Proceedings of ICRC 2001: 1029 © Copernicus Gesellschaft 2001

ICRC 2001

The flux of atmospheric muons

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Abstract. We present the results of a 3D calculation of the flux of atmospheric muons using the new updated version of the hadronic interaction code TARGET 0.1. We compare with a 1D calculation performed with the same interaction model and with a set of experimental data. We discuss the differences between the two calculations and the consequences of the muon deflection in the geomagnetic field and of the use of different models for the primary cosmic ray flux.

1 Introduction

With the increasing evidence for oscillations of the atmospheric neutrinos (Fukuda *et al.*, 1998) interest to the results of the measurements of the cosmic ray flux and the muon fluxes in the atmosphere has greatly increased. Atmospheric muons and neutrinos have very similar physical origin - the meson decay chain in atmospheric showers - and it has become common wisdom that cascade calculations that do not reproduce in detail the measurements of atmospheric muons cannot predict reliably the atmospheric neutrino flux and thus help determine of the neutrino oscillation parameters more precisely.

We present calculations with the same interaction model (TARGET 2.1 (Engel *et al.*, 2001)) in 1D and 3D codes and discuss the differences introduced by the 3D geometry. We then perform the 3D calculation with two models of the primary cosmic ray spectrum and analyze the differences introduced by the used cosmic ray spectrum. Finally, we introduce muon deflection in the geomagnetic field and again compare the resulting muon spectra.

Our aim in this paper is not that much to fit perfectly a measurement of the muon spectra and charge ratio at different atmospheric depths, but rather to determine the influence of different inputs and cascade treatment for the correct calculation of the atmospheric muons.

2 CAPRICE 94 cosmic ray flux and atmospheric muon measurement

As a starting point we use the 1994 measurements of the atmospheric muon spectra by the CAPRICE experiment (Boezio *et al.*, 2000). To avoid the need for correction of the primary cosmic ray spectra for the solar modulation, and the related to them uncertainties, we use the H and He spectra measured during the same flight as reported by Boezio *et al.* (1999a). We do not account for the contribution of cosmic ray nuclei heavier than He, which would have increased the all nucleon flux by 5 to 10%. Figs. 1 and 2 show our calculations and the experimental data on μ^+ and μ^- at six representative atmospheric depths: at very high altitudes corresponding to depths of 3.9 and 25. g/cm^2, around shower maximum (104 and 218 g/cm^2), at high mountain altitudes (470 g/cm^2) and at sea level (1000 g/cm^2). The measurements were made at Lynn Lake in northern Canada and there is no effect the geomagnetic cutoff for protons of kinetic energy above 0.3 GeV in a wide angular range. In the 3D calculation (shown here with a dashed line) we inject primary cosmic rays within a cone of opening angle 60° and collect all muons that reach the observation level with $\cos\theta > 0.98$. The 3D calculations only collects muons of momentum up to 10 GeV/c, while the 1D calculation (histogram) continues to higher energy.

The comparison between the two calculations shows several interesting and not entirely unexpected features. At the ‘float’ altitude of 3.9 g/cm^2 the two calculations coincide with each other within the statistical error of the calculations. They are, however, about 20% lower than the experimental data in the 1 GeV/c range. With increasing atmospheric depth the ratio between data and calculation decreases, although the 1D version overpredicts below 1 GeV/c as already noted by Circella *et al.* (1997). The 3D treatment decreases somewhat the predicted flux below 1 GeV/c, which is still higher than the measured one, quite significantly at mountain level. At sea level, where the muon fluxes were measured on the ground with very high precision, the 3D calculation represents very well the shape of the muon energy spectra,

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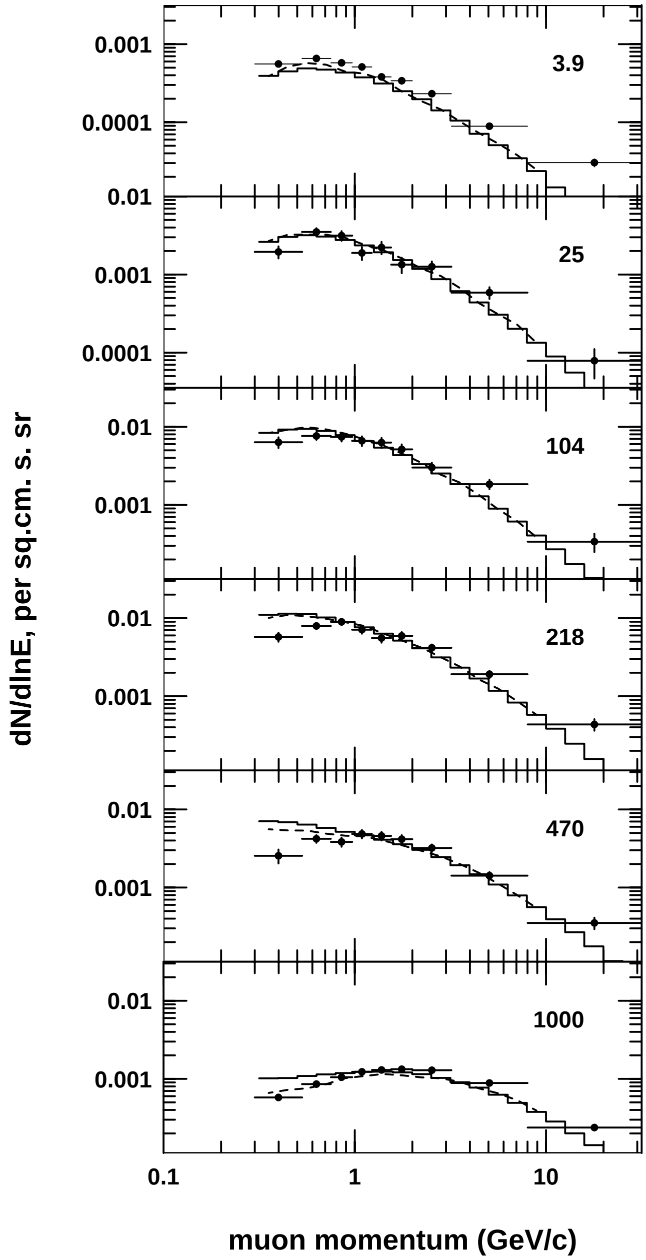

Fig. 1. Dots show the experimental results, the histograms - 1D calculation, and the dashed line - 3D calculation of the spectra of vertical μ^- at different atmospheric depths.

but is somewhat lower than the measured μ^- flux. At all altitudes the current calculation is below the measurements above 3 GeV/c, which could be easily understood in terms of the CAPRICE 94 H and He spectra, that are fit with very steep rigidity power laws. Although this is a totally new calculation, the results are not dissimilar to the comparison with our prediction presented in (Boezio *et al.*, 1999b), where the agreement at ‘float’ and at ground level was better than at intermediate atmospheric depths.

As previously noted, we inject primary cosmic nucleons isotropically in a very wide cone extending to $\cos\theta$ of 0.5. This is needed to collect all primary nucleons, whose interactions contribute to the flux of muons below 1 GeV/c, especially at ‘float’ altitude. For such muons, primary nucleons hitting the atmosphere with $\cos\theta$ bigger than 0.95 contribute only about 40% of the measured flux. The region of $\cos\theta < 0.60$ still contributes about 3%. Since our 3D and 1D treatment give almost the same results for the ‘float’ altitude, there is obviously a compensation between higher muon production (due to the increased thickness of the atmosphere) and higher muon decay rate, as suggested by Stanev *et al.* (1999). For muons of momentum above 3.16 GeV/c only almost vertical showers contribute 99.8%, which explains the 1D/3D agreement in this momentum range.

Inclined showers have only slightly lower contribution at sea level - about 50% below 1 GeV/c. At higher muon momenta the almost vertical showers give from 80% (1 - 3.16 GeV/c) to 100% above 3.16 GeV/c.

The 3D calculation also revealed interesting differences between the production characteristics of positive and negative muons, shown in Table 1.

Table 1. Differences between the production height and primary nucleon energy of negative and positive muons that reach sea level.

momentum, GeV/c	0.316 - 1		1 - 3.16		3.16 - 10.	
charge	μ^+	μ^-	μ^+	μ^-	μ^+	μ^-
<height>, km	10.1	8.6	14.0	13.0	16.2	15.0
$< E_0 >$, GeV	59.	70.	91.	116.	156.	196.

The numbers in Table 1 are clearly related to the properties of the hadronic interaction model. The fastest pions in proton-air interactions are most likely positive, which explains the lower primary energy and higher altitude for μ^+. These numbers will change for a different interaction model, as well as with use of a different primary cosmic ray flux.

The large contribution to the muon fluxes from non–vertical showers as well as the differences between the production height for μ^+ and μ^- suggest that accounting for the muon deflection in the geomagnetic field would affect the calculated muon fluxes even at a low geomagnetic cutoff location such as Lynn Lake. We used a field with constant B_x (North), B_y (West) and B_z (up) local components of 0.098, -0.017 and -0.587 Gauss. The altitude dependence of the magnetic field is negligible for the altitudes involved in the calculation.

We do not show here the muon fluxes with account for the magnetic field because most of the results are almost identical to those of the 3D calculation, at least on the scale of Figs. 1 and 2. The only clearly visible change is at sea level, where the μ^- flux below 1 GeV/c decreases by about 10%, while the μ^+ increases by about the same amount. The same trend appears at all altitudes, although the fluxes change by a smaller amounts. The muon deflection in the geomagnetic field affects the muons through two different effects. The straight muon trajectories are bent and the pathlength to detection level is modified as a function of the muon rigidity

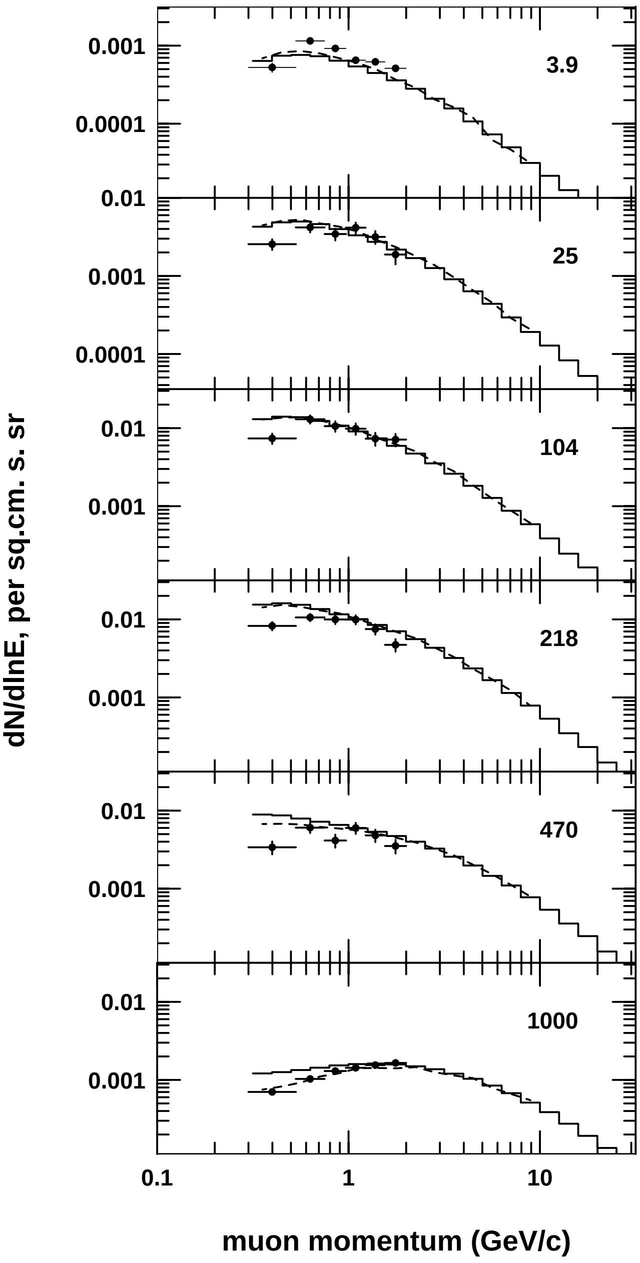

Fig. 2. Dots show the experimental results, the histograms - 1D calculation, and the dashed line - 3D calculation of the spectra of vertical μ^+ at different atmospheric depths.

and direction. Muons with longer tracks lose more energy and become more likely to decay. Since the number of muons generated above any observation depth is significantly larger than the ones that reach it, a small correction to the decay probability can affect in a significant way the muon flux at the observation level. The curved trajectory can also bring the muons in (or take them out of) the defined detector opening angle of $\cos\theta > 0.98$.

For reasons that we do not yet fully understand positive and negative muons are affected in the opposite way by the geomagnetic field in the current calculation. These changes affect strongly the muon charge ratio. We show the charge ratio at float altitude calculated with and without accounting for the geomagnetic field in Fig. 3, compared to the data of CAPRICE94. Although the Montecarlo statistics is clearly insufficient for a stable prediction, the calculation with magnetic field systematically generates higher μ^+/μ^- ratio, reaching 2.0 at muon momentum 0.35 GeV/c. The trend continues to the highest calculated muon momentum of 8.9 GeV/c, where the two values are 1.25 (1.45) without (with) account for the magnetic field.

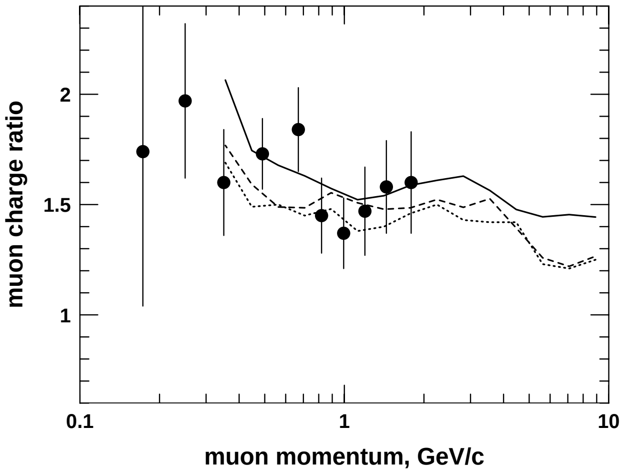

Fig. 3. Muon charge ratio calculated for the CAPRICE ‘float’ altitude of 3.9 g/cm^2 – points. The dashed line shows the results of the 3D calculation with primary cosmic ray spectrum as in Boezio *et al.* (1999a), and the solid line - the calculation that accounts for the geomagnetic field. The dotted line shows the charge ratio generated by the use of cosmic ray spectrum as derived by Agrawal *et al.* (1996) for solar minimum with no magnetic field.

3 Different primary cosmic ray spectrum

The muon spectra shown in Figs. 1 and 2 obviously do not describe well the flux measured at high muon momentum. We believe that the reason for this disagreement is not in the hadronic interaction model, rather in the very steep cosmic ray spectrum derived from the CAPRICE 94 measurement. The parametrization recommended by Boezio *et al.* (1999a), which we used, has a $R^{-2.93}$ power law in rigidity for both H and He, which is steeper by about 0.2 for H or more for He in the spectral index, than our own parametrization (Agrawal *et al.*, 1996).

For this reason we repeated the calculation using the cosmic ray spectrum of Agrawal *et al.* (1996) for solar minimum. The calculation is performed without account for the geomagnetic field. The results for μ^- at float altitude and sea level are shown in Fig. 4 together with measurements. At float the use of the Agrawal *et al.* (1996) solar minimum spectrum fits the measurement very well. At sea level, however, this spectrum introduces muon excess in the whole momentum range, and especially below 1 GeV. At intermediate

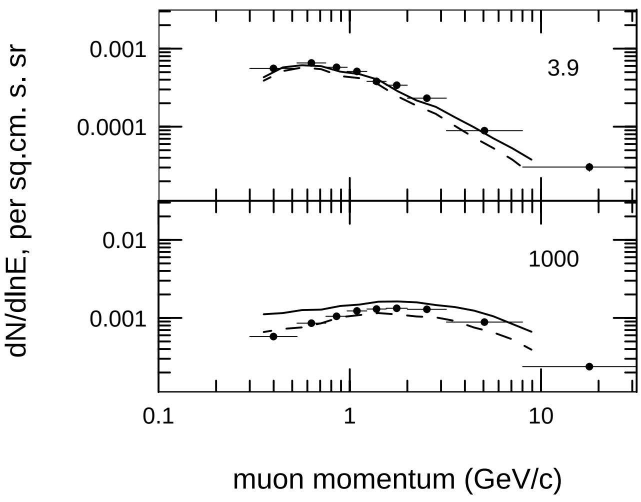

Fig. 4. The dashed line is as in Fig. 1 and the solid shows the fluxes at ‘float’ and sea level calculated with the cosmic ray spectrum of Agrawal *et al.* (1996). None of these calculations accounts for the geomagnetic field.

altitudes, that are now shown here, the behavior is similar, with an excess at low momentum developing with the atmospheric depth. At least a part of the reason for this excess is that the CAPRICE 94 flight was performed not at solar minimum, and some degree of solar modulation (710 MV for H and 840 MV for He is recommended by Boezio *et al.* (1999a)) has to be applied to the solar minimum flux.

Fig. 3 shows with a dotted line the μ^+/μ^- ratio that corresponds to the muon flux shown in Fig. 4. It appears to be systematically lower than the one calculated with the Boezio *et al.* (1999a) cosmic ray flux.

The reasons for the different impact of the two cosmic ray flux models on the muons measured at ‘float’ and at sea level is most likely related to the different energy ranges of the primary cosmic ray flux involved in the production of muons. Muons at ‘float’ are generated by lower energy cosmic rays, where the difference between the models is smaller. Muon fluxes at sea level are sensitive to the higher energy part of the cosmic ray flux, where these two models are very different. The differences in the muon charge ratio can be understood in terms of the higher neutron to proton ration in the model of Agrawal *et al.* (1996).

4 Discussion and Conclusions

Using the primary cosmic ray flux measured by the CAPRICE 94 experiment we are able to predict, with a 3D calculation, fairly well the spectrum of μ^+ and μ^- measured at ground level by the same experiment. The calculation does not, however, represent well the muon spectra below 1 GeV/c measured during the ascent of the balloon. At muon momenta above 5 GeV the simulated spectrum is always below the measurement, which we attribute to the extremely steep primary spectrum model of Boezio *et al.* (1999a).

Important lessons, learned from this exercise, include:

- A very wide angular range of cosmic ray interactions contributes to the vertical flux of muons - $\cos\theta > 0.98$ in this calculation
- There is a significant difference in the production of positive and negative muons. μ^+ are generated higher in the atmosphere then μ^- and by lower energy primary nucleons.
- The account for the geomagnetic field does not change significantly the total muon flux, but affects the muon charge ratio even at a location with low geomagnetic cutoff
- The muon charge ratio is indeed a good measure of the fraction of neutrons in the primary cosmic ray spectrum, i.e. a measure of the cosmic ray composition

It is worth noting that at a location with higher geomagnetic cutoff the differences in the production height and in primary energy, combined with the wide angular acceptance of the muon detectors for primary cosmic rays and the East–West effect, will affect the muon charge ratio very strongly. The trajectory of a negative muon coming from the West at a relatively large zenith angle will bend to make the muon more vertical, and thus bring it into the acceptance cone of a detector. The same will happen to a positive muon arriving from the East. The net effect should be a decrease of the muon charge ratio.

Our general conclusion is that the flux of atmospheric muons, and especially the muon charge ratio, are very sensitive to details of the calculation, that only affect the neutrino flux in second order. The reason is that only a small fraction of the muons generated above any observation level traverse it and are measured. An exact muon calculation thus subtracts two large numbers to obtain the small flux of measured muons, and thus often suffers from large errors. Neutrinos are products of the large number of decaying mesons and muons, and are thus subject to much smaller errors.

5 Acknowledgments

This research is supported in part by the US DOE contract DE-FG02 91ER 40626.

References

V. Agrawal *et al.*, Phys. Rev. D54, 1314, 1996.
Y. Fukuda *et al.*, Phys. Rev. Lett., 81, 1562, 1998.
M. Boezio *et al.*, Phys. Rev. D, 62: 032007, 2000.
M. Boezio *et al.*, Ap. J., 518, 457, 1999.
M. Boezio *et al.*, Phys. Rev. Lett., 82, 4757, 1999.
M. Circella *et al.* Proc. 25th ICRC (Durban), ed. by M.S. Potgieter, B.C. Raubenheimer & D.J. van der Walt, 7, 117, 1997.
R. Engel *et al.*, these Proceedings
T. Stanev *et al.*, Proc 26th ICRC (Salt Lake City), ed. by D. Kieda, M. Salamon & B. Dingus, 2, 96, 1999.