POMERON AND ODDERON CONTRIBUTIONS AT LHC ENERGIES

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Abstract

We consider the first LHC data for pp collisions in the framework of Regge theory. The integral cross sections and inclusive densities of secondaries are determined by the Pomeron exchange, and we present the corresponding predictions for them. The first measurements of inclusive densities in midrapidity region are in agreement with these predictions. The possible contribution of Odderon (Reggeon with $\alpha_{Od}(0) \sim 1$ and negative signature) exchange to the differences in the inclusive spectra of particle and antiparticle in the central region could be significant at LHC energies. The first data of ALICE Collaboration are consistent with a very small Odderon contribution. Probably, further LHC data will definitely settle the question of the Odderon existence.

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1 Introduction

In Regge theory the Pomeron exchange dominates in the high energy soft hadron interaction. The Pomeron has vacuum quantum numbers. At LHC energies the contributions of all other exchanges to the total or inelastic cross sections becomes negligibly small that one can directly extract the Pomeron parameters directly from the experimental data.

The Quark-Gluon String Model (QGSM) [1] is based on Dual Topological Unitarization (DTU), Regge phenomenology, and nonperturbative notions of QCD. This model is successfully used for the description of multiparticle production processes in hadron-hadron [2, 3, 4, 5], hadron-nucleus [6, 7], and nucleus-nucleus [8] collisions. In particular, the inclusive densities of different secondaries produced in pp collisions at $\sqrt{s} = 200$ GeV in midrapidity region were reasonably described in ref. [5].

In the QGSM high energy interactions are considered as proceeding via the exchange of one or several Pomerons, and all elastic and inelastic processes result from cutting through or between Pomerons [9]. Inclusive spectra of hadrons are related to the corresponding fragmentation functions of quarks and diquarks, which are constructed using the Reggeon counting rules [10]. The quantitative predictions of the QGSM depend on several parameters which were fixed by the comparison of the calculations with the experimental data obtained at fixed target energies.

The first experimental data obtained at LHC allow one to test the stability of the QGSM predictions and of the values of the parameters. Fortunately, we see that the model predictions are in reasonable agreement with the data so there is no reason for the corrections in the parameter values.

The difference in the the total interaction cross sections and in the inclusive spectra of antiparticles and particles is governed by the numerically small contributions of Regge-poles with negative signature. A well-known such a Regge-pole is the $\omega$-reggeon with $\alpha_\omega(0) \sim 0.4 - 0.5$. Due to the small value of $\alpha_\omega(0)$ its contribution at LHC energies should be very small.

The Odderon is a singularity in the complex $J$-plane with intercept $\alpha_{Od} \sim 1$, negative $C$-parity, and negative signature. Thus, its zero flavour-number exchange contribution to particle-particle and to antiparticle-particle interactions, e.g., to pp and to $\bar{p}p$ total cross sections, or to the inclusive production of baryons and of antibaryons in pp collisions has opposite signs. In QCD the Odderon singularity is connected [11] to the colour-singlet exchange of three reggeized gluons in $t$-channel. The theoretical and experimental status of Odderon has been recently discussed in refs. [12, 13]. The possibility to detect Odderon effects has also been investigated in other domains, as
the $\pi p \rightarrow \rho N$ reaction \[14\] and charm photoproduction \[15\].

The Odderon coupling should be very small with respect to the Pomeron coupling. However, several experimental facts favouring the presence of the Odderon contribution exist, e.g., the energy behaviour of the difference of total $\bar{p}p$ and $pp$ cross sections \[16 \ 17\], and the difference in the $d\sigma/dt$ behaviour of elastic $pp$ and $\bar{p}p$ scattering at $\sqrt{s} = 52.8$ GeV and $|t| = 1 \pm 1.5$ GeV$^2$ presented in references \[12 \ 18\]. The behaviour of $pp$ and $\bar{p}p$ elastic scattering and total cross sections at ISR and SPS energies was analyzed in \[19\].

The differences in the yields of baryons and antibaryons produced in the central (midrapidity) region of high energy $pp$ interactions \[5 \ 16 \ 17 \ 20 \ 21 \ 22 \ 23 \ 24\] can also be significant in this respect. The question of whether the Odderon exchange is needed for explaining these experimental facts, or they can be described by the usual exchange of a reggeized quark-antiquark pair with $\alpha_\omega(t) = \alpha_\omega(0) + \alpha'_\omega t$, it is a fundamental one.

In this paper we present the description of the first LHC data in the framework of QGSM, as well as some predictions for the Pomeron and Odderon effects at LHC energies.

## 2 Cross sections at LHC energies

Let us start with the analysis of high energy elastic particle and antiparticle scattering on the proton target. Here, the simplest contribution is the one Regge-pole $R$ exchange corresponding to the scattering amplitude

$$A(s, t) = g_1(t) \cdot g_2(t) \cdot \left(\frac{s}{s_0}\right)^{\alpha_R(t) - 1} \cdot \eta(\Theta),$$

where $g_1(t)$ and $g_2(t)$ are the couplings of a Reggeon to the beam and target hadrons, $\alpha_R(t)$ is the $R$-Reggeon trajectory, and $\eta(\Theta)$ is the signature factor which determines the complex structure of the scattering amplitude ($\Theta$ equal to +1 and to −1 for reggeon with positive and negative signature, respectively):

$$\eta(\Theta) = \begin{cases} 
  i - \tan^{-1}\left(\frac{\pi \alpha_R}{2}\right) & \Theta = +1 \\
  i + \tan\left(\frac{\pi \alpha_R}{2}\right) & \Theta = -1
\end{cases},$$

so the amplitude $A(s, t = 0)$ becomes purely imaginary for positive signature and purely real for negative signature when $\alpha_R \rightarrow 1$.

The interaction of a particle or of an antiparticle with a proton target is the same for the Reggeon exchange with positive signature, but in the case of negative signature the two contributions have opposite signs, as it is shown in Fig. 1.
Figure 1: Diagram corresponding to the Reggeon-pole exchange in particle $h$ (a) (its antiparticle $\bar{h}$ (b)) interactions with a proton target. The positive signature ($\Theta = +1$) exchange contributions are the same, while the negative signature ($\Theta = -1$) exchange contributions have opposite signs.

The corresponding pole trajectory is given by

$$\alpha_R(t) = \alpha_R(0) + \alpha'_R t,$$

(3)

where $\alpha_R(0)$ (intercept) and $\alpha'_R$ (slope) are some numbers.

In the case of Pomeron trajectory with $\alpha_P(0) > 1$ the correct asymptotic behavior $\sigma_{tot} \sim \ln^2 s$ [25, 26], compatible with the Froissart bound can only be obtained by taking into account the multipomeron cuts.

Figure 2: Regge-pole theory diagrams: (a) single $R$-pole exchange in the binary process $1+2 \rightarrow 3+4$, double $RP$ (b) and triple $RPP$ (c) exchanges in elastic $NN$ scattering.

Indeed, for the Pomeron trajectory

$$\alpha_P(t) = 1 + \Delta + \alpha'_P t, \ \Delta > 0,$$

(4)
the one-Pomeron contribution to $\sigma_{hN}^{tot}$ equals

$$\sigma_P = 8\pi \gamma e^{\Delta \xi}, \text{ with } \xi = \ln s/s_0,$$

(5)

where $\gamma = g_1(0) \cdot g_2(0)$ is the Pomeron coupling, $s_0 \simeq 1 \text{ GeV}^2$, and $\sigma_P$ rises with energy as $s^\Delta$. To obey the $s$-channel unitarity, and the Froissart bound in particular, this contribution should be screened by the multipomeron discontinuities. A simple quasi-eikonal treatment [27] yields to

$$\sigma_{hN}^{tot} = \sigma_P f(z/2), \quad \sigma_{hN}^{el} = \frac{\sigma_P}{C} [f(z/2) - f(z)],$$

(6)

$$f(z) = \sum_{k=1}^{\infty} \frac{1}{k \cdot k!} (-z)^{k-1} = \frac{1}{z} \int_0^z \frac{dx}{x} (1 - e^{-x}),$$

(7)

$$z = \frac{2C\gamma}{\lambda} e^{\Delta \xi}, \quad \lambda = R^2 + \alpha'_P \xi.$$  

(8)

The numerical values of the Pomeron parameters were taken [25, 3] to be:

$$\Delta = 0.139, \quad \alpha'_P = 0.21 \text{GeV}^{-2}, \quad \gamma = 1.77 \text{GeV}^{-2}, \quad R^2 = 3.18 \text{GeV}^{-2}, \quad C = 1.5.$$  

(9)

Here, $R^2$ is the radius of the Pomeron and $C$ is the quasi-eikonal enhancement coefficient (see [28]).

The predictions of Regge theory with obtained these values of the parameters (a small contribution from non-Pomeron exchange with parameters taken from [25] is accounted for) are presented in Table 1.

| $\sqrt{s}$          | $\sigma_{hN}^{tot}$ | $\sigma_{hN}^{el}$ | $\sigma_{hN}^{inel}$ |
|---------------------|---------------------|---------------------|----------------------|
| 900 GeV             | 67.4                | 13.2                | 54.2                 |
| 7 TeV               | 94.5                | 21.1                | 73.4                 |
| 14 TeV              | 105.7               | 24.2                | 81.5                 |

Table 1. The Regge theory predictions for total, total elastic and total inelastic cross sections (in mb) in $pp$ collisions at LHC energies.

At asymptotically high energies ($z \gg 1$) we obtain

$$\sigma_{hN}^{tot} = \frac{8\pi \alpha'_P \Delta}{C} \xi^2, \quad \sigma_{hN}^{el} = \frac{4\pi \alpha'_P \Delta}{C^2} \xi^2,$$

(10)

according to the Froissart limit [29].
However, in the complete Reggeon diagram technique \[30\] not only Regge-poles and cuts, but more complicated diagrams (e.g. the so-called enhanced diagrams of the type of Fig. 3) should be taken into account. In the numerical calculations of such diagrams some new uncertainties appear, because the vertices of the coupling of \(n\) and \(m\) Reggeons (see Fig. 3c) are unknown, so some model estimations are needed.

![Figure 3: Examples of enhanced Reggeon diagrams.](image)

The common feature of the calculations in which enhanced diagrams are included results in the additional increase of the Pomeron intercept \(\alpha_P(0) = 1 + \Delta\), needed for the description of the experimental data. For example, a value \(\Delta = 0.21\) was obtained in \[31\]. In models with strong interactions among the produced strings also a larger \(\Delta\) is obtained. Thus, in string percolation \(\Delta = 2/7\) \[32\]. Also in color glass condensate \(\Delta\) is large, \(\Delta = 0.28\) \[33\]. On the other hand, the QCD solution corresponding to a bare Pomeron is known to the leading log accuracy \[34, 35, 36, 37\]:

\[
\Delta = N_c \frac{\alpha_s}{\pi} 4 \ln 2; \tag{11}
\]

where \(N_c\) is the number of colors. However, the next-to leading corrections to these solutions are very large \[38, 39\]. The situation with the Pomeron intercept is not clear \[40\] up to now. The value of the Pomeron slope is also discussed. Phenomenologically, in many papers it is chosen to be \(\alpha'_P \sim 0.25\) GeV\(^{-2}\). A more theoretical (QCD) point of view with \(\alpha'_P \to 0\) at \(s \to \infty\) is presented in \[41\].

The numerical calculations which account for enhanced diagrams \[42, 43, 44\] lead to the values of \(\sigma^{inel}\) of the same order \((\pm 10\% \text{ at } \sqrt{s} = 14\text{ TeV})\) as those presented in Table. 1.
3 Inclusive spectra in midrapidity region

The inclusive cross section for the production of a secondary $h$ in high energy $pp$ collisions in the central region is determined by the Regge-pole diagrams shown in Fig. 4 [45]. The diagram with only Pomeron exchange (Fig. 4a) is the leading one, while the diagrams with one secondary Reggeon $R$ (Figs. 4b and 4c) correspond to corrections which disappear with the increase of the initial energy.

![Regge-pole diagrams](image)

Figure 4: Regge-pole diagrams for the inclusive production of a secondary hadron $h$ in the central region.

The inclusive production cross section of hadron $h$ with transverse momentum $p_T$ corresponding to the diagram shown in Fig. 4b has the following expression:

$$F(p_T, s_1, s_2) = \frac{1}{\pi^2 s} g_R^{pp} \cdot g_P^{pp} \cdot g_R^{hh}(p_T) \cdot \left( \frac{s_1}{s_0} \right)^{\alpha_R(0)} \cdot \left( \frac{s_2}{s_0} \right)^{\alpha_P(0)},$$

(12)

where

$$s_1 = (p_a + p_h)^2 = m_T \cdot s^{1/2} \cdot e^{-y}$$

$$s_2 = (p_b + p_h)^2 = m_T \cdot s^{1/2} \cdot e^{y},$$

(13)

with $s_1 \cdot s_2 = m_T^2 \cdot s$ [46], and the rapidity $y$ defined in the center-of-mass frame.

At very high energies, only the one-Pomeron exchange diagram in Fig. 4a contributes to the inclusive density in the central region $y \sim 0$ (AGK theorem [9]). This leads to

$$\frac{d\sigma}{dy} \sim \left( \frac{s}{s_0} \right)^{\alpha_P(0)-1} = \left( \frac{s}{s_0} \right)^{\Delta_P}.$$
Now one can estimate \[47\] the intercept of the supercritical Pomeron by considering

\[ \frac{d\sigma}{dy} = \sigma_{pp}^{\text{inel}} \frac{dn}{dy}, \]  

(15)

and by defining

\[ \Delta_P = \Delta_\sigma + \Delta_n, \]  

(16)

where \( \Delta_\sigma \) comes from the energy dependence of \( \sigma_{pp}^{\text{inel}} \) and \( \Delta_n \) corresponds to the energy dependence of \( dn/dy \).

The analysis of the \( dn/dy \) energy behaviour in the energy interval \( \sqrt{s} = 15 - 900 \) GeV was provided in ref. \[48\], and it corresponds to a value:

\[ \Delta_n = 0.105 \pm 0.006. \]  

(17)

From recent LHC (ALICE Collaboration) data \( \sqrt{s} = 900 \) GeV – 7 TeV, one obtains

\[ \Delta_n = 0.110 \pm 0.008, \]  

(18)

and showing a very stable behaviour.

For the value of \( \Delta_\sigma \) in the last energy interval Regge theory predicts

\[ \Delta_\sigma = 0.07, \]  

(19)

so for \( \Delta_P \) we obtain

\[ \Delta_P = 0.18. \]  

(20)

The only problem is that the values of \( dn_{ch}/d\eta \) in ref. \[49\] were obtained under the condition that in the considered kinematical window as a minimum one charged particle should exist. This condition increase the value of \( dn_{ch}/d\eta \) at \( \sqrt{s} = 900 \) GeV more significantly than at \( \sqrt{s} = 7 \) TeV, so the value of \( \Delta \) presented in Eq. (15) should be slightly increased.

In the case of only Pomeron exchange, Fig. 4a, the yields of particle and antiparticle in the central region are equal. The difference between them comes from the first correction to the Pomeron diagram. This correction is shown in Figs. 4b, 4c, where \( R \) is the effective sum of all amplitudes with negative signature (\( \Theta = -1 \) in Eq. (2), so its contribution to the inclusive spectra of secondary protons and antiprotons has the opposite sign. In the midrapidity region, i.e. at \( y \sim 0 \), the ratios of \( \bar{p} \) and \( p \) (or any other antibaryon and baryon) yields integrated over \( p_T \) (\( \langle m_T \rangle \approx 1 \) GeV) can be written as

\[ \frac{\bar{p}}{p} = \frac{1 - r_-(s)}{1 + r_-(s)}, \]  

(21)
where \( r_-(s) \) is the ratio of the negative signature \((R)\) to the positive signature \((P)\) contributions \([16, 17]\):

\[
r_-(s) = c_1 \cdot \left( \frac{s}{s_0} \right)^{(\alpha_R(0) - \alpha_P(0))/2}.
\] (22)

Here \( c_1 \) is a normalization constant and the physically important quantity is the difference of intercepts \((\alpha_R(0) - \alpha_P(0))\), which can be determined from the comparison with the experimental data.

### 4 Inclusive spectra of secondary hadrons in the Quark-Gluon String Model

The Quark-Gluon String Model (QGSM) \([1, 2, 3]\) allows us to make quantitative predictions of different features of multiparticle production, in particular, the inclusive densities of different secondaries both in the central and in beam fragmentation regions. In QGSM high energy hadron-nucleon collisions are considered as taking place via the exchange of one or several Pomerons, all elastic and inelastic processes resulting from cutting through or between Pomerons \([9]\).

Each Pomeron corresponds to a cylindrical diagram (see Fig. 5a), and thus, when cutting one Pomeron, two showers of secondaries are produced as it is shown in Fig. 5b. The inclusive spectrum of a secondary hadron \( h \) is then determined by the convolution of the diquark, valence quark, and sea quark distributions \( u(x, n) \) in the incident particles, with the fragmentation functions \( G^h(z) \) of quarks and diquarks into the secondary hadron \( h \). These distributions, as well as the fragmentation functions are constructed using the Reggeon counting rules \([10]\). Both the diquark and the quark distribution functions depend on the number \( n \) of cut Pomerons in the considered diagram.

For a nucleon target, the inclusive rapidity \((y)\) or Feynman-\(x\) \((x_F)\) spectrum of a secondary hadron \( h \) has the form \([1]\):

\[
\frac{dn}{dy} = \frac{x_F}{\sigma_{inel}} \cdot \frac{d\sigma}{dx_F} = \frac{dn}{dy} = \sum_{n=1}^{\infty} w_n \cdot \phi_n^h(x),
\] (23)

where the functions \( \phi_n^h(x) \) determine the contribution of the diagram with \( n \) cut Pomerons and \( w_n \) is the relative weight of this diagram. Here we neglect the contribution of diffraction dissociation processes which is very small in the midrapidity region.

For \( pp \) collisions

\[
\phi_{pp}^h(x) = f_{qq}(x_+, n) \cdot f_q^h(x_-, n) + f_q^h(x_+, n) \cdot f_{qq}(x_-, n) +
\]
Figure 5: (a) Cylindrical diagram corresponding to the one–Pomeron exchange contribution to elastic \( pp \) scattering, and (b) the cut of this diagram which determines the contribution to the inelastic \( pp \) cross section (b). Quarks are shown by solid curves and string junction by dashed curves.

\[
+ 2(n - 1)f_s^h(x_+, n) \cdot f_s^h(x_-, n),
\]

\[
x_\pm = \frac{1}{2} \left[ \sqrt{4m_T^2/s + x^2} \pm x \right],
\]

where \( f_{qq} \), \( f_q \), and \( f_s \) correspond to the contributions of diquarks, valence quarks, and sea quarks, respectively.

These functions are determined by the convolution of the diquark and quark distributions with the fragmentation functions, e.g. for the quark one can write:

\[
f_q^h(x_+, n) = \int_{x_+}^{1} u_q(x_1, n) \cdot G_q^h(x_+/x_1) dx_1.
\]

The diquark and quark distributions, which are normalized to unity, as well as the fragmentation functions, are determined by the corresponding Regge intercepts [10].

At very high energies both \( x_+ \) and \( x_- \) are negligibly small in the midrapidity region, and so all fragmentation functions, which are usually written [10] as \( G_q^h(z) = a_h(1-z)^\beta \), become constants and equal for a particle and its antiparticle:

\[
G_q^h(x_+/x_1) = a_h.
\]

This leads, in agreement with [45] and with Eq. (14), to

\[
\frac{dn}{dy} = g_h \cdot (s/s_0)^{\alpha_P(0)-1} \sim a_h^2 \cdot (s/s_0)^{\alpha_P(0)-1},
\]
that corresponds to the only one-Pomeron exchange diagram in Fig. 4a, i.e. to the only diagram contributing to the inclusive density in the central region (AGK theorem [9]) at asymptotically high energy. The values of the Pomeron parameters presented in Eq. (9) are used in the QGSM numerical calculations.

The QGSM predictions for the initial energy dependence of the inclusive densities \( d\eta/d\eta|\eta=0 \) for all charged secondaries produced in high energy \( pp \) collisions are presented in Fig. 6.

Figure 6: The QGSM predictions for the inclusive densities in the midrapidity region for all charged secondaries as a function of the initial energy. Old data of ISR and SpS for all inelastic \( pp \) (\( p\bar{p} \)) collisions [48] are shown by triangles, ALICE data [50] for all inelastic collisions by points, and ALICE data [49] for events with \( \text{INEL}>0 \) by squares (see full text).

The theoretical curve slightly overestimates the data for all inelastic collisions. This small disagreement rests inside the model accuracy. At the same time, the curve lies below the points of ALICE Collaboration shown by squares [49], which were obtained
for the events INEL > 0, that is for events in which as minimum one charged particle should be detected in the kinematical window |\eta| > 1 (see [49]). Thus the events without any charged particle in this kinematical window are ignored, what evidently increases the inclusive density.

It is necessary to note that the calculated values of $dn/d\eta(\eta = 0)$ depend on the averaged transverse momenta of secondaries. The values $\langle p_T\rangle_\pi = 0.35$ GeV/c, $\langle p_T\rangle_K = 0.52$ GeV/c, and $\langle p_T\rangle_p = 0.68$ GeV/c [51] were used in the Fig. 6 for energies $\sqrt{s} \geq 900$ GeV. The values of $dn/d\eta$ would increase with energy slightly faster if the averaged transverse momenta of secondaries would increase.

The QGSM predictions for the $dn/d\eta$ distributions of all charged secondaries produced in inelastic pp and $\bar{p}p$ collisions at different energies are shown in Fig. 7. The experimental data are taken from [52].

![Figure 7: The QGSM predictions for the pseudorapidity distributions of all charged secondaries produced in inelastic pp and $\bar{p}p$ collisions at different energies.](image-url)
The QGSM allows one to calculate the inclusive spectra of different secondaries. In Fig. 8 we compare the QGSM predictions for the integral multiplicities of charged kaons which are compiled in ref. [53]. The agreement with the existing data for $pp$ collisions in the energy interval $\sqrt{s} = 17 - 200$ GeV is good.

Figure 8: The QGSM predictions for the integral multiplicities of $K^+$ and $K^-$ as a functions of the initial energy.

In the kaon sector the most interesting case is that of the $K^0_s$-mesons, which can be used for measurement of CP-violation, etc. In Fig. 9 we present the experimental data on the midrapidity inclusive densities of $K^0_s$-mesons produced in $pp$ and $\bar{p}p$ collisions at different energies ref. [53], together with the results of QGSM calculations.

In Fig. 10 we compare the QGSM predictions for the rapidity distributions of $K^0_s$ produced in $pp$ collisions at $\sqrt{s} = 900$ GeV (solid curve) with the experimental data of LHCb Collaboration [54], together with RHIC (PHENIX and STAR Collaboration) data [55], as well as the QGSM predictions at $\sqrt{s} = 200$ GeV (dashed curve).
Figure 9: The QGSM predictions for the inclusive densities in the midrapidity region for $K^0_s$-mesons produced in $pp$ and $\bar{p}p$ collisions as a function of the initial energy.

The theoretical curve for RHIC energy is in agreement with the experimental data [55]. The curve for LHCb clearly overestimates the inclusive cross section of $K^0_s$ production, but it is necessary to keep in mind that the curve corresponds to the $d\sigma/dy$ values integrated over transverse momenta, while the data [54] were obtained in the region $0.2 < p_T < 1.6$ GeV/c, so they will be increased after accounting for the contributions of very low and high $p_T$. 

The difference in the total cross section of high energy particle and antiparticle scattering on the proton target is (see Fig. 1)

\[ \Delta \sigma_{\text{tot}}^{\text{hp}} = \sum_{R(\Theta = -1)} 2 \cdot Im A(s, t = 0) = \sum_{R(\Theta = -1)} 2 \cdot g_1(0) \cdot g_2(0) \cdot \left( \frac{s}{s_0} \right)^{\alpha_{R(0)-1}} \cdot Im \eta(\Theta = -1). \tag{29} \]

The experimental data for the differences of \( \bar{p}p \) and \( pp \) total cross sections at \( \sqrt{s} > 8 \) GeV are presented in Fig. 11. Here we use the data compiled in ref. [56] by presenting at every energy the experimental points for \( pp \) and \( \bar{p}p \) by the same experimental group and with the smallest error bars. At ISR energies (last three points in Fig. 11) we present the data in ref. [57] as published in their most recent version of ref. [56].

From the results of this fit one can see that the usual one-power fit [58, 59] of \( \Delta \sigma_{\text{tot}}^{pp} \) by only \( \omega \)-Reggeon is not good enough, and one additional Odderon contribution with \( \alpha_{\text{Odd}}(0) \sim 0.9 \) is in agreement with the experimental data. The contributions of Odderon and \( \omega \)-reggeon to the differences in \( \bar{p}p \) and \( pp \) total cross sections would be approximately equal at \( \sqrt{s} \sim 25 - 30 \) GeV. In any case, a more detailed analysis is needed, especially concerning the experimental error bars for the differences in \( pp \) and...
Figure 11: Experimental differences of $\bar{p}p$ and $pp$ total cross sections at $\sqrt{s} > 8$ GeV, together with their one-Reggeon fit (solid curve), fit of [59] (dashed curve), and fit by the sum of $\omega$-Reggeon and Odderon contribution (dash-dotted curve).

$\bar{p}p$ cross sections.

In the string models, baryons are considered as configurations consisting of three connected strings (related to three valence quarks) called string junction (SJ) [60, 61, 62, 63], as it is shown in Fig. 12.

Figure 12: The composite structure of a baryon in string models. Quarks are shown by open points and SJ by black point.

The colour part of a baryon wave function reads as follows [60, 62]:

$$B = \psi_i(x_1) \cdot \psi_j(x_2) \cdot \psi_k(x_3) \cdot J^{ijk}(x_1, x_2, x_3, x), \quad (30)$$
\[ J^{ijk}(x_1, x_2, x_3, x) = \Phi^i_i(x_1, x) \cdot \Phi^j_j(x_2, x) \cdot \Phi^k_k(x_3, x) \cdot \epsilon^{ij'k'}, \quad (31) \]

\[ \Phi^i_i(x_1, x) = \left[ T \cdot \exp \left( g \cdot \int_{P(x_1, x)} A_\mu(z) dz^\mu \right) \right]^i_{i'}, \quad (32) \]

where \(x_1, x_2, x_3,\) and \(x\) are the coordinates of valence quarks and SJ, respectively, and \(P(x_1, x)\) represents a path from \(x_1\) to \(x\) which looks like an open string with ends at \(x_1\) and \(x\). Such a baryon structure is supported by lattice calculations [64].

This picture leads to some general phenomenological predictions. In particular, it opens room for exotic states, such as the multiquark bound states, 4-quark mesons, and pentaquarks [62] [65] [66]. In the case of inclusive reactions the baryon number transfer to large rapidity distances in hadron-nucleon and in hadron-nucleus reactions can be explained [20] by SJ diffusion.

The production of a baryon-antibaryon pair in the central region usually occurs via \(SJ-SJ\) pair production (according to Eqs. (30), (31), SJ has upper color indices, whereas antiSJ (\(\overline{SJ}\)) has lower indices) which then combines with sea quarks and sea antiquarks into, respectively, \(\overline{BB}\) pair [62] [67], as it is shown in Fig. 13.

![Figure 13: Diagram corresponding to the diquark fragmentation function for the production of a central \(\overline{BB}\) pair. Quarks are shown by solid curves and SJ by dashed curves.](image)

In processes with incident baryons, say, in \(pp\) collisions there exists another possibility to produce a secondary baryon in the central region. This second possibility leads to the diffusion in rapidity space of the two SJ existing in the initial state that leads to significant differences in the yields of baryons and antibaryons in the midrapidity region even at rather high energies [20] [22]. Probably, the most important experimental fact in favour for this process is the rather large asymmetry in \(\Omega\) and \(\overline{\Omega}\) baryon production in high energy \(\pi^- p\) interactions [68].

The quantitative theoretical description of the baryon number transfer via SJ mechanism was suggested in the 90’s and used to predict [69] the \(p/\bar{p}\) asymmetry at HERA.
energies, which was experimentally observed [70]. It was also noted in ref. [71] that the $p/\bar{p}$ asymmetry measured at HERA can be obtained by simple extrapolation of ISR data. The quantitative description of the baryon number transfer due to SJ diffusion in rapidity space was firstly obtained in [20] and following papers [5, 21, 22, 23, 24, 16, 17].

In the QGSM the differences in the spectra of secondary baryons and antibaryons produced in the central region appear for processes which present SJ diffusion in rapidity space. These differences only vanish rather slowly when the energy increases.

To obtain the net baryon charge we consider according to ref. [20], we consider three different possibilities. The first one is the fragmentation of the diquark giving rise to a leading baryon (Fig. 14a). A second possibility is to produce a leading meson in the first break-up of the string and one baryon in a subsequent break-up [10, 72] (Fig. 14b). In these two first cases the baryon number transfer is possible only for short distances in rapidity. In the third case, shown in Fig. 14c, both initial valence quarks in the diquark recombine with sea antiquarks into mesons $M$, while a secondary baryon is formed by the SJ together with three sea quarks.

![Figure 14: QGSM diagrams describing secondary baryon $B$ production by diquark $d$: initial SJ together with two valence quarks and one sea quark (a), initial SJ together with one valence quark and two sea quarks (b), and initial SJ together with three sea quarks (c).](image-url)

The fragmentation functions for the secondary baryon $B$ production corresponding to the three processes shown in Fig. 14 can be written as follows (see [20] for more details):

\[
G_{qq}^B(z) = a_N \cdot v_{qq}^B \cdot z^{2.5}, \tag{33}
\]

\[
G_{qs}^B(z) = a_N \cdot v_{qs}^B \cdot z^2 \cdot (1 - z), \tag{34}
\]

\[
G_{ss}^B(z) = a_N \cdot \varepsilon \cdot v_{ss}^B \cdot z^{1-\alpha_{SJ}} \cdot (1 - z)^2, \tag{35}
\]

for Figs. 14a, 14b, and 14c, respectively, and where $a_N$ is the normalization parameter, and $v_{qq}^B$, $v_{qs}^B$, $v_{ss}^B$ are the relative probabilities for different baryons production that can be found by simple quark combinatorics [73, 74].
The fraction $z$ of the incident baryon energy carried by the secondary baryon decreases from Fig. 14a to Fig. 14c, whereas the mean rapidity gap between the incident and secondary baryon increases. The first two processes can not contribute to the inclusive spectra in the central region, but the third contribution is essential if the value of the intercept of the SJ exchange Regge-trajectory, $\alpha_{SJ}$, is large enough. At this point it is important to stress that since the quantum number content of the SJ exchange matches that of the possible Odderon exchange, if the value of the SJ Regge-trajectory intercept, $\alpha_{SJ}$, would turn out to be large and it would coincide with the value of the Odderon Regge-trajectory, $\alpha_{SJ} \simeq 0.9$, then the SJ could be identified to the Odderon, or, at last, to one baryonic Odderon component.

Let’s finally note that the process shown in Fig. 14c can be very naturally realized in the quark combinatorial approach [73] through the specific probabilities of a valence quark recombination (fusion) with sea quarks and antiquarks, the value of $\alpha_{SJ}$ depending on these specific probabilities.

The contribution of the graph in Fig. 14c is weighted in QGSM by coefficient $\varepsilon$ which determines the small probability for such a baryon number transfer to occur.

At high energies the SJ contribution to the inclusive cross section of secondary baryon production at large rapidity distance $\Delta y$ from the incident nucleon can be estimated as

$$\frac{1}{\sigma}d\sigma^B/dy \sim a_B \cdot \varepsilon \cdot e^{(1-\alpha_{SJ})\Delta y},$$

(36)

where $a_B = a_N \cdot v_{ss}^B$. The baryon charge transferred to large rapidity distances can be determined by integration of Eq. (35), so it is of the order of

$$\langle n_B \rangle \sim a_B \cdot \varepsilon / (1 - \alpha_{SJ}).$$

(37)

It is clear that the value $\alpha_{SJ} \geq 1$ should be excluded due to the violation of baryon-number conservation at asymptotically high energies.

6 Comparison of the QGSM predictions with the experimental data

Here we compare the results of QGSM predictions with all available experimental data on the $\bar{p}/p$ ratios at high energy.

To obtain the QGSM predictions for the $\bar{p}/p$ ratios we use the values of the probabilities $w_n$ in Eq. (23) that are calculated in the frame of Reggeon theory [1], and the values of the normalization constants $a_\pi$ (pion production), $a_K$ (kaon production),
As an example of the experimental data description we present in Table 2 the calculated yields of different secondaries produced in $pp$ collisions at energy $\sqrt{s} = 200$ GeV in midrapidity region together with RHIC data (STAR Collaboration).

| Particle | RHIC ($\sqrt{s} = 200$ GeV) | Experiment 51 |
|----------|-----------------------------|---------------|
| $\pi^+$  | 1.27                        | $1.44 \pm 0.11$ |
| $\pi^-$  | 1.25                        | $1.42 \pm 0.11$ |
| $K^+$    | 0.13                        | $0.150 \pm 0.013$ |
| $K^-$    | 0.12                        | $0.145 \pm 0.013$ |
| $p$      | 0.0755                      | $0.138 \pm 0.012$ |
| $\bar{p}$ | 0.0707                     | $0.113 \pm 0.01$ |
| $\Lambda$ | 0.0328                     | $0.0385 \pm 0.0035$ |
| $\bar{\Lambda}$ | 0.0304                  | $0.0351 \pm 0.0032$ |
| $\Xi^-$  | 0.00306                    | $0.0026 \pm 0.0009$ |
| $\Xi^+$  | 0.00298                    | $0.0029 \pm 0.001$ |
| $\Omega^-$ | 0.00020                   | $0.00025$ |
| $\Xi^-_{\Omega}$ | 0.00020               | $0.00020$ |

$* \text{ dn/dy}(\Omega^- = \bar{\Xi}^+) = 0.00034 \pm 0.00019$

Table 2. The QGSM results for midrapidity yields $dn/dy (|y| < 0.5)$ for different secondaries at energy $\sqrt{s} = 200$ GeV. The results for $\varepsilon = 0.024$ are presented only when different from the case $\varepsilon = 0$.

In all cases our calculations generally underestimate the experimental points. However, the theoretical calculations correspond to all inelastic $pp$ collisions, while the experimental data are obtained for events without single diffraction dissociation. In all cases, the agreement of the order of 10% should be considered as good enough.

The ratio of $p$ to $\bar{p}$ yields at $y = 0$ calculated with the QGSM is shown in Fig. 15. The results with $\alpha_{SJ} = 0.9$ and $\varepsilon = 0.024$, $\alpha_{SJ} = 0.6$ and $\varepsilon = 0.057$, and $\alpha_{SJ} = 0.5$ and $\varepsilon = 0.0757$ are presented by dashed ($\chi^2/\text{ndf}=21.7/10$), dotted ($\chi^2/\text{ndf}=12.2/10$), and dash-dotted ($\chi^2/\text{ndf}=11.1/10$) curves, respectively. Thus, the most probable value of $\alpha_{SJ}$ from the point of view of the $\chi^2$ analysis is $\alpha_{SJ} = 0.5 \pm 0.1$.

However, this conclusion comes from the global analysis of all experimental points, but one can see in Fig. 15 that the calculated value of $\bar{p}$ to $p$ production ratio with $\alpha_{SJ} = 0.5$
Figure 15: The experimental ratios of $\bar{p}$ to $p$ production cross sections in high energies $pp$ collisions at $y = 0$ [75, 76, 77, 78, 79, 80], together with their fits [17] (solid curves), and by the QGSM description (dashed, dotted, and dash-dotted curves).

0.9 is in very good agreement with the experimental point of PHENIX Collaboration $0.71 \pm 0.01 \pm 0.08$ [79], so the situation is not clear.

7 Predictions for $\bar{B}/B$ ratios at LHC

We present in Tables 3 and 4 our predictions for antibaryon/baryon ratios in midrapidity region at energies $\sqrt{s} = 900$ GeV, 7 TeV, and 14 TeV for two possibilities of SJ contribution, $\alpha_{SJ} = 0.5$ ($\omega$-reggeon contribution) and $\alpha_{SJ} = 0.9$ (Odderon contribution).

First of all we predict practically equal $\bar{B}/B$ ratios for the baryons with different strangeness, the small differences presented in Tables 3 and 4 seem to be inside the accuracy of our calculations. The calculated $\bar{B}/B$ ratios do not practically depend either on the averaged transverse momenta of the considered secondaries.

At $\sqrt{s} = 900$ GeV we expect the values of $\bar{B}/B$ ratios to be about 0.96 in the case of $\alpha_{SJ} = 0.5$ ($\omega$-reggeon contribution) and about 0.90 in the case of $\alpha_{SJ} = 0.9$ (Odderon contribution). At $\sqrt{s} = 7$ TeV these ratios are predicted to be 0.99 and
0.95, respectively. We do not present the predictions corresponding to no contribution of Reggeon with negative signature ($\varepsilon = 0$ in Eq. (35)), because it is in contradiction with the high energy data [16, 17].

Table 3. The QGSM predictions for antibaryon/baryon yields ratios in pp collisions in midrapidity region ($|y| < 0.5$) for energies $\sqrt{s} = 900$ GeV and $\sqrt{s} = 7$ TeV. Two possibilities are considered: $\alpha_{SJ} = 0.5$ ($\omega$-reggeon contribution) and $\alpha_{SJ} = 0.9$ (Odderon contribution).

At $\sqrt{s} = 14$ TeV the $\bar{B}/B$ ratios are predicted to be larger than 0.99 for $\alpha_{SJ} = 0.5$ and about 0.96 for $\alpha_{SJ} = 0.9$. So the experimental accuracy $\sim 1\%$ in these ratios is needed to discriminate between these two possibilities of $\alpha_{SJ}$ values.

Table 4. The QGSM predictions for antibaryon/baryon yields ratios in pp collisions in midrapidity region ($|y| < 0.5$) for $\sqrt{s} = 14$ TeV. Two possibilities are considered: $\alpha_{SJ} = 0.5$ ($\omega$-reggeon contribution) and $\alpha_{SJ} = 0.9$ (Odderon contribution).

The absolute values of midrapidity densities of produced secondaries are more model dependent in comparison with the antiparticle/particle ratios. We present in Table 5 the corresponding QGSM predictions at LHC energies $\sqrt{s} = 900$ GeV, $\sqrt{s} = 7$ TeV, and $\sqrt{s} = 14$ TeV. Baryon densities can be obtained with the help of Tables 3 and 4.

The QGSM predictions for the spectra of secondary charged pions, charged kaons, protons, and antiprotons produced in pp collisions at energies $\sqrt{s} = 900$ GeV and $\sqrt{s} = 7$ TeV are presented in Fig. 16.
Figure 16: The QGSM predictions for the spectra of secondary pions, kaons, protons and antiprotons at energies $\sqrt{s} = 900$ GeV (left panel) and $\sqrt{s} = 7$ TeV (right panel).

Table 5. The QGSM results for the midrapidity yields $dn/dy (|y| < 0.5)$ of different secondaries at LHC energies.

| Particle | $\sqrt{s} = 900$ GeV | $\sqrt{s} = 7$ TeV | $\sqrt{s} = 14$ TeV |
|----------|----------------------|-------------------|---------------------|
| $\pi^+$  | 1.68                 | 2.32              | 2.54                |
| $\pi^-$  | 1.66                 | 2.31              | 2.54                |
| $K^+$    | 0.17                 | 0.23              | 0.25                |
| $K^-$    | 0.16                 | 0.23              | 0.25                |
| $\bar{p}$| 0.10                 | 0.16              | 0.18                |
| $\Lambda$| 0.05                 | 0.08              | 0.09                |
| $\Xi^+$ | 0.005                | 0.009             | 0.011               |
| $\Omega^+$| 0.0004              | 0.0008            | 0.0009              |

Preliminary data by the ALICE Collaboration [81] presented in Table 6 show that the $\omega$-reggeon contribution is enough for description of antiproton/proton ratios at LHC energies. If this is confirmed by further LHC data, it would mean that the Odderon coupling must be very small.
| Variant               | $\sqrt{s} = 900$ GeV | $\sqrt{s} = 7$ TeV |
|----------------------|---------------------|-------------------|
| $\alpha_{SJ} = 0.9$  | 0.89                | 0.95              |
| $\alpha_{SJ} = 0.5$  | 0.95                | 0.99              |
| Without C-negative   | 0.98                | 1.00              |
| exchange             |                     |                   |
| ALICE Coll.          | 0.957 ± 0.006       | 0.991 ± 0.014     |
|                      | 0.005 ± 0.014       |                   |

Table 6. The QGSM predictions for $\bar{p}/p$ in $pp$ collisions at LHC energies and the data by the ALICE Collaboration [81].

The LHCb Collaboration plans to measure the ratios of antibaryons to baryons spectra in some interval of pseudorapidities. Thinking of this, we present in Figs. 17 and 18 the $\eta$-dependences of $\bar{p}/p$ and $\bar{\Lambda}/\Lambda$ at energies $\sqrt{s} = 900$ GeV and $\sqrt{s} = 7$ TeV.

Figure 17: The QGSM predictions for the ratios of the spectra of secondary antiprotons to protons as the functions of their pseudorapitities at energies $\sqrt{s} = 900$ GeV (left panel) and $\sqrt{s} = 7$ TeV (right panel).
Figure 18: The QGSM predictions for the ratios of the spectra of secondary $\bar{\Lambda}$ to $\Lambda$ as the functions of their pseudorapitities at energies $\sqrt{s} = 900$ GeV (left panel) and $\sqrt{s} = 7$ TeV (right panel).

8 Conclusion

The first experimental data obtained at LHC are in general agreement with the calculations provided in the framework of Regge theory and of the QGSM with the same values of parameters which were determined at lower energies (mainly for description the fixed target experiments).

We neglect the possibility of interactions between Pomerons (so-called enhancement diagrams) in the calculations of integrated cross sections and inclusive densities. Such interactions are very important in the cases of heavy ion [82] and nucleon-nucleus [83] interactions at RHIC energies, and their contribution should increase with energy. However we estimate that the contributions of these enhanced diagrams inclusive density of secondaries produced in $pp$ collisions at LHC energies is not large enough to be significant.

In the case of the inclusive production of particles and antiparticles in central (midrapidity) region in $pp$ collisions the only evidence for the Odderon exchange with $\alpha_{Odd}(0) \simeq 0.9$ in the inclusive reactions is proved by two experimental points for $BB$ production asymmetry obtained by the H1 Collaboration [70, 84]. The first point [70]
(for $\bar{p}/p$ ratio) is until now not published, and the second one \cite{84} (for $\bar{\Lambda}/\Lambda$ ratio) shows a very large error bar. On the other hand, only for these two points the kinematics would allow the energy of the Odderon exchange to be large enough ($\sqrt{s} \simeq 10^2$ GeV) to be noticed.

ALICE Collaboration data are in disagreement with a numerically large contribution of the Odderon with $\alpha_{S,J} = 0.9$, the coupling of such an Odderon should be suppressed.

ALICE Collaboration data are in agreement with the only $\omega$-Reggeon contribution.

One has to expect that further LHC data will make the situation more clear.

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