Correlation between mean transverse momentum and multiplicity of charged particles in $pp$ and $p\bar{p}$ collisions: from ISR to LHC

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Abstract. We present an analysis of the available experimental data on correlation between mean transverse momentum and charged particles multiplicity ($\langle p_T \rangle$-$N_{ch}$) at central rapidity in $pp$ and $p\bar{p}$ collisions at $\sqrt{s}$ from 17 GeV to 7 TeV. A multi-pomeron exchange model based on Regge-Gribov approach provides quantitative description of $\langle p_T \rangle$-$N_{ch}$ correlation data and their energy dependence. Results are found to be in agreement with string fusion model hypothesis.

Keywords: $pp$ and $p\bar{p}$ collisions, charged multiplicity, transverse momentum, correlations, quark-gluon strings, pomerons, string interaction

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INTRODUCTION

It came first from the observations in the cosmic rays experiments [1, 2] and it was confirmed later in numerous collider studies that the majority of particles (pions) produced in high energy $pp$ and $p\bar{p}$ collisions have their transverse momentum $p_T$ as small as a few hundreds of MeV/c. The existence of correlation of charged particles mean transverse momentum ($\langle p_T \rangle$) with the event multiplicity ($N_{ch}$) was established in a wide energy range, changing from the negative (at low collision energies of $\sqrt{s}$=17 GeV) to positive one (above 40 GeV), see a compilation of results in [3]. Besides this, a peculiar dependence of $p_T$ spectra on the event complexity – a tendency of flattening of the mean transverse momentum of charged particles with the multiplicity – was established with the growth of collision energy. It was argued by Van Hove [4] that this anomalous behavior (a plateau-like structure) of the mean transverse momentum as a function of hadron multiplicity could be a signal for the deconfinement transition of hadronic matter in $pp$ and $p\bar{p}$ high energy collisions.

Recently, the new set of detailed experimental data on the mean transverse momentum ($\langle p_T \rangle$) versus the charged-particle multiplicity $N_{ch}$ appeared, showing dramatic difference of correlation functions for different colliding systems [5]. In $pp$ and $p$-$Pb$ collisions at LHC energies, a strong increase of $\langle p_T \rangle$ with $N_{ch}$ is observed, which is much stronger than that measured in $Pb$-$Pb$ collisions. In the last case a striking flat behaviour of $\langle p_T \rangle$-$N_{ch}$ correlation was found for the first time in a wide region of collision centralities. It is discussed in [5] that for the $pp$ collisions, the behavior of $\langle p_T \rangle$-$N_{ch}$ correlation could be attributed, within a model of hadronizing strings, to multiple-parton interactions and to a final-state color reconnection mechanism. At the same time it is noted in [5] that the data in $p$-$Pb$ and $Pb$-$Pb$ collisions cannot be described by an incoherent superposition of nucleon-nucleon collisions challenging most of the event generators. However, quantitative and consistent description of behavior of $\langle p_T \rangle$-$N_{ch}$ correlation in nucleon-nucleon collisions and, in particular, its energy dependence, still remains an open basic problem. It is evident that the last one should be completely understood, on a single approach base, before any use of event-generator calculations for the more complicated cases of $p$-$Pb$ or $Pb$-$Pb$ collisions analysis. Overview of different models trying to explain the effects observed in $\langle p_T \rangle$-$N_{ch}$ correlations in high energy $pp$ and $p\bar{p}$ collisions could be found in [3].

In the present study we continue the analysis [6, 7] of $\langle p_T \rangle$-$N_{ch}$ correlation for charged particles using available data in a wide energy range of $pp$ and $p\bar{p}$ collisions and basing on the Regge-Gribov approach. It is assumed [8], [9] that low-$p_T$ multiparticle production is a result a few ($n$) pomeron exchange. After this exchange hadrons become joined by $n$ pairs of strings. Fission of the strings during the separation of hadrons results in production of $n$-pomeron showers, so that the multiplicity exceeds by a factor $n$ the one-pomeron shower multiplicity. In case of identical strings the $p_T$ distributions of charged particles have no dependence on multiplicity. However, when there is possible interaction between strings [10] one may expect the $p_T$ distributions of charged particles to be different from those...
produced by non-interacting strings. It is in the case of interaction between quark-gluon strings in a form of color strings fusion [11] that new types of particle-emitting sources (strings) might be formed, characterized by a higher energy density (described by string tension parameter $\tau$). As a result, the higher values of mean transverse momenta of charged particles could be expected in hadronization of such types of strings.

We are using a modified variant [6, 7] of multi-pomeron model [3] with collectivity effects. Similar to [3], both multiplicity of charged particles and their transverse momenta are treated within the same model where the multi-pomeron exchange is combined with Schwinger mechanism [12] of particle production. Thus the collectivity effects like string fusion are included into the model [3] in an effective way by a single parameter $\beta$, and the $\langle p_T\rangle$-$N_{ch}$ correlation appears to be the intrinsic property of the model.

It is shown below that this concept allows to provide good quantitative description of $\langle p_T\rangle$-$N_{ch}$ correlation pattern and various observables in $pp$ and $p\gamma$ collisions and their energy dependence in a wide energy range. It is also shown that the model has the predictive power that allows extrapolation to the higher collision energies. Besides, the model could be extended to the long-range $\langle p_T\rangle$ and $\langle N_{ch}\rangle$ correlations which might be studied by using event-by-event data in separated pseudorapidity intervals.

The paper is organized as follows: in the next section we give a very brief description of the modified variant of multi-pomeron exchange model with collectivity used in our analysis. In Section 3 we describe how the values of the parameters in the model are extracted by fits to experimental data. In Section 4 we discuss the results obtained and show some predictions. Finally, we present our conclusions.

**MODIFIED MULTI-POMERON EXCHANGE MODEL**

In the present study we use the modifications of the multi-pomeron exchange model with string fusion [3] as described in [6, 7]. We consider the multiplicity and the transverse momenta of charged particles produced in high energy nucleon-nucleon collisions into a given pseudo(rapidity) interval $\delta$.

Basing on [9], [13] and following [3], the function $f(N_{ch}, p_T; z; k, \beta, t)$ is introduced to describe both multiplicity and transverse momentum distributions in soft multi-particle production in hadron collisions:

$$f(N_{ch}, p_T; z; k, \beta, t) = C_w \sum_{n=0}^{\infty} \frac{1}{2^n} \left(1 - \exp(-z) \sum_{l=0}^{n-1} \frac{z^l}{l!}\right) \exp(-2nk\delta) \frac{(2nk\delta)^{N_{ch}}}{N_{ch}!} \cdot \frac{1}{n!} \exp\left(-\pi p_T^2/n^2T\right).$$

(1)

Here $C_w$ is a normalization factor which is introduced in order to enforce the normalization condition:

$$2\pi \sum_{N_{ch}}^{\infty} \int_0^\infty f(N_{ch}, p_T; z; k, \beta, t)p_Tdp_T = 1.$$

(2)

The function $f$ (see eq.(1)) represents combined probability distribution of the number of charged particles $N_{ch}$ and their transverse momentum spectra ($p_T$). The first factor in eq.(1) gives a probability of $n$ pomeron production in a single event [9, 13]. Parameter $z$ is responsible for the dependence of this distribution on collision energy $\sqrt{s}$. We use the following values of the parameters [14]:

$$z = \frac{2C\gamma^\Delta}{R^2 + \alpha' \log(s)}, \quad \Delta = 0.139, \quad \alpha' = 0.21 \text{ GeV}^{-2}, \quad \gamma = 1.77 \text{ GeV}^{-2}, \quad R_0^2 = 3.18 \text{ GeV}^{-2}, \quad C = 1.5.$$

(3)

The second multiplier in eq.(1) represents the probability of $N_{ch}$ particles production in $n$-pomeron showers. The Poisson distribution is used with mean being proportional to the number of pomeron $n$ and the width of pseudo(rapidity) interval $\delta$. Parameter $k$ is, accordingly, the mean number of charged particles per rapidity unit from one string.

The last factor was introduced in eq. (1) in [3]. It reflects Schwinger mechanism of particle production [12], which prescribes the transverse spectrum of charged particles from one string to be of a Gaussian form:

$$\frac{d^2N_{ch}}{dp_T^2} \sim \exp\left(-\frac{\pi(p_T^2 + m^2)}{\tau}\right).$$

(4)

where $\tau$ corresponds to the string tension.
A simplified assumption is used in our work: we do not discriminate the particle species, considering only production of pions. Thus the particle mass dependence in the expression eq.(1) is eliminated. In the current model, similar to [3], the string interaction is introduced in an effective way through a single parameter $\beta$ responsible for the collectivity effects, that gives us an effective string tension $\eta^0$. 

$\langle p_T \rangle$-$N_{ch}$ correlation function in the present model is calculated as

$$\langle p_T \rangle_{N_{ch}} = \frac{\int_0^\infty f(N_{ch}, p_T; z, k, \beta, t) p_T^2 d p_T}{\int_0^\infty f(N_{ch}, p_T; z, k, \beta, t) p_T d p_T},$$  \hspace{1cm} (5)$$

or

$$\langle p_T \rangle_{N_{ch}} = \frac{1}{\int_0^\infty f(N_{ch}, p_T; z, k, \beta, t) p_T d p_T} \sum_{n=1}^\infty \int_0^\infty f_n(N_{ch}, p_T; z, k, \beta, t) p_T^2 d p_T,$$  \hspace{1cm} (6)$$

where $f_n(N_{ch}, p_T; z, k, \beta, t) p_T^2 d p_T$ here is defined similar to eq.(1), but without the sum symbol.

Note, that it is possible to integrate out $p_T$ dependence from eq.(1) and obtain the charged particles distribution and mean multiplicity:

$$P(N_{ch}) = 2\pi \int_0^\infty f(N_{ch}, p_T; z, k, \beta, t) p_T d p_T,$$  \hspace{1cm} (7)$$

$$\langle N_{ch} \rangle(s) = \sum_{N_{ch}=0}^\infty N_{ch} P(N_{ch}) = \langle n(s) \rangle k(s) \delta.$$  \hspace{1cm} (8)$$

The dependence of the mean transverse momentum of charged particles on energy can be calculated using:

$$\langle p_T \rangle(\sqrt{s}) = \frac{\sum_{N_{ch}=0}^{\infty} N_{ch} \int_0^\infty f(N_{ch}, p_T; z, k, \beta, t) p_T^2 d p_T}{\sum_{N_{ch}=0}^{\infty} N_{ch} \int_0^\infty f(N_{ch}, p_T; z, k, \beta, t) p_T d p_T} = 2\pi \sum_{N_{ch}=0}^{\infty} N_{ch} \langle p_T \rangle_{N_{ch}} = 2\pi \sum_{N_{ch}=0}^{\infty} \frac{N_{ch}}{(N_{ch})} \int_0^\infty f(N_{ch}, p_T; z, k, \beta, t) p_T^2 d p_T.$$  \hspace{1cm} (9)$$

One should mention, that the picture where transverse momentum of charged particles increases with multiplicity and collision energy is natural for a string fusion model [15, 16]. According to this model, with the increase of the collision energy one may expect a general growth in the number of multi-pomeron in exchange in nucleon-nucleon collision. Thus the total number of strings will increase and they could start to overlap, forming clusters. In case of string fusion one may expect the formation of new sources with higher string tension and, therefore, the increase of both mean multiplicity and mean $p_T$ of charged particles emitted from such type fused strings. It could cause non-zero correlation between transverse momentum and multiplicity with allowance to both positive [14, 17, 18] and negative [19, 20] $\langle p_T \rangle$-$N_{ch}$ correlations.

This increase in mean $p_T$ is relevant to the degree of strings overlap in transverse space that is characterized by the string density parameter [15, 16] which is denoted here as $\eta$. According to string fusion model, the mean multiplicity $\mu$ and mean value of $p_T^2$ emitted from a cluster of fused strings are modified compared to multiplicity $\mu_0$ and transverse momentum squared $p_0^2$ of a single string:

$$\mu = \mu_0 \sqrt{\eta}, \hspace{1cm} p_T^2 = p_0^2 \sqrt{\eta}.$$  \hspace{1cm} (10)$$

Here $\mu_0$ and $p_0^2$ are treated as some universal, independent on energy parameters, as they correspond to the properties of single (none-fused) string. Thus one can obtain the following ratio, which in case of the string fusion we should expect energy independent:

$$\frac{\mu}{p_T^2} = \frac{\mu_0}{p_0^2}.$$  \hspace{1cm} (11)$$

In this connection, we have to note that it is possible to obtain this ratio with two basic quantities of our model: $k$ (mean number of particles produced per unit rapidity by one emitter) and the mean value of squared transverse
FIGURE 1. Left: Experimental data on charged particle pseudorapidity density at midrapidity vs. collision energy (see compilation of pp and $p\bar{p}$ collision data in [21] and the modified multi-pomeron exchange model – solid line (see text). Right: Energy dependence of parameter $k$ obtained in the present model using data at different energies. Straight line – approximation by $k = 0.255 + 0.0653 \log \sqrt{s}$.

momentum $\sim \langle n \rangle^{\beta_{t}}$. So the both quantities, as in eq.(10), could be defined using the $\langle p_{T} \rangle$-$N_{\text{ch}}$ correlation function at the given $\sqrt{s}$. Therefore, the condition eq.(10) could be checked in the framework of the present model by plotting the values

$$R = \frac{k}{\langle n \rangle^{\beta_{t}}}$$

as a function of collision energy using 2 parameters extracted from the experimental data at the given $\sqrt{s}$.

**DETERMINATION OF MODEL PARAMETERS**

**Determination of the energy dependence of the parameter $k$**

In our modified variant [6, 7], contrary to [3], $k$ – the mean number of particles produced per unit of rapidity per string – is not considered as a free model parameter but assumed to be the energy dependent: $k=k(\sqrt{s})$. This energy dependence was fixed in the model by fitting a set of available experimental data on charged particles yields vs. $\sqrt{s}$. We used the experimental data on the energy dependence of the charged particle multiplicity density in $pp$ and $p\bar{p}$ collisions (see compilation in [21]). The parameter $k$ was determined by fitting the data in the energy range from 20 GeV to 7 TeV, the result of fitting is shown in the Fig. 1 (left) by solid line.

Charged particles pseudorapidity density in the left plot Fig.1 was calculated basing on the eq. 8, where the mean number of pomerons $\langle n(s) \rangle$ was estimated at a given $\sqrt{s}$ using Regge-Gribov approach, and the pseudorapidity width $\delta$ was selected to match the relevant experimental one. Thus the parameter $k$ was defined by fitting experimental data (see the left plot Fig.1). We have to note here that the ISR data (diamonds in the left plot Fig.1) were not used in our fitting procedure, so that the results of extrapolation of our model are shown in this region.

As a result of this fitting parameter $k$ was defined. The values of the parameter $k$ are plotted as a function of $\sqrt{s}$ in Fig.1 (right). A smooth logarithmic growth of multiplicity density from one string with energy was obtained as:

$$k = 0.255 + 0.0653 \log \sqrt{s}.$$  

This result is in agreement with string fusion model predictions [15, 16], where the growth of string tension with the collision energy is expected for fused strings due to the growing string density.
Determination of the energy dependence of the parameters $\beta$ and $t$

Two free parameters of the modified model, $\beta$ - that takes account of string fusion, and the average string tension parameter $t$, are extracted in our work from the available experimental data on $\langle p_T \rangle$-$N_{ch}$ correlation in proton-(anti)proton collisions at wide energy region from 17 GeV to 7 TeV. The expression for the correlation function eq.5 was used in our fitting procedure. Some results of fitting of $\langle p_T \rangle$-$N_{ch}$ correlation in $\bar{p}p$ and $pp$ collisions at different energies, starting from 17 GeV and to 7 TeV, are shown in Fig. 2 – 5 (a full data set is available in [6]).

Parameters $\beta$ and $t$ were extracted by fitting $\langle p_T \rangle$-$N_{ch}$ correlation data, the relevant values are shown as function on energy at the Fig. 6. Both parameters are showing smooth behavior with the collision energy.

For the parameter $t$ two subsets are obtained: $t = 0.566 \text{ GeV}^2$ and $t = 0.428 \text{ GeV}^2$ which are very close to those obtained in [3]. As it was explained previously [3], this fact points to the systematic effects of the different experimental estimates of the mean $p_T$ values for low-multiplicity events (i.e. for a single pomeron exchange region). The upper value of string tension is used here $t = 0.566 \text{ GeV}^2$ as the one ensuring the values of event mean $p_T$ values corresponding to
FIGURE 4. ...the same as in Fig.2 for \( \sqrt{s} = 540 \) GeV. Data from [24], \(|\eta| < 2.4\).

FIGURE 5. ...the same as in Fig.2 for \( \sqrt{s} = 7 \) TeV. Data from CMS [25]. Midrapidity, pseudorapidity interval is \(|\eta| < 2.4\).

the experiment (see Fig. 9 below).

In case of \( \beta \) A smooth behavior of parameter \( \beta \) with energy is obtained and approximated at fig. 6 by
\[
\beta = \beta_0 ((1 - \log \sqrt{s} - \beta_2)^{\beta_1})
\]
Here we have \( \beta_0 = 1.16 \pm 0.39 \), \( \beta_1 = 0.19 \pm 0.08 \), \( \beta_2 = 2.52 \pm 0.03 \).

RESULTS AND DISCUSSION

Multipomeron exchange contributions vs. \( \sqrt{s} \)

Fig. 7 contains results of our calculations of mean number of pomerons (solid line) and their variance vs. collision energy. One may see a rather smooth growth of the mean number of pomerons with energy, reaching the value about 3 at the LHC region. This increase is combined with a much faster growth of variance of the mean number of pomerons.

Contributions to the correlation function of several first terms (\( n = 1, 2, 3 \) etc. – see formula (6)) are shown at various energies in the Figures 2 - 5. One may see that the dominant contribution of single pomeron exchange is concentrated...
in the low multiplicity region, bringing there the values of $\langle p_T \rangle$ from $\sim 0.32$ GeV/c to 0.4 GeV/c (for the relevant collision energies of 17-7000 GeV, see Figures 2 and 5).

With the growing energy the role of the multi-pomeron exchange increases. The number of pomerons and fluctuations in the number of pomerons are growing with energy leading to the observed flattening of the $\langle p_T \rangle - N_{ch}$ correlation functions.

We have to note here that the growth of fluctuations in the number of pomerons exchanged in the collision of protons at the LHC energies brings relevant large fluctuations in the number of particle-emitting strings and, therefore, has a natural prediction of the existence of a long-range $\langle p_T \rangle - N_{ch}$ correlations. The last ones might be observed in the event-by-event studies of observables measured in separated pseudorapidity intervals.

**Charged-particle multiplicity distribution**

The multiplicity distributions of charged particles formed as the result of processes going via the exchange of $n$ soft pomerons in $pp$ collisions at the given energy, calculated in the modified multi-pomeron exchange model, are compared to the relevant experimental data in the Figure 8. Calculations were done using equation (7). Examples are
FIGURE 8. Charged particles multiplicity distributions in \( p\bar{p} \) collisions at various energies \( \sqrt{s} \) (200 GeV, 900 GeV) [25] and in \( pp \) collisions (2360 GeV, 7 TeV) [26] in pseudorapidity interval \( |\eta| < 0.5 \) (dots). The results of the modified multi-pomeron exchange model (lines) are calculated with the model parameters \( \beta \) and \( t \) as defined in Fig. 1, 6.

shown for the collision energies of \( \sqrt{s} = 200, 900, 2360 \) and 7000 GeV.

We may conclude here that the overall tendencies of multiplicity distributions are well reproduced in wide energy range. The model predictions slightly deviate from experimental data, that is observed in the region of the high-multiplicity tails, however this could be related both to some assumptions used in the present calculations and to the still possible contributions of hard processes.

Energy dependence of \( \langle p_T \rangle \) values

Results of calculations in the modified multi-pomeron model with collectivity of the mean \( p_T \) values vs. \( \sqrt{s} \) are compared to the experimental data in the Figure 9. Calculations were done using equation (9). The parameters of the model are the same as were defined above (see Fig. 1, 6).

Energy dependence of string fusion model ratio \( k/p_T^2 \)

We also made checks of the string fusion model condition (10). Results are shown in the Fig. 10 approximated by a straight line. Thus we can conclude here that the collectivity effects, relevant to quark-gluon string interaction phenomenon (string fusion), could be considered as important in \( pp \) and \( p\bar{p} \) collisions and in a wide energy range, much wider than it was previously expected.
FIGURE 9. Energy dependence of mean $p_T$ values calculated in the modified multi-pomeron model with collectivity and comparison to the experiment. Data – (black points) were borrowed from [27]. Red points, approximated by a curve – modified multi-pomeron exchange model with parameters $k$, $\beta$ and $t$ as in Fig. 1, 6.

FIGURE 10. Relation to string fusion hypothesis: ratio of $k$- mean multiplicity of charged particles from one string to characteristic string tension at different $pp$ and $p\bar{p}$ collision energies. Dots – experimental values from our analysis. Straight line – approximation.

$$\frac{k}{\langle n \rangle^\beta t} = 0.87 \pm 0.08.$$  \hfill (12)

CONCLUSIONS

All features of $\langle p_T \rangle - N_{ch}$ correlations experimentally observed in the central rapidity region in $pp$ and $p\bar{p}$ collisions, in a wide energy range from the ISR to Tevatron and LHC, are successfully described in the framework of a new variant of the multi-pomeron exchange model in which string collectivity has been included in an effective way. The crucial feature of new model is the smooth logarithmic growth of mean multiplicity per string (the parameter $k$) with energy.
whereas in previous works it was supposed to be constant. Thus the number of the model parameters is reduced from three to two: $\beta$—parameter, responsible for the collective properties and $t$—string tension. Both $\beta$ and $t$ are showing smooth energy dependence when extracted from the available experimental data on $\langle p_T \rangle$-$N_{ch}$ correlations in $p\bar{p}$ and $pp$ collisions.

The transition from negative to positive $\langle p_T \rangle$-$N_{ch}$ correlation pattern and tendency for flattening of the $\langle p_T \rangle$ with multiplicity and with increase of energy $\sqrt{s}$ from 17 GeV to 7000 GeV in $p\bar{p}$ and $pp$ collisions are quantitatively described within this single approach. The experimental data on multiplicity distributions in the whole interval of collision energies and the $\langle p_T \rangle$ vs. energy dependence are also well reproduced numerically. Finally, the predictions of the string fusion model are also checked for the energy dependence of two model quantities - $k$ and $\beta$. All these results on $\langle p_T \rangle$-$N_{ch}$ correlation analysis in $pp$ and $p\bar{p}$ collisions at $\sqrt{s}$ from 17 GeV to 7 TeV are found to be in agreement with string fusion model hypothesis.

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