Inclusive cross sections of proton-proton and proton-antiproton scattering

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We have predicted the difference in inclusive cross sections on pseudorapidity in pp and $p\bar{p}$ interactions at $\sqrt{s} = 900$ GeV. Their ratio $R = \left(\mathrm{d}\sigma^{p\bar{p}}/\mathrm{d}\eta\right)/(\mathrm{d}\sigma^{pp}/\mathrm{d}\eta) > 1$ in the whole pseudorapidity range. On the basis of AGK theorem we show that the ratio of inclusive cross sections of pp and $p\bar{p}$ at $\sqrt{s} = 900$ GeV in the region of low transverse momenta $p_\perp$ up to 2 GeV $\left(\frac{1}{2\pi p_\perp}\frac{\mathrm{d}^2\sigma^{p\bar{p}}}{\mathrm{d}\eta\mathrm{d}p_\perp}\right)\Big/\left(\frac{1}{2\pi p_\perp}\frac{\mathrm{d}^2\sigma^{pp}}{\mathrm{d}\eta\mathrm{d}p_\perp}\right) = R$. Experimental measurements by the ATLAS Coll. give value $R \simeq 1.2$ for interval $|\eta| < 2.5$.

The difference in inclusive cross sections results from presence of additional subprocess in $p\bar{p}$ – hadrons production from decay of three quark strings, which is absent in pp scattering.

1 Introduction

It is generally accepted that total cross sections of pp and $p\bar{p}$ interactions at high energies are the same

$$\sigma^{pp}_{tot} \equiv \sigma^{p\bar{p}}_{tot} \qquad (s \to \infty).$$

Also elastic cross sections are equal $\sigma^{pp}_{el} \equiv \sigma^{p\bar{p}}_{el}$ and differential elastic cross sections are equal $\mathrm{d}\sigma^{pp}_{el}/\mathrm{d}t \equiv \mathrm{d}\sigma^{p\bar{p}}_{el}/\mathrm{d}t$.

It follows from the Pomeranchuk theorem [1], which was proved for constant total cross sections in condition $s \to \infty$. This theorem was generalized by Iden [2] for increasing total cross sections, which fulfill the Froissare theorem.

It is also generally accepted that multiplicity properties of pp and $p\bar{p}$ interactions, such as inclusive cross sections and distributions of charged particles are the same.

In the paper [3] we have shown that inclusive cross sections of $p\bar{p}$ scattering $\mathrm{d}\sigma^{p\bar{p}}/\mathrm{d}\eta$ are larger than inclusive cross sections of pp scattering $\mathrm{d}\sigma^{pp}/\mathrm{d}\eta$ at $\sqrt{s} = 900$ GeV.

The ATLAS Coll. have published data [4] on inclusive cross sections from which it follows that

$$\frac{1}{2\pi p_\perp}\frac{\mathrm{d}^2\sigma^{p\bar{p}}}{\mathrm{d}\eta\mathrm{d}p_\perp}\Bigg/\frac{1}{2\pi p_\perp}\frac{\mathrm{d}^2\sigma^{pp}}{\mathrm{d}\eta\mathrm{d}p_\perp} \simeq 1.2 \qquad (1)$$

for pseudorapidity $|\eta| < 2.5$ in interval of transverse momenta up to $p_\perp \simeq 2$ GeV/c.

The ALICE Coll. confirmed this result [5] for $|\eta| < 0.8$ and transverse momenta up to $p_\perp \simeq 1.5$ GeV/c.

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In the present work we will show that ratio (1) is equal to

$$\frac{1}{2\pi p_\perp}\frac{\mathrm{d}^2\sigma^{p\bar{p}}}{\mathrm{d}\eta\mathrm{d}p_\perp}\Bigg/\frac{1}{2\pi p_\perp}\frac{\mathrm{d}^2\sigma^{pp}}{\mathrm{d}\eta\mathrm{d}p_\perp}=\frac{\mathrm{d}\sigma^{p\bar{p}}}{\mathrm{d}\eta}\Bigg/\frac{\mathrm{d}\sigma^{pp}}{\mathrm{d}\eta}=R. \tag{2}$$

We have estimated the value $R \simeq 1.12$ both for pseudorapidity intervals $|\eta| < 0.8$ and $|\eta| < 2.5$.

2 Low Constituents Number Model

We are based on the Low Constituents Number Model (LCNM) [6], [7], [8] which can be represented as follows.

1. On the first step before the collision there is small number of constituents in initial hadrons. In every hadron there are components either with only valence quarks or with valence quarks and one additional gluon.

2. On the second step the hadrons interaction is carried out by gluon exchange between the valence quarks and initial gluons. The hadrons gain the color charge.

3. On the third step after interaction the colored hadrons move apart and when the distance between them becomes larger than the confinement radius, the lines of color electric field gather into the string. This string breaks out into secondary hadrons.

Hadrons production in this model is depicted by phenomenological diagrams in Fig. 1. Solid lines correspond to valence quarks and antiquarks. Wavy line corresponds to exchanging gluon, which performs the interaction. Additional gluons are also represented by wavy lines, one in every projectile hadron. Formation of color field string (shown as spiral) and its breakup to secondary hadrons takes place at the third stage. This process corresponds to interaction in final state. It should be noted that there is subprocesses of hadrons production from three quark strings in $p\bar{p}$ interaction. There is no such subprocess in pp interaction. This subprocess defines the difference in inclusive cross sections and multiplicity distributions in pp and $p\bar{p}$.

We consider only one gluon exchange, this is our hypothesis. Therefore interaction between components with only valence quarks both in pp and $p\bar{p}$ leads to separation of color charges with octet quantum numbers.

Since we consider only one gluon exchange, there is no three-sheet configuration which was proposed in [9], [10] in the diagram with only valence quarks in proton and valence antiquarks in antiproton.

3 Difference in inclusive cross sections of pp and $p\bar{p}$

Let us define topological inclusive cross section of production of one charged particle in case with n charged particles

$$(2\pi)^3 2E\frac{\mathrm{d}^3\sigma_n^{incl}}{\mathrm{d}^3 p}, \qquad \int \mathrm{d}^3 p\frac{\mathrm{d}^3\sigma_n^{incl}}{\mathrm{d}^3 p}=n\,\sigma_n, \tag{3}$$

where σ_n – topological cross sections of n charged particles production. We consider only non single diffractive events so

$$\sum \sigma_n = \sigma^{nsd}. \tag{4}$$

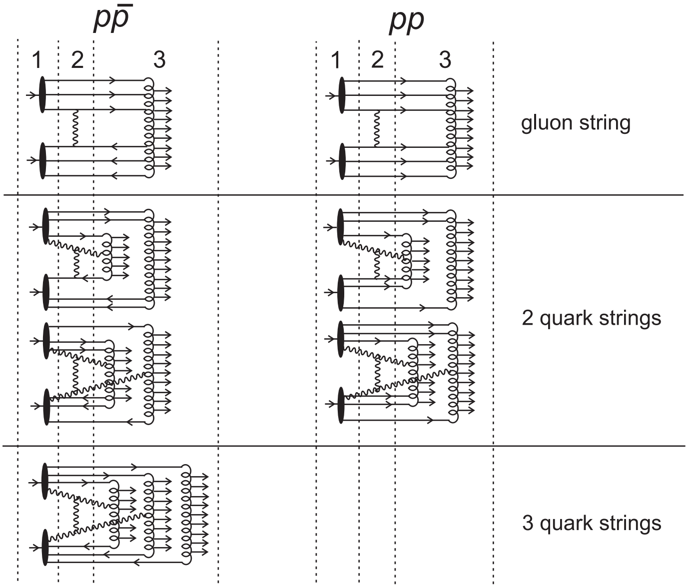

Figure 1: Three types of inelastic subprocesses in pp and $p\bar{p}$ scattering in the LCNM.

Here we are based on the UA5 Coll. data [11] on the inclusive cross sections in 9 multiplicity bins: $2 \leqslant n \leqslant 10$, $12 \leqslant n \leqslant 20$, $\ldots$, $n \geqslant 82$. In accordance with UA5 Coll. we define inclusive cross sections in every of these bins ($i = 1, \ldots, 9$)

$$\frac{\mathrm{d}^3\sigma^{(i)incl}}{\mathrm{d}^3p} = \sum_{n \text{ in bin } (i)} \frac{\mathrm{d}^3\sigma_n^{incl}}{\mathrm{d}^3p}, \quad \left(\frac{\mathrm{d}^3\sigma^{incl}}{\mathrm{d}^3p} = \sum_{i=1}^{9} \frac{\mathrm{d}^3\sigma^{(i)incl}}{\mathrm{d}^3p}\right), \tag{5}$$

which are normalized as follows

$$\int \mathrm{d}^3p \frac{\mathrm{d}^3\sigma^{(i)incl}}{\mathrm{d}^3p} = \sum_{n \text{ in bin } (i)} n\,\sigma_n = \sigma^{nsd} \sum_{n \text{ in bin } (i)} n\,P_n = \sigma^{nsd}\,\bar{n}^{(i)} \tag{6}$$

where $P_n = \sigma_n/\sigma^{nsd}$ – probability of n charged particles production in non single diffractive event. Inasmuch as we consider that inclusive cross sections of pp and $p\bar{p}$ are different we write down relation (6) separately for pp and $p\bar{p}$

$$\int \mathrm{d}^3p \frac{\mathrm{d}^3\sigma_{p\bar{p}}^{(i)incl}}{\mathrm{d}^3p} = \sigma^{nsd}\,\bar{n}_{p\bar{p}}^{(i)}, \quad \int \mathrm{d}^3p \frac{\mathrm{d}^3\sigma_{pp}^{(i)incl}}{\mathrm{d}^3p} = \sigma^{nsd}\,\bar{n}_{pp}^{(i)}. \tag{7}$$

It was shown in [12] that σ^{sd} – cross section of single diffractive events is the same for pp and $p\bar{p}$ interactions at high energies. Therefore cross section $\sigma^{nsd} = \sigma_{tot} - \sigma_{el} - \sigma_{sd}$ is also the same for pp and $p\bar{p}$ interactions.

From ratio of $p\bar{p}$ over pp in (7) we obtain the following relation

$$\int \mathrm{d}^3p \frac{\mathrm{d}^3\sigma_{p\bar{p}}^{(i)incl}}{\mathrm{d}^3p} = \frac{\bar{n}_{p\bar{p}}^{(i)}}{\bar{n}_{pp}^{(i)}} \int \mathrm{d}^3p \frac{\mathrm{d}^3\sigma_{pp}^{(i)incl}}{\mathrm{d}^3p}. \tag{8}$$

Value of $\bar{n}^{(i)}_{p\bar{p}}/\bar{n}^{(i)}_{pp}$ does not depend on momentum of observed particle p. Therefore one of solutions of (8) (perhaps, the only solution) has the form

$$\frac{\mathrm{d}^3\sigma^{(i)incl}_{p\bar{p}}}{\mathrm{d}^3p} = \frac{\bar{n}^{(i)}_{p\bar{p}}}{\bar{n}^{(i)}_{pp}}\frac{\mathrm{d}^3\sigma^{(i)incl}_{pp}}{\mathrm{d}^3p}. \tag{9}$$

(If pp and $p\bar{p}$ interactions are the same then we obtain a trivial result.)

Factorization of inclusive cross sections results from the AGK theorem [13], so we can write down

$$\frac{1}{2\pi p_\perp}\frac{\mathrm{d}^2\sigma^{incl}_{pp}}{\mathrm{d}\eta\mathrm{d}p_\perp} = f_{pp}(p_\perp)\frac{\mathrm{d}\sigma^{incl}_{pp}}{\mathrm{d}\eta}, \quad \frac{1}{2\pi p_\perp}\frac{\mathrm{d}^2\sigma^{incl}_{p\bar{p}}}{\mathrm{d}\eta\mathrm{d}p_\perp} = f_{p\bar{p}}(p_\perp)\frac{\mathrm{d}\sigma^{incl}_{p\bar{p}}}{\mathrm{d}\eta} \tag{10}$$

where $\mathrm{d}\sigma^{incl}/\mathrm{d}\eta$ – inclusive distribution on pseudorapidity. It is easy to show from the equation (9) that

$$f_{pp}(p_\perp) = f_{p\bar{p}}(p_\perp). \tag{11}$$

Therefore from ratio of $p\bar{p}$ over pp in (10) we can obtain strict equality

$$\left(\frac{1}{2\pi p_\perp}\frac{\mathrm{d}^2\sigma^{incl}_{p\bar{p}}}{\mathrm{d}\eta\mathrm{d}p_\perp}\right)\Bigg/\left(\frac{1}{2\pi p_\perp}\frac{\mathrm{d}^2\sigma^{incl}_{pp}}{\mathrm{d}\eta\mathrm{d}p_\perp}\right) = \left(\frac{\mathrm{d}\sigma^{incl}_{p\bar{p}}}{\mathrm{d}\eta}\right)\Bigg/\left(\frac{\mathrm{d}\sigma^{incl}_{pp}}{\mathrm{d}\eta}\right). \tag{12}$$

In the paper [3] we have obtained the inclusive cross sections $\mathrm{d}\sigma^{incl}_{pp}/\mathrm{d}\eta$ in pp interactions at $\sqrt{s} = 900$ GeV. The result is shown in Fig. 2 together with experimental data of the UA5 Coll. [11]. From this graph it can be seen that the ratio $R = \left(\mathrm{d}\sigma^{incl}_{p\bar{p}}/\mathrm{d}\eta\right)/\left(\mathrm{d}\sigma^{incl}_{pp}/\mathrm{d}\eta\right) \simeq 1.12$ both for pseudorapidity intervals $|\eta| < 0.8$ and $|\eta| < 2.5$.

It should be noted that the relation (10) must be fulfilled in region of soft physics for transverse momenta up to $p_\perp = 1.5 \div 2$ GeV/c, where the AGK theorem is valid. Therefore, in this region the ratio of inclusive cross sections

$$\left(\frac{1}{2\pi p_\perp}\frac{\mathrm{d}^2\sigma^{incl}_{p\bar{p}}}{\mathrm{d}\eta\mathrm{d}p_\perp}\right)\Bigg/\left(\frac{1}{2\pi p_\perp}\frac{\mathrm{d}^2\sigma^{incl}_{pp}}{\mathrm{d}\eta\mathrm{d}p_\perp}\right) = R \simeq 1.12. \tag{13}$$

The comparison of experimental results of collaborations ATLAS and ALICE for pp with results of the UA1 Coll. [14] for $p\bar{p}$ is shown in Fig. 3 together with our estimation (graphs are taken from [4] and [5]). In our opinion, these data show that inclusive cross sections of $p\bar{p}$ interaction exceed inclusive cross sections of pp interaction. We suppose that the excess is determined by presence of subprocess of hadrons production from three quark strings, which exists in $p\bar{p}$ and is absent in pp interactions.

We will not comment here the explanation of difference of inclusive cross sections ratio from 1 by systematic uncertainties of the experiments UA1, ATLAS and ALICE. This question demands thorough analysis.

It should be noted that the presence of inelastic subprocess of hadrons production from three quark strings might be important in nucleus-nucleus collisions. Protons and antiprotons produced from the first collisions will give different cascades when passing through nucleus.

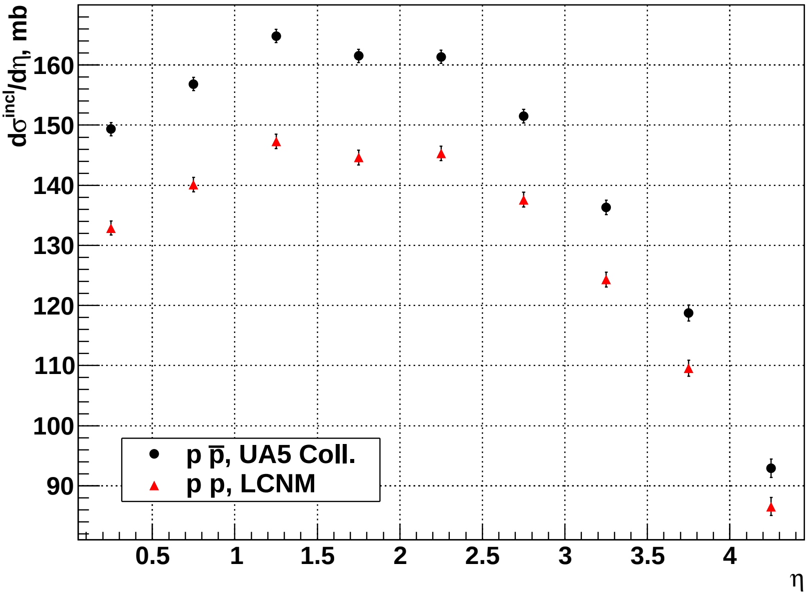

Figure 2: Absolute value of inclusive cross section at $\sqrt{s} = 900$ GeV [3].

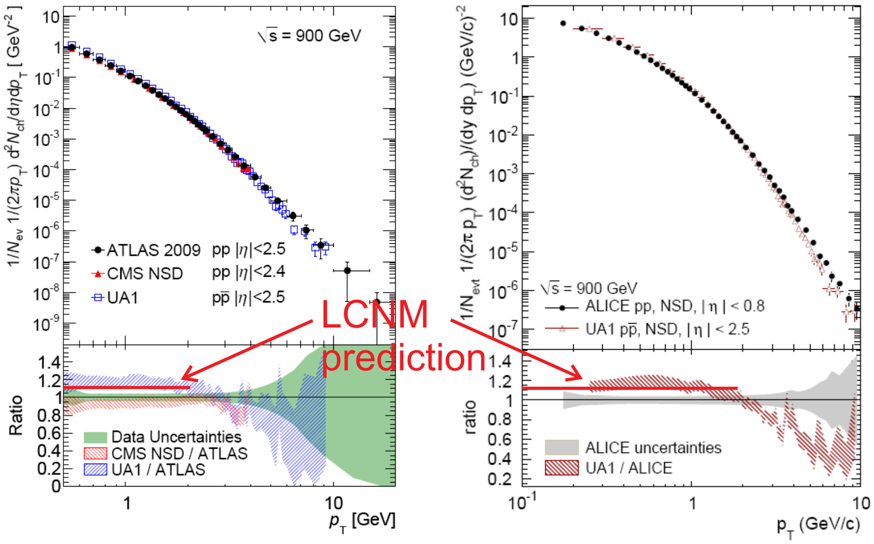

Figure 3: Ratio of inclusive cross sections of $p\bar{p}$ (UA1 Coll. [14]) over pp (ATLAS Coll. [4] and ALICE Coll. [5]) and Low Constituents Number Model prediction.

4 Conclusion

We think that ATLAS Coll. discovered a new effect – the difference in multiparticle production in pp and $p\bar{p}$ interactions. ALICE Coll. confirmed this effect. We propose to experimentalists to measure inclusive cross section in bins with high multiplicities, where the difference will be the most evident.

On the basis of the Low Constituents Number Model we also predict the value $\left.\frac{d\sigma^{pp}}{d\eta}\right|_{\eta=0} = 6.62 \pm 0.70$ at energy $\sqrt{s} = 14$ TeV.

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