Similarity of Initial States in A+A and p+p Collisions in Constituent Quarks Framework

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Abstract. The multiparticle production results from A+A and p(¯p)+p collisions have been compared based on the number of nucleon participants and the number of constituent quark (parton) participants. In both normalizations, we observe that the charged particle densities in Au+Au and Cu+Cu collisions are similar for both $\sqrt{s_{NN}} = 62.4$ and 200 GeV. This implies that in symmetric nucleus-nucleus collisions the charged particle density does not depend on the size of the two colliding nuclei but only on the collision energy. In the nucleon participants framework, the particle density at mid-rapidity as well as in the limiting fragmentation region from A+A collisions are higher than those of p(¯p)+p collisions at the same energy. Also the integrated total charged particle in A+A collisions as a function of number nucleon participants is higher than p(¯p)+p collisions at the same energy indicating that there is no smooth transition between peripheral A+A and nucleon-nucleon collisions. However, when the comparison is made in the constituent quarks framework, A+A and p(¯p)+p collisions exhibit a striking degree of agreement. The observations presented in this paper imply that the number of constituent quark pairs participating in the collision controls the particle production. One may therefore conjecture that the initial states A+A and p+p collisions are similar when the partonic considerations are used in normalization. Another interesting result is that there is an overall factorization of $dN_{ch}/d\eta$ shapes as a function of collision centrality between Au+Au and Cu+Cu collisions at the same energy, $\sqrt{s_{NN}} = 200$ GeV.

1. INTRODUCTION

Since the first collisions were delivered at the Relativistic Heavy Ion Collider (RHIC), the experiments have obtained extensive results on multiparticle production in both nucleus-nucleus (A+A) and nucleon-nucleon (p(¯p)+p) collisions at the same energies [1]. However, several aspects of the comparison between A+A and p(¯p)+p collisions are not well understood. For example it has been found that the particle density per participant pair, $N_{n-part}/2$, in A+A collisions is substantially higher than in p(¯p)+p collisions at $\sqrt{s_{NN}} = 200$ GeV [2]. It has also been observed that the integrated total charged particle production, per participant nucleon pair, as a function of $N_{n-part}$ is essentially constant and is higher than for p(¯p)+p collisions at the same energy [3] indicating that there is no smooth transition between the two systems. These comparisons are, however, based on scaling with the number of nucleon participants. In the following, I will show that the A+A and p(¯p)+p collisions have similar initial states if the results are scaled instead by the number of constituent quark participants, $N_{q-part}$. Within this framework, the similarity between A+A and p(¯p)+p collisions will be explored through global observables, which reflect the initial state of the system.
FIGURE 1. Panel a): number of nucleon participants (denoted $N_{n\text{-part}}$; solid curves) and number of constituent quark participants (denoted $N_{q\text{-part}}$; dashed curves) as a function of the impact parameter of Au+Au collisions at $\sqrt{s_{NN}} = 19.6, 62.4, 130$ and 200 GeV. The inset figure represent a zoom on the solid curves. Panel b): ratio of $N_{q\text{-part}}/N_{n\text{-part}}$ as a function of the number of nucleon participants.

2. CALCULATION OF THE NUMBER OF PARTICIPANTS

The constituent quark (parton) model has been introduced in Refs. [4]. The present work is a continuation of the study started by Ref. [5] which extends to global observables, namely the comparison of particle density and limiting fragmentation scaling in A+A and p(\bar{p})+p collisions.

The number of nucleon participants, $N_{n\text{-part}}$ and the number of constituent quark participants, $N_{q\text{-part}}$ are estimated using the nuclear overlap model in a manner similar to that used in Ref. [5]. The nuclear density profile is thus assumed to have a Woods-Saxon form,

$$n_A(r) = \frac{n_0}{1 + \exp[(r-R)/d]},$$

where $n_0 = 0.17 \text{ fm}^{-3}$, $R = (1.12 A^{1/3} - 0.86 A^{-1/3}) \text{ fm}$ and $d = 0.53 \text{ fm}$.

The number of nucleon participants, $N_{n\text{-part}}$, for nucleus-nucleus (A+B) collisions is calculated using the relation,

$$N_{n\text{-part}}|_{AB} = \int d^2s T_A(\vec{s}) \left\{ 1 - \left[ 1 - \frac{\sigma_{NN}^{\text{inel}} T_B(\vec{s}-\vec{b})}{B} \right]^B \right\}$$

$$+ \int d^2s T_B(\vec{s}-\vec{b}) \left\{ 1 - \left[ 1 - \frac{\sigma_{NN}^{\text{inel}} T_A(\vec{s})}{A} \right]^A \right\}$$

where $T(b) = \int_{-\infty}^{+\infty} dz n_A(\sqrt{b^2 + z^2})$, is the thickness function. $A$ and $B$ are the mass number of the two colliding nuclei and the $\sigma_{NN}^{\text{inel}}$ is the inelastic nucleon-nucleon cross section.

The number of constituent quark participants, $N_{q\text{-part}}$, is calculated in a similar manner by taking into account the following changes related to the physical realities: 1) the density is three times that of nucleon density with $n_0^q = 3n_0 = 0.51 \text{ fm}^{-3}$; 2) the cross sections $\sigma_{qq} = \sigma_{NN}^{\text{inel}}/9$; 3) the mass numbers of the colliding nuclei are three times their values, keeping the size of the nuclei same as in the case of $N_{n\text{-part}}$. For p(\bar{p})+p
TABLE 1. Inelastic cross section for nucleon-nucleon collisions ($\sigma_{NN}^{inel}$) as function of colliding energy. My calculation for $\sigma_{NN}^{inel}$ adopt similar manner as in Ref. [7]

| $\sqrt{s_{NN}}$ | 19.6 | 53 | 56 | 62.4 | 130 | 200 | 540 | 630 | 900 | 1800 |
|----------------|------|----|----|------|-----|-----|-----|-----|-----|-----|
| $\sigma_{NN}^{inel}$ | 31.5 | 35.0 | 35.3 | 36.0 | 39.3 | 42.0 | 48.0 | 48.6 | 51.0 | 56.0 |

FIGURE 2. Quantitative evaluation of the model calculations expressed as the ratio of the average number of nucleon participants of the PHOBOS Glauber calculations [8] to the present work as a function of centrality. Panel a) and b) correspond to Au+Au collisions at $\sqrt{s_{NN}} = 200$ and 19.6 GeV, respectively. The gray bands correspond to the systematic errors on the $\langle N_{n-part} \rangle$ of PHOBOS Glauber calculations.

collisions the same procedure has been used to calculate the number of constituent quark participants by using $A = 3$ and $B = 3$ and considering nucleons as hard spheres of uniform radii of 0.8 fm [6].

Figure 1a) shows the number of nucleon (solid curves) and constituent quark (dashed curves) participants for Au+Au collisions as a function of the impact parameter. Figure 1b) presents the ratio of $N_{q-part}/N_{n-part}$ as a function of $N_{n-part}$ for Au+Au collisions at RHIC energies. The ratio shows that the correlation between $N_{n-part}$ and $N_{q-part}$ is not linear and that it depends slightly on the colliding energy. The inelastic nucleon-nucleon cross sections, $\sigma_{NN}^{inel}$, used in the present work are listed in TABLE 1.

Figure 2 presents the ratio of the $N_{n-part}$ from the PHOBOS Glauber calculation based on HIJING [8] to the present calculation and shows good agreement (within systematic errors).

3. CHARGED PARTICLE DENSITIES

Figure 3 shows the primary charged particle density for central collisions at mid-rapidity divided by the number of participant nucleon pairs ($N_{n-part}/2$) and participant constituent quark pairs ($N_{q-part}/2$) as solid and open symbols, respectively. The plotted data are for Au+Au collisions at AGS, Pb+Pb collisions at the CERN SPS [9, 10, 11] and for Au+Au and Cu+Cu collisions at RHIC [12]. Also shown for comparison are results from p($\bar{p}$)+p collisions data [13, 14].

The particle density per nucleon participant pair for A+A collisions (solid points) shows an approximately logarithmic rise with $\sqrt{s_{NN}}$ over the full range of collision energies. The comparison of the particle density per nucleon of Au+Au to Cu+Cu collisions
Figure 3. Particle density per constituent quark pair (open symbols) and particle density per nucleon participant pair (solid points) produced in central (6%) nucleus-nucleus (A+A) collisions as function of collision energy at AGS, SPS [9, 10, 11] and RHIC [12] and in p(\bar{p})+p collisions at ISR energies [13] and p+p at 200 GeV at RHIC [14]. The errors bars correspond to the systematic errors. The solid line represents a linear fit through solid points for A+A data, $f_{AA} = -0.287 + 0.757 \ln(\sqrt{s})$. The dashed dotted line corresponds to the fit through solid points of p(\bar{p}) + p collisions, $f_{pp} = 2.25 - 0.41 \ln(\sqrt{s}) + 0.09 \ln^2(\sqrt{s})$. The dashed line corresponds to a linear fit trough the open symbols in the constituent quarks framework, $f_{p(\bar{p})p/AA} = -0.02 + 0.27 \ln(\sqrt{s})$.

at the same energies, $\sqrt{s_{NN}} = 62.4$ and 200 GeV indicates that in the symmetric nucleus-nucleus collisions the density per nucleon participant does not depend on the size of the two colliding nuclei but only on the collision energy. This means for Si+Si collisions at $\sqrt{s_{NN}} = 200$ GeV, the particle density per nucleon participant will be similar to Au+Au collisions at the same energy. Figure 3 shows (solid points) that the charged particle multiplicity per participant nucleon pair in A+A collisions is higher compared to p(\bar{p})+p collisions at the same energy.

In contrast, we observe that the multiplicity per constituent quark participant pair (open symbols in figure 3) is similar for nucleus-nucleus collisions and nucleon-nucleon collisions at the same energy. It thus appears that using partonic participants accounts for the observed multiplicity in both A+A and p(\bar{p})+p collisions. One may therefore conjecture that the initial states in A+A and p(\bar{p})+p collisions are similar.

4. EXTENDED LONGITUDINAL SCALING

In general, the charged particle production in the limiting fragmentation region is thought to be distinct from that at mid-rapidity, although there is no obvious evidence for two separate regions at any of the RHIC energies. This observation is made based on the $dN_ch/d\eta$ distributions of charged particle presented in Ref. [15].

Figure 4 shows a comparison of the most central (6%) Au+Au and Cu+Cu collisions at several RHIC energies compared to p(\bar{p})+p (inelastic and non single diffractive
FIGURE 4. Pseudorapidity distributions of charged particle for Au+Au, Cu+Cu [12] collisions at RHIC energies compared to p(¯p)+p collisions at 200 GeV [13]. The distributions have been shifted to $\eta - y_{\text{beam}}$ in order to study the fragmentation regions in one of the nucleus rest frame. Panels a) and b) correspond to $dN_{\text{ch}}/d\eta$ distributions scaled to the number of nucleon participants and to the number of constituent quark participants, respectively. For clarity the systematic errors have been removed.

(NSD)) collisions at 200 GeV. When normalized to $N_{n-part}/2$, (figure 4a), we observe that the multiplicity in the limiting fragmentation region in A+A collisions is higher than for p(¯p)+p collisions. If, however, the comparison is carried out for multiplicities normalized to $N_{q-part}/2$ (figure 4 b), A+A and p(¯p)+p collisions exhibit a striking degree of agreement. Again, this observation implies that the number of constituent quark pairs participating in the collision controls the particle production.

5. SYSTEM SIZE INDEPENDENCE OF PSEUDORAPIDITY SHAPES

For 0-6% central collisions we find that the multiplicity shapes are essentially identical for Au+Au and Cu+Cu collisions and differ only by a constant factor,

$$R_{Au}^{Cu}(0-6\%) = \frac{dN/d\eta(Cu + Cu : 0-6\%)}{dN/d\eta(Au + Au : 0-6\%)}. \quad (3)$$

Figure 5 illustrates the fact that the same ratio between Au+Au and Cu+Cu collisions pseudorapidity distributions holds for all centrality bins (see figure 5) such that the shapes of the $dN_{\text{ch}}/d\eta$ distributions for the same centrality bin are similar for the two systems. The small difference at mid-rapidity can be related to the difference of the mean $P_T$ of charged particle in Cu+Cu and Au+Au collisions but it falls well within the systematic errors so this difference is not significant. It thus appears that the $dN_{\text{ch}}/d\eta$
shapes are independent of the overall size of the colliding nuclei, at least between the Cu+Cu and Au+Au systems studied here.

6. SUMMARY

I have shown that the charged particle multiplicity, both at mid-rapidity and in the limiting fragmentation region scale with the number of constituent quark participants, both in nucleus-nucleus systems of different sizes and in nucleon-nucleon collisions. This observation implies that both the overall the particle production and the distribution in pseudorapidity is controlled by at the participant quark level. In addition, I have shown that shapes of the charged particle multiplicity in Au+Au and Cu+Cu collisions at the same energies are very similar and that they differ only by a overall factor, even at different centralities given by the fraction of the overall cross section.

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