Gluon Shadowing and Hadron Production at RHIC

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Hadron multiplicity in the central rapidity region of high-energy heavy-ion collisions is investigated within a two-component mini-jet model which consists of soft and semi-hard particle production. The hard contribution from mini-jets is reevaluated using the latest parameterization of parton distributions and nuclear shadowing. The energy dependence of the experimental data from RHIC requires a strong nuclear shadowing of the gluon distribution in this model. The centrality dependence of the hadron multiplicity at \( \sqrt{s} = 130 \text{ GeV} \) is reproduced well with the impact-parameter dependent parton shadowing. However, energy variation of the centrality dependence is needed to distinguish different particle production mechanisms such as the parton saturation model.

Formation of quark-gluon plasma (QGP) in high-energy heavy-ion collisions hinges crucially on the initial condition that is reached in the earliest stage of the violent nuclear interaction. Though many proposed signals can provide more direct measurements of the initial parton density, they must compliment results inferred indirectly from the measurement of final hadron multiplicity using either simple scenarios such as the Bjorken model \[\text{(1)}\] or other dynamic models. Therefore, global observables such as the rapidity density of hadron multiplicity can provide an important link of a puzzle that can eventually lead one to a more complete picture of the dynamics of heavy-ion collisions and formation of QGP. Furthermore, the study of energy and centrality dependence of central rapidity density \[\text{(2)}\] can also provide important constraints on models of initial entropy production and shed lights on the initial parton distributions in nuclei. For example, the available RHIC experimental data \[\text{(3)}\] can already rule out the simple two-component model without nuclear modification of the parton distributions in nuclei \[\text{(4)}\]. In this paper, we will study within the two-component model how the RHIC data constrain the unknown nuclear shadowing of the gluon distribution in nuclei and how to further distinguish such a conventional parton production mechanism from other novel physics such as parton saturation \[\text{(5)}\].

Mini-jet production in a two-component model has long been proposed to explain the energy dependence of total cross section \[\text{(6)}\] and particle production \[\text{(7)}\] in high-energy hadron collisions. It has also been proposed \[\text{(8)}\] and incorporated in the HIJING model \[\text{(9)}\] to describe initial parton production in high-energy heavy-ion collisions. In this simple two-component model, one assumes that events of nucleon-nucleon collisions at high energy can be divided into those with and without hard or semi-hard processes of jet production. The soft and hard processes are separated by a cut-off scale \( p_0 \). While the cross section of soft interaction \( \sigma_{\text{soft}} \) is considered nonperturbative and thus noncalculable, the jet production cross section \( \sigma_{\text{jet}} \) is assumed to be given by perturbative QCD (pQCD) for transverse momentum transfer \( p_T > p_0 \). The two parameters, \( \sigma_{\text{soft}} \) and \( p_0 \), are determined phenomenologically by fitting the experimental data of total \( p + p(\bar{p}) \) cross sections within the two-component model \[\text{(10)}\].

The cut-off scale \( p_0 \), separating nonperturbative and pQCD components, could in principle depend on both energy and nuclear size. Using Duke-Owens parameterization \[\text{(11)}\] of parton distributions in nucleons, it was found in the HIJING \[\text{(12)}\] model that an energy independent cut-off scale \( p_0 = 2 \text{ GeV}/c \) is sufficient to reproduce the experimental data on total cross sections and the hadron multiplicity in \( p + p(\bar{p}) \) collisions, assuming that the soft cross section \( \sigma_{\text{soft}} \) is also constant. Since then, analysis of recent experimental data from deep-inelastic scattering (DIS) of lepton and nucleon at HERA indicated \[\text{(13)}\] that gluon distribution inside a nucleon is much larger than the DO parameterization at small \( x \). Many new parameterizations of the parton distributions have become available. Using the Gluck-Reyva-Vogt (GRV) parameterization \[\text{(14)}\] of parton distributions and following the same procedure as in the original HIJING \[\text{(15)}\], we find that one can no longer fit the experimental \( p + p(\bar{p}) \) data using a constant cut-off scale \( p_0 \) within the two-component model. One has to assume an energy dependent cut-off scale \( p_0(\sqrt{s}) \). Because of the rapid increase of gluon distribution at small \( x \), we find that the cut-off \( p_0(\sqrt{s}) \) has to increase slightly with energy in order to fit the experimental data.

Shown in Fig. \[\text{1}\] is the calculated central rapidity density,

\[
\frac{dN_{ch}}{d\eta} = \langle n \rangle_\text{s} + \langle n \rangle_\text{h} \frac{\sigma_{\text{soft}}(s)}{\sigma_{\text{jet}}(s)},
\]

for \( p + p(\bar{p}) \) collisions as a function of energy \( \sqrt{s} \), where \( \langle n \rangle_\text{s} = 1.6 \) and \( \langle n \rangle_\text{h} = 2.2 \) represent particle production from soft interaction and jet hadronization, respectively. The jet cross section in lowest order of pQCD is given by
\[ \sigma_{jet} = K \int_{p_0^2}^{\sqrt{s}/4} \, dp_1^2 \, dp_1 \, dy_1 \, dy_2 \, \frac{1}{2} \sum_{a,b,c,d} x_1 x_2 f_a(x_1) f_b(x_2) \left( \frac{d\sigma_{ab \rightarrow cd}}{dt} \right), \]

with the GRV parameterization of parton distributions \( f_a(x) \), a \( K \)-factor of 2 and an energy-dependent cut-off scale

\[ p_0(\sqrt{s}) = 3.91 - 3.34 \log(\log(\sqrt{s})) + 0.98 \log^2(\log(\sqrt{s})) + 0.23 \log^3(\log(\sqrt{s})). \]

Assuming eikonalization of hard and soft processes, the total inelastic \( p+p(\bar{p}) \) cross section in this two-component model is

\[ \sigma_{in} = \int d^2b \left[ 1 - e^{-(\sigma_{jet} + \sigma_{soft})T_{NN}(b)} \right], \]

where \( T_{NN}(b) \) is the nucleon-nucleon overlap function and \( \sigma_{soft} = 57 \text{ mb} \) represents the inclusive soft cross section. Notice that the energy-dependence of \( p_0(\sqrt{s}) \) is quite weak, ranging from \( p_0 = 1.7 \text{ GeV}/c \) at \( \sqrt{s} = 20 \text{ GeV} \) to \( 3.5 \text{ GeV}/c \) at \( \sqrt{s} = 5 \text{ TeV} \).

\[ \frac{dN_{ch}}{d\eta} = \frac{1}{2} \langle N_{part} \rangle \langle n \rangle_s + \langle n \rangle_h \langle N_{binary} \rangle \frac{\sigma_{AA}^N(s)}{\sigma_{in}}, \]

where \( \sigma_{jet}^N(s) \) is the averaged inclusive jet cross section per NN in AA collisions. The average number of participant nucleons and number of binary collisions for given impact-parameters can be estimated using HIJING Monte Carlo simulation. If one assumes that the jet production cross section \( \sigma_{jet}^N(s) \) is the same as in \( p+p \) collisions, the resultant energy dependence of the multiplicity density in central nuclear collisions is much stronger than the RHIC data as shown in Fig. 1. Therefore, one has to consider nuclear effects of jet production in heavy-ion collisions.

In high-energy nuclear collisions, multiple mini-jet production can occur within the same transverse area. If there are more than one pair of mini-jet production within the transverse area given by the jet’s intrinsic size \( \pi/p_0^2 \), jet production within this area might not be independent any more. If such a criteria is used for independent jet production within one unit of rapidity, one can then obtain a cut-off scale \( p_0 \) in a so-called final state saturation model.

\[ p_0 \approx 0.187 A^{0.136}(\sqrt{s})^{0.205} \]

that also depends on nuclear size for central heavy-ion collisions. This cut-off scale, though increasing with nuclear size, ranges from \( 0.7 \text{ GeV}/c \) at \( \sqrt{s} = 20 \text{ GeV} \) to \( 2.2 \text{ GeV}/c \) at \( \sqrt{s} = 5 \text{ TeV} \) for central \( Au + Au \) collisions, which is much smaller than what we have obtained in Eq. (3) by fitting \( p + p(\bar{p}) \) data. Therefore, if we apply the two-component model to heavy-ion collisions with the same cut-off scale in Eq. (3) as determined in \( p + p(\bar{p}) \) collisions, the criteria for independent jet production will never be violated. Instead, we will assume the cut-off scale to be independent of nuclear size in this paper.

In principle, jets produced in the early stage of heavy-ion collisions will also suffer final state interaction and induced gluon bremsstrahlung. For an energetic jet, this will lead to induced parton energy loss and the suppression of large transverse momentum hadrons. Such a jet quenching effect could also lead to increased total hadron multiplicity due to the soft gluons from the bremsstrahlung. However, a recent study of parton energy loss in a thermal environment found that the effective energy loss is significantly reduced for less energetic partons due to detailed balance by thermal absorption. Thus, only large energy jets lose significant energy via gluon bremsstrahlung. Since the production rates of these large energy jets are very small at the RHIC energy, their contributions to the total hadron multiplicity via jet quenching should also be small. Similarly we also assume that parton thermalization during the early stage contributes little to the final hadron multiplicity.

One important nuclear effect we have to consider in our two-component model is the nuclear shadowing of
partron distributions or the depletion of effective parton distributions in nuclei at small $x$. Such a nuclear shadowing effect in jet production can be taken into account by assuming modified parton distributions in nuclei,

$$f_a^A(x, Q^2) = AR_a^A(x, Q^2)f_a^N(x, Q^2).$$

Using the experimental data from DIS off nuclear targets and unmodified DGLAP evolution equations, one can parameterize $R_a^A(x, Q^2)$ for different partons and nuclei [31,32]. Recent new data [30] however indicate that the simple parameterization for nuclear shadowing used in HIJING [14] is too strong for heavy nuclei. In this paper, we will use the following new parameterization,

$$R_g^A(x) = 1.0 + 1.19 \log^{1/6}(x^3 - 1.2x^2 + 0.21x) - s_g (A^{1/3} - 1)^{0.6}(1 - 3.5\sqrt{x}) \exp(-x^2/0.01)$$

with $s_g = 0.1$ for all quark distributions as shown in Fig. 2 (solid lines) in comparison with the experimental data [30]. Also shown in the figure are parameterizations (dashed lines) by Hirai, Kumano and Miyama (HKM) [32] and the old HIJING parameterization [14]. The shadowing in the old HIJING parameterization (dotted-dashed) is apparently too strong for heavy nuclei. The HKM parameterizations also take into account constraints by momentum sum rules, as similarly in the original parameterizations by Eskola,Kolhinen and Salgado (EKS) [31]. For the purpose of this paper, one can neglect the scale dependence of the shadowing.

The nuclear shadowing for gluons is somewhat constrained by the momentum sum rules in the HKM parameterization. However, the constraint is not very strong, leaving a lot of room for large variation of gluon shadowing. Shown in Fig. 3 are the shadowing factors for gluon distribution from EKS and HKM parameterizations. They both have strong anti-shadowing around $x \sim 0.1$. The stronger anti-shadowing in EKS parameterization is due to additional constraints by the $Q^2$ dependence of $F_2(Sn)/F_2(C)$, assuming the same unmodified DGLAP evolution equation for parton distributions of a nucleon. Since gluon-gluon scattering dominate the jet production cross section, such a strong gluon anti-shadowing leads to larger jet cross section and thus larger hadron multiplicity than in the case of no shadowing at the RHIC energies. Such a scenario within the two-component model is clearly inconsistent with the experimental data. We therefore propose the following parameterization for gluon shadowing,

$$R_g^A(x) = 1.0 + 1.19 \log^{1/6}(x^3 - 1.2x^2 + 0.21x) - s_g (A^{1/3} - 1)^{0.6}(1 - 1.5^0.35) \exp(-x^2/0.004),$$

with $s_g = 0.24-0.28$. This is shown in Fig. 3 as the solid lines. The hadron multiplicity density in the two-component model using the above gluon shadowing is shown in Fig. 4. The shaded area corresponds to the variation of $s_g = 0.24-0.28$. The RHIC data thus indicate that such a strong gluon shadowing is required within the two-component model. If one assumes the same gluon shadowing as the quarks in Eq. 8, the resultant $dN/dy$ is only slightly smaller than the one without shadowing. Such a constraint on gluon shadowing is indirect and model dependent. It is important to study directly the gluon shadowing in other processes in $AA$ or $pA$ collisions.
To take into account the impact-parameter dependence of the shadowing, we simply replace the shadowing parameters $s_a$ in Eqs. (9) and (10) by

$$ s_a(b) = s_a \left( 1 - b^2/R_A^2 \right), $$

(10)

where $R_A = 1.12A^{1/3}$ is the nuclear size. With this impact-parameter dependence, the calculated jet cross section $\sigma_{AA}^{jet}(s)/\sigma_{nn}$ will also depend on the centrality of heavy-ion collisions, decreasing from peripheral to central collisions. One can then calculate the centrality dependence of the hadron multiplicity density. The results are shown in Fig. 4 as a function of $N_{\text{part}}$ for Au + Au collisions at $\sqrt{s} = 56$, 130 and 200 GeV. The shaded areas again correspond to the variation of the gluon shadowing parameter $s_g = 0.24 - 0.28$. Within statistical and systematic errors, the two-component mini-jet model with impact-parameter dependent parton shadowing describes the PHOBOS and PHENIX data [3,5] at $\sqrt{s} = 130$ GeV well.

![Fig. 4.](image)

To illustrate the effect of the impact-parameter dependence of the parton shadowing, we compare the results with a two-component parameterization,

$$ \frac{dN_{ch}}{d\eta} = \frac{1}{2} (N_{\text{part}}) n_s + (N_{\text{binary}}) n_h, $$

(11)

shown as dot-dashed lines, where the two parameters, $n_s$ and $n_h$, fixed at each energy by values of $dN_{AA}^{jet}/d\eta$ in $p + p$ collisions and the most central Au + Au collisions, are assumed to be independent of the centrality. The increase of $dN_{ch}/d\eta/(N_{\text{part}})$ with $(N_{\text{part}})$ is driven only by the centrality dependence of $(N_{\text{binary}})/(N_{\text{part}})$ in this two-parameter fit. Comparing to such a two-parameter fit, the two-component mini-jet model has a flatter centrality dependence at high energies because the effective jet cross section decreases from peripheral to central collisions due to the impact-parameter dependence of parton shadowing. The better agreement between the experimental data and the two-component mini-jet model at $\sqrt{s} = 130$ GeV is another indication of strong nuclear shadowing of the gluon distribution in mini-jet production.

Similar centrality dependencies are also predicted by other models [22,33], in particular the initial-state parton saturation model [21]. It is based on the nonlinear Yang-Mills field dynamics [14,34] assuming that non-linear gluon interaction below a saturation scale $Q_s^2 \sim \alpha_s x G_A(x, Q^2)/(\pi R_A^2)$ leads to a classical behavior of the gluonic field inside a large nucleus, where $G_A(x, Q^2_s)$ is the gluon distribution at $x = 2Q_s/\sqrt{s}$. Assuming particle production in high-energy heavy-ion collisions is dominated by gluon production from the classical gluon field, one has a simple form [3] for the charged hadron rapidity density at $\eta = 0$,

$$ \frac{2}{\langle N_{\text{part}} \rangle} \frac{dN_{ch}}{d\eta} = c \left( \frac{s}{s_0} \right)^{\lambda/2} \left[ \log \left( \frac{Q^2_0}{\Lambda_{QCD}^2} \right) + \frac{\lambda}{2} \log \left( \frac{s}{s_0} \right) \right], $$

(12)

with $c \approx 0.82$ [3]. This is shown in Fig. 5 as solid lines. Here, $\Lambda_{QCD} = 0.2$ GeV, $\lambda = 0.25$ and the centrality dependence of the saturation scale $Q^2_0$ at $\sqrt{s_0} = 130$ GeV is taken from Ref. [3].

![Fig. 5.](image)
than the two-component model. In this region, there are still strong fluctuations in parton production in the two-component model through the fluctuation of $N_{\text{binary}}$ while $N_{\text{part}}$ is limited by its maximum value of 2.4. That is why $dN_{\text{ch}}/dy$/$\langle N_{\text{part}} \rangle$ continues to increase with $\langle N_{\text{part}} \rangle$ in the central region. Such a fluctuation is not currently taken into account in the saturation model calculation. More accurate measurements with small errors (less than 5%) will help to distinguish these two different behaviors. For peripheral collisions, saturation model results fall off more rapidly than the mini-jet results. However, the experimental errors are very big in this region because of large uncertainties related to the determination of the number of participants. Therefore, it will be very useful to have light-ion collisions at the same energy to map out the nuclear dependence of the hadron multiplicity in this region. An alternative is to study the ratios of hadron multiplicity of heavy-ion collisions at two different energies as a function of centrality. In this case, the errors associated with the determination of centrality will mostly cancel. Shown in Fig. 3 are the ratios of hadron multiplicity at three different energies as a function of the averaged number of participants predicted by saturation and two-component model. One notices that while the results from saturation model have the same centrality dependence at all three energies the two-component model predicts slightly different behavior at different energies, indicating the energy dependence of the mini-jet component. So the ratios given by the saturation model are almost independent of centrality. On the other hand, two-component model predicts noticeable centrality dependence of the ratios. This is especially true for the ratio between collisions at $\sqrt{s} = 200$ and 56 GeV.

It is interesting to point out that in the saturation model that assumes a particle production mechanism dominated by coherent mini-jet production below the saturation scale $Q_s$, the value of $Q_s$ determined in Ref. [1] is much smaller than the cut-off $p_0$ in the two-component model constrained by the $p + p(\bar{p})$ data. As demonstrated in this paper, the number of mini-jet production below such scale is still very large and should contribute to the final hadron multiplicity.

In summary, we have studied the energy and centrality dependence of the central rapidity density of hadron multiplicity in heavy-ion collisions at RHIC energies within a two-component mini-jet model. As a consequence of the latest parameterization of parton distributions [17] which have a higher gluon density than the old parameterization [16] used in previous studies [15], the cut-off scale that separates soft and hard processes is found to increase slightly with energy in order to fit the $p + p(\bar{p})$ data. The cut-off scale, however, is still large enough that the independent jet production picture is still valid. With a new parameterization of nuclear shadowing of parton distributions in nuclei, we also found that RHIC data require a strong shadowing of gluon distribution. Using this strong gluon shadowing with an assumed impact-parameter dependence, the predicted centrality dependence of the hadron multiplicity agrees well with the recent RHIC results. We have also compared our results with the parton saturation model [18]. We point out that in order to differentiate the two models one needs more accurate experimental data in both the most central and peripheral regions of centrality or study the centrality dependence of the ratios at different colliding energies.

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