Hadronic interaction models in the light of the color glass condensate

S. Ostapchenko[1,2]
[1]Institutt for fysikk, NTNU Trondheim, Norway,
[2]D. V. Skobeltsyn Institute of Nuclear Physics, Moscow State University, Russia
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Abstract

Implementation of screening and saturation effects in cosmic ray interaction models is reviewed in comparison with the corresponding treatment of the color glass condensate approach. A feasibility of developing a color glass-based hadronic Monte Carlo generator is discussed, underlying the related and yet unsolved problems. Finally, existing contradictions between model predictions and high energy cosmic ray data are considered and the potential of the color glass condensate approach to resolve the remaining puzzles is analyzed.

1 Introduction

Nowadays hadronic Monte Carlo (MC) generators have a wide range of applicability both in collider and in cosmic ray (CR) fields. In the latter case, among the crucial requirements to the MC models is the corresponding predictive power, due to the necessity to extrapolate such models from accelerator energies up to the highest ones studied with cosmic rays. Traditionally, CR interaction models are developed in the Reggeon Field Theory (RFT) framework [1]: the scattering process is described as a multiple exchange of composite states – Pomerons, each one corresponding to an independent parton cascade. Depending on parton virtualities, one distinguishes "soft" and "semihard" contributions to the Pomeron exchange amplitude, corresponding to whether all the partons are soft, $|q^2| < Q_0^2$, Q_0^2 being a virtuality cutoff for the pQCD being applicable, or a part of the underlying cascade enters the perturbative domain (some $|q^2| > Q_0^2$). Applying the Abramovskii-Gribov-Kancheli (AGK) cutting procedure [2] to the corresponding elastic scattering diagrams, one obtains various interaction cross sections and relative probabilities for particular hadronic final states, which are then employed in the MC procedures.

2 Screening and saturation effects in MC models

Crucial differences between present hadronic MC generators are related to how they treat nonlinear interaction effects emerging in the high parton density regime. The latter appear naturally when considering hadron-hadron and, especially, nucleus-nucleus scattering in the limit of high energies and small impact parameters, where a large number of parton cascades develops in parallel, being closely packed in the interaction volume. In the QCD framework, the corresponding dynamics is described as merging of parton ladders, leading to the saturation picture: at a given virtuality scale parton density can not exceed a certain value; going to smaller momentum fractions x, further parton branching is compensated by merging of parton cascades [3]. Importantly, at smaller x, the saturation is reached at higher and higher virtuality scale $Q^2_{\rm sat}(x)$.

The approach has been further developed in the large N_c-based color glass condensate (CGC) framework, where detailed predictions for the $Q^2_{\rm sat}(x)$ behavior have been derived [4].

In MC generators one usually attempts to mimic the saturation picture in a phenomenological way. Standard method, employed e.g. in the `SIBYLL` model [5], is to treat the virtuality cutoff Q_0^2 between soft and semihard parton processes as an effective energy-dependent saturation scale: $Q_0^2 = Q^2_{\rm sat}(s)$ and to neglect parton (and hadron) production at $|q^2| < Q_0^2(s)$. The parameters of the corresponding $Q_0^2(s)$ parametrization are usually tuned together with the other model parameters by fitting the measured proton-proton cross section.

A more sophisticated procedure has been applied in the `EPOS` model [6], where effective saturation effects, being described by a set of parameters, depend on energy, impact parameter, types of interacting hadrons (nuclei). The corresponding mechanism influences not only the configuration of the interaction (how many processes of what type occur) but also the energy partition between multiple scattering processes and the hadronization procedure, the relevant parameters being fitted both with cross section and with particle production data.

An alternative approach has been employed in the `QGSJET-II` model [7] which provides a microscopic treatment of nonlinear effects in the RFT framework by describing the latter with help of enhanced diagrams [8] corresponding to Pomeron-Pomeron interactions. In particular, the procedure proposed in [9] allowed one to resum contributions of dominant enhanced graphs to the scattering amplitude to all orders in the triple-Pomeron coupling. Furthermore, to treat secondary particle production the unitarity cuts of the corresponding diagrams have been analyzed and a procedure has been worked out to resum the corresponding contributions for any particular final state of interest [10], which allowed one to implement the algorithm in the MC generator and to sample various configurations of the interaction in an iterative fashion. The main drawback of the approach is the underlying assumption that Pomeron-Pomeron coupling is dominated by soft ($|q^2| < Q_0^2$) parton processes. Thus, in contrast to the perturbative CGC treatment, the model has no dynamical evolution of the saturation scale: the saturation may only be reached at the Q_0^2 scale; at $|q^2| > Q_0^2$ parton evolution is described by purely linear DGLAP formalism.

3 Prospects for CGC-based MC generators

A promising framework for the development of a new generation of hadronic MC models is the color glass condensate scheme. Indeed, it seems very attractive to fully exploit the recent progress in the theoretical understanding of low-x QCD and to have a larger part of the kinematic space being described by perturbative methods, compared to present day MC generators. The ultimate goal for such a procedure is to enhance the predictive power, which is of utmost importance for model applications at the LHC and, especially, at the highest CR energies. However, to achieve this ambitious goal a number of key developments is still missing in the approach.

Let us recall that what one basically needs are coherent predictions for elastic scattering amplitude, hence, for total and inelastic cross sections, and for relative probabilities of various configurations of hadronic final states. The latter can be specified in different ways, e.g., as configurations of final (s-channel) partons, which can be resolved from each other (by imposing a cutoff on the parton virtuality or on some suitable angular scale) and which can then be mapped into secondary hadron production patterns, using, for example, string fragmentation procedures.

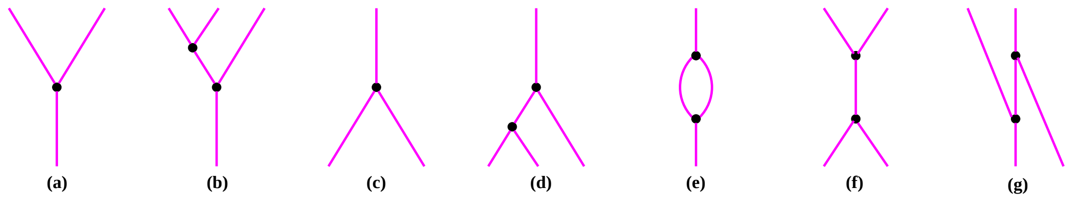

Fig. 1: Enhanced Pomerons diagrams up to the second order in G_{3P}.

When describing the scattering amplitude in the framework which treats Pomeron-Pomeron interactions, it is extremely important to have a complete resummation of all significant contributions of the kind, since diagrams with different numbers of Pomerons contribute with altering signs and since more complicated topologies become generally important when moving to higher energies. Meanwhile, most of the present applications of the CGC scheme are based on the Balitsky-Kovchegov (BK) approach [11], which is just the QCD analog of the Schwimmer model, corresponding to taking into consideration the diagrams of "fan" type only. Despite ongoing progress in accounting for contributions of more complicated diagrams, the full CGC evolution kernel remains unknown. Should one actually expect significant corrections to the BK approach? The affirmative answer comes already from considering the simplest enhanced diagrams up to the second order in the triple-Pomeron coupling, as depicted in Fig. 1.[1] Indeed, in addition to the "fan" type diagrams of Fig. 1 (a), (c) and Fig. 1 (b), (d), which are proportional to $G_{3P}\, s^{2\Delta_P}$ and $G_{3P}^2\, s^{3\Delta_P}$ correspondingly, one has the contributions of graphs of Fig. 1 (e-g), whose weights are proportional to $G_{3P}^2\, s^{2\Delta_P} / (\lambda_P + 2\lambda_{3P})$ (e), $G_{3P}^2\, s^{2\Delta_P}$ (f), and $G_{3P}^2\, s^{3\Delta_P}$ (g). Here λ_P is the slope and Δ_P the effective energy exponent (intercept minus unity) of the Pomeron exchange amplitude, whereas G_{3P} and λ_{3P} are the residue and the slope for the triple-Pomeron vertex. While the graph of Fig. 1 (f) is sub-leading in the high energy limit compared to the ones of Fig. 1 (b) and (d), this is not the case for the diagram of Fig. 1 (g). More delicate issue is the contribution of the "loop" diagram of Fig. 1 (e), which formally is also sub-leading. However, taking into account the smallness of both the BFKL Pomeron slope and of the one for the triple-Pomeron coupling, it appears to be *at least competitive* with the lowest order ones of graphs Fig. 1 (a), (c).

The fundamental problem of the CGC approach is related to the predicted too quick expansion of the black disk towards large impact parameters, the scattering slope rising with energy in a power-like way, in a contradiction with the unitarity [12]. It appears that the scheme works well in the region of the impact parameter space where the saturation scale is well-defined and fails outside that region. Though phenomenological approaches have been proposed to cure the problem by suppressing the emission of nonperturbative large size dipoles [13], it is not clear yet if the approach is suitable enough for the description of peripheral hadronic collisions.

Finally, to obtain probabilities for different hadronic final states, a necessary ingredient for a self-consistent MC procedure, one has to deal with unitarity cuts of elastic scattering diagrams. Till present, no systematic analysis of the kind has been performed in the CGC framework. As a possible alternative one may consider the "black box" strategy: developing a phenomenological MC model on the basis of the CGC predictions for *inclusive* gluon spectra. However, such

[1] For the sake of simplicity, here we restrict ourselves to the triple-Pomeron vertex only.

a model would have a very limited range of applicability, the basic correlations of hadronic observables being driven by the chosen *ad hoc* prescriptions rather than by the underlying theory.

4 UHECR puzzles

An interesting application of hadronic MC generators is related to the studies of very high energy cosmic rays. Those are generally detected using an indirect method: studying the development of nuclear-electro-magnetic cascades, extensive air showers (EAS), initiated by primary cosmic ray (PCR) particles in the atmosphere. Among the basic EAS observables is the shower maximum position $X_{\max}$ – the depth in the atmosphere (in g/cm^2) where maximal number of ionizing particles is observed, as well as total numbers of charged particles N_e and muons N_μ at ground level. The former depends mainly on the inelastic cross section for the primary particle interaction with air and on the corresponding inelasticity – the relative energy difference between the initial and the most energetic secondary particle. In turn, N_μ depends on the development of the nuclear cascade in the atmosphere, being mainly (but not only) related to the multiplicity of pion-air interactions. Hadronic MC models are employed in the simulation of EAS development, the results being compared to experimental data and used to infer the properties of PCR, like the energy spectrum and the elemental composition.

It appears that present day models behave reasonably well in CR applications up to the energies of the order of 10^9 GeV lab. For example, the results of the KASCADE-Grande Collaboration on the EAS muon content are well bracketed by the corresponding predictions for primary protons and iron nuclei (the two extreme PCR mass groups), if the `QGSJET-II` model is employed in the analysis [14]. However, the situation proved to be much more confusing in what concerns the properties of ultra-high energy cosmic rays (UHECR), with energies in excess of $10^9 \div 10^{10}$ GeV lab. The correlations between the measured UHECR arrival directions and the positions of near-by Active Galactic Nuclei (AGN), reported recently by the Pierre Auger Collaboration [15], give a strong support to the proton dominance of the PCR composition, if the angular size of the mentioned correlations is considered. On the other hand, the results of the very same collaboration on the PCR composition indicate that the latter is a mixture of protons and heavier nuclei: the measured $X_{\max}$ position is well in between model predictions for primary protons and iron nuclei [16]. Even more confusing are the Pierre Auger results for the EAS muon number: using three independent, although indirect, analysis methods, the inferred N_μ appeared to be 60% higher than predicted by `QGSJET-II` for p-induced air showers [17].

A possible explanation of the latter puzzle has been proposed in `EPOS` framework: a substantial enhancement of (anti-)baryon production in the model resulted in a significant increase of the predicted N_μ [18]. However, the model proved to be unable to resolve the above-discussed contradiction: the inferred N_μ appears to be some $20 \div 50\%$ (depending on the method) higher than expected for proton-induced EAS, if `EPOS` is employed in the simulation procedure [17].

A question arises if a potential CGC-based MC model could provide a coherent description of the Pierre Auger data. For the predicted EAS characteristics for p-induced air showers to be consistent with the Pierre Auger results, $X_{\max}$ has to be moved deeper in the atmosphere while N_μ has to be significantly enhanced, desirably for muon energies in excess of $5 \div 10$ GeV. The former may be achieved by increasing proton-air inelastic cross section or, alternatively, by enhancing the interaction inelasticity. In principle, a quick expansion of the black disk may provide the necessary enhancement of $\sigma^{\rm inel}_{p-{\rm air}}$, apart from the fact that the process can not be consistently described within the perturbative framework. In turn, a high inelasticity may be obtained if one assumes an independent fragmentation of constituent quarks of the incident proton, when the latter go through a dense gluon cloud of the target nucleus [19]. More difficult would be to obtain a significantly higher N_μ than, e.g., in `QGSJET-II`, which will require a substantial increase of pion-air multiplicity. The main feature of the CGC approach is a dynamical treatment of the saturation effects, whereas in `QGSJET-II`, parton saturation may only be reached below the cutoff scale Q_0^2. Additional saturation effects for $|q^2| > Q_0^2$ should generally lead to a suppression of the average parton density, hence, to a reduction of the multiplicity and of the N_μ predicted. However, one still has the freedom in the normalization of the saturation parton density, which is defined up to a constant factor. The latter circumstance, in combination with a quicker expansion of the high parton density towards large impact parameters may, in principle, allow one to achieve a very significant enhancement of secondary particle multiplicity, hence, of EAS muon content. It is worth stressing, however, that the main question is whether such properties come out as *natural predictions* of the color glass condensate approach. The answer will, probably, not come until a coherent CGC-based MC model emerges on the market.

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