Inclusive light hadron production in pp scattering at the LHC

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The inclusive production of light mesons in pp-scattering is considered in the framework of Reggeon phenomenology with supercritical Pomeron. Available low-energy data can be explained with three Reggeon particles taken into account. With the results obtained rapidity and pseudorapidity distributions for light-meson production at the LHC energies are predicted.

I. INTRODUCTION

It is well known that the growth of total cross sections can be explained in the framework of Reggeon theory with supercritical Pomeron [1]. In this approach the amplitude of an elastic hadron-hadron scattering is written down as a sum of Reggeon diagrams which corresponds to multiple rescattering. The first term of such eikonal expansion is the contribution of a "bare" Pomeron:

$$A(s, t) = \left(i - \cot\frac{\pi\alpha(t)}{2} \right) s^{\alpha(t)} \gamma(t), \qquad (1)$$

where the Regge trajectory in the j-plane is parameterized by a linear function $\alpha(t) = 1 + \Delta + \alpha' t$ with the intercept $\alpha(0) = 1 + \Delta$.

According to the perturbative QCD calculations [2] the vacuum exchange singularity has a rather complex form. It can be expressed as a sum of poles in the angular momentum plane with $1 \leq j \leq 1 + \Delta$, where

$$\Delta < \frac{12\alpha_s \ln 2}{\pi}. \qquad (2)$$

For $\alpha_s = 0.2 \div 0.25$ this allows Δ to approach a rather large value of $0.55 \div 0.65$.

The information on the parameter Δ can also be obtained from the analysis of deep inelastic scattering structure functions in the region of small Bjorken variable x [3], where the Regge asymptotic is valid. The power parameter Δ, defined as $\Delta = \partial \ln f / \partial \ln(1/x) - 1$, varies from $\Delta = 0.23$ at $Q^2 = 16 \text{ GeV}^2$ to $\Delta = 0.5$ at $Q^2 = 400 \text{ GeV}^2$.

The data on total cross sections were analyzed using the eikonal model with different values of parameter Δ. In earlier works [4], total cross sections were fitted using $\Delta \sim 0.13$. In Ref. [5] a double-pole approximation for bare Pomeron was used for the first time with Δ being in the region $0.09 < \Delta < 0.3$. In the recent work [6] the triple-pole approximation was used with $\Delta_1 = 0.058$, $\Delta_2 = 0.0167$, $\Delta_3 = 0.203$.

Another approach to determine the parameters of bare Pomeron is connected with the inclusive production in the central region [7–9]. The argument in support of such method is the Abramovsky-Gribov-Kancheli cancellation of cut contributions in this region [10]. Therefore, one deals only with the first term—double bare Pomeron diagram. As a result, the asymptotic behavior of inclusive production cross section in the central region has a simple form:

$$\frac{d\sigma}{dy}\bigg|_{y=0} \sim s^\Delta. \qquad (3)$$

As was mentioned earlier, only the leading term is taken into account in the expression (3), while the contributions of secondary trajectories are neglected. However, at low and moderate energies ($\sqrt{s} < 100$ GeV) the growth of particle density is caused by contributions of secondary trajectories in Mueller-Kancelli diagrams [11]. These terms are also important at higher energies for large values of rapidity $y \sim \ln x + \ln(\sqrt{s}/m_\perp)$. The analysis of experimental data on $d\sigma/dy|_{y=0}$ presented in our previous works [8,9] shows that power behavior of this inclusive cross section is caused by the Pomeron singularity with $\Delta \approx 0.17$. In that analysis only low-energy data with $\sqrt{s} \leq 900$ GeV were used. In the present work we are going to check whether new measurements of cross sections of inclusive production of charged particles and K_S-mesons, obtained at LHC at $\sqrt{s} = 0.900$, 2.36, and 7 TeV energies agree with predictions based on the low-energy data analysis.

II. DOUBLE-REGGEON EXCHANGE

According to the generalized optical theorem and factorization of the leading Regge singularities, the inclusive cross section of the reaction $ab \to c + X$ in the central region can be written down as

$$E_c \frac{d^3\sigma}{d^3 p_c} = \frac{1}{\pi} \frac{d^2\sigma}{dm_T^2 dy} = \frac{1}{s} \sum_{i,j} f_{ij}(m_T)\left(\frac{-t}{s_0}\right)^{\alpha_i(0)}\left(\frac{-u}{s_0}\right)^{\alpha_j(0)},$$

$$(4)$$

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where $i, j = R, P$, and F stand for Reggeon, soft Pomeron, and hard Pomeron (Froissaron) exchange, respectively. The intercept parameters for these particles are

$$\Delta_R = -0.5, \qquad \Delta_P = 0.06, \qquad \Delta_F = 0.17. \quad (5)$$

These intercepts are taken from Ref. [9] with a small change of Δ_P. The kinematical variables are defined as $t = (p_a - p_c)^2 \approx -\sqrt{s} m_T e^{-y}$, $u = (p_b - p_c)^2 \approx -\sqrt{s} m_T e^{y}$, $s = (p_a + p_b)^2$, $m_T = \sqrt{m_c^2 + p_T^2}$, $s_0 = 1$ GeV^2, and rapidity y is defined as

$$y = \ln\frac{E_c + p_L}{m_T}, \quad (6)$$

where E_c, p_L, and p_T are energy, longitudinal, and transverse momentum of particle c in the center of mass system. The dependence on transverse momentum is contained in the vertex functions $f_{ij}(m_T)$ which are determined from the experimental data. In our work the following parametrization for these vertex functions is used:

$$f_{ij}(m_T) = A_{ij}\varphi_{ij}(m_T), \quad (7)$$

where constants A_{ij} are determined from the fit of low-energy data ($\sqrt{s} \leq 900$ GeV) on cross sections of inclusive $pp \to c + X$ reactions in the central region. Transverse momentum dependence of $\varphi_{ij}(m_T)$-functions cannot be determined from Regge phenomenology, so, following the work [7], the following simple exponential parametrization is used in our article:

$$\varphi_{ij}(m_T) = \frac{\beta_{ij}^2}{2(\beta_{ij}m_c + 1)} e^{-\beta_{ij}(m_T - m_c)}. \quad (8)$$

This function obeys a normalization condition

$$\int_{m^2}^{\infty} \varphi_{ij}(m_T)dm_T^2 = 1. \quad (9)$$

Parameter β_{PP} for Pomeron singularity was determined from the fit of low-energy data and equals

$$\beta_{PP} = 6 \text{ GeV}^{-1}. \quad (10)$$

For $\Delta = 0.17$ singularity, which dominates at high energies, p_T-spectrum of charge particles at LHC energies was used to obtain

$$\beta_{FF} = 4.7 \text{ GeV}^{-1}. \quad (11)$$

The decrease of this slope parameter with the growth of Δ can be connected with the decrease of the effective radius of the Pomeron singularity, observed, for example, in the description of total and elastic cross sections in the three-Pomeron model [6].

Let us first consider rapidity distributions at various energies squared s. Integrating the expression (4) over the transverse mass one obtains

$$\frac{d\sigma}{dy} = \frac{1}{s_0}\sum_{i,j}A_{ij}\left(\frac{s}{s_0}\right)^{(\Delta_i + \Delta_j)/2} \cosh[(\Delta_i - \Delta_j)y]. \quad (12)$$

It is clear that this distribution does not depend on slope parameters β_{ij}. It is important to note that both y and $\sqrt{s}$ dependencies are determined by Eq. (12). Thus both rapidity distributions and the $\sqrt{s}$ dependence of production at zero rapidity are important for the A_{ij} determination.

Experimental data on these distributions and references to original works are given in [8] (see references [10–27] in that paper). Using this data we obtain the values of parameters A_{ij}, presented in Table I. The negative value of the parameter A_{RR} is natural in spite of the fact it leads to negative cross sections at low energies. The reason is that Reggeon framework is correct only at high energies i.e. much larger than the proton mass.

In Fig. 1 rapidity distributions of inclusive production of charged particles (upper figure) and K_S meson (lower figure) in proton-proton interactions at different energies and energy dependence of $d\sigma/dy$ cross section at $y = 0$ are given. Dots in these figures represent experimental data used in the fitting procedure. Theoretical description, obtained in the framework of the Regge model with the parameters A_{ij} presented above, are shown with lines.

Experimental data on charged particles distributions at LHC energies are usually reported as distributions over pseudorapidity

$$\eta = \frac{1}{2}\ln\frac{1 + \cos\theta}{1 - \cos\theta} = \ln\cot\frac{\theta}{2}, \quad (13)$$

where θ is the scattering angle of the final particle. The relation that connects rapidity and pseudorapidity is

$$y = \frac{1}{2}\ln\frac{\sqrt{m^2 + p_T^2\cosh^2\eta} + p_T \sinh\eta}{\sqrt{m^2 + p_T^2\cosh^2\eta} - p_T \sinh\eta}. \quad (14)$$

It is clear that in the limit of zero mass one has $\eta = y$.

To transfer from rapidity to pseudorapidity distribution the information on the m_T-dependence of vertex functions φ_{ij} is needed:

TABLE I. Numerical values of parameters A_{ij} for c^- and K_S production in inclusive pp scattering.

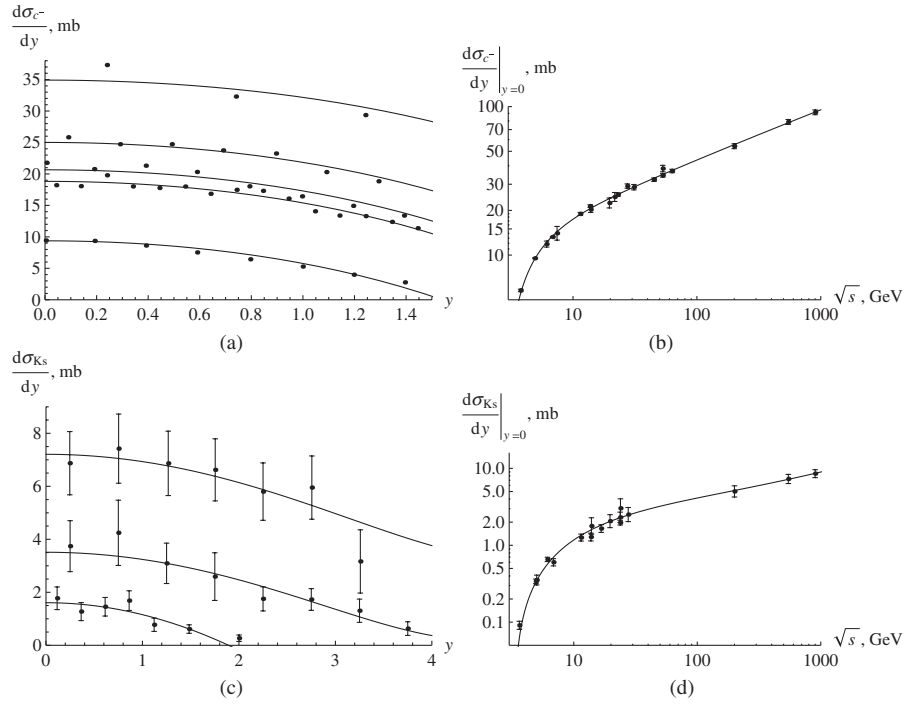| $pp \to c^- + X$				$pp \to K_S + X$		
i/j	R	P	F	i/j	R	P	F
R	−81.8	67.9	−53.1	R	11.6	−11.5	4.37
P	67.9	6.39	−0.741	P	−11.5	12.5	−6.09
F	−53.1	−0.741	9.16	F	4.37	−6.09	3.88

FIG. 1. Fits of available experimental data by double-Reggeon exchange model: (a) rapidity distributions of $pp \to c^- + X$ reaction cross section. Curves and data sets in the figure correspond to energies $\sqrt{s} = 4.9, 11.5, 13.9, 21.7$, and 53 GeV from bottom to top; (b) energy dependence of differential cross section of the reaction $pp \to c^- + X$ at $y = 0$; (c) rapidity distributions of $pp \to K_S + X$ reaction cross section at $\sqrt{s} = 13.76, 63$, and 546 GeV; (d) energy dependence of the differential cross section of the reaction $pp \to K_S + X$ at $y = 0$.

$$\frac{d\sigma}{d\eta} = \int_{m^2}^{\infty} \frac{p}{E} \frac{d^2\sigma}{dy\,dm_T^2}\, dm_T^2. \tag{15}$$

It was earlier mentioned, that Regge theory gives no information about the form of these functions. So the exponential parametrization (8) which agrees with the experimental data is used. In addition, we assume factorization of the slope parameters of these functions, so that the following relation is fulfilled:

$$\beta_{ij} = \beta_i + \beta_j, \tag{16}$$

where

$$\beta_R = 2.5\ \text{GeV}^{-1}, \qquad \beta_P = 3\ \text{GeV}^{-1}, \qquad \beta_F = 2.35\ \text{GeV}^{-1}. \tag{17}$$

Now we have enough information to obtain pseudorapidity distributions of the cross sections of $pp \to c + X$ reaction at different energies. Experimental data at LHC energies are reported normalized to nonsingle diffraction cross section σ_{NSD}. The following parametrization for σ_{NSD} is used in our work:
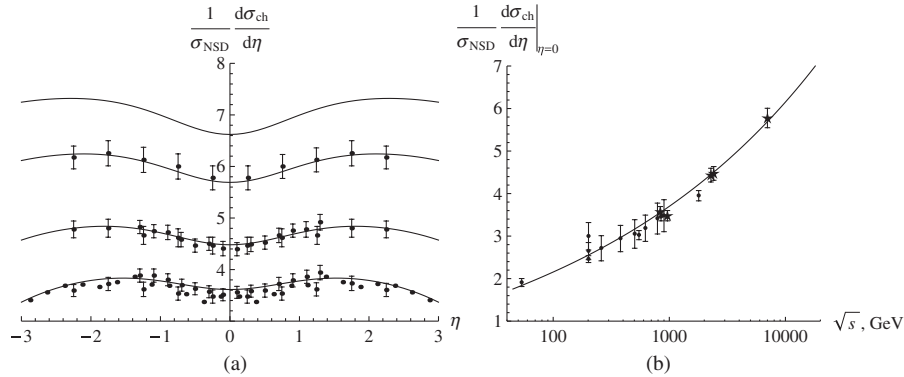

FIG. 2. (a) pseudorapidity distributions of $pp \to c^{\pm} + X$ reaction cross section. Curves in the figure correspond to energies $\sqrt{s} = 0.9, 2.36, 7$, and 14 TeV from bottom to top; (b)—energy dependence of differential cross section of the reaction $pp \to c^{\pm} + X$ at $\eta = 0$. Recent values obtained by ALICE and CMS collaborations are marked with stars.
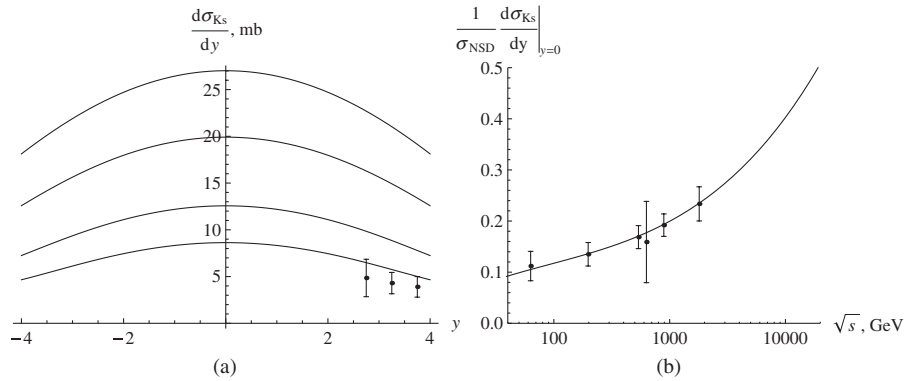
FIG. 3.   (a) rapidity distributions of $pp \rightarrow K_S + X$ reaction cross section. Curves in the figure correspond to energies $\sqrt{s} = 0.9$, 2.36, 7, and 14 TeV from bottom to top; (b) energy dependence of differential cross section of the reaction $pp \rightarrow K_S + X$ at $\eta = 0$.

$$\sigma_{\text{NSD}}(s) = \left[1.76 + 19.8 \left(\frac{s}{\text{GeV}^2} \right)^{0.057} \right] \text{mb}. \qquad (18)$$

In Fig. 2(a) pseudorapidity distributions at high energies are shown in comparison with experimental data taken from the works [12–14]. In these works distributions for both positively and negatively charged particles are given, thus they are doubled in comparison with those presented in Fig. 1. Energy dependence of differential cross section of the reaction $pp \rightarrow c^{\pm} + X$ at zero rapidity is presented in Fig. 2(b) together with both low-energy data taken from [8] and recent LHC results [12–15]. One can clearly see, that in the framework of Regge phenomenology we get good agreement with the higher energy experimental data, although these values were not used in the fitting procedure.

As K_S-mesons have definite mass, distributions over rapidity y are experimentally measured. Recent data from the LHC contains only LHCb results in the $2.5 < y < 4$ region at $\sqrt{s} = 0.9$ TeV. These points together with the Regge model predictions at $\sqrt{s} = 0.9$, 2.36, 7, and 14 TeV are shown in Fig. 3(a). The agreement within the error bars is achieved but experimental points are systematically below the theoretical prediction. These measurements are reported in units of cross section as opposed to others, reported in units of multiplicity. Thus, the uncertainty from the normalization cross section may arise. The rapidity density at $y = 0$ have been measured up to 1.8 TeV energy [16–19]. All these measurements are in pretty good agreement with our theoretical predictions.

III. DISCUSSION

The energy dependence of elastic and diffractive cross sections is usually discussed in the framework of Regge phenomenology [20–23]. In this approach the amplitude of the process is written as a sum of Reggeonic diagrams: Pomeron and secondary trajectories. According to perturbative QCD, the Pomeron singularity can be presented as a

number of poles in an angular momentum plane with $1 \leq j \leq 1 + \Delta$. The saturation effects complicate determination of bare Pomeron parameters. On the other hand, according to the Abramovsky-Gribov-Kancheli theorem cut contributions and saturation effects cancel in the central region and we deal with bare Pomerons only.

In our work we concentrate on the rapidity densities and $\sqrt{s}$ dependencies of light charged and K_S mesons production. It was sufficient to consider two Pomeron poles with the intercepts $\alpha(0) = 1$ and $\alpha(0) = 1.17$ to describe low-energy data on proton-proton scattering, published long before LHC started. This approach gave both energy dependence of total cross sections and rapidity distributions at different energy values [9]. We would like to mention that the intercept of hard Pomeron, which dominates at high energies, remained unchanged. What regard to the soft Pomeron, we changed its intercept slightly according to recent works. However, this change does not affect final distributions significantly.

The constants of Pomeron interaction with protons and final particles can be determined from a simple fit of experimental data. In our article we used low-energy data at $\sqrt{s} \leq 900$ GeV energies to determine Pomeron coupling constants and predict rapidity and pseudorapidity distributions of light charged and K_S mesons at LHC. At $\sqrt{s} = 0.9$, 2.36, and 7 TeV energies good agreement with the available experimental data is observed. We also gave predictions of pseudorapidity distributions of charged particles and K_S meson production at $\sqrt{s} = 7$ and 14 TeV.

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