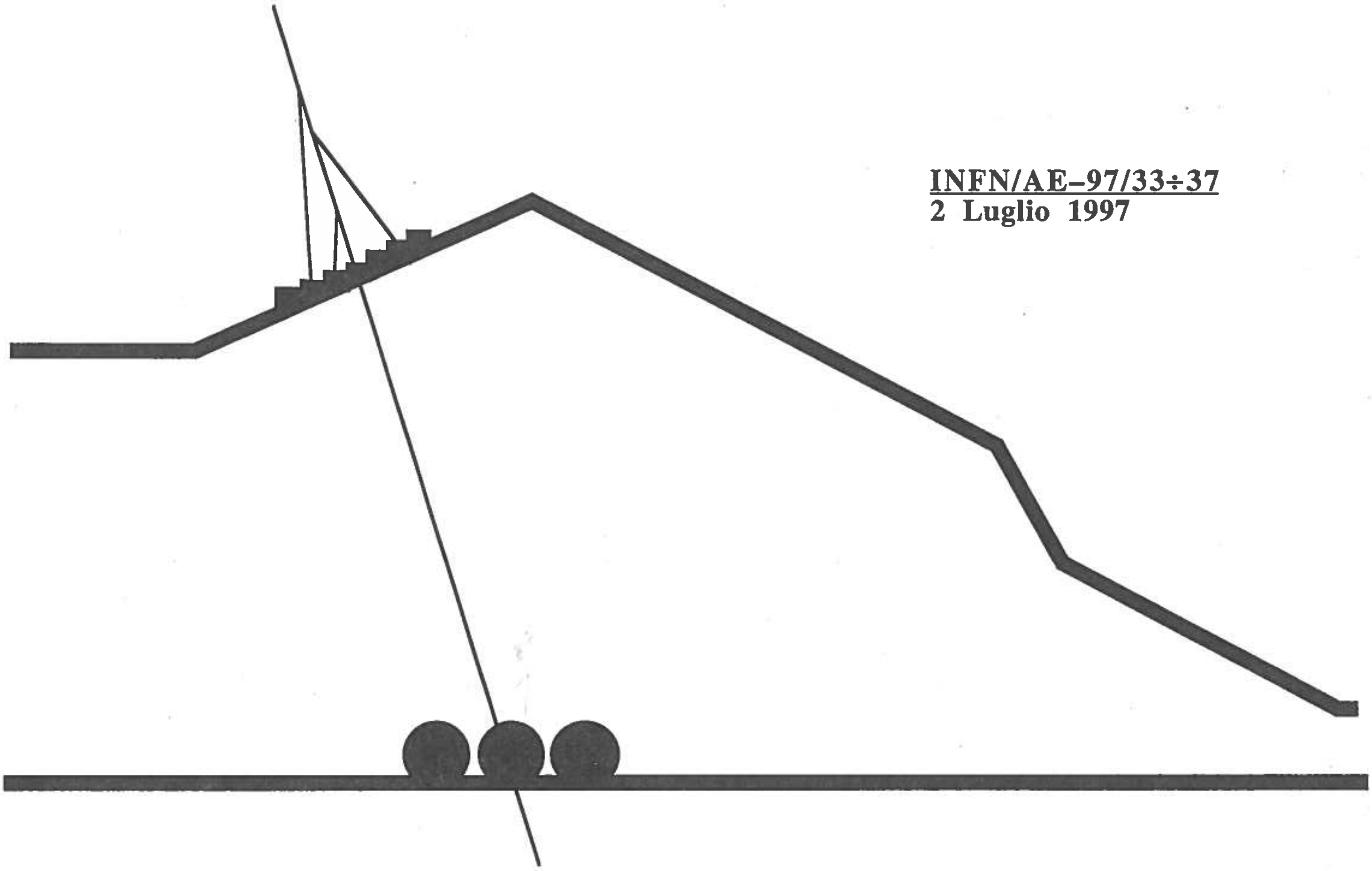

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LVD COLLABORATION

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STUDY OF NEUTRINOS FROM STELLAR COLLAPSES WITH THE LVD EXPERIMENT IN THE GRAN SASSO LABORATORY

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ABSTRACT

The Large Volume Detector (LVD) in the Gran Sasso Underground Laboratory is a ν observatory mainly designed to study low energy neutrinos from gravitational stellar collapses. The experiment is sensitive to collapses in our Galaxy since June 1992, nowaday with an active mass of about 560 tons.

The detector performances and the method used to search for Supernova events and to identify different neutrino interactions is presented. No evidence for burst candidates has been found untill april 1997, for a total lifetime of 1309 days.

INTRODUCTION

The Large Volume Detector is a neutrino telescope located in the Gran Sasso Underground Laboratory at a minimum depth of about 3000 m.w.e. The telescope consists of 2 kinds of detectors, namely: liquid scintillator, for a total mass of 1840 tons, and streamer tubes for a total surface of about 7000 m^2. At present $\approx 1/3$ of the detector is in operating conditions. The main purpose of the experiment is to study gravitational stellar collapses in our Galaxy by detecting its ν burst.

The main LVD characteristics connected to the search for ν burst are:

- detector modularity: 1840 tons of liquid scintillator contained into 1520 self-triggering counters;
- energy threshold: about 4 MeV for the core counters;
- average neutron detection efficiency: about 60%.

SUPERNOVA NEUTRINO DETECTION IN LVD

Most theoretical models agree in predicting the total energy emitted as ν 's during the stellar collapse, the energy equipartition among the different ν flavours and the time duration of the ν burst. Precisely, for a collapsing star at the distance of 10 Kpc, with ν-sphere temperatures $T_{\nu_e} = 3$ MeV and $T_{\nu_\mu} = 6$ MeV we have computed (Aglietta et al.,1992) a total of ≈ 400 interactions, in agreement within 5% with other calculations (A.Burrows et al.,1992).

For any scintillator detector the bulk of events (about 90% of the total number of interactions) is due to the capture reaction:

$$\bar{\nu}_e + p \to n + e^+ \qquad\qquad n + p \to d + \gamma_{2.2MeV}. \qquad (1)$$

The possibility of detecting both products of reaction (1): e^+ and n, allows LVD to identify $\bar{\nu}_e$ interactions, and thus to measure the temperature of the $\bar{\nu}_e$ neutrino-sphere.

Further, we wish to recall that in LVD about 5% of the events are due to neutral current interactions with ^{12}C which deexcites emitting a 15.1 MeV γ. The detector efficiency on detecting these signals has been evaluated in (P.Antonioli et al.,1991). Because μ and τ neutrino-spheres are located deeper in the collapsing stellar core, and because of a temperature gradient, their energy spectra have higher temperatures as compared with the electron neutrino spectra. As a consequence more then 90% of the n.c. interactions with Carbon nuclei are produced by ν_μ and ν_τ.

Moreover, 3% of events in LVD, are due to elastic scattering of all neutrino flavours on electrons, and less then 1% to c.c. interactions of ν_e and $\bar{\nu}_e$ with ^{12}C nuclei. These reactions could easily be separated by subsequent β decay, but because of their relative high thresholds they are strongly suppressed. If energetic μ and τ neutrinos oscillate in electron neutrinos, the $\bar{\nu}_e$ spectrum will be distorced and c.c. interaction channel will open (O.G.Ryazhskaya et al.,1994).

DETECTOR PERFORMANCES

In the search for ν bursts from gravitational stellar collapses, the most important performances of LVD are the following.

- The information related to each signal is stored in a temporary memory buffer which is shared by 8 scintillator counters. This buffer can store up to 2 10^5 pulses, which corresponds to the signal from a standard supernova at a distance closer then 1 Kpc from the Earth.
- The total deadtime corresponds to a maximum detectable frequency (per counter) of 500 kHz. The read out procedure does not introduce any additional deadtime.
- The time of each event, relative to the U.T. time ($\pm$ 1 μsec. from the Gran Sasso facility), is measured with an accuracy of $\pm$12.5 nsec.
- The experiment duty cycle averaged since June '92, when the first LVD tower started taking data, is 76%. Fig.1 shows the detail of the last year.

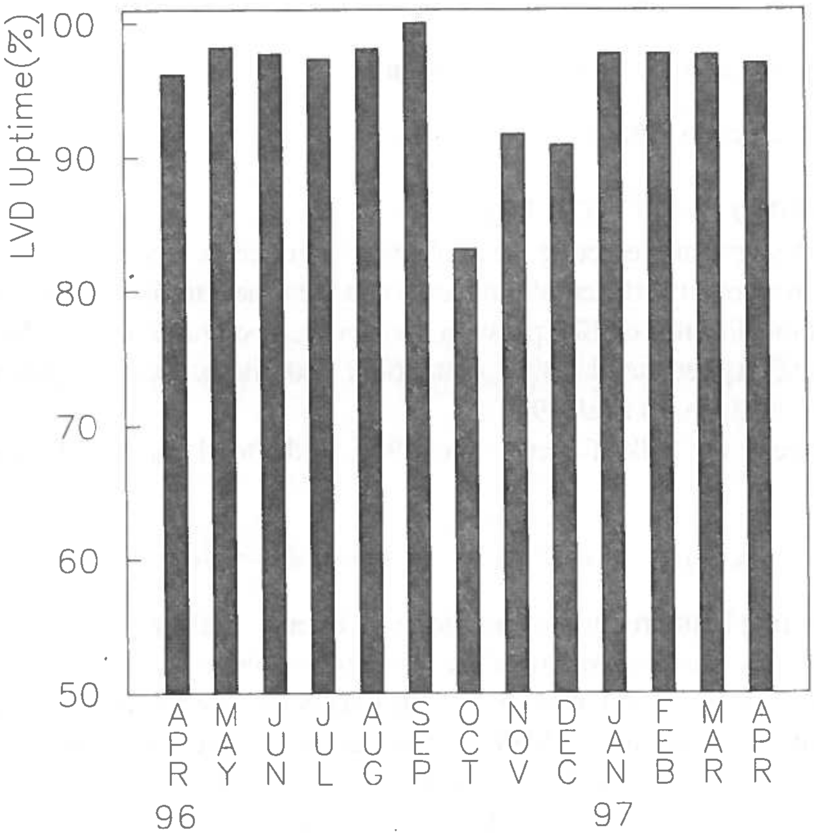

Fig. 1: LVD uptime during the last year of data taking

EVENT RECOGNITION AND NEUTRINO IDENTIFICATION

The search for ν burst candidates is performed by studying the trigger time sequences and searching for signal clusterization. The background due to cosmic ray muons is rejected by the tracking system. The total counting rate of the experiment after μ rejection is 0.2 Hz tower^{-1}, dominated by the internal counters which operate at a lower energy threshold ($E \geq 3-4$ MeV). At $E \geq 7$ MeV all LVD counters are active and the total counting rate is 0.06 Hz tower^{-1}, the ratio between the counting rate of external and internal counters is 3 (in LVD about 1/2 of the total mass belongs to the detector core).

Candidate selection and detector sensitivity:

The technique we use to select burst candidates and to evaluate their significance, explained in detail in (W.Fulgione et al.,1996), is operating (on-line on the experimental data stream) since June '92. We call this the Supernova On-line Monitor (SOM).

The detector sensitivity as a function of the burst duration for the LVD mass active at present (560 tons) is shown in Fig. 2. The two lines are obtained by setting the imitation frequency to 1 event/100 years, for the detector as a single telescope, and to 1 event/month for the detector inserted into a network. With the present LVD active mass, the survey of our full Galaxy is guaranteed, the Large and Small Magellanic Clouds will eventually become observable with LVD in the final configuration.

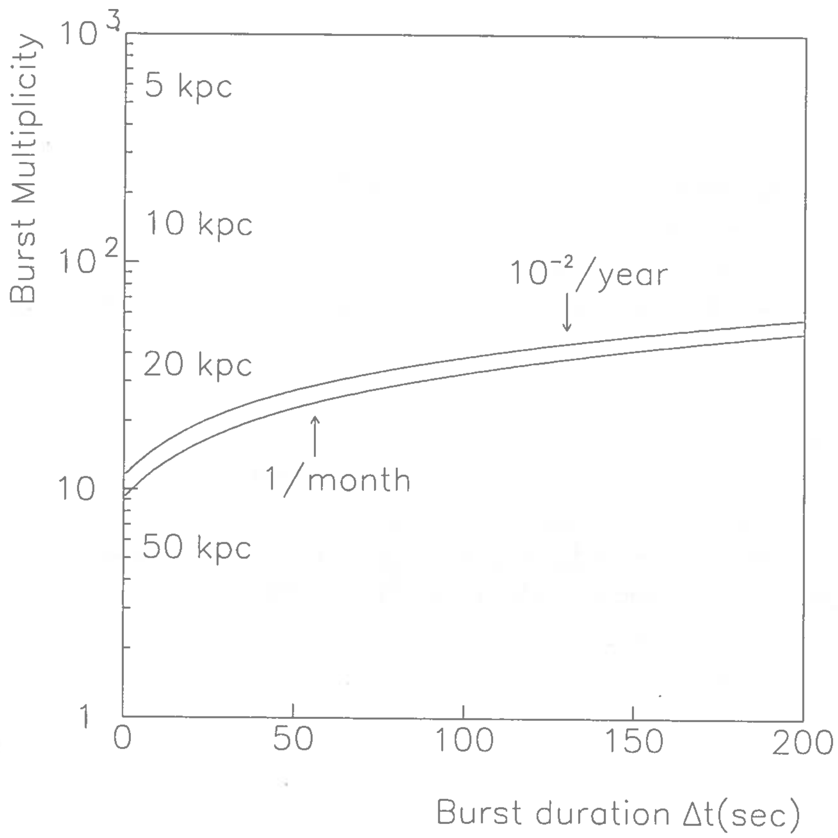

Fig. 2: Detector sensitivity for different durations of the ν emission (560 tons)

Neutrino identification:

After the selection of any cluster of pulses, by means of a pure statistical analysis based on their temporal sequence, the burst candidate is analysed to test its consistency with a ν signal. Three independent tests are performed:

a) presence of signals due to n-capture, from reaction (1);

b) event topology;
c) energy spectra.
a) The efficiency in detecting the 2.2 MeV photons from n-capture, measured on some counters by using a n-source (^{252}Cf), was found to be $\approx 60\%$. The average counting rate per counter for $E \geq 1$ MeV is 120 sec^{-1}. On the average in a time window of 600 μsec the signal to noise ratio is about 10. Moreover the time distribution of these delayed signals is different in the case of background (flat distribution) or n-capture (exponential with mean life 185μsec).
b) Background events are concentrated in regions of the telescope more exposed to the natural radioactivity. Neutrino interactions must be uniformly distributed inside the volume of the detector. Thus we study the spatial distribution of events inside the telescope for each burst candidate by two independent methods.(W.Fulgione et al.,1996 and V.G.Ryasny,1996). Both methods, if we exclude the background contamination (that depends on the burst duration), are completely independent on the time features of the cluster, and they are very effective in rejecting burst candidates produced by non Poissonian fluctuation of the noise, namely electronic troubles.
c) The expected energy distribution of e^+ from $\bar{\nu}_e$ interactions strongly differs from the background energy spectrum (M.Aglietta et al.,1995). By studying the measured spectra one can also determine the temperature of the $\bar{\nu}_e$-sphere and the number of n.c. interactions on ^{12}C.

CONCLUSION

Since June '92, LVD is surveying our Galaxy in the search for ν burst from gravitational stellar collapses. During this period no candidate survived at the analysis at the level of 1 event every 100 year.

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 Technologies, the Russian Foundation of Basic Research (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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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 $1 \times 1 \times 1.5\ m^3$ to cover a total volume of $13 \times 6 \times 12\ m^3$ 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 $\Delta E = 185\ MeV$. The error on ΔL depends both on angular resolution and 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 $\Delta L > 50\ cm$ and tracks with $|\varphi| > 4.5^0$ or $|\varphi - 180^0| > 4.5^0$ 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 $9 < x < 13\ km\ w.e.$ (interval S, with smaller depths) and $x > 13\ km\ w.e.$ (interval L, with larger depths) have been compared. Separately for the two intervals, $< \Delta E/\Delta L >$ 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 $< \Delta E/\Delta L >$ 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 $< \Delta E/\Delta L >$ values is reported. In the figure also the L value is added. Note that the deviation of $< \Delta E/\Delta L >$ value for the interval L is only marginally compatible with a fluctuation from the mean value of interval S.

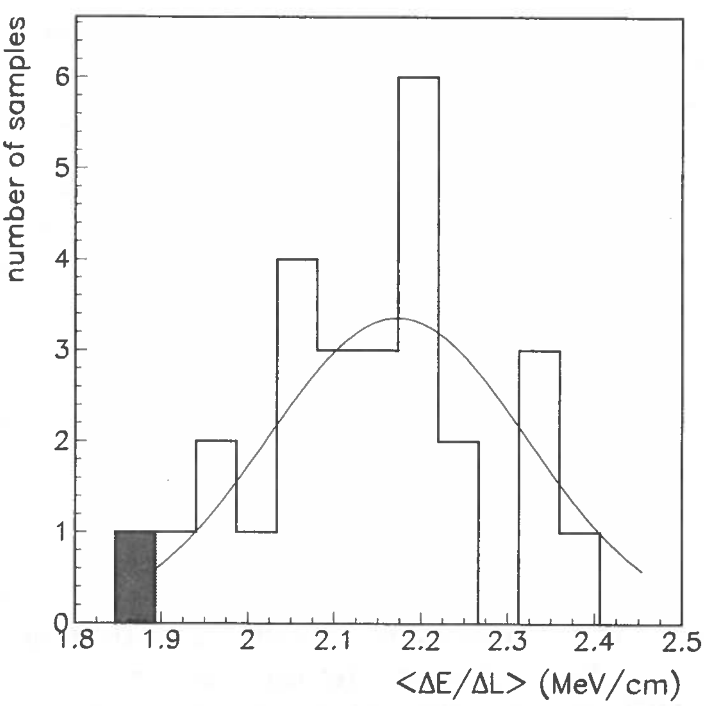

Fig. 1: $< \Delta E/\Delta L >$ distribution for the muon samples at smaller depths (interval S) with a gaussian fit (solid curve). The muon sample at largest depths is added (filled).

The obtained result is $< \Delta E/\Delta L > = 2.13 \pm 0.03\ MeV/cm$ for interval S, whereas $< \Delta E/\Delta L > = 1.88 \pm 0.13\ MeV/cm$ 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 $< \Delta E/\Delta L >$ 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 $< \Delta E/\Delta L >$ values. Simulations have been made to investigate the sensitivity of $< \Delta E/\Delta L >$ values to muon energy. The distributions of $< \Delta E/\Delta L >$ 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 $< \Delta E/\Delta L >$ 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 $< \Delta E/\Delta L >$. In the region $<\Delta E/\Delta L> < 1.95\ MeV/cm$, 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.

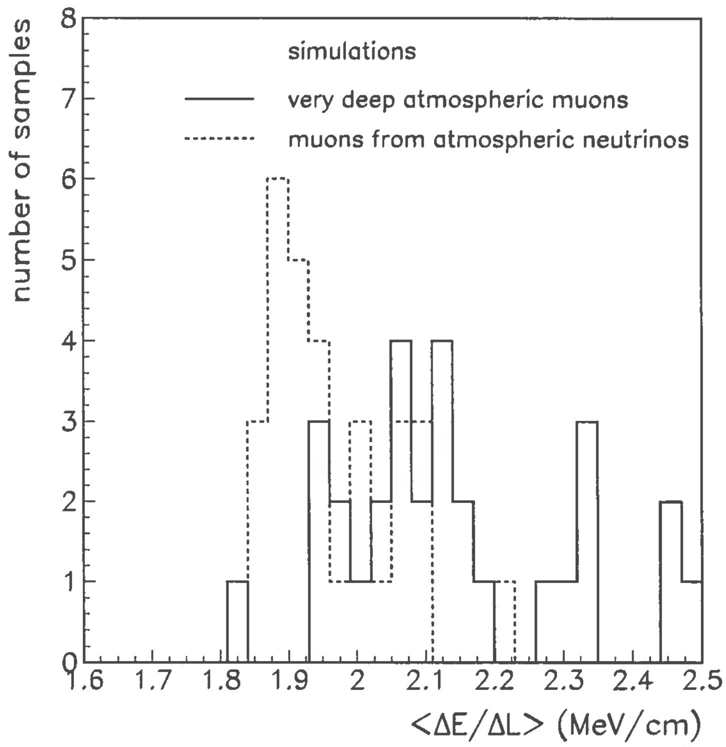

Fig. 2: Distribution of $< \Delta E/\Delta L >$ from simulations for atmospheric muons (continuous) and for ν-induced muons (dashed). Each entry corresponds to a muon sample with the same size as in the data.

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UPPER LIMIT ON THE PROMPT MUON FLUX DERIVED FROM THE LVD DATA

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2 Luglio 1997

ABSTRACT

We present the analysis of muon events with all muon multiplicities collected during 21804 hours of operation of the first LVD tower. The measured depth – angular distribution of muon intensities has been used to obtain the parameters of the muon energy spectrum at sea level. The values of the power index of the primary spectrum (see Eq. 1), $\gamma = 2.77 \pm 0.05$ (68% C.L.), and of the upper limit on the ratio of prompt muon flux to that of pions, $R_c < 2 \cdot 10^{-3}$ (95% C.L.), have been obtained.

INTRODUCTION

The depth – angular distribution of muon intensity measured in an underground experiment is closely related to the muon energy spectrum at the surface. Assuming the muon survival probabilities are well known for every depth and every muon energy at surface, the analysis of the measured depth – zenith angle distribution of intensity allows us to evaluate the parameters of the muon spectrum at the sea level, i.e. the normalization constant, the power index of the primary all-nucleon spectrum and the prompt muon flux from the decay of charmed particles produced together with pions and kaons in the high-energy hadron-nucleus interactions. Numerous calculations of the prompt muon flux have been done during the last ten years (see, for example, Volkova et al., 1987, Zas et al., 1993, Bugaev et al., 1994, Thunman et al., 1996, Battistoni et al., 1996). The intensities of prompt muons strongly depend on the model used and vary by 2 orders of magnitude. This difference is mainly due to the uncertainty of the x-distribution of charmed particles in the fragmentation region, important for cosmic-ray experiments. The accelerator experiments are not very sensitive to the large values of $x = E_c/E$. The search for the prompt muon flux has been done with several detectors located at the surface and underground (see, for example, Krishnaswami et al., 1983, Andreyev et al., 1987, Battistoni et al., 1986, Il'ina et al., 1995). In practice, it is convenient to express the prompt muon flux in terms of the ratio, R_c, of prompt muon flux to that of pions at vertical. Since the slope of the prompt muon spectrum is close to that of pion spectrum, the ratio R_c is almost constant for all muon energies available in the existing experiments. The experimental data, collected up to now, show a large variation of R_c (from 0 to $4 \cdot 10^{-3}$). Muon intensities measured by LVD underground have been used to obtain the parameters of the muon spectrum at sea level, in particular, the ratio of prompt muons to pions. The results of such analysis are presented here.

DATA ANALYSIS

The LVD (Large Volume Detector) (Aglietta et al., 1994), located in the underground Gran Sasso Laboratory, measures the atmospheric muon intensities from 3000 hg/cm^2 to more than 12000 hg/cm^2 (which correspond to the median muon energies at the sea level from 1.5 TeV to 40 TeV) at the zenith angles from 0^o to 90^o (on the average, the larger depths correspond to higher zenith angles). The data presented here were collected with the 1st LVD tower during 21804 hours of live time. The data sample includes about two million reconstructed muon events with all muon multiplicities. The acceptances for each angular bin have been calculated using the simulation of muons passing through LVD taking into account muon interactions with the detector materials and the detector response. The acceptances for both single and multiple muons were assumed to be the same. To obtain the parameters of the muon spectrum at sea level we have analysed the depth – zenith angle distribution of muon intensity derived from the measured angular distribution of the number of events corrected for the simulated acceptances. The depth bin width has been chosen increasing with the depth from about 100 m w.e. at 3000 m w.e. to more than 500 m w.e. at about 10000 m w.e. to have comparable statistics for all depth bins. The muon intensities have been converted to the middle points of the depth and angular bins taking into account the predicted depth – intensity relation and angular distributions for conventional muons (we have used the parameters of the muon spectrum at sea level which fit well the depth – vertical muon intensity relation measured by LVD (Aglietta et al., 1995)).

The data analysis has included the procedure of fitting of the measured depth – zenith angle distribution of muon intensity with the distributions calculated using the known muon survival probabilites (see, Aglietta et al., 1995, and references therein) modified for a new muon bremsstrahlung cross-section (Kelner et al., 1997) and muon spectrum at sea level with three free parameters: normalization constant, A, power index of primary all-nucleon spectrum, γ, and the ratio of prompt muons to pions, R_c. The analytical expression of Gaisser (1991) for the muon spectrum at sea level has been used:

$$\frac{dI_\mu(E_\mu,\cos\theta)}{dE_\mu} = A\cdot 0.14\cdot E_\mu^{-\gamma}\cdot\left(\frac{1}{1+\frac{1.1E_\mu\cos\theta^\star}{115GeV}}+\frac{0.054}{1+\frac{1.1E_\mu\cos\theta^\star}{850GeV}}+R_c\right) \qquad (1)$$

where the values of $\cos\theta$ have been substituted by $\cos\theta^\star$ which have been taken from either the calculations of Volkova (1969) or a simple consideration of the curvature of the Earth atmosphere. In the calculations of Volkova (1969) $\cos\theta^\star = E^{cr}_{\pi,K}(\cos\theta=1)/E^{cr}_{\pi,K}(\cos\theta)$, where $E^{cr}_{\pi,K}$ are the critical energies of pions and kaons. $\cos\theta^\star$ can be understood also as the cosine of zenith angle of muon direction at the height of muon production. The height of muon production increases from 17 km at $\cos\theta = 1$ to about 32 km at $\cos\theta = 0$. We have found that the values of $\cos\theta^\star$ depend on the model of the atmosphere in the range of $\cos\theta = 0-0.3$. To be independent of the model we have restricted the range of $\cos\theta$ used in the analysis to 0.3 – 1. This increase the statistical error of the results decreasing at the same time the systematical uncertainty related to model used.

We have added to the original formula of Gaisser (1991) the term R_c, which is the ratio of prompt muons to pions. We have assumed that the power index of the prompt muon spectrum is equal to that of primary spectrum. We have multiplied the full formula by the additional normalization constant A which has been considered as a free parameter together with γ and R_c.

RESULTS AND DISCUSSION

As a result of the fitting procedure we have obtained the values of the free parameters: $A = 1.84\pm0.31$, $\gamma = 2.77\pm0.02$ and the upper limit on $R_c < 2\cdot10^{-3}$. Here and hereafter we present the errors at 68% confidence level (C.L.) and the upper limits at 95% C.L. The errors of the parameters include both statistical and systematic uncertainties. The latter one takes into account the possible uncertainties in the depth, rock composition, density etc., but does not take into account the uncertainty in the cross-sections used to simulate the muon transport through the rock. If we restrict our analysis to the depth range 5 – 10 km w.e., we obtain the following values of parameters: $A = 1.6^{+0.8}_{-0.6}$, $\gamma = 2.76\pm0.06$ and $R_c < 3\cdot10^{-3}$. The angular distributions of muon intensities for different depth ranges are presented in Figure 1 together with calculations with $R_c = 0$ (best fit – solid curve) and $R_c = 2\cdot10^{-3}$ (upper limit – dashed curve). The calculated distributions have been obtained using the formula of Gaisser (1991) and the values of $\cos\theta^\star$ of Volkova (1969). Similar analysis performed for single muons also shows no evidence for prompt muon flux. We found the same values of power index and upper limit to the prompt muon flux, while the absolute intensity is 10% smaller.

The conservative upper limit to the fraction of prompt muons, even in the simple assumption that the power index of the prompt muon spectrum is equal to that of primary spectrum, rules out several models of the prompt muon production, which predict a fraction of prompt muons more than $2\cdot10^{-3}$ (for example, model A of Zas et al., 1993). The predictions of the models B and C of Zas et al. (1993), recombination quark-parton model (RQPM) of Bugaev et al. (1994) and model of Volkova et al. (1987) are comparable with the LVD upper limit. At the same time the LVD result favours the models of charm production based on QGSM (see, for example, Bugaev et al., 1994) and the dual parton model (Battistoni et al., 1996) which predict low prompt muon flux.

The upper limit (95% C.L.) obtained with the LVD data is lower than the value of R_c found in the MSU experiment ($R_c = (2.6 \pm 0.8) \cdot 10^{-3}$ at E_μ=5 TeV, Il'ina et al., 1995). The LVD upper limit does not contradict the values of prompt muon flux, obtained in Baksan (Andreyev et al., 1990) and KGF (Krishnaswami et al., 1983) underground experiments. Our result agrees with that of NUSEX (Battistoni et al., 1987) which didn't reveal any deviation from the angular distribution expected for conventional muons.

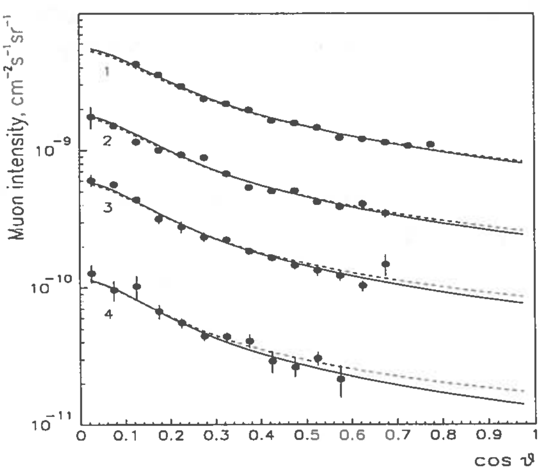

Fig. 1: Dependence of muon intensity on zenith angle for 4 depth ranges: 1 – 5 - 6 km w.e., 2 – 6 - 7 km w.e., 3 – 7 - 8 km w.e., 4 – 8 - 10 km w.e.

To obtain the 'depth – vertical muon intensity' relation we have converted the muon intensities measured at different zenith angles to the vertical taking into account the predicted angular distributions of conventional muon intensities at various depths. We have fitted this relation with the calculated one with two free parameters (A and γ) and obtained the following values: $A = 1.95 \pm 0.31$, $\gamma = 2.78 \pm 0.02$, in good agreement with the results of the analysis of the depth – angular distribution. The 'depth – vertical muon intensity' relation is shown in Figure 2a for all-muon sample together with the best fit. If we add the uncertainty in the muon interaction cross-sections, the error of γ will increase from 0.02 to 0.05 (for the discussion about the uncertainty due to different cross-sections see Antonioli et al., 1997). This uncertainty, however, does not influence the upper limit on R_c.

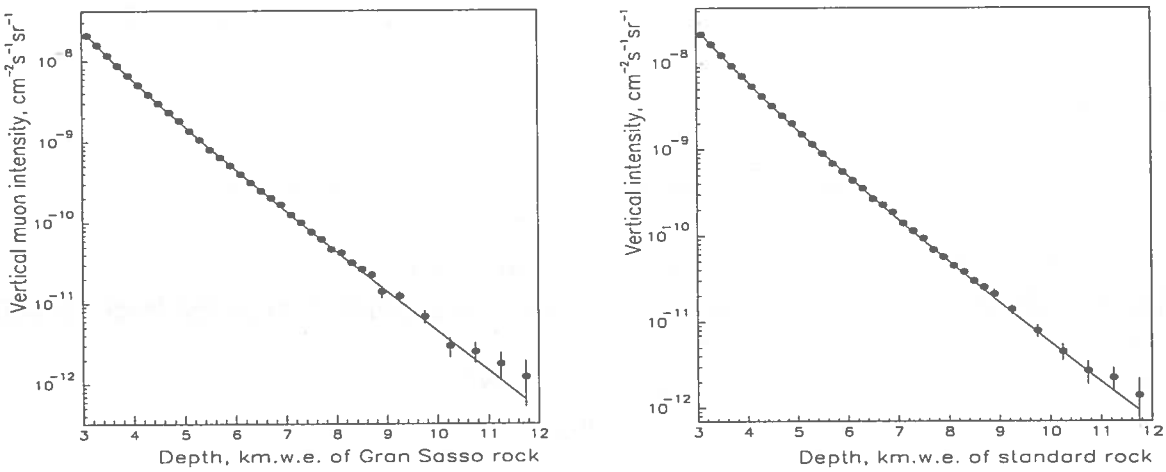

Fig. 2: 'Depth – vertical muon intensity' relations in Gran Sasso (left) and standard (right) rocks for all-muon sample.

If the formula of Volkova et al. (1979) is used for the muon spectrum at sea level instead of formula of Gaisser (1991), the best fit values of γ will be decreased by 0.04-0.05 and will be in agreement with the previously published values for single muons (Aglietta et al., 1995) analysed using the formula of Volkova et al. (1979).

The simulations of muon transport carried out for Gran Sasso and standard rocks allow us to obtain the formula for the conversion of the depth in Gran Sasso rock, x_{gs}, to that in standard rock, x_{st}.

This was done by comparing the values of x_{st} and x_{gs} for the same muon intensity: $I_\mu(x_{st}) = I_\mu(x_{gs})$. The muon intensities have been calculated with the value of γ which fit well the LVD data. The depth in standard rock can be evaluated from the depth in Gran Sasso rock using the formula:

$$x_{st} = -9.344 + 1.0063 x_{gs} + 1.7835 \cdot 10^{-6} x_{gs}^2 - 5.7146 \cdot 10^{-11} x_{gs}^3, \qquad (2)$$

where the depth is measured in hg/cm^2. This formula is valid for depth range 1–12 km w.e.

The 'depth – vertical intensity' relation in the standard rock for all-muon sample is presented in Figure 2b. It can be fitted with a three parameter function:

$$I_\mu(x) = A \left(\frac{x_0}{x}\right)^\alpha \exp^{-\frac{x}{x_0}}, \qquad (3)$$

where $A = (2.15 \pm 0.08) \cdot 10^{-6}$ cm^{-2} s^{-1} sr^{-1}, $x_0 = (1155^{+60}_{-30})$ hg/cm^2, $\alpha = 1.93^{+0.20}_{-0.12}$.

CONCLUSIONS

The analysis of the depth – angular distribution of all-muon and single muon intensities measured by LVD in the depth range 3000-12000 hg/cm^2 has been done. The parameters of the muon energy spectrum at the sea level have been obtained (see Eq. 1): $A = 1.8 \pm 1.0$, $\gamma = 2.77 \pm 0.05$ and $R_c < 2 \cdot 10^{-3}$ (95% C.L.). The errors include both statistical and systematic uncertainties. The upper limit to the fraction of prompt muons, R_c, favours the models of charm production based on QGSM (Bugaev et al., 1994) and the dual parton model (Battistoni et al., 1996).

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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 Technologies, the Russian Foundation of Basic Research (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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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 multi-purpose 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

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

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

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

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.

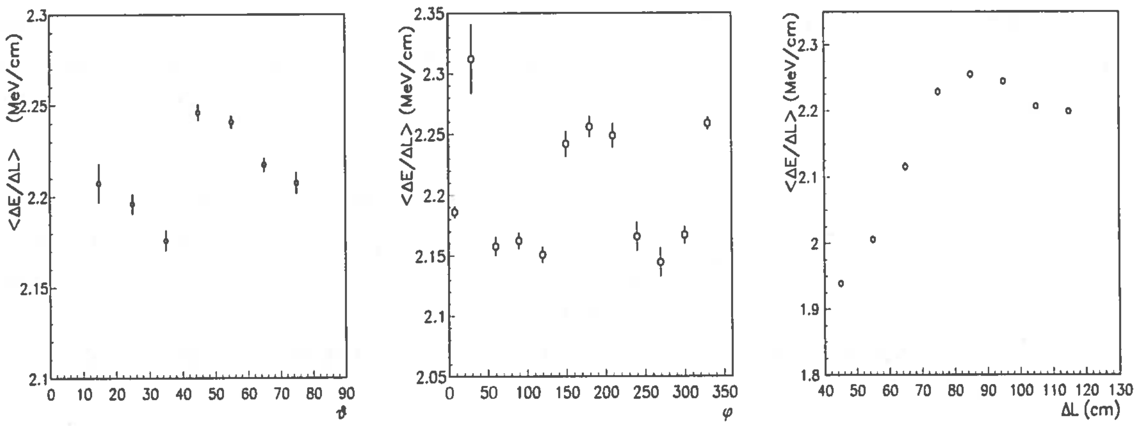

Fig. 1: $< \Delta E/\Delta L >$ measured for muons coming from 4000-4500 m w.e. in LVD external counters as a function of zenith angle (a), as a function of the φ angle (b) and as a function of different track lengths (c).

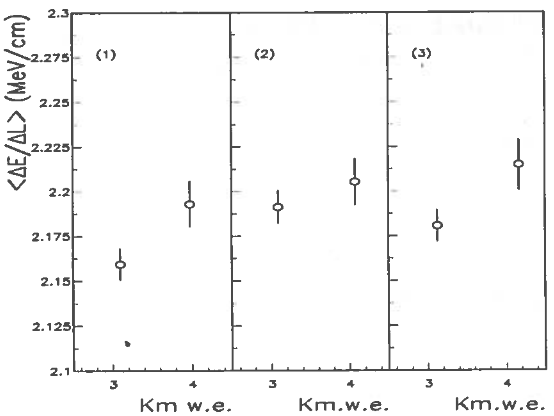

Fig. 2: Measured $< \Delta E/\Delta L >$ values in the three ϑ regions (see text) for symmetric φ corresponding to different depths.

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 increas-

ing 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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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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SEARCH FOR POINT SOURCES WITH MUONS OBSERVED BY LVD

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2 Luglio 1997

ABSTRACT

Single muons collected by the first tower of LVD during 14431 hours of live time were used in a search for point sources of ultra high energy photons. We have made an all–sky survey of point sources of cosmic muons. We searched for any significant excess in the muon flux above simulated background in the right ascension – declination coordinates. We found no evidence for point sources. We also report a search for an excess of undeground muons from the directions of several known sources. Analysis of the data contained in the narrow cones around the source positions shows no signals from the sources.

INTRODUCTION

The experiments to search for point sources of underground muons started more than 10 years ago when Samorski and Stamm (Samorski and Stamm, 1983) observed high energy gammas from the Cyg X-3 direction in their EAS experiment. In 1985 NUSEX (Battistoni et al., 1985) and SOUDAN (Marshak et al., 1985) collaborations reported a muon excess from the same direction in the sky. The source of high-energy muons could be neutral stable particles (gammas or neutrinos). However, the signal was too high to be explained by known processes of muon production in the atmosphere. The production of high-energy muons in the gamma-induced showers in the atmosphere and possible detection of these muons underground were discussed by Kudryavtsev and Ryazhskaya (1985), Stanev et al. (1985), Stanev (1986) and Berezinsky et al. (1988).

Since 1985 many underground detectors have continued to look for excesses of downward-going muons in their data. Single muons measured by LVD underground have been used to search for anisotropies in the flux of underground cosmic–ray muons. The results of such analysis are presented here.

DATA ANALYSIS

The LVD (Large Volume Detector) (Aglietta et al., 1994, 1995), located in the underground Gran Sasso Laboratory at a latitude of $42^o27'$ N and longitude $13^o34'$ E, detects atmospheric muons passing through 3000 hg/cm^2 to more than 12000 hg/cm^2 (which correspond to the muon energies at the sea level from 1.5 TeV to 40 TeV) at the zenith angles from 0^o to 90^o. For the present analysis we used the single muons observed by the first tower of LVD. It has a dimensions 13m $\times$ 6.3m $\times$ 12m and geometric acceptance of about 1700 m^2 sr. The staggered double layers of limited streamer tubes and their orthogonal readout strips providing bidimensional information about the muon impact point allow LVD to reach high detection efficiency and accuracy of muon track reconstruction better than 1^o. A muon track is defined by alignment of at least 3 impact points in the tracking planes and the presence of at least 2 firing scintillation counters along the muon track. For this analysis we have chosen runs with duration more than 1 hour. The muons coming from nearly horizontal zenith angles (greater than 88^o) were excluded from the analysis due to the ambiguity of the track direction. After these cuts we selected 1185866 muons for further analysis.

The sky was surveyed from 0^o to 360^o in right ascension and from -10 ^{o} to 90 ^{o} in declination using the sample of single muons. The right ascension (R.A.) and declination, δ, for each muon were calculated and a two – dimensional map was stored using a cell size of 0.01 $\times$ 1^o from -1 to 1 in $\sin\delta$ and from 0^o to 360^o in R.A. (and $1^o \times 1^o$ in R.A. – δ coordinates). To search for a muon excess from any angular cell we compared the measured distribution in R.A. – $\sin\delta$ coordinates with a simulated background of atmospheric muons produced in hadronic showers initiated in the interactions of the primary nuclei with air. To calculate the background the following procedure was used. The direction of incoming muon was simulated from the experimental zenith and azimuthal distribution of muons observed by LVD in the same set of runs. The time of muon arrival was simulated as a Poisson process following the procedure described in (Ahlen et al., 1994). The mean time between two consecutive muons was calculated for each run and used in the simulation. Then, zenith and azimuthal angles and time of muon arrival were converted to right ascension–declination coordinates. The total number of simulated muons is 30 times more than the number of detected muons. Figure 1a shows a distribution of the data versus declination (after summing over R.A.). The shape of this distribution reflects the mountain structure at the LVD site. Figure 1b shows a distribution of the muon flux versus R.A. (summed over declination). For both these distributions the data and the Monte Carlo simulation of the atmospheric muon background are found to be in good agreement.

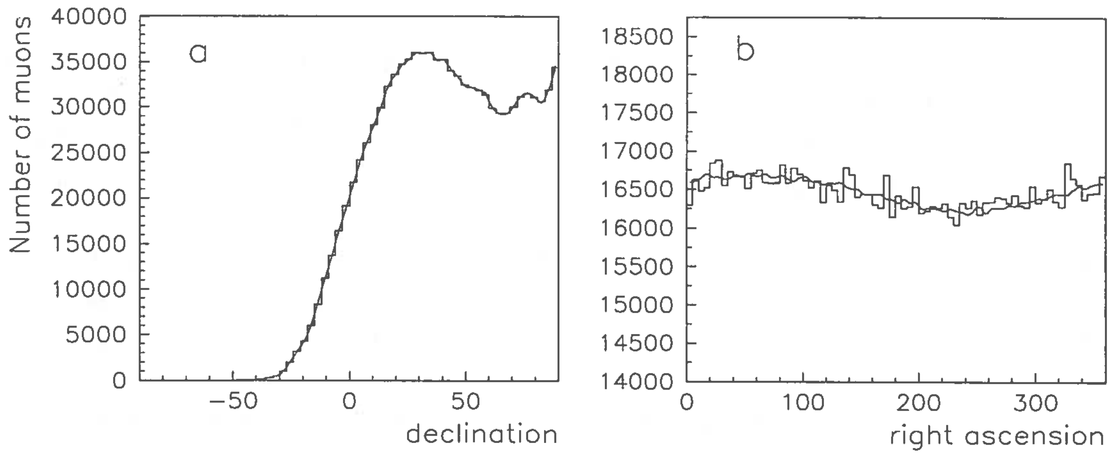

Fig. 1: Distribution of muon events versus declination (a) and right ascension (b). The histograms are experimental data, solid curves show Monte Carlo simulated background from atmospheric muons initiated in hadronic showers

Equal solid angle bins (3° in right ascension and 0.04 in $\sin\delta$) were chosen to search for steady emission from point sources. The number of muons accumulated in each bin, n_{exp}, was compared to the Monte Carlo simulated background in the same bin, n_{mc}. We plot in Figure 2 the distribution of deviations from the mean $\Delta = \frac{n_{exp}-n_{mc}}{\sqrt{n_{exp}}}$ and a Gaussian fit to this distribution. We have no positive deviations greater than 3.5 σ. We have used the data for the bin with 3.5 σ muon excess to calculate the upper limit on the flux from any angular cell. The upper limit (95% C.L.) on the time independent flux from any point source of underground muons is $8.2{\cdot}10^{-12}$ cm^{-2}s^{-1}.

We also made a search in narrow cones (1.5° half angle) around the positions of several possible sources of UHE photons and obtained the upper limits on steady fluxes of muons coming from those directions at the 95% C.L. using the formula:

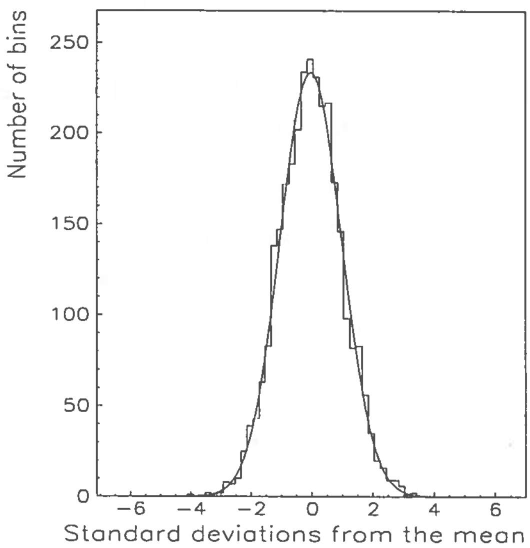

Fig. 2: Distribution of deviations from mean value of muon flux and Gaussian fit

$$F = \frac{1.65 \cdot \sqrt{n_{mc}}}{\langle \epsilon \cdot A \rangle \cdot T} \quad (1)$$

where $\langle \epsilon \cdot A \rangle$ is the weighted average of the product of efficiency of muon detection and reconstruction by the area of the cross–section of detector perpendicular to the muon track, and T is the exposure time.

Table 1: The steady flux limits (95% C.L.) from selected sources.

Source	⟨Depth⟩, m.w.e.	n_{exp}	n_{mc}	Flux limit, $cm^{-2}s^{-1}$
Cyg X–3	4037	320	314	$6.74 \cdot 10^{-13}$
Her X–1	4018	349	341	$1.16 \cdot 10^{-12}$
Crab Nebula	3429	394	399	$7.40 \cdot 10^{-13}$
SS433	3493	310	294	$7.13 \cdot 10^{-13}$
3C273	3551	290	261	$6.89 \cdot 10^{-13}$
Geminga	3410	384	401	$7.58 \cdot 10^{-13}$
Mrk 421	4009	324	321	$6.99 \cdot 10^{-13}$

CONCLUSIONS

We looked for an excess of muons both in an all-sky search with no a priori sources and in a search around positions of possible sources of UHE gammas. We did not see statistically significant muon excess (more than 3.5 σ), above the simulated background from any angular cell on the sky. The upper limit (95% C.L.) on the time independent flux from any point source of underground muons is $8.2 \cdot 10^{-12}$ $cm^{-2}s^{-1}$. This limit corresponds to the angular bin $3^o \times 0.04$ in R.A.–$\sin\delta$ coordinates. We obtained also the steady flux limits from selected astrophysical objects.

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