EMC effect and jet energy loss in relativistic deuteron-nucleus collisions

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We investigate the influence of modified nuclear parton distribution functions (PDFs) on high-$p_T$ hadron production at RHIC and LHC energies using a pQCD-improved parton model. For application at RHIC, we focus on the possible contribution of the EMC modification of the nuclear PDFs in the $x \gtrsim 0.3$ region to the observed suppression of $\pi^0$ production at $p_T \gtrsim 10$ GeV/c in $dAu$ collisions. We study three different parameterizations of the nuclear PDF modifications and find that they give consistent results for $R_{dAu}(p_T)$ for neutral pions in the region $10$ GeV/c $\lesssim p_T \lesssim 20$ GeV/c. We find that the EMC suppression of the parton distributions in the $Au$ nucleus does not strongly influence the $R_{dAu}$ for $\pi^0$ in the $p_T$ region where the suppression is observed. Using the HKN parameterization, we evaluate systematic errors in the theoretical $R_{dAu}(p_T)$ resulting from uncertainties in the nuclear PDFs. The measured nuclear modification factor is inconsistent with the pQCD model result for $p_T \gtrsim 10$ GeV/c even when the systematic uncertainties in the nuclear PDFs are accounted for. The inclusion of a small final-state energy loss can reduce the discrepancy with the data, but we cannot perfectly reproduce the $p_T$ dependence of the measured $R_{dAu}(p_T)$. For the LHC, we find that shadowing of the nuclear PDFs produces a large suppression in the yield of hadrons with $p_T \lesssim 100$ GeV/c in $p(d)A$ collisions.

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I. INTRODUCTION

Deuteron-gold ($dAu$) collisions have been extensively studied at the Relativistic Heavy Ion Collider (RHIC), both for their intrinsic interest and as a control experiment to judge the suppression seen in central gold-gold ($AuAu$) collisions at sufficiently high transverse momenta ($p_T$). Unexpectedly, not only $AuAu$ data, but recent extended $p_T$ coverage $dAu$ data also display a suppressed nuclear modification factor in central collisions. This motivates a study of possible mechanisms that may result in a nuclear modification factor smaller than unity at sufficiently high transverse momenta ($p_T \gtrsim 6$ GeV/c) in central $dAu$ collisions.

The nuclear modification factor $R_{dAu}$ compares the spectra of produced particles in $dAu$ collisions to a hypothetical scenario in which the nuclear collisions are assumed to be a superposition of the appropriate number of nucleon-nucleon collisions. In the transverse momentum window $2$ GeV/c $\lesssim p_T \lesssim 6$ GeV/c, the nuclear modification factors are dominated by the Cronin peak. Several physical pictures of this enhancement have been proposed.

One family of models advances an explanation of the Cronin effect in terms of the interplay between nuclear shadowing and the multiple scattering of particles propagating in the strongly-interacting medium (multiscattering). Our model gave a reasonable description of the Cronin effect in central collisions at midrapidity. At the same time, we obtained nuclear modification factors close to unity at high transverse momenta ($6$ GeV/c $\lesssim p_T \lesssim 20$ GeV/c).

In the high-$p_T$ region multiscattering no longer affects $R_{dAu}$. It is then natural to ask if nuclear shadowing can explain suppression effects at high $p_T$. In particular, since at $\sqrt{s_{NN}} = 200$ AGeV we are in the EMC region of the shadowing function for $6$ GeV/c $\lesssim p_T \lesssim 20$ GeV/c, we ask if the EMC effect plays a role in understanding these experiments.

In this paper we first investigate $dAu$ collisions at the highest RHIC energies and the role of the EMC effect at transverse momenta up to $50-70$ GeV/c. We then examine whether recent shadowing parameterizations incorpo-
rating theoretical uncertainties for the first time\cite{25,26} can account for the experimental information. We also display calculational results with a modest energy loss using energy-loss parameters applied earlier to AuAu data. Finally we extend our considerations to the energy range of the Large Hadron Collider (LHC).

II. THE EMC EFFECT IN DEUTERON-GOLD COLLISIONS

Figure 1 displays recent PHENIX data (triangles with error bars)\cite{6} for the most central dAu collisions, where a high-\(p_T\) suppression is clearly seen. While incoherent multiscattering can only lead to enhancement in \(R_{dAu}\), nuclear shadowing displays two regions where an \(R_{dAu} < 1\) can be expected: (i) at small \(x\) (\(x \lesssim 0.2\)), and (ii) in the EMC region (\(0.5 \lesssim x \lesssim 0.9\))\cite{21}. At RHIC energies the small-\(x\) region is inconsequential at \(p_T \gtrsim 6\) GeV/c. Thus we focus attention on the EMC effect as a possible mechanism for the measured suppression. Various shadowing parameterizations developed in the last 15 years \cite{22,23,24,25,26} show different behaviors at small-\(x\), but the EMC region appears rather robust in most models.

To see the effect of the EMC region, we calculate pion production in a wide momentum range. For this purpose we use a perturbative QCD improved parton model \cite{18}. The model is based on the factorization theorem and generates the invariant cross section as a convolution of (nuclear) parton distribution functions \(f_{a/A}(x_a, Q^2, k_{T a})\) perturbative QCD cross sections \(d\sigma_{ab \to cd}/d\hat{t}\), and fragmentation functions \(D_{\pi/c}(z_c, \hat{Q}^2)\). We perform the calculation in leading order, following Refs. \cite{18,27,28,30,31,32}:

\[
E_{\pi} \frac{d\sigma_{dAu}}{d^3p_\pi} = f_{a/d}(x_a, Q^2, k_{T a}) \otimes f_{b/Au}(x_b, Q^2, k_{T b}) \otimes \int \frac{d\sigma_{ab \to cd}/d\hat{t}}{d\hat{t}} \otimes D_{\pi/c}(z_c, \hat{Q}^2),
\]

where \(Q^2\) and \(\hat{Q}^2\) represent the factorization and fragmentation scales, respectively, \(x_a, x_b,\) and \(z_c\) are momentum fractions, and \(k_{T}\)-s stand for two-dimensional transverse momentum vectors. The initial state effects of shadowing and multiscattering are included following the treatment in Refs. \cite{18,27,28}.

Since the effects we investigate are on the 10 – 20\% level, it is customary to present the obtained results on a linear scale in terms of the nuclear modification factor

\[
R_{dAu}(p_T) = \frac{1}{\langle N_{bin} \rangle} \cdot \frac{E_{\pi} \frac{d\sigma_{dAu}}{d^3p_\pi}}{E_{\pi} \frac{d\sigma_{pp}}{d^3p_\pi}}.
\]

Here \(\langle N_{bin} \rangle\) is the average number of binary collisions in the various impact-parameter bins.

Together with the data in central dAu collisions, we display our results with several shadowing parameterizations in Fig. 1. We use the HIJING shadowing including nuclear multiscattering (solid lines), the EKS shadowing (where multiscattering is represented by strong anti-shadowing) (dashed line), and the HKN parameterization (with and without nuclear multiscattering, dotted and dash-dotted lines, respectively). It can be seen in Fig. 1 that the suppression associated with the EMC effect shows up at transverse momenta \(p_T \gtrsim 20\) GeV/c in all models considered, and does not explain the suppression in the data at around 10 GeV/c. The Cronin peak at \(p_T \approx 3\) GeV/c is best reproduced by the HIJING parameterization. The “HKN+multiscattering” model appears to overshoot the data at low \(p_T\), while it gives.

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**Figure 1:** (Color online) The nuclear modification factor, \(R_{dAu}\) in central (0 – 20\%) dAu collisions for \(\pi^0\). Data are from Ref. \cite{6}. Theoretical results are calculated with different shadowing parameterizations (see text).

**Figure 2:** (Color online) The influence of the uncertainty in the HKN shadowing parameterization \cite{26} on the factor \(R_{dAu}\) in the most central dAu collisions. Data are from Ref. \cite{6}.
very similar results to HIJING at $p_T \gtrsim 5$ GeV/c. Since the uncertainty of the HKN nuclear parton distribution functions is also available, we next examine the theoretical uncertainty of the description.

In Fig. 2 the effect of the uncertainty given by the HKN shadowing parameterization is illustrated on the nuclear modification factor, $R_{dAu}$. The errors are calculated by the Hessian method, using the original code of the HKN group. The mean value as a function of $p_T$ is represented by a solid line, surrounded by an error band of approximately ±10%. Although the data fall within this band at low $p_T$, for $p_T \gtrsim 8$ GeV/c the observed suppression is stronger than allowed by this calculation.

Since we are not aware of any other initial-state suppression, we consider physics operating in the final state. In particular, jet energy loss suggests itself [35, 36]. This idea is supported by the presence of a minor energy loss effect in peripheral $AuAu$ collisions [37]. Assuming $L = 1.5$ fm for the average static transverse size of the traversed medium, and the usual GLV parameters of $\lambda = 1.5$ fm mean free path and $\mu = 0.5$ GeV screening mass, we calculate the effect of jet energy loss on the nuclear modification factor for central $dAu$ collisions. This is displayed in Fig. 3. It can be seen that inclusion of this energy loss results in a parallel down-shift of $R_{dAu}$ relative to curves in Fig. 2. The slope of the data as a function of $p_T$ is still very different from that of the calculated results. Nevertheless, taking into account all experimental and theoretical uncertainties, one could consider the displayed result with $L/\lambda = 1.0$ to be an acceptable compromise.

Jet energy loss depends on the transverse parton density, which relates to the measurable hadronic quantity $1/A_L \cdot dN_{ch}/dy$, where $A_L$ is the transverse area of the deconfined region. Assuming a realistic geometry for central $AuAu$ and $dAu$ collisions and considering the experimental data on $dN_{ch}/dy$, we obtain only a factor of 2 difference for the transverse parton densities between the $AuAu$ and $dAu$ cases. On this basis, one could expect the jet-quenching effect in $dAu$ to be even stronger than shown by the calculated band in Fig. 3. However, jet energy loss in non-thermal matter is an open question, which we plan to investigate in a forthcoming paper [38].

III. PREDICTIONS FOR THE LHC

We expect that the EMC region will shift to higher and higher transverse momenta with increasing collision energy. At the same time, due to the increasing parton density, the energy loss should also become larger. We repeat our calculation for $dPb$ collisions at $\sqrt{s_{NN}} = 900$ GeV and 8.8 TeV to display these tendencies. The results are shown in Fig. 4. Following the ordering of the lines on the left of the Figure, the top curve represents the results with HIJING shadowing from Fig. 1. The second line corresponds to a similar calculation (i.e. HIJING shadowing, no energy loss) at 900 GeV c.m. energy. The next line shows the result at 8.8 TeV without jet quenching, while the dotted and dashed lines illustrate the effect of energy loss. First we took $L = 1.5$ fm for the transverse size of the medium, and used the value of $\lambda = 1.5$ fm as earlier. The introduction of a smaller $\lambda$ value to represent the increase in the transverse density of colored scattering centers with increasing c.m. energy gives $L/\lambda = 3.0$. It can be seen that the dip corresponding to the EMC effect shifts to higher transverse momenta with increasing energy as expected. While $R_{dAu}$ is above unity at $p_T \approx 3$ GeV/c for 0.2 TeV (Cronin effect), at 0.9 and 8.8 TeV, where we are deep in the shadowing re-
gion at these transverse momenta, at most a small ripple appears on $R_{dAu}$, which is rising towards one with increasing transverse momentum in this region. The effect of varying $\lambda$ at 8.8 TeV is minimal at transverse momenta $p_T \gtrsim 100$ GeV/c, but quite significant at 5 GeV/c $\lesssim p_T \lesssim 10$ GeV/c.

IV. CONCLUSION

In conclusion, while this solution appears initially tempting, the EMC effect does not explain the unexpected suppression seen at $p_T \approx 10$ GeV/c in $R_{dAu}$ at $\sqrt{s_{NN}} = 200$ AGeV. Taking into account experimental uncertainties as well as the uncertainties of the HKN nuclear parton distribution functions, the experimental and theoretical results can be brought into agreement using a non-negligible amount of final state parton energy loss (with standard opacity parameters). The non-thermal nature of the $dAu$ system casts some doubt on the parameter values. The presence of jet quenching in the $dAu$ system is somewhat surprising at first sight, but is justified by the similarity (within a factor of 2) of the real transverse densities in the $AuAu$ and $dAu$ systems.

For LHC energies we do not have a fully reliable baseline calculation at present. It is clearly seen, however, that shadowing (i.e. suppression) will dominate the momentum region up to $p_T \lesssim 100 \sim 200$ GeV/c. The effect of final state interactions (jet energy loss) may also reduce the nuclear modification factor, especially in this momentum region. The EMC dip in the nuclear modification factor moves toward higher and higher transverse momenta with increasing energy.

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[1] S.S. Adler et al. (PHENIX), Phys. Rev. Lett. 91, 072303 (2003); Phys. Rev. C74, 024904 (2006).
[2] B.A. Cole, Nucl. Phys. A774 225 (2006).
[3] J. Adams et al. (STAR), Phys. Rev. Lett. 91, 072304 (2003); Phys. Rev. C70, 064907 (2004).
[4] K. Adcox et al. (PHENIX), Nucl. Phys. A757, 184 (2005).
[5] J. Adams et al. (STAR), Nucl. Phys. A757, 102 (2005).
[6] S.S. Adler et al. (PHENIX), [arXiv:nucl-ex/0610006] [arXiv:nucl-ex/0610006]
[7] J.W. Cronin et al. [CP Coll.], Phys. Rev. D11, 3105 (1975).
[8] D. Antreasyan et al. [CP Coll.], Phys. Rev. D19, 764 (1979).
[9] M. Gyulassy and P. Lévai, Phys. Lett. B442, 1 (1998).
[10] B.Z. Kopeliovich, J. Nemchik, A. Schafer, A.V. Tarasov, Phys. Rev. Lett. 88, 232303 (2002).
[11] D. Kharzeev, Yu.V. Kovchegov, K. Tuchin, Phys. Rev. D68, 094013 (2003).
[12] A. Accardi, M. Gyulassy, Phys. Lett. B586, 244 (2004).
[13] J.P. Blaizot, F. Gelis, R. Vemugopalan, Nucl. Phys. A743, 12 (2004).
[14] R.C. Hwa, C.B. Yang, Phys. Rev. Lett. 93, 082302 (2004).
[15] C.Y. Wong and H. Wang, Phys. Rev. C58, 376 (1998).
[16] X.N. Wang, Phys. Rev. C61, 064910 (2000).
[17] G. Papp, P. Lévai, and G. Fai, Phys. Rev. C61, 021902 (2000).
[18] Y. Zhang et al., Phys. Rev. C65, 034903 (2002).
[19] G. Papp, G.G. Barnaföldi, G. Fai, P. Levai, and Y. Zhang, Nucl. Phys. A698, 627 (2002).
[20] G.G. Barnaföldi, P. Lévai, G. Papp, G. Fai, and M. Gyulassy, Eur. Phys. J. C33, s609 (2004).
[21] D.F. Geesaman et al., Ann. Rev. Nucl. Part. Sci. 45, 337 (1995).
[22] K. Eskola, V.J. Kolhinen, and C.A. Salgado, Eur. Phys. J. C9, 61 (1999).
[23] X.-N. Wang and M. Gyulassy, Phys. Rev. D44, 3501 (1991); Comput. Phys. Commun. 83, 307 (1994).
[24] S.J. Li and X.N. Wang, Phys. Lett. B527, 85 (2002).
[25] M. Hirai, S. Kumano, and M. Miyama, Phys. Rev. D64, 034003 (2001).
[26] M. Hirai, S. Kumano, and T.-H. Nagai, Phys. Rev. D70, 044905 (2004); Nucl. Phys. Proc. Suppl. 139, 21 (2005).
[27] P. Lévai, G.G. Barnaföldi, G. Fai, and G. Papp, [arXiv:nucl-th/0306019].
[28] P. Lévai, G.G. Barnaföldi, G. Fai, and G. Papp, Nucl. Phys. A783, 101c (2007).
[29] B.A. Kniehl, G. Kramer and B. Pöpper, Nucl. Phys. B597, 337 (2001).
[30] G.G. Barnaföldi et al., J. Phys. G30, s1125 (2004).
[31] G.G. Barnaföldi et al., Nucl. Phys. A774, 801 (2006).
[32] G.G. Barnaföldi et al., Heavy Ion Phys. A18, 79 (2003).
[33] P. Lévai et al. Nucl. Phys. A698, 631 (2002).
[34] I. Vitev and M. Gyulassy, Phys. Rev. Lett. 89, 252301 (2002).
[35] M. Gyulassy, P. Lévai, I. Vitev, Phys. Rev. Lett. 85, 5535 (2000); Nucl. Phys. B571, 197 (2000).
[36] M. Gyulassy, P. Lévai, I. Vitev, Nucl. Phys. B594, 371 (2001).
[37] G.G. Barnaföldi, P. Lévai, G. Papp and G. Fai, [arXiv:hep-ph/0609023].
[38] G.G. Barnaföldi, P. Lévai, G. Papp and G. Fai, in preparation.