Scaling trends in proton-proton collisions from SPS to LHC in quark-gluon string model

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Abstract. Fulfillment of scaling relations, such as Feynman scaling, extended longitudinal scaling and Koba-Nielsen-Olesen (KNO) scaling, in ultrarelativistic proton-proton collisions are checked within the microscopic quark-gluon string model (QGSM). The model is based on Reggeon Field theory accomplished by string phenomenology. Multiplicity, rapidity and transverse momentum spectra are described quite well in a wide span of the collision energy. Predictions are made for $pp$ collisions at $\sqrt{s} = 14$ TeV.

1. Introduction

The theory of multiparticle production in elementary proton-proton collisions at ultrarelativistic energies is not completed yet, because even at very high energies the main contribution to multiparticle production in hadronic interactions comes from the processes with small momentum transfer. The running coupling constant $\alpha_s(Q^2)$ is not small and other techniques based on non-perturbative methods should be utilized. The quark-gluon string model (QGSM) [1, 2] relying on the Reggeon Field Theory (RFT) [3] is one of the few possible approaches. Its basic principles are sketched below.

QGSM employs the $1/N$ series expansion of the amplitude of a process in QCD, where $N$ is either the number of colors [4] or the number of flavors [5]. This method is also called topological expansion, because of emergence of diagrams of various topologies. Although it is not possible to assign weights for the diagrams within the QCD, there is one-to-one mapping between the diagrams in $1/N$-expansion and the processes with exchange of Regge singularities in the $t$-channel. For instance, exchange of quantum numbers via Reggeons corresponds to planar diagrams, whereas the cylinder diagrams are represented by the reactions without the quantum number exchange. The latter proceed via the exchange of Pomerons. Therefore, the perturbative Reggeon Field Theory (RFT) [3] is directly linked to quantum chromodynamics.

The Monte Carlo version of the QGSM [6, 7, 8, 9] employs statistical weights, hadron structure functions and leading quark fragmentation functions obtained from the Regge approach in [1, 2] to choose subprocesses of string production, to compute mass and momentum of strings and to simulate string decays, respectively. The hadron-hadron collision part of the model includes single and double diffraction subprocesses, antibaryon-baryon annihilation and elastic scattering. The hadron inelastic interaction cross section $\sigma_{inel}(s) = \sigma_{tot}(s) - \sigma_{el}(s)$ is split further into the cross section for single diffractive interactions $\sigma_{SD}(s)$ and the cross section for non-diffractive
reactions $\sigma_{ND}(s)$, similar to analysis of experimental data. By means of the Abramovskii-Gribov-Kancheli (AGK) cutting rules [10] the inelastic non-diffractive interaction cross section $\sigma_{ND}(s)$ can be expressed via the sum of the cross sections for the production of $n = 1, 2, \ldots$ pairs of quark-gluon strings, or cut Pomerons, and the cross section of double diffractive process $\sigma_{ND}(s) = \sum_{n=1}^{\infty} \sigma_n(s) + \sigma_{DD}(s)$. To find $\sigma_n(s)$ one can utilize the quasi-eikonal model [11, 12]. For the modeling of string fragmentation the Field-Feynman algorithm [13] is employed. It enables one to consider emission of hadrons from both ends of the string with equal probabilities. The break-up procedure invokes the energy-momentum conservation and the preservation of the quark numbers.

2. Results

Feynman scaling. Recall that at energies $\sqrt{s} \geq 50$ GeV the annihilation cross section is extremely small and, therefore, the main features of particle production in $pp$ interactions are similar to those in $\bar{p}p$ ones. Thus, for the comparison with the model results we utilized data obtained by the UA5 Collaboration for proton - antiproton collisions at c.m. energies $\sqrt{s} = 200$ GeV, 546 GeV and 900 GeV [14], by the UA1 Collaboration for $pp$ collisions at $\sqrt{s} = 546$ GeV [15, 16], by the CDF and the E735 Collaborations for $\bar{p}p$ collisions at $\sqrt{s} = 1800$ GeV [17, 18], and more recent CERN LHC data obtained in $pp$ interactions at $\sqrt{s} = 900$ GeV, 2360 GeV, and 7 TeV by the ALICE Collaboration [19] and by the CMS Collaboration [20].

Pseudorapidity spectra of charged particles in elastic and non-single diffraction (NSD) proton-proton interactions at $200 \text{GeV} \leq \sqrt{s} \leq 14 \text{ TeV}$ are shown in Fig. 1(a). Available experimental data are plotted onto the model calculations as well. The hypothesis of the so-called Feynman scaling [21] postulates that the density of produced charged particles at midrapidity $dN^{ch}/d\eta$ should be saturated somewhere at very high energies. This scaling regime is obviously not reached yet. Moreover, at LHC energies $dN^{ch}/d\eta|_{\eta=0}$ demonstrates a non-linear rise with $\ln s$, as suggested by the saturation of the Froissart bound. For $pp$ collisions at top LHC energy $\sqrt{s} = 14 \text{ TeV}$ the QGSM predicts $dN_{inel}/d\eta|_{\eta=0} = 6.1$, $dN_{NSD}/d\eta|_{\eta=0} = 7.0$, respectively. The transverse momentum distributions of charged hadrons in NSD collisions at energies in question
inclusive densities \( n \) at \( \sqrt{s} \) where the distributions \( 1 \) fragment of particle \( 1 \) + \( 2 \) inclusive process \( 1 + 2 \) and, therefore, the particles with large rapidity difference are uncorrelated. Consider now the QGSM these slopes are identical in the fragmentation region \( y \) - \( y_{max} \) obtained in QGSM for \( pp \) collisions.

Extended longitudinal scaling and KNO scaling. Another scaling relation is the extended longitudinal scaling (ELS) [22] exhibited by the slopes of (pseudo)rapidity spectra. In the QGSM these slopes are identical in the fragmentation region \( y_{beam} \geq -2.5 \) as shown in Fig. 2, where the distributions \( \frac{1}{\sigma_{NSD}} \frac{d\sigma_{NSD}}{dy} \) are expressed as functions \( y - y_{max} \). QGSM indicates that the ELS remains certainly valid at LHC. Obtained result contradicts to the prediction based on the statistical thermal model [23]. The latter fits the measured rapidity distributions to the Gaussian, extracts the widths of the Gaussians and implements the energy dependence of the obtained widths to simulate the rapidity spectra at LHC. The extrapolated distribution was found to be much narrower [23] compared to that presented in Fig. 2. Further LHC measurements of \( pp \) collisions in the fragmentation regions are needed to resolve this obvious discrepancy. Note, that experimentally the extended longitudinal scaling was found to hold to 10% in a broad energy range from \( \sqrt{s} = 30.8 \) GeV to 900 GeV [14].

The extended longitudinal scaling in the QGSM emerges merely due to short range correlations in rapidity space. The correlation function of particle \( i \) and particle \( j \), produced as a result of a string fragmentation, drops exponentially with rising rapidity difference

\[
C(y_i, y_j) = \frac{d^2\sigma}{\sigma_{inel} dy_i dy_j} - \frac{d\sigma}{\sigma_{inel} dy_i} \frac{d\sigma}{\sigma_{inel} dy_j} \propto \exp \left[ -\lambda (y_i - y_j) \right],
\]

and, therefore, the particles with large rapidity difference are uncorrelated. Consider now the inclusive process \( 1 + 2 \rightarrow i + X \). Its single particle inclusive cross section \( f_1 = d^2\sigma(y_1 - y_i, y_i - y_2, p_{T}^2) / dy_i dy_2 p_{T} \) becomes independent of \( y_i - y_2 \) at sufficiently high collision energy in the fragmentation region of particle \( i \), provided \( y_1 - y_i \approx 1 \) and \( y_i - y_2 \approx y_1 - y_2 \gg 1 \). Thus, the inclusive densities \( n_i = f_i / \sigma_{inel} \) are determined by only two variables \( n_i = \phi(y_i - y_1, p_{T}^2) \).

Next scaling dependence is known as Koba-Nielsen-Olesen (KNO) scaling [24]. It claims that at \( \sqrt{s} \rightarrow \infty \) the normalized multiplicity distribution just scales up as \( \ln s \) or, equivalently, that

\[
\frac{(n)}{\sum n} = \Psi \left( \frac{n}{(n)} \right),
\]
with $\sigma_n$ being the partial cross section for $n$-particle production, $\langle n \rangle$ - the average multiplicity and $\Psi(n/\langle n \rangle)$ - energy independent function. KNO-scaling was found to hold up to ISR energies, $\sqrt{s} \leq 62$ GeV. Violation of the KNO-scaling was predicted within the QGSM in [1, 2]. Later on the violation was observed experimentally by the UA5 and UA1 collaborations in $pp$ collisions at $\sqrt{s} = 546$ GeV in the full phase space [14]. The rapidity range is crucial for this study. In very central pseudorapidity window $|\eta| < 0.5$ the KNO-scaling is still maintained at $\sqrt{s} = 2.36$ TeV [19], as seen in Fig. 3, whereas already the UA5 Collaboration observed progressive violation of the scaling with increasing $\eta$ intervals at much lower energies. For a bit broader midrapidity intervals at LHC a peak at low multiplicities seems to appear, see Fig. 3. The origin of this phenomenon in the model is the following. At ultrarelativistic energies the main contribution to particle multiplicity comes from the cut-Pomerons, and each cut results to formation of two strings. Short range correlations inside a single string lead to a Poisson-like multiplicity distribution of produced secondaries. At energies below 100 GeV the multi-string (or chain) processes are not very abundant and invariant masses of the strings are not very large. Therefore, different contributions to particle multiplicity overlap strongly, and the KNO-scaling is nearly fulfilled. With rising $\sqrt{s}$ the number of strings increases as $(s/s_0)^{A}$ and their invariant masses increase as well. This leads to enhancement of high multiplicities, deviation of the multiplicity distribution from the Poisson-like behavior and violation of KNO-scaling [1, 2, 6].

3. Conclusions

Several scaling properties predicted or observed in particle production at relativistic energies have been examined. QGSM favors violation of Feynman scaling in the central rapidity region. Extended longitudinal scaling is shown to hold at LHC, whereas further violation of the KNO-scaling in multiplicity distributions is demonstrated. The origin of both conservation and violation of the scaling trends is traced to short range correlations of particles in the strings and interplay between the multi-Pomeron processes at ultra-relativistic energies.

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