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Hadronic Interactions in QGSJET-II: Physics and Results

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A new hadronic interaction model QGSJET-II is presented. The key feature of the model is the treatment of non-linear interaction effects described by enhanced Pomeron diagrams, which are re-summed to all orders. This allows us to employ realistic parton momentum distribution functions, measured in deep inelastic scattering experiments, while being consistent with hadronic cross section measurements. On the other hand, the model tuning to the data of fixed target experiments has been significantly improved compared to original QGSJET. The model predictions for extensive air shower (EAS) characteristics are analyzed, in particular, concerning the energy dependence of shower maximum position and of EAS electron and muon numbers.

1. Introduction

During the last decade a significant progress has been observed in experimental studies of high energy cosmic rays (CR) by means of extensive air shower (EAS) techniques. To a large extent this was due to a new strategy of data analysis, most consequently put forward by the KASCADE experiment [1], which devoted significant efforts to achieve a proper understanding of their measurements, based on extensive simulation studies of both nuclear-electro-magnetic cascading process in the atmosphere and of particle interactions in the ground detectors. Thus, contemporary EAS experiments greatly resemble their accelerator counterparts: actively using simulation tools, in particular the CORSIKA program [2], with different particle interaction models employed, they significantly enhance the accuracy of data analysis, which allows to obtain impressive results. On the other hand, studying correlations of various shower characteristics allows one to discriminate between available interaction models and to increase the quality of the simulation procedures.

An important part of the latter are so-called hadronic interaction models. Being calibrated at comparatively low energies, mainly with the data of fixed target experiments, they have to extrapolate corresponding knowledge over many energy decades, thus relying heavily on the underlying theoretical approach. For practical applications the most powerful one proved to be the Gribov-Regge scheme [3], which treats high energy hadron-hadron (hadron-nucleus, nucleus-nucleus) collisions as multiple scattering processes; elementary re-scatterings correspond to microscopic parton cascades and are described phenomenologically as Pomeron exchanges.

Among a number of hadronic Monte Carlo (MC) generators, developed in this framework, the QGSJET model [4] has been widely used in the field by a large number of experimental collaborations. This MC generator is essentially based on the physics picture of the Quark-Gluon String model [5]. The latter supplements the general Gribov-Regge treatment with a specific hadronization model: each elementary particle production process is assumed to give rise to creation and fragmentation of two strings, with the corresponding parameters being expressed via intercepts of secondary Regge trajectories. In turn, the basic innovation of the QGSJET model has been an explicit treatment of perturbative parton evolution in an elementary re-scattering process. Thus, a general Pomeron is represented there by a sum of the ”soft” Pomeron contribution, corresponding to a pure non-perturbative (low p_t) parton cascade, and of the ”semi-hard Pomeron”, composed of a piece of QCD ladder sandwiched between two soft Pomerons [4], – for a cascade which at least partly develops in the high p_t region. The mentioned semi-hard contribution dominates hadronic interactions in the very high energy limit. Consequently, the approach allows to relate high energy asymptotics of hadronic scattering amplitudes to the perturbative QCD evolution and thus to enhance the predictive power of the model.

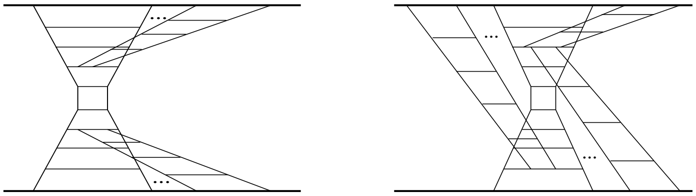

Figure 1. Examples of diagrams which give rise to non-linear parton effects.

However, an essential drawback of the whole scheme is that individual re-scattering processes are assumed to proceed independently, with any non-linear interaction effects being completely neglected. This approximation is invalid in the limit of very high energies and small impact parameters of the interaction, where one inevitably encounters high parton density effects: individual parton cascades start to overlap and to interact with each other. Due to the lack of such mechanisms present Gribov-Regge models can be considered as rather effective ones; there is no possibility to employ realistic parton momentum distribution functions (PDFs), measured at the HERA collider, without being in contradiction with observed energy behavior of total proton-proton cross section and of the multiplicity of secondary particles produced. In particular, the original QGSJET model is based on rather ”flat” (pre-HERA) PDFs.

2. Hadronic interactions in the QGSJET-II model

To obtain a reliable description of hadronic interactions at very high energies, one necessarily has to account for non-linear interaction effects, which appear to be of extreme importance at sufficiently high parton densities. At microscopic level, this amounts to consider contributions of diagrams of Fig. 1, corresponding to mutual interaction of individual parton cascades, the latter being treated as merging of parton ladders [6]. In the Gribov-Regge scheme such parton cascades are described by Pomeron contributions whereas multi-ladder vertices correspond to Pomeron-Pomeron interactions [7]. Using a phenomenological parameterization for the latter one can re-sum all significant contributions of that kind and to develop a self-consistent MC generation procedure for hadronic and nuclear collisions [8]. As a result, the approach allows to resolve the inconsistency between the realistic PDFs and the observed hadronic cross sections, as shown in Fig. 2.

In addition to this main development, model calibration to the data of fixed target experiments has been significantly improved, in particular, concerning secondary particle multiplicity, see Fig. 3.

Though parton densities of QGSJET-II model increase much faster in the small Feynman x limit than in

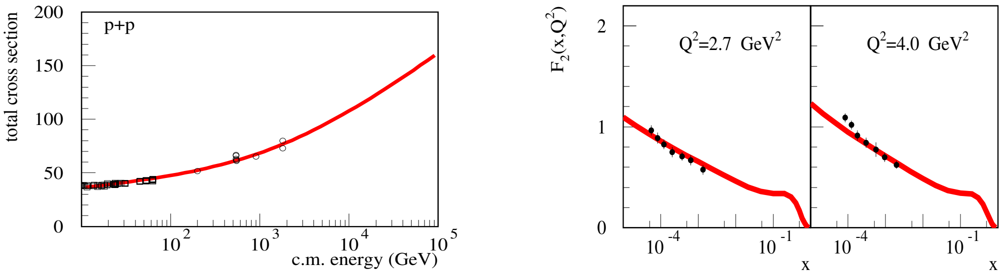

Figure 2. Total pp cross section (left) and proton structure function F_2 (right) as calculated in the QGSJET-II model compared to experimental data [9, 10].

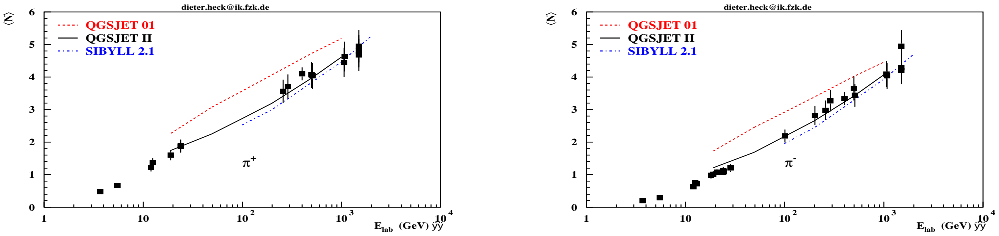

Figure 3. Multiplicity of positive (left) and negative (right) pions in proton-proton collisions as calculated with the QGSJET-II, QGSJET, and SIBYLL models.

original QGSJET, being now fixed by the measured structure function $F_2(x, Q^2)$, the corresponding effect is essentially compensated by the non-linear screening corrections in what concerns proton-proton cross sections and secondary particle multiplicity. Similarly, the proton-air cross section of the QGSJET-II model is very similar to old QGSJET results. The corresponding energy increase is significantly slower than, for example, in the SIBYLL model [11], where non-linear effects are introduced via an energy-dependent p_t-cutoff for semi-hard processes and thus are neglected for non-perturbative (low p_t) processes.

On the other hand, the influence of non-linear effects on particle production in hadron-nucleus and nucleus-nucleus collisions is much stronger compared to the hadron-hadron case, the corresponding corrections increasing with projectile and target mass numbers. In particular, the model appears to be in agreement with the data of the RHIC collider on the multiplicity of secondary hadrons produced in central nucleus-nucleus collisions, as shown in Fig. 4. In turn, for hadron-air collisions the inelasticity and multiplicity are significantly reduced compared to QGSJET results, being in a wide energy range even lower than in the SIBYLL model, see Fig. 5.

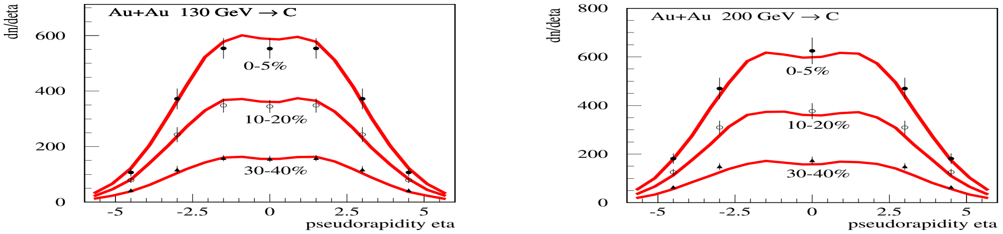

Figure 4. Multiplicity of charged particles in $Au-Au$ collisions of 130 AGeV (left) and 200 AGeV (right) c.m. energies for different event "centrality" selections (indicated in the Figure as the percentage of all minimum bias events) as calculated in the QGSJET-II model compared to the data of BRAHMS collaboration [12].

3. Impact on extensive air shower characteristics

The discussed reduction of secondary particle production in hadron-nucleus and nucleus-nucleus interactions makes a strong impact on the calculated EAS characteristics. The position of the shower maximum $X_{\max}$ is systematically shifted deeper in the atmosphere compared to original QGSJET, as seen in Fig. 6(left). The calculated electron number at sea level, being strongly correlated with $X_{\max}$, is significantly enhanced – correspondingly by about 20% and 30% for vertical proton- and iron-initiated showers of energy 10^{15} eV; at the energy 10^{19} eV this reduces to 10% effect compared to QGSJET results. On the other hand, one obtains a sizable reduction of EAS muon number, as shown in Fig. 6(right), with the difference between the QGSJET-II and SIBYLL models being only about 10% at highest CR energies.

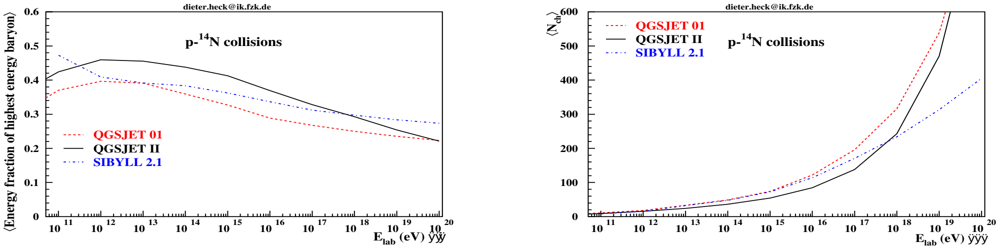

Figure 5. Elasticity and multiplicity in $p-{}^{14}N$ collisions as calculated with QGSJET-II, QGSJET, and SIBYLL.

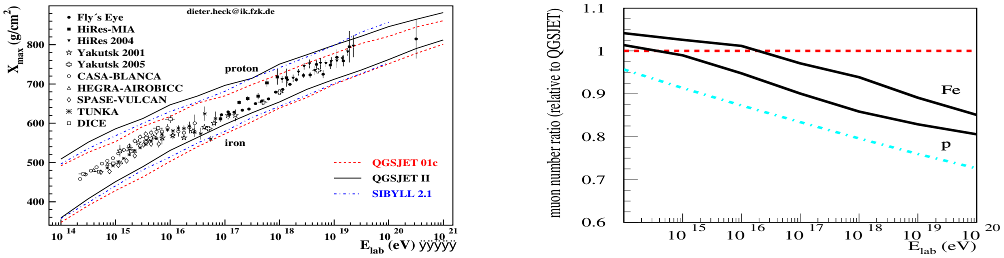

Figure 6. Left: position of the shower maximum for proton- and iron-induced EAS, as calculated with QGSJET-II, QGSJET, and SIBYLL, compared to cosmic ray data [13]. Right: ratio of EAS muon number ($E_\mu > 1$ GeV) as calculated with QGSJET-II (for p- and Fe-induced EAS) and SIBYLL (for p-induced EAS) with respect to QGSJET results.

In conclusion, the main feature of QGSJET-II is a microscopic treatment of non-linear interaction effects. This allows us to obtain a consistent description of hadronic cross sections and parton momentum distributions and to account for non-linear screening effects in individual hadronic and nuclear collisions. The discussed developments provide a more solid ground for model extrapolation towards highest CR energies.

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