Suppression of the High-p_T Charged-Hadron R_{AA} at the LHC

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We present a parameter-free postdiction of the high-p_T charged-hadron nuclear modification factor (R_{AA}) in two centralities, measured by the CMS Collaboration in Pb-Pb collisions at the LHC. The evolution of the bulk medium is modeled using viscous fluid dynamics, with parameters adjusted to describe the soft hadron yields and elliptic flow. Assuming the dominance of radiative energy loss, we compute the medium modification of the R_{AA} using a perturbative QCD-based formalism, the higher twist scheme. The transverse momentum diffusion coefficient $\hat{q}$ is assumed to scale with the entropy density and is normalized by fitting the R_{AA} in the most central Au-Au collisions at the Relativistic Heavy-Ion Collider. This setup is validated in noncentral Au-Au collisions at the Relativistic Heavy-Ion Collider and then extrapolated to Pb-Pb collisions at the LHC, keeping the relation between $\hat{q}$ and entropy density unchanged. We obtain a satisfactory description of the CMS R_{AA} over the p_T range from 10 to 100 GeV.

Jet quenching, or the modification of hard jets in a dense extended medium, is one of the most studied discoveries at the Relativistic Heavy-Ion Collider (RHIC) [1]. Numerous experiments have established the suppression of high transverse momentum (high-p_T) hadrons [2] at RHIC energies. There now exist volumes of theoretical calculations based on both perturbative QCD (pQCD) [3] and the AdS/CFT conjecture [4] aiming to describe jet modification at RHIC. Collisions of heavy ions at the LHC, as measured by all three detectors (ATLAS, ALICE, CMS), have demonstrated significant evidence for the modification of hard jets [5–7].

Before any such measurement may be applied to the detailed study of the structure of the dense medium, theoretical calculations must be able to describe the basic jet quenching observables. A standard jet quenching measure, as established by the RHIC experiments, is the nuclear modification factor R_{AA}, defined as,

$$R_{AA} = \frac{\frac{d^2 N_{AA}(b_{\min}, b_{\max})}{dp_T^2 dy}}{N_{\mathrm{bin}}(b_{\min}, b_{\max}) \frac{d^2 N_{pp}}{dp_T^2 dy}}. \qquad (1)$$

In the equation above, $d^2 N_{AA}(b_{\min}, b_{\max})$ represents the yield of hadrons in narrow bins of p_T, rapidity (y), and centrality (designated by a range of impact parameters $b_{\min}$ to $b_{\max}$) of the heavy-ion collision. In the denominator, N_{bin} represents the number of binary nucleon-nucleon collisions in the same centrality bin and $d^2 N_{pp}$ represents the yield of hadrons in p-p collisions, in the same bin of p_T and y. So far both ALICE and CMS have reported the R_{AA} of charged hadrons at the LHC [6,7].

In this Letter, we present a parameter-free comparison with the 0%–5% and 10%–30% CMS data [7]. The calculation consists of two factorized parts: a fluid dynamical simulation whose initial conditions and transport coefficients were tuned to describe the hadron spectrum and

elliptic flow at $p_T < 2$ GeV in Au-Au collisions at RHIC and successfully extrapolated to Pb-Pb collisions at the LHC [8], and a pQCD-based radiative energy loss calculation which computes the medium modified spectrum of high-p_T hadrons. Unlike soft hadrons, these hard hadrons will be assumed to stem from the fragmentation of hard jets, modified due to passage through the medium.

By "parameter-free" we mean that the transverse momentum diffusion coefficient $\hat{q}$, which controls the amount of radiative energy loss encountered by a hard jet, will be related to intrinsic quantities in the fluid dynamics simulation which are entirely controlled by the soft hadron observables. In this case, it will be scaled with the temperature dependent entropy density s:

$$\hat{q}(\vec{r}, t) = \hat{q}_0 s(T(\vec{r}, t)) / [s(T_0)\sqrt{1 - v_\perp^2(\vec{r}, t)}], \qquad (2)$$

where q_0 refers to the value of the transport coefficient at the highest RHIC temperature of $T_0 = 344$ MeV, reached at the center of the 0%–5% central Au-Au collisions at 0.6 fm/c, and $v_\perp$ refers to the local flow velocity transverse to the jet. Once related to temperature in this way, $\hat{q}$ is completely controlled by the fluid dynamics simulation at any point in space-time, in any collision at any energy or centrality. Given Eq. (2), the space-time dependent entropy density in the simulation for LHC energies will predict the value of $\hat{q}$ at any space-time point.

The remaining Letter is organized as follows: after a brief review of the essential features of the higher twist method to describe parton energy loss, we discuss specific ingredients of the current calculation. This will be followed by a comparison to R_{AA} in central and semicentral collisions at RHIC (i.e., Au-Au at $\sqrt{s} = 200$ GeV/nucleon), as well as the in- and out-of-plane R_{AA} in semicentral RHIC events; $\hat{q}_0$ will be dialed to obtain a best fit to this data.

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Following this the R_{AA} will be computed for 0%–5% and 10%–30% centrality events at the LHC (i.e., Pb-Pb at $\sqrt{s} = 2.76$ TeV). We will conclude with a discussion of possible reasons why the theory underpredicts the R_{AA} at $p_T \lesssim 8$ GeV at the LHC.

It will be assumed that processes such as the production of high-p_T hadrons which engender a hard scale ($Q \gg \Lambda_{\rm QCD}$) through much of their space-time evolution may be computed using pQCD. Furthermore, the hard scale allows for the use of factorization, effectively separating soft subprocesses from the part where the scales involved are hard [9]. In such a factorized formalism, the invariant cross section to produce a high-p_T hadron in a heavy-ion collision may be expressed as

$$\frac{d\sigma^{AA}(p_T, y)_{b_{\min}}^{b_{\max}}}{dy d^2 p_T} = K \int_{b_{\min}}^{b_{\max}} d^2 b \int d^2 r t_A(\vec{r}) t_B(\vec{r} - \vec{b})$$
$$\times \int dx_a dx_b G_a^A(x_a, Q^2) G_b^B(x_b, Q^2)$$
$$\times \frac{d\hat{\sigma}_{ab \to cd}}{d\hat{t}} \frac{\tilde{D}_c^h(z, Q^2, \zeta_L(\vec{r}, \theta_j), \hat{p}_c)}{\pi z}. \quad (3)$$

In the equation above, y, $\vec{p}_T$ represents the rapidity and transverse momentum of the detected parton, K is a multiplicative factor to account for higher order

corrections, $\vec{r}$ is the location of the jet production vertex, $t_{A/B}(\vec{r} \pm \vec{b}/2)$ is the nuclear thickness function $[t_A(\vec{r} + \vec{b}/2) = \int dz \rho(\vec{r} + \vec{b}/2, z)$ with $\rho(\vec{r}, z)$ the nucleon density inside a nucleus], $x_a(x_b)$ represents the momentum fractions of the incoming partons, $Q^2 \sim p_T^2$ is the hard scale of the process, $G_{a/b}^{A/B}(x_a, Q^2)$ is the nuclear parton distribution function, $d\hat{\sigma}_{ab \to cd}/d\hat{t}$ is the short distance cross section for incoming partons a, b to scatter and produce partons c, d with a squared momentum transfer $\hat{t} = (\hat{p}_c - \hat{p}_a)^2$, $\tilde{D}$ represents the medium modified fragmentation with hadronic momentum fraction $z = p_T/p_{cT}$, and $\zeta_L(r, \theta_j)$ is the distance traveled by a jet produced at $\vec{r}$ and propagating at an angle θ_j with respect to the reaction plane. Both $\vec{b}$ and $\vec{r}$ are two-dimensional vectors transverse to the beam direction. All calculations will be carried out at midrapidity ($y = 0$).

In this effort we will ignore shadowing corrections, both at LHC and at RHIC. This will give the calculated RHIC R_{AA} a slightly rising slope with p_T, compared to previous calculations. The medium modified fragmentation function is calculated by solving an in-medium Dokshitzer-Gribov-Lipatov-Altarelli-Parisi evolution equation [10] valid when $Q^2 \gg \hat{q}\tau_f$ (where, $\tau_f \sim p/Q^2$ is the lifetime of a parton with energy p and virtuality Q^2, undergoing a split),

$$\frac{\partial \tilde{D}_c^h(z, Q^2, \hat{p}_c)|_{\vec{r}}^{\vec{r}+\hat{n}\zeta_L}}{\partial \log Q^2} = \frac{\alpha_s}{2\pi} \int_z^1 \frac{dy}{y} \tilde{P}(y) \left[\tilde{D}_c^h\left(\frac{z}{y}, Q^2, \hat{p}_c\right)_{\vec{r}}^{\vec{r}+\hat{n}\zeta_L} + \int_{\vec{r}}^{\vec{r}+\hat{n}\zeta_L} d\zeta K_{\hat{p}_c, Q^2}^{\vec{r}, \theta_j}(y, \zeta) D_q^h\left(\frac{z}{y}, Q^2, \hat{p}_c y\right) \Big|_{\vec{r}+\hat{n}\zeta}^{\vec{r}+\hat{n}\zeta_L} \right], \quad (4)$$

where, $\tilde{P}(y)$ is the Altarelli-Parisi splitting function for a parton c to split into two other partons which carry y and $1 - y$ fractions of the momentum of c. The in-medium single emission kernel $K_{\hat{p}_c, Q^2}^{\vec{r}, \theta_j}$ [11] is given as

$$K_{\hat{p}_c, Q^2}^{\vec{r}, \theta_j} = \frac{\hat{q}}{Q^2}(\vec{r} + \hat{n}\zeta)\left[2 - 2\cos\left\{\frac{Q^2(\zeta)}{2\hat{p}_c y(1 - y)}\right\}\right], \quad (5)$$

involving the space-time dependent transport coefficient $\hat{q}$ introduced in Eq. (2).

As stated in Eq. (2), the jet transport parameter depends on the local entropy density s. The entropy density is obtained from a 2 + 1D viscous fluid dynamical simulation where the input parameters, such as the magnitude of the components of the initial energy momentum tensor as well as the viscosity and the final freeze-out criteria, are tuned to obtain the best fit with the spectra and elliptic flow of hadrons with $p_T \lesssim 2$ GeV. As this Letter will deal solely with the spectra and azimuthal anisotropy at high p_T ($p_T \gtrsim 6$ GeV), we will only provide the most salient features of these simulations in the current Letter and direct the reader to Refs. [12,13] for further details.

In the fluid dynamical simulations used, the thermalization time is $\tau_0 = 0.6$ fm/c for both RHIC and LHC collisions. Initial conditions are based on the

Kharzeev-Levin-Nardi [14] parametrization of the collision of two nuclei with saturated gluon distributions [12]. The jets are assumed to be produced according to a binary collision profile at the moment of collision, i.e., at $t_0 = 0$. For times between t_0 and τ_0, the conditions at τ_0 are extrapolated back to $t_0 = 0$ fm/c unchanged; i.e., we assume that the soft medium remains unchanged from 0 to 0.6 fm/c.

Like prior calculations of jet modification in a fluid dynamical setup, the hadronic phase is also simulated as a viscous fluid and not in terms of a hadronic cascade. While such hybrid calculations are currently available, we have picked the simplest simulation for this attempt to calculate the R_{AA} at the LHC. As we use the entropy density to scale the local value of $\hat{q}$, there is no extra rescaling factor for the hadronic phase as in prior attempts where $\hat{q}$ was scaled with T^3 [15,16]. The produced jets are assumed to decouple from the medium when the local temperature reaches 160 MeV. Given the above conditions, a space-time profile for $\hat{q}$ is obtained for jets traveling in all directions, starting at $t = 0$ at any location in the medium, and vanishing when $T(\vec{r}, t) = 160$ MeV. This profile is completely specified with the value of $\hat{q}_0 = 2.2$ GeV^2/fm at $T = 344$ MeV, which is the highest temperature reached at RHIC, at $\vec{r} = 0$ in the 0%–5%

most central collisions at $t = \tau_0$. This $\hat{q}_0$ is obtained by requiring that the computed R_{AA} in 0%–5% central collisions at $p_T = 10$ GeV is approximately 0.2.

Using this $\hat{q}$ profile, one can compute the medium modified fragmentation function $\tilde{D}$ [Eq. (4)] for jets which originate at $\vec{r}$ and travel in a given direction $\theta_j(\hat{n})$, decoupling from the medium after traveling a distance $\zeta_L(\vec{r}, \theta_j)$ [when $T(\vec{r} + \hat{n}\zeta_L, \zeta_L) = 160$ MeV], with a given initial energy $\hat{p}_c$, and a final hadron momentum specified in terms of p_T and y. The medium modified fragmentation function is obtained by solving the differential equation in Eq. (4) starting with an input vacuum fragmentation function at $Q^2 = Q^2_{min}$ and evolving up to $Q^2 = p^2_T$. The physical picture is that of a hard jet that starts with a high virtuality $Q^2 = p^2_T$ and drops down in virtuality as it splits into less virtual partons while propagating through the medium. Eventually at a $Q^2 = Q^2_{min}$ it exits the medium. Thus, there is a strong correlation between energy, virtuality, and distance traveled by the jet.

For this attempt to predict the R_{AA} at the LHC, we will make two sets of approximations which will include the correlation between energy, virtuality, and position in terms of their averages, thus providing a systematic error in extrapolating the calculations at a given p_T, centrality, and energy of collision to other systems. First, we integrate the product of the energy loss kernel K in Eq. (5) and the nuclear overlap function $[T_{AA}(\vec{b}) = \int d^2 r t_A(\vec{r} - \vec{b}/2) t_B(\vec{r} + \vec{b}/2)]$ over all jet origins and directions of exit, for all values of the ratio $Q^2/(2\hat{p}_c)$. Note that the energy loss kernel correlates location with energy $\hat{p}_c$ and virtuality Q^2 through this ratio. We then carry out the evolution in virtuality Q^2 for jets with all allowed energies using the position and jet direction integrated kernel. For each p_T of the detected hadron, $Q^2_{min} = \langle \hat{p}_c \rangle / \langle \zeta_L \rangle$, where $\langle \hat{p}_c \rangle$ is the mean energy of the parent parton in vacuum and $\langle \zeta_L \rangle$ is the mean distance traveled by the jets that escape the medium with a virtuality $Q^2 \geq Q^2_{min}$. For one set of curves (dashed lines in all plots), the mean $\hat{q}$ of the medium is calculated by averaging over all possible jet paths in the fluid medium. Then a single emission formalism (in a homogeneous static medium with the mean $\hat{q}$) is used to calculate the length ζ_{max} over which a parton with energy $\langle \hat{p}_c \rangle$ will lose all its energy. The mean path length $\langle \zeta_L \rangle$ is then calculated by averaging over paths in the fluid medium with ζ_{max} as the maximum allowed length. Since a single emission is somewhat inefficient in removing the energy from the parton, this yields a larger $\langle \zeta_L \rangle$ leading to smaller Q^2_{min} and thus an overestimate of the quenching. For hadron $p_T \sim 10$ GeV in 0%–5% collisions at RHIC, $\zeta_{max} = 5$ fm. For the other set of curves (solid lines in all plots), $\langle \zeta_L \rangle$ is calculated with the restriction that all lengths larger than 5 fm are excluded. Since jets with larger energy should penetrate deeper in the medium, this provides an underestimate of the quenching.

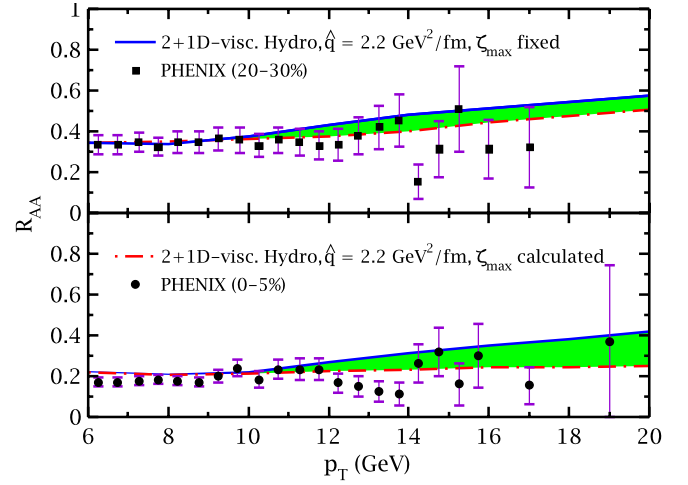With this setup, we can now calculate the invariant cross section to produce a high-p_T hadron in a heavy-ion

FIG. 1 (color online). The R_{AA} versus p_T for two centralities. The green bands represent the calculations presented in this Letter with a $\hat{q}_0 = 2.2$ GeV^2/fm. No shadowing is included and the minimum virtuality (Q^2_{min}) is set to max$\{\langle \hat{p}_c \rangle / \langle \zeta_L \rangle, 1$ GeV$^2\}$. See text for details.

collision using Eq. (3) and obtain the R_{AA} using Eq. (1). The results for RHIC are shown in Fig. 1, compared with the R_{AA} measured by PHENIX in two centrality bins (0%–5% and 20%–30%). As mentioned above, the one dimensionful parameter $\hat{q}_0$ is dialed so that the calculated R_{AA} matches the experimental value in the 0%–5% collisions at $p_T = 10$ GeV [i.e., $R_{AA}(0\%–5\%, p_T = 10$ GeV$) \simeq 0.2$]. The slope of the curve with p_T and the shift with centrality are predictions. The $\hat{q}_0$ required is 2.2 GeV^2/fm. In these calculations, $Q^2_{min} = \langle \hat{p}_c \rangle / \langle \zeta_L \rangle$ until this value drops below 1 GeV^2 wherein we hold it fixed at 1 GeV^2 (this occurs at a $p_T \lesssim 8$ GeV). Our choice of $\hat{q}_0$ is validated by comparing with the in-plane and out-of-plane R_{AA} in the 20%–30% centrality collisions as measured by PHENIX (plotted in Fig. 2). The solid black
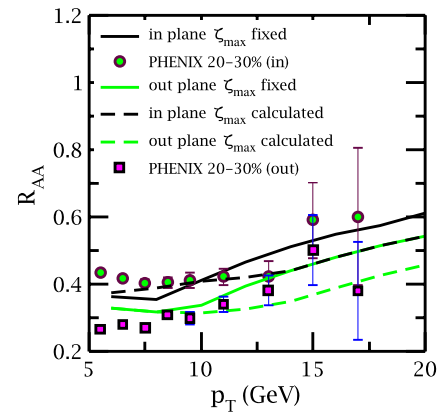

FIG. 2 (color online). A parameter free calculation of the R_{AA} in plane and out of plane in the 20–30% centrality collisions and comparison with PHENIX data for the same.
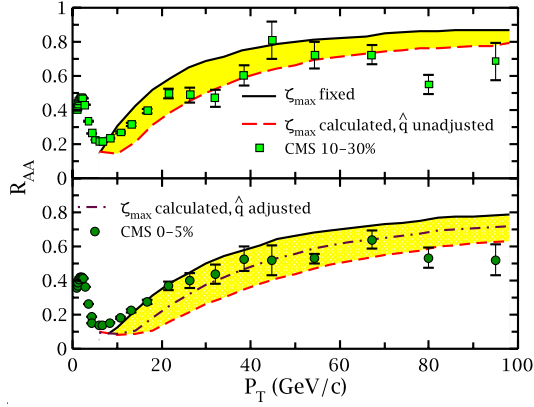
FIG. 3 (color online). A parameter-free calculation of the R_{AA} in the 0%–5% most central and 20%–30% central collisions, and comparison with CMS data for the same.

curve represents the R_{AA} for jets with θ_j chosen such that $0 < \theta_j < \pi/12$, for a case of a fixed $\langle \zeta_{\max} \rangle$. Note, $\theta_j = 0$ is the direction of $\vec{b}$. The solid gray (green) line is the R_{AA} with $5\pi/12 < \theta_j < \pi/2$, for a case of a fixed $\langle \zeta_{\max} \rangle$. The dashed black and gray (green) lines are the same calculations but with calculated $\langle \zeta_{\max} \rangle$. We obtain a good description of the data for $p_T \gtrsim 8$ GeV. For $p_T < 8$ GeV, the $Q^2_{\min} \gtrsim 1$ GeV^2 restriction begins to affect the calculation.

With the value of $\hat{q}_0$ extracted from RHIC collisions and $\hat{q}$ scaled with the entropy density of the medium, we now calculate the R_{AA} in Pb-Pb collisions at $\sqrt{s} = 2.76$ ATeV, at the LHC. In order to fit the increased charged-hadron multiplicities, one requires the fluid dynamical simulation to possess almost twice as much entropy density at thermalization as at RHIC ($T_{\max} = 436$ MeV). Also, larger velocity gradients drive the system to larger sizes than at RHIC prior to freeze-out [8]. As a result, the mean length traversed by jets escaping the medium ($\langle \zeta_L \rangle$) is larger. To obtain the R_{AA} we perform an almost identical calculation as that for RHIC energies, the sole difference being the range of available jet energies. As shown in Fig. 3, we obtain a good description of the measured R_{AA} (for both 0%–5% and 10%–30% centralities) for $p_T \gtrsim 9$ GeV. The solid and dashed lines indicate the cases of fixed and calculated $\langle \zeta_{\max} \rangle$ as before. This indicates that, in spite of the produced medium being both larger and denser, the basic jet quenching observables at high p_T at the LHC can be described in an identical pQCD-based formalism as that used at RHIC.

No doubt, future efforts will improve on various approximations made in this calculation, in particular the treatment of the correlation between energy, virtuality, and distance traveled by a parton. However, it is not clear if these corrections are the only source of the discrepancy between the calculation and the data at $p_T \sim 6$ GeV. It is entirely possible that nonperturbative phenomena such as recombination extend up to 8–9 GeV at the LHC, due to the larger flow at these energies. The extraordinarily high

densities may also enhance the magnitude of nonlinear effects in jet quenching which have so far been ignored. In order to gauge this uncertainty, we also plot the R_{AA} with a calculated $\langle \zeta_{\max} \rangle$ and adjust the $\hat{q}_0$ to obtain a better fit with the 0%–5% LHC data. This seems to require a 30% lower value of $\hat{q}_0$. Another source of correction is the drag and diffusion experienced by the partons [17], not included in this calculation.

In conclusion, we have performed a pQCD-based calculation of the suppression of the high-p_T hadron spectra due to radiative energy loss of hard partons at both RHIC and LHC. The local transport coefficient $\hat{q}$ which controls the magnitude of radiative energy loss is scaled with the entropy density. The entropy density profile of the produced matter is controlled by a $2 + 1$D viscous fluid dynamical simulation which has been tuned to describe the soft spectrum and elliptic flow. The overall normalization of $\hat{q}$ is provided by setting its value at a given T or s, in this case $\hat{q}_0 = 2.2$ GeV^2/fm at the maximum RHIC temperature of $T = 344$ MeV. With this value being set, we predict the p_T dependence of the R_{AA} in 0%–5% and 20%–30% centrality events at RHIC as well as the R_{AA} versus reaction plane, and the R_{AA} measured in 0%–5% and 20%–30% centrality events at $\sqrt{s} = 2.76$ ATeV at the LHC.

[1] I. Arsene *et al.*, Nucl. Phys. **A757**, 1 (2005); B. B. Back *et al.*, *ibid.* **A757**, 28 (2005); J. Adams *et al.*, *ibid.* **A757**, 102 (2005); K. Adcox *et al.*, *ibid.* **A757**, 184 (2005).

[2] K. Adcox *et al.*, Phys. Rev. Lett. **88**, 022301 (2001); C. Adler *et al.*, Phys. Rev. Lett. **89**, 202301 (2002).

[3] A. Majumder and M. Van Leeuwen, Prog. Part. Nucl. Phys. **66**, 41 (2011); N. Armesto *et al.*, arXiv:1106.1106; M. Gyulassy *et al.*, arXiv:nucl-th/0302077.

[4] S. S. Gubser *et al.*, arXiv:0902.4041; J. Casalderrey-Solana *et al.*, arXiv:1101.0618.

[5] G. Aad *et al.*, Phys. Rev. Lett. **105**, 252303 (2010).

[6] K. Aamodt *et al.*, Phys. Lett. B **696**, 30 (2011).

[7] S. Chatrchyan *et al.*, Eur. Phys. J. C **72**, 1945 (2012).

[8] C. Shen, U. Heinz, P. Huovinen, and H. Song, Phys. Rev. C **84**, 044903 (2011).

[9] J. C. Collins, D. E. Soper, and G. F. Sterman, Nucl. Phys. **B261**, 104 (1985); J. w. Qiu and G. F. Sterman, Nucl. Phys. **B353**, 137 (1991).

[10] A. Majumder, arXiv:0901.4516.

[11] X. F. Guo and X. N. Wang, Phys. Rev. Lett. **85**, 3591 (2000); Nucl. Phys. **A696**, 788 (2001); A. Majumder and B. Muller, Phys. Rev. C **77**, 054903 (2008); A. Majumder, Phys. Rev. D **85**, 014023 (2012).

[12] H. Song, S. Bass, U. Heinz, T. Hirano, and C. Shen, Phys. Rev. Lett. **106,** 192301 (2011); **109,** 139904(E) (2012).

[13] C. Shen, U. Heinz, P. Huovinen, and H. Song, Phys. Rev. C **82,** 054904 (2010).

[14] D. Kharzeev, E. Levin, and M. Nardi, Phys. Rev. C **71,** 054903 (2005).

[15] S. A. Bass, C. Gale, A. Majumder, C. Nonaka, G.-Y. Qin, T. Renk, and J. Ruppert, Phys. Rev. C **79,** 024901 (2009).

[16] A. Majumder, C. Nonaka, and S. A. Bass, Phys. Rev. C **76,** 041902 (2007).

[17] A. Majumder, Phys. Rev. C **80,** 031902 (2009).