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Atmospheric Neutrino Event Rates: The Expectations

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1 Introduction

Hess discovered the cosmic radiation of extraterrestrial origin (Hess, 1912) by measuring the effects of secondary interactions of cosmic rays in the atmosphere. Over the next 35 years the understanding of the various secondary components developed in close connection with related discoveries in particle physics, as documented by Hillas (1972). Fig. 1 shows the main components of the cosmic radiation in the atmosphere. Because they interact only through the weak interaction, neutrinos were the last secondary component to be measured, even though they are as abundant as muons deep in the atmosphere.

The idea of detecting neutrinos by looking for neutrino-induced upward or horizontal muons was suggested by Markov & Zheleznykh (Markov, 1960). The process is

$$\nu_\mu + N \rightarrow \mu + \text{anything}, \tag{1}$$

where N is a nucleon in the material surrounding the detector. The muon range increases with energy. This extends the effective target volume and makes it possible to see neutrino-induced muons with detectors of moderate size. At about the same time Greisen (1960) described a neutrino detector very much like the current large water Cherenkov detectors, and he estimated the event rate to be expected for interactions of atmospheric neutrinos inside a 3 kilotonne sensitive volume. Two groups (Achar, et al., 1965; Reines et al., 1965) reported the first observations of atmospheric neutrinos with the detection of horizontal muons in detectors so deep that the muons could not have been produced in the atmosphere. These results were among the subjects of an earlier Royal Society Discussion Meeting in 1966 (Menon et al., 1967; Reines, 1967).

Atmospheric neutrinos are of current interest, despite their long history and apparently mundane origin, because of the anomalous flavor ratio observed for neutrino interactions in the large proton decay detectors (Hirata et al., 1992; Becker-Szendy et al., 1992a). The experimental situation is the subject of the preceding paper in these proceedings (Beier & Frank, 1993). The essential point is that, because of their large volume, these detectors can measure interactions of neutrinos inside the detector. They need not depend on the large external target mass provided by the long range of energetic muons produced in charged current

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interactions of muon-type neutrinos. They can therefore study both ν_e and ν_μ interactions. The anomaly is that the observed ratio of events produced by electron neutrinos to those from muon neutrinos is significantly larger than expected.

For both kinds of events the signal can be written as the convolution of neutrino flux, neutrino cross section and detection efficiency,

$$\text{Signal} = \phi_\nu \otimes \sigma_\nu \otimes \epsilon.$$

In the case of events of external origin, the detection efficiency ϵ contains the range of the produced muons as well as the projected effective area of the detector. Figure 2 shows the distribution of energies of the neutrinos that produce three classes of events: (1) interactions of $\nu_\mu + \bar{\nu}_\mu$ inside the detector, (2) neutrino-induced upward muons (zenith angle $> 90°$) that enter the detector and stop (here $E_\mu < 4$ GeV) and (3) upward muons with $E > 4$ GeV.

For most of the interactions inside the detector the neutrino energy is less than 1 GeV. In the large water Cherenkov detectors nearly all the neutrino interactions occur on oxygen nuclei rather than free nucleons. The Fermi Gas Model (FGM) has been used in obtaining the configurations of the neutrino events for studies of detector response and interpretation of the data. The adequacy of this simple model in this context has been questioned from time to time. There are two indications that use of the FGM is not the source of the anomalous flavor ratio. Merenyi et al. (1992) show that data taken on deuterium and neon targets with $E_\nu > 400$ MeV are consistent with what is expected in the Fermi Gas Model for atmospheric neutrinos (Gaisser & O'Connell, 1986). On the theoretical side, Engel et al. (1993) have investigated several nuclear effects beyond the FGM. They find a negligible effect on the predicted ratio of ν_e/ν_μ interactions.

This paper emphasizes the calculation of the flux of atmospheric neutrinos, both in the low energy region relevant to internal events and in the higher energy region important for external events. The subject of neutrino-induced upward muons and their implications for interpretation of the contained event anomaly is also discussed.

2 Neutrino flux

In the early 1960's there were several increasingly detailed calculations of the intensity of atmospheric neutrinos for $E_\nu \geq 1$ GeV (Markov & Zheleznykh, 1961; Zatsepin & Kuzmin, 1962; Cowsik, Pal & Tandon, 1966; Osborne, Said & Wolfendale, 1965). Tam & Young (1970) extended the calculations down to 200 MeV. Some of these calculations inferred the production spectrum of parent pions from the observed muon flux, then used the pion spectrum to derive the neutrino flux. More recent calculations start from the primary cosmic ray spectrum and calculate both muons and neutrinos. In either case, the comparison with measured fluxes of atmospheric muons provides an important check on the calculations.

2.1 Low energy region

Here I will compare four detailed calculations of the low energy neutrino flux with the aim of estimating the uncertainty in the expected neutrino flux. The calculation of Barr, Gaisser & Stanev (1989, hereafter called BGS) began with the work of Gaisser, Stanev, Bludman & Lee (1983). It is a one-dimensional Monte Carlo calculation that starts from the primary spectrum, uses a fit of inclusive cross sections to accelerator data (e.g. T. Eichten et al. 1972)

and assumes all secondaries propagate along the direction of the primary. The calculation is described in detail by Gaisser, Barr & Stanev (1988).

Lee & Koh (1990, LK) use an interaction model related to that of Gaisser et al. (1983, 1988) extended to include transverse momentum of the secondaries. They then make a three-dimensional calculation of the neutrino flux. In a preliminary version of the calculation they state that the result is the same as the one-dimensional calculation for $E_\nu > 200$ MeV. The common origin of the hadronic production model does not guarantee that the results will be the same as BGS above 200 MeV because LK independently treat the primary spectrum and the geomagnetic cutoffs.

The other calculations are completely independent of the first two and of each other. The work of Honda, Kasahara, Hidaka & Midorikawa (1990, HKHM) is a Monte Carlo calculation that includes a detailed treatment of the effect of the geomagnetic field. Cutoffs are calculated for each detector location by propagating antiprotons outward from Earth through a detailed map of the geomagnetic field along a set of initial directions centered on each detector. The calculation of Bugaev & Naumov (1989, BN) is a numerical integration of the cascade equations. All four calculations include the effect of muon polarization on the neutrinos from muon decay, following the remark of Volkova (1988) who emphasized its importance in this context. (The fluxes shown by Bugaev & Naumov (1989) do not include muon polarization, but they have since been corrected for this effect; V.A. Naumov, private communication.)

The Tables 1 and 2 illustrate the differences and similarities among the flux calculations. Table 1 gives the ratio of the neutrino fluxes in three energy intervals compared to the BGS calculation. The biggest discrepancy is between the Bugaev & Naumov calculation and that of BGS, which differ by almost a factor of two in the lowest energy bin. As energy increases, however, the two calculations give similar results. Bugaev, Domogatsky & Naumov (1986) show a compilation of measurements (Bogomolov et al. 1979) of the high altitude (11 to 16 km) intensity of muons with kinetic energy in the range 100 MeV to 1 GeV. Stanev (1993) has compared the muon fluxes from the BGS calculation to the same data. As with the neutrino fluxes, the BGS muon fluxes are significantly higher than those of Bugaev et al. below 1 GeV, and they approach each other as energy increases. The higher muon intensities appear to agree somewhat better with the data, though the experimental uncertainties are large.

The second table is similar to a figure of Honda (1993) in which he compared ratios of neutrinos from the four flux calculations. Here I have tabulated $R_{e/\mu} = (\nu_e + \frac{1}{3}\bar{\nu}_e)/(\nu_\mu + \frac{1}{3}\bar{\nu}_\mu)$ because the cross section for quasi-elastic interactions of antineutrinos is roughly one-third that of the neutrinos in the low energy range relevant for single-ring contained events. The antineutrino/neutrino ratios in Table 2 are $R_\mu = \bar{\nu}_\mu/\nu_\mu$ and $R_e = \bar{\nu}_e/\nu_e$. The results of the comparisons made here can be summarized as follows:

- In the energy range between 0.1 and 1 GeV $R_\mu \approx 1$, as expected from the kinematics of pion and muon decay, which causes the secondary ν_μ from pion decay to have roughly the same energy on average as the tertiary $\bar{\nu}_\mu$ from muon decay.

- $R_e < 1$ as expected from the predominance of positive charge among the fast secondaries (as in the μ^+/μ^- ratio). The exception here is the anomalous value of $R_e \approx 1$ of LK. There are also differences among the other calculations for R_e which are not at present understood.

- $R_{e/\mu} \approx 0.49 \pm 0.01$.

Although the fluxes at low energy differ by as much as 50%, the ν_e/ν_μ ratio is the same within 5% in the four calculations. This is a consequence of the fact that the main uncertainties in the calculation cancel to first order when the ratio is taken. Second order effects remain. They include

- The primary energy spectrum. A softer spectrum will give fewer high energy neutrinos, which can affect the measured ratio in two ways, first because the threshold for detection of muons is higher than for electrons and second because the relative weights of ν_μ and ν_e depend on the spectral slope.
- The primary composition. The ratio of neutrons to protons affects the ratio $\nu_e/\bar{\nu}_e \sim \mu^+/\mu^-$ because of the tendency of protons to produce more fast π^+ than π^- and vice versa for neutrons.
- The treatment of the geomagnetic cutoffs. Because nuclei of the same energy per nucleon have twice the magnetic rigidity of free protons, increasing the cutoff rigidity will enhance the contribution of neutrons to the neutrino flux.

Various comparisons among the different calculations have been made in an attempt to identify specific sources of the differences in the expected neutrino fluxes. This effort is in progress at present and was discussed most recently at a workshop at Louisiana State University. The structure of the BGS calculation allows one to test the effect of changing various elements of the calculation one by one. The last step of the BGS calculation is to combine the neutrino yields with the primary spectrum weighted with the geomagnetic cutoffs (separately for free protons and bound nucleons). For example, when we substitute the HKHM cutoffs at Kamioka for those used by BGS, the neutrino fluxes between 0.4 and 1 GeV decrease by about 10%. Use of the HKHM primary spectrum instead of the BGS primary spectrum has an opposite effect of about the same magnitude. Replacing the BGS primary spectrum with that of BN (including an underestimate by BN of the effective number of interacting nucleons from a primary nucleus) decreases the neutrino flux by only about 5% below 1 GeV and increases it by a similar amount above 2 GeV. This is not sufficient to account for the strong suppression of the neutrino flux at low energy in the BN calculation. By a process of elimination, we conjecture that the differences among the models arise primarily from differences in the representation of pion production in interactions of nucleons in the atmosphere.

Of primary interest for the contained event anomaly is the ratio $R_{e/\mu}$, which evidently remains stable under changes in primary spectrum, cutoffs and interaction model. The factor in the calculation that most directly affects this ratio is the treatment of muon energy loss and decay, since electron neutrinos in the energy range above $\sim$ 100 MeV up to $\sim$ 2 GeV come almost entirely from decay in flight of muons. The physics here is completely well-known and unambiguous, but it requires care to implement it correctly in a Monte Carlo program or numerical calculation. In this regard, the fact that several independent calculations give very similar results for $R_{e/\mu}$ is an important check. For the same reason, precision measurements of the intensity and energy spectrum of $\sim$GeV muons as a function of atmospheric depth are important.

2.2 High energy region

Three groups have measured the flux of neutrino-induced upward muons with large detectors (Baksan: Boliev et al., 1991, 1993; Kamiokande: Mori et al, 1991; and IMB: Becker-Szendy et al., 1992b). Results will be forthcoming soon from the full MACRO detector (Ronga, 1993). Three calculations of the flux of ν_μ have been used in interpreting these experiments, Volkova (1980), Mitsui (Mitsui et al. 1986) and Butkevich (Butkevich et al. 1988). All of these calculations cover the energy range $E_\nu > 1$ GeV. For comparison I will also discuss an extension of the BGS calculation to high energy (Agrawal et al., 1993). A principal motivation of this new calculation is to have a single atmospheric neutrino flux for both low and high energy regions.

A curious feature of the high energy spectrum of muon neutrinos is the increasing importance of kaons as the parents of these neutrinos. Osborne et al. (1965) and Cowsik et al. (1966) noted that in certain circumstances charged kaons indeed become the dominant source of muon neutrinos at high energy. A consequence of this fact is the importance of the inclusive cross section for kaon production for the flux of ν_μ. One needs the inclusive cross section on nuclear targets for energies of incident nucleons up to several TeV beam energy in the lab.

To a very good approximation, the flux of neutrinos from $\pi^\pm \to \mu\nu_\mu$ and from $K^\pm \to \mu\nu_\mu$ is proportional to $Z_{p\pi^\pm}$ and $Z_{pK^\pm}$ respectively, where

$$Z_{p\pi} = \int_0^1 x^\gamma \frac{\mathrm{d}n_{p\pi}}{\mathrm{d}x}\mathrm{d}x.$$

Here x is the fractional momentum of the produced pion and $\gamma \approx 1.7$ is the integral spectral index of the primary spectrum. The ratio $R_{K/\pi} = Z_{pK^\pm} \,/\, Z_{p\pi^\pm}$ is the appropriate K/pi ratio to characterize neutrino production. Accelerator data for pp collisions give values between 0.10 and 0.13. There is less information on nuclear targets, where the coverage of phase space is not as complete as for proton targets. Values of $R_{K/\pi}$ ranging from 0.10 to 0.15 have been used in the various calculations. For example, Perkins (1993) uses $R_{K/\pi} = 0.10$, Mitsui et al. (Minorikawa & Mitsui, 1984) 0.13 and Volkova 0.15 (Volkova et al., 1979). The extension of BGS to high energy (Agrawal et al.) also has a relatively high value of $R_{K/\pi}$.

This source of uncertainty is of particular importance because it cannot be easily removed by comparison to high energy muon fluxes. This is because kaons are relatively much more important in the neutrino spectrum than in the muon spectrum. Pions are the dominant source of muons at high energy as well as low, so the calculated muon spectrum is relatively insensitive to $R_{K/\pi}$.

Perkins (1993) has made an interesting comparison between his estimate of the neutrino flux and several others. Figure 3-a is a similar plot, which shows five calculations of the neutrino flux. Note that plotting $E^2 \times dN/d\ln E$ – as Perkins has done – gives a display that reflects the importance of the neutrinos for producing a muon signal. Roughly speaking, one power of E comes from the rising charged current cross section (up to $\sim$ 3 TeV) and the other from the increasing muon range (up to $\sim$ 500 GeV). Figure 3-b compares the corresponding vertical muon fluxes with a compilation of the data. Note the relatively large spread in the neutrino fluxes as compared to the muon spectra.

3 Neutrino-induced muons

The large differences among the various neutrino flux calculations in the high energy region limit the certainty with which the neutrino-induced upward muon flux can be calculated. This uncertainty becomes important when one wants to use the measured rate of upward muons to constrain explanations of the contained event puzzle in terms of neutrinos oscillations.

For example, the Kamiokande group (Hirata et al., 1992) give a preferred "allowed" set of values for interpretation of their anomalous neutrino flavor ratio for contained events in terms of oscillations in the $\nu_\mu \rightarrow \nu_\tau$ sector: $\delta m^2 = 8 \times 10^{-3}$ eV^2 and $\sin^2 2\theta \approx 0.87$. This value of δm^2 gives the first node in the oscillation probability at $E_\nu \approx 65$ GeV for pathlength $L \approx 10^4$ km:

$$P_{\nu_\mu \rightarrow \nu_\tau} = \sin^2 2\theta \sin^2(1.27\delta m^2 \frac{L_{km}}{E_{\mathrm{GeV}}}).$$

One would therefore expect a significant reduction of the observed flux of upward, throughgoing muons relative to the expectation in the absence of oscillations.

Interpretations of the measurements (Mori et al., 1991; Becker-Szendy et al., 1992b), while noting that the conclusions depend on the assumptions, have focussed on a particular combination of flux calculation and neutrino cross section; namely, the Volkova (1980) flux and cross sections computed with the EHLQ2 structure functions (E. Eichten et al., 1984). As is apparent from Fig. 3-a, the Volkova flux is rather low in the energy range important for neutrino-induced, upward muons. Moreover, the EHLQ2 parametrization of the structure functions underestimates the neutrino cross section by about 12%. (Frati et al., 1993).

In a recent paper, we (Frati et al., 1993) have systematically investigated the sensitivity of the expected rate of upward muons to the input assumptions. We calculated the expected rate of upward muons in ten equal bins of zenith angle, $-1 < \cos\theta < 0$ and compared the results to the observations of the Kamiokande group (Mori et al., 1991). We defined an upward throughgoing muon exactly in accord with the experimental definition (Oyama, 1989). Table 3 from Frati et al. (1993) summarizes the results for two combinations of flux and cross section and various assumed oscillation parameters for $\nu_\mu \leftrightarrow \nu_\tau$. The two sets of flux and cross section are:

1. Volkova plus EHLQ2
2. Bartol (Agrawal et al. 1993) plus Owens (Owens, 1991).

When we use assumption (1) compared in detail to Kamiokande measurements of upward muons, the assumption of no oscillations gives a good fit. In addition, when we use this calculation of the expected rate in 2π sr to determine an excluded region in the neutrino-oscillation space, we find the same excluded region found by IMB (Becker-Szendy et al., 1992b) from their data with the same input assumptions. This suggests consistency of the IMB and Kamiokande data sets. With assumption (2), however, we find a better fit with a set of oscillation parameters that leads to significant ($\approx 15\%$) reduction in the predicted rate of upward muons.

The same is apparently not true for the Baksan data. Mikheyev (private communication and Boliev et al., 1993) has used the Butkevich et al. neutrino flux and a renormalized cross section, essentially equivalent to Owens (1991), and still finds the Kamiokande allowed region of oscillation parameters to be largely excluded.

4 Conclusions

Good progress is being made in understanding differences among the neutrino flux calculations in the low energy region. The Bugaev & Naumov calculation produces an anomalously flat spectrum at low energy as compared to the other calculations. The Lee & Koh calculation has an unphysical value of unity for the $\nu_e/\bar{\nu}_e$ ratio. Sources of these and other differences are under active investigation and should be resolved in the coming months.

Comparison of the muon spectrum from the BGS calculation to new measurements (Circella et al., 1993) of ~GeV muons at high altitude (especially 10 to 20 km, in the peak of the neutrino production region) are quite promising. This and other new measurements of muon spectra at high altitude should make it possible to reduce the uncertainty in the absolute normalization of the neutrino flux calculation in the ~GeV range from ±25% to ±10%.

In a quite plausible scenario (neutrino flux similar to Agrawal et al. (1993) or Butkevich et al. (1989) and renormalized neutrino cross section) the Kamiokande measurement of upward, throughgoing muons is quite consistent with a $\nu_\mu \rightarrow \nu_\tau$ interpretation of their contained event flavor anomaly. There is indirect evidence (described above) that the IMB data on throughgoing muons is consistent with the Kamiokande data. This is apparently not the case with the Baksan measurement ($-1.0 < \cos\theta < -0.6$) which large excludes this oscillation scenario, even with the higher flux and cross section. New data from MACRO should be helpful in clarifying the situation.

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Table 1. Calculated neutrino fluxes at Kamiokande normalized to BGS

E_ν	$\nu_\mu + \bar{\nu}_\mu$			$\nu_e + \bar{\nu}_e$		
(GeV)	HKHM	LK	BN	HKHM	LK	BN
0.4 – 1	0.90	0.79	0.63	0.87	0.79	0.62
1 – 2	0.95	0.80	0.79	0.91	0.81	0.74
2 – 3	1.04	0.81	0.95	0.97	0.83	0.87

Table 2. Neutrino ratios $0.4 < E_\nu < 1$ GeV.

Ref.	R_μ	R_e	$R_{e/\mu}$
BGS	0.99	0.89	0.49
HKHM	0.99	0.84	0.48
LK	1.00	0.99	0.48
BN	0.98	0.76	0.50

Table 3. Fits to Kamiokande upward muons (Frati et al., 1993).

Oscillation	parameters	χ^2 for	10 bins
$\sin^2 2\theta$	δm^2	(1)	(2)
0.0	0.0	8.7	18.2
0.5	0.01	14.6	10.3
0.8	0.0046	19.1	10.0
0.5	0.10	19.5	10.9

FIGURE CAPTIONS

Figure 1. Vertical fluxes of cosmic rays in the atmosphere. The curves show the integral intensities of particles with energies greater than 1 GeV.

Figure 2. Distribution of energies of muon neutrinos (plus antineutrinos) that give rise to contained events, upward muons with $E_\mu < 4$ GeV and upward muons with $E_\mu > 4$ GeV. The average over solid angle is taken.

Figure 3. a) Five neutrino flux calculations averaged over solid angle. Solid: Agrawal et al. (1993); dotted: Butkevich et al. (1988); points: Mitsui et al. (1986); dashed: Volkova (1980); dot-dashed: Perkins (1993).

b) Corresponding calculations of vertical muon flux at sea level (except Mitsui et al.) compared to a compilation of data. Kiel data from 1 to 600 GeV (Allkofer et al., 1971): diamonds; Durham data from 20 to 400 GeV (Ayre et al., 1975): squares; Durham data above 800 GeV (Thompson et al., 1977): points; Nottingham data (Rastin, 1984): crosses; Houston data (Greene et al., 1979): small square with X superimposed; underground data with $E_\mu > 3$ TeV (Ivanenko et al., 1985).

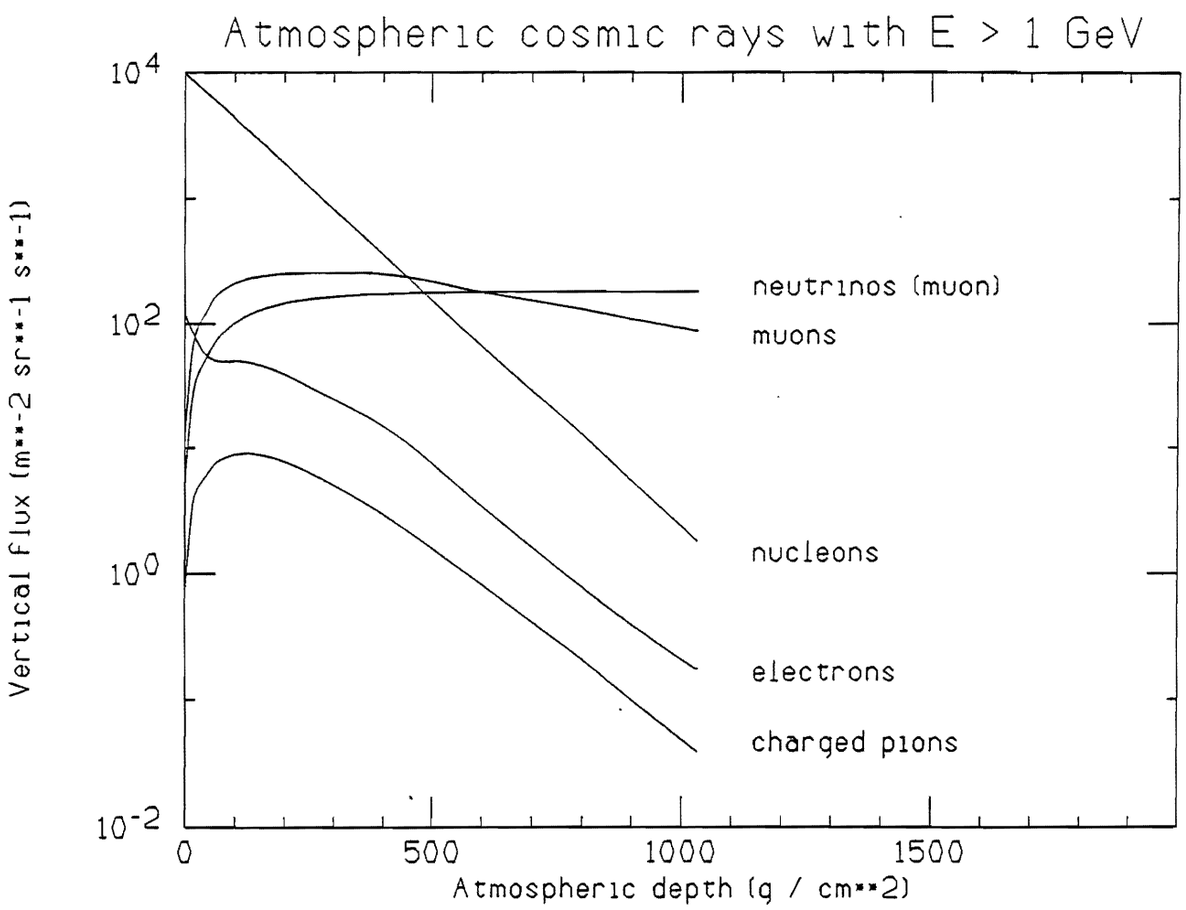
Atmospheric cosmic rays with E > 1 GeV
Vertical flux (m**-2 sr**-1 s**-1)
10^4
10^2
10^0
10^-2
0
500
1000
1500
Atmospheric depth (g / cm**2)
neutrinos (muon)
muons
nucleons
electrons
charged pions

Fig. 1

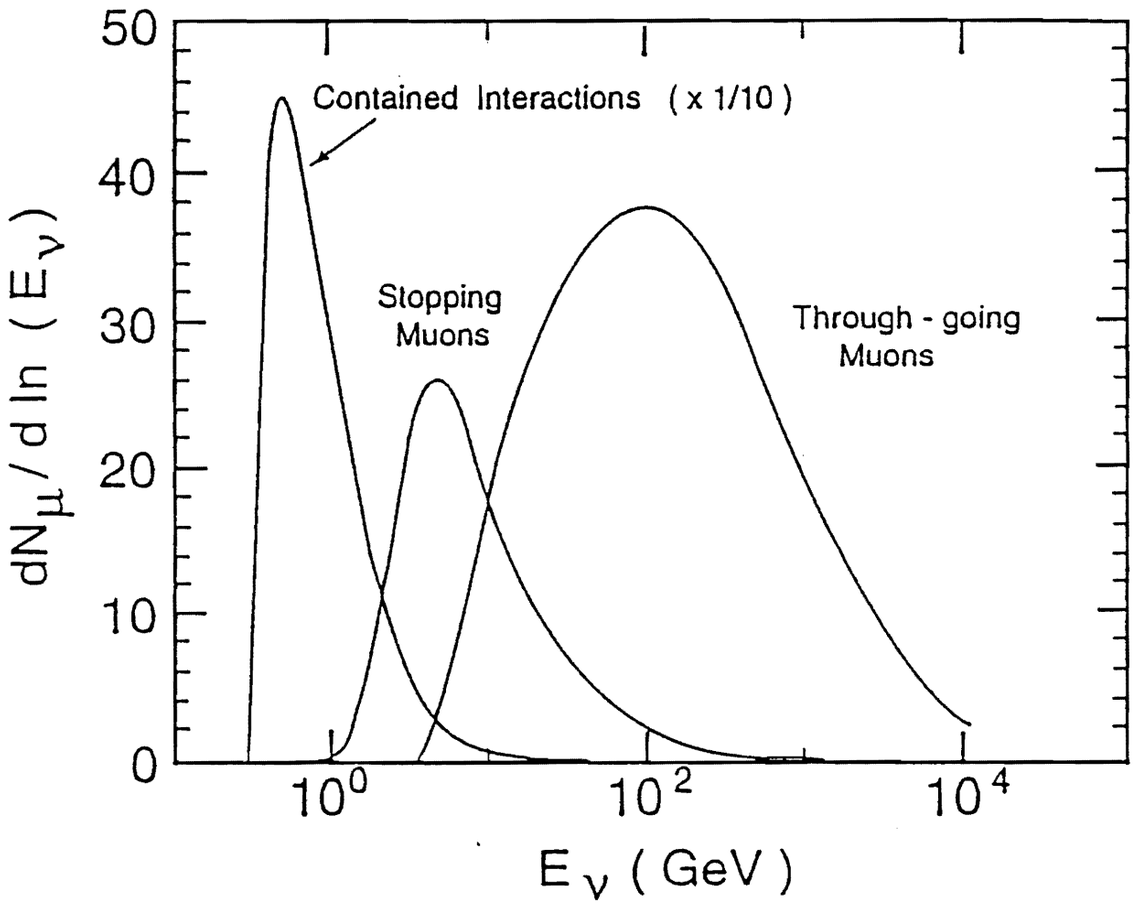
50
40
30
20
10
0
Contained Interactions (x 1/10)
Stopping Muons
Through - going Muons
$dN_\mu / d\ln(E_\nu)$
10^0
10^2
10^4
E_ν (GeV)

Fig. 2

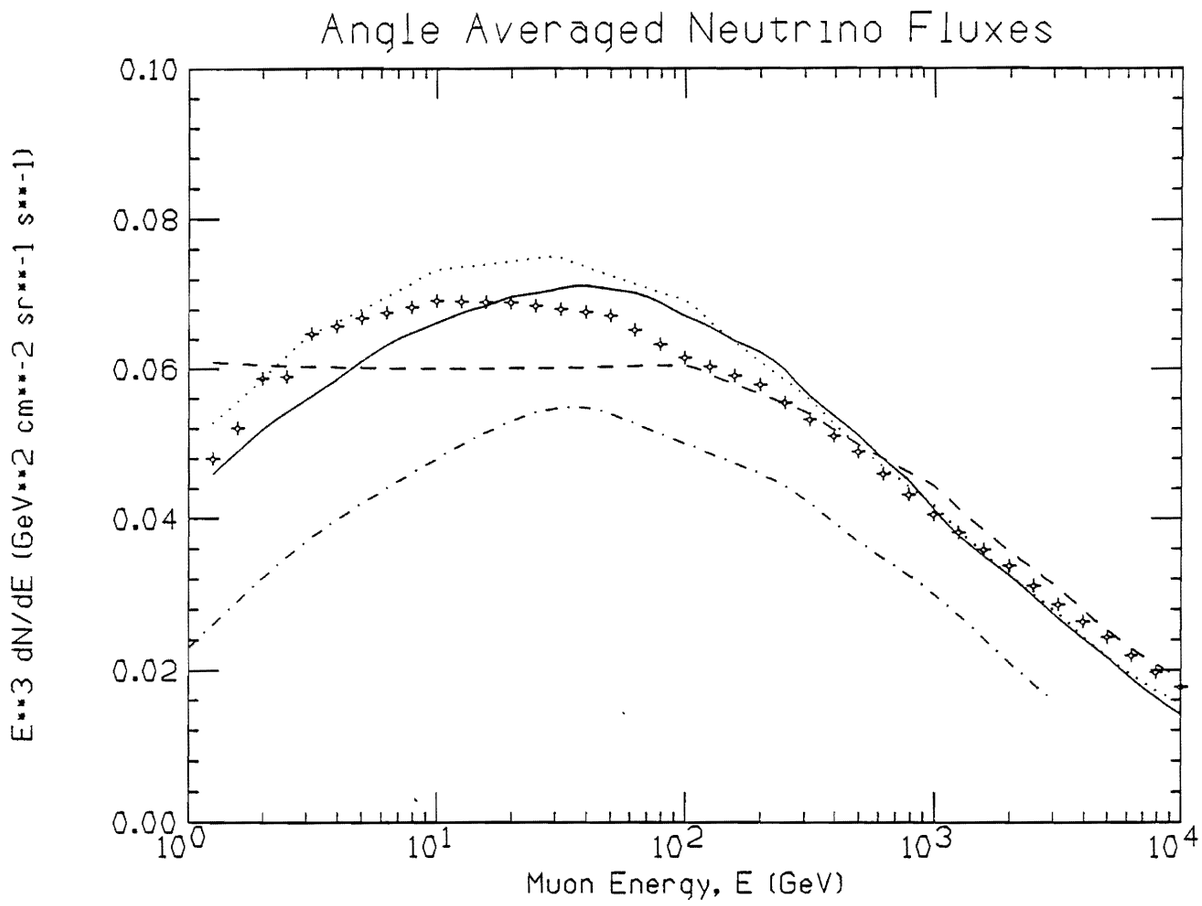
Angle Averaged Neutrino Fluxes
0.10
0.08
0.06
0.04
0.02
0.00
E**3 dN/dE (GeV**2 cm**-2 sr**-1 s**-1)
10^0
10^1
10^2
10^3
10^4
Muon Energy, E (GeV)

Fig. 3a

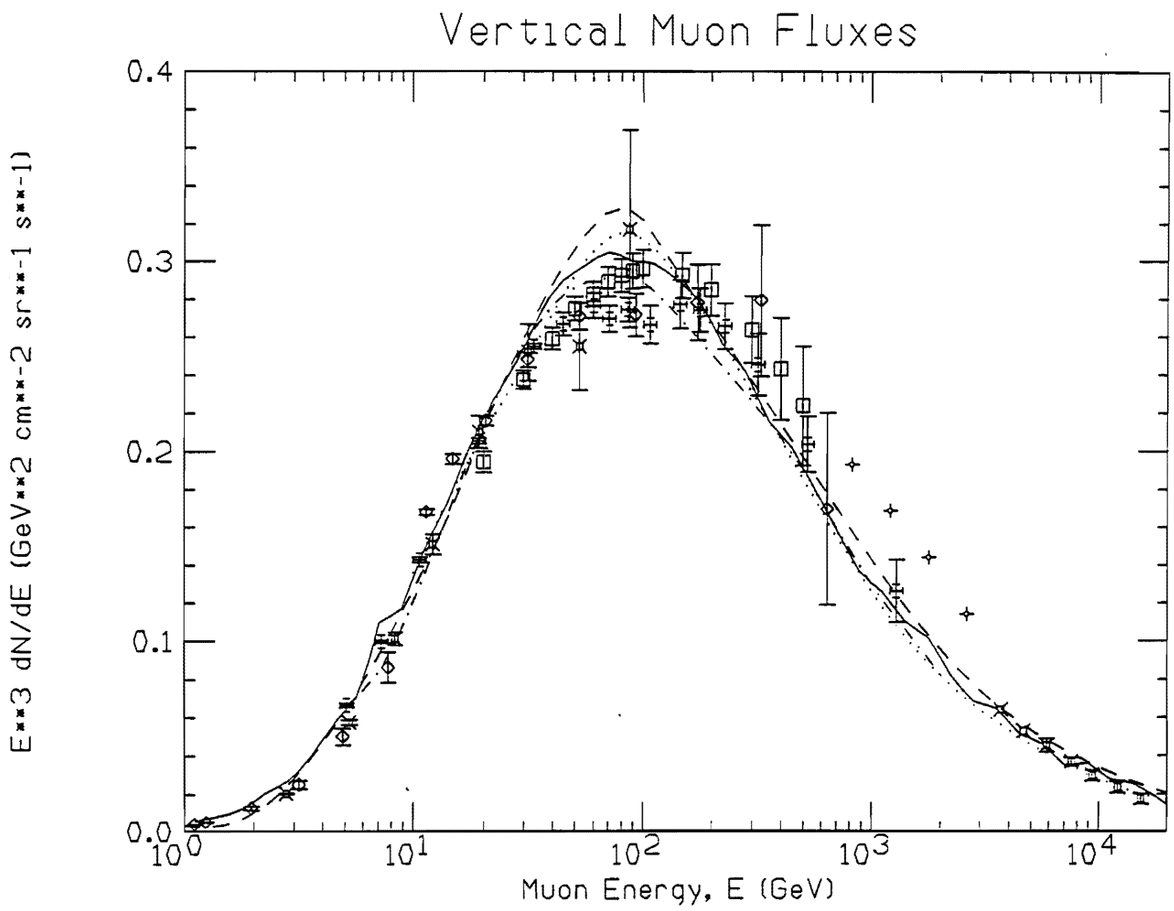
Vertical Muon Fluxes
0.4
0.3
0.2
0.1
0.0
E**3 dN/dE (GeV**2 cm**-2 sr**-1 s**-1)
10^0
10^1
10^2
10^3
10^4
Muon Energy, E (GeV)

Fig. 3 b