Comparison of high energy interaction models used for atmospheric shower simulations above 1 TeV

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Abstract. We present here a comparison of interaction models commonly used for simulating cosmic ray shower development in the atmosphere at energies greater than 1 TeV. The implementations of these models in CORSIKA and the FLUKA transport and interaction code are relevant for extensive air shower experiments, neutrino telescopes, and gamma-ray surface-based detectors. We compare the pion, kaon, charmed meson and baryon energy fractions and the multiplicities at the first interaction stage of monoenergetic protons on nitrogen nuclei in the range 1 TeV-100 PeV. We also show comparisons in terms of *Z-moments*, a spectrum-weighted multiplicity often used in the cosmic ray community. The transverse and longitudinal momentum distributions of the secondary muons produced in proton-nitrogen collisions are also shown.

1. Introduction

The main backgrounds for the detection of extraterrestrial neutrino fluxes are the atmospheric muons and neutrinos produced from the interaction of cosmic rays with the atmosphere. The predicted atmospheric neutrino and muon fluxes depend on the assumed primary cosmic ray spectrum and composition, as well as the hadronic models used to describe these interactions. Discrepancies between these models become very large at energies above 1 TeV. The hadronic interaction models used in cosmic ray air shower Monte Carlo codes are built based on various theoretical scenarios. These can be checked by accelerator experiments up to energies achievable by fixed target experiments and colliders but must be extrapolated to higher energies [1]. The L3+C data up to 2 TeV show that the the muon flux predicted using different interaction models can differ by up to 30 percent [3]. The muon rate as measured by the AMANDA-II detector is higher by about thirty percent than simulations using the QGSJET model with the Wiebel-Sooth parametrization for the cosmic ray spectrum [2]. Comparisons like these indicate that more benchmarks with data and improvements of the hadronic interaction models are necessary. In this report we present a comparison of interaction models in CORSIKA [4] when used in its interaction test mode for beams of monoenergetic protons on nitrogen nuclei (the most abundant component of air). In this mode only the first interaction of a shower calculation is performed. The energy range at which we have generated high-statistics proton beams is 1 TeV to 100 PeV.

We did not generate interactions with heavier nuclei since at these energies the superposition model[1] is very effective, and quantities scale as energy per nucleon in high energy showers.

All secondaries, including the spectator nucleons from projectile and target, are stored in the particle stack, and further shower calculations are omitted. In this mode, many interactions can be generated, and all information about the particles can be stored. In the released CORSIKA version, charmed hadrons cannot be handled properly. In this work we have used a preliminary version of CORSIKA in which the charmed particle decays are enabled in DPMJET-II.55 [5]. The energy fractions, multiplicities and Z-moments[2] of these particles are compared to the FLUKA+DPMJET-III interaction and transport code [6]. For model comparison we have used both diffractive and non-diffractive events in a mixture as given by respective models. Diffractive events are visible as peaks at large energy fractions, as events typically have a forward-going meson with a direction slightly different from that of the original proton.

2. Results and Conclusions

In this section we will show the results of our analysis in a series of figures.

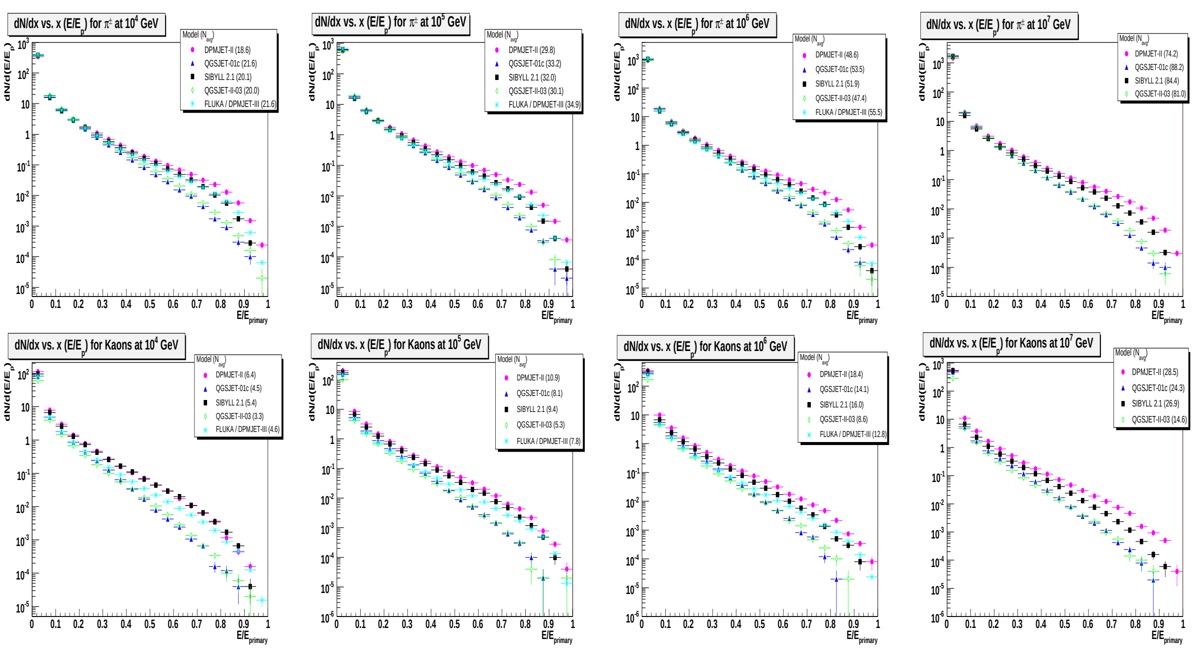

Figure 1. Energy fraction ($E_{secondary}/E_{primary}$) distributions using various models for secondary pions and kaons for monochromatic proton beams of energies of 10, 10^2, 10^3, and 10^4 TeV.

From Figure 1 we see that SIBYLL and FLUKA+DPMJET-III are in very good agreement with each other and in reasonable agreement with DPMJET-II for conventional mesons (charged pions and kaons). However, QGSJET-01 [7] and QGSJET-II [8] predict a lower energy fraction

[1] The superposition model treats a nucleus of mass number A and energy E_0 as A nucleons of energy E_0/A.

[2] The *Z-moments* are defined as:

$$Z_{p\to S} = \int_0^1 dx x^{\gamma} \frac{dN_S(x, E_p)}{dx} \tag{1}$$

where S is the secondary of the interaction, $x = E_S/E_p$ is the fraction of the primary energy E_p taken by that secondary, and $-\gamma$ is the integral spectral index of the primaries. We have assumed γ=1.7 at all energies.

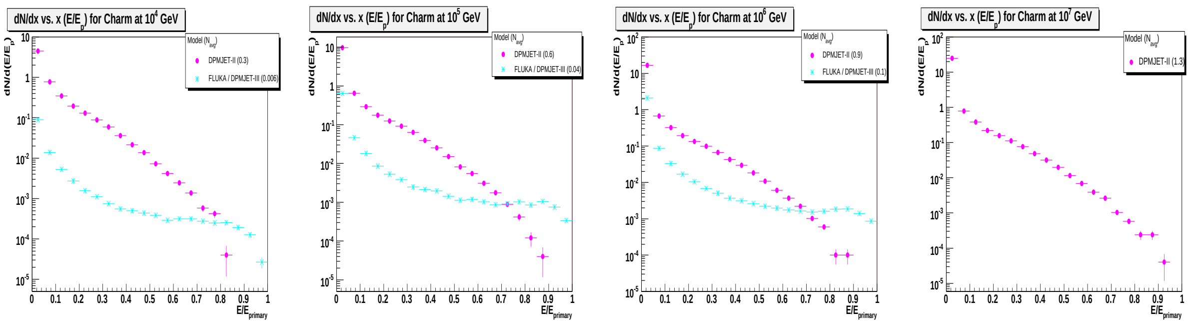

Figure 2. Energy fraction ($E_{secondary}/E_{primary}$) distributions using various models for charmed baryon and mesons for monochromatic proton beams of energies of 10, 10^2, 10^3, and 10^4 TeV.

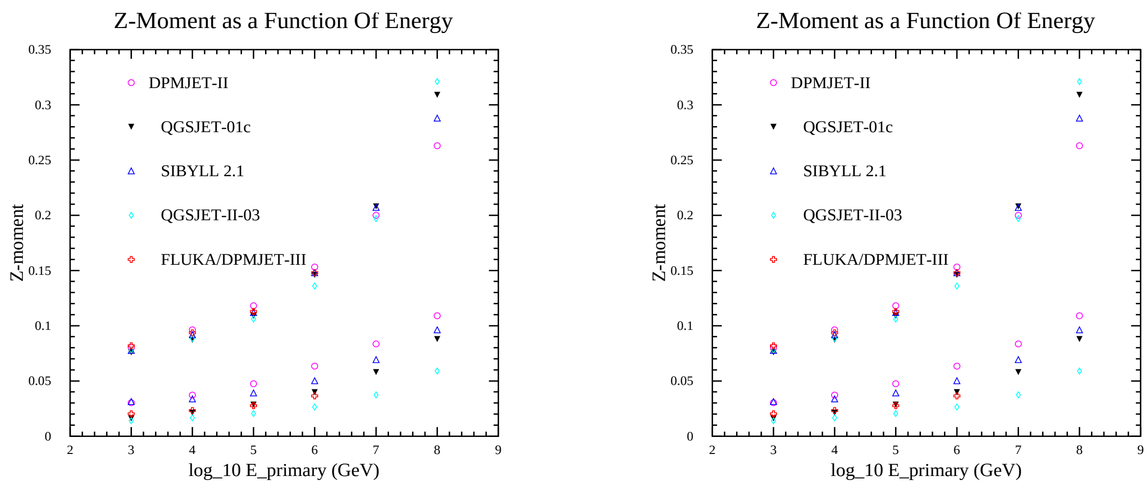

Figure 3. The mean multiplicity and the Z-moments of pions and kaons as a function of primary energy. The top ensemble of points denote pions while the bottom one denotes kaons.

in the region where secondaries take a very large fraction of the primary energy. This could explain the disagreement in the AMANDA-II muon intensity distribution, since the depth of the detector selects higher energy secondaries. The fact that the AMANDA data are higher about 30% higher than the simulation indicates that models like SIBYLL, FLUKA+DPMJET III and DPMJET II.55, as well as a harder proton primary spectrum parametrization (e.g. the one in Ref. [9]) could better account for the data. Fig. 2 shows the same distributions for the two interaction models we have used for charmed particle simulation: DPMJET II.55 (preliminary CORSIKA version) and FLUKA combined at energies larger than 100 GeV with DPMJET III. The disagreement is quite consistent. It seems that for charmed hadrons, this implementation of DPMJET-II in CORSIKA underestimates diffractive processes. This is particularly evident for charmed baryons.

In Figure 3, the Z-moments and the multiplicities are shown for all energies and models. Z-moments show a similar trend to what described for the energy fractions with a weight that takes into account the slope of the cosmic ray spectrum. It is also noticeable that the spread between models is much larger for kaons than for pions. Figure 4 shows the transverse and longitudinal momenta for 'conventional' mesons (pions and kaons) and for prompt charm mesons and baryons

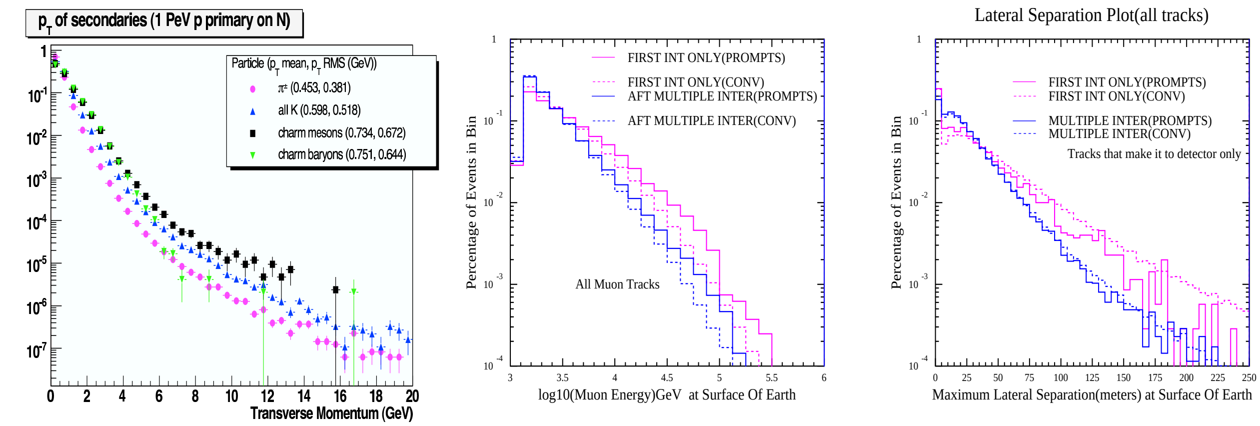

Figure 4. The trasverse momentum, longitudinal momentum and lateral separation of the secondary particles produced by air showers for a 1 PeV monoenergetic beam of primary protons at a fixed zenith angle of 65 degrees.

from proton interactions on nitrogen at 1 PeV. As expected, they are both on average larger for charmed secondaries of proton interactions than for conventional mesons. Since both p_T and p_L are larger, the lateral distribution of muons induced by conventional mesons and by prompt ones at the surface measured from the shower axis is not much different both after the first interaction and after the full shower development, since the secondary angle with respect to the shower axis is given by $\tan\theta = p_T/p_L$. This is true also for the muons that have such a high energy to reach the detector and even setting higher energy cuts. These preliminary results seem to indicate that the lateral distribution is not a useful parameter for discriminating prompt muons from conventional ones [10].

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