Experimental evidences of difference in $pp$ and $p\bar{p}$ interactions at high energies

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Abstract

Hadrons production is different in $p\bar{p}$ and $pp$ interactions at high energies. There is process of hadrons production from three quark strings in $p\bar{p}$ which is absent in $pp$. This process grows as $(\ln \sqrt{s})^2$ and becomes significant when energy of collision increases. Inclusive cross sections of $p\bar{p}$ interaction exceed inclusive cross sections of $pp$. Theoretical estimation of the ratio of $p\bar{p}$ to $pp$ at energy $\sqrt{s} = 900$ GeV gives $R = 1.12 \pm 0.03$. The UA1 data on $p\bar{p}$ transverse momentum distribution are about 1.2 – 1.3 times higher than the CMS, ATLAS and ALICE data on $pp$ at energy $\sqrt{s} = 900$ GeV.

Keywords: inclusive cross section, multiparticle production, multiplicity distribution, quark string, Pomeranchuk theorem

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1. Introduction

The Collaborations CMS \cite{1}, ATLAS \cite{2} and ALICE \cite{3} have published inclusive charged particle transverse momentum distributions in $pp$ interaction at center-of-mass energy $\sqrt{s} = 900$ GeV\footnote{We define invariant inclusive cross section in standard form after pioneer papers \cite{4,5}}. The ATLAS and ALICE compared their measurements to inclusive cross sections of $p\bar{p}$ interaction obtained by the UA1 Collaboration \cite{6} at the same energy $\sqrt{s} = 900$ GeV. The UA1 data overlaid with the ATLAS, ALICE and CMS data are shown in Fig.1. As an immediate consequence of Fig.1, the ratio of $p\bar{p}$ to $pp$ inclusive cross sections at the same energy $\sqrt{s} = 900$ GeV

$$R = \left[ \frac{1}{2\pi p_T} \frac{d^2n_{p\bar{p}}^{ch}}{d\eta dp_T} \right] / \left[ \frac{1}{2\pi p_T} \frac{d^2n_{pp}^{ch}}{d\eta dp_T} \right]$$

is greater than unity, $R \approx 1.2$ for the ATLAS and ALICE data and $R \approx 1.3$ for the CMS data.

The ATLAS and ALICE state that the difference is bound to systematic uncertainties of the UA1 experiment. The CMS did not compare their data on $p_T$ distribution with the UA1 data and made no comments.

The Pomeranchuk theorem states that total, elastic and differential elastic cross sections of $pp$ and $p\bar{p}$ interactions are equal at asymptotic high energies.
Figure 1: The ratios of invariant inclusive cross sections of the UA1 \cite{6} to ATLAS \cite{2} (a), ALICE \cite{3} (b) and CMC \cite{1} (c) at $\sqrt{s} = 900$ GeV. The shaded areas indicate the errors of the ratios. The dashed line shows the value of ratio $R = 1.12$, our prediction from the LCNM. The solid line at unity is shown for visibility.

It is commonly believed that characteristics of multiple production such as, for example, invariant inclusive cross section $E d^3\sigma/dp^3$ are also equal for $pp$ and $p\bar{p}$ interactions at high energies. So it is expected that at high energies there must be equality $R = 1$ and experimentalists naturally try to explain the ratio $R > 1$ by the UA1 uncertainties.

The purpose of the present work is to argue that inclusive cross sections of $p\bar{p}$ interactions are higher than $pp$ at the same energy. Thus experimental
data of the CMS, ATLAS and ALICE do correspond to reality.

2. Inclusive cross sections of the CDF and CMS Collaborations

Our first argument is based on analysis of the CDF data on $p\bar{p}$ interactions at $\sqrt{s} = 1.96$ TeV \cite{7} together with the CMS data on $pp$ interactions at $\sqrt{s} = 2.36$ TeV \cite{1}. We calculated the ratio of $Ed^3\sigma^{p\bar{p}}/dp^3$ to $Ed^3\sigma^{pp}/dp^3$ which is shown in Fig.2. The result is amazing – the ratio of inclusive cross sections equals unity with good accuracy. If we accept that $Ed^3\sigma^{p\bar{p}}/dp^3 = Ed^3\sigma^{pp}/dp^3$ at the same energy, these cross sections must be different as the energy increases by 400 GeV. That is, $Ed^3\sigma^{pp}/dp^3$ at $\sqrt{s} = 2.36$ TeV must be higher than $Ed^3\sigma^{p\bar{p}}/dp^3$ at $\sqrt{s} = 1.96$ TeV. Therefore the ratio given in the lower panel of Fig.2 must be systematically lower than unity.

Let us discuss some details of our analysis. Since there are no measurements of $p\bar{p}$ cross sections (total, inelastic or NSD) at $\sqrt{s} = 1.96$ TeV, we obtained the inclusive cross section $Ed^3\sigma^{pp}/dp^3$ from the CMS data $\frac{1}{2\pi p_T} \frac{d^2N_{ch}}{d\eta dp_T}$ \cite{1} multiplied by $\sigma_{NSD}$. We used value $\sigma_{NSD} = 49.86$ mb which was estimated by the ALICE for $\sqrt{s} = 2.36$ TeV \cite{8}. (Lower value $\sigma_{NSD} = 48.77$ mb which gives lower value of $pp$ inclusive cross section was obtained in \cite{9}.) Therefore the experimental ratio given in Fig. 2 presumably confirms our assumption that $Ed^3\sigma^{p\bar{p}}/dp^3 > Ed^3\sigma^{pp}/dp^3$ at the same energy.

3. Subprocesses of multiple production in $pp$ and $p\bar{p}$

In this section we will argue that it is possible to explain the difference in inclusive spectra of $pp$ and $p\bar{p}$ interactions. Previously we have demonstrated...
Figure 2: The ratio of invariant inclusive cross sections of CDF at $\sqrt{s} = 1.96$ TeV to CMS at $\sqrt{s} = 2.36$. The shaded area indicates the errors of the ratio. The solid line at unity is shown for visibility.

the possibility of difference in multiplicity distributions in $pp$ and $p\bar{p}$ scatterings. It is almost impossible to prove this difference experimentally. But we can use this approach to analyze possible inequality in $E d^3\sigma^{pp}/dp^3$ and $E d^3\sigma^{pp}/dp^3$. We are based on the Low Constituents Number Model (LCNM). As it should be in any collision theory, the model contains three stages: preparation of initial state, interaction, and separation of reaction products. Schematic illustration of hadrons interaction and multiple production in this model is given by phenomenological diagrams in Fig.3.
A key feature of the model is assumption that there are only few scatters (constituents) in initial state of each colliding hadrons – these are valence quarks (antiquarks) and only one gluon. This gluon appears with low probability which grows slowly as energy increases\(^2\). Interaction is carried out by gluon exchange which corresponds to Low–Nussinov two-gluon pomeron \(^{13}\). Due to gluon exchange colorless hadrons gain color charge. Separation of reaction products (colored hadrons) occurs after interaction. When the charges are separated by distance larger than the confinement radius, color electric

\(^2\)This assumption allows to explain small value of the Pomeranchuk trajectory slope \(^{11}\). It also allows to describe value and growth with energy of \(pp, \bar{p}p, \pi^\pm p, K^\pm p\) total cross sections \(^{12}\).
field strings are produced. These strings break up to primary hadrons. Formation of color field string and its breakup into primary hadrons corresponds to the interaction in the final state.

It should be emphasized that because color objects are not emitted, the process of converting color charges to hadrons occurs with probability which equals to unity and does not affect interaction probability. Therefore values of total cross sections for both $pp$ and $p\bar{p}$ are defined only by one gluon exchange in the second stage and so they are the same. Thus the Pomeranchuk theorem is fulfilled in the proposed LCNM approach.

We distinguish the following inelastic processes of hadrons production (or they might be better defined as inelastic subprocesses in multiple hadron production) in $pp$ and $p\bar{p}$ interactions.

*Hadrons production from decay of gluon string.* Gluon string is produced when objects carrying octet quantum numbers fly apart after interaction. In this case it is impossible to separate gluon from valence quarks. Wavelength of the gluon is such, that it overlaps with the valence quarks. This subprocess gives constant contribution to total cross sections. This subprocess is the same for both $pp$ and $p\bar{p}$ interactions (Fig.3, first column).

*Hadrons production from decay of two quark strings.* Quark strings are produced between quark and antiquark and between diquark and antidiquark in $p\bar{p}$ interaction and between quark and diquark in $pp$ interaction. Since gluon spectrum is $d\omega/\omega$ ($\omega$ – gluon energy), contribution from the component with one gluon in the initial state grows as $\ln \sqrt{s}$. This gluon is absorbed after the interaction by one of the quark strings, and it changes the string color charge – “recolor” the string. This contribution is the same for both
and $p\bar{p}$ interactions (Fig.3, second column).

The contribution from two gluons in the initial state grows as $(\ln \sqrt{s})^2$. Both gluons are absorbed by quark strings “recoloring” them. In case of $pp$ interaction the two gluons initial state can only give configuration with two quark strings in the final state (Fig.3, third column).

*Hadrons production from decay of three quark strings.* In case of $p\bar{p}$ interaction the two gluons initial state besides the configuration with two quark strings can lead to configuration with three quark strings (Fig.3, fourth column). The quark strings are produced between each quark and each antiquark. Since the contribution of this subprocesses grows as $(\ln \sqrt{s})^2$, it is quite essential at high energies 3.

We suppose that difference in inclusive cross sections in $pp$ and $p\bar{p}$ interactions is governed by presence of three quark strings in $p\bar{p}$. This subprocess gives contribution in multiplicity distribution $P_n$ in the region of high $n$ ($n$ - number of charged particles). In this region the value of $P_n$ is about one order of magnitude smaller than in the maximum region and so it is hard to experimentally study it because of large uncertainties. Therefore the difference in $P_n$ distributions in $pp$ and $p\bar{p}$ interactions will be difficult to detect.

One has to use another observable value, which is able to increase the difference between $P_n$ distributions in $pp$ and $p\bar{p}$ scatterings. We propose to use

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3Our approach is different from approach with exchange of decameron [14], which gives difference in multiplicity distributions and inclusive cross sections in $pp$ and $p\bar{p}$ interactions. Contribution from decameron is low and constant with energy [14]. The AFS [15] and UA5 [16] Collaborations have not found this contribution at energy $\sqrt{s} = 53$ GeV. Moreover it will not be seen at higher energies.
Let us define inclusive cross section of one charged particle production in an event with \( n \) charged particles – a topological inclusive cross section ("semi-inclusive" cross section of Koba, Nielsen and Olesen [17])

\[
E \frac{d^3 \sigma_n}{dp^3}, \quad \int dp^3 \frac{d^3 \sigma_n}{dp^3} = n \sigma_n, \tag{2}
\]

where \( \sigma_n \) – topological cross section of \( n \) charged particles production. We consider here only non single diffractive events, so \( \sum_n \sigma_n = \sigma_{NSD} \). We stress that (2) is normalized to \( n \sigma_n \), where \( n \) – number of particles in an event.

In what follows we are based on the UA5 Collaboration data [18] on the inclusive cross sections in 9 multiplicity bins: \( 2 \leq n \leq 10, 12 \leq n \leq 20, \ldots, n \geq 82 \) at energy \( \sqrt{s} = 900 \) GeV. We define inclusive cross sections in bin \((i)\)

\[
\frac{d^3 \sigma^{(i)}}{dp^3} = \sum_{n \text{ in bin } (i)} \frac{d^3 \sigma_n}{dp^3} \tag{3}
\]

which are normalized as follows

\[
\int dp^3 \frac{d^3 \sigma^{(i)}}{dp^3} = \sigma_{NSD} \sum_{n \text{ in bin } (i)} n P_n = \sigma_{NSD} \bar{n}^{(i)}. \tag{4}
\]

Here \( P_n = \sigma_n/\sigma_{NSD} \) – probability of \( n \) charged particles production in a NSD event. Since we believe that inclusive cross sections of \( pp \) and \( p\bar{p} \) are different we write down relation (4) separately for \( pp \) and \( p\bar{p} \). It was shown in [19] that single diffractive cross sections \( \sigma_{SD} \) are the same for \( pp \) and \( p\bar{p} \) interactions. Therefore \( \sigma_{NSD} = \sigma_{tot} - \sigma_{el} - \sigma_{SD} \) are also the same.

From ratio of \( pp \) to \( p\bar{p} \) in (4) we obtain the following relation

\[
\int dp^3 \frac{d^3 \sigma_{pp}^{(i)}}{dp^3} = \frac{\bar{n}_{pp}^{(i)}}{\bar{n}_{pp}^{(i)}} \int dp^3 \frac{d^3 \sigma_{pp}^{(i)}}{dp^3}. \tag{5}
\]

9
Value of $\tilde{n}_{pp}^{(i)}/\tilde{n}_{pp}^{(i)}$ does not depend on momentum of observed particle $p$. Besides, bin limits can be chosen arbitrary. Therefore one of solutions of (5) (perhaps, the only solution) has the form

$$\frac{d^3\sigma_{pp}^{(i)}}{d^3p} = \frac{\tilde{n}_{pp}^{(i)}}{\tilde{n}_{pp}^{(i)}} \frac{d^3\sigma_{pp}^{(i)}}{d^3p}. \tag{6}$$

(If $pp$ and $p\bar{p}$ interactions are the same, we obtain a trivial result.) The relation for the inclusive pseudorapidity cross sections in bin $(i)$ is

$$\frac{d\sigma_{pp}^{(i)}}{d\eta} = \frac{\tilde{n}_{pp}^{(i)}}{\tilde{n}_{pp}^{(i)}} \frac{d\sigma_{pp}^{(i)}}{d\eta}. \tag{7}$$

We calculated the values of $\tilde{n}_{pp}^{(i)}$ from the UA5 data in each bin. The values of $\tilde{n}_{pp}^{(i)}$ are calculated from multiplicity distribution $P_{n}^{pp}$, obtained in frame of LCNM \[10\]. Then we obtained inclusive pseudorapidity cross section for $pp$ interaction at $\sqrt{s} = 900$ GeV.

$$\frac{d\sigma_{pp}}{d\eta} = \sum_{i} \frac{d\sigma_{pp}^{(i)}}{d\eta} = \sum_{i=1}^{9} \frac{\tilde{n}_{pp}^{(i)}}{\tilde{n}_{pp}^{(i)}} \frac{d\sigma_{pp}^{(i)}}{d\eta}. \tag{8}$$

The values of the inclusive cross sections $d\sigma_{pp}/d\eta$ and $d\sigma_{pp}/d\eta$ are shown in Fig.4 for whole multiplicity range (a) and for multiplicity from 62 to 70 (b). In this multiplicity bin the difference in the inclusive cross sections is very large because of high values of $n$.

Factorization of inclusive cross sections results from the Abramovsky–Gribov–Kacheli (AGK cancellations) theorem \[20\]. Phenomenological factorization relations were proposed by Hagedorn \[21\] and Tsallis \[22\]. Therefore we can write down separate formulas for $pp$ and $p\bar{p}$

$$\frac{1}{2\pi p_{T}} \frac{d^2\sigma_{pp}}{d\eta dp_{T}} = f_{pp}(p_{T}) \frac{d\sigma_{pp}}{d\eta}, \quad \frac{1}{2\pi p_{T}} \frac{d^2\sigma_{pp}}{d\eta dp_{T}} = f_{p\bar{p}}(p_{T}) \frac{d\sigma_{p\bar{p}}}{d\eta}. \tag{9}$$
It is easy to obtain from the relations (5) – (8) that $f_{p\bar{p}}(p_T) \equiv f_{pp}(p_T)$. One can obtain from (9) the following ratio

$$
\left( \frac{1}{2\pi p_T} \frac{d^2\sigma_{p\bar{p}}}{d\eta dp_T} \right) / \left( \frac{1}{2\pi p_T} \frac{d^2\sigma_{pp}}{d\eta dp_T} \right) = \frac{d\sigma_{p\bar{p}}}{d\eta} / \frac{d\sigma_{pp}}{d\eta} = R. \quad (10)
$$

It should be noted that the relations (9), (10) must be fulfilled in region of soft physics where the AGK theorem is valid. Therefore the relation (10) must be fulfilled for transverse momenta up to $p_T = 1.5 \div 2$ GeV. As it can
be seen in Fig.4, the ratio of the inclusive cross sections is approximately equal to $R \simeq 1.12$. We can write down more strictly $R = 1.12 \pm 0.03$. On basis of relation (10) we can state that ratio of inclusive cross sections of $p\bar{p}$ to $pp$ is equal to $1.12 \pm 0.03$. This value is depicted in Fig.1 by dashed line.

4. Discussion

We have shown that excess of $p\bar{p}$ inclusive cross section over $pp$ inclusive cross section at the same energy is connected with hadrons production in three quarks string configuration in $p\bar{p}$, which is absent in $pp$ interaction. We have predicted this difference in our paper [23] before the data of the CMS [1], ATLAS [2] and ALICE [3] were published. It should be noted that difference in $pp$ and $p\bar{p}$ increases with rising collision energy in our approach. We emphasize that we have a physical picture which was, probably, confirmed by results of the experiments UA1, CDF, CMS, ATLAS and ALICE.

We do not agree with the following statements of the ALICE and ATLAS. “The excess of the UA1 data of about 20% at low $p_T$ is possibly due to the UA1 trigger condition, which suppresses events with very low multiplicity” [3]. “A shift in this direction is expected from the double-arm scintillator trigger requirement used to collect the UA1 data, which rejected events with low charged-particle multiplicities” [2].

Inclusive cross sections in our notations and in notations of the ATLAS

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4 Three-sheet annihilation of Rossi–Veneziano [24] decreases as $s^{-1/2}$. 
and ALICE can be written as equality

\[
\frac{1}{2\pi p_T} \frac{d^2 n_{ch}}{d\eta dp_T} = \frac{1}{N_{ev}} \frac{1}{2\pi p_T} \frac{d^2 N_{ch}}{d\eta dp_T}
\]  

(11)

where \(N_{ev}\) is the number of events inside the selected kinematic range, \(N_{ch}\) is the total number of charged particles in the data sample. It follows from simple logic that increase of inclusive cross section in the left part of (11) is possible if \(N_{ev}\) decreases, and that is the basis of the ATLAS and ALICE statements. However, it is very hard to accept that the UA1 Collaboration have lost about 17\% of their data in case of comparing with the ATLAS and ALICE and 21\% in case of comparing with the CMS.

In this case a serious discrepancy arises, which should be noticed by experimentalists. The Hagedorn–Tsallis factorization formula is generally accepted by experimentalists for describing of transverse momentum dependence of inclusive cross sections. Let us just use it to data given in Fig.1 without pointing out any theoretical considerations. Since all data were taken at the same energy \(\sqrt{s} = 900\) GeV then all factors determining \(p_T\) dependence cancel each other. Therefore it follows from data given in Fig.1 that \(dn_{ch}^{pp}/d\eta > dn_{ch}^{p\bar{p}}/d\eta\). From the other side, direct measurement of the CMS [1] and ALICE [25] gave \(dn_{ch}^{p\bar{p}}/d\eta \approx dn_{ch}^{pp}/d\eta\).

We want to stress that discovery of an additional inelastic process in \(p\bar{p}\) interaction is very important by itself. If existence of this process is experimentally proved, it will greatly change theoretical concepts of high energy physics. It is also important for Monte Carlo event generators which use data on \(pp\) and \(p\bar{p}\) simultaneously in tuning of parameters, what may produce incorrect results.
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