Systematic Uncertainties in High-Energy Hadronic Interaction Models

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Abstract

Hadronic interaction models for cosmic ray energies are uncertain since our knowledge of hadronic interactions is extrapolated from accelerator experiments at much lower energies. At present most high-energy models are based on Gribov-Regge theory of multi-Pomeron exchange, which provides a theoretical framework to evaluate cross-sections and particle production. While experimental data constrain some of the model parameters, others are not well determined and are therefore a source of systematic uncertainties. In this paper we evaluate the variation of results obtained with the QGSJET model, when modifying parameters relating to three major sources of uncertainty: the form of the parton structure function, the role of diffractive interactions, and the string hadronisation. Results on inelastic cross sections, on secondary particle production and on the air shower development are discussed.

1. Introduction

Cosmic rays at energies $\gg 10^{14}$ eV cannot be recorded directly but are measured via the extensive air showers (EAS) of secondary particles they produce in the Earth's atmosphere. Direction, energy and mass of the primary particles have to be deduced from the properties of the showers as observed by the experimental setup. Since the relation of the primary properties to those of the air showers is complicated the event reconstruction relies on numerical models which simulate the interaction and particle transport through the air in great detail. A major source of uncertainty in those models is the simulation of the nuclear and hadronic interactions, cross sections and particle production, at very forward emission angles and at energies far beyond what can be examined at man-made accelerators. Specifically, it is not well defined how to combine consistently soft (non-perturbative) interactions, which are most important for EAS, and hard (QCD-type) interactions, which become prevalent with rising energy. The model uncertainty translates into a systematic error of every physics result that is inferred from experimental data, and is, unfortunately, for some cosmic ray analyses already the dominant error. In the past various independent shower programs and hadronic interaction models have been constructed. Usually they

pp. 515–518

are tuned at lower energies to reproduce the existing accelerator data and are then extrapolated in various ways to higher energies, small emission angles and nuclear projectiles and targets. In principle the differences between their predictions allow an estimate of the size of the systematic uncertainties. However, the models are not really independent. Most of them use the same theoretical framework as a basis and the actual differences come from differences in its implementation and in the modelling of extensions to the basic processes, such as the nuclear collisions, diffraction or string fragmentation. Therefore, the differences between existing models are likely just a lower limit of the systematic uncertainties. The theoretical model at the basis of most current air shower programs is the Gribov-Regge theory (GRT) of multi-Pomeron exchange. It has proven very successful in describing many cosmic ray experiments over a wide range of energies [5]. While a number of free parameters of those models are fixed by the overall structure of GRT and by tuning the simulations to reproduce experimental data, there are a few major unknowns at the core of the models that dominate the uncertainties. They are: (i) the parton (quark & gluon) momentum distributions, (ii) treatment of diffraction, and (iii) string hadronisation. In this paper we examine the influence these quantities have on inelastic cross sections and particle production, and, thus, on the EAS development.

2. Model variants

To study the systematics, CORSIKA [2] with QGSJET [3,4] as hadronic interaction model was used. For all three unknowns mentioned above the driving parameters were identified and values were chosen that somehow map out the range from conservative (standard) values to "extreme cases". The form of the parton distribution function (PDF) inside a nucleon for small values of Feynman x determines crucially the rise of total and inelastic cross sections at high energies. In principle a PDF can be inferred from hadron structure functions measured in deep inelastic scattering. However, this leads directly to a contradiction with measured hadronic interaction cross sections. To solve this one is forced to consider non-linear screening corrections to the interaction dynamics, i.e. enhanced Pomeron diagrams [1,6]. On the other hand, the form of the PDF depends on the choice of so-called factorisation scale M_{F}^2 at which the PDF should be evaluated for the production of partons of given $p_\perp$, i.e. $M_{\mathrm{F}}^2 = f \cdot p_\perp^2$ [1]. Also the contribution of semi-hard processes, leading to high-$p_\perp$ parton jets, depends strongly on the choice of the transverse momentum cutoff Q_0^2 which defines the border between non-perturbative "soft" physics ("soft" Pomeron exchange), and perturbative parton evolution (QCD). Choosing a higher Q_0^2 or a smaller f, decreases the semi-hard contribution to the cross sections. Diffraction is difficult to measure at accelerator experiments since its secondary particles emerge at very small angles to the incoming beam. Diffractive events can be simulated in various

Table 1. Parameter settings for the 5 options of QGSJET investigated. (see text)

option	1	2	3	4	5
Q_0^2 (GeV^2)	2.25	2.25	9	9	9
f	1/4	1/4	1	1	1
K	1.5	1.5	2	2	2
α	-0.5	-0.5	-0.5	-0.7	-0.9
Λ	1.5	1.5	1.6	1.6	2.7
Diffraction	2-comp.	quasi-eik.	2-comp.	2-comp.	2-comp.

ways, and since diffractive interactions leave the projectile virtually unchanged, they can transport energy effectively deep into the atmosphere. A modified fraction of diffractive events, therefore, influences the shower development markedly. Finally, there is a basic uncertainty concerning the energy-momentum partition between particle production processes in hadronic (and nuclear) collisions and the treatment of hadronisation for those processes. In practice, one chooses different momentum distributions for parton ends of the strings, which is governed by the effective exponent α of the distribution at low x, and the choice of string tension, governed by Λ, for the string fragmentation procedure [1,6]. Though one can describe available data at low energies choosing either "valence-like" string distributions ($\alpha \approx -0.5$) and low string tension or using "sea-like" distributions ($\alpha \approx -1$) and high string tension. The two settings give quite different results at very high energies: valence-like strings produce flat and long distributions of secondaries in rapidity, while sea-like strings produce particles mostly in the central rapidity region. 5 non-standard options of QGSJET have been constructed with the parameters as listed in Table 1. Each option was tuned to reproduce the experimental data at lower energies. All options are characterised by a steeper (improved) gluon momentum distributions compared to the original model version and lead therefore to a steeper energy increase of both total interaction cross section and of multiplicity of secondary hadrons. Opt. 1 and 2 employ a comparatively low Q_0^2 and f. Correspondingly the factor K, which accounts for higher order QCD corrections, is set to 1.5. The difference between them is the treatment of diffraction: opt. 1 uses the multi-component approach with two active diffraction states [3], whereas opt. 2 is based on the quasi-eikonal approach from the standard version of QGSJET [4]. While giving essentially equivalent diffraction spectra for low energy interactions the two approaches differ at much higher energies and for hadron-nucleus reactions. The amount of diffractive events is reduced in opt. 1, where diffraction production corresponds to just peripheral interactions. Opt. 3 is similar to opt. 1, but employs a higher Q_0^2, f and K. Opt. 4 and 5 are similar to opt. 3 but use different string end distributions than opt. 1-3. Opt. 3-5 have increased string tension. Apart from the parameters mentioned here, a number of auxiliary parameters have been adjusted for each option to improve the agreement with data at low energies.

3. Preliminary results

The cross sections of all options agree at low energies but diverge above about 10^{16} eV (see fig. 1). As expected, opt. 5 with higher Q_0^2 and f produces about 20% higher cross sections than opt. 2, with enhanced diffraction. However, the variation between the QGSJET options is smaller than the variation between other models (e.g. DPMJET and SIBYLL). The spread in the average charged multiplicity $\langle N_{\mathrm{ch}} \rangle$ between the options is about 20% at 10^{19} eV and approaching 100% above 10^{20} eV. Also here the variation between opt. 1-5 is much smaller than the differences to other models (see e.g. [5]). The e/γ densities of 10^{19} eV proton showers at ground level at about 1 km core distance vary within 20% (opt. 2 more opt. 5), whereas muon numbers change by about 30% (opt. 5 more opt. 2). As expected opt. 5 reaches the shower maximum highest in the atmosphere and opt. 2 lowest. Proton showers simulated with CORSIKA and the 5 options of QGSJET exhibit differences in x_{max} of the order of 30 g/cm^2. Due to limited statistics these numbers have still large errors. Nevertheless, it seems that even substantial variation of parameters within one specific model cannot produce the systematic differences between different models.

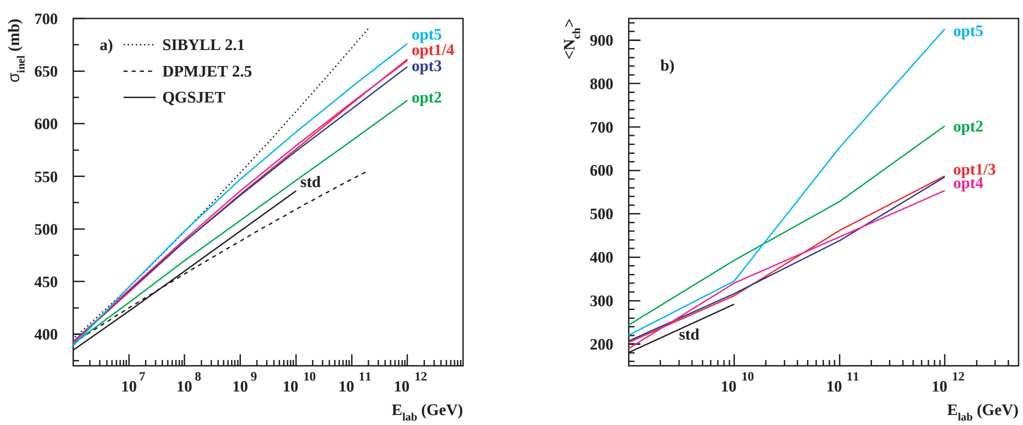

Fig. 1. a) Cross section for inelastic proton-air collisions, σ_{inel}, for the 5 options and some models used in CORSIKA. b) Average charged multiplicity, $\langle N_{\mathrm{ch}} \rangle$, in p-$\bar{\mathrm{p}}$ collisions.

Support from British Council and from BMBF (Grant 05 CU1VK1/9) is highly appreciated.

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