Influence of the hadronic interaction model on the calculation of the atmospheric muon flux

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***Abstract*— We report in this work a comparison between Monte Carlo simulations of the atmospheric muon differential fluxes performed with the air shower code CORSIKA and their corresponding measurements obtained by the BESS experiment. As input, we have used the primary fluxes of protons and helium nuclei parameterized by the force field model for a given local interstellar spectra. The influence of the hadronic interaction models is investigated, namely with UrQMD and FLUKA below 80 GeV/n and NeXUS above 80 GeV/n. The sensitivity of the muon fluxes to the variation of climate is also explored by the opportunity of implementing different atmospheres in CORSIKA.**

I. Introduction

Atmospheric muon observations lead to fundamental information about atmospheric neutrinos, since production and decay processes of muons are accompanied by neutrino production. They are also helpful for the calibration of the hadronic interaction models used in extensive air shower simulations.
In this work, we report a comparison between the atmospheric muon flux measurements obtained by the BESS-2001 balloon flight [1] and Monte Carlo calculations performed by the CORSIKA code [2]. We have used NEXUS v3.97 [3] for the hadronic interactions above 80 GeV/n and FLUKA 2005 [4] and UrQMD v1.3 [5] below this energy. The contribution of nuclei other than H and He has not been accounted.
For the primary cosmic rays we have used the spectra obtained by Burger [6]. The solar modulation is described by the force field model [7] and the used modulation potentials are those of Usoskin [8]. The local interstellar spectrum (LIS) for protons is given by:

$$J_{\mathrm{LIS}} = \frac{1.9 \cdot 10^4 \cdot P(E_{\mathrm{K}})^{-2.78}}{1 + 0.4866 \cdot P(E_{\mathrm{K}})^{-2.51}} \tag{1}$$

where

$$P(E_{\mathrm{K}}) = \sqrt{E_{\mathrm{K}}(E_{\mathrm{K}} + 2 \cdot E_{\mathrm{R}})} \tag{2}$$

E_{K} is the kinetic energy per nucleon and E_{R} the proton rest mass. For helium, we have used the number ratio He/H $=$ $(5.0 \pm 0.2)\%$ in the high-energy range (> 10 GeV/nucleon).

The modulated primary cosmic ray intensity is expressed by Eq. 3, where $\Phi = (Ze/A)$ and $\varphi = 891$ MV is the modulation potential for the BESS 2001 flight.

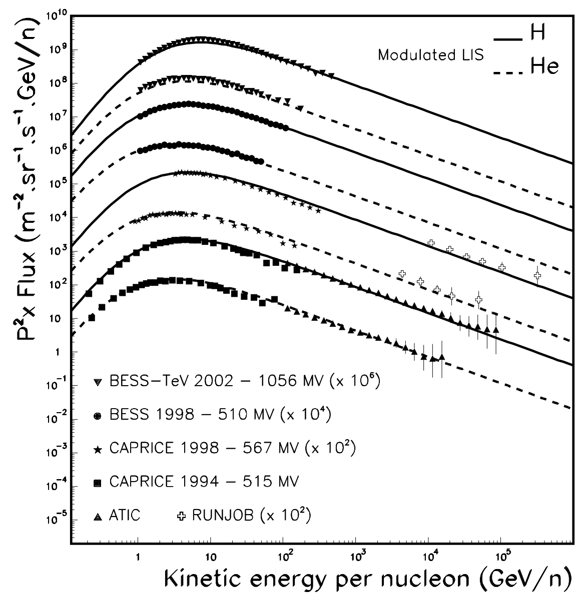

Fig. 1. Primary cosmic ray spectra measured at different solar epochs compared to the modulated LIS.

$$J(E_{\mathrm{K}}, \Phi) = J_{\mathrm{LIS}}(E_{\mathrm{K}} + \Phi) \times \frac{E_{\mathrm{K}}(E_{\mathrm{K}} + 2 \cdot E_{\mathrm{R}})}{(E_{\mathrm{K}} + \Phi)(E_{\mathrm{K}} + \Phi + 2 \cdot E_{\mathrm{R}})} \tag{3}$$

Fig. 1 shows the validation of this method for different primary cosmic ray direct measurements at different solar epochs, obtained by BESS-TeV [9], BESS 98 [10], CAPRICE 94 [11] and 98 [12], ATIC [13] and RUNJOB [14] experiments.

To study the influence of the structure of the atmosphere on the muon flux calculations, we have used, on the one hand, the U.S. standard atmosphere (US-AtmL) as parameterized by Linsley [15] and, on the other hand, the one parameterized by Keilhauer (US-AtmK) [16]. We should point out here that the measured atmospheric depths during the BESS-2001 flight agrees better with the US-AtmL atmosphere than the US-AtmK one (Fig. 2).

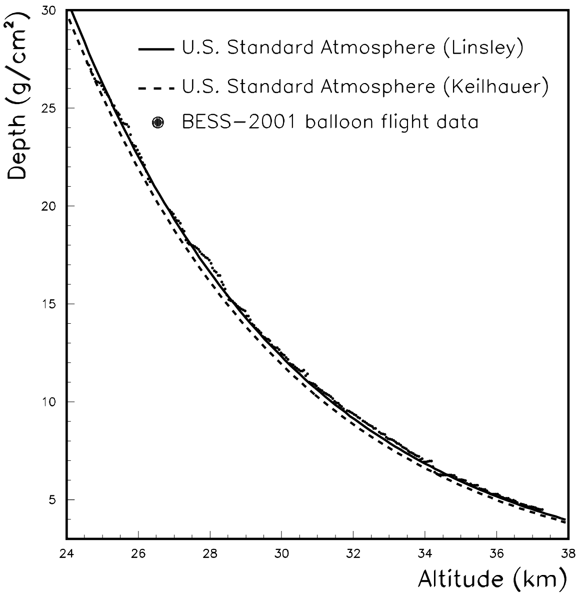

Fig. 2. The atmospheric depth measuredduring the BESS-2001 flight compared to the US-AtmL and US-AtmK atmospheric models.

II. Comparison of the data with calculation

We have calculated the muon flux for different momentum bins and different atmospheric depths for the BESS-2001 flight (minimum rigidity $R_{\rm min} = 4.2$ GV). We have treated the hadronic interaction above 80 GeV/n by NEXUS and those below by FLUKA and UrQMD. The results of the Monte Carlo calculations are shown in Figs. 3 and 4. The curves are very close especially in the region above 2 GeV/c. Below, the discrepancy is mainly due to the fact that with UrQMD we can follow hadrons up to 0.3 GeV, while for FLUKA this limit is 0.05 GeV. But this difference, more pronounced for μ^+ than for μ^-, is related to the properties of the hadronic interaction models. Indeed, μ^+ are produced by lower primary energy and at higher altitude than those of μ^- [17].

Figs. 5 and 6 show the calculated muon flux for different momentum bins and different atmospheric depths using two different parametrisations of the atmosphere (US-AtmL and US-AtmK). It is clear from theses figures that the predicted muon fluxes are not affected by the atmospheric density structure, at least in the considered depth range 4–26 g/cm^2.

III. Conclusion

In this work, we have investigated the influence of the interaction model on the calculation of the atmospheric muon flux. For this purpose, we have compared the data of the BESS-2001 experiment with the results of the Monte Carlo calculation carried out on the basis of the program CORSIKA, applying different hadronic interaction and atmospheric models. The use of FLUKA or UrQMD gives similar results above 2 GeV/c, but with much CPU time for UrQMD. Below 2 GeV/c, a disagreement, more pronounced for μ^+ than for μ^-, appears between the two calculations. It may be attributed to the fact that we can follow hadrons up to 0.3 GeV with UrQMD while for FLUKA this limit is 0.05 GeV and that μ^+ are produced by lower primary energy and at higher altitude than those of μ^-. We have also noticed there is no influence of the atmospheric model on the predicted muon flux at lower atmospheric depths (from 4 to 26 g/cm^2).

Acknowledgment

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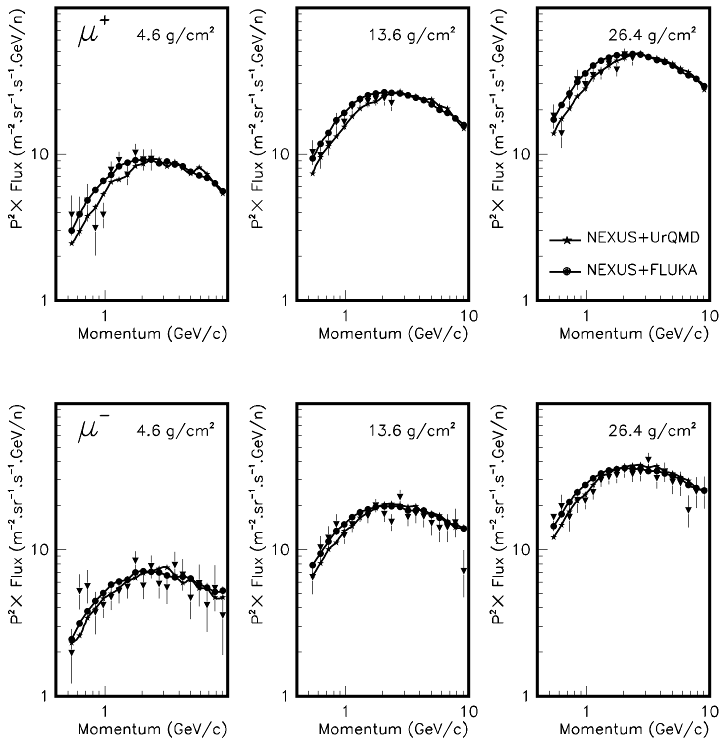

Fig. 3. Muon flux versus momentum for different atmospheric depths by using different hadronic models.

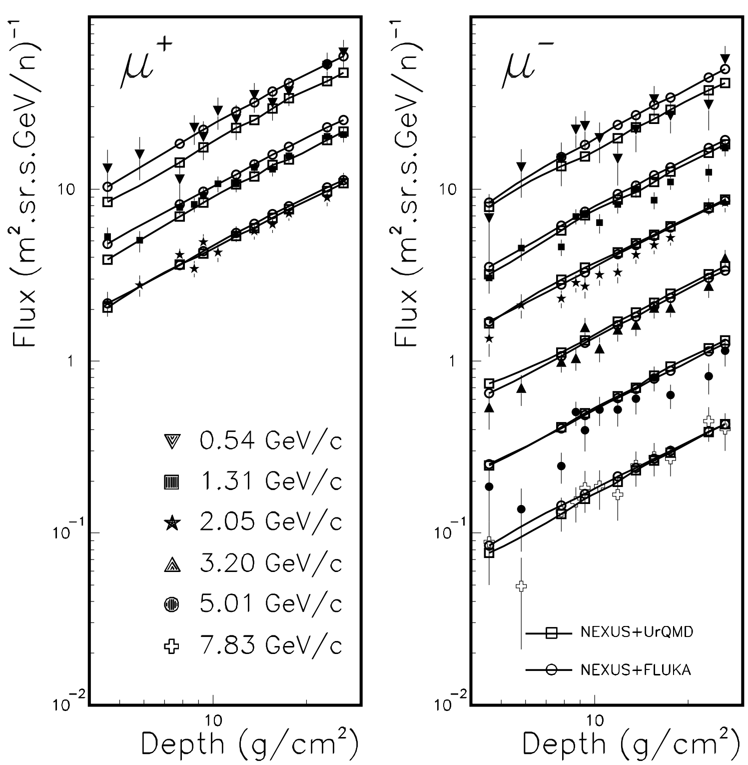

Fig. 4. Growth curves for different momentum bins by using different hadronic models.

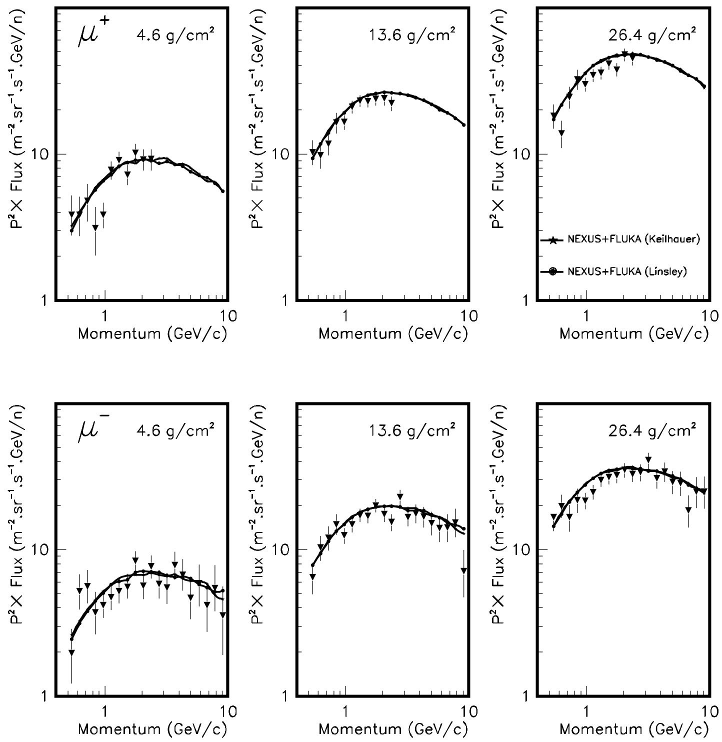

Fig. 5. Muon flux versus momentum for different atmospheric depths by using different atmospheric models.

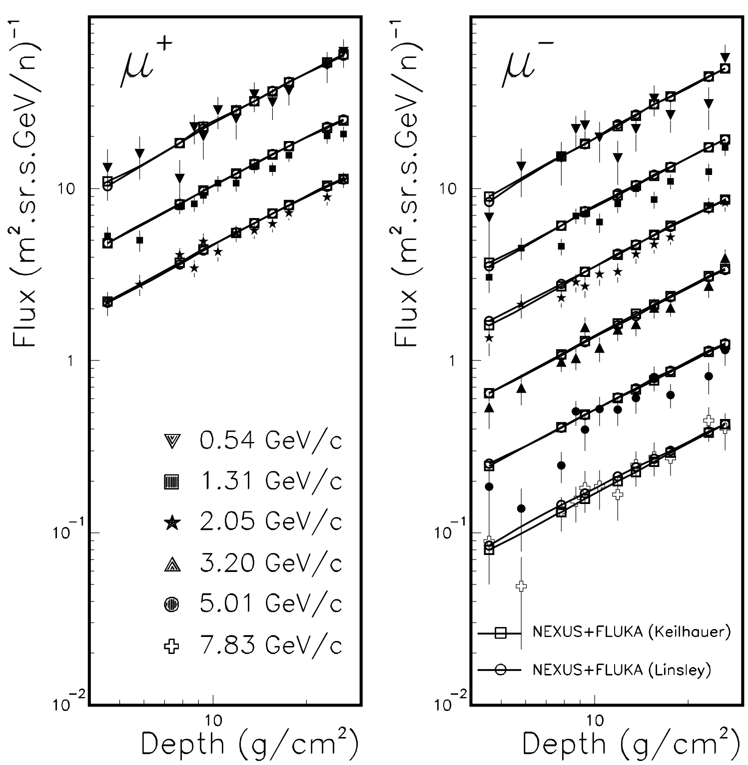

Fig. 6. Growth curves for different momentum bins by using different atmospheric models.