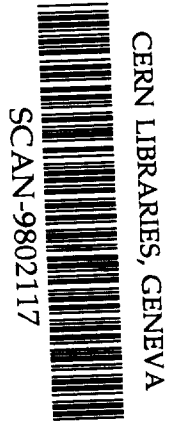
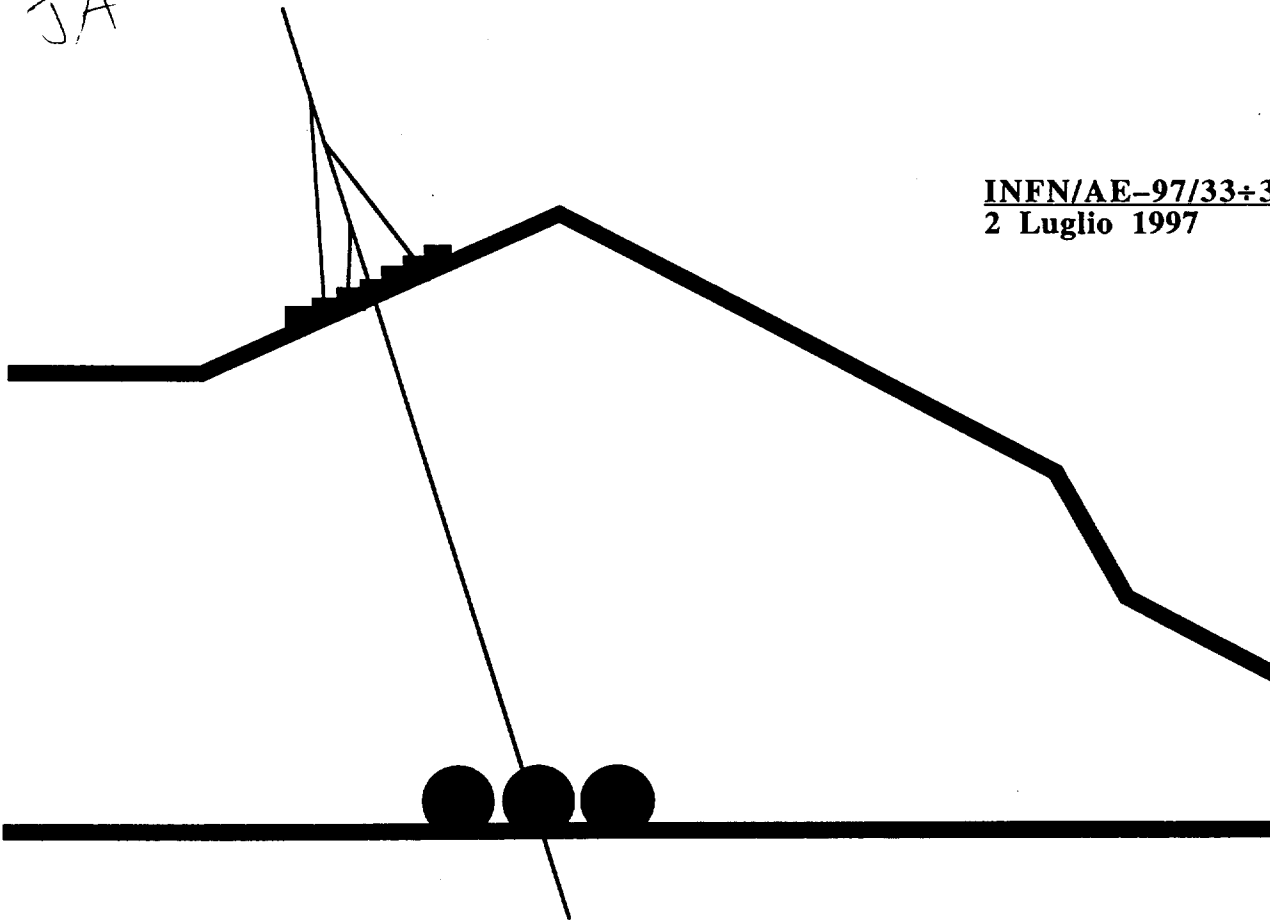


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LVD COLLABORATION

M. Aglietta¹⁶, B. Alpat¹³, E.D. Alyea⁷, P. Antonioli¹, G. Badino¹⁶, G. Bari¹, M. Basile¹, V.S. Berezinsky¹⁰, F. Bersani¹, M. Bertaina¹⁶, R. Bertoni¹⁶, G. Bonoli¹, A. Bosco², G. Bruni¹, G. Cara Romeo¹, C. Castagnoli¹⁶, A. Castellina¹⁶, A. Chiavassa¹⁶, J.A. Chinellato³, L. Cifarelli¹, F. Cindolo¹, G. Conforto¹⁷, A. Contin¹, V.L. Dadykin¹⁰, A. De Silva², M. Deutsch⁸, P. Dominici¹⁷, L.G. Dos Santos³, L. Emaldi¹, R.I. Enikeev¹⁰, F.L. Fabbri⁴, W. Fulgione¹⁶, P. Galeotti¹⁶, C. Ghetti¹, P. Ghia¹⁶, P. Giusti¹, R. Granella¹⁶, F. Grianti¹, G. Guidi¹⁷, E.S. Hafen⁸, P. Haridas⁸, G. Jacobucci¹, N. Inoue¹⁴, E. Kemp³, F.F. Khalchukov¹⁰, E.V. Korolkova¹⁰, P.V. Korchaguin¹⁰, V.B. Korchaguin¹⁰, V.A. Kudryavtsev¹⁰, K. Lau⁶, M. Luvisetto¹, G. Maccarone⁴, A.S. Malguin¹⁰, R. Mantovani¹⁷, T. Massam¹, B. Mayes⁶, A. Megna¹⁷, C. Melagrana¹⁶, N. Mengotti Silva³, C. Morello¹⁶, J. Moromisato⁹, R. Nania¹, G. Navarra¹⁶, L. Panaro¹⁶, L. Periale¹⁶, A. Pesci¹, P. Picchi¹⁶, L. Pinsky⁶, I.A. Pless⁸, J. Pyrlík⁶, V.G. Rjasny¹⁰, O.G. Ryazhskaya¹⁰, O. Saavedra¹⁶, M. Selvi¹, K. Saitoh¹⁵, S. Santini¹⁷, G. Sartorelli¹, N. Taborgna⁵, V.P. Talochkin¹⁰, J. Tang⁸, G.C. Trinchero¹⁶, S. Tsuji¹¹, A. Turtelli³, I. Uman¹³, P. Vallania¹⁶, G. Van Buren⁸, S. Vernetto¹⁶, F. Vetrano¹⁷, C. Vigorito¹⁶, E. von Goeler⁹, L. Votano⁴, T. Wada¹¹, R. Weinstein⁶, M. Widgoff², V.F. Yakushev¹⁰, I. Yamamoto¹², G.T. Zatsepin¹⁰, A. Zichichi¹

¹ University of Bologna and INFN-Bologna, Italy

² Brown University, Providence, USA

³ University of Campinas, Campinas, Brazil

⁴ INFN-LNF, Frascati, Italy

⁵ INFN-LNGS, Assergi, Italy

⁶ University of Houston, Houston, USA

⁷ Indiana University, Bloomington, USA

⁸ Massachusetts Institute of Technology, Cambridge, USA

⁹ Northeastern University, Boston, USA

¹⁰ Institute for Nuclear Research, Russian Academy of Sciences, Moscow, Russia

¹¹ Okayama University, Okayama, Japan

¹² Okayama University of Science, Okayama, Japan

¹³ University of Perugia and INFN-Perugia, Italy

¹⁴ Saitama University, Saitama, Japan

¹⁵ Ashikaga Institute of Technology, Ashikaga, Japan

¹⁶ Institute of Cosmo-Geophysics, CNR, Torino, University of Torino and INFN-Torino, Italy

¹⁷ University of Urbino and INFN-Firenze, Italy

AN ENERGY SIGNATURE FOR VERY DEEP UNDERGROUND MUONS OBSERVED BY THE LVD EXPERIMENT

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ABSTRACT

An energy analysis of all muon data for the period from June 1992 to June 1996 of operation of LVD at the Gran Sasso Laboratory has been performed. The deepest component, i.e. the muons belonging to the constant tail of the depth-intensity relation, are significantly softer than that at smaller depths (i.e. atmospheric muons). This agrees well with the results of simulations of muons coming from atmospheric neutrinos interacting in the rock near the apparatus.

INTRODUCTION

As various experiments have found (Crouch et al., 1978; Aglietta et al., 1995; Rhode et al., 1996), the depth-intensity muon curve shows at very large depths x ($x > 13$ km w.e.) a plateau, i.e. a region where the strong decrease due to atmospheric muons stops and the muon flux is no longer dependent on depth. To account for these muons a muon source near the detector is needed. Atmospheric neutrinos interacting in the rock near the apparatus should induce these muons, as the agreement between the expected ν -induced muon flux and the measured muon flux confirms.

Another possible hint on the origin of these muons can be given by their energy. In fact expected energy spectra of atmospheric ν -induced muons are strongly softer than atmospheric muons (median energies of some 10 GeV for the former and of some hundreds of GeV for the latter). On the other hand neutrino spectra from AGN (Stecker et al., 1991; Gaisser et al., 1995) are expected to be strongly harder than atmospheric ones (roughly TeV energies). Recently an energy analysis on detected very deep underground muons (Rhode et al., 1996) has shown no evidence of TeV muons, excluding then TeV neutrinos as parent particles. In this work a first direct indication of the energy of this very deep underground muons is presented.

ENERGY ANALYSIS

The LVD detector (Bari et al., 1989) is located in the underground Gran Sasso laboratories with some 3000 m w.e. of rock overburden. The depth of the intercepted rock depends on the direction, and the topology of the mountain combined with detector acceptance allows very large depths ($x > 20$ km w.e.) at nearly horizontal directions. The main characteristics of the detector can be found in (Aglietta et al., 1992, 1994). Present analysis refers to data of one tower only. A tower is constituted of 304 1.2 t liquid scintillation counters of dimensions $1 \times 1 \times 1.5$ m³ to cover a total volume of $13 \times 6 \times 12$ m³ grouped into 38 modules. The tracking system, also modular, is made of L-shaped chambers attached to the bottom (horizontal element) and to one vertical side (vertical element) of each module. The vertical elements of tracking system are of best importance to tag horizontal muons. Each element contains two staggered layers of limited streamer tubes, on both sides of which there are pickup strips to provide bidimensional information on the impact point of the particle. The angular resolution in the track reconstruction is within 4 mrad. The corresponding error on the depth of the intercepted rock is quite small, increasing with depth. At largest depths is lower than 200 m w.e..

The analysis here reported corresponds to 4 years of operation of the detector for a total live time of 3.0×10^4 hours and a total number of 2.4×10^6 reconstructed muon tracks. Vertical single muon intensity derived from LVD data with evidence of a plateau at large depths was already presented (Aglietta et al., 1995). The all muon flux with large statistics and with comparisons with other experiments is presented elsewhere (Aglietta et al., 1997).

The energy of the muons is tagged through the energy losses per unit path length in the counters. That is the quantities $\Delta E/\Delta L$ are considered where ΔE is the energy deposition in the counter and ΔL is the intercepted track length. The estimated error on ΔE as deduced from calibration procedure is within 3% at $\Delta E = 185 \text{ MeV}$. The error on ΔL depends both on angular resolution and on small inaccuracies in the knowledge of the counter position. After a best fit to counter positions is made using the data, the error on ΔL for nearly horizontal events is found to be less than 5% provided that counters with $\Delta L > 50 \text{ cm}$ and tracks with $|\varphi| > 4.5^\circ$ or $|\varphi - 180^\circ| > 4.5^\circ$ are selected, where the azimuthal angle φ is taken from the direction perpendicular to the vertical planes of tracking.

Muons from the two depth intervals $9 < x < 13 \text{ km w.e.}$ (interval S , with smaller depths) and $x > 13 \text{ km w.e.}$ (interval L , with larger depths) have been compared. Separately for the two intervals, $\langle \Delta E/\Delta L \rangle$ values have been evaluated. Muons in interval L give rise to a total of some 50 crossed active counters after the cut cited above.

To quote the errors on the results, the size of fluctuations on $\langle \Delta E/\Delta L \rangle$ values connected with so low statistics has been investigated. Muons in the interval S have been subdivided into thin sub-intervals in depth to obtain in each of them roughly the same number of active counters crossed as in the interval at larger depths. In interval S we are dominated by atmospheric muons. Deep underground they have an energy spectrum practically not dependent on depth. This procedure then corresponds to extract small samples of muons of size fixed from always the same energy distribution. We have obtained 27 such samples in this interval, and in fig.1 the distribution of their $\langle \Delta E/\Delta L \rangle$ values is reported. In the figure also the L value is added. Note that the deviation of $\langle \Delta E/\Delta L \rangle$ value for the interval L is only marginally compatible with a fluctuation from the mean value of interval S .

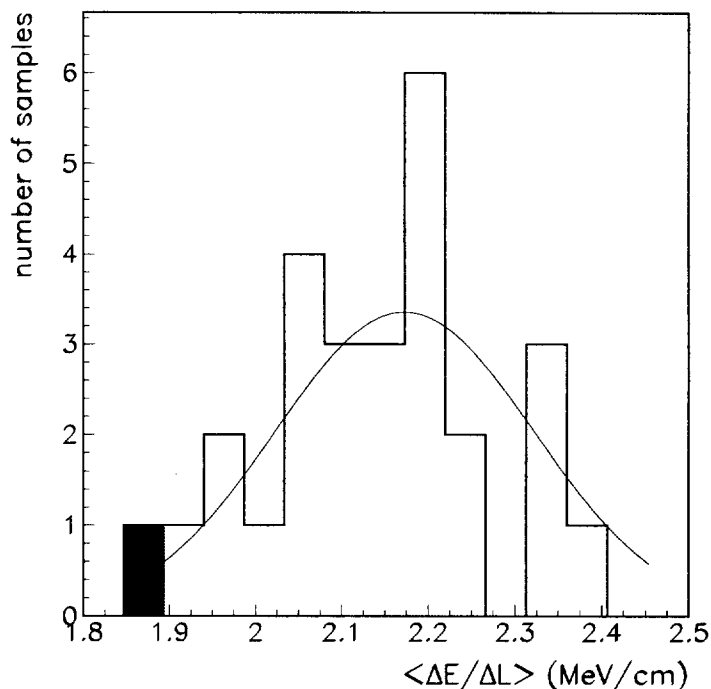


Fig. 1: $\langle \Delta E/\Delta L \rangle$ distribution for the muon samples at smaller depths (interval S) with a gaussian fit (solid curve). The muon sample at largest depths is added (filled).

The obtained result is $\langle \Delta E/\Delta L \rangle = 2.13 \pm 0.03 \text{ MeV/cm}$ for interval S , whereas $\langle \Delta E/\Delta L \rangle = 1.88 \pm 0.13 \text{ MeV/cm}$ for interval L . The errors are purely statistical and are quoted from the r.m.s. of the sample distribution (nearly gaussian) in interval S (see fig.1).

It comes out that the deviation observed for interval L is globally at roughly 2σ statistical significance level. This deviation is in the sense that muons in the plateau region have energies lower than muons at smaller depths.

SIMULATIONS

Simulations have been done to investigate systematic errors tied to the different arrival directions in the two depth intervals S and L . No appreciable difference has been found in the $\langle \Delta E/\Delta L \rangle$ distributions for muon samples of the same size as in the data. At some hundred GeV energies direct

pair production and bremsstrahlung losses are present in addition to δ -rays (active also at much lower energies) increasing $\langle \Delta E/\Delta L \rangle$ values. Simulations have been made to investigate the sensitivity of $\langle \Delta E/\Delta L \rangle$ values to muon energy. The distributions of $\langle \Delta E/\Delta L \rangle$ values for samples of monochromatic muons at 10 GeV and 300 GeV energy of the same size of the data are quite well separated.

In simulations the whole expected energy spectra of atmospheric muons and of atmospheric ν -induced muons have been finally used. Fig.2 reports results for muons from atmospheric neutrinos (dashed) and for atmospheric muons (continuous) on $\langle \Delta E/\Delta L \rangle$ values. Muons are coming in the same solid angle of plateau events (interval L). Also in this case muon samples have each one the same statistics of the data sub-intervals. The calculation of the ν -induced spectrum is made (Bonoli, 1996) using the ‘‘Bartol’’ flux (Agrawal et al., 1996) with the Owens (Owens, 1991) parton distributions for the cross-sections of neutrino interactions in the rock (Lipari, 1995). Atmospheric muon spectrum underground is obtained assuming a power law spectrum at the surface and using the survival probabilities extracted from (Kudryavtsev, 1987; Antonioli et al., 1997). The distributions for ν -induced muons and for atmospheric muons appear quite distinguishable at low values of $\langle \Delta E/\Delta L \rangle$. In the region $\langle \Delta E/\Delta L \rangle < 1.95 \text{ MeV/cm}$, for example, we have some 5:1 chance to have a ν -induced muon sample instead of an atmospheric muon sample with a $\sim 60\%$ retention efficiency of atmospheric ν -induced muon samples.

CONCLUSIONS

In summary:

- the energy analysis of the largest depth events of the depth-intensity curve shows evidence for a deviation of energy losses per unit path length for these muons from the mean value of muons coming from smaller depths, at a 2σ statistical significance level;
- the deviation is towards lower energies and the found values of energy deposition per unit path length fit well with expectations from simulations for atmospheric ν -induced muons.

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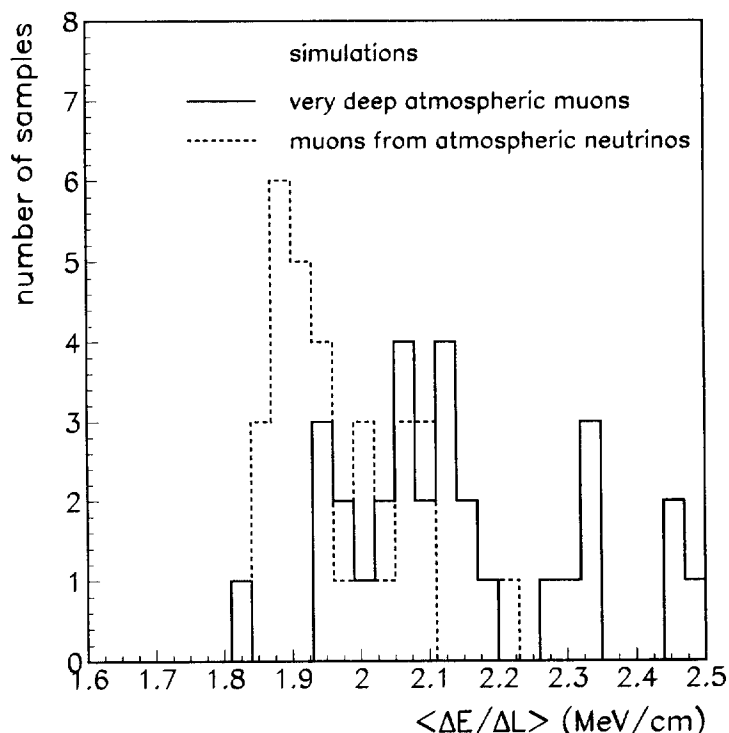


Fig. 2: Distribution of $\langle \Delta E/\Delta L \rangle$ from simulations for atmospheric muons (continuous) and for ν -induced muons (dashed). Each entry corresponds to a muon sample with the same size as in the data.

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