Suppressing the high \( p_T \) charged hadron \( R_{AA} \) at the LHC

A. Majumder\(^1,2 \) and C. Shen\(^1 \)

\(^1\)Department of Physics, The Ohio State University, Columbus, OH 43210, USA
\(^2\)Department of Physics and Astronomy, Wayne State University, Detroit, MI 48201, USA

(Dated: January 13, 2013)

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 Large Hadron Collider (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 normalized by fitting the \( R_{AA} \) in the most central \( Au-Au \) collisions at the Relativistic Heavy-Ion Collider (RHIC). This set up is validated in non-central \( Au-Au \) collisions at RHIC 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 10-100 GeV.

PACS numbers: 12.38.Mh, 11.10.Wx, 25.75.Dw

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,

\[
R_{AA} = \frac{d^2N_{AA}(b_{min},b_{max})}{d^2p_Tdy} \frac{N_{bin}(b_{min},b_{max})}{d^2N_{pp}} .
\]

(1)

In the equation above, \( d^2N_{AA}(b_{min},b_{max}) \) 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 \( d^2N_{pp} \) 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 \( s \):

\[
\hat{q}(\vec{r},t) = \hat{q}_0 s(T(\vec{r},t)) \left[ \frac{s(T_0)}{s(T_0)} \right] \sqrt{1 - v_{\perp}^2(\vec{r},t)} , \tag{2}
\]

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 semi-central 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 semi-central RHIC events; \( \hat{q}_0 \) will be dialed to obtain a best fit to this data.

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 $p_T \leq$ 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 ($Q \gg Q_{CD}$) 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

$$\frac{d\sigma^{AA}_{p_T,y}}{dy d^2 p_T}^{\text{max}} = K \int d^2 b \int d^2 r_A (r - b) A_B (r - b) \times \int dx_a dx_b G_A (x_a, Q^2) G_B (x_b, Q^2) \times \left[ \frac{d\sigma_{ab \rightarrow cd}}{dt} \hat{D}_c^h (z, Q^2, \zeta_L, r, \theta_j, \hat{p}_c) \right] \frac{\pi z}{y} \left( \hat{p}_c \right),$$

In the equation above, $y, \hat{p}_T$ represents the rapidity and transverse momentum of the detected parton, $K$ is a multiplicative factor to account for higher order corrections, $r$ is the location of the jet production vertex, $t_A/B (r \pm \bar{b}/2)$ is the nuclear thickness function, $t_A (r + \bar{b}/2) = \int dz \rho (r + \bar{b}/2, z)$ with $\rho (r, z)$ 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, $G_{a/B} (x_a, Q^2)$ is the nuclear parton distribution function, $d\sigma_{ab \rightarrow cd}/dt$ is the short distance cross section for incoming partons $a, b$ to scatter and produce partons $c, d$ with a squared momentum transfer $t = (\hat{p}_c - \hat{p}_a)^2$. $\hat{D}_c$ represents the medium modified fragmentation with hadronic momentum fractions, $z = p_T/\hat{p}_T$, and $\zeta_L (r, \theta_j)$ is the distance travelled by a jet produced at $r$ and propagating at an angle $\theta_j$ with respect to the reaction plane. Both $\bar{b}$ and $r$ are two dimensional vectors transverse to the beam direction. All calculations will be carried out at mid-rapidity ($y = 0$).

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 DGLAP 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),

$$\frac{\partial \hat{D}_c^h (z, Q^2, \hat{p}_c)}{\partial \log Q^2} \bigg|_{\hat{r} = \hat{r} + \hat{n}_L} = \alpha_s \frac{1}{\pi} \frac{dy}{y} \hat{P} (y) \left[ \hat{D}_c^h \left( \frac{z}{y}, Q^2, \hat{p}_c \right) \bigg|_{\hat{r} = \hat{r} + \hat{n}_L} \int d\zeta K_{\hat{r}, \theta_j} (y, \zeta) D_{\hat{q}}^h \left( \frac{z}{y}, Q^2, \hat{p}_c \right) \bigg|_{\hat{r} = \hat{r} + \hat{n}_L} + \int d\zeta K_{\hat{r}, \hat{q}, \zeta} (y, \zeta) D_{\hat{q}}^h \left( \frac{z}{y}, Q^2, \hat{p}_c \right) \bigg|_{\hat{r} = \hat{r} + \hat{n}_L} \right],$$

where, $\hat{P} (y)$ 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 $K_{\hat{r}, \theta_j, \zeta} (y, \zeta)$ is given as

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

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 freezeout criteria are tuned to obtain the best fit with the spectra and elliptic flow of hadrons with $p_T \leq$ 2 GeV. As this Letter will deal solely with the spectra and azimuthal anisotropy at high $p_T$ ($p_T \geq$ 6 GeV), we will only provide the most salient features of these simulations in the current paper 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 KLN 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 $t_0$, the conditions at $t_0$ 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 set up, 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 $T^3$ [14, 15]. 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 $q_0 = 2.2$ 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 $t = t_0$. This $q_0$ 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 $\hat{D}$ [Eq. (4)] for jets which originate at $\vec{r}$ and travel in a given direction $\theta_j$, deconvoluting from the medium after traveling a distance $\zeta_L (\vec{r}, \theta_j)$.
[when \( T(\vec{r} + \hat{n} \zeta_L, \zeta_L) = 160 \text{ MeV} \)], 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 \( Q^2 = p_T^2 \). The physical picture is that of a hard jet that starts with a high virtuality \( Q^2 = p_T^2 \) 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 position travelled 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 \[ \langle \hat{p}_c \rangle/\langle \zeta_L \rangle \] 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 \( \hat{p}_c \) is the mean energy of the parent parton in vacuum and \( \langle \zeta_L \rangle \) is the mean distance travelled 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 \( \bar{q} \) 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 \( \bar{q} \)) is used to calculate the length \( \zeta_{max} \) over which a parton with energy \( \hat{p}_c \) 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 \( \zeta_{max} \) 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 over estimate of the quenching. For hadron \( p_T \sim 10 \text{ GeV} \) in 0-5% collisions at RHIC, \( \zeta_{max} = 5 \text{ fm} \). 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 set up, we can now calculate the invariant cross section to produce a high \( p_T \) hadron in a heavy-ion 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 dimensionfull parameter \( \bar{q}_0 \) is dialed so that the calculated \( R_{AA} \) matches the experimental value in the 0-5% collisions at \( p_T = 10 \text{ GeV} \) [i.e. \( R_{AA}(0-5\%, p_T = 10\text{GeV}) \sim 0.2 \)]. The slope of the curve with \( p_T \) and the shift with centrality are predictions. The \( \bar{q}_0 \) 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 \( p_T \lesssim 8 \text{ GeV} \)). Our choice of \( \bar{q}_0 \) 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 curve represents the \( R_{AA} \) for jets with \( \theta_j \) 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 \( b \). The solid red 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 green lines are the same calculations but with calculated \( \langle \zeta_{max} \rangle \). We obtain a good description of the data for \( p_T \geq 8 \text{ GeV} \). For \( p_T < 8 \text{ GeV} \), the \( Q^2_{min} \geq 1 \text{ GeV}^2 \) restriction begins to affect the calculation.

With the value of \( \bar{q}_0 \) extracted from RHIC collisions and \( \bar{q} \) scaled with the entropy density of the medium we now calculate the \( R_{AA} \) in \( Pb-Pb \) collisions at \( \sqrt{s} = 2.76 \text{ ATeV} \) 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 (\( T_{max} = 436 \text{ MeV} \)). Also larger velocity gradients drive the system to larger sizes than at RHIC prior to freezeout [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 \( p_T \geq 9 \text{ GeV} \). The solid and dashed lines indicate the cases of fixed and calculated \( \langle \zeta_{max} \rangle \) as before.
between the calculation and the data at high $p_T$ if these corrections are the only source of the discrepancy and distance travelled by a parton. However it is not clear what the contributions are due to the larger flow at these energies. The extraordi-
narily high densities may also enhance the magnitude of such as recombination extend up to 8-9 GeV at the LHC, due to the larger flow at these energies. The extraordi-
narily high densities may also enhance the magnitude of non-linear 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 $\langle \zeta_{\text{max}} \rangle$ and adjust the $q_0$ to obtain a better fit with the 0-5% LHC data. This seems to require a 30% lower value of $q_0$. Another source of correction is the drag and diffusion experienced by the partons [16], 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+1D 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 $\hat{q}_0 = 2.2 \text{GeV}^2/\text{fm}$ at the maximum RHIC temperature of $T = 344 \text{MeV}$. 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 $\sqrt{s} = 2.76 \text{ TeV}$ at the LHC.

The authors thank U. Heinz, Y. Kovchegov, M. A. Lisa and B. Müller for discussions, and the WSU grid for computer time. This work was supported in part by the U.S. DOE under grant nos. de-sc0004286 and (within the framework of the JET collaboration) de-sc0004104, and in part by the NSF under grant no PHY-1207918.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig2.png}
\caption{(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.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig3.png}
\caption{(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.}
\end{figure}

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 travelled 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 $p_T \sim 6 \text{ GeV}$. It is entirely possible that non-perturbative phenomena such as recombination extend up to 8-9 GeV at the LHC, due to the larger flow at these energies. The extraordinary high densities may also enhance the magnitude of non-linear 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 $\langle \zeta_{\text{max}} \rangle$ and adjust the $q_0$ to obtain a better fit with the 0-5% LHC data. This seems to require a 30% lower value of $q_0$. Another source of correction is the drag and diffusion experienced by the partons [16], 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+1D 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 $\hat{q}_0 = 2.2 \text{GeV}^2/\text{fm}$ at the maximum RHIC temperature of $T = 344 \text{MeV}$. 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 $\sqrt{s} = 2.76 \text{ TeV}$ at the LHC.

The authors thank U. Heinz, Y. Kovchegov, M. A. Lisa and B. Müller for discussions, and the WSU grid for computer time. This work was supported in part by the U.S. DOE under grant nos. de-sc0004286 and (within the framework of the JET collaboration) de-sc0004104, and in part by the NSF under grant no PHY-1207918.

\begin{thebibliography}{16}
\bibitem{1} I. Arsene \textit{et al.}, Nucl. Phys. A \textbf{757}, 1 (2005); B. B. Back \textit{et al.}, \textit{ibid.} \textbf{757}, 28 (2005); J. Adams \textit{et al.}, \textit{ibid.} \textbf{757}, 102 (2005); K. Adcox \textit{et al.}, \textit{ibid.} \textbf{757}, 184 (2005).
\bibitem{2} K. Adcox \textit{et al.}, Phys. Rev. Lett. \textbf{88}, 022301 (2002); C. Adler \textit{et al.}, Phys. Rev. Lett. \textbf{89}, 202301 (2002)
\bibitem{3} A. Majumder and M. Van Leeuwen, Prog. Part. Nucl. Phys. \textbf{66}, 41 (2011); N. Armesto \textit{et al.}, \textit{arXiv:1106.1106} [hep-ph]. M. Gyulassy \textit{et al.}, \textit{arXiv:nucl-th/0302077}.
\bibitem{4} S. S. Gubser \textit{et al.}, \textit{arXiv:0902.4041} [hep-th]; J. Casalderrey-Solana \textit{et al.} \textit{arXiv:1101.0618} [hep-th].
\bibitem{5} G. Aad \textit{et al.}, Phys. Rev. Lett. \textbf{105}, 252303 (2010).
\bibitem{6} K. Aamodt \textit{et al.}, Phys. Lett. B \textbf{696}, 30 (2011).
\bibitem{7} S. Chatrchyan \textit{et al.}, Eur. Phys. J. C \textbf{72}, 1945 (2012).
\bibitem{8} C. Shen \textit{et al.}, Phys. Rev. C \textbf{84}, 044903 (2011).
\bibitem{9} J. C. Collins, D. E. Soper and G. F. Sterman, Nucl. Phys. B \textbf{261}, 104 (1985); J. W. Qiu and G. F. Sterman, Nucl. Phys. B \textbf{353}, 137 (1991).
\bibitem{10} A. Majumder, \textit{arXiv:0901.4516} [nucl-th].
\bibitem{11} X. F. Guo and X. N. Wang, Phys. Rev. Lett. \textbf{85}, 3591 (2000); Nucl. Phys. A \textbf{696}, 788 (2001); A. Majumder and B. Muller, Phys. Rev. C \textbf{77}, 054903 (2008); A. Majumder, Phys. Rev. D \textbf{85}, 014023 (2012).
\bibitem{12} H. Song \textit{et al.}, \textit{arXiv:1011.2789} [nucl-th].
\bibitem{13} C. Shen \textit{et al.}, Phys. Rev. C \textbf{82}, 054904 (2010).
\bibitem{14} S. A. Bass \textit{et al.}, Phys. Rev. C \textbf{79}, 024901 (2009).
\bibitem{15} A. Majumder, C. Nonaka and S. A. Bass, Phys. Rev. C \textbf{76}, 041902 (2007).
\bibitem{16} A. Majumder, Phys. Rev. C \textbf{80}, 031902 (2009).
\end{thebibliography}