Influence of Low-Energy Hadronic Interaction Programs on Air Shower Simulations with *CORSIKA*

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Abstract

In hadron-induced extensive air showers (EAS) low-energy collisions of secondary hadrons with nuclei of the atmosphere form the final branches of the hadronic shower skeleton. In the EAS Monte Carlo simulation program CORSIKA these interactions were treated up to now by the GHEISHA code. Recently correction patches became available for GHEISHA, overcoming a number of obvious deficiencies in the simulated kinematics of low-energy interactions. Additionally the hadronic part of the FLUKA code has been coupled for the description of low-energy hadronic interactions as an alternative to GHEISHA. The predictions of the implemented low-energy models are compared to data and their influence on the simulated EAS development is investigated.

1. Introduction

The simulation of EAS is inherently linked to modeling hadronic multiparticle production over a wide energy range. The dependence of EAS simulations on high-energy hadronic interaction models has been discussed in [14, 15]. The present contribution focuses on the influence of low-energy ($E_{\rm lab} \lesssim 100$ GeV) hadronic interactions in EAS simulations with CORSIKA [13]. In the past mostly GHEISHA routines [11] have been used for this purpose, but it is known [10] that GEANT-GHEISHA suffers from deficiencies in handling the reaction kinematics properly. For example, in EAS simulations using GHEISHA the sum of the energy of the secondary particles and the deposited energy is often larger than the primary energy by several %, depending on the primary energy and the low-energy threshold (typically 300 MeV) above which hadronic particles are followed. As

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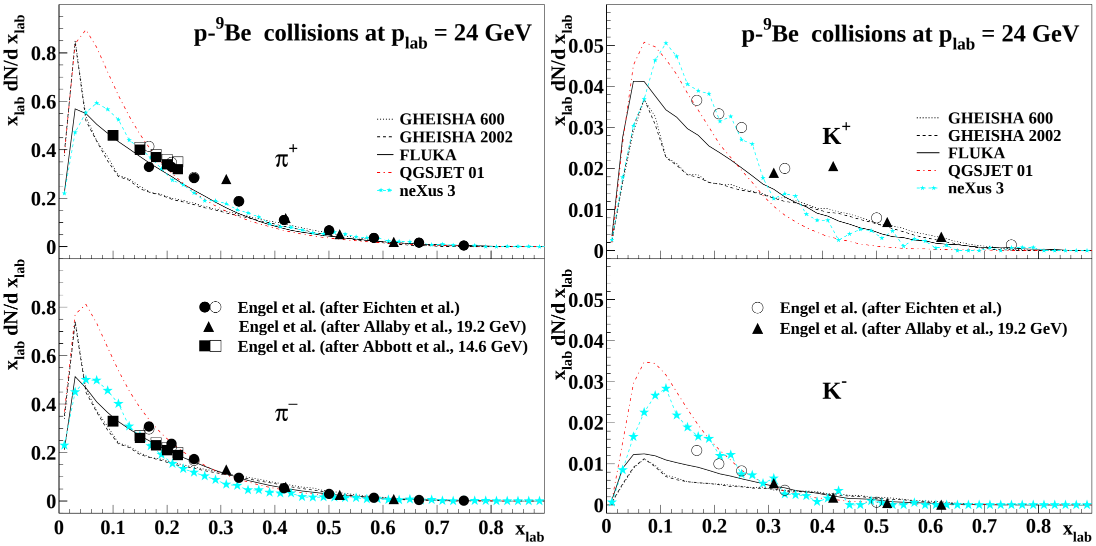

Fig. 1. Distribution of secondary particle momenta $x_{\rm lab} = p_{\rm tot}/p_{\rm beam}$ in p-^{9}Be collisions at $p_{\rm lab} = 24$ GeV. *Left*: Pions. *Right:* Kaons. The experimental data points were derived [8] from the measurements of [6, 2, 1].

an alternative to GHEISHA, the hadronic event generator of the FLUKA 2002 code [9] has been coupled with CORSIKA. Independently, correction patches [4] for GHEISHA became available which improve energy and momentum conservation, but do not change basic properties like particle multiplicities or differential cross sections. In the following we compare these models to fixed-target data and calculate air shower predictions using various combinations of low- and high-energy interaction models. We also study the importance of the threshold energy (currently $E_{\rm lab} = 80$ GeV) for switching from low- to high-energy models.

2. Comparison with Experimental Data

As in EAS ^{14}N is by far the most frequent target nucleus, a check of low-energy interaction models should be performed with target materials with similar nucleon number. For p-^{9}Be interactions several experimental data sets are available [6, 2, 1] at $E_{\rm lab} \approx 20$ GeV. In Fig. 1 the distributions of secondary mesons in $x_{\rm lab} = p_{\rm tot}/p_{\rm beam}$ are shown. The data points are obtained by integrating the published double differential cross sections [8]. For completeness the high-energy hadronic interaction programs QGSJET 01 [16] and neXus 3 [5], which technically handle these low energies, have been included in the comparison.

The good agreement of FLUKA predictions on pseudorapidity distributions has already been demonstrated in [3]. Generally the experimental data are well described by FLUKA, while GHEISHA (600 = uncorrected; 2002 = corrected) produces significantly less mesons at $x_{\rm lab} \approx 0.15$ and slightly more in the

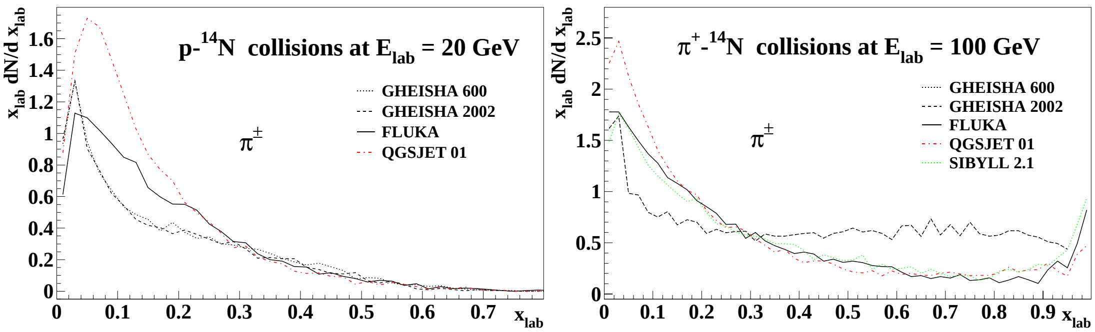

Fig. 2. Distributions of charged pion momenta $x_{\rm lab} = p_{\rm tot}/p_{\rm beam}$. *Left:* p-^{14}N collisions at $E_{\rm lab} = 20$ GeV. *Right:* π^+-^{14}N collisions at $E_{\rm lab} = 100$ GeV.

region of $x_{\rm lab} \approx 0.45$. This feature holds also for other types of hadronic collisions with ^{14}N targets, as is demonstrated in Fig. 2. In EAS simulations the understanding of π-^{14}N collisions is very important since charged pions are by far the most frequent secondary hadrons.

3. Influence on Shower Parameters

GHEISHA and FLUKA predict different momentum distributions of secondary $\pi^{\pm}$-mesons. Therefore spectra of muons with $E_{\rm lab} \lesssim 30$ GeV, which result mainly from the decay of pions produced in low-energy interactions, depend on the used low-energy model. Fig. 3 displays muon energy spectra for several combinations of low- and high-energy interaction models with transition energies of 80 GeV and 1.5 TeV. For all combinations 500 proton induced EAS with vertical incidence were averaged, considering all muons arriving at ground irrespective of their distance from the shower axis.

The largest differences between the energy spectra amount to ≈ 15 % at $E_\mu \approx 0.8$ GeV and they are clearly correlated with the differences in the predicted distributions of π-mesons at $x_{\rm lab} \approx 0.15$. Another difference of ≈ 10 % is observed at $E_\mu \approx 10$ GeV, probably related to the distribution of charged pions in π^+-^{14}N collisions at $x_{\rm lab} \approx 0.6$. The uncorrected GHEISHA 600 shows a flatter muon energy spectrum below 1 GeV than the corrected version. This difference has to be attributed to secondaries of protons emitted with by far too high energy in preceding collisions that do not conserve energy.

4. Conclusions

While the electron densities of simulated EAS show no significant dependence on the used low-energy model, its influence on the hadronic and muonic component is obvious. For CORSIKA applications that are sensitive to low-energy muon numbers and energy spectra the replacement of GHEISHA by FLUKA is

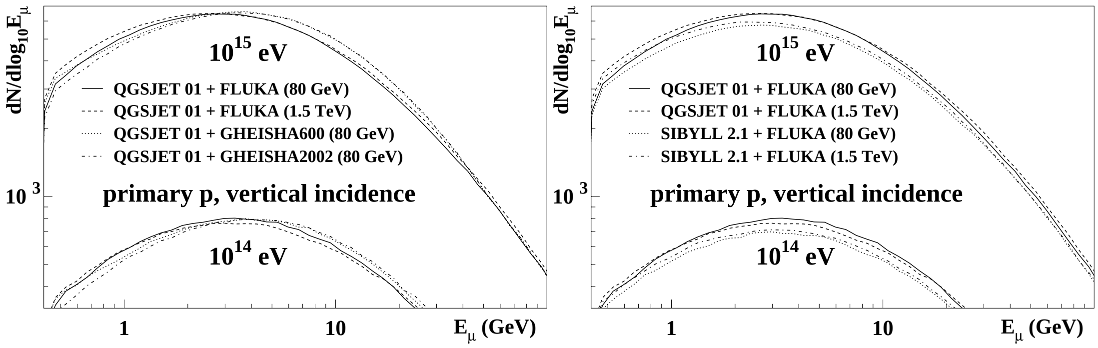

Fig. 3. Energy spectra of muons arriving at detector level (110 m a.s.l.) for primary protons of 10^{14} and 10^{15} eV, vertical incidence. *Left:* QGSJET 01 [16] combined with different low-energy models and transition energies. *Right:* QGSJET 01 and SIBYLL 2.1 [7] combined with FLUKA at transition energies of 80 GeV and 1.5 TeV.

recommended. The KASCADE detector allows the measurement of muons with different energy thresholds (approx. 490 MeV and 2.4 GeV) [12]. The observed ratio of the muon rates in EAS seems to favor FLUKA, but a detailed analysis is needed to specify the significance of the improvement.

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