High-p_T Tomography of $d + \mathrm{Au}$ and $\mathrm{Au} + \mathrm{Au}$ at SPS, RHIC, and LHC

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The interplay of nuclear effects on the $p_T > 2$ GeV inclusive hadron spectra in $d + \mathrm{Au}$ and $\mathrm{Au} + \mathrm{Au}$ reactions at $\sqrt{s_{NN}} = 17$, 200, and 5500 GeV is compared to leading order perturbative QCD calculations for elementary $p + p$ ($\bar{p} + p$) collisions. The competition between nuclear shadowing, Cronin effect, and jet energy loss due to medium-induced gluon radiation is predicted to lead to a striking energy dependence of the nuclear suppression/enhancement pattern in $A + A$ reactions. We show that future $d + \mathrm{Au}$ data can be used to disentangle the initial and final state effects.

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Introduction.—Tomography is the study of the properties of matter through the attenuation pattern of fast particles that propagate and lose energy as a result of multiple elastic and inelastic scatterings. Recently, this technique has been applied in the field of nuclear physics [1,2] to map out the evolution of the QCD matter density produced in ultrarelativistic heavy ion reaction. It is based on the theoretical advances in understanding QCD multiparton interactions in non-Abelian media [3,4].

The determination of the opacity of the transient quark-gluon plasma produced in such reactions via jet tomography requires theoretical control over the interplay between many competing nuclear effects that modify the high-p_T hadron spectra. These include nuclear modifications to the parton distribution functions (PDFs), referred to as shadowing [5], Cronin effect [6], and jet quenching [7], as well as the energy dependence of the underlying perturbative QCD (pQCD) parton spectra. In this Letter, we propose an approach to disentangle these effects by comparing high-p_T hadron yields in $p + p$ ($\bar{p} + p$), $d + A$ ($p + A$), and $A + A$ reactions over a very wide energy range. In particular, predictions are presented for $d + \mathrm{Au}$ and central $\mathrm{Au} + \mathrm{Au}$ at center of mass energies per nucleon $\sqrt{s_{NN}} = 17$, 200, and 5500 GeV typical of the CERN Super Proton Synchrotron (SPS), the Relativistic Heavy Ion Collider (RHIC), and the future Large Hadron Collider (LHC).

We demonstrate that at SPS the puzzling absence of quenching of π^0 in central $\mathrm{Pb} + \mathrm{Pb}$ [8] can be understood as due to a larger than previously expected Cronin enhancement [9] dominating over our predicted [4] suppression due to jet energy loss. At RHIC energies, on the other hand, we find that quenching dominates over both Cronin and shadowing effects. Furthermore, the interplay of these effects leads to a surprising approximately constant suppression factor of the Glauber geometry scaled [10] pQCD prediction in the $4 \leq p_T \leq 20$ GeV range. At LHC we predict that the π^0 suppression factor is substantially larger than at RHIC but also decreases systematically with transverse momentum in the $6 \leq p_T \leq 100$ GeV range due to the higher initial gluon densities expected and the hardening of the underlying initial jet spectra.

Particle spectra in $d + A$ and $A + A$.—The scaling of high-p_T hadron production in $d + A$ and $A + A$ is simply controlled by nuclear geometry in the absence of initial and final state interactions. The Glauber multiple collision model [10] can be used to calculate the number of binary nucleon-nucleon collisions at any impact parameter b. In $p + A$ the experimental *cross section* has usually been presented without centrality selection, while in $A + A$ reactions *hadron multiplicity distributions* are generally presented with restricted centrality (impact parameter b) cuts. Dynamical nuclear effects for these cases are detectable through the nuclear modification ratio

$$R_{BA}(p_T) = \begin{cases} \frac{d\sigma^{dA}}{dyd^2\mathbf{p}_T} \Big/ \frac{2Ad\sigma^{pp}}{dyd^2\mathbf{p}_T} & \text{in } d + A, \\ \frac{dN^{AA}(b)}{dyd^2\mathbf{p}_T} \Big/ \frac{T_{AA}(b)d\sigma^{pp}}{dyd^2\mathbf{p}_T} & \text{in } A + A, \end{cases} \quad (1)$$

where $2A$ and $T_{AA}(b) = \int d^2\mathbf{r}\, T_A(\mathbf{r})T_B(\mathbf{r} - \mathbf{b})$ in terms of nuclear thickness functions $T_A(r) = \int dz\, \rho_A(\mathbf{r}, z)$ are the corresponding Glauber scaling factors of $d\sigma^{pp}$. The lowest order pQCD differential cross section for inclusive $A + B \to h + X$ production that enters Eq. (1) is given by

$$\left.\begin{matrix} \frac{1}{2A}\frac{d\sigma^{dA}}{dyd^2\mathbf{p}_T} \\ \frac{1}{T_{AA}(b)}\frac{dN^{AA}(b)}{dyd^2\mathbf{p}_T} \end{matrix}\right\} = K \sum_{abcd} \int dx_a dx_b \int d^2\mathbf{k}_a d^2\mathbf{k}_b\, g(\mathbf{k}_a)g(\mathbf{k}_b)$$
$$\times\, S_A(x_a, Q_a^2)S_B(x_b, Q_b^2)f_{a/A}(x_a, Q_a^2)f_{b/B}(x_b, Q_b^2)\frac{d\sigma^{ab\to cd}}{d\hat{t}}\int_0^1 d\epsilon\, P(\epsilon)\frac{z_c^*}{z_c}\frac{D_{h/c}(z_c^*, Q_c^2)}{\pi z_c}. \quad (2)$$

In Eq. (2), x_a, x_b are the initial momentum fractions carried by the hard-scattered partons with probabilities sampled from the PDFs $f_{\alpha/A}(x_\alpha, Q_\alpha^2)$. The momentum fraction carried away by the leading hadron $z_c = p_h/p_c$ is sampled from the fragmentation functions (FFs) $D_{h/c}(z_c, Q_c^2)$. We use the leading order (LO) Glück-Reya-Vogt (GRV98) parametrization of PDFs [11] and the LO Binnewies-Kniehl-Kramer parametrization of the FFs [12].

A constant K factor and parton k_T broadening function, $g(\mathbf{k}) = \exp(-\mathbf{k}_T^2/\langle \mathbf{k}_T^2 \rangle_{pp})/\pi\langle \mathbf{k}_T^2 \rangle_{pp}$, are included to account phenomenologically for next-to-leading order corrections. In systematic fits [13] to the inclusive hadron production in $p + p$ ($\bar{p} + p$) reactions, these parameters are fixed from data [6,14]. The K factor drops out in the ratios of $B + A$ to scaled $p + p$, but the phenomenological k_T broadening in $p + p$ is essential to establish an accurate nuclear geometry scaled baseline. We find that a fixed $\langle k_T^2 \rangle_{pp} = 1.8\ \text{GeV}^2$ reproduces to within 30% the spectral shapes in $p + p$ ($p + \bar{p}$) for $p_T > 2$ GeV over the whole energy range of interest.

In $B + A$ reactions, isospin effects are accounted for on average in the PDFs for a nucleus with Z protons and N neutrons via $f_{\alpha/A}(x_\alpha, Q_\alpha^2) = (Z/A) f_{\alpha/p}(x_\alpha, Q_\alpha^2) + (N/A) f_{\alpha/n}(x_\alpha, Q_\alpha^2)$. Nuclear modifications to the PDFs [5] are included through the shadowing function $S_A(x_\alpha, Q_\alpha^2)$ from the Eskola-Kolhinen-Salgado (EKS98) parametrization [15].

The Cronin effect observed in $p + A$ reactions relative to the Glauber-scaled $p + p$ result [6] is modeled via multiple initial state scatterings of the partons in cold nuclei. For an initial state parton distribution $dN^{(0)}(\mathbf{k})$, random elastic scattering induces further k_T broadening as shown, for example, in [9]. The possibility of hard fluctuations along the projectile path leads to a power law tail of the k_T distribution that enhances $\langle \Delta k_T^2 \rangle_\chi$ beyond the naive Gaussian random walk result $\chi\mu^2$, where $\chi = \langle n \rangle = L/\lambda$ is the cold nuclear opacity in terms of the path length L and the parton mean free path λ. The screening scale μ regulates the Rutherford divergence in a cold nucleus. For $\chi\mu^2 \ll k_T^2 \leq Q_{\max}^2$ the Rutherford tail leads to a logarithmic enhancement of the mean square momentum transfer $\langle \Delta k_T^2 \rangle_\chi = \chi\mu^2 \ln(1 + c\, Q_{\max}^2/\mu^2)$, where c depends on the detailed form of the kinematic cutoff. For a high energy parton with transverse momentum p_T produced in a $p + A$ reaction, $Q_{\max}^2 \sim p_T^2$. We therefore model the Cronin effect by using

$$\langle k_T^2 \rangle_{pA} \approx \langle k_T^2 \rangle_{pp} + L_A \frac{\mu^2}{\lambda} \ln(1 + c p_T^2/\mu^2) \qquad (3)$$

in the k_T broadening functions $g(\mathbf{k}_\alpha)$ in Eq. (2), taking $L_A = 4/3 R_A$ as the mean nuclear thickness traversed. Figure 1 shows that the calculation is consistent with the energy dependence $\sqrt{s} = 27.4, 38.8$ GeV [6] observed in $p + \text{W}/p + \text{Be}$ with transport parameters set as follows: $c/\mu^2 = 0.18\ /\text{GeV}^2$, $\lambda = 3.5$ fm, and $\mu^2/\lambda = 0.05\ \text{GeV}^2/\text{fm}$. These are consistent with $\mu^2/\lambda = 0.064 \pm 0.036\ \text{GeV}^2/\text{fm}$ extracted from fits to Drell-Yan data [16]. Figure 1 also shows that the expected Cronin + shadowing effect in $p + \text{W}/p + \text{Be}$ at RHIC energies

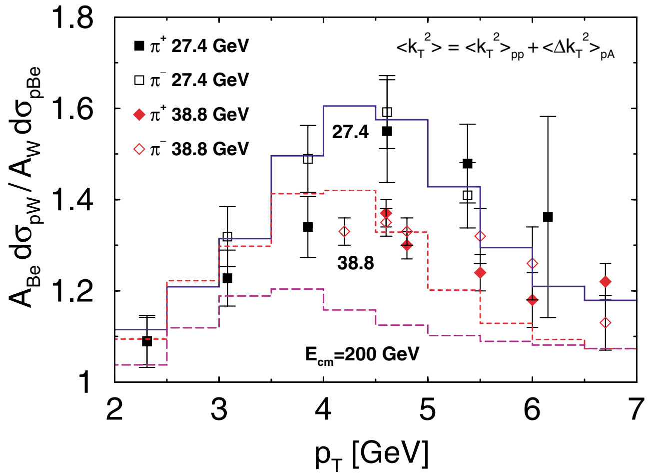

FIG. 1 (color online). The ratio of A-scaled $p + \text{W}/p + \text{Be}$ data on π^+, π^- production at $\sqrt{s} = 27.4, 38.8$ GeV from [6]. Calculations for $\frac{1}{2}(\pi^+ + \pi^-)$ include nuclear shadowing and initial parton broadening as in Eq. (3) with $\mu^2/\lambda = 0.05\ \text{GeV}^2/\text{fm}$. The anticipated $p + \text{W}/p + \text{Be}$ ratio at $\sqrt{s} = 200$ GeV is also shown.

is much smaller than at lower energies because the high-p_T pQCD spectra at $\sqrt{s_{NN}} = 200$ GeV are considerably less steep.

The effects of multiple scattering and nuclear shadowing in $d + \text{Au}$ and $\text{Au} + \text{Au}$ *without* final state interactions at SPS, RHIC, and LHC are shown in Fig. 2 for neutral pions. The numerical results for charged particles are comparable. Variations arise from the different partonic contribution and the correspondingly different shadowing for various hadron species [13]. In our model of the Cronin effect, the enhancement in $\text{Au} + \text{Au}$ at SPS energies of $\sqrt{s_{NN}} = 17$ GeV may reach a factor ~ 4 at $p_T \simeq 4$–5 GeV. This is greater than observed in $\text{Pb} + \text{Pb}$ reactions and also greater than estimated with the Cronin model of Ref. [8]. Unfortunately, at these low energies the results are extremely sensitive to model assumptions due the very rapid falloff of the partonic spectra. We note that, at least within our model, there is room for hadron suppression due to energy loss even at SPS. At RHIC for $\sqrt{s_{NN}} = 200$ GeV the Cronin enhancement spans the $p_T = 1$–8 GeV range and is seen to peak at $p_T \simeq 3$ GeV. Its maximum value in $d + \text{Au}$ and $\text{Au} + \text{Au}$ is 1.3 (1.6), respectively. Similar and even smaller magnitudes of the Cronin effect at RHIC have been discussed in [17]. At higher transverse momenta, the effects of isospin and shadowing lead to $R_{BA} \simeq 0.8$ at $p_T \simeq 20$ GeV. At LHC energies of $\sqrt{s_{NN}} = 5500$ GeV, Cronin effect is overwhelmed by shadowing at small x ($p_T < 10$ GeV) and antishadowing at larger x when the EKS98 [15] parametrization is used. The net nuclear modification due to Cronin effect and shadowing at LHC is expected to be tiny ($\lesssim 15\%$) throughout the p_T range shown.

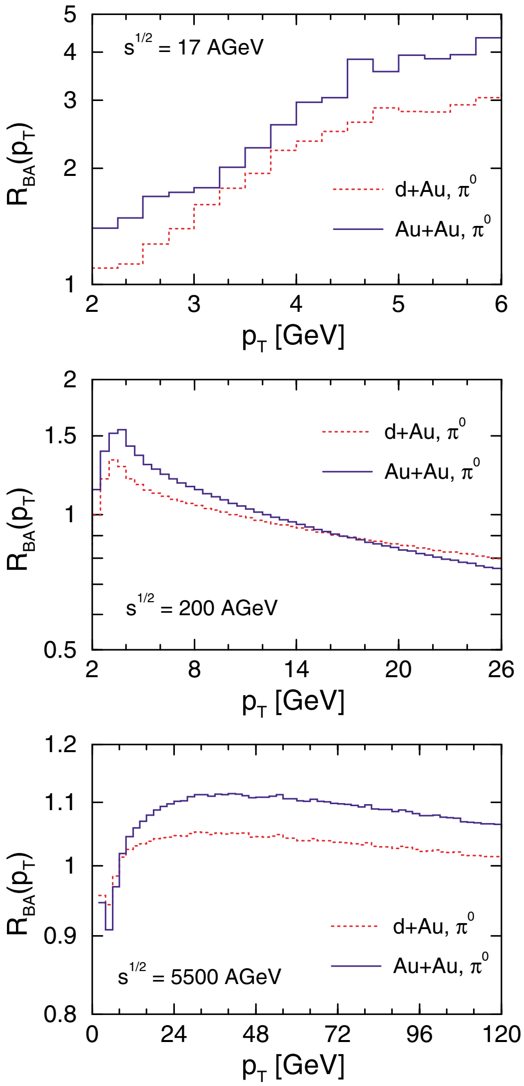

FIG. 2 (color online). The nuclear modification $R_{BA}(p_T)$ due to Cronin effect and shadowing (but not energy loss) for π^0 in $d + \mathrm{Au}$ ($B = d, A = \mathrm{Au}$) and central Au + Au ($B = A = \mathrm{Au}$) reactions at $\sqrt{s_{NN}} = 17$, 200, and 5500 GeV.

We turn next to the predicted suppression effects in nucleus-nucleus reactions due to jet quenching [7]. In Eq. (2) this is taken into account in the fragmentation function via the modification of the momentum fraction carried away by the leading hadron. If a jet of momentum p_c prior to hadronization loses a fraction $0 \leq \epsilon < 1$ of its energy, then $z = p_h/p_c \to z^* = z/(1 - \epsilon)$. The distribution $P(\epsilon, E)$ of the fractional energy loss of a fast parton with energy E due to multiple gluon emission is computed as in Gyulassy-Levai-Vitev [2].

We compute $P(\epsilon, E)$ taking into account the longitudinal Bjorken expansion the plasma (gluon) density $\rho(\tau) = (\tau_0/\tau)\rho(\tau_0)$, where $\tau_0\rho_0 = (1/\pi R_A^2) dN^g/dy$ relates to the gluon rapidity density produced in central $A + A$ that fixes the initial opacity. It has been shown that the azimuthally averaged energy loss is insensitive to transverse expansion [18]. The mean number of radiated gluons $\langle N^g(E)\rangle$ remains small due to the plasmon mass cutoff $\omega_{\mathrm{pl}} \sim 0.5$ GeV [2]. Therefore, there is a finite $n = 0$ (no radiation) contribution $P_0(\epsilon, E) = e^{-\langle N^g(E)\rangle}\delta(\epsilon)$. We have checked the sensitivity of the results to reducing the plasmon mass by a factor of 2. This was found to lead to $\sim$25% more suppression at $p_T = 5$ GeV and to $<$10% increased suppression at $p_T = 20$ GeV for RHIC energies.

Our main results for central Au + Au including all three nuclear effects (Cronin + shadowing + quenching) are presented in Fig. 3. Jet tomography consists of determining the effective initial gluon rapidity density dN^g/dy that best reproduces the quenching pattern of the data [8,19–21]. At SPS the large Cronin enhancement is reduced by a factor of 2 with $dN^g/dy = 350$, but the data are more consistent with a smaller gluon density $\lesssim 200$. Unfortunately, as emphasized above, at

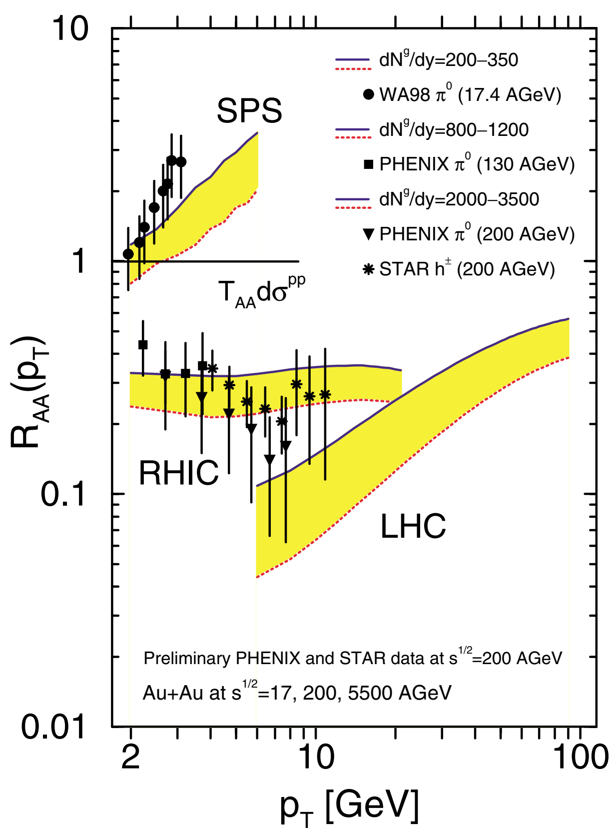

FIG. 3 (color online). The suppression/enhancement ratio $R_{AA}(p_T)$ ($A = B = \mathrm{Au}$) for neutral pions at $\sqrt{s_{NN}} = 17$, 200, and 5500 GeV. Solid (dashed) lines correspond to the smaller (larger) effective initial gluon rapidity densities at given $\sqrt{s}$ that drive parton energy loss. Data on π^0 production in central Pb + Pb at $\sqrt{s_{NN}} = 17.4$ GeV from WA98 [8] and in central Au + Au at $\sqrt{s_{NN}} = 130$ GeV [19], as well as *preliminary* data at 200 GeV [20] from PHENIX and $h^{\pm}$ central/peripheral data from STAR [21] are shown. The sum of estimated statistical and systematic errors are indicated.

this low energy the results are very sensitive to the details of the model. At RHIC, for $p_T > 2$ GeV jet quenching dominates, but surprisingly the rate of variation with p_T of the Cronin enhancement and jet quenching conspire to yield an approximately constant suppression pattern with magnitude dependent only on the initial dN^g/dy. At higher $p_T > 20$ GeV, the softening of the initial jet spectra due to the EMC modification of the PDFs compensates for the reduced energy loss. This unexpected interplay between the three nuclear effects at RHIC is the main prediction of this Letter. At LHC energies, the much larger gluon densities $dN^g/dy \sim 2000$–3500 are expected to lead to a dramatic variation of quenching with p_T as shown.

In nuclear media of high opacity, the mean fractional energy loss $\langle \Delta E \rangle / E$ of moderately hard partons can become on the order of unity. For LHC this may be reflected in the $p_T \leq 10$ GeV region through deviations from the extrapolated high-p_T suppression trend. Hadronic fragments coming from energetic jet would tend to compensate the rapidly increasing quenching (seen in Fig. 3) with decreasing transverse momentum and may restore the hydrodynamiclike participant scaling in the soft regime.

Conclusions.—In this Letter, we predicted a characteristic evolution pattern of the *magnitude* and the p_T *dependence* of the nuclear modification factor in $d + A$ and $A + A$ reactions as a function of the center of mass energy per nucleon. A systematic approach was used to take into account Cronin effect, nuclear shadowing, as well as jet quenching. Our results suggest that at SPS energies the Cronin enhancement may be larger than expected previously, leaving room for moderate energy loss. At RHIC, we predict that the three nuclear effects in central Au + Au lead to a surprising approximately constant suppression pattern of π^0 with $R_{AA}(p_T) \simeq 0.3$–0.2 for $dN^g/dy \sim 800$–1200. We emphasize that none of the nuclear effects alone would lead to such a flat $R_{AA}(p_T)$. At LHC, shadowing and Cronin effect in the $6 \leq p_T \leq 100$ GeV range were found to be essentially negligible, leading to $\leq 15\%$ correction, while the jet quenching was predicted to be large and with a strong p_T dependence. We emphasize the importance of future d + Au data at RHIC to isolate and test the initial state Cronin and shadowing effects predicted in Fig. 2. While it is still too early to draw conclusions from the preliminary data [20,21] shown in Fig. 3, the combined future analysis of d + Au and Au + Au high-p_T measurements will improve the tomographic determination of the initial gluon densities produced at RHIC.

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