable difference on muon $\langle \Delta E/\Delta L \rangle$ values. The discrimination is larger in the lowest size bins where threshold effects for the two detectors are still present. An indication of such systematics effects is given in Fig. 7 and in Fig. 8 in the error bars for shower size: they do not affect the significance of the reported effect.

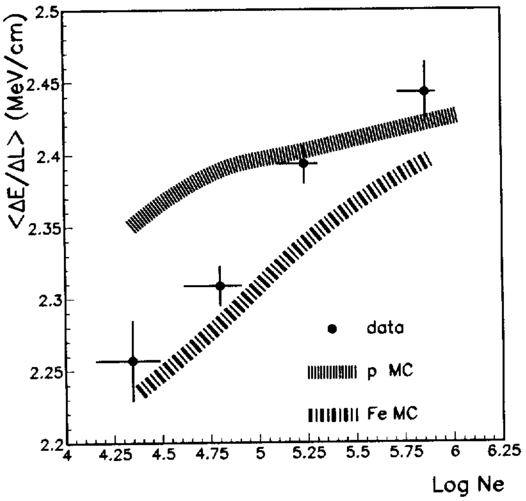

Fig. 8. From simulations: $\langle \Delta E/\Delta L \rangle$ as a function of shower size for pure proton and pure iron compositions. Data are also shown.

5. Conclusions

The present LVD–EAS-TOP combined data analysis shows that (a) the mean muon energy loss in LVD per unit path length increases with shower size at $(5.9 \pm 0.8 \pm 0.3)\%$ per decade variation of N_e at $N_e \sim 10^5$; (b) this is compatible with the expectations from a mixed primary cosmic ray composition and an interaction-propagation model of the cascades in the atmosphere (CORSIKA).

This energy loss method, combined with additional parameters, provides further information on the high energy interaction model and primary composition, at least concerning the heavier components [18].

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 Italian Consiglio Nazionale delle Ricerche (CNR), 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.

References

[1] V.N. Bakatanov et al., in: Proc. 19th ICRC, La Jolla, Vol. 8 (1985) pp. 24; 28.
[2] Ch. Berger et al., Phys. Rev. D 40 (1989) 2163.
[3] M. Aglietta et al., EAS-TOP Collaboration, Nucl. Phys. B 14B (1990) 193.
[4] S. Ahlen et al., MACRO Collaboration, Phys. Rev. D 46 (1992) 4836.
[5] M. Aglietta et al., EAS-TOP and MACRO Collaborations, Phys. Lett. B 337 (1994) 376.
[6] The EAS-TOP Collaboration, Nucl. Phys. B 54 (Proc. Suppl.) (1997) 263.
[7] J.N. Capdevielle et al., KfK Report 4998, Karlsruhe (1992).
[8] V.A. Kudryavtsev, Preprint INR, 0529 (1987) [in russian].
[9] P. Antonioli et al., Astropart. Phys. 7 (1997) 357.
[10] I.S. Alekseyev, G.T. Zatsepin, in: Proc. Int. Cosmic Ray Conf., Vol. 1, Moscow (1960) p. 324.
[11] C. Castagnoli et al., in: Proc. 3rd Cosmic-Physics National Conf. SI, (1986) p. 317.
[12] C. Castagnoli et al., Astropart. Phys. 6 (1997) 187.
[13] M. Calicchio et al., Phys. Lett. B 193 (1987) 131.
[14] S. Ahlen et al., MACRO Collaboration, in: Proc. 25th Int. Cosmic Ray Conf., Vol. 6, Durban (1997) p. 385.
[15] V.A. Kudryavtsev, O.G. Ryazhskaya, Nucl. Phys. B (Proc. Suppl.) 35 (1994) 264.
[16] M. Aglietta et al., LVD Collaboration, in: Proc. 25th Int. Cosmic Ray Conf., Vol. 6, Durban (1997) p. 345.
[17] L. Emaldi, Thesis, University of Bologna (1996), unpublished.
[18] M. Aglietta et al., EAS-TOP and LVD Collaborations, in: Proc. 25th Int. Cosmic Ray Conf., Vol. 6, Durban (1997) p. 165.
[19] M. Aglietta et al., EAS-TOP Collaboration, Nucl. Instr. & Meth. A 277 (1989) 23.
[20] M. Aglietta et al., EAS-TOP Collaboration, Nucl. Instr. & Meth. A 336 (1993) 310.
[21] G. Bari et al., Nucl. Instr. & Meth. A 277 (1989) 11.
[22] M. Aglietta et al., LVD Collaboration, Nuovo Cimento A 12 (1992) 1793.
[23] M. Aglietta et al., LVD Collaboration, Astropart. Phys. 2 (1994) 103.
[24] M. Aglietta et al., EAS-TOP and LVD Collaborations, Nuovo Cimento A 12 (1992) 1815.
[25] M. Aglietta et al., LVD Collaboration, in: Proc. 24th Int. Cosmic Ray Conf., Vol. 1, Roma (1995) p. 861.
[26] P. Antonioli, W. Fulgione, P. Galeotti, L. Panaro, Nucl. Instr. & Meth. A 309 (1991) 569.
[27] V.A. Kudryavtsev, O.G. Ryazhskaya, Energy calibration of LVD scintillation counters using cosmic ray muons, LNGS 92-26 (1992).
[28] R. Brun et al., CERN report, DD/EE, 84-1 (1987).
[29] G. Battistoni et al., Astropart. Phys. 7 (1997) 101.