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# Neutrino-induced and atmospheric single-muon fluxes measured over five decades of intensity by LVD at Gran Sasso Laboratory

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**Abstract**

We report data taken by the LVD Experiment during a live-time period of 11 556 h. We have measured the muon intensity at slant depths of standard rock from about 3000 hg/cm$^2$ to about 20000 hg/cm$^2$. This is an exclusive study, namely our data include only events containing single muons. This interval of slant depth extends into the region where the dominant source of underground muons seen by LVD is the interaction of atmospheric neutrinos with the rock surrounding LVD. The interesting result is that this flux is independent of slant depth beyond a slant depth of about 14000 hg/cm$^2$ of standard rock. Due to the unique topology of the Gran Sasso Laboratory the muons beyond about 14000 hg/cm$^2$ of standard rock are at a zenithal angle near 90°. Hence we have, for this fixed angle, a muon flux which is independent of slant depth. This is direct evidence that this flux is due to atmospheric neutrinos interacting in the rock surrounding LVD. The value of this flux near 90° is $(8.3 \pm 2.6) \times 10^{-13}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$, which is the first reported measurement at a zenithal angle near 90° and for slant depths between 14000 and 20000 hg/cm$^2$. Our data cover over five decades of vertical intensity, and can be fit with just three parameters over the full range of our experiment. This is the first time a single experiment reports the parameters of a fit made to the vertical intensity over such a large range of standard rock slant depth. The results are compared with a Monte Carlo simulation which has as one of the two free parameters $\gamma_{\pi k}$, the power index of the differential energy spectrum of the pions and kaons in the atmosphere. This comparison yields a value of $2.75 \pm 0.03$ for $\gamma_{\pi k}$, where the error includes the systematic uncertainties. Our data are compared to other measurements made in our slant depth interval. We also report the value of the muon flux in Gran Sasso at $\theta = 90°$ as a function of the azimuthal angle.

## 1. Introduction

The muon intensity underground has been the subject of experimental investigations for many years, e.g. [1-10]. These investigations explore both high energy astrophysics and elementary particle interactions. The muon intensity as a function of slant depth can illuminate the features of both topics.

The muons reaching LVD are of three types:

1. Muons that are the decay products of pions and kaons. These pions and kaons are produced by the interaction of cosmic rays with the Earth's atmosphere.
2. Muons that are the decay products of short lived particles such as charm mesons, etc. These short lived particles are also produced by the interaction of cosmic rays with the earth's atmosphere.
3. Muons that are produced by the charged current interactions of muon neutrinos that interact in the rock near the LVD detector. The muon neutrinos are the decay products of particles that decay in the earth's atmosphere.

At slant depths less than about 14000 hg/cm$^2$ of standard rock the major contribution to the muon vertical intensity is muons of type 1 cited above, that is, muons resulting from the decay of pions and kaons which were created by the interaction of the cosmic rays with the Earth's atmosphere.

Muons of type 2 above, so called prompt muons, certainly contribute to the muon intensity at slant depths less than 12000 hg/cm$^2$ of standard rock, but they constitute a much less frequent source of muons than the pions and kaons. However, because of their parent's decay properties they should be detectable at slant depths around 7000 hg/cm$^2$ of standard rock. However, in this paper we neglect this source of muons.

The muons of type 3, namely muons resulting from neutrinos interacting in the rock close to LVD, have properties much different from the muons of type 1 as seen by the LVD detector. These muons are dominant at slant depths greater than about 14 000 $hg/cm^2$ of standard rock.

We will discuss in detail the differences between muons of type 1 and muons of type 3 and the different manner used in analyzing these two types. In particular we will present our analysis and measurement of the flux of muons produced by neutrinos in the rock close to LVD at a zenithal angle of about 90° and energy above about 1 GeV.

Our data consists of a sample of events containing only single muons which have been acceptance corrected. In order to compare our data with other published work, we fit the vertical intensity of our data from 3000 $hg/cm^2$ to 20 000 $hg/cm^2$. These data cover over five decades of vertical intensity. The data can be fit with three parameters over the full range and this is the first time a single experiment has reported such a fit and the fit parameters.

We have generated a Monte Carlo simulation to extract from our data the pion-kaon power index of the differential energy spectrum $\gamma_{\pi k}$. We have included in our Monte Carlo simulation the LVD detector, the mountain topology surrounding LVD, the energy loss of muons in the mountain rock, and the energy dependence of the sea level muon spectrum.

We compare our data with other experiments in the relevant slant depth region. Given the spread of the various measurements, the agreement is reasonable for the measurements quoted in this paper.

In Section 2 we briefly describe the LVD detector; in Section 3 we explain our data selection procedure; in Section 4 we present our acceptance correction technique; in Section 5 we discuss the depth intensity relations we use in this paper; in Section 6 we display our data and the analysis of our data. In particular we discuss the special case of muons created by neutrinos interacting in the rock close to the LVD detector. In Section 7 we summarize this paper and present our conclusions.

## 2. Detector

The LVD (Large Volume Detector) underground experiment [11] is located in the Gran Sasso Laboratory in central Italy. The minimum rock cover is about 1100 meters with average values $A = 22.88$, $Z = 11.41$ and density, $\rho = 2.71$ $g/cm^3$ [5]. We convert Gran Sasso rock to standard rock by interpolating the information in [12].

LVD is designed for the study of various phenomena in neutrino astrophysics, cosmic rays and elementary particle physics. The data reported here come from the first of five towers of LVD each containing 38 modules (Fig. 1). Every module contains eight, 1.2 ton liquid scintillator counters, each of which is viewed by three photomultipliers. A module supports an L-shaped tracking detector attached to the bottom (horizontal element) and one vertical side (vertical element).

Each element of an L-shaped tracking detector contains two staggered layers of 6.3 m long limited streamer tubes. The tube has 8 cells with $9 \times 9$ $mm^2$ active cross sectional area for each cell. Below and parallel to, and above and perpendicular to, the streamer tube wires, are 4 cm wide pickup strips ($x$ and $y$ strips) to provide bidimensional information about an ionizing particle's impact point. The staggered double layers of streamer tubes and their orthogonal readout strips yield an effective strip width of 2 cm with no dead space, high overall tracking efficiency, and an angular resolution better than 4 mrad [13].

The first tower of LVD has been running since June 1992. It has a volume of $13$ m $\times$ $6$ m $\times$ $12$ m and geometric acceptance of about 1700 $m^2$ sr. The detailed characteristics of the detector are described in [14].

## 3. Data selection

The selection of the data sample required that at least one scintillation counter was triggered in the event and there was a minimum of three space points available for track reconstruction. This implies that a minimum of three different elements of the L-shaped tracking detectors were hit such that a space point is determined in each element. In addition, at least one

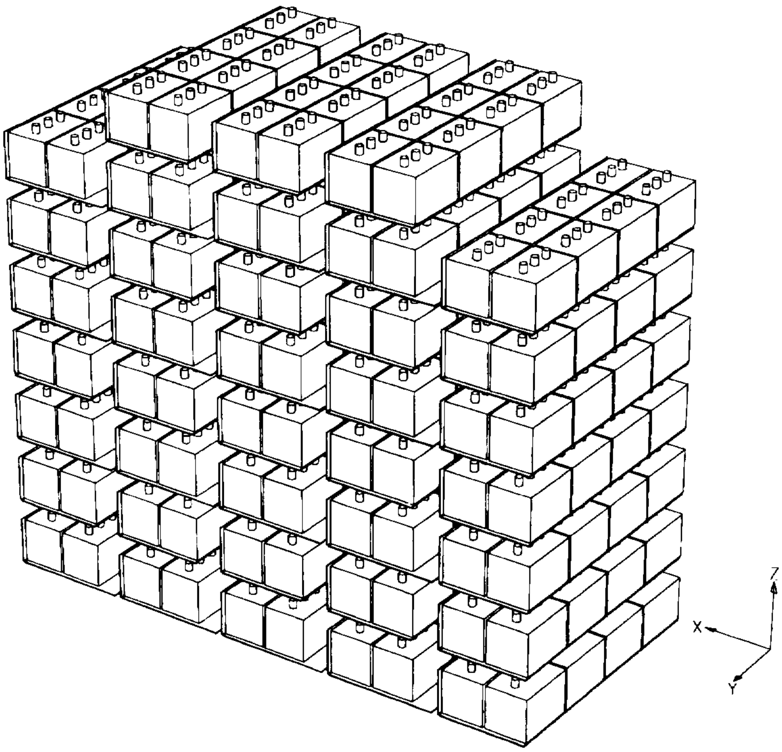


Fig. 1. View of LVD tower one.

of the three elements must have contained a space point defined by two strips, each of which is parallel to its associated tube, and at least one strip perpendicular to the tubes. A complete description of our data selection criteria can be found in Ref. [14]. In total, 978 074 single muon events were selected during 11 566 h of live time.

## 4. Detector acceptance correction

The detector acceptance correction for the single muon events is described in [14], as is the definition of the LVD coordinate system and the geographic coordinate system. We summarize our acceptance correction technique here.

Fig. 2 shows a lego plot of the LVD acceptance (1 tower) for our selection criteria. The zenithal angle $\theta$ is measured from the $z$ axis in Fig. 1 and the azimuthal angle $\phi$ is measured from the $x$ axis in Fig. 1. This plot is derived from a Monte Carlo calculation with detector inefficiencies included as a function of muon azimuth and $\cos\theta$ in the LVD reference system [14]. Note that the LVD acceptance extends to $\cos\theta = 0$ along the $x$ axis, and is zero on only 8% of the Monte Carlo sphere, in directions along the $y$ axis. Using the data in this plot, we can correct the number of events found in any $\cos\theta$, $\phi$ solid angle interval.

## 5. Depth-intensity relation

The thickness of rock crossed by muons was determined from the mountain map of Gran Sasso. The muon intensity in a given depth interval $(h \pm \Delta h/2)$ was obtained from the number of events at the corresponding slant depth, by using the formula

$$I(h) = \frac{1}{\Delta T \Omega(h)} \sum_{i}^{n} \frac{N_i}{A_i(\theta_i, \phi_i)} \tag{1}$$

where $\Delta T$ is the live time of the experiment, $\Omega(h)$ is the solid angle corresponding to the slant depth

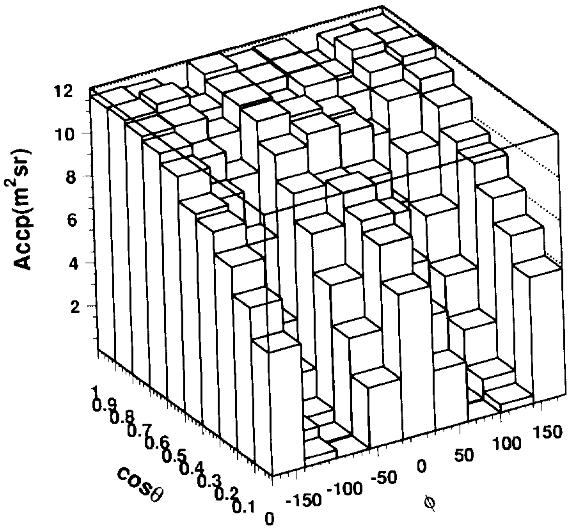


Fig. 2. Lego plot of the acceptance of LVD (one tower) for single muon events.

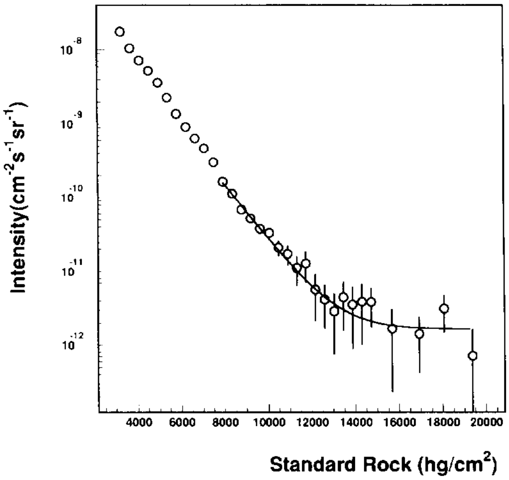


Fig. 3. Muon intensity as a function of slant depth in standard rock. The solid line is the fit to the data for slant depths greater than 8000 hg/cm$^2$ using an exponential term plus a constant. The data beyond 14000 hg/cm$^2$ is double counted. See text for details.

interval, $n$ is the number of $(\theta, \phi)$ bins contributing to the slant depth interval, $N_i$ is the number of events in bin $i$ of slant depth $h$, $A_i$ is the acceptance of the detector, $\theta_i$ is the muon zenithal angle and $\phi_i$ is muon azimuthal angle. In this way, we obtain the single muon intensity distribution versus slant depth.

In order to compare our data with other experiments, we also calculate the vertical intensity $I_v$ for $h < 12\,500$ hg/cm$^2$:

$$I_v(h) = \frac{1}{\Delta T \Omega(h)} \sum_i^n \frac{N_i \cos(\theta_i)}{A_i(\theta_i, \phi_i)}. \qquad (2)$$

## 6. Data and discussion

There is evidence that the muon flux at large slant depths is dominated by neutrinos interacting in the rock [2,15-19]. The unique topology of Gran Sasso Laboratory allows us to explore slant depths from 14 000 to 20 000 hg/cm$^2$ of standard rock at a fixed zenithal angle close to 90°. A direct way to establish the existence of atmospheric neutrinos interacting in the rock near an underground detector is to show that for a fixed zenithal angle close to 90° the muon flux is independent of slant depth for depths greater than about 14 000 hg/cm$^2$ of standard rock. In addition, a measurement of the muon flux at this zenithal angle beyond that slant depth is important as a check of the validity of current models concerning the muon intensity generated by neutrinos interacting in the rock surrounding an underground detector.

Using Eq. (1), we plot in Fig. 3 the muon intensity as a function of slant depth. There is a strong and complicated variation of slant depth with respect to the zenithal angle which is determined by the mountains in the vicinity of the Gran Sasso Laboratory. Hence Fig. 3 cannot be directly compared with any other experiment for slant depths less than about 14 000 hg/cm$^2$ of standard rock except those experiments which are physically located in the Gran Sasso Laboratory. The interesting features of Fig. 3 are roughly the exponential shape up to a slant depth of about 13 000 hg/cm$^2$ of standard rock and the roughly constant behavior beyond that point.

We have fit the data in Fig. 3 with an exponential plus a constant term. We find the value for this constant term, $C$ to be:

$$C = (1.65 \pm 0.53) \times 10^{-12}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}.$$

The errors are only statistical with a $\chi^2$ per degree of freedom of 0.5 for this fit.

Beyond a slant depth of 14 000 hg/cm$^2$ of standard rock there are 17 single muon events. The average cosine of the 17 zenithal angles is 0.07. Hence, we have established that for a fixed zenithal angle of about 90° and for a slant depth greater than 14000 hg/cm$^2$ the muon flux is independent of slant depth. This is direct evidence of the existence of a muon flux induced by neutrinos interacting in the rock surrounding LVD.

Due to the event selection criteria, all muons in our sample have an energy higher than 1 GeV. It should be noted that muons of energy 1 GeV or greater which are created by neutrinos interacting in the rock near the LVD detector have a special property, namely if such a muon has a certain probability of entering the LVD detector with angles $\theta$ and $\phi$, then there is an equal probability for a muon to enter the LVD detector with angles $\pi - \theta$ and $\pi + \phi$. At present, LVD cannot tell the difference between up and down. We assume all muons have a positive cos $\theta$. This leads to double counting for the points in Fig. 3 which have a slant depth greater than about 14000 hg/cm$^2$ of standard rock.

Taking into account this double counting, we calculate the muon intensity near the 90° zenithal angle, $I(90°)$:

$$I(90°) = (8.3 \pm 2.6) \times 10^{-13}\ \mathrm{cm^{-2}\ s^{-1}\ sr^{-1}}.$$

We wish to point out that this value of the intensity should be measured by any detector at a zenithal angle of 90° as long as the slant depth in that direction is greater than 14000 hg/cm$^2$ of standard rock and the detected muons have energy greater than 1 GeV. This is the first time the neutrino induced muon flux near 90° has been reported, for slant depth between 14000 and 20000 hg/cm$^2$ of standard rock.

This measurement agrees within two standard deviations with our calculation of the neutrino induced muon flux as well as other theoretical calculations [18,19] of $I(90°)$ which range from about (4.3 to 5.2) $\times 10^{-13}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$. For our calculations we have used three estimations of the neutrino flux [20–22] and two sets of parton distribution functions [23,24]. Given our statistical error and the spread in the theoretical calculations, we can only conclude that at present measurement and theory are in agreement.

A measurement near 90° and at slant depths of about 180000 hg/cm$^2$ of standard rock has been reported by Crouch et al. [2]. In this work they have fitted their data to theoretical forms of the angular distribution of the neutrino spectrum. The result of their fit to the theoretical expectation, with which our measurement is in agreement, is

$$I(90°) = (4.59 \pm 0.42) \times 10^{-13}\ \mathrm{cm^{-2}\ s^{-1}\ sr^{-1}}.$$

We can use Eq. (2) to analyse our data in terms of vertical intensity. We point out that Eq. (2) is the definition of the vertical intensity at a given slant depth. This is the usual definition for detectors under mountains [3,5,6]. Eq. (2) uses the zenithal angle, which is correct for a flat atmosphere. However, for large angles one should replace $\theta$ by $\theta^*$, the angle relevant for a spherical atmosphere. As will be discussed, the difference between $\theta$ and $\theta^*$ is not important for this study. The work of Crouch [2] explores zenithal angles up to about 65° in order to make measurements at slant depths out to about 20000 hg/cm$^2$ of standard rock. In order to make measurements in the same slant depth range, this experiment explores zenithal angles up to 89°. Besides the problem of the difference in angular ranges, we have just shown that for slant depths greater than about 14000 hg/cm$^2$ of standard rock, the muon flux is dominated by muons induced by neutrinos interacting in the rock surrounding the detector. Hence Eq. (2) cannot be used to calculate the vertical intensity for slant depths greater than about 14000 hg/cm$^2$ of standard rock. As noted, the work of Ref. [2] makes measurements out to angles near 90° and out to slant depths of about 180000 hg/cm$^2$ of standard rock.

For the region beyond about 14000 hg/cm$^2$ of standard rock we have shown for the zenithal angle near 90° there is no dependence on slant depth. In fact, this is also clearly true for any zenithal angle beyond the slant depth of about 14000 hg/cm$^2$. Therefore we must treat the region beyond about 14000 hg/cm$^2$ in different manner than the region less than about 14000 hg/cm$^2$.

For the region less than about 12500 hg/cm$^2$ we will use Eq. (2) to calculate the vertical intensity. We will show that for the region beyond about 14500 hg/cm$^2$, the data in Fig. 3, which is flux at about 90° for various slant depths, is converted into an estimate of the vertical intensity at the same slant depth by dividing the flux shown in Fig. 3 by 4.6. The value of 4.6 is derived from our calculation of the angular dependence of the neutrino induced muon

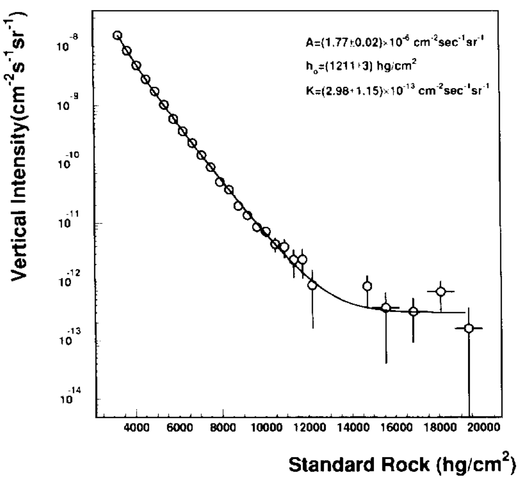


Fig. 4. Muon vertical intensity as a function of slant depth in standard rock. Note that the size of the circles does not represent the statistical errors, it represents the bin width. The horizontal bars also represent the bin width.

flux and other theoretical calculations [18,19]. The calculations predict the ratio $R$ between the flux near $90^\circ$ and the flux at $0^\circ$ to be

$$R = 2.3 \pm 0.2.$$

We note that $R$ is the average of the theoretical predictions while 0.2 represents the spread of the predictions.

Since the data points beyond about 14 000 hg/cm$^2$ in Fig. 3 are double counted, we must reduce the value of these points by a factor of two. If we designate our measured horizontal flux at slant depth $h$ as $I_H(h)$ (shown in Fig. 3) and our estimated vertical flux as $I_V(h)$, then for data points beyond about 14 000 hg/cm$^2$ the following relation holds:

$$I_V(h) = I_H(h)/2R = I_H(h)/4.6.$$

In other words, we use the theoretical ratio of the flux at about $90^\circ$ to the flux at $0^\circ$ to scale our measurements at $90^\circ$ to a value at $0^\circ$.

Fig. 4 displays the vertical intensity as a function of slant depth. We have removed the data points of Fig. 3 from the slant depth of 12 500 hg/cm$^2$ to a slant depth of 14 500 hg/cm$^2$. This has been done because in this region it is not clear, for a group of events in a slant depth bin in this slant depth interval, whether to use Eq. (2) or divide by 4.6.

The main features of this plot are the roughly exponential shape up to a slant depth of about 14 000 hg/cm$^2$ of standard rock and the roughly constant behavior beyond that point. We have used the Frejus function plus a constant term to fit our data. The function we fit is:

$$I_v(h) = A_0 \cdot e^{-h/h_0}(h_0/h)^2 + K_0. \quad (3)$$

Our best fits to these three parameters are:
$A_0 = (1.77 \pm 0.02) \times 10^{-6}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$,
$h_0 = 1211 \pm 3$ hg/cm$^2$ of standard rock,
$K_0 = (2.98 \pm 1.15) \times 10^{-13}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$.

Note that all quoted errors are statistical. The $\chi^2$ per degree of freedom for this fit is 3.9. The relatively high value of the $\chi^2$ could be due to the fact that we do not include the possibility of prompt muons in our fitting function or that we have not included the systematic errors in our data.

The value of the constant term is in good agreement with the result of Crouch [2] who finds a value of $K_0 = (2.17 \pm 0.21) \times 10^{-13}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$, from a compilation of results of various experiments.

We note that this is the first time the parameters from the fit to the data from a single experiment for this range of slant depth have been reported [15].

Fig. 4 gives evidence that Eq. (2) is a useful parameterization out to a slant depth of about 10 000 hg/cm$^2$. This region contains zenithal angles from zero degrees to $75^\circ$. This is to be expected as $\cos\theta$ for a flat atmosphere differs from $\cos\theta^*$ for a spherical atmosphere at $75^\circ$ by only about five percent. For our data this small difference at $75^\circ$, which is the maximum angle used at 10 000 hg/cm$^2$ of standard rock, has a much smaller effect on our calculation of the vertical intensity than does our statistical error at this slant depth, which is 21%. For slant depths between 10 000 hg/cm$^2$ and 12 000 hg/cm$^2$ our statistical error also outweighs the effect of the difference between $\cos\theta$ and $\cos\theta^*$ in our calculation of the vertical intensities for those slant depths. For example, at 12 000 hg/cm$^2$ of standard rock, the maximum angle used is $80^\circ$. The difference between $\cos\theta$ and $\cos\theta^*$ at $80^\circ$ is about 13% while our statistical error at 12 000 hg/cm$^2$ of standard rock is about 80%.

In Fig. 5 we compare the results of four experiments in the region between 3000 hg/cm$^2$ and 9000

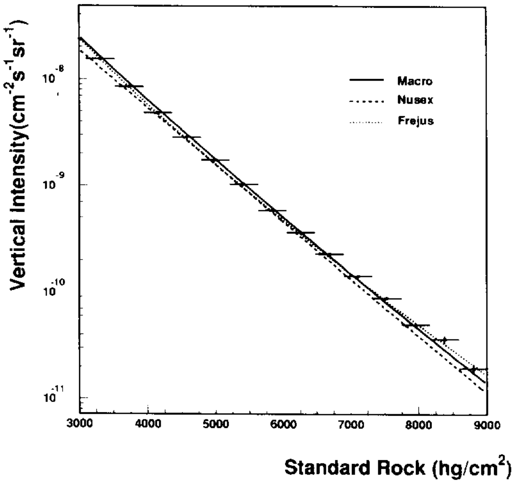


Fig. 5. The vertical intensity from LVD compared with the results of three other experiments. Note that the horizontal bars represent the bin width.

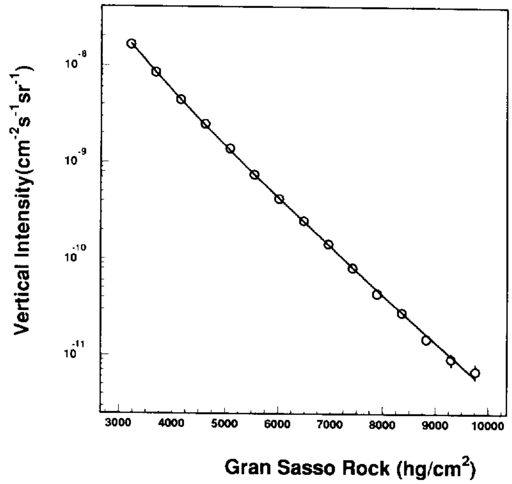


Fig. 6. Muon vertical intensity as a function of slant depth in Gran Sasso rock. The open circles are our data and the line is the Monte Carlo prediction for atmospheric muons. The data yield a value for $\gamma_{\pi k}$. See text for details.

hg/cm$^2$. The data from our experiment and the other three experiments are in reasonable agreement. We note that the NUSEX data are fit from 4700 hg/cm$^2$ to 10 000 hg/cm$^2$, the FREJUS data are fit from 4000 hg/cm$^2$ to 9000 hg/cm$^2$, and the MACRO data are fit from 3000 hg/cm$^2$ to 7000 hg/cm$^2$. We note that the NUSEX, FREJUS and MACRO studies are inclusive studies (muons from all multiplicities are included in the data) while this work is an exclusive study (only single muons are included in data with appropriate corrections). Our points should therefore be about 10% lower than the other three experiments. This difference is smaller than the spread of the other three experiments. All experiments are in reasonable agreement.

Our values for the vertical intensities at two slant depths are:

$$I_v = [1.54 \pm 0.003(\text{sta}) \pm 0.08(\text{sys})] \times 10^{-8}\ \text{cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}, \quad \text{at } h = 3300\ \text{hg/cm}^2,$$

$$I_v = [1.76 \pm 0.01(\text{sta}) \pm 0.09(\text{sys})] \times 10^{-9}\ \text{cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}, \quad \text{at } h = 5000\ \text{hg/cm}^2.$$

This result agrees with other experiments such as [3,5,6], with the comment noted above about the difference between inclusive and exclusive studies.

The data in Fig. 4 can be used to calculate the power index ($\gamma_{\pi k}$) of the differential energy spectrum of the pions and kaons in the atmosphere. The calculation was performed using the muon survival probabilities for Gran Sasso rock obtained by Monte Carlo simulation procedures described in [25]. The survival probabilities agree quite well with the results of [26]. The muon spectrum at sea level was taken in the most general form [27] modified to take into account the rise of the cross section of hadron-nucleon interactions at high energies [28]. This muon spectrum at sea level is a function of two parameters; a normalization parameter and the power index $\gamma_{\pi k}$. We fit the data using the two free parameters. In the fitting procedure we included both statistical and systematic errors. Our best fit gave the following result:

$$\gamma_{\pi k} = 2.75 \pm 0.03.$$

The $\chi^2$ for this fit was 0.74 per degree of freedom. Fig. 6 displays our data and our fit to this data.

At low muon surface energies there is a dependence of the ratio between the flux at a given cosine $\theta$ and the vertical flux on the muon energy. This dependence is very small for muon energies larger than two TeV and $\cos\theta$ larger than 0.5. The larger the muon energy, the smaller $\cos\theta$ must be in order to have any dependence of the ratio of the intensity at a given $\cos\theta$ to the vertical intensity on the muon

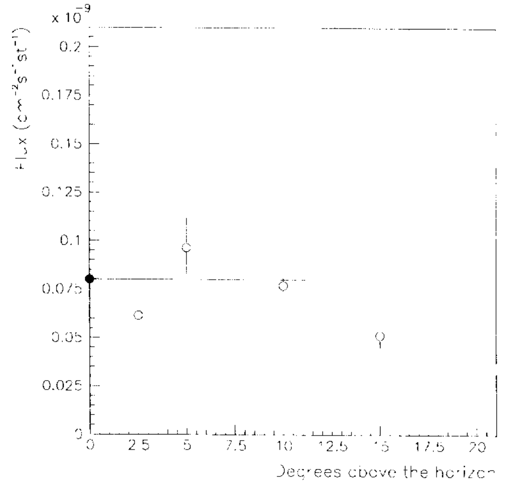


Fig. 7. Horizontal flux at 90° extrapolated from 80° to 90°. (90° is 0° above the horizon; 75° is 15° above the horizon.) Fluxes are integrated above slant depths greater than 8000 hg/cm$^2$.

energy. In order to check our sensitivity to this effect, we removed the first two points of Fig. 6 from our data sample and redid our analysis. These two points contain muons of small surface energy. The calculated value of $\gamma_{\pi k}$ remained unchanged. Hence we have demonstrated that our analysis is not sensitive to the effect of muons having small surface energy.

We have measured the horizontal flux at slant depths greater than 8000 hg/cm$^2$ of standard rock at the Gran Sasso Laboratory as a function of $\phi$. The azimuthal angle is measured in the LVD coordinate system. The relationship between the LVD coordinate system and the geographic coordinate system is

$$\phi(\text{geographic}) = 218.4^\circ - \phi(LVD).$$

The complete definitions of these coordinate systems can be found in [14]. The zenithal angle is measured from $z$ axis in Fig. 1, while the azimuthal angle is measured from the $x$ axis in Fig. 1. The horizontal flux points were evaluated by extrapolating 75° to 90° by using either a zero degree, a first or second degree polynomial. An example of this extrapolation with the zero degree polynomial for the azimuthal region from −180° to −140° is shown in Fig. 7. The flux in this figure is the integral over all slant depths larger than 8000 hg/cm$^2$ of standard rock. Fig. 8 shows our data for the horizontal flux at a zenithal angle of 90° integrated over all slant depths

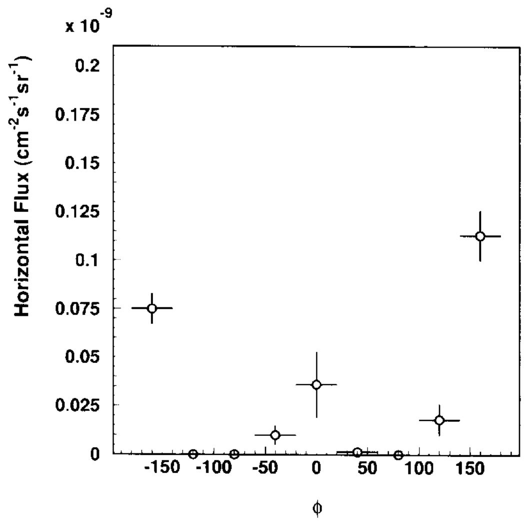


Fig. 8. Horizontal flux at slant depths greater than 8000 hg/cm$^2$ of standard rock at the Gran Sasso Laboratory as a function of the azimuthal angle in the LVD reference system.

greater than 8000 hg/cm$^2$ of standard rock as a function of azimuthal angle. As already suggested [29], this figure indicates that it would be possible, and useful, to set up an experiment with the EASTOP array above the Gran Sasso Laboratory concentrating on the study of horizontal air showers because the EASTOP array has a solid angle acceptance that overlaps the data in Fig. 8. The shape of the data in Fig. 8 reflects the mountain shape in the vicinity of the Gran Sasso Laboratory.

## 7. Summary and conclusions

The mountain topology in the vicinity of the Gran Sasso Laboratory is such that for fixed zenithal angles the LVD detector can explore a wide range of slant depths. We utilize this feature to measure both the intensity at about 90° as a function of slant depth (for slant depths greater than about 14 000 and 20 000 hg/cm$^2$ of standard rock) and the vertical intensity as a function of slant depth.

We find the muon flux is constant for the slant depth range from about 14 000 hg/cm$^2$ to 20 000 hg/cm$^2$. This is direct evidence that the muons at a zenithal angle near 90° that enter LVD and have energy greater than 1 GeV are generated by the interaction of neutrinos in the rock near LVD. We measure the value of this flux near 90°, $I(90°)$ to be

$$I(90°) = (8.3 \pm 2.6) \times 10^{-13}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}.$$

This is the value of the flux that will be measured by any underground detector near 90° provided the slant depth in that direction is greater than 14000 hg/cm$^2$ and the muons have energy greater than 1 GeV. This measured value is in reasonable agreement with the theoretical estimates of this flux. This is the first time a measurement of the flux of muons induced by neutrinos at a zenithal angle of 90° has been reported for slant depths between 14000 and 20000 hg/cm$^2$ of standard rock.

Our measurement of the vertical intensity extends from about 3000 hg/cm$^2$ to about 20000 hg/cm$^2$. The data covers over five decades of vertical intensity. This is the first time a single experiment has reported the fit parameters over this span of vertical intensities. Our fit is in good agreement with the fit of Crouch [2] which is a summary of various experiments.

We compare our measurements of the single muon flux with the reported results of other experiments. We note our measurement is an exclusive study (only events containing single muons are included in our data). The other experiments are inclusive studies (multiple muon events are included in their data). These experiments report their measurement out to about 10000 hg/cm$^2$ of standard rock. Our measurements are in good agreement with these experiments considering the difference in the type of studies.

Using Monte Carlo techniques we have used our vertical intensity data to extract the power index $\gamma_{\pi k}$ for the differential energy spectrum of the pions and kaons in the atmosphere. We find

$$\gamma_{\pi k} = 2.75 \pm 0.03.$$

Finally we have measured the flux of muons incident on LVD at a zenithal angle of 90° integrated over all slant depths greater than 8000 hg/cm$^2$ of standard rock as a function of azimuthal angle.

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