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Very high energy hadronic interactions - solution of the main puzzle

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Abstract. A consistent treatment of hadronic and nuclear interactions at high energies is developed. A special attention is paid to the correct description of energy-momentum sharing processes in multiple scattering collisions. Also we stress the necessity to consider contributions of so-called enhanced Pomeron diagrams, which provide important screening corrections to the interaction mechanism. The latter ones appear to dominate the interaction process at very high energies and allow to solve many consistency problems of present hadronic interaction models, in particular, the seeming contradiction between the realistic parton structure functions, measured in deep inelastic scattering experiments, and the energy behavior of hadronic cross sections.

1 Introduction

Nowadays nobody would question the importance of reliable hadronic interaction models in the physics of high energy cosmic rays. Currently they are used to project new air shower arrays, to make interpretations of experimental data, to analyze different astrophysical hypothesises. All those topics significantly wenf forward since microscopic Monte Carlo models, developed in the Gribov-Regge framework, like VENUS (Werner, 1993), QGSJET (Kalmykov and Ostapchenko, 1993; Kalmykov *et al.*, 1994, 1997), DPMJET (Ranft, 1995), as well as the alternative approaches – HDPM (Capdevielle, 1992), MOCCA (Hillas, 1995), and SIBYLL (Fletcher *et al.*, 1994) – have become available for applications in cosmic ray physics and went into a common use, mainly due to their implementation in the CORSIKA air shower simulation program (Heck, 1998), and later on – in the AIRES code (Sciutto, 1999).

Naturally arises a question on the reliability of the available models in the region of extremely high interaction energies. The analysis showed that calibrating the models on the hadronic collider data along does not provide a unique possibility for their extrapolation towards very high energies (Kalmykov *et al.*, 1999), which explains to a great extent the existing differences between model predictions (Heck, 2001). On the other hand, there exist serious theoretical inconsistences in the very construction of presently available models.

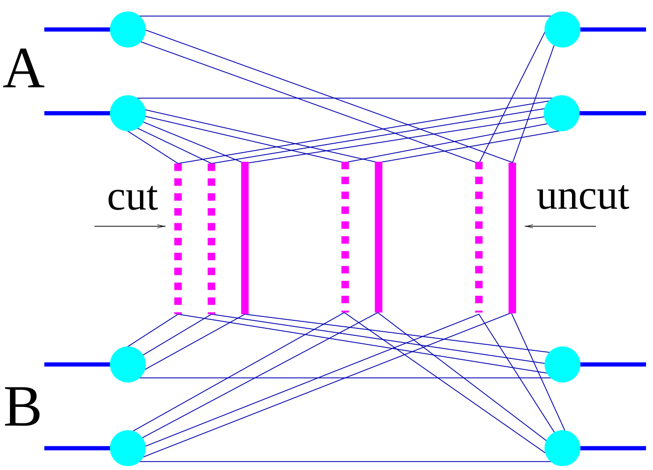

Fig. 1. Typical contribution to the nucleus A – nucleus B interaction cross section; cut and uncut Pomerons are shown as dashed and smooth thick lines correspondingly.

Recently we have developed a principally new universal model NEXUS (Drescher *et al.*, 2001). The universality of the model allowed to test its main algorithms and to tune reliably its parameters on the basis of a combined description of different reactions, including hadronic and nuclear collisions as well as electron-positron annihilation and deep inelastic lepton-proton scattering processes (Drescher *et al.*, 1999). This ensured much more reliable model extrapolation towards very high energies. Besides that, we have found for the first time satisfactory solutions for many severe consistency problems of the present models, like the correct treatment of the energy-momentum sharing mechanism in multiple scattering processes (Hladik *et al.*, 2001) as well as the

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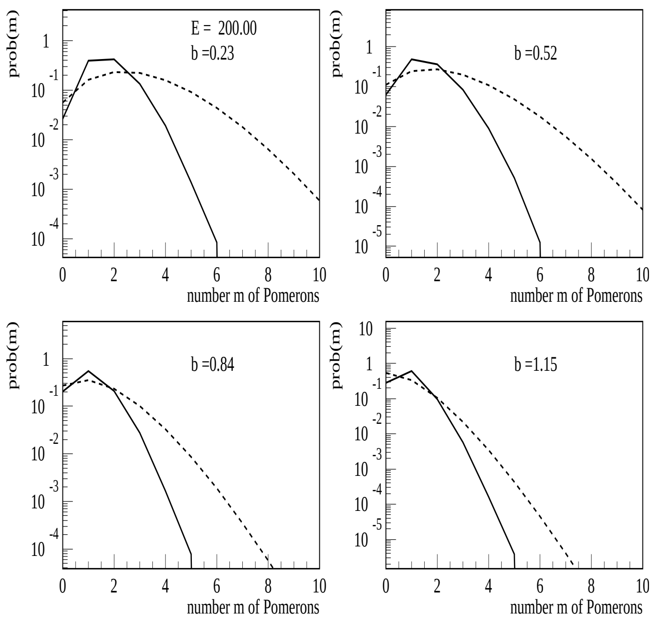

Fig. 2. Distribution of the number of Pomerons in proton-proton scattering at c.m. energy $\sqrt{s} = 200$ GeV/c for different impact parameters b. We show the results of a full simulation (solid curves) as well as the Poissonian distribution obtained by ignoring the energy conservation (dashed curves).

account for the contributions of Pomeron-Pomeron interactions (Drescher *et al.*, 2001; Ostapchenko *et al.*, 2001). The latter provide very important screening corrections to the interaction mechanism and appear to be of crucial importance for model applications at very high energies. In the current work we discuss some of these most recent developments and present the obtained preliminary results which illustrate their effect on the important interaction characteristics.

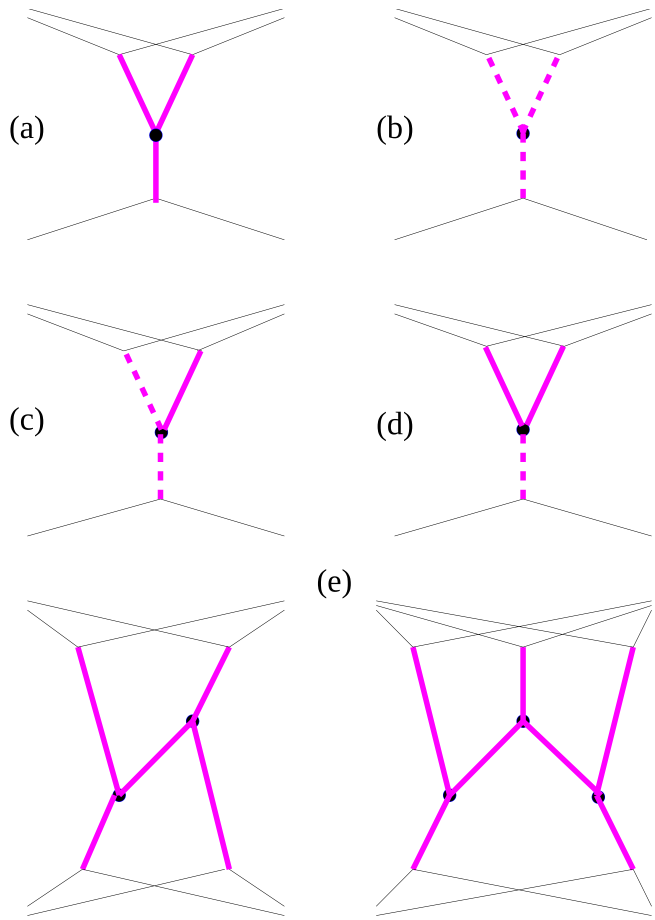

Fig. 3. The lowest order Pomeron-Pomeron interaction diagram – (a) and its different cuts: cut Pomeron "fusion" – (b), screening correction to one-cut-Pomeron process – (c), and high mass diffraction process – (d). Also shown some contributions of higher orders – (e). Cut and uncut Pomerons are represented by dashed and smooth thick lines correspondingly.

2 The model

In NEXUS model (Drescher *et al.*, 2001) high energy hadron-hadron (hadron-nucleus, nucleus-nucleus) interactions are treated within the Gribov-Regge framework (Gribov, 1968, 1969) as multiple scattering processes consisting of many individual elementary interactions happening in parallel, as shown schematically in Fig. 1. Each individual interaction is represented by a long microscopic parton cascade which mediates the scattering of parton constituents (quarks and antiquarks) of the interacting hadrons (nuclei) on each other. Correspondingly, one has to consider two main contributions to these elementary interactions: the nonperturbative "soft" scattering - when all the partons in the cascade are characterized by small virtualities $Q_i^2 < Q_0^2$, with $Q_0^2 \simeq 2$ GeV^2 being a reasonable scale for the perturbative quantum chromodynamics (QCD) being applicable, and the "semihard" interaction - when at least a part of this cascade develops in the perturbative region $Q_i^2 \geq Q_0^2$.

The first contribution is described phenomenologically as the soft Pomeron exchange (Werner, 1993), whereas in the second case we use the soft Pomeron description for the non-perturbative part of the parton evolution ($Q_i^2 < Q_0^2$) and treat the "hard" part ($Q_i^2 > Q_0^2$) using the QCD techniques - thus arriving to the concept of the "semihard Pomeron" (Ostapchenko *et al.*, 1997; Drescher *et al.*, 2001). The sum of the two contributions constitutes the "generalized Pomeron" which works as the basic ingredient for the construction of a general Gribov-Regge scheme.

An important feature of the Gribov's approach is that in each hadronic collision one has to consider both real elementary interactions, which result in the production of secondary particles and which are described as so-called cut Pomerons [1], shown symbolically as the dashed thick lines in Fig. 1, and virtual interactions, shown as the smooth thick lines in the Figure, when hadron constituents scatter elastically on each

[1] Cutting procedure amounts to replace the Pomeron exchange amplitude by its absorptive part, as the sum of contributions of any number of intermediate on-shell hadrons.

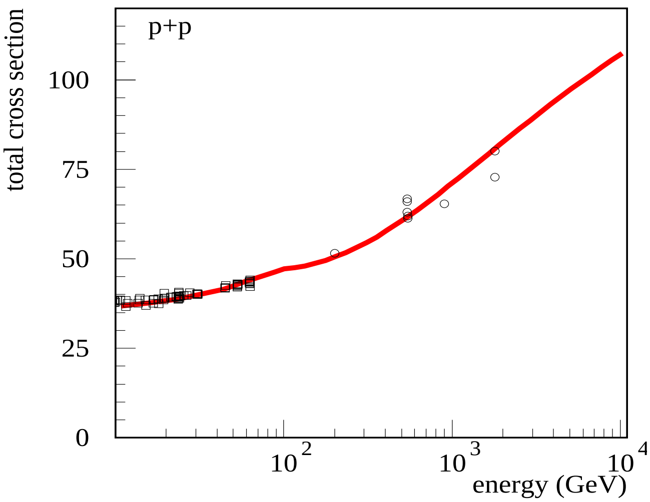

Fig. 4. The calculated total proton-proton interaction cross section as a function of the c.m. energy $\sqrt{s}$ – full curve; the points represent experimental data (Caso *et al.*, 1998).

other and the intermediate parton cascades recombine back to the initial hadrons. Those virtual contributions provide important screening corrections to the process and finally assure the unitarity of the scheme.

2.1 Energy-momentum sharing

To calculate both the interaction cross sections and the probabilities for different configurations of the hadronic (nuclear) collisions, as well as to simulate individual interaction events, down to the production of final secondary hadrons, one has to account for the sharing of the initial energy-momentum between many elementary scattering processes, both real and virtual, so that each process disposes only a part of the total initial energy (Braun, 1990; Abramovskii and Leptoukh, 1992). The solution of this problem has been provided for the first time in our work (Hladik *et al.*, 2001), allowing to develop a fully self-consistent treatment of the reactions, both concerning cross section calculations and particle production simulation. At high energies, the account for this mechanism results in a dramatic reduction of the average number of elementary interactions per hadronic (nuclear) collision – Fig. 2. This effect is especially strong in central nucleus-nucleus interactions.

2.2 Enhanced Pomeron diagrams

One of the most recent and very important developments in NEXUS model is the treatment of Pomeron-Pomeron interactions (Ostapchenko *et al.*, 2001), described by so-called enhanced Pomeron diagrams, with the lowest order graph depicted in Fig. 3a. One naturally encounters such contributions at high energies, when the number of elementary interactions, happening in hadron-hadron and, especially, nucleus-nucleus collisions, becomes large and the corresponding microscopic parton cascades start to overlap and to interact with each other.

Table 1. The calculated diffractive proton structure function, $x_{\mathrm{P}}F_2^{D(3)}(x_{\mathrm{P}},\beta,Q^2)$, for diffractive scattering via $\gamma^* p \to XN$ for $Q^2 = 8$ GeV^2 and for the mass of the nucleonic system N $M_N < 5.5$ GeV. Experimental data are from ZEUS collaboration (Breitweg *et al.*, 1999).

x_{P}	β	$x_{\mathrm{P}}F_2^{D(3)}$ (NEXUS)	$x_{\mathrm{P}}F_2^{D(3)}$ (exp.)
0.00871	0.062	0.0304	0.0288±0.0018
0.00580	0.062	0.0318	0.0312±0.0018
0.00391	0.062	0.0324	0.0328±0.0020

There, one has to take into account not only interactions of real cascades - cut Pomerons, shown in Fig. 3b and generally known as string fusion, but also an important process of elastic interaction between a real and a virtual cascades - Fig. 3c, which provides screening corrections of a new type and modifies considerably the final spectra of secondary hadrons, as well as the contribution of high mass diffraction dissociation, represented by the diagram of Fig. 3d.

Naturally, one can not restrict himself with just lowest order graphs discussed above and has to include all important diagrams of higher orders for a given interaction energy of interest, with some examples shown in Fig. 3e. For example, considering diagrams with four Pomeron-Pomeron vertexes, we had to deal with nearly a hundred contributions of that type.

The main parameter which controls the magnitude of those contributions is the value of the Pomeron-Pomeron interaction vertex, the so-called triple-Pomeron coupling, $r_{3\mathrm{P}}$. It is remarkable that one can reliably fix this coupling using the information on the diffractive structure function of the proton $F_2^{D(3)}(x_{\mathrm{P}},\beta,Q^2)$ [2], measured by ZEUS collaboration (Breitweg *et al.*, 1999) – see Table 1.

The main effects of the described mechanism are:

– suppression of hadron-hadron interaction cross sections at high energies;

– suppression of secondary hadron multiplicity, especially, in central nucleus-nucleus collisions;

– serious modifications of final particle spectra, especially, for central collisions of asymmetric systems;

– significant increase of fluctuations of secondary hadron multiplicity.

[2]In the standard interpretation of the diffractive process by means of the Pomeron exchange x_{P} corresponds to the momentum fraction of the proton carried by the hadronic system X into which the virtual photon dissociated and β is the momentum fraction of the struck quark within this system.

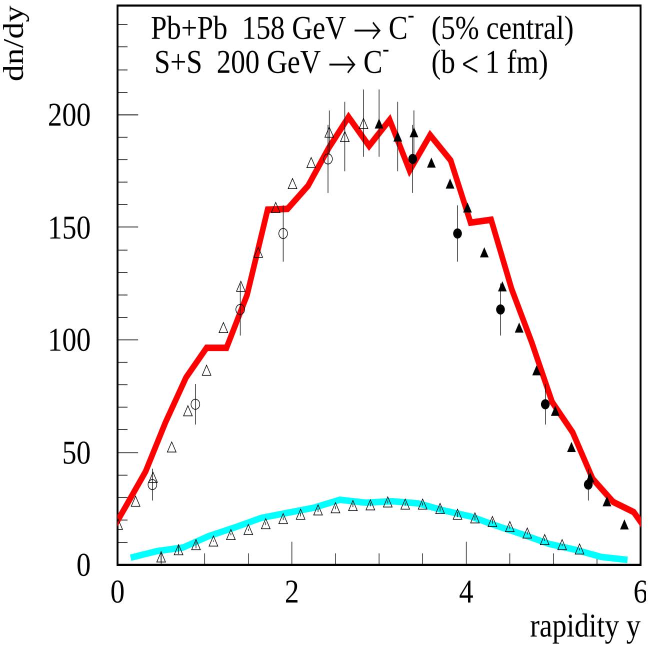

Fig. 5. The calculated rapidity distributions of negatively charged particles for $Pb-Pb$ collision at $\sqrt{s}$=158 GeV/c and for $S-S$ collision at $\sqrt{s}$=200 GeV/c – full curves; the points represent experimental data (Alber *et al.*, 1998; Appelshauser *et al.*, 1999).

The first point needs a special stressing. Our approach allows to obtain a consistent description of hadron-hadron interaction cross sections - Fig.4, while being in consistency with the realistic proton structure functions, measured in deep inelastic scattering experiments. Thus, we can avoid the invention of any artificial energy-dependent cutoff for the QCD evolution (see, for example, Bopp *et al.*, 1994) - the recipe which would rule out any predictive power of the perturbative QCD for high energy hadronic interactions. The key point here is that the inclusion of enhanced diagrams affects hadronic cross sections to much greater extent than it does for partonic distributions. This can be illustrated, for example, by the contributions of diagrams shown in Fig. 3e, which appear to be the dominant ones in hadron-hadron interactions at high energies but which do not give any contribution to the structure functions (Ostapchenko *et al.*, 2001).

Both the suppression of secondary hadron multiplicity and the modifications of final particle spectra come from the interplay between different cuts of the enhanced diagrams, known as the violation of Abramovskii-Gribov-Kancheli cancellations (Abramovskii *et al.*, 1974) for the secondary hadron spectra (Kaidalov, 1991). In particular, our scheme allows to obtain a consistent description of secondary hadron multiplicity in central heavy ion collisions - Fig. 5, which was a severe problem for the most of currently available models.

3 Conclusions

We presented the new hadronic interaction model NEXUS and discussed its most important features as well as illustrated their importance for the main characteristics of hadronic and nuclear interactions. The theoretical approach realized in this model is currently the only one which takes systematically into account all important microscopic interaction mechanisms and allows to obtain a self-consistent description of hadron-hadron, hadron-nucleus, and nucleus-nucleus collisions. In particular, we showed that the consistent treatment of Pomeron-Pomeron interactions is of crucial importance for the correct description of high energy hadronic and nuclear reactions.

The extension of the model validity till the highest cosmic ray energies should provide a reliable tool for the investigation of the composition of Ultra High Energy Cosmic Rays.

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