High-energy interaction models and systematic uncertainties in the ground-based observation of air showers

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At energies $\geq 10^{12}$ eV, the exceedingly low flux of primary cosmic rays (CR) makes their direct measurement generally difficult. Instead, their properties are reconstructed from the shape and particle content of the extensive air showers (EAS) they produce in the atmosphere. The reconstruction is based on numerical models of the air shower developement.

Hadronic interaction models at cosmic ray energies are inherently uncertain due to the lack of a fundamental theoretical description of soft hadronic and nuclear interactions and the large extrapolation required from collider energies to the range of the most energetic cosmic rays observed ($> 10^{20}$ eV). In this work, model uncertainties are evaluated within the QGSJET model, by varying some of the crucial parameters in the limits allowed by collider data, and between QGSJET-II and other models commonly used in air shower simulations, namely SIBYLL 2.1 [1] and EPOS 1.99 [2].

For this study we chose the latest version of the QGSJET model, QGSJET-II-3 [3]. The standard version of the model is labeled option 1 in the following. The crucial parameters modified to build five alternative versions of the model (options 2-6) relate to hard processes, string fragmentation, diffraction and baryon production (see Tab. 1 and [4,5] for a more detailed description). In options 2 and 6 the parameters are varied in two different ways to increase the proportion of diffractive events: in option 2 the low mass diffraction is enhanced for protons, pions and kaons, while in option 6 the proton diffraction is unchanged with respect to the standard QGSJET, but the diffraction for pions and kaons is decreased. Q_0^2 is the virtuality cutoff defining the transition from the non-perturbative soft to the perturbative hard part of the cascade. When this value is increased, as in option 3, the rise with energy of the cross section and the secondary particle production is reduced. Option 4 and 5 vary the energy-momentum partition between elementary production processes and string fragmentation.

option	diffraction $\frac{\lambda_1}{\lambda_2}(p)$	diffraction $\frac{\lambda_1}{\lambda_2}(\pi)$	Q_0^2 (GeV^2)	BJM	SE
1 (std)	4	4.7	2.5	on	0.5
2	**7**	**9**	2.5	on	0.5
3	4	4.7	**4**	on	0.5
4	4	4,7	2.5	**off**	0.5
5	4	4.7	2.5	**off**	**0.7**
6	4	**3**	2.5	on	0.5

Table 1
Parameter settings of six options of QGSJET-II. Option 1 represents the standard settings of QGSJET-II. See text and [4,5] for further explanations.

Using the different versions of the QGSJET model, the properties of single interactions relevant for the EAS developement have been investigated: cross-section, inelasticity, number of charged particles produced (Fig. 1), transverse momentum, pseudorapidity and Feynmann-x distribution.

Results on the properties of air showers measured by ground detectors from energies of 10^{12} eV (domain of the Cherenkov detectors) to 10^{15} eV (KASCADE) up to 10^{19} eV (energy range of the Pierre Auger Observatory) are obtained using the CORSIKA [6] code, modified to include the alternative versions of QGSJET. As an example, the differences in the lateral distribution of electromagnetic particles and muons for different models are shown in Fig. 2 for a single energy. Fig. 3 shows the analogous results for the longitudinal energy deposit. Estimates of relevant experimental observables, as predicted by the different models, have been also computed [4,5].

This study shows that the parameters variations within one model does not capture the full

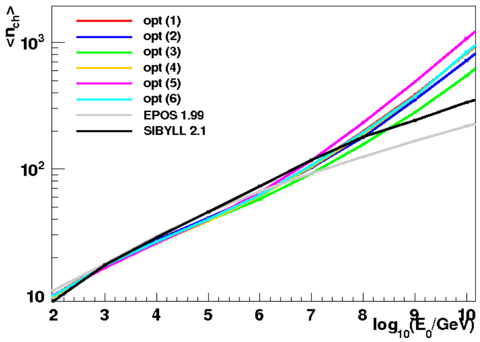

Figure 1. Average multiplicity of charged particles produced in proton-Nitrogen interactions as a function of the lab energy.

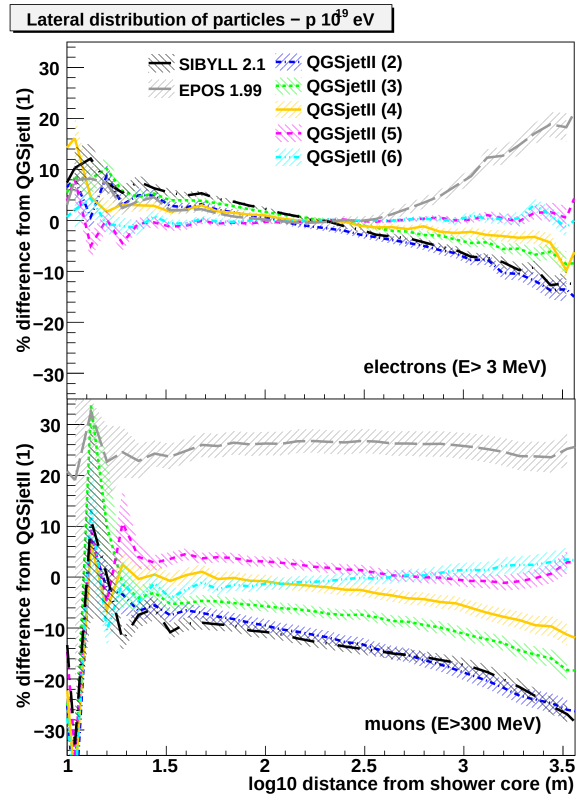

Figure 2. Average percentage difference (to QGSJET standard) of the number of electrons (top) and muons (bottom) for proton induced showers with a zenith angle of 20°. Shaded areas show the statistical uncertainties on the mean values.

variance between possible models of hadronic interactions. At highest energy the size of model uncertainties make the analysis of mass composition very difficult, being, at present, comparable to the differences between proton and iron induced showers. LHC and RHIC data are expected to increasingly constrain the models and make their extrapolation at EeV energies more reliable.

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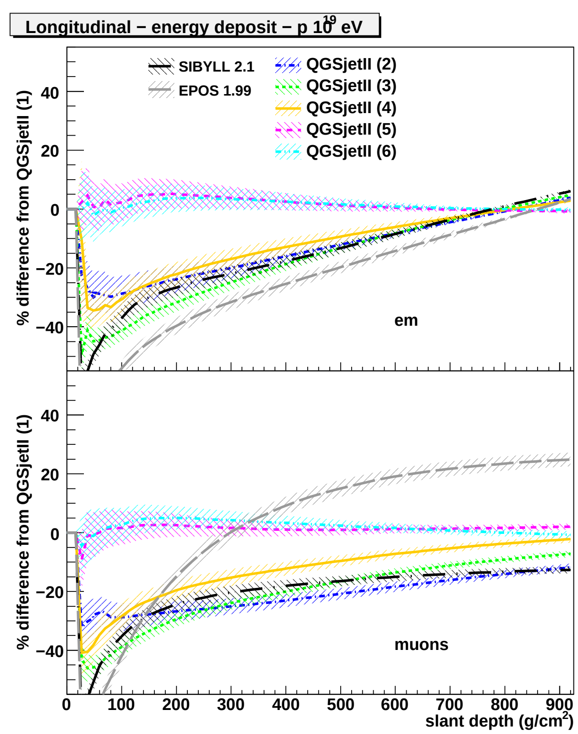

Figure 3. Average percentage difference (to QGSJET standard) of the longitudinal energy deposit electrons (top) and muons (bottom) for proton induced showers with a zenith angle of 20°.