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Formation of the atmospheric muon spectrum

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Abstract

We discuss the calculation of the flux of muons near the vertical as a function of atmospheric depth. In the past few years, GeV muons have been measured at float altitude and during ascent with several balloon–borne magnetic spectrometers. We find that the evolution of the muon spectrum through the atmosphere is significantly influenced by three-dimensional effects in the presence of the geomagnetic field. The effects on the atmospheric neutrino flux should be much smaller.

1 Introduction

Calculations that have been used for the analysis of the fluxes of atmospheric muons and neutrinos have been performed in one dimension (1D), assuming that all atmospheric leptons follow the direction of the primary cosmic ray particle. Recent muon measurements (Circella et al. 1999; Coutu et al. 1999; Carlson et al. 1999; Krizmanic et al. 1999; S. Orito (BESS, *private communication*)) have shown substantial deviations from the one dimensional predictions, especially in the momentum range below 1 GeV/c. There are two general features of the difference between calculations and measurements that are qualitatively the same for all experimental sets:

1. The sub-GeV muon spectrum measured during ascent is flatter than the predictions.
2. The agreement between predictions and measurements is better for the highest (floating) altitude, usually 4 – 5 g/cm^2 and for ground level, while the differences are significant for the intermediate altitudes.

It is obvious that 1D calculations, although they predict quatitatively well all main features of the atmospheric muons, cannot be exact. Charged pions, that are predominantly the parents of the detected GeV muons, are generated with an average transverse momentum of 300 MeV/c, which corresponds a Lab angle of 18° for 1 GeV pion. Thus cosmic rays that interact in the atmosphere at angles different from the vertical can produce vertical muons. The non–vertical angle of the primary cosmic rays has a dual effect: at high altitudes, where the vertical atmospheric depth X is much less than the proton interaction length λ_{p-air} it increases the muon yield as $\cos^{-1}\theta$. At the same time muons have longer pathlength to the observation level, that increases the muon energy loss and decay probability. For $X \gg \lambda_{p-air}$ only the muon energy loss and decay will be important.

There are, however, many additional effects that also affect the formation of the muon fluxes in the atmosphere. To gain understanding of such effects, we performed three dimensional Montecarlo studies (3D) of 0.2 to 10 GeV/c muons reaching different atmospheric depths.

2 Three dimensional calculation of the muon yields

Different versions of magnetic spectrometers that have measured atmospheric muons have momentum dependent opening angle that varies between 15 and 25°. To mimic the response of such detectors to primary cosmic rays hitting the atmosphere at different angles we performed the following Montecarlo experiment: the angle of the primary cosmic ray is sampled uniformly between $\cos\theta$ = [0.85, 1]. The atmospheric cascade is followed in 3D. A new 3D version of the event generator TARGET is used in the calculation. All muons that reach a given observation level with $\cos\theta_\mu \geq$ 0.9 are recorded as a function of the zenith angle of the primary nucleon.

Fig. 1 shows the contrinbution of primary cosmic ray nucleons interacting in the atmosphere at different zenith angles to the muon reaching atmospheric depths of 5, 100 and 1000 g/cm^2 with $\cos\theta \geq$ 0.90. The

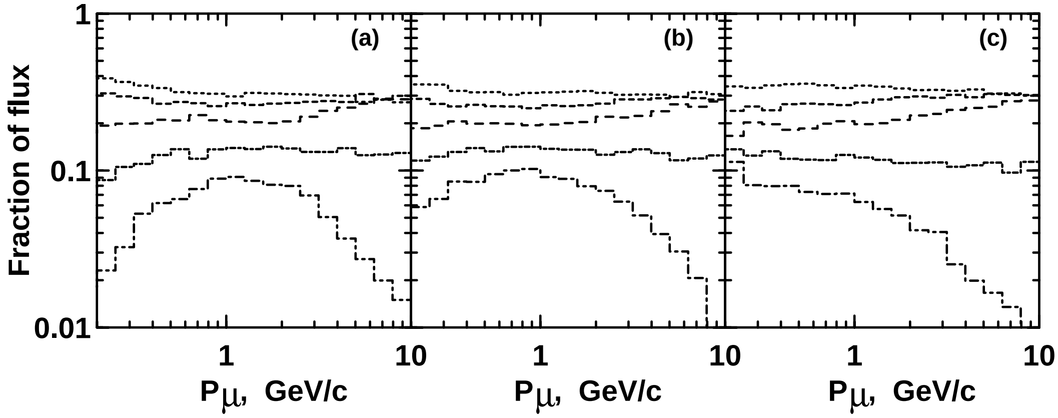

Figure 1: Relative contribution of primary cosmic ray nucleons interacting in the atmosphere at different zenith angles to the muon flux with $\cos\theta_\mu \geq 0.9$ at depths of 5 (a), 100 (b) and 1000 (c) g/cm^2. Cosmic rays interacting with $\cos\theta$ from 1.00 to 0.97 are shown with dotted line. Short dashes: 0.97–0.94, long dashes: 0.94–0.91, dot–short dash: 0.91–0.88, dot–long dash: 0.88–0.85.

five histograms from top to bottom are for $\cos\theta$ 1.00 – 0.97, 0.97 – 0.94, etc. In 1D calculation the three top histograms and 1/3 of the fourth one would give the total muon flux. In the 3D cascade there is a slightly higher contribution from the fourth $\cos\theta$ bin plus a contribution from the fifth one, which is totally out of the opening angle of the detector.

It is instructive to follow the different contributions as a function of the muon momentum. At 5 g/cm^2 and muon momenta below $\sim$0.5 GeV/c the contribution decreases with the zenith angle of the primary nucleon. The decay length for 0.2 GeV/c muons is $\sim$1.2 km, which corresponds to vertical depth of about 1 g/cm^2 at that altitude. A small change in the muon pathlength thus affects drastically the muon decay probability. At momenta above 1 GeV/c the top four bins contribute as expected in 1D treatment, while there is a strong decrease of the contribution of the most inclined cosmic rays. This is simply a geometric effect, because the angle of $\sim$10 GeV pions is much smaller than that of low energy ones.

The relative contribution to the muon flux for the three most vertical hystograms does not change much with the atmospheric depth. One could see more clearly the 'decay effect' on the higher momentum muons. On the other hand the contribution of the highest angular bin to the low energy muon flux grows with atmospheric depth and exceeds 10% at sea level. This must be related to the fact that muons are generated deeper in the atmosphere, after several nuleon interactions, when the probability for creation of pions with large zenith angle increases.

Fig. 1 shows that within 30% or so the muon flux in the atmosphere could be represented by a 1D calculation after accounting for the opening angle of the detectors. More exact calculations have to be performed in 3D. A valid comparison to experimental data can only be made if the experimental efficiency as a function of muon momentum and of zenith angle is well understood and included in the calculation. On the other hand, the measured angular distribution of atmospheric muons at different altitudes could be used for tunning of the muon and neutrino Montecarlo codes. Note that the geomagnetic effects will emphasize some of the 3D effects as the muons move on curved tracks, that increase their pathlengths and correspondingly the decay probability.

3 Geomagnetic effects on the μ^+/μ^- ratio

To estimate the influence of the geomagnetic effects on the μ^+/μ^- ratio we did the following: from a location with low geomagnetic latitude (Kamiokande) we backtracked muons with different momenta and production altitude, calculated in advance with 1D Montecarlo. The muon angle on the ground was sampled uniformly in solid angle up to maximum zenith angle of 25°.

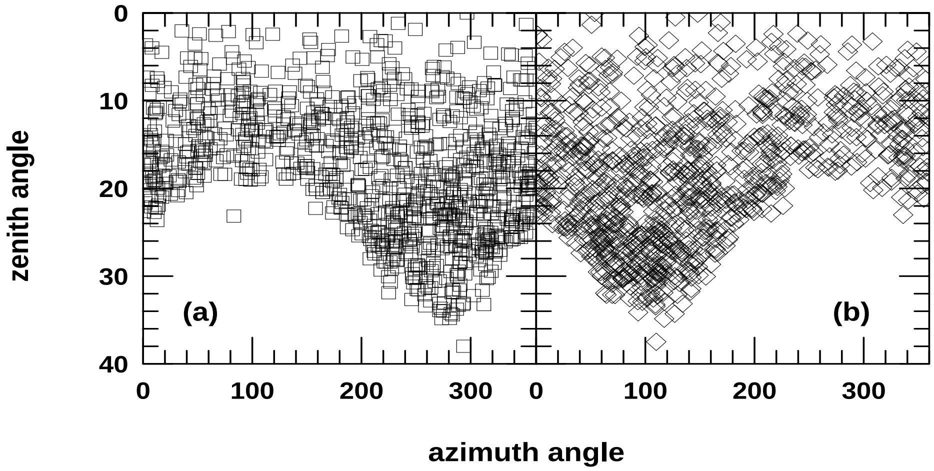

Figure 2: The final direction of positive (a) and negative (b) muons with momenta between 0.2 and 0.5 GeV/c backtracked from sea level to their generation point in the geomagnetic field at the location of Kamiokande. Azimuthal angle of 0° points at North and 90° is West.

Fig. 2 shows the muon direction at production for positive and negative muons. Because of the East–West effect μ^+ come predominantly from East, while μ^- come from the West. The geomagnetic cutoffs in these two directions are significantly different. We mapped the directions of the muons at production and constructed separate cutoff distributions for the parents of the positive and of the negative muons. We then calculated the muon fluxes and the μ^+/μ^- ratio.

Fig. 3 shows the μ^+/μ^- ratio at sea level for three different assumptions for the geomagnetic cutoffs: no cutoff, the vertical cutoff at Kamioka, and separate cutoffs for μ^+ and μ^- as described above. In the absence of geomagnetic cutoffs the sea level muon charge ratio increases form a minimum value of about 1.2 to about 1.25. The reason for the low charge ratio at muon momenta of 0.2 – 0.3 is that many of the parent pions are generated in the central region of the interactions which is not affected by the charge of the incident nucleon. The picture is very different at high altitude, where the charge ratio has a maximum at low muon momenta.

The use of the vertical cutoff depresses the charge ratio by a large amount because of the increased importance of He and heavier nuclei in the relevant energy range as well as the high geomagnetic cutoff that emphasises the central region of the interactions. Finally, accounting for the East–West effect depresses the charge ratio for the lowest energy bit to about 1. Note that at high altitude, where in the absence of geomag-

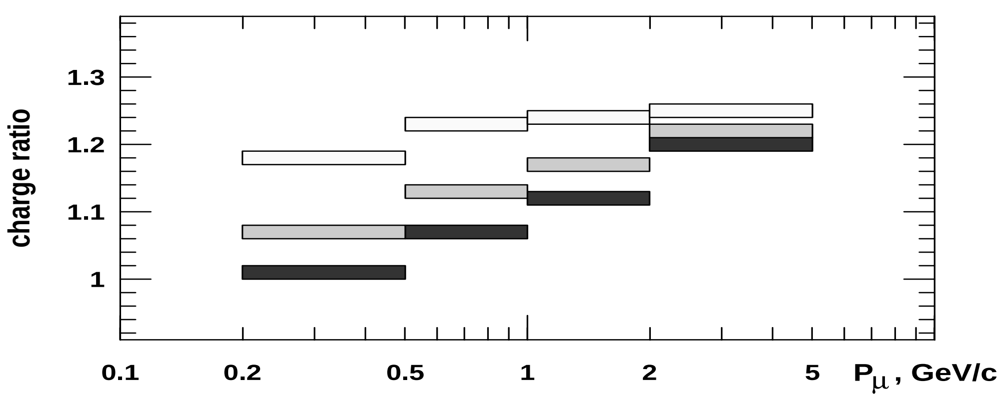

Figure 3: Muon charge ratio at sea level: a) no geomagnetic effects – boxes; b) Kamioka vertical cutoffs – light shadowing; c) with East–West effect – heavy shadowing.

netic cutoff the charge ratio may reach (or even exceed 1.4) its depression by the East–West effect will be relatively stronger.

4 Conclusions

A correct description of the atmospheric flux can be made only with a 3D Montecarlo calculation including the geomagnetic effects at the location of the experiment. 3D calculations follow more precisely the muon trajectories and generally increase their pathlengths to reach a given observation level. This increases the muon decay probability and changes the shape of the muon momentum spectrum, especially below 1 GeV/c. Although we do not present specific flux calculations here, our preliminary 3D estimates show flatter muon spectra that are in a better agreement with data. Comparisons with experimental data have to accout for the detector efficiency as a function of angle.

Since the changes in the atmospheric muon flux stem from muon decay, we believe that the corresponding changes in the atmospheric neutrino flux are minor: muons may not reach certain observation level because thay have already decayed and produced neutrinos. 3D effects will lead to second order changes in the neutrino angular and energy distributions with a possible excess of low energy neutrinos in horizonthal direction, as suggested by G. Battistoni and P. Lipari (*private communication*).

The East–West effect changes the muon charge ratio at sites with low geomagnetic latitude. Integrated over the whole surface of the Earth this effect will be somewhat smaller but still noticeable. The relative suppression of the μ^+ flux will lead to a decrease in the predicted $\nu_e/\bar{\nu}_e$ ratio. Since $\sigma_{\nu_e N}$ is higher than $\sigma_{\bar{\nu}_e N}$ this will lead to a decrease in the calculated ratio of electron–like to muon–like events, and effect opposite to that needed to account for the atmospheric neutrino anomaly.

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