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A new approach to modeling cosmic ray interactions

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We present a new approach to modeling cosmic ray (CR) interactions, which relies on a very basic interaction picture, while using a reasonable and transparent formalism, in the framework of the Reggeon Field Theory. Our main motivation is to provide a new CR interaction model characterized by relatively transparent physics, sufficient parameter flexibility, and high computational efficiency, which can be easily managed by external users, including a re-tuning of the model parameters. Such a model can be used for studying potential modifications of the interaction treatment, necessary for describing particular sets of data on extensive air showers (EAS) initiated by high energy cosmic rays, at a microscopic level, thereby keeping a consistency with general restrictions, like the unitarity, energy-momentum and charge conservation, Lorentz and isospin invariance. Importantly, this should allow one to study a compatibility of such modifications with relevant accelerator data. The preliminary version of the new model is presented and its results for particle production and for EAS characteristics are discussed.

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1. Introduction

Studies of ultra high energy cosmic rays (UHECRs) are traditionally performed using indirect detection techniques: inferring the properties of primary cosmic ray (CR) particles from measured characteristics of extensive air showers (EAS) – nuclear-electromagnetic cascades initiated by interactions of primary CRs in the atmosphere of the Earth. Consequently, such experimental activities imply a numerical modeling of EAS development. A special role in EAS simulations is played by Monte Carlo (MC) generators of hadronic interactions, which form a bridge from accelerator experiments studying such interactions in great detail to the CR field and which are responsible for the description of EAS backbone – the cascade of nuclear interactions of both primary CRs and of produced secondary hadrons in the atmosphere [1]. MC generators of CR interactions have been considerably improved over the past decades, reaching a high level of sophistication [2–4], while the parameters of those models have been tuned based on a variety of accelerator data.

However, recent UHECR studies revealed that a number of experimental observations can not be consistently described using present CR interaction models [5–7]. Because of their considerable complexity, such models are typically regarded by experimental groups as "black boxes", since a retuning of model parameters by external users has not generally been envisaged. This motivated one to consider an *ad hoc* rescaling of the predictions of EAS simulations for particular air shower observables (e.g., [8]): to approach the experimental observations. While providing useful hints on how the simulations should be changed in order to better describe the EAS data, such a practice suffer a lack of consistency. First of all, doing so one neglects correlations between different EAS observables, which follow from a microscopic description of the interaction process. Secondly and perhaps more importantly, proceeding that way one is unable to check whether the desirable modifications are sensible in view of existing ample experimental data on the properties of hadron-proton and hadron-nucleus (nucleus-nucleus) collisions at high energies. Moreover, certain extreme modifications may come into conflict with basic conservation laws.

All of the above motivated us to develop a new relatively simple MC generator of hadronic interactions, staying within a very basic interaction picture while using a reasonable and transparent formalism, within the Reggeon Field Theory (RFT) approach [9, 10]. Physics-wise, we are essentially coming back to the concepts of the original Quark-Gluon String and Dual Parton models [11, 12]. Therefore we use the name QGSb [Quark-Gluon Strings (basic)] for our model. The main motivation for our work is twofold. Firstly, we wish to have a model characterized by a sufficient parameter freedom, constrained mainly by accelerator data, as a basic framework for studying uncertainties for EAS predictions. Secondly and more importantly, we want to provide experimental teams with a model characterized by relatively transparent physics and sufficient parameter flexibility, which can be used for studying potential modifications of the interaction treatment, necessary for describing particular sets of EAS data, at a microscopic level, thereby keeping a consistency with general restrictions, like the unitarity, energy-momentum and charge conservation, Lorentz and isospin invariance. The goal is to allow the experimentalists to check the "cost" of describing particular EAS data sets, in terms of (in)consistency with accelerator data.

Here we present the first version of the QGSb MC generator, designed to treat hadronic interactions in the "standard" high energy range: above ~ 100 GeV laboratory energy. In the cause of its development, we used and suitably adapted various technical procedures of the QGSJET(-

II/III) models [13–15], e.g., regarding calculations of interaction cross sections, generation of nucleon distributions in nuclei, energy-momentum partition between multiple scattering processes, string fragmentation, production of nuclear fragments, etc.

2. Basic physics

High energy hadronic collisions are predominantly multiple scattering processes, being mediated by parton cascades developing between the interacting projectile and target hadrons (nuclei). For such parton cascades, we use an effective macroscopic description – treating them as Pomeron exchanges. Here we have to take into account two mechanisms which impact the "parton content" of the Pomeron. First, with increasing energy, the contribution of semihard processes corresponding to parton cascades developing, at least partly, in the domain of high parton virtualities becomes important. Instead of treating such perturbative cascades explicitly, we consider two contributions to the Pomeron amplitude: the one corresponding to "soft" (low virtuality) parton cascade, characterized by a rather slow energy rise, and the "semihard" one quickly rising with energy [16]. Further, at sufficiently high energies, an important role in the interaction dynamics is played by nonlinear effects arising from "splitting" and "fusion" of parton cascades, both real and virtual ones, typically described as Pomeron-Pomeron interactions (e.g., [17]). Here we assume that the main consequence of such nonlinear corrections is to "renormalize" the Pomeron amplitude [18], yielding, in particular, a small intercept of the "soft" Pomeron component, corresponding to the above-mentioned slow energy rise of the corresponding contribution. Thus, we expect that our two-component Pomeron amplitude effectively takes into account the effects of both mechanisms: the perturbative parton cascading and the nonlinear corrections to the interaction dynamics, in what concerns the predictions for EAS characteristics.

To account for inelastic screening effects [10], we rely on the Good-Walker approach [19]: considering hadrons to be represented by superpositions of a large number of Fock states characterized by different transverse sizes and by different couplings to the Pomerons, assuming a coupling to be proportional to the transverse area of the state. It is noteworthy that this mechanism gives rise to three important effects: a milder energy rise of the interaction cross sections, especially, for hadron-nucleus collisions, the emergence of low mass diffraction, and larger fluctuations for secondary particle production.

Having defined the Pomeron exchange amplitude, one can calculate total, elastic, and inelastic cross sections for hadron-proton, hadron-nucleus, and nucleus-nucleus collisions. Moreover, considering unitarity cuts of the corresponding elastic scattering diagrams and applying the so-called Abramovskii-Gribov-Kancheli cutting rules [20], one is able to obtain partial cross sections for various inelastic final states corresponding to having precisely n "elementary" production processes (n "cut Pomerons"), hence, to sample "macro-configurations" of the collisions, using the MC method. However, for treating secondary particle production, one has to define the hadronization procedure. In that respect, we traditionally assume that each cut Pomeron corresponds to a creation of a pair of strings of color field, stretched between constituent partons [(anti)quarks or diquarks] of the interacting hadrons [11, 12]. With such partons flying apart, the strings break up and hadronize via a creation of quark-antiquark and diquark-antidiquark pairs from the vacuum. Here we employ the string fragmentation procedure of the QGSJET model [13], the current implementation being described in [15]. While the parameters of this procedure can be expressed via intercepts of relevant Regge trajectories [21], we treat them as adjustable ones. In particular, since one expects important differences between soft and semihard parton cascades, notably, a higher parton density per unit rapidity for the latter, the string fragmentation parameters generally differ between the "soft" and "semihard" Pomerons.

There is a number of additional effects to be taken into account, notably, the high mass diffraction. While the corresponding self-consistent treatment requires an all-order resummation of enhanced Pomeron diagrams [22], here we rely on an effective approach: considering only the diffractive cut of the simplest triple-Pomeron graph describing an interaction between three "soft" Pomerons. The corresponding contributions are treated as parts of each cut Pomeron, with the respective relative weights.

Further, in view of its importance for EAS muon number predictions, one has to take into account t-channel pion exchange in the Reggeon-Reggeon-Pomeron ($\mathbb{RRP}$) configuration [23]. Here we improve the corresponding treatment of the QGSJET-III model [15], considering explicitly a rescattering of the virtual pion on the partner hadron (nucleus), including the corresponding inelastic and elastic scattering contributions and accounting for the impact parameter dependent absorptive corrections for the process.

To improve the description of forward hadron production, we consider also a t-channel exchange of f-Reggeon in the $\mathbb{RRP}$ configuration, using the same procedure as in the QGSJET-III model [15]: assuming the corresponding contribution to be a fixed part of the one for single cut Pomeron. Further, when treating the first hadron emission off a string attached to a "remnant" parton [diquark for a nucleon, light (anti)quark for a pion, and strange (anti)quark for a kaon], we introduce additional adjustable parameters – the weights for a strange quark-antiquark pair or a diquark-antidiquark pair, where relevant, creation from the vacuum, which differ from the standard string fragmentation parameters. Phenomenologically, those can be interpreted as being related to the "intrinsic strangeness" in nucleons or pions, and the "intrinsic baryonic content" of pions or kaons. While a more theoretically consistent approach would be to consider relevant Reggeon exchanges in the $\mathbb{RRP}$ configuration, with $\mathbb{R} = N, \Delta, K, K^*$, etc., we prefer to use the above-discussed phenomenological treatment since it is more economic parameter-wise and more intuitively understandable for a potential non-expert model user.

Overall, the available parameter freedom allowed us to achieve the quality of the description of soft particle production in hadronic collisions, which is comparable to the one of the current MC generators of CR interactions [2–4]. On the other hand, without an explicit treatment of perturbative parton cascades, one can not describe consistently the production of hadrons at large ($\gtrsim$ 2 GeV) transverse momenta. A more detailed description of the model and a comparison with relevant accelerator data will be provided elsewhere.

3. Selected results

The energy dependence of the total $\sigma^{\rm tot}_{pp}$ and elastic $\sigma^{\rm el}_{pp}$ proton-proton cross sections, obtained for the default set of the model parameters, is shown in Fig. 1 (left), while the one for the corresponding forward elastic scattering slope $B^{\rm el}_{pp} = d\ln(d\sigma^{\rm el}_{pp}/dt)/dt\big|_{t=0}$ is plotted in Fig. 1 (right). The correct description of the latter is also of importance since $B^{\rm el}_{pp}$ is proportional to the average impact

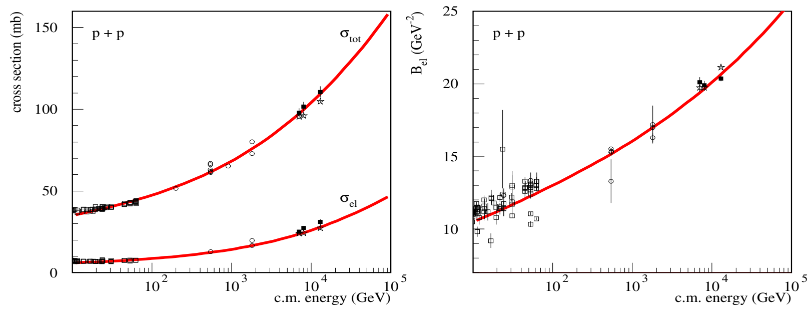

Figure 1: Calculated center-of-mass energy dependence of $\sigma^{\rm tot}_{pp}$ and $\sigma^{\rm el}_{pp}$ (left) and of $B^{\rm el}_{pp}$ (right), compared to experimental data [24] (points).

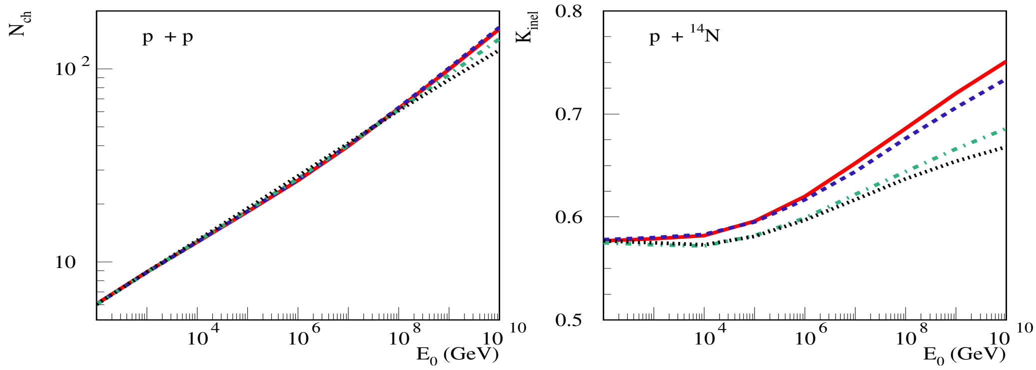

Figure 2: Laboratory energy dependence of the multiplicity of charged hadrons in pp collisions (left) and of the inelasticity of proton-nitrogen interactions (right), calculated using the different options of the hadronization procedure, corresponding to $\alpha_q = 0.5$, 0.7, 0.9, and 0.95 – solid, dashed, dash-dotted, and dotted lines, respectively.

parameter squared for pp collisions and thereby characterizes the "fatness" of the proton, i.e., the characteristic transverse area occupied by its parton "cloud", which, in turn, impacts the multiple scattering rate in proton-proton and, especially, proton-nucleus (nucleus-nucleus) collisions (see, e.g., the discussion in [25]).

When treating secondary hadron production, of significant importance is the choice of momentum distributions of constituent partons of interacting hadrons, to which strings of color field are attached. Indeed, this governs the energy dependence of the inelasticity $K_{\rm inel}$ of hadron-proton and hadron-nucleus collisions, which is the largest source of uncertainty regarding model predictions for EAS maximum depth $X_{\rm max}$ [26–28]. While the default model choice is $\propto x^{-0.5}$ momentum fraction x distributions for all such partons, both for the "soft" and "semihard" Pomeron components, we produced a number of alternative model tunes, choosing softer distributions, $\propto x^{-\alpha_q}$, with $\alpha_q = 0.7$, 0.9, and 0.95, for constituent sea (anti)quarks, for the "semihard" Pomeron contribution. Since the "soft" part is unchanged, the model predictions at fixed target energies remain unaffected. Moreover, as one can see in Fig. 2 (left), the multiplicity of proton-proton collisions has a weak sensitivity to such changes, which poses a challenge for discriminating between these options, based on the data of the Large Hadron Collider (LHC). On the other hand, a larger α_q results in a slower energy rise of $K_{\rm inel}$, see Fig. 2 (right), as demonstrated previously in [26–28].

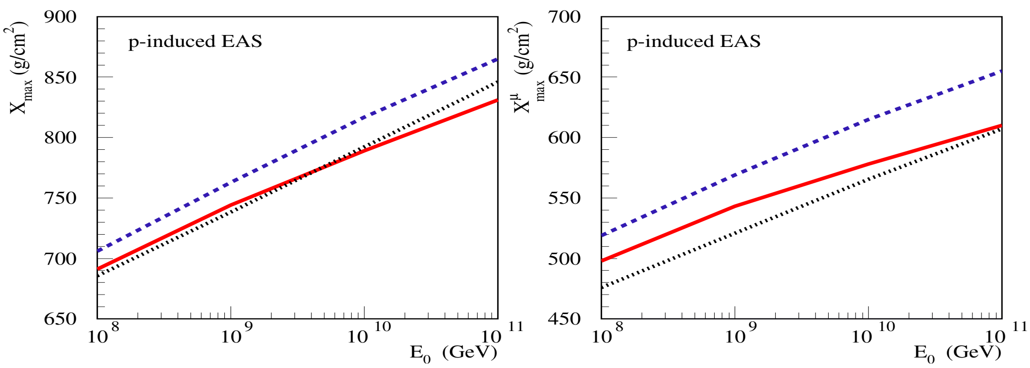

Figure 3: Energy dependence of $X_{\max}$ (left) and $X^{\mu}_{\max}$ (right), for p-induced EAS, calculated using the options of the hadronization procedure, corresponding to $\alpha_q = 0.5$ (solid lines) and $\alpha_q = 0.95$ (dashed lines). The respective results of the QGSJET-II-04 model [14] are plotted by dotted lines.

For CR-induced extensive air showers, the obtained differences for EAS muon content are rather small: $< 7\%$. On the other hand, for the two most extreme options, for $\alpha_q = 0.5$ and $\alpha_q = 0.95$, the predicted $X_{\max}$ differs by up to $\simeq 30$ g/cm^2, see Fig. 3 (left). Regarding LHC data, the strongest discrimination of the considered modifications is provided by measurements of forward neutron production by the LHCf experiment [29], which disfavor the trend towards larger α_q [28]. On the EAS side, such a trend is on one side favored by studies from the Pierre Auger Observatory like [8] pointing to the need of larger $X_{\max}$ in the models, but at the same time disfavored by other data from the same experiment on the maximum muon production depth $X^{\mu}_{\max}$ [30] since the impact of a larger α_q on $X^{\mu}_{\max}$ is stronger than on $X_{\max}$ [28], see Fig. 3 (right). This shows, that using a model like QGSb and high quality EAS data, such inconsistencies could be used to better understand the hadronic interactions in phase space not accessible in accelerator experiments.

4. Outlook

We presented the first version of the QGSb MC generator, designed to treat hadronic interactions in the "standard" high energy range, which can be used for studying model uncertainties for EAS predictions and for investigating a possibility to describe particular sets of CR data by suitably re-tuning the model parameters. It is noteworthy that a high computational efficiency of the developed model may allow one to apply automated tuning procedures, e.g., using a combination of accelerator and CR data. In future, it is planned to extend the range of applicability of the model towards lower energies and to generalize the approach for a treatment of photoproduction processes.

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