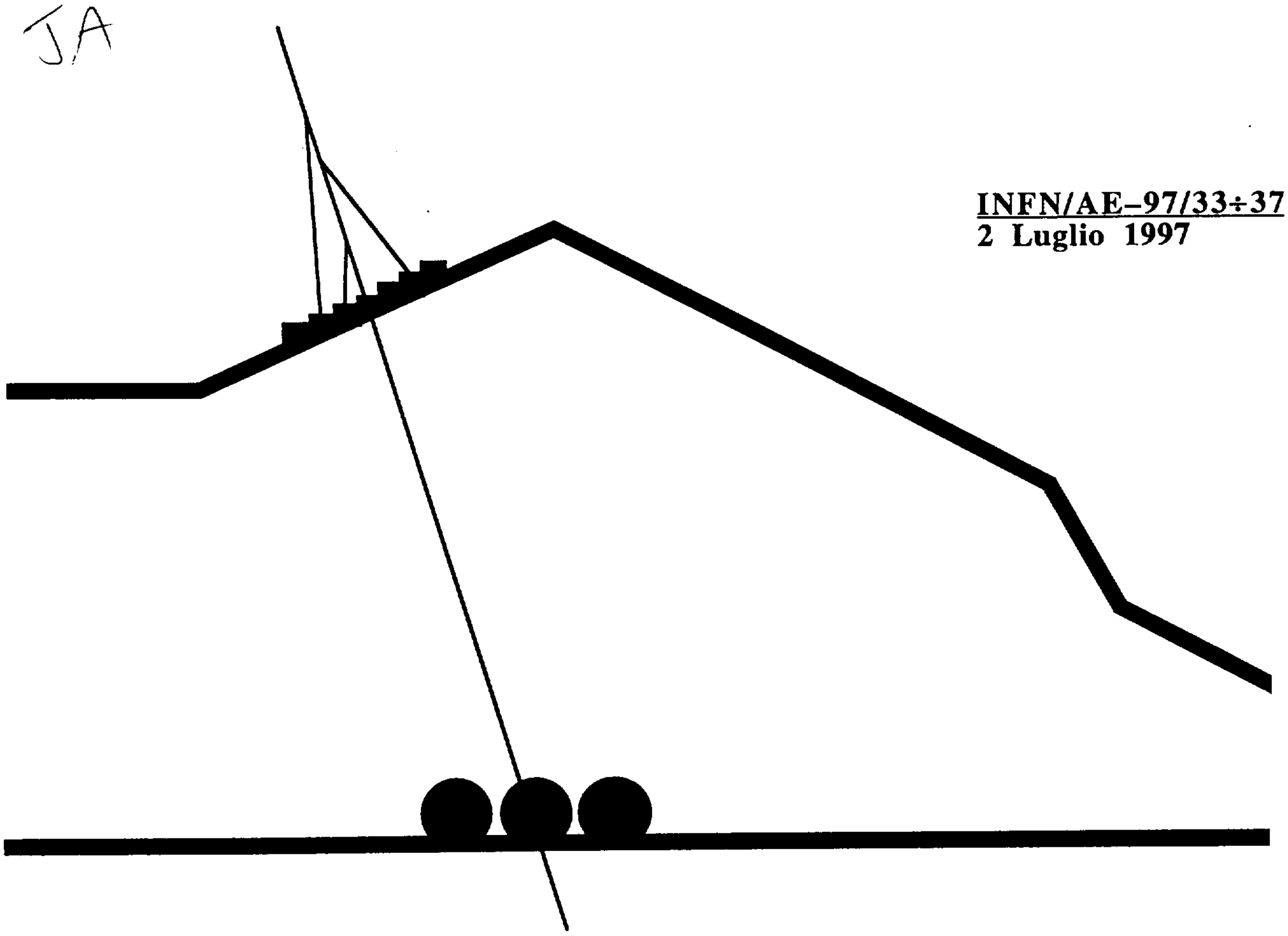
JA

INFN/AE-97/33÷37
2 Luglio 1997



Sw9809

Contributions of the LVD Collaboration to the XXV ICRC
Durban, South Africa July 28–Aug. 10, 1997

INFN – Laboratori Nazionali del Gran Sasso

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

LVD COLLABORATION

M.Aglietta[16], B.Alpat[13], E.D.Alyea[7], P.Antonioli[1], G.Badino[16], G.Bari[1], M.Basile[1], V.S.Berezinsky[10], F.Bersani[1], M.Bertaina[16], R.Bertoni[16], G.Bonoli[1], A.Bosco[2], G.Bruni[1], G.Cara Romeo[1], C.Castagnoli[16], A.Castellina[16], A.Chiavassa[16], J.A.Chinellato[3], L.Cifarelli[1], F.Cindolo[1], G.Conforto[17], A.Contin[1], V.L.Dadykin[10], A.De Silva[2], M.Deutsch[8], P.Dominici[17], L.G.Dos Santos[3], L.Emaldi[1], R.I.Enikeev[10], F.L.Fabbri[4], W.Fulgione[16], P.Galeotti[16], C.Ghetti[1], P.Ghia[16], P.Giusti[1], R.Granella[16], F.Grianti[1], G.Guidi[17], E.S.Hafen[8], P.Haridas[8], G.Iacobucci[1], N.Inoue[14], E.Kemp[3], F.F.Khalchukov[10], E.V.Korolkova[10], P.V.Korchaguin[10], V.B.Korchaguin[10], V.A.Kudryavtsev[10], K.Lau[6], M.Luvisetto[1], G.Maccarone[4], A.S.Malguin[10], R.Mantovani[17], T.Massam[1], B.Mayes[6], A.Megna[17], C.Melagrana[16], N.Mengotti Silva[3], C.Morello[16], J.Moromisato[9], R.Nania[1], G.Navarra[16], L.Panaro[16], L.Periale[16], A.Pesci[1], P.Picchi[16], L.Pinsky[6], I.A.Pless[8], J.Pyrlik[6], V.G.Ryasny[10], O.G.Ryazhskaya[10], O.Saavedra[16], M. Selvi[1], K.Saitoh[15], S.Santini[17], G.Sartorelli[1], N.Taborgna[5], V.P.Talochkin[10], J.Tang[8], G.C.Trinchero[16], S.Tsuji[11], A.Turtelli[3], I.Uman[13], P.Vallania[16], G. Van Buren[8], S.Vernetto[16], F.Vetrano[17], C.Vigorito[16], E. von Goeler[9], L.Votano[4], T.Wada[11], R.Weinstein[6], M.Widgoff[2], V.F.Yakushev[10], I.Yamamoto[12], G.T.Zatsepin[10], A.Zichichi[1]

[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

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

INFN/AE–97/35
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:

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

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: $A = 1.84 \pm 0.31$, $\gamma = 2.77 \pm 0.02$ and the upper limit on $R_c < 2\cdot 10^{-3}$. 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: $A = 1.6^{+0.8}_{-0.6}$, $\gamma = 2.76 \pm 0.06$ and $R_c < 3\cdot 10^{-3}$. 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 $R_c = 2\cdot 10^{-3}$ (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 $2\cdot 10^{-3}$ (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.

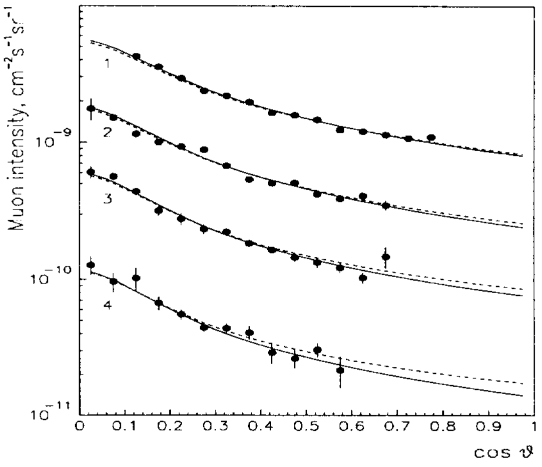


Fig. 1: Dependence of muon intensity on zenith angle for 4 depth ranges: 1 – 5 - 6 km w.e., 2 – 6 - 7 km w.e., 3 – 7 - 8 km w.e., 4 – 8 - 10 km w.e.

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.

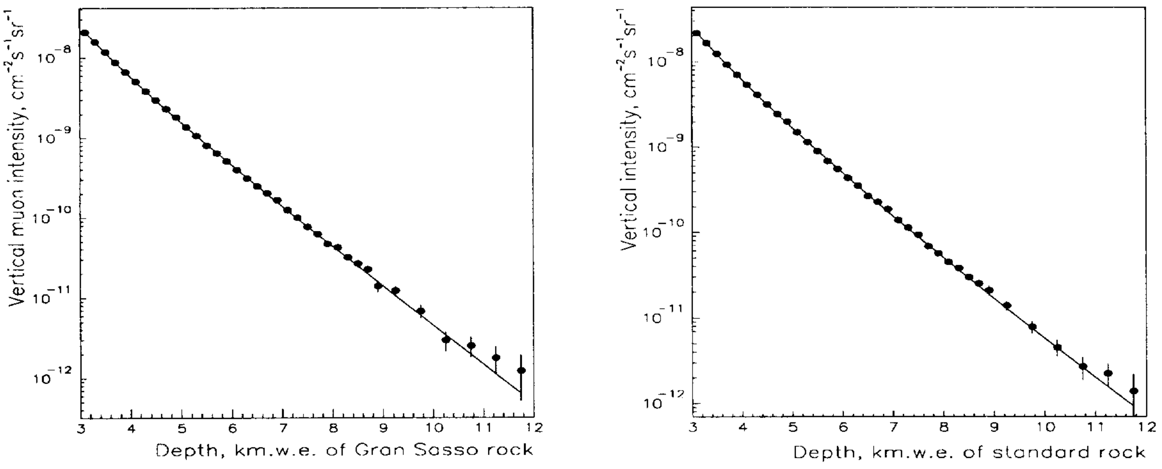


Fig. 2: 'Depth – vertical muon intensity' relations in Gran Sasso (left) and standard (right) rocks for all-muon sample.

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).

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.

REFERENCES

Aglietta, M. et al. (LVD Collaboration), *Astroparticle Phys.*, 2, 103 (1994);

Aglietta, M. et al. (LVD Collaboration), *Astroparticle Phys.*, 3, 311 (1995); Aglietta, M. et al. (LVD Collaboration), *Proc. 24th ICRC* (Rome), 1, 557 (1995).

Andreyev, Yu. M. et al. *Proc 21th ICRC* (Adelaide), 9, 301 (1990).

Antonioli, P. et al. A Three-Dimensional Code for Muon Propagation through the Rock: MUSIC, *these Proceedings*, HE 3.2.2 (1997).

Battistoni, G. et al., *Proc. 20th ICRC* (Moscow), 9, 195 (1987).

Battistoni, G. et al., *Astroparticle Phys.*, 4, 351 (1996).

Bugaev, E. V. et al., *Proc. RIKEN Intern. Workshop on Electromagnetic and Nuclear Cascade Phenomena in High and Extremely High Energies*, 264 (1994).

Gaisser, T. K., Cosmic Rays and Particle Physics, Cambridge University Press (1990).

Il'ina, N. P. et al., *Proc. 24th ICRC* (Rome), 1, 524 (1995).

Kelner, S. R., Kokoulin, R. P., and Petrukhin, A. A., *Physics of Atomic Nuclei* (1997), to be published.

Krishnaswami, M. R. et al., *Proc. 18th ICRC* (Bangalore), 11, 450 (1983).

Thunman, M., Ingelman, G., and Gondolo, P., *Astroparticle Phys.*, 5, 309 (1996).

Volkova, L. V., Preprint Lebedev Physical Institute, N 72 (1969).

Volkova, L. V., Zatsepin, G. T., and Kuzmichev, L. A., *Sov. J. Nucl. Phys.*, 29, 1252 (1979).

Volkova, L. V. et al., *Nuovo Cimento C*, 10, 465 (1987).

Zas, E., Halzen, F., and Vazquez, R. A., *Astroparticle Phys.*, 1, 297 (1993).