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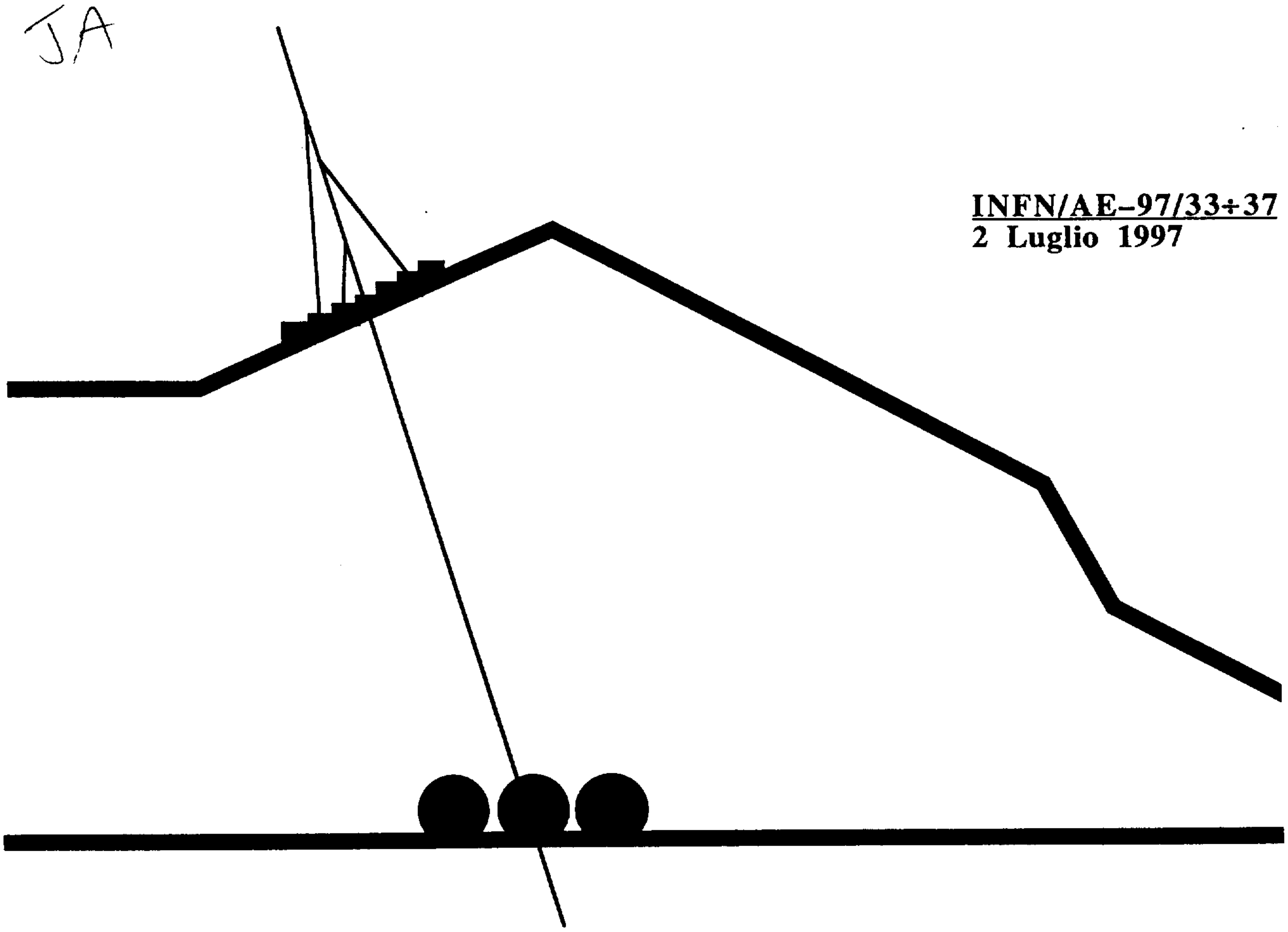

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STUDY OF MUON ENERGY LOSSES IN THE LVD EXPERIMENT

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ABSTRACT

We report an analysis of energy losses of muon events collected during 4 years of operation (June '92 - June '96) of the first LVD tower. A detailed study of instrumental effects is presented. An increase of mean energy losses per unit of length of the order of $1.2\% \pm 0.4\%$ between muons coming from 3000 m w.e. and 4000 m w.e. is seen, in agreement with local muon underground energy spectrum expectations.

INTRODUCTION

The average energy of muons increases with depth, due to the high energy tail of the spectrum, that is determined by the distortion of the muon spectrum at the surface level due to muon interactions inside the rock. Many authors have performed independent Monte Carlo calculations for muon propagation in rock (Bilokon et al., 1991, Lipari and Stanev, 1991,Kudryavtsev, 1987, Antonioli et al., 1997) obtaining quite different results with respect to the mean energy of muons at different dephts: even if a straightforward comparison is not easy (depending on different values for input spectral index, cross sections to describe muon interactions in the rock, approximations and cuts implemented inside the codes) the increase of the muon energy with depth is a well understood effect.

From the experimental point of view, some direct measurements of muon energy exist (Rhode et al., 1996, Castagnoli et al., 1996, Castellano et al., 1987) or are in progress (Ahlen et al., 1997) at different depths from different experiments, giving results in qualitative agreement with the expected behaviour. We have explored the sensitivity of the Large Volume Detector (LVD), (Bari et al. 1989), to show the increase of average muon energy with depth. The LVD, matching information of its tracking (Aglietta et al. 1994) and scintillator systems (Aglietta et al., 1992), can provide a good measurement of the energy loss of the muons per unit of path length (hereafter $\Delta E/\Delta L$) (Aglietta et al. 1995a). Due to the high statistics available, this search is a good method to study systematic effects (e.g. dependence on muon arrival direction) due to the detector and data selection criteria: a relative increase of mean energy losses increasing with depth should be seen. This is an important preliminary step for a study of energy losses of muons coming from very large depths detected by the LVD (Aglietta et al. 1995b) where the background of atmospheric muons is negligible and neutrino induced muons are dominant (Aglietta et al., 1997).

DATA ANALYSIS

The LVD experiment is installed in Hall A of the underground Gran Sasso laboratories. It is a multipurpose detector consisting of a large volume of liquid scintillator interleaved with limited-streamer tubes in a compact geometry. In this analysis a muon track is defined by the alignment of at least 3 impact points in the tracking planes, and the presence of at least 2 firing scintillation counters. From the fitted muon track parameters and the energy releases inside the scintillation counters, it is possible (for each counter crossed by the track) to obtain the ratio of the energy deposition ΔE to the track length ΔL inside the counter, allowing a precise measurement of energy loss of the muon per unit of length. When two or more tracks cross the same counter in multiple muons events, this counter is disregarded. Data presented here were collected in the first LVD tower from 11 June 1992 until 6 May 1996. The full data sample corresponds to 29319 hours of live time and includes about 2.4×10^6 reconstructed muons. The local energy underground spectrum at depth X is the result of the convolution of the muon energy losses in the rock and the input sea-level muon energy spectrum; this one is dependent on $cos\vartheta$ and in a real experimental situation the observed muon flux is modulated by the profile of the rock surrounding the detector. Therefore, it is necessary to sample muon energies according to the following distribution

$$\frac{dN_\mu}{dE_\mu}(X(\vartheta,\varphi)) = \frac{dN_{\mu 0}}{dE_{\mu 0}}(E_{\mu 0},\cos\vartheta) \otimes \frac{dE_{\mu 0}}{dE_\mu} \tag{1}$$

where $X(\vartheta,\varphi)$ describes the mountain map. An input sea-level flux of muons has been taken in the form proposed in (Volkova et al., 1979) with the normalization factor $A = 0.30 \pm 0.13\ cm^{-2}\ s^{-1}\ sr^{-1}\ GeV^{\gamma_{\pi,K}-1}$ and the spectral index of pions and kaons $\gamma_{\pi,K} = 2.72 \pm 0.05$. From muon survival probabilities (Kudryavtsev, 1987) and Gran Sasso mountain map, we have consequently calculated the muon intensity with a bin width $1^o \times 1^o$.

The distribution $\frac{dN_\mu}{dE_\mu}(X, E_\mu, \cos\vartheta)$ has been obtained using the formula

$$\frac{dN_\mu}{dE_\mu}(X, E_\mu, \cos\vartheta) = \int_0^\infty P(E_{\mu 0}, E_\mu, X) \cdot \frac{dN_{\mu 0}(E_{\mu 0},\cos\vartheta)}{dE_{\mu 0}} \cdot dE_{\mu 0} \tag{2}$$

where $P(E_{\mu 0}, E_\mu, X)$ is the probability for a primary muon of energy $E_{\mu 0}$ to reach a depth X with energy E_μ. In order to sample the energy in a given range of depth, we determine the angular regions contributing to the chosen depth, then we generate muon arrival directions according to the distribution evaluated in those regions. Furthermore, for a given depth and ϑ, the muon energy is sampled according to equation 2. The simulation of the muon energy losses and of the energy measurement by the scintillation counters was done using a simplified Monte-Carlo code which took into account the geometry and the structure of the first LVD tower, the Landau fluctuations of ionization energy loss of muons, the interactions of muons inside the rock, iron and scintillator, the one-dimensional development of the muon-produced cascades, and the light collection effect inside the scintillation counter (Kudryavtsev et al. 1992). The simulated $\Delta E/\Delta L$ distributions and the mean values of $< \Delta E/\Delta L >$ agree quite well with the measured ones.

We start this analysis by investigating the dependence of $\Delta E/\Delta L$ on instrumental effects. The direct comparison of the energy releases from muons coming from very different depths could introduce some biases due to the different arrival directions. With this aim we used the data set containing muons coming from depths 4000 m w.e. $< X <$ 4500 m w.e.: their arrival directions span over a very large range of azimuthal angles and a quite large range of zenith angles (from 15^o to 70^o).

The arrival direction influences the intersection points of a muon track with the walls of the scintillation counters and therefore the relative position of the muon track with respect to the photomultipliers. This can result in a different counter response due to light collection. We checked this effect by studying the variation of $< \Delta E/\Delta L >$ in the sample as a function of zenith angle in seven different windows with 10^o width. The result is shown in Fig. 1a. We considered track lengths ΔL with 80 cm $< \Delta L <$ 120 cm. Only statistical errors are quoted. A track can cross a counter in different ways, passing through two horizontal planes, from a vertical plane to a horizontal one or vice versa, or through two vertical planes. We have evaluated the percentage of the tracks of each category contributing to the distribution: the variation observed in Fig. 1a is due to this different topology. Tracks from vertical plane to vertical plane yield a little bit higher values of total light seen by the photomultipliers. This effect could artificially mimic an increase of muon energy release with slant depth. However we stress that the variation is less than 3% with respect to the average value. Then we also checked dependencies on φ (φ is expressed in the LVD internal reference system: $\varphi_{LVD} = \varphi_{NW} + 38.5^o$), in Fig. 1b is presented the variation of $< \Delta E/\Delta L >$ with φ in $\Delta\varphi$ windows of 30^o. The variation observed may have the following interpretation: the two minima are observed corresponding to tracks crossing the apparatus along the y-axis of the detector (e.g. on average only four counters are crossed), where the thickness of the detector (iron of the structure and liquid scintillator) crossed by the muon is minimal. On the other hand the maxima are observed for muons traversing the detector along the x-axis, where the thickness is larger. This shows that LVD is sensitive to secondaries produced inside the detector, mainly in iron. However, even in this case, excluding one point with low statistics, all points are within 3% of the average value over the full range of φ. Finally, we studied the variations on $< \Delta E/\Delta L >$ due to the use of different track lengths. As it was expected (see Fig. 1c), there is a dependence of the measured values on ΔL. The observed increase can be interpreted to come from two effects: the decrease of the relative importance of a leakage effect using longer track lengths and the reduced light collection in the regions near the counter walls. However all these effects (arrival directions and track lengths) are interlaced in a tricky way: the small decrease seen for longer track lengths is due to the fact that these track lengths correspond to the muon directions along the y-axis of the detector. To check our comprehension of instrumental effects and systematics errors, we tried to observe the predicted effect of muon energy increase with depth. To remove all discussed effects, we adopted the following strategy: to identify several regions where, with the same ϑ and symmetric φ with respect to the apparatus, we have a reasonable (e.g. $\Delta X \sim 1000$ m w.e.) difference in slant depths.

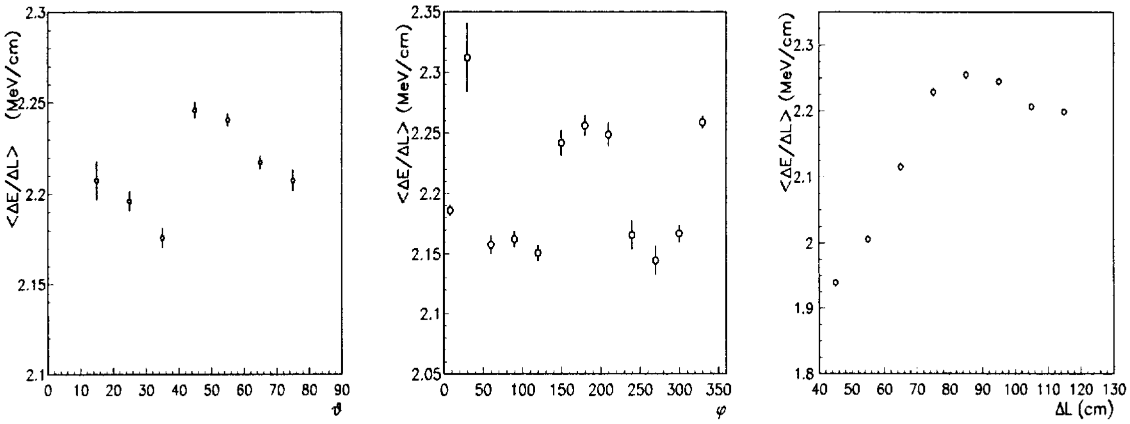

Fig. 1: $< \Delta E/\Delta L >$ measured for muons coming from 4000-4500 m w.e. in LVD external counters as a function of zenith angle (a), as a function of the φ angle (b) and as a function of different track lengths (c).

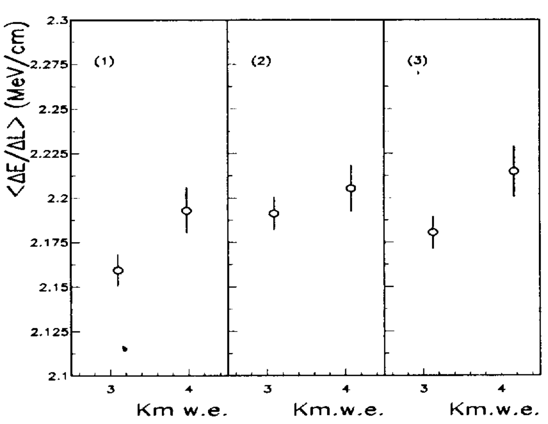

Fig. 2: Measured $< \Delta E/\Delta L >$ values in the three ϑ regions (see text) for symmetric φ corresponding to different depths.

Then, we use the following additional cuts:

a) only tracks crossing the two horizontal planes of the counter are considered. Consequently for a sufficiently small (ϑ,φ) window, the geometry (e.g. the track length) results very well determined. We note also that this cut reduces drastically the error on the determination of ΔL.

b) to exclude production of secondaries inside the detector, only counters on the top-level of LVD (40 counters) are considered;

c) only counters with gain between 140 keV/ADC $channel$ and 170 keV/ADC $channel$ are considered to avoid a systematic effect due to non homogeneous counters response.

In Fig. 2, the average values of $< \Delta E/\Delta L >$ obtained in three ϑ regions ($20^o - 24^o$ (1), $24^o - 28^o$ (2), $28^o - 32^o$ (3)) are shown for 3000 $m.w.e.$ and 4000 $m.w.e.$. In all distributions, as expected, we see an enhancement of $< \Delta E/\Delta L >$ with increasing depth. The relative increase is of the order of $0.6\% - 1.6\%$. Our preliminary Monte Carlo results predict a similar increase $0.5\% - 0.7\%$, compatible within less than two standard deviations. Weighting over errors, we found a total increase of $1.2\% \pm 0.4\%$ from our data, to be compared with $0.6\% \pm 0.1\%$ on Monte Carlo.

CONCLUSIONS

A detailed analysis of energy losses of muons in the LVD experiment over a statistically large data sample has been done. The main conclusions are:

a) instrumental effects due to non-uniformity of light collection, asymmetry of the detector with respect to the production of secondaries and leakage effects are well understood. For track lengths between $80 - 120\ cm$, these effects are only of the order of 3%;

b) applying special cuts to remove any instrumental effects, LVD was able to detect the hardening of the local underground muon spectrum with the increase in depth from 3000 $m.w.e.$ to 4000 $m.w.e.$, in reasonable agreement with preliminary Monte Carlo predictions. For an average muon energy difference of $\sim 35\ GeV$, an increase of $< \Delta E/\Delta L >$ of the order of 1.2% has been measured;

c) the capability of LVD to distinguish between different muon spectra (even if the difference is little) has consequently been proved. This feature has been used (Aglietta et al., 1997) to study energy releases of neutrino-induced muons coming from very large depths, where the statistics is lower, but the expected difference of muon spectra (for muons originated from different sources) is larger.

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