Simulation of the flux of muons at energies relevant for the atmospheric neutrino anomaly

J. Wentz[1 †], B. Vulpescu[2], D. Heck[1], and H.J. Mathes[1]
[1]*Forschungszentrum Karlsruhe, Institut für Kernphysik, D-76021 Karlsruhe, Germany*
[2]*National Institute of Physics and Nuclear Engineering, RO-7690 Bucharest, Romania*

Abstract

The feasibility of calculating fluxes and the charge ratio of muons relevant for the atmospheric neutrino anomaly with CORSIKA is investigated. It is shown that the differential fluxes and directional intensities are in good agreement with experimental data. But the hadronic interaction model GHEISHA used for $\mathrm{E_{lab}} <$ 80 GeV/u fails to calculate the charge ratio of muons. The ratio between produced positive and negative pions and muons, respectively, is compared for different high energy hadronic interaction models.

1 Introduction:

Atmospheric neutrinos are produced in the interaction of the primary cosmic rays, consisting of protons and nuclei up to iron, with the Earth's atmosphere. Thereby pions, kaons, baryons and nuclear fragments are produced. Mainly the decay of the charged pions:

$$\begin{aligned} \pi^+ &\rightarrow \mu^+ + \nu_\mu \\ \pi^- &\rightarrow \mu^- + \overline{\nu_\mu} \end{aligned} \tag{1}$$

and the subsequent decay of the muons:

$$\begin{aligned} \mu^+ &\rightarrow e^+ + \nu_e + \overline{\nu_\mu} \\ \mu^- &\rightarrow e^- + \overline{\nu_e} + \nu_\mu \end{aligned} \tag{2}$$

are the sources of atmospheric neutrinos. At higher energies where the production of kaons becomes important, also the decay of K^+ and K^- contributes to the neutrino flux. A rough adding of the flavours involved in eqs 1 and 2 lead to the ratio:

$$R_\nu = \frac{\nu_\mu + \overline{\nu_\mu}}{\nu_e + \overline{\nu_e}} = 2 \tag{3}$$

This relation fails at high energies when a larger number of muons reach sea-level without decaying. The ratio of muon to electron neutrinos is measured by the Super-Kamiokande experiment, with the result that the expected ratio is considerable less than the theoretical expectation (Fukuda 1998a, Fukuda 1998b). Moreover, data for neutrinos from above show agreement, while the disagreement increases with the angle of the neutrinos, reaching its maximum for neutrinos which passed the whole Earth. This seems to be a clear evidence for neutrino oscillations, i.e. a non-zero rest mass of the neutrinos.

The interpretation of the experiment is based on Monte Carlo simulations of the neutrino fluxes. Various simulations have been made with quite different codes using such different approaches like diffusion equations for the transport of the particles, or complete Monte Carlo simulation of air shower development in atmosphere. The results of all calculations agree more or less in the ratio of ν_e/ν_μ, but there are considerable differences in the ratio of $\nu_e/\overline{\nu_e}$ and the absolute fluxes of all neutrino flavours. These differences play an important role in the interpretation of the oscillation feature. Even the strongly disfavoured oscillation $\nu_\mu \rightarrow \nu_e$ cannot be ruled out, due to large uncertainties in calculation of the absolute ν_e-fluxes.

A second difficulty arises from the flavour dependent cross-sections in the detection. For energies for which most of the Super-Kamiokande data exist, the cross-section for interactions of neutrinos is about 3 times higher than for antineutrinos. Therefore the theories must give a precise calculation for the fluxes of neutrinos and antineutrinos, in order to correct the experimental results.

†corresponding author; e-mail: wentz@ik3.fzk.de

In case of the muon neutrinos the different theories agree in a ratio of 1, what is understandable from eqs 1 and 2, where ν_μ and $\overline{\nu_\mu}$ are produced symmetrically in the production and the decay of muons. A small distortion originates from different energies of π^+ and π^- produced by p+n and p+p collisions, leading to a different number of decaying muons.

In case of the electron neutrino the situation is more difficult. The primary radiation as well as the atmosphere consist only of matter, i.e. of positive or neutral charged hadrons. The number of π^+ is considerable higher than the number of π^- produced. As can be seen in eq. 2 the ratio $\nu_e/\overline{\nu}_e$ is reflected in the ratio of μ^+/μ^-, which is known to be about 1.3 for $\mathrm{p}_\mu > 2$ GeV. At lower energies the situation is less clear and the simulations show large differences. New experiments like WILLI (Vulpescu 1998) will give precise results for the muon charge ratio for $\mathrm{p}_\mu < 1$ GeV, in the region interesting for Super-Kamiokande. The intention of this work is to study various hadronic interaction models in view of their feasibility of calculating the fluxes and the charge ratio of muons, as base of future calculations for atmospheric neutrino fluxes.

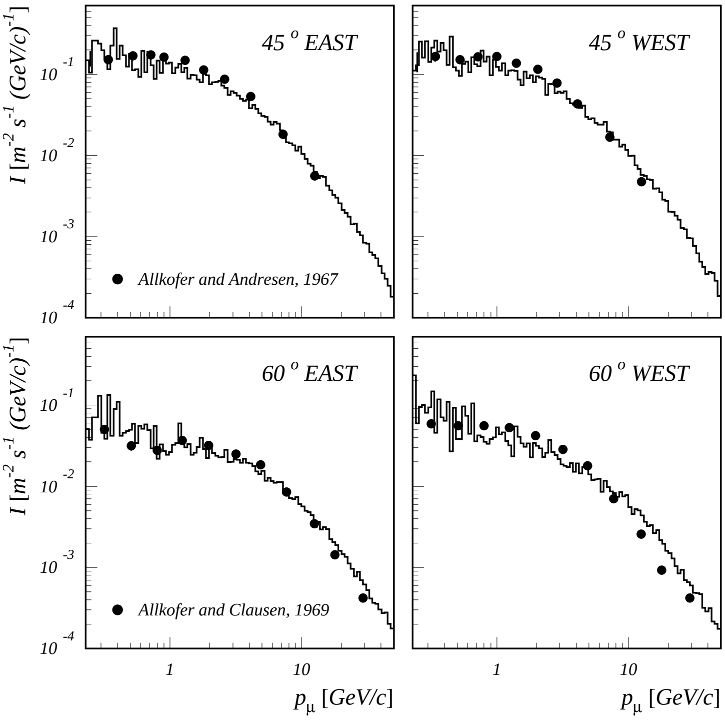

Figure 1: CORSIKA simulation of differential momentum spectra for muons from different direction at sea level compared with measurements (Allkofer 1967, Allkofer 1969). The absolute values result from integration over a solid angle of 10°.

2 Simulation of Muons on Sea-Level with CORSIKA:

CORSIKA is a complex Monte Carlo code, developed originally for the simulation of extended air showers (Heck 1998). It contains different interaction models for the simulation of hadron-hadron collisions for $\mathrm{E_{lab}} > 80$ GeV/u. Below, all reactions are simulated by GHEISHA (Fesefeldt 1985) as implemented in GEANT 3 (CERN 1993). CORSIKA handles the tracking in the Earth's magnetic field and the decay of all unstable particles.

Fig. 1 shows the results of CORSIKA simulations for differential momenta of muons from various directions at sea-level. As can be noticed, the simulations are in good agreement with the majority of measurements. This result has only partial value, because a too low pion/muon production could be compensated by a higher primary flux. Only the comparison of measurements in different depths of the atmosphere may overcome this difficulty.

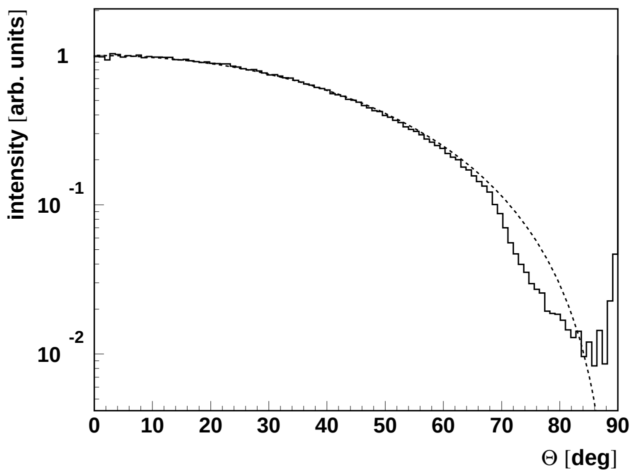

Figure 2: Directional intensity of muons simulated with CORSIKA (plane atmosphere model) compared with a $cos^{2.02}(\theta)$-distribution (dashed line) (Wentz 1995).

Fig. 2 shows the behaviour on the zenith angle. It can be noticed that actual CORSIKA with its plane atmosphere model can be used up to 70° zenith angle. For calculations in more horizontal direction the effect of the curvature of the Earth becomes important. A "curved" version of CORSIKA, which approximates the curvature step by step with a rotated local plane atmosphere is in work and will allow calculations up to the horizontal direction (Heck 1999).

The simulation of the important charge ratio of muons turns out to be more complicated. Tests with GHEISHA at fixed energy show, that there are serious problems in charge conservation. Fig. 3 displays the charge and nucleon number of the remaining nucleus, in $\mathrm{E_{lab}}$ = 80 GeV p + ^{14}N reactions. Because GHEISHA does not give the remnant of the target nucleus directly, the values are calculated by charge and baryon number conservation. It can be seen that these conservation laws are not fulfilled by GHEISHA; even if the main number of reactions leads to a possible number of protons and neutrons, the existence of negative charges and baryon numbers for the target rest shows that GHEISHA involves no physical model for the charge exchange from the target to the ejectiles. This results from the simple parametrisations used for the particle generation in the final channel, giving only global conservation of charge, but no conservation in the single reaction.

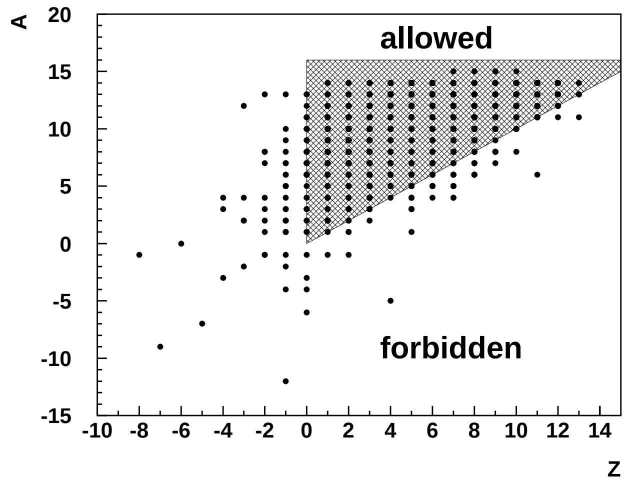

Figure 3: Distribution of the nucleon number A over the charge Z of the remaining nucleus in $\mathrm{E_{lab}}$ = 80 GeV p + ^{14}N reactions calculated with GHEISHA, considering charge and nucleon number conservation. The hatched area shows the allowed region between the extremes of a "nucleus" consisting only of protons and a "nucleus" consisting only of neutrons.

3 Simulation of the Charge Ratio at High Energies:

For hadronic interactions with $\mathrm{E_{lab}} > 80$ GeV/u, there are different reaction models implemented in CORSIKA. Fig. 4 shows the ratio of π^+ to π^- vs. momentum of the ejectiles. The results of QGSJET (Kalmykov and Ostapchenko 1993), SIBYLL (Vers. 1.6) (Fletcher 1994) and VENUS (Vers. 4.12) (Werner 1993) are compared. All the three models agree in the general tendency, that the π^+ to π^--ratio increases with the energy. This behaviour is understandable because for the highest energy pions the multiplicity in production is very low and therefore the charge excess highest. At low energies, i.e. in high multiplicity reactions there is an equilibrium of charges and the ratio approaches 1.

But there are also considerable differences between the models. QGSJET shows the lowest excess of positive charge at all pion energies. While VENUS shows a continuous increase towards higher energies, the charge ratio of pions from the SIBYLL is smallest at lowest energies, but supersedes all models at highest pion energies.

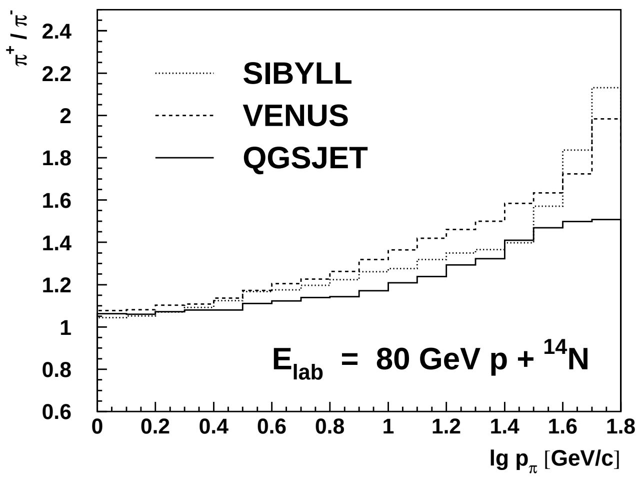

Figure 4: Differential spectra of the charge ratio of pions produced by different high energy hadronic interaction models.

Fig. 5 shows how the difference in the pion production between the models affects the charge ratio of muons on ground-level. The simulations for all three models are based on a primary $E^{-2.7}$-spectrum between 80 - 10^6 GeV. It can be noticed that the SIBYLL-model results in the highest charge ratio of muons, where the QGSJET-model give the lowest. This means, that especially the high charge excess at high ejectile energies propagates in air shower development. The intermediate and constant results of the VENUS model seems to agree best with experimental results.

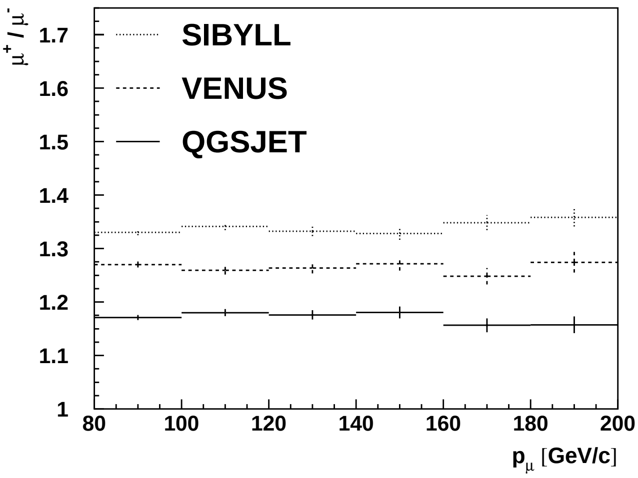

Figure 5: Differential spectra of the charge ratio of vertical muons at sea-level, simulated by CORSIKA with different high energy hadronic interaction models.

4 Conclusions:

The feasibility of calculating the fluxes of atmospheric muons with the air shower simulation program CORSIKA is investigated. The results show that CORSIKA is able to reproduce the differential fluxes and directional intensities very well. But the included hadronic interaction model GHEISHA, responsible for all interactions with $E_{lab} < 80$ GeV/u, producing most of the muons relevant for the atmospheric neutrino anomaly, is not conserving charge in individual reactions. Further it is not based on a fundamental model for describing the flux of charge from the target to the fast moving ejectiles. The code GHEISHA has to be improved or replaced by more sophisticated approaches. The high energy model VENUS seems to be the best choice for reactions with $E_{lab} > 80$ GeV/u. In conclusion it can be stated, that the simulation of atmospheric neutrino fluxes is possible with CORSIKA.

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