Suppression of high $p_T$ hadrons in $Pb + Pb$ Collisions at LHC

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Nuclear modification factor $R_{AA}(p_T)$ for large transverse momentum pion spectra in $Pb + Pb$ collisions at $\sqrt{s} = 2.76$ TeV is predicted within the NLO perturbative QCD parton model. Effect of jet quenching is incorporated through medium modified fragmentation functions within the higher-twist approach. The jet transport parameter that controls medium modification is proportional to the initial parton density and the coefficient is fixed by the RHIC data on suppression of large $p_T$ hadron spectra. Data on charged hadron multiplicity $dN_{ch}/d\eta = 1584 \pm 80$ in central $Pb + Pb$ collisions from the ALICE Experiment at the LHC are used to constrain the initial parton density both for determining the jet transport parameter and the 3+1D ideal hydrodynamic evolution of the bulk matter that is employed for the calculation of $R_{PbPb}(p_T)$ for neutral pions.

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I. INTRODUCTION

One important evidence for the formation of strongly coupled quark-gluon plasma (QGP) in high-energy heavy-ion collisions at the Relativistic Heavy Ion Collider (RHIC) is the observation that the produced dense matter is opaque to a propagating parton due to jet quenching which suppresses not only the single inclusive hadron spectra at large transverse momentum but also back-to-back high $p_T$ dihadron and $\gamma$-hadron correlation. These observed jet quenching patterns in heavy-ion collisions at RHIC can be described by perturbative QCD (pQCD) parton models well that incorporate parton energy loss, as it propagates through dense matter. Since the energy loss or medium modification of the effective jet fragmentation functions depends on the space-time profile of parton density in the medium, any systematic and qualitative extraction of the properties of the medium through phenomenological study of jet quenching has to take into account the dynamical evolution of the bulk matter. The initial condition for the evolution of bulk matter is either provided by model calculation or experimental data on the total charged hadron multiplicity. Without any experimental data on hadron production in heavy-ion collisions at the Large Hadron Collider (LHC), all predictions for jet quenching have to rely on theoretical or phenomenological models on the initial conditions for parton production and evolution. However, these theoretical and phenomenological predictions for the bulk hadron production vary by almost a factor of two and, consequently, lead to the same amount of uncertainties in the predictions for suppression of large transverse momentum hadrons in heavy-ion collisions at LHC.

Recently, ALICE Experiment at LHC published the first experimental data on the charged hadron multiplicity density at mid-rapidity in central $Pb + Pb$ collisions at $\sqrt{s} = 2.76$ TeV. The measured $dN_{ch}/d\eta = 1584 \pm 4$(stat.) $\pm 76$(sys.) for the top 5% central $Pb + Pb$ collisions is larger than most of theoretical predictions, especially those from the so-called color-glass-condensate models. Such an unexpected large hadron multiplicity will have important consequences on theoretical predictions for jet quenching in $Pb + Pb$ collisions at the LHC energies. The predictions for single and dihadron suppression in the most central $Pb + Pb$ collisions at $\sqrt{s} = 5.5$ TeV by Wang, Wang and Zhang relied on the modified HIJING calculation of the charged hadron multiplicity in heavy-ion collisions at the LHC. The modification has now been incorporated into HIJING 2.0 version of the original HIJING1.0 model. The new HIJING2.0 results agree well with the first ALICE data within experimental errors and theoretical uncertainty which is controlled mainly by the uncertainty in nuclear shadowing of gluon distribution in nuclei.

With the first ALICE data providing more stringent constraints on the theoretical uncertainty in the bulk hadron production, we would like to revisit the predictions on suppression of single inclusive hadron spectra at large $p_T$ in heavy-ion collisions at LHC. Moreover, we will use the 3+1D ideal hydrodynamic model for more realistic description of the bulk matter evolution whose initial conditions at LHC are also much better constrained by the first ALICE data.

The rest of the paper is organized as follows. In the next section, we will provide a brief overview of the pQCD parton model for single inclusive hadron spectra and the high-twist (HT) approach to the medium modified fragmentation functions. In Sec. III, we will give a brief description of the 3+1D ideal hydrodynamic model for the bulk evolution with initial condition provided by HIJING2.0 model and further constrained by the first ALICE data. In Sec. IV, we present predictions for the nuclear modification factor $R_{AA}(p_T)$ for neutral pions in $Pb + Pb$ collisions at LHC energy $\sqrt{s} = 2.76$ TeV/$n$ and discuss about first LHC data for the charged hadrons from the ALICE Experiment. We will give a summary and discussion in Sec. V.
II. PQCD PARTON MODEL AND MEDIUM-MODIFIED FRAGMENTATION FUNCTIONS

We will employ the next leading order (NLO) pQCD parton model for the initial jet production spectra which has been shown to work well for large pr hadron production in high energy nucleon-nucleon collisions [33]. We use the same factorized form for the inclusive particle production cross section in the initial jet is implicated over the azimuthal angle of the initial jet is implic-ation distribution functions inside the nuclei (nucleons), elementary parton-parton scattering cross sections and effective parton fragmentation functions,

\[
\frac{d\sigma_{ab}}{dyd^2p_T} = \sum_{abcd} \int d^2b^2 rdx_adb t_B(r) t_B(r-b) \\
\times f_{a/A}(x_a, \mu^2) f_{b/B}(x_b, \mu^2) \frac{d\sigma}{dt}(ab \rightarrow cd) \\
\times \frac{D_{h/f}(z_c, E, b, r)}{\pi z_c} + O(\alpha_s^3),
\]

where \(d\sigma(ab \rightarrow cd)/dt\) are elementary parton scattering cross sections at leading order (LO) \(\alpha_s^2\). The average over the azimuthal angle of the initial jet is implicitly implied in the above equation since we focus on azimuthal integrated single inclusive hadron cross section. The NLO contributions include 2 to 3 tree level contributions and 1-loop virtual corrections to 2 to 2 tree processes [33]. The nuclear thickness function is normalized to \(\int d^2r t_A(r) = A\). The nuclear parton distributions per nucleon \(f_{a/A}(x_a, \mu^2, r)\) are assumed to be factorized into the parton distributions in a free nucleon \(f_{a/N}(x, \mu^2)\) and the nuclear shadowing factor \(S_{a/A}(x, \mu^2, r)\),

\[
f_{a/A}(x, \mu^2, r) = S_{a/A}(x, \mu^2, r) \frac{Z_A}{A} f_{a/p}(x, \mu^2) \\
+ \left(1 - \frac{Z}{A}\right) f_{a/n}(x, \mu^2),
\]

where \(Z\) is the charge and \(A\) the mass number of the nucleus. The CTEQ6M parameterization [34] for parton distribution functions will be used for nucleon parton distributions \(f_{a/N}(x, \mu^2)\). The parton shadowing factor \(S_{a/A}(x, \mu^2, r)\) describes the nuclear modification of parton distributions per nucleon inside a nucleus and can be given by parameterizations [33]. With an impact-parameter-dependent parton shadowing the effect of shadowing is the strongest for hard scatterings at the center of the transverse plane. But partons from these hard scatterings at the center are mostly quenched due to parton energy loss and do not contribute to the final hadron spectra. Therefore, the effect of parton shadowing is negligible for the final hadron spectra in \(A + A\) collisions that are dominated by hard scattering close to the surface of the overlapping nuclei [30]. We will set \(S_{a/A}(x, \mu^2, r) = 1.0\) in the calculation. Effect of jet quenching in dense medium in heavy-ion collisions will be described by effective medium modified parton fragmentation functions \(\hat{D}_{f}^h(z_h, Q^2, E, b, r)\) within the HT approach.

Within the generalized factorization of twist-four processes, one can calculate the parton energy loss and medium modified fragmentation functions of a propagating parton in the medium after it is produced via a hard process [37, 38]. Within such a high-twist approach, the medium modification to the parton fragmentation functions is caused by multiple scattering inside the medium and induced gluon bremsstrahlung. The medium modified quark fragmentation functions take a form very similar to the vacuum bremsstrahlung corrections that lead to the evolution equations in pQCD for fragmentation functions, except that the medium modified splitting functions, \(\Delta_{f - \gamma g}(z, \ell_T^2)\) and \(\Delta_{f - g g}(z, \ell_T^2) = \Delta_{f - g g}(1 - z, \ell_T^2)\) depend on the properties of the medium via the jet transport parameter \(\hat{q}\).

\[
\hat{q} = \rho \int dq_T^2 \frac{d\sigma}{dq_T^2} q_T^2.
\]

or the average squared transverse momentum broadening per unit length, which is also related to the gluon density of the medium [39, 40]. The corresponding quark energy loss can be expressed as [26, 39],

\[
\frac{\Delta E}{E} = \frac{2N_c\alpha_s}{\pi} \int dy^+ dz^+ d\ell_T^2 \frac{1 + z^2}{\ell_T^2} \\
\times \left(1 - \frac{1 - z}{2}\right) \hat{q}(E, y) \sin^2 \left[\frac{\gamma - \ell_T^2}{4Ez(1 - z)}\right],
\]

in terms of the jet transport parameter. Note that we include an extra factor of \((1 - z)/2\) as compared to that used in Refs. [39, 41] due to corrections beyond the helicity amplitude approximation [38]. We refer readers to Ref. [26] for details of the modified fragmentations. The fragmentation functions \(D_{h/f}^h(q_c, \mu^2)\) in the vacuum are given by the updated AKK parametrization [42].

According to the definition of jet transport parameter, we can assume it to be proportional to local parton density in a QGP and hadron density in a hadronic gas. Therefore, in a dynamical evolving medium, one can express it in general as

\[
\hat{q}(\tau, r) = \left[\hat{q}_0 \frac{\rho_{QGP}(\tau, r)}{\rho_{QGP}(\tau, 0)} (1 - f) + \hat{q}_h(\tau, r) f\right] \cdot \frac{d^\mu u_\mu}{p_0},
\]
where $\rho_{\text{QGP}}$ is the parton (quarks and gluon) density in an ideal gas at a given temperature, $f(\tau, r)$ is the fraction of the hadronic phase at any given space and time, $\hat{q}_0$ denotes the jet transport parameter at the center of the bulk medium in the QGP phase at the initial time $\tau_0$, $p^\mu$ is the four momentum of the jet and $u^\mu$ is the four flow velocity in the collision frame. We assume the hadronic phase of the medium is described as a hadron resonance gas, in which the jet transport parameter is approximated as,

$$\hat{q}_h = \frac{\hat{q}_N}{\rho_N} \left[ \frac{2}{3} \sum_M \rho_M(T) + \sum_B \rho_B(T) \right], \quad (7)$$

where $\rho_M$ and $\rho_B$ are the meson and baryon density in the hadronic resonance gas at a given temperature, respectively, $\rho_N = n_0 \approx 0.17 \text{ fm}^{-3}$ is the nucleon density in the center of a large nucleus and the factor $2/3$ accounts for the ratio of constituent quark numbers in mesons and baryons. The jet transport parameter at the center of a large nucleus $\hat{q}_h$ has been studied in deeply inelastic scattering (DIS) [43–45]. We use a recently extracted value [44] $\hat{q}_N \approx 0.02 \text{ GeV}/\text{fm}$ from the HERMES [46] experimental data. The hadron density at a given temperature $T$ and zero chemical potential is

$$\rho_h(T) = \frac{T^3}{2\pi^2} \left( \frac{m_h}{T} \right)^2 \sum_{n=1}^{\infty} \eta_n^{n+1} nK_2\left( n \frac{m_h}{T} \right), \quad (8)$$

where $\eta_n = \pm$ for meson (M)/baryon (B). In the paper, we will include all hadron resonances with mass below 1 GeV.

III. 3+1D IDEAL HYDRODYNAMIC EVOLUTION OF BULK MATTER

In the model for medium modified fragmentation functions as described in the last section, one needs information on the space-time evolution of the local temperature and flow velocity in the bulk medium along the jet propagation path. We will use a full three-dimensional 3+1D ideal hydrodynamics in our calculation to describe the space-time evolution of the bulk matter in heavy-ion collisions.

We solve equations of energy-momentum conservation in full 3+1D space ($\tau, x, y, \eta$) under the assumption that local thermal equilibrium is reached at an initial time $\tau_0 = 0.6 \text{ fm/c}$ and maintained thereafter until freeze-out. Here $\tau, \eta, x,$ and $y$ are proper time, space-time rapidity, and two transverse coordinates perpendicular to the beam axis, respectively. Ideal hydrodynamics is characterized by the energy-momentum tensor,

$$T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu - Pg^{\mu\nu}, \quad (9)$$

where $\epsilon, P$ and $u^\mu$ are energy density, pressure and local four velocity, respectively. We neglect the finite net-baryon density which is supposed to be small both at RHIC and LHC energies. For the quark-gluon plasma (QGP) phase at high temperature ($T > T_c = 170 \text{ MeV}$), we use the equation of state (EOS) of a relativistic massless parton gas ($u, d, s$ quarks and gluons) with a bag pressure $B$:

$$p = \frac{1}{3}(\epsilon - 4B). \quad (10)$$

The bag constant is tuned to be $B^{1/4} = 247 \text{ MeV}$ to match the pressure of the QGP phase to that of a hadron resonance gas at critical temperature $T_c = 170 \text{ MeV}$. Below the critical temperature $T < T_c$, a hadron resonance gas model including all hadrons up to the mass of the $\Delta(1232)$ is employed for the EOS. The hadron resonance gas EOS employed in this study implements chemical freeze-out at $T_{ch} = 170 \text{ MeV}$ [48] so that evolution of chemically frozen, but thermally equilibrated hadronic matter is described. In the calculation of parton energy loss and medium modified fragmentation functions, jets propagate along a straight path in the evolving medium until the decoupling of the medium at $T^{\text{dec}} = 100 \text{ MeV}$.

For the initial condition of the longitudinal flow velocity, Bjorken’s scaling solution [49] is employed. The initial entropy distribution in the transverse plane is proportional to a linear combination of the number density of participants, $n_{\text{part}}$, and that of binary collisions, $n_{\text{coll}}$. The proportionality constant and the fraction of soft and hard components are so chosen that the centrality dependence of charged particle multiplicity agrees with the experimental data at RHIC [50] and HIJING2.0 results at the LHC energy [51] which agree with the recent ALICE data for the most central Pb+Pb collisions at $\sqrt{s} = 2.76 \text{ TeV}$ [28]. Shown in Fig. I is the hydrodynamic calculation (solid square) of the charged hadron multiplicity density at mid-rapidity as compared with the HIJING2.0 result (solid circle).

We will use these hydrodynamic solutions to provide values of temperature and flow velocity along the trajectory of parton propagation for the evaluation of local jet transport parameter in Eq. (6) for the calculation of medium modified fragmentation functions. The hydrodynamic results obtained in this way such as temperature and energy density at each space-time position are publicly available [51]. Note that these hydrodynamic results provide the evolution of the space-time profiles of jet transport parameter and gluon density relative to their values at the center of overlapped region of dense matter ($r = 0$) in the most central collisions ($b = 0$) at an initial time $\tau_0$. The normalization of the initial values at $\tau_0$ and $r = 0, b = 0$ is included in the value of $\hat{q}_0$. It should be proportional to the initial parton density, which in turn is determined by fitting the final charged hadron multiplicity density in mid-rapidity (see Fig. I) of the hydrodynamics results. Therefore, approximately,

$$\hat{q}_0 \propto \frac{1}{\pi \tau_0 R_A^2} \frac{dN_{ch}}{d\eta}, \quad (11)$$

We determine the coefficient of the above relation by fit-
NLO program, the factorization scale and the renormalization scale in our study. In this approach, we have determined \( \hat{q}_0 \tau_0 \) and are all proportional to the transverse momentum of the final hadron by 

\[
\frac{dN_{ch}/d\eta}{N_{part}} = 1584 \pm 4(\text{stat.}) \pm 76(\text{sys.})
\]

in the most central 5\% \( Pb + Pb \) collisions at \( \sqrt{s} = 2.76 \) TeV versus \( dN_{ch}/d\eta = 687 \pm 37 \) for 0-5\% \( Au + Au \) collisions at \( \sqrt{s} = 0.2 \) TeV [32]. We obtain the extrapolated value \( q_0 \tau_0 = 1.0 - 1.4 \) GeV\(^2\) for \( Pb + Pb \) collisions at \( \sqrt{s} = 2.76 \) TeV. Shown in Fig. 2 is the predicted nuclear modification factor for pion spectra in the 0-5\% central \( Pb + Pb \) collisions at \( \sqrt{s} = 2.76 \) TeV. The suppression factor increases with \( p_T \) partially because of the energy dependence of parton energy loss and partially because of the less steep initial jet production spectra [34]. This trend is similar to almost all LHC predictions by many other parton energy loss model calculations [27].

We also show in Fig. 2 the recently published ALICE data [52] (filled square) on the suppression factor for charged hadrons in the most 0-5\% central \( Pb + Pb \) collisions at the LHC energy \( \sqrt{s} = 2.76 \) TeV. Since there are no experimental data on charged hadron spectra in \( p + p \) collisions at the LHC energy \( \sqrt{s} = 2.76 \) TeV, ALICE data on the suppression factor were obtained with \( p + p \) spectra interpolated from experimental data at Tevatron energies. The histograms in Fig. 2 represent the errors on the suppression factor from the uncertainty in the interpolation. Charged hadrons contain significant fraction of protons and anti-protons which could have negligible contributions from parton recombination [24, 25]. Because of the abundance of jet production at the LHC energy, recombination among these hard partons becomes possible and therefore contribute to hadron, especially baryon spectra at high \( p_T \). One therefore should take into account the contribution from hard parton recombination in the calculation of the final charged hadron spectra, which could push the suppression factor for charged hadrons higher than that for pions at large \( p_T \).

Because of the increased initial parton density which we assume to be proportional to the final hadron multiplicity density, the initial jet transport parameter \( \hat{q}_0 \) in \( Pb + Pb \) collisions at the LHC energy \( \sqrt{s} = 2.76 \) TeV are more than twice larger than that in \( Au + Au \) collisions at the RHIC energy \( \sqrt{s} = 0.2 \) TeV. The hadron suppression factors in \( Pb + Pb \) collisions at LHC at moderate transverse momentum \( p_T < 20 \) GeV/c are therefore about twice smaller than that at RHIC [24]. Shown in Fig. 3 are the scaled jet transport parameter \( \hat{q}(r, \tau)/\hat{q}(0, \tau_0) \) as a function of \( \tau - \tau_0 \) which is related to the parton and hadron density [Eq. (4)] as given by the hydrodynamics evolution. The kink in the time dependence is caused by the first-order phase transition assumed in the hydrodynamics evolution as the EOS of the dense matter. For most part of the evolution history, the scaled jet transport parameters are very similar at RHIC and LHC energies. Therefore, the increased hadron suppression at

\[
R_{AB} = \frac{\frac{d \sigma_{h}}{d^2 \eta d^2 p_T}}{N_{bin}^A B(b) d \sigma^h_{pp}/d^2 p_T},
\]

where \( N_{bin}^A B(b) \) is the medium modified fragmentation functions which are used to calculate the suppression factor (or nuclear modification factor) for large \( p_T \) hadron spectra in heavy-ion collisions [52].

\[
N_{bin}(b) = \int d^2 \tau A(r) t_B(|\vec{b} - \vec{r}|)
\]

The fixed value of impact-parameters in the calculation of the spectra and the modification factor are determined through the Glauber geometric fractional cross sections for given centrality of the heavy-ion collisions.

In the HT approach, we have determined \( \hat{q}_b \tau_0 = 0.54 - 0.63 \) GeV\(^2\) from the experimental data on pion spectra in the most 0-10\% central \( Au + Au \) collisions at \( \sqrt{s} = 0.2 \) TeV [26]. We assume that the jet transport parameter is proportional to the initial parton density or the transverse density of charged hadron multiplicity in mid-rapidity [Eq. (11)]. With the new ALICE data on charged particle pseudo-rapidity density at mid-rapidity \( dN_{ch}/d\eta = 1584 \pm 4(\text{stat.}) \pm 76(\text{sys.}) \) in the most central 5\% \( Pb + Pb \) collisions at \( \sqrt{s} = 2.76 \) TeV versus \( dN_{ch}/d\eta = 687 \pm 37 \) for 0-5\% \( Au + Au \) collisions at \( \sqrt{s} = 0.2 \) TeV [32], we obtain the extrapolated value \( q_0 \tau_0 = 1.0 - 1.4 \) GeV\(^2\) for \( Pb + Pb \) collisions at \( \sqrt{s} = 2.76 \) TeV. The suppression factor increases with \( p_T \) partially because of the energy dependence of parton energy loss and partially because of the less steep initial jet production spectra [34]. This trend is similar to almost all LHC predictions by many other parton energy loss model calculations [27].
LHC is caused mainly by the overall increase of the initial parton density. The increased initial parton density, however, will also increase the life-time of the dense matter through-out the phase transition and hadronic phase. This will also contribute to the increased suppression of hadron spectra at the LHC as compared to at RHIC.

IV. CONCLUSIONS

We used the new ALICE data on charged hadron multiplicity density at mid-rapidity in central $Pb + Pb$ collisions at the LHC energy $\sqrt{s} = 2.76$ TeV [28] to estimate the initial jet quenching parameters in $Pb + Pb$ collisions at the LHC and the initial condition for the hydrodynamic evolution of the bulk matter. With the initial values of the jet transport parameter and the initial condition for hydrodynamic evolution of the bulk matter, we predict the suppression factor for the hadron spectra in $Pb + Pb$ collisions at $\sqrt{s} = 2.76$ TeV within the HT model for medium modified fragmentation functions. Because of the increased initial parton density of about a factor of two, and the longer life-time of the dense matter or the duration of jet quenching, the hadron spectra are found to be suppressed more at LHC than at RHIC. However, because the energy dependence of the parton energy loss and the less steep initial jet spectra, the suppression factors will increase with $p_T$ more strongly at LHC than at RHIC.

Because of the increased number of jet production in heavy-ion collisions at LHC energies, there are increased possibility of larger $p_T$ hadron production from recombination of parton showers from independent jets. This production mechanism will be more important than the shower-thermal and thermal-thermal parton recombination that have been considered more relevant in heavy-ion collisions at the RHIC energy [54, 55]. Such contributions from jet-jet parton recombination will likely increase the hadron yield at moderate $p_T$ and increase the values of the suppression factor $R_{AA}$ at the LHC energies.

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[1] I. Arsene et al. [BRAHMS Collaboration], Nucl. Phys. A 757, 1 (2005).
[2] B. B. Back et al., Nucl. Phys. A 757, 28 (2005).
[3] J. Adams et al. [STAR Collaboration], Nucl. Phys. A 757, 102 (2005).
[4] K. Adcox et al. [PHENIX Collaboration], Nucl. Phys. A 757, 184 (2005).
[5] X. N. Wang and M. Gyulassy, Phys. Rev. Lett. 68, 1480 (1992).
[6] J. Adams et al. [STAR Collaboration], Phys. Rev. Lett. 91, 072304 (2003); Phys. Rev. Lett. 91, 172302 (2003).
[7] S. S. Adler et al. [PHENIX Collaboration], Phys. Rev. Lett. 91, 072301 (2003).
[8] C. Adler et al., Phys. Rev. Lett. 90, 082302 (2003).
[9] X. -N. Wang, Z. Huang, I. Sarcevic, Phys. Rev. Lett. 77, 231-234 (1996). [hep-ph/9605213].
[10] A. Adare et al. [PHENIX Collaboration], Phys. Rev. C 80, 024908 (2009) [arXiv:0903.3399 [nucl-ex]].
[11] B. I. Abelev et al. [STAR Collaboration], Phys. Rev. C 82, 034909 (2010) [arXiv:0912.1871 [nucl-ex]].
[12] X. -N. Wang, Nucl. Phys. A750, 98-120 (2005). [nucl-th/0405017].
[13] I. Vitev and M. Gyulassy, Phys. Rev. Lett. 89, 252301 (2002).
FIG. 3: (Color Online) The scaled jet transport parameter $\hat{q}(r, \tau)/\hat{q}(0, \tau_0)$ as a function of $\tau - \tau_0$ at $r = 0$ fm and $r = 4$ fm in central $Au + Au$ collisions at RHIC ($\sqrt{s} = 0.2$ TeV) and $Pb + Pb$ collisions at LHC ($\sqrt{s} = 2.76$ TeV) from 3+1D hydrodynamic evolution.

[14] X. N. Wang, Phys. Lett. B 595, 165 (2004) [arXiv:nucl-th/0305010].
[15] K. J. Eskola, H. Honkanen, C. A. Salgado and U. A. Wiedemann, Nucl. Phys. A 747, 511 (2005).
[16] T. Renk, Phys. Rev. C 74, 024903 (2006).
[17] H. Zhang, J. F. Owens, E. Wang and X. N. Wang, Phys. Rev. Lett. 98, 212301 (2007).
[18] G. Y. Qin, J. Ruppert, C. Gale, S. Jeon, G. D. Moore and M. G. Mustafa, Phys. Rev. Lett. 100, 072301 (2008) [arXiv:0710.0605 [hep-ph]].
[19] T. Renk, Phys. Rev. C 74, 034906 (2006) [hep-ph/0607166].
[20] H. Zhang, J. F. Owens, E. Wang and X.-N. Wang, Phys. Rev. Lett. 103, 032302 (2009) [arXiv:0902.4000 [nucl-th]].
[21] G. Y. Qin, J. Ruppert, C. Gale, S. Jeon and G. D. Moore, Phys. Rev. C 80, 054909 (2009) [arXiv:0906.3280 [hep-ph]].
[22] M. Gyulassy, I. Vitev, X. -N. Wang et al., In *Hwa, R.C. (ed.) et al.: Quark gluon plasma* 123-191. [nucl-th/0302077].
[23] A. Kovner, U. A. Wiedemann, In *Hwa, R.C. (ed.) et al.: Quark gluon plasma* 192-248. [hep-ph/0304151].
[24] S. A. Bass, C. Gale, A. Majumder, C. Nonaka, G. Y. Qin, T. Renk and J. Ruppert, Phys. Rev. C 79, 024901 (2009).
[25] N. Armesto, M. Cacciari, T. Hirano, J. L. Nagle and C. A. Salgado, [arXiv:0907.0667 [hep-ph]].
[26] X. -F. Chen, C. Greiner, E. Wang, X.-N. Wang and Z. Xu Phys. Rev. C 81, 064908 (2010) [arXiv:1002.1165 [nucl-th]].
[27] N. Armesto et al., J. Phys. G 35, 054001 (2008) [arXiv:0711.0974 [hep-ph]].
[28] K. Aamodt et al. [The ALICE Collaboration], [arXiv:1011.3916 [nucl-ex]].
[29] S.-Y. Li, X.-N. Wang, Phys. Lett. B 527, 85-91 (2002). [nucl-th/0110075].
[30] W.-T. Deng, X.-N. Wang, R. Xu, [arXiv:1008.1841 [hep-ph]].
[31] X.-N. Wang, M. Gyulassy, Phys. Rev. D 44, 3501-3516 (1991).
[32] W. T. Deng, X. N. Wang and R. Xu, [arXiv:1011.5907 [nucl-th]].
[33] N. Kidonakis and J. F. Owens, Phys. Rev. D 63, 054019 (2001); B. W. Harris and J. F. Owens, Phys. Rev. D 65, 094032 (2002).
[34] H. L. Lai et al. [CTEQ Collaboration], Eur. Phys. J. C 12, 375 (2000).
[35] K. J. Eskola, H. Paukkunen and C. A. Salgado, JHEP 0807, 102 (2008), arXiv: hep-ph/0802.0139.
[36] See contribution by H.-Z. Zhang, E. Wang and X.-N. Wang in Ref. [27].
[37] X. F. Guo and X. N. Wang, Phys. Rev. Lett. 85, 3591 (2000); X. N. Wang and X. F. Guo, Nucl. Phys. A 696, 788 (2001).
[38] B. W. Zhang and X. N. Wang, Nucl. Phys. A 720, 429 (2003).
[39] J. Casalderrey-Solana and X. N. Wang, Phys. Rev. C 77, 024902 (2008).
[40] R. Baier, Y. L. Dokshitzer, A. H. Mueller, S. Peigne and D. Schiff, Nucl. Phys. B 484, 265 (1997).
[41] W. T. Deng and X. N. Wang, Phys. Rev. C 81, 024902 (2010).
[42] S. Albino, B. A. Kniehl and G. Kramer, Nucl. Phys. B 803, 42 (2008).
[43] E. Wang and X. N. Wang, Phys. Rev. Lett. 89, 162301 (2002).
[44] A. Majumder, E. Wang and X. N. Wang, Phys. Rev. Lett. 99, 152301 (2007).
[45] A. Majumder, arXiv:0901.4516 [nucl-th].
[46] A. Airapetian et al. [HERMES Collaboration], Nucl. Phys. B 780, 1 (2007).
[47] T. Hirano, Phys. Rev. C 65, 011901 (2002).
[48] T. Hirano and K. Tsuda, Phys. Rev. C 66, 054905 (2002).
[49] J. D. Bjorken, Phys. Rev. D 27, 140 (1983).
[50] T. Hirano, U. Heinz, D. Kharzeev, R. Lacey and Y. Nara, Phys. Lett. B 636, 299 (2006); Phys. Rev. C 77, 044909 (2008).
[51] http://tkynt2.phys.s.u-tokyo.ac.jp/~hirano/parevo/parevo.html
[52] X. N. Wang, Phys. Rev. C 61, 064910 (2000).
[53] K. Adcox et al. (PHENIX), Phys. Rev. Lett. 86, 3500 (2001). arXiv:nucl-ex/0012008.
[54] X. N. Wang, Phys. Rev. C 70, 031901 (2004) arXiv:nucl-th/0405029.
[55] K. Aamodt et al. [ALICE Collaboration], Phys. Lett. B 696, 30 (2011) arXiv:1012.1001 [nucl-ex].
[56] R. C. Hwa and C. B. Yang, Phys. Rev. C 67, 034902 (2003).
[57] V. Greco, C. M. Ko and P. Levai, Phys. Rev. Lett. 90, 202302 (2003).
[58] R. J. Fries, B. Müller, C. Nonaka and S. A. Bass, Phys. Rev. Lett. 90, 202303 (2003).