Systematic uncertainties in air shower measurements from high-energy hadronic interaction models

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***Abstract*. 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). Model uncertainties are evaluated within the QGSjet-II 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. The crucial parameters relate to hard processes, string fragmentation, diffraction and baryon production. Results on inelastic cross sections, on secondary particle production and on the properties of air showers measured by ground detectors from energies of 10^{12} to 10^{19} eV are discussed.**

***Keywords*: hadronic interaction models, air showers, CORSIKA-QGSjet**

I. Introduction

Primary cosmic rays with energies $> 10^{14}$ eV can not be measured directly, due to their exceedingly low flux. Instead, their properties are reconstructed from the shape and particle content of the extensive air showers they produce in the atmosphere. The reconstruction is based on numerical models of the air shower development. As there is currently no reliable fundamental theory describing soft hadronic interactions at high energies, large systematic uncertainties limit the precision of the results. Most current hadronic interaction models use Gribov-Regge theory (GRT) of multi-Pomeron exchange between nucleons as basis for the treatment of high-energy, soft interactions, which are prevalent in air showers. Perturbative quantum chromodynamics (pQCD) can describe hard interactions with high $p_\perp$, which are rare in cosmic ray interactions, but become more important at higher energies. In addition, diffractive interactions, collisions of nuclei, and interactions and decays of all possible secondary particles at energies from MeV to beyond 10^{20} eV are needed for a complete simulation of an air shower. Nuclear interactions are usually deduced from nucleon-nucleon collision via the Glauber formalism. Particle tracking and their electromagnetic interactions are straight forward to simulate. The major problem is the seamless and coherent combination of the different parts of hadronic models. Different numerical codes implement the same theoretical ideas in different ways, with approximate agreement at lower energies where collider data are used for tuning, but diverging in the region where extrapolations are required, e.g. to ultra high energies, or to very forward emission directions. In this paper we study the systematic uncertainties, within the QGSjet-II-3 model ([1], released in 2006), due to the variation of some crucial model parameters within the limits still allowed by collider data. The results of the model variation (options 2-6) are compared with predictions with the standard version of QGSjet-II (option 1), SIBYLL 2.1 [2] and the new EPOS 1.99 model [3]. The distinctive feature of EPOS is an enhanced baryon production, in agreement with data from heavy ion colliders, which leads to more energy in the muonic component of showers. The standard versions of these models are available in the framework of the CORSIKA 6.735 air shower simulation package [4].

II. Parameter Variations in QGSjet-II

The crucial model parameters relate to the treatment of diffraction, the cut-off between hard and soft interactions and the distribution of momentum in secondary particles. Six versions of the QGSjet-II model have been created, with varying parameter settings, and tuned to reproduce the collider data within errors. The effects of these variations are then investigated for both single interactions and air showers as a whole. The first option (1) corresponds to the standard parameter settings of QGSjet-II (see Tab. I).

Diffractive interactions are very important for the shower development, as they transport the primary energy effectively through the atmosphere. Both, projectile

option	diffraction		Q_0^2	BJM	SE
	$\frac{\lambda_1}{\lambda_2}(p)$	$\frac{\lambda_1}{\lambda_2}(\pi)$	(GeV^2)		
1 (std)	4	4.7	2.25	on	0.5
2	**9**	4.7	2.25	on	0.5
3	4	4.7	**4**	on	0.5
4	4	4,7	2.25	**off**	0.5
5	4	4.7	2.25	**off**	**0.7**
6	4	**3**	2.25	on	0.5

TABLE I
Parameter settings of six options of QGSjet-II. Option 1 represents the standard settings of QGSjet-II (See text for explanation.)

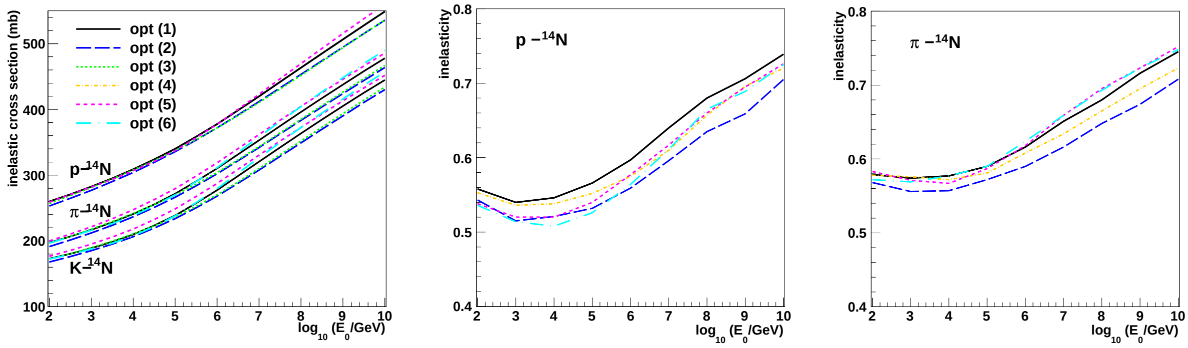

Fig. 1. Left: inelastic hadron-nitrogen cross sections for the QGSjet-II options. Centre and right: inelasticity of p-nitrogen and π-nitrogen.

and target nucleons can undergo low-mass diffraction excitation. The strength of diffraction is regulated by two constants λ_1 and λ_2, relating to the total cross sections and the rate of diffractive interactions. The parameters are varied in two different ways to increase the proportion of diffractive events and influence the rise with energy of total inelastic hadron-hadron and hadron-nucleus cross sections. In the default version of QGSjet-II (option 1) the corresponding ratios are $\frac{\lambda_1}{\lambda_2}(p) = 4$ for protons and $\frac{\lambda_1}{\lambda_2}(\pi) = 4.7$ for pions and kaons. In option 2 we enhance low-mass diffraction by choosing $\frac{\lambda_1}{\lambda_2}(p) = 9$, and in option 6 we leave proton diffraction unchanged but decrease diffraction of pions and kaons, $\frac{\lambda_1}{\lambda_2}(\pi) = 3$.

QGSjet is a GRT model. It simulates the interactions as sum of a soft and a semi-hard (QCD) part where the cut-off value Q_0^2 denotes the transition from the semi-hard ($|q|^2 > Q_0^2$) to the soft ($|q|^2 < Q_0^2$) part of the cascade. The performance of the model depends strongly on this parameter and on the parton distribution function obtained from deep inelastic scattering. As the semi-hard contribution rapidly increases with energy, one can significantly reduce the energy rise of the total and inelastic cross sections and the secondary particle production when this cut-off is increased from its default value 2.25 GeV^2 to 4 GeV^2, as done in option 3.

Option 4 and 5 vary the energy-momentum partition between elementary production processes and string fragmentation. In option 4 the "baryon junction" mechanism (BJM), related to di-quark valence quark interactions, is switched off, and in option 5, in addition the string end (SE) distribution parameter was modified from the default value 0.5 to 0.7, both entailing a more pronounced leading particle effect in high energy interactions. For each set a re-tuning of other model parameters was performed to keep agreement with accelerator data. In particular, for the option 5 a significant modification of the string fragmentation procedure was necessary to compensate the decrease of particle multiplicity due to shorter strings. The parameter settings of the various options are listed in Tab. I.

While the parameters investigated here are certainly crucial ones, it is not clear whether they are the only ones that matter. The comparison with EPOS shows that there are other parameters which can influence significantly the shower properties and consequently affect the interpretation of air shower experiment.

III. Single Interactions

Overall, for all options a good agreement between the available data and the simulations was achieved. Fig. 1 shows the inelastic hadron-nitrogen cross sections and the inelasticity of p-nitrogen and π-nitrogen collisions as function of energy, for the QGSjet options. Even at highest energies the differences between the options are moderate. The differences between the QGSjet models and SIBYLL and EPOS are much larger.

IV. Air Showers

Showers were simulated at energies of 10^{12} eV, 10^{15} eV and 10^{19} eV, i.e. at typical energies measured by Cherenkov telescopes, KASCADE and the Pierre Auger Observatory, respectively. The first interaction points were fixed, at typical values for the respective primary energy, to exclude the shower-to-shower fluctuations due to the varying point of first interaction. For each energy the average longitudinal development and lateral distribution of particles at ground level were calculated. Also characteristic observables were evaluated, such as the average values of the atmospheric depth of the shower maximum, $X_{\max}$, the particle number at shower maximum, $N_{\max}$, the electron-to-muon ratio at ground level, the energy hat would be released in an Auger-like water Cherenkov detector at 1000 m core distances (S_{1000}) and the time in which the integrated signal grows from 10% to 50%, $t_{1/2}$. Simulations were also made with the SIBYLL 2.1 and EPOS 1.99 models to allow comparisons between the scale of the uncertainties due to parameter variations within a model, and due to model-to-model variations.

At 10^{12} eV very little variation is found for the QGSjet options, with differences being $\leq$ 10% for all quantities investigated. This is not surprising as the energy is close to the accelerator energies at which the models have been tuned.

In Fig. 2 differences in electron and muon numbers as function of core distance (lateral distribution) and in ionization energy deposit as a function of atmospheric depth (longitudinal distribution), are shown for 10^{15} and

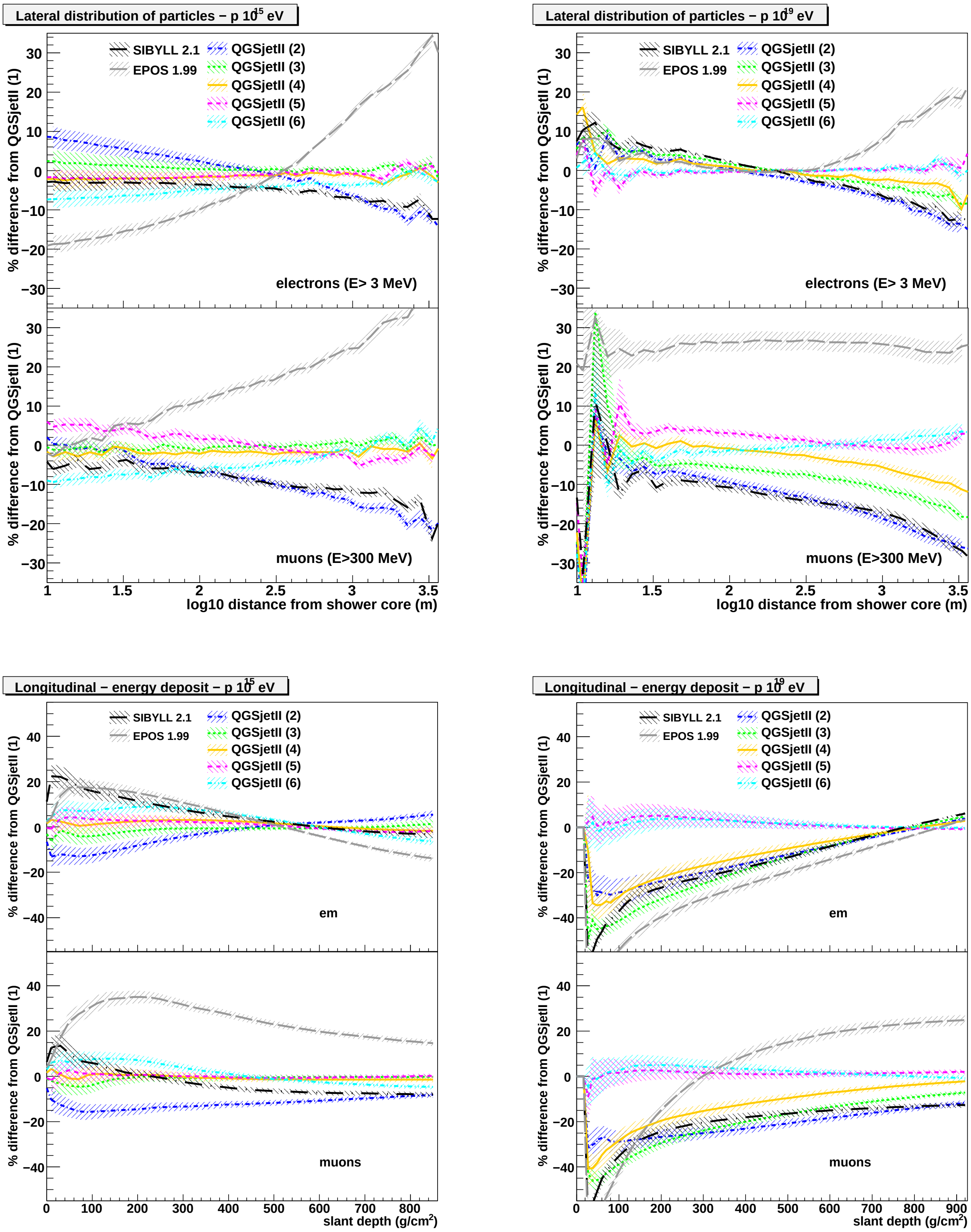

Fig. 2. Average percentage difference (compared to the standard QGSjet-II model; e.g. $(X_i - X_{\rm std})/X_{\rm std}$) of the particle number as function of the core distance at ground level for electrons and muons (upper plots) and of the ionization energy deposit as a function of the atmospheric depth for the em component and for muons (lower plots). Results refer to 300 vertical proton showers of $E = 10^{15}$ eV (left) and 100 proton showers at 20° with $E = 10^{19}$ eV (right).

	10^{15} eV; 0°			10^{19} eV; 20°			
Model	N_e/N_μ	$X_{\max}$ (g/cm^2)	$N_{\max}(10^3)$	S_{1000} (GeV)	$t_{1/2}$ (ns)	$X_{\max}$ (g/cm^2)	$N_{\max}(10^7)$
QGSjet-II (1)	20.8 ± 0.4	546 ± 3	566 ± 4	10.01 ± 0.09	373.2 ± 1.4	773 ± 4	647 ± 2
QGSjet-II (2)	24.0 ± 0.5	552 ± 4	577 ± 4	8.86 ± 0.11	385.7 ± 1.7	794 ± 4	642 ± 2
QGSjet-II (3)	21.6 ± 0.8	548 ± 4	571 ± 3	9.38 ± 0.09	382.2 ± 1.4	796 ± 4	645 ± 2
QGSjet-II (4)	21.0 ± 0.5	542 ± 3	574 ± 3	9.68 ± 0.10	378.9 ± 1.4	791 ± 5	645 ± 2
GGSjet-II (5)	20.1 ± 0.4	542 ± 3	567 ± 3	10.01 ± 0.08	371.6 ± 1.4	771 ± 4	644 ± 2
QGSjet-II (6)	20.6 ± 0.5	534 ± 3	579 ± 3	10.07 ± 0.10	372.9 ± 1.3	772 ± 4	648 ± 2
SIBYLL 2.1	22.1 ± 0.5	539 ± 3	571 ± 4	9.00 ± 0.09	388.0 ± 1.7	797 ± 4	651 ± 2
EPOS 1.99	16.3 ± 0.6	528 ± 3	564 ± 4	11.61 ± 0.18	368.9 ± 2.0	803 ± 4	630 ± 2

TABLE II
Estimated mean observables for proton showers of energy 10^{15} eV at 0° and 10^{19} eV at 20°.

10^{19} eV. At 10^{15} eV differences between the QGSjet model variations are less than ±10% at core distances of 10 to 1000 m for electrons and muons. The longitudinal distributions show very good agreement around the shower maximum (~550 g/cm^2) and differences up to ±10% at ground level. SIBYLL lies well within the spread of the QGSjet predictions, but EPOS shows a very different behaviour with many more particles at large core distances and overall about 20-30% more muons. At ground level there are 15% fewer electrons and 15% more muons than the reference model. The differences are big enough that comparison with KASCADE data should be able to tell which of the models fits better. At 10^{19} eV the deviations from the standard model are largest, as expected, as the parameter extrapolations from collider energies are at their largest. Deviations in the lateral distributions of electrons and photons are less than +10% within 1000 m from the shower axis. For muons the variations within the QGSjet family are less than 20% at 1 km core distance, but all options produce always smaller muon numbers than the standard version. SIBYLL gives almost the same results for electron and muon lateral distributions as QGSjet option 2, the version with the enhanced proton diffraction. For the longitudinal distribution, the QGSjet options 2, 3 and 4 and SIBYLL have markedly lower particle numbers, and energy deposit (40-20%) in the upper part of the shower than the standard. Again, EPOS is clearly different, with 25% more muons at ground level for all core distances. The QGSjet and SIBYLL muon numbers at ground are within 0 to -15% from the standard version. The EPOS electron numbers at ground are in agreement with the other models.

Significant differences are also seen in S_{1000}, a common observable used for energy reconstruction in the 10^{19} eV region (see Tab. II). An energy scale based on option 2 would give ~10% higher cosmic ray energies than one using on the standard QGSjet version, while EPOS would give 16% smaller energies. The actual differences in $t_{1/2}$ and $X_{\max}$, which are variables used for composition analyses, are less than 5%. Again SIBYLL is similar to the QGSjet simulations, whereas EPOS is very different.

V. DISCUSSION

Analysis of shower simulations demonstrates the increase in the systematic uncertainties introduced by the parameter variations as the primary particle energy increases, and with it the extrapolation needed from the energy range covered by collider data. At all primary energies the largest effects are observed from the increase of the rate of diffraction for protons and pions making diffraction the most important parameter for the overall development of the shower. The lateral distribution of QGSjet option 2 is very similar to that of SIBYLL at both 10^{15} and 10^{19} eV, suggesting that one of the major differences between the development of showers using the two models may lie in the rate of diffraction.

None of the parameter variations in QGSjet was able to produce a larger muon number than the standard version. More muons seem to be required to reproduce data from experiments directly measuring muon numbers such as KASCADE and HiRes-MIA and may also explain the differences between energy reconstruction based on fluorescence detection and on Monte Carlo simulations seen in the Pierre Auger Observatory [5]. EPOS seems to address the muon deficit problem, but requires a different energy scale. EPOS is a relatively new model and still has to prove its qualities by being compared in detail to results from different (past and present) experiments at TeV to EeV energies. The model uncertainties at high energies are of a size that will make analyses of nuclear composition rather difficult, as differences between proton and iron induced showers are not much larger than the uncertainties from the models. This study illustrates that parameter variation within one model usually do not capture the full variance possible between models. Convergence of models over the years, as experienced between QGSjet and SIBYLL in the last decade, does not necessarily reduce the systematic uncertainty inherent to hadronic interaction models. New data from LHC and RHIC have the potential to constrain the models, but only a coherent description of cosmic ray and hadronic interaction physics will be proof of the correct interpretation of cosmic ray data.

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