Nuclear effects in dAu collisions from recent RHIC data ⋆

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Abstract

Neutral pion (π^0) production is calculated in a leading order (LO) perturbative QCD-based model in pp and dAu collisions at $\sqrt{s}$ = 200 AGeV at midrapidity. The model includes the transverse component of the initial parton distribution. We compare our results for pp collision to experimental data at RHIC energy. We repeat our calculation for the dAu collision and investigate the interplay between shadowing and multiple scattering. In central dAu collisions the influence of possible jet energy loss on cold nuclear matter is discussed and numerical results are displayed.

Key words: Nuclear multiscattering, nuclear shadowing, energy loss
PACS: 12.38.Bx, 13.87.-a, 24.85.+p, 25.75.-q, 25.75.Gz

1 Introduction

Experimental data on π^0 production in $Au + Au$ collisions at $\sqrt{s} = 200$ AGeV display a very strong suppression pattern in the transverse momentum region 2 GeV $< p_T <$ 20 GeV [1], which indicates a clear evidence of the presence of induced jet energy loss in hot dense matter [2–5]. Quantitative calculations of the energy loss in $Au + Au$ collisions require the precise description of the available data from $d + Au$ collisions. These data incorporate initial state effects (nuclear multiscattering and nuclear shadowing) and possible final state effects (e.g. energy loss in cold nuclear matter), which should be understood.

⋆ Supported in part by U.S. DE-FG02-86ER40251, U.S. NSF INT-0435701, and Hungarian OTKA grants T043455, T047050, and NK062044.

2 The parton model for pp collisions

In this paper we accomplish the analysis of pp and dAu data in a leading-order (LO) perturbative QCD based model [6,7]. We plan to repeat our analysis in next-to-leading (NLO) order [8], when final data will be available for pion production in dAu collisions. The invariant cross section for pion production in pp collision can be described in a LO pQCD-improved parton model on the basis of the factorization theorem as a convolution [6,7]:

$$E_{\pi^0} \frac{\mathrm{d}\sigma_{\pi^0}^{pp}}{\mathrm{d}^3 p} = \sum_{abcd} \int \mathrm{d}x_a \mathrm{d}x_b \mathrm{d}z_c \; f_{a/p}(x_a, \mathbf{k}_{Ta}, Q^2) \; f_{b/p}(x_b, \mathbf{k}_{Tb}, Q^2) \cdot$$
$$\cdot \frac{\mathrm{d}\sigma}{\mathrm{d}\hat{t}}(ab \to cd) \, \frac{D_{\pi^0/c}(z_c, Q'^2)}{\pi z_c^2} \, \hat{s} \, \delta(\hat{s} + \hat{t} + \hat{u}) \quad , \tag{1}$$

where $\mathrm{d}\sigma/\mathrm{d}\hat{t}$ is the hard scattering cross section of the partonic subprocess $ab \to cd$, and the fragmentation function (FF), $D_{h/c}(z_c, Q'^2)$ gives the probability for parton c to fragment into hadron h with momentum fraction z_c at scale Q'. For fragmentation functions we use the KKP parameterization [9].

The functions $f_{a/p}(x, \mathbf{k}_{Ta}, Q^2)$ and $f_{b/p}(x, \mathbf{k}_{Tb}, Q^2)$ are the parton distribution functions (PDFs) for the colliding partons a and b in the interacting protons as functions of momentum fraction x, at scale Q. We use a product approximation, namely $f(x, \mathbf{k}_T, Q^2) = f(x, Q^2) g(\mathbf{k}_T)$, where the function $f(x, Q^2)$ represents the standard LO PDF (here it is the GRV set [10]). In our phenomenological approach the transverse-momentum distribution is described by a Gaussian,

$$g(\mathbf{k}_T) \;= \frac{1}{\pi \langle k_T^2 \rangle} \; \exp\left(- \frac{k_T^2}{\langle k_T^2 \rangle} \right) \quad . \tag{2}$$

Here, $\langle k_T^2 \rangle$ is the 2-dimensional width of the k_T distribution and it is related to the magnitude of the average transverse momentum of a parton as $\langle k_T^2 \rangle = 4 \langle k_T \rangle^2 / \pi$.

The validity of this approximation and the introduction of the transverse component into the PDFs were under debate for a long time. However, recent measurement of di-hadron correlations by PHENIX [11] and the theoretical investigation of these data [12] have shown that a large value for the k_T-imbalance can be extracted from existing di-hadron data. The origin of this k_T-imbalance is three-fold: intrinsic transverse momenta of the partons, non-perturbative soft radiation and higher order radiation terms. We consider these effects phenomenologically and our $\langle k_T^2 \rangle$ value accumulates all of these effects. As we will see, the size of this $\langle k_T^2 \rangle$ can be extracted consistently from one-particle spectra and two-particle correlations.

In our present study we consider fixed scales: the factorization scale is connected to the momentum of the intermediate jet, $Q = \kappa \cdot p_q$ (where $p_q = p_T/z_c$), while the fragmentation scale is connected to the final hadron momentum, $Q_F = \kappa \cdot p_T$. The value of κ can be varied in a wide range, however we will use $\kappa = 2/3$, which is the best choice to obtain agreement between data and theory at high-p_T, where non-perturbative effects have a small contribution.

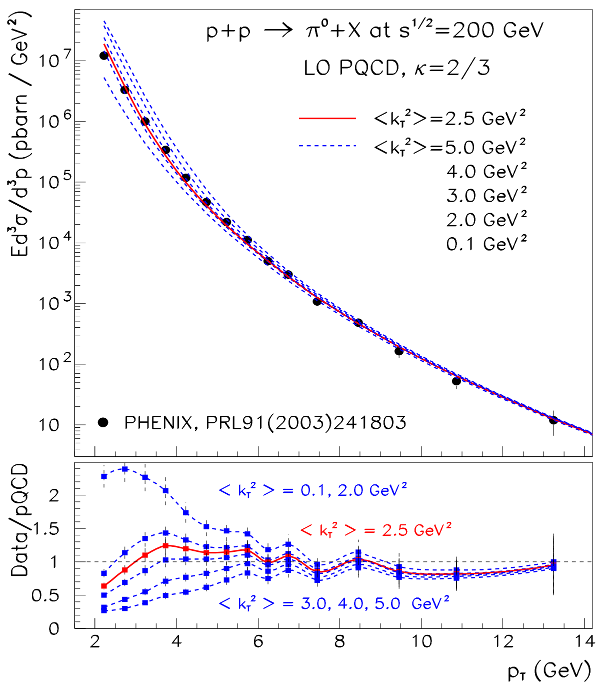

Fig. 1. (Color online) One-particle spectra for π^0 production in pp collisions at $\sqrt{s} = 200$ GeV at different intrinsic k_T values compared to PHENIX data [13].

Figure 1 displays our results at $\sqrt{s} = 200$ GeV for $pp \to \pi^0 X$ [13] at different values of the k_T-imbalance. Without transverse momentum component for partons the theoretical results underestimate the data by a factor of 2 in the window 2 GeV $< p_T <$ 5 GeV. To minimize the difference between RHIC data and the model, a value of $\langle k_T^2 \rangle = 2.5$ GeV^2 can be selected. This value indicates $\langle p_{T,pair}^2 \rangle = 2\langle k_T^2 \rangle = 5$ GeV^2, which is compatible with the value obtained in Refs. [11,12] from di-hadron spectra.

Our earlier studies have shown that the theoretical reproduction of the one-hadron spectra in a pQCD frame strongly requires the introduction of a large k_T-imbalance in both LO and NLO calculations [14]. The analysis of di-hadron correlations in NLO frame would give more insight into this problem.

3 The parton model for dAu collisions

Considering the dAu collision, the hard pion production cross section can be written as an integral over impact parameter b, where the geometry of the collision is described in the Glauber picture [6,7]:

$$E_\pi \frac{\mathrm{d}\sigma_\pi^{dAu}}{\mathrm{d}^3p} = \int \mathrm{d}^2b\, \mathrm{d}^2r\; t_d(r)\; t_{Au}(|\mathbf{b}-\mathbf{r}|) \cdot E_\pi \frac{\mathrm{d}\sigma_\pi^{pp}(\langle k_T^2\rangle_{pAu}, \langle k_T^2\rangle_{pd})}{\mathrm{d}^3p} \quad , \qquad (3)$$

where the proton-proton cross section on the right hand side represents the cross section from eq. (1), but with the broadened widths of the transverse-momentum distributions in eq. (2), as a consequence of nuclear multiscattering (see eq. (4)). In eq. (3), $t_{Au}(b) = \int \mathrm{d}z\, \rho_{Au}(b,z)$ is the nuclear thickness function (in terms of the density distribution of the gold nucleus, ρ_{Au}), normalized as $\int \mathrm{d}^2b\, t_{Au}(b) = A_{Au} = 197$. For the deuteron, one could use a superposition of a pAu and a nAu collision, or a distribution for the nucleons inside the deuteron. Here we apply a hard-sphere approximation for the deuteron with A=2 for estimating the nuclear effects. Also, since π^0 production is not sensitive to isospin, we continue to use the notation "pA" when talking about the interaction of any nucleon with a nucleus.

The initial state broadening of the incoming parton distribution function is accounted for by an increase in the width of the gaussian parton transverse momentum distribution in eq. (2) [7,15]:

$$\langle k_T^2 \rangle_{pA} = \langle k_T^2 \rangle_{pp} + C \cdot h_{pA}(b) \ . \tag{4}$$

Here, $\langle k_T^2 \rangle_{pp}$ is the width of the transverse momentum distribution of partons in *pp* collisions, $h_{pA}(b)$ describes the number of *effective* nucleon-nucleon (NN) collisions at impact parameter b, which impart an average transverse momentum squared C. The effectivity function $h_{pA}(b)$ can be written in terms of the number of collisions suffered by the incoming proton in the target nucleus, $h_{pA}(b) = \nu_A(b) - 1$. Here, $\nu_A(b) = \sigma_{NN} t_A(b)$, with σ_{NN} being the inelastic nucleon-nucleon cross section. For the factor C and $\nu_A(b)$ we will use the findings of Ref. [7], where the systematic analysis of pA reactions was performed in LO and the characteristics of the Cronin effect were determined at LO level. Following Ref. [7], we assume that only a limited number of semi-hard collisions (with maximum $\nu_A(b)_{max} = 4$) contributes to the broadening, and we have found $C = 0.4$ GeV^2. The maximum of the broadening is $\sim$1 GeV^2 and this value determines the maximum increase in the particle yield.

It is well-known that the PDFs are modified in the nuclear environment and nuclear shadowing appears for partons with momentum fraction $x < 0.1$. This is taken into account by various shadowing parameterizations [16–19]. In the present work, we display results obtained with the EKS parameterization, which has an antishadowing feature[16], and with the updated HIJING parameterization[17], which incorporates different quark and gluon shadowing and requires the introduction of nuclear multiscattering. As a third case, we consider the nuclear parton distribution functions introduced by HKM [18]. Since beyond nuclear shadowing the nuclear multiscattering may appear, we will apply the HKM parametrization alone and in a combination with our multiscattering description.

4 Results on pion production in dAu collisions

Including the multiscattering and shadowing effects one can calculate the invariant cross section for pion production in $d + Au$ collision. Moreover, introducing the nuclear modification factor R_{dAu}, as

$$R_{dAu} = \frac{E_\pi \mathrm{d}\sigma_\pi^{dAu}/\mathrm{d}^3p}{N_{bin} \cdot E_\pi \mathrm{d}\sigma_\pi^{pp}/\mathrm{d}^3p} = \frac{E_\pi \mathrm{d}\sigma_\pi^{dAu}(\texttt{ with nuclear effects})/\mathrm{d}^3p}{E_\pi \mathrm{d}\sigma_\pi^{dAu}(\texttt{ no nuclear effects})/\mathrm{d}^3p} \ ,(5)$$

nuclear effects can be investigated clearly and efficiently, using a linear scale. The value of N_{bin} can be determined using the Glauber geometrical overlap integral as in eq. (3). Here we apply the right-most equation in our theoretical calculations, which does not require the determination of N_{bin} from the Glauber model.

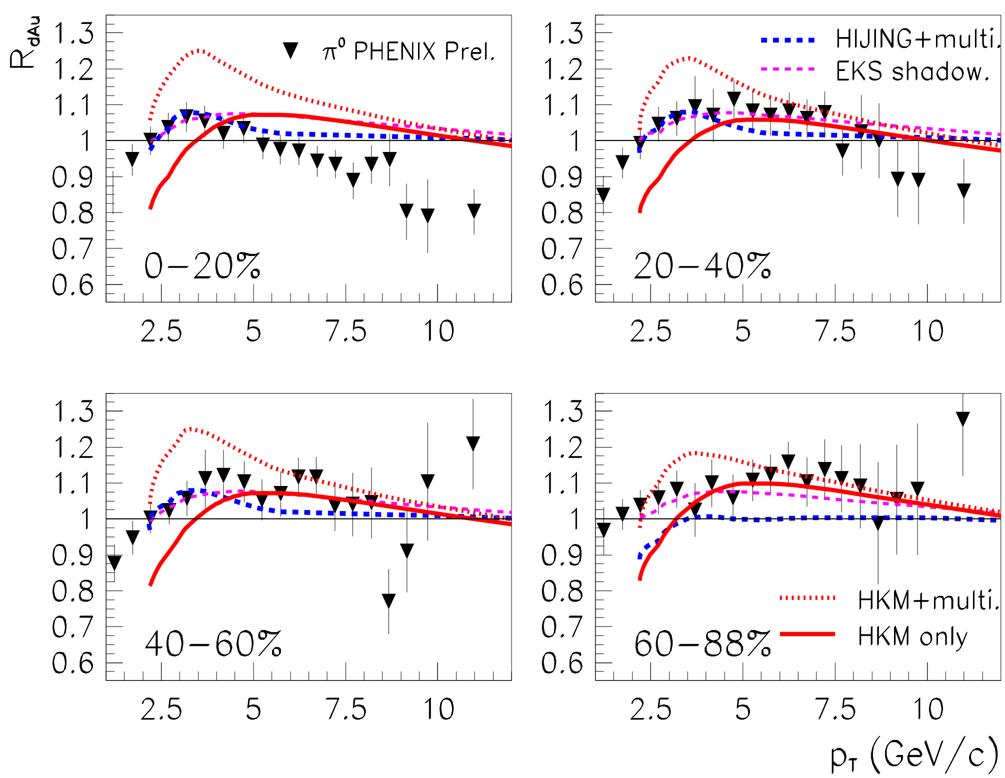

Fig. 2. (Color online) Nuclear modification factor for π^0 production in dAu collisions at $\sqrt{s_{NN}} = 200$ AGeV at different centralities. Theoretical results (see text for details) are compared to preliminary PHENIX data [20].

Figure 2 summarizes our theoretical results in four centrality bins for the nuclear modification factor R_{dAu} in dAu collisions at $\sqrt{s} = 200$ AGeV, displaying different shadowing models. Preliminary PHENIX data are from Ref. [20].

At first glance, the experimental data have a striking message at all centrality bins: the nuclear modification factor shows a $\pm 10\%$ deviation from unity in wide momentum regions in all centrality bins, including the most central and the most peripheral ones. Since these $\pm 10\%$ deviations overlap with the systematic error of these experimental data, we can not exclude the scenario of a null effect, which means no multiscattering and no shadowing are present at RHIC energies. Fortunately the nuclear modification factor has been measured at higher rapidities and the influence of nuclear shadowing can be seen clearly [21], which excludes the null effect scenario. This means that there is a delicate interplay between nuclear shadowing and multiscattering (or the antishadowing feature of the shadowing functions).

Investigating the experimental data from this point of view, we may recognize a slight b-dependence for both multiscattering and shadowing. In the most peripheral collisions (60-88 %) multiscattering overwhelms the shadowing - or shadowing function has a clear antishadowing region to be involved in the pion production in the region $3 < p_T < 7$ GeV/c. The enhancement can be reproduced by the EKS (thin dashed line) and the HKM shadowing (solid line), the scenario of 'HKM+multiscattering' (dotted line) is satisfactory only because of the large error bars. HIJING (thick dashed line) displays no nuclear modification — more precise data may help us to choose between the different scenarios. In the most central collisions (0-20 %) in the intermediate transverse momentum window the +10% enhancement appears through the superposition of a stronger shadowing and a more effective multiscattering connected to the geometry of the collisions. If final data will have a smaller error bars, then we may be able to select between the different theoretical models.

However, data in the most central bins (0-20 %) display an interesting phenomenon at high-p_T: although all model calculations with nuclear multiscattering and shadowing lead to unity, the experimental data are decreasing with increasing transverse momentum. The authors are not aware of any shadowing parametrization, which could yield such a suppression around $p_T = 6 - 10$ GeV at RHIC energies, and any nuclear multiscattering should work in the opposite direction. This suppression in central dAu collisions may indicate the presence of a new phenomena, namely a moderate jet energy loss in the cold matter produced in dAu collisions. Cold quenching of high energy quarks is known from the HERMES experiment [22], and recently it was investigated theoretically (see Refs. [23–25]). The question of cold quenching is very complicated, and it is strongly related to the microscopical description of hadronization (see Ref. [25]). Thus recent dAu data with large error bars can not give a deep insight into this phenomena beyond indicating its existence in the most central bins. We estimated this effect with a simple rescaling of the 'HKM+multiscattering' scenario. Figure 3 indicates that dAu data in the most central bin can accommodate a 10-15 % suppression.

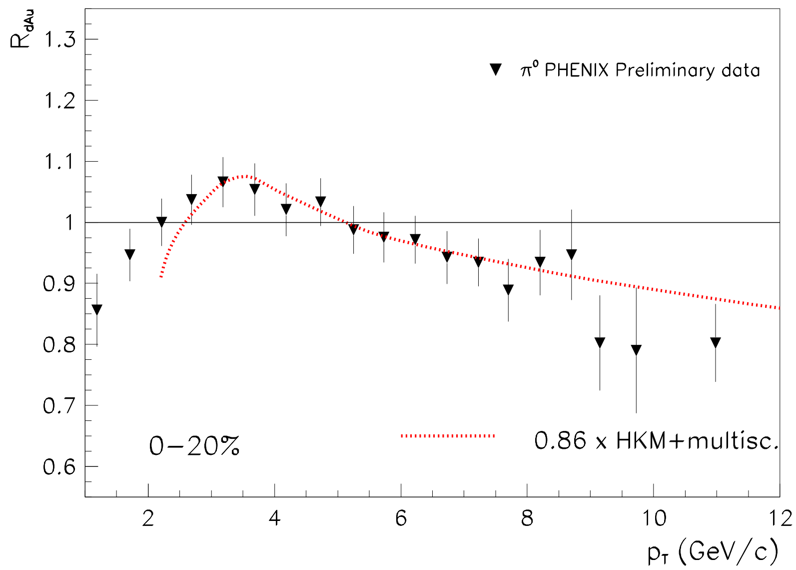

Fig. 3. (Color online) Nuclear modification factor for π^0 production in central dAu collisions at $\sqrt{s_{NN}} = 200$ AGeV. Theoretical result (dotted line) is obtained by simple rescaling of the 'HKM+multiscattering' scenario (see text for details). Preliminary PHENIX data are from Ref. [20].

5 Summary

We have investigated the interplay between nuclear shadowing and multiscattering at RHIC energies in dAu collisions. Since the nuclear modification factor, R_{dAu}, has a value close to unity in large transverse momentum regions, the two effects seem to balance each other within ±15%, which makes the separation and the quantitative analysis of these effects in the mid-rapidity difficult. Final data with smaller error bars may lessen this complication. The characteristic suppression of the nuclear modification factor at high-p_T in the most central dAu collisions may indicate the presence of a moderate jet energy loss. Quantitative analysis requires the introduction of proper theoretical models for jet energy loss in cold nuclear matter.

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