\textbf{\large \gamma\text{-hadron spectra in p + Pb collisions at } \sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}}

Man Xie,\textsuperscript{1} Xin-Nian Wang,\textsuperscript{1,2} and Han-Zhong Zhang\textsuperscript{1}

\textsuperscript{1}Key Laboratory of Quark and Lepton Physics (MOE) and Institute of Particle Physics, Central China Normal University, Wuhan 430079, China
\textsuperscript{2}Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

Under the assumption that a quark-gluon plasma droplet is produced and its evolution can be described by hydrodynamics in p + A collisions, \gamma\text{-triggered hadron spectra are studied within a next-to-leading-order perturbative QCD parton model with the medium-modified parton fragmentation functions. The initial conditions and space-time evolution of the small QGP droplet are provided by the superSONIC hydrodynamic model simulations and parton energy loss in such a medium is described by the high-twist (HT) approach. The scaled jet transport coefficient \( \hat{q}/T^3 \) in this HT approach is extracted from single hadron suppression in central A + A collisions at the same colliding energy. Numerical results for this scenario show that \gamma\text{-hadron spectra at } p_T^\gamma = 12 - 40 \text{ GeV/c} \text{ are suppressed by } 5\% - 10\% \text{ in the most central } 0 - 10\% \text{ p + Pb collisions at } \sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}. \text{ The suppression becomes weaker at higher transverse momentum of the \gamma trigger. As a comparison, \gamma\text{-hadron suppression in Pb + Pb collisions at } \sqrt{s_{\text{NN}}} = 2.76 \text{ and 5.02 TeV is also predicted.}

\section{I. INTRODUCTION}

Jet quenching\textsuperscript{[1–3]} as reflected in the suppression and azimuthal anisotropy of high \( p_T \) hadron spectra \textsuperscript{[4–8]} are two key evidences for the formation of hot and dense quark-gluon plasma (QGP) in heavy-ion collisions. Recently some phenomena observed in p + Pb collisions seem also to indicate the existence of such small systems of hot and dense medium. For example, the azimuthal anisotropies \( v_n \) from two-particle and four-particle correlation measurements in p + Pb collisions at 5.02 TeV \textsuperscript{[9,12]} show a similar behavior of the collective flow as in Pb + Pb collisions. Enhancement of strangeness productions in p + Pb collisions also exhibits similarities to what is observed in Pb + Pb collisions \textsuperscript{[13,14]}. However, single charged hadron \textsuperscript{[15–19]} and single jet spectra \textsuperscript{[20,21]} do not indicate strong jet quenching phenomena in p + Pb collisions as one would expect if a small droplet of QGP is formed. Similar behaviors are also observed for heavy flavor mesons spectra in p+Pb collisions.

In the experimental study of single hadron and jet suppression, one needs to determine the number of binary collisions for a given class of centrality to calculate the suppression factor relative to the spectra in p + p collisions. This is problematic for p + A collisions due to relatively large dynamical fluctuations of hadron production and leads to large uncertainties \textsuperscript{[10]}. One can circumvent this problem by measuring the hadron and jet spectra in coincidence with another particle or jet such as in the spectra of dihadron, dijet, hadron-jet or \gamma\text{-jet. Since one measures the hadron or jet yields per trigger, there is no need to determine the number of binary collisions for normalization. Experimental data \textsuperscript{[22]} on dijet spectra in p+Pb collisions at \( \sqrt{s_{\text{NN}}} = 5.02 \text{ TeV} \), however, show no significant effect of jet quenching within the experimental errors in the nuclear modification of the dijet asymmetry in transverse momentum. Since trigger biases in dihadron and dijet measurements prefer surface and tangential configurations for coincident production of hadrons or jets, the effect of jet quenching should be smaller than in \gamma\text{-hadron production where the direct photon does not have strong interaction with the hot medium before being detected. This will be the focus of our study in this paper.

It is generally believed that \gamma\text{-jet production is a “golden probe” for studying parton energy loss since the color-neutral photon does not interact strongly with the hot and dense medium \textsuperscript{[23,24]} and can be used to best approximate the transverse momentum of the accompanying jet which is produced together with the photon in the hard processes of the Compton (\( qg \rightarrow q\gamma \)) or annihilation (\( gg \rightarrow g\gamma \)) scattering \textsuperscript{[25,26]}. Since the produced direct photon does not interact with the hot and dense medium, using it as the coincidence trigger does not lead to biases in the geometrical configuration of the initial production as in the dihadron, hadron-jet or dijet production. Medium modification of \gamma\text{-hadron spectra in Au + Au collisions at the Relativistic Heavy-ion Collider (RHIC) \textsuperscript{[27,30]} and \gamma\text{-jet spectra in Pb + Pb collisions at the Large Hadron Collider (LHC) \textsuperscript{[31,34]} have been observed that are consistent with the picture of jet quenching in the suppression of single hadron and jet spectra. The average fraction of quark jets versus gluon jets in \gamma\text{-jet production is larger than that of single and dijet at the same transverse momentum and colliding energy. Quarks also lose about half (4/9) less energy as gluons in the QGP medium. However, experimental results indicate a stronger average parton energy loss in \gamma\text{-hadron and \gamma\text{-jet production than in the single hadron and jet spectra \textsuperscript{[35]}. These are all because there is no surface or tangential trigger bias in \gamma\text{-hadron (jet) production as in single hadron (jet) and di-hadron (di-jet) production. If small droplets of QGP are formed in p + A collisions and energetic partons also experience parton energy loss as in the QGP in A+A collisions, one should expect to observe more sizable medium modification of \gamma\text{-hadron spectra in p + A collisions.

To calculate the medium modification of \gamma\text{-hadron spectra in p + A collisions, we assume that partons will...}
lose their energy loss mostly via medium-induced gluon radiation when traversing the medium created in p + A collisions. The radiative jet energy loss is controlled by jet transport coefficient \( q / T^3 \) as extracted from the suppression of single hadron spectra in A + A collisions with similar highest initial temperature as in p + A collisions. We will use the initial condition and hydrodynamic evolution of the QGP medium in p + A collisions as provided by the superSONIC hydrodynamic model \[42\]. As comparisons, we also predict the nuclear modification of \( \gamma \)-hadron spectra in Pb + Pb collisions at the LHC energies.

The remainder of this paper is organized as follows. In Sec. II, we briefly introduce our framework for the study of the invariant cross section of direct-\( \gamma \) and \( \gamma \)-hadron spectra with large transverse momenta \( p_T^\gamma \) in proton-proton (p + p) and proton-nucleus (p + A) collisions. In Sec. III, we calculate the photon spectra for Au + Au collisions at \( \sqrt{s_{NN}} = 0.2 \) TeV, Pb + Pb collisions at \( \sqrt{s_{NN}} = 2.76 \) TeV and 5.02 TeV as compared with experimental data. In addition, we will also show the prediction for photon spectra in p + Pb collisions at \( \sqrt{s_{NN}} = 5.02 \) TeV. In Sec. IV, we focus on cold nuclear matter (CNM) effects on direct photon and \( \gamma \)-hadron productions without medium modification from final state interaction. In Sec. V, we calculate the \( \gamma \)-triggered fragmentation function \( D_{pp}^{\gamma}(x_T) \) in p + p collisions and the \( \gamma \)-hadron suppression factors \( I_{AA}^{\gamma} \) in central Au + Au collisions at 0.2 TeV, and compare them with experimental data to illustrate the applicability of our model. We also present our predictions for \( \gamma \)-hadron suppression factors \( I_{AA}^{\gamma} \) in Pb + Pb collisions at \( \sqrt{s_{NN}} = 2.76 \) and 5.02 TeV in this section. In Sec. VI, \( \gamma \)-hadron suppression factors \( I_{pA}^{\gamma} \) for 5.02 TeV p + Pb collisions are shown. A brief summary is given in Sec. VII.

II. PQCD PARTON MODEL

The photon spectrum is the elementary part of the hard processes in high-energy heavy-ion collisions. Photon production is mainly from three mechanisms: (i) quark-gluon Compton scattering \( gg \rightarrow g\gamma \), (ii) quark-antiquark annihilation \( gg \rightarrow g\gamma \), and (iii) photon production from collinear fragmentation of final-state partons. Photons from the first two sources are called "direct" photons and that from the last source are called "fragmentation" photons. The combination of these three sources are called "prompt" photons \[43\] to differentiate them from photons from hadron decays. The fragmentation photons will be suppressed if an isolation-cut is applied since they are always accompanied by nearly collinear hadrons \[45\] [40]. Such isolation cuts can reduce the fraction of fragmentation photons to less than 10% \[47\]. With such isolation cuts it is therefore safe for us to focus mainly on the direct photon production and neglect photons via induced bremsstrahlung. In addition, we also neglect photons that are produced via jet-photon conversion \[48\]. Thermal productions \[49\] [50] in high-energy heavy-ion collisions are negligible at large transverse momentum as compared to prompt photons.

The differential cross-section of direct photon production in p + p collisions \[51\] [52] in perturbative QCD (pQCD) parton model can be expressed as,

\[
\frac{d\sigma_{pp}^{\gamma}}{dyd^2p_T} = \sum_{abd} \int_{x_{\text{min}}}^{1} dx_a f_{a/p}(x_a, \mu^2) f_{b/p}(x_b, \mu^2) \times 2 \frac{x_a x_b}{\pi} \frac{d\sigma_{ab \rightarrow \gamma d}}{dt} + O(\alpha_s^2),
\]

where \( x_T = 2p_T/\sqrt{s}, x_b = x_a x_T e^{-y}/(2x_a - x_T e^y), x_{\text{min}} = x_T e^y/(2 - x_T e^{-y}), f_a(x_a, \mu^2) \) is parton distribution functions (PDF’s) which we take from CT14 parametrization \[53\] and \( d\sigma_{ab \rightarrow \gamma d}/dt \) are the tree-level 2 \( \rightarrow 2 \) partonic scattering cross sections. The NLO correction at \( O(\alpha_s^2) \) order included in our calculation contains 2 \( \rightarrow 2 \) virtual diagrams and 2 \( \rightarrow 3 \) tree diagrams.

Taking into account of the initial-state cold nuclear matter (CNM) effect, one can write down the invariant cross section of direct photon productions in p + A as \[52\],

\[
\frac{d\sigma_{pA}^{\gamma}}{dyd^2p_T} = \sum_{abd} \int d^2r \int_{x_{\text{min}}}^{1} dx_a t_A(\vec{r}) f_{a/A}(x_a, \mu^2) \times f_{b/p}(x_b, \mu^2) \frac{2x_a x_b}{\pi} \frac{d\sigma_{ab \rightarrow \gamma d}}{dt} + O(\alpha_s^2),
\]

where \( t_A(\vec{r}) \) is the nuclear thickness function given by the Woods-Saxon distribution \[54\]. Since one of the incoming partons comes from a nucleus, the PDF in the nuclear target should be the nuclear modified PDF \( f_{a/A}(x_a, \mu^2) \) \[53\] [56]:

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

where \( Z \) is the proton number of the nucleus. The nuclear modification factor \( S_{a/A}(x_a, \mu^2) \) of the PDFs will be given by the EPPS16 \[57\] parameterization.

In A + A collisions, the yield of direct photon production at high transverse momentum may be obtained as \[52\],

\[
\frac{dN_{AB}^{\gamma}}{dyd^2p_T} = \sum_{abd} \int d^2r \int_{x_{\text{min}}}^{1} dx_a t_A(\vec{r}) t_B(\vec{r} + \vec{b}) \times f_{a/A}(x_a, \mu^2, \vec{r}) f_{b/B}(x_a, \mu^2, \vec{r} + \vec{b}) \times 2 \frac{x_a x_b}{\pi} \frac{d\sigma_{ab \rightarrow \gamma d}}{dt} + O(\alpha_s^2),
\]
The invariant cross section of direct photon production in $A + B$ collisions can be obtained after the integration over the impact parameter $d\sigma_{A^B}^\gamma/dy d^2p_T = \int d^2bdN_A^B/dy d^2p_T$.

If the contributions from fragmentation photons are neglected, the invariant cross section of $\gamma$-hadron production only involves the fragmentation function of one parton to a hadron. In $p + p$ collisions, the cross section of $\gamma$-hadron can be expressed as [51].

$$\frac{d\sigma_{\gamma p}^h}{dy d^2p_T d^2q_T^b} = \sum_{ab} \int d^2x d^2x_d \frac{d\sigma_{ab,\gamma}}{d^2q_T} \frac{d\sigma_{\gamma p}}{dy d^2p_T} \frac{dN^{\gamma h}}{d^2q_T^b}$$

where $z_d = p_{T\gamma}/p_{T\gamma}$.

We use the Kniehl-Kramer-Potter parametrization [55] for the vacuum fragmentation function $D_{h/d}(z_d, \mu^2)$. Similarly, the invariant cross section of $\gamma$-hadron productions in $p + A$ collisions can be written as,

$$\frac{d\sigma_{\gamma p A}^h}{dy d^2p_T d^2q_T^b} = \sum_{ab} \int d^2r d^2z d\tau_A(\vec{r}) f_{a/A}(x_a, \mu^2) \frac{d\sigma_{ab,\gamma}}{d^2q_T} \frac{d\sigma_{\gamma p A}}{dy d^2p_T} \frac{dN^{\gamma h}}{d^2q_T^b}$$

where $z_d = p_{T\gamma}/p_{T\gamma}$.

Similarly, the invariant cross section of $\gamma$-hadron productions in $p + A$ collisions can be expressed as,

$$\frac{d\sigma_{\gamma p A}^h}{dy d^2p_T d^2q_T^b} = \sum_{ab} \int d^2r d^2z d\tau_A(\vec{r}) f_{a/A}(x_a, \mu^2) \frac{d\sigma_{ab,\gamma}}{d^2q_T} \frac{d\sigma_{\gamma p A}}{dy d^2p_T} \frac{dN^{\gamma h}}{d^2q_T^b}$$

$$\times f_{b/p}(x_b, \mu^2) \frac{d\sigma_{ab,\gamma}}{d^2q_T} \frac{d\sigma_{\gamma p A}}{dy d^2p_T} \frac{dN^{\gamma h}}{d^2q_T^b}$$

$$\times D_{h/d}(z_d, \mu^2) + O(\alpha_s^2).$$

The yield of $\gamma$-hadron productions in $A + A$ collisions can be expressed as,

$$\frac{dN_{\gamma A}^h}{dy d^2p_T d^2q_T^b} = \sum_{ab} \int d^2r d^2z d\tau_A(\vec{r}) t_B(\vec{r} + \vec{b}) f_{a/A}(x_a, \mu^2, \vec{r}) f_{b/B}(x_b, \mu^2, \vec{r} + \vec{b})$$

$$\times f_{a/b}(x_a, \mu^2, \vec{r}) f_{b/p}(x_b, \mu^2, \vec{r} + \vec{b})$$

$$\times D_{h/d}(z_d, \mu^2) + O(\alpha_s^2).$$

The medium-modified fragmentation function $D_{h/d}(z_d, \mu^2, \Delta E_d)$ can be calculated as [47,59,60],

$$D_{h/d}(z_d, \mu^2, \Delta E_d) = (1 - e^{-\langle N_d \rangle}) \left[ z_d' \frac{d\sigma_{\gamma p A}}{d^2p_T} \frac{dN_{\gamma A}^h}{d^2q_T^b} \left( \frac{z_d}{z_d'} \right) \right]$$

$$+ \langle N_d \rangle \frac{z_d'}{z_d} \frac{d\sigma_{\gamma p A}}{d^2p_T} \frac{dN_{\gamma A}^h}{d^2q_T^b}$$

$$\times e^{-\langle N_d \rangle} \frac{d\sigma_{\gamma p A}}{d^2p_T} \frac{dN_{\gamma A}^h}{d^2q_T^b}$$

where $\Delta E_d$ is the energy loss of parton $d$, $z_d' = p_{T\gamma}/(p_{T\gamma} - \Delta E_d)$, $z_d = \langle N_d \rangle$, and $\langle N_d \rangle$ is the average number of gluons radiated by parton $d$.

For the parton energy loss due to medium induced gluon radiation, we use the high-wist formalism [41,61,63]. For a parton $d$ with initial energy $E$, the total energy loss $\Delta E_d$ can be calculated as,

$$\Delta E_d = \frac{2C_A^s}{\pi} \int d\tau \int \frac{dt^2}{t^2} \int dz$$

$$\times \left[ 1 + (1 - z)^2 \right] \hat{q} \sin^2 \left[ \frac{\hat{r}^2 (\tau - \tau_0)}{4\tau(1 - z)E} \right].$$

where $C_A = 3$, and $\hat{r}$ is the transverse momentum of the radiated gluon. Note that the jet transport coefficient for a gluon and a quark is related by a constant color factor $\hat{q}_A/\hat{q}_F = C_A/C_F$. Therefore the energy loss of a gluon is simply $\hat{q}_A/C_F$ times that of a quark [61]. The average number of radiated gluons from the propagating hard parton $d$ is [64],

$$\langle N_d \rangle = \frac{2C_A^s \delta \hat{q}}{\pi} \int d\tau \int \frac{dt^2}{t^2} \int dz$$

$$\times \left[ 1 + (1 - z)^2 \right] \hat{q} \sin^2 \left[ \frac{\hat{r}^2 (\tau - \tau_0)}{4\tau(1 - z)E} \right].$$

We also assume the jet transport parameter have the following temperature scaling and dependence on the fluid velocity [37],

$$\hat{q} = \hat{q}_0 \frac{T^3}{\tau^3} \frac{p \cdot u}{\tau_0^3} p_0,$$
For $\gamma$-hadron spectra at high transverse momentum in $p + A$ collisions, the $\gamma$-triggered fragmentation function (FF) $D^{\gamma h}_{pA}(z_T)$ is defined as [66],

$$D^{\gamma h}_{pA}(z_T) = \frac{\int d\phi dp_T^\gamma dp_T^\gamma p_T^\gamma \frac{d\sigma^{\gamma h}_{pA}}{dy dp_T^\gamma dp_T^\gamma}}{\int dp_T^\gamma dp_T^\gamma \frac{d\sigma^{\gamma h}_{pA}}{dy dp_T^\gamma dp_T^\gamma}},$$

(14)

where the numerator is $\gamma$-hadron cross section and the denominator is the cross section of trigger photon production. Similarly for in $A + A$ collisions, $\gamma$-triggered fragmentation function is defined as,

$$D^{\gamma h}_{AA}(z_T) = p_T^\gamma \frac{dN_{\gamma AA}^h/\gamma d\gamma dp_T^\gamma dp_T^\gamma}{d\gamma dp_T^\gamma dp_T^\gamma}.$$  

(15)

The nuclear modification factor of the triggered fragmentation function $\Gamma^{\gamma h}_{pA}(z_T)$ as a function of $z_T = p_T^h/p_T^\gamma$ can be defined as [66],

$$\Gamma^{\gamma h}_{pA}(z_T) = \frac{D^{\gamma h}_{pA}(z_T)}{D^{\gamma h}_{pp}(z_T)},$$

(16)

which can be similarly defined for $A + A$ collisions.

Furthermore, $\Gamma^{\gamma h}_{pA}(z_T)$ can be rewritten in the following form,

$$\Gamma^{\gamma h}_{pA}(z_T) = \frac{J^{\gamma h}_{pA}(z_T)}{R^{\gamma}_{pA}(p_T)},$$

(17)

where $J^{\gamma h}_{pA}$ is the ratio of $\gamma$-hadron yield in $p + A$ collisions over that in $p + p$ collisions,

$$J^{\gamma h}_{pA}(z_T) = \frac{\frac{d\sigma^{\gamma h}_{pA}}{dy dp_T^\gamma dp_T^\gamma}}{\langle N_{\text{binary}} \rangle \frac{d\sigma^{\gamma h}_{pp}}{dy dp_T^\gamma dp_T^\gamma}},$$

(18)

without normalization by the production cross section of the trigger photon. In the absence of any CNM effect on direct photon spectra, i.e., $R^\gamma_{pA}(p_T) = 1$, then $\Gamma^{\gamma h}_{pA}(z_T) = J^{\gamma h}_{pA}(z_T)$.

III. DIRECT PHOTON PRODUCTION CROSS SECTION

The numerical results for the photon invariant cross section in $p + p$ and central $Au + Au$ collisions at $\sqrt{s_{NN}} = 0.2$ TeV are compared with PHENIX data [23,24] in Fig. 1. The cross sections of direct photon and prompt photon are both shown in this figure and their ratios are shown in the lower panel. The pQCD parton model can describe the experiment data well. With isolation cuts ($R_{\text{cone}} < 0.5$, $E^{\text{had}} < 0.1 E^\gamma$) contributions of the fragmentation photons are about 10% both in $p + p$ and 0 - 5% $Au + Au$ collisions at 0.2 TeV.

We also show the direct photon spectra in 0 - 10%, 10 - 30%, 30 - 100%, 0 - 100% $Pb + Pb$ collisions (scaled by $\langle T_{AA} \rangle$) and $p + p$ collisions at $\sqrt{s_{NN}} = 2.76$ TeV as compared with experimental data [44,67]. The ratio of contributions of direct photon productions to prompt photon productions for $0 - 10% \ Pb + Pb$ collisions and $p + p$ collisions are shown in the ratio plot.

FIG. 1. Direct photon and prompt photon spectra as a function of $p_T^\gamma$ for $p + p$ collisions and 0 - 5% $Au + Au$ collisions at $\sqrt{s_{NN}} = 0.2$ TeV as compared with PHENIX data [23,24]. The contributions of direct photon productions to prompt photon productions in $p + p$ and 0 - 5% $Au + Au$ collisions are shown in the ratio plot.

FIG. 2. Direct photon spectra as a function of $p_T^\gamma$ for 0 - 10%, 10 - 30%, 30 - 100%, 0 - 100% $Pb + Pb$ collisions (scaled by $\langle T_{AA} \rangle$) and $p + p$ collisions at $\sqrt{s_{NN}} = 2.76$ TeV as compared with experimental data from CMS and ATLAS.
The pQCD parton model results are in good agreement with the experimental data. In the lower panel of Fig. 2, the ratios of direct photons to prompt photons with isolation cuts \( R_{\gamma,\text{direct}}(p + p) \times 10^2 \) for \( p + p \) collisions and \( 0 - 10\% \) Pb + Pb collisions are shown to vary from about 80\% to 90\%. The contributions of fragmentation photons become smaller at larger \( p_T^\gamma \) and it is less than 10\% for \( p_T^\gamma > 50 \text{ GeV/c} \).

Finally in Fig. 3, the direct photon spectra from pQCD model as a function of \( p_T^\gamma \) in 0 - 10\% Pb + Pb collisions (scaled by \( \langle T_{AA} \rangle \)) and \( p + p \) collisions at 5.02 TeV are compared with CMS preliminary data [68]. The prediction for direct photon spectrum (scaled by \( \langle T_{AA} \rangle \)) for \( 0 - 10\% \) p + Pb collisions at 5.02 TeV are also shown. With isolation cuts \( R_{\gamma,\text{direct}}(p + p) \times 10^2 \) for \( p + p \) collisions and \( 0 - 10\% \) Pb + Pb collisions are also shown in the lower panel. Compared to Fig. 2, the contributions of fragmentation photons are greatly reduced as the selection (isolation cuts) conditions become more strict, and it becomes negligible for \( p_T^\gamma > 20 \text{ GeV/c} \). One can, therefore, neglect the contributions of fragmentation photons in numerical calculations with such isolation cuts in the following.

To study the net suppressions of \( \gamma \)-hadron spectra caused by jet quenching, we need to examine the cold nuclear matter (CNM) effect on \( \gamma \)-hadron spectra first. We study therefore in this section, the CNM effects on direct photon and \( \gamma \)-hadron spectra in \( A + A \) and \( p + A \) collisions.

In the upper panel of Fig. 4, we show our calculations of \( \gamma \)-hadron suppression factor \( \frac{d^3N}{dp_Td\eta d\phi} \gamma_{AA} \) (without normalization by number of trigger photons) as a function of \( z_T = \frac{p_T^\gamma}{p_T^\gamma} \) (with \( 8 < p_T^\gamma < 16 \text{ GeV/c} \)) in \( 0 - 10\% \) Au + Au collisions at \( \sqrt{s_{NN}} = 0.2 \text{ TeV} \). In the lower panel, we show direct photon suppression factor \( \frac{d^3N}{dp_Td\eta d\phi} \gamma_{AA} \) for \( 0 - 5\% \) Au + Au collisions at 0.2 TeV which agree with the experimental data [24] well. Taking these two panels together, we find the CNM effect on \( \gamma \)-hadron spectra suppression \( \gamma_{AA} \) when normalized by trigger photon number will have a slight enhancement according to Eq. (17).

Similarly, \( \gamma \)-hadron and direct photon spectra in 0 - 10\% Pb + Pb collisions at \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \) and in 0 - 10\% p + Pb collisions at \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \) are shown in the left and right panels, respectively, of Fig. 5. Results for Pb + Pb collisions at 5.02 TeV are almost the same as at 2.76 TeV. The \( \gamma \)-hadron suppression factors \( \frac{d^3N}{dp_Td\eta d\phi} \gamma_{AA} \) with \( 12 < p_T^\gamma < 40 \text{ GeV/c} \) (without normalization by trigger photon yields) as a function of

FIG. 3. Direct photon spectra as a function of \( p_T^\gamma \) for 0 - 10\% Pb + Pb collisions (scaled by \( \langle T_{AA} \rangle \)) and \( p + p \) collisions at 5.02 TeV as compared with CMS preliminary data [68]. and the prediction for direct photon spectrum for 0 - 10\% p + Pb collisions (scaled by \( \langle N_{\text{binary}} \rangle \)) at 5.02 TeV, scaled by the factors shown in the figure for easier viewing. The ratio of contributions of direct photon productions to prompt photon productions for these three collisions are shown in loser panel.

FIG. 4. The cold nuclear matter (CNM) effect on \( \gamma \)-hadron productions with \( 8 < p_T^\gamma < 16 \text{ GeV/c} \) in 0 - 10\% Au + Au collisions and on direct photon productions in 0 - 5\% Au + Au collisions as compared with PHENIX data [24], both at \( \sqrt{s_{NN}} = 0.2 \text{ TeV} \).
\( z_T \) approximately equal to one shown in the upper panels of Fig. 5. The direct photon suppression factor \( R^\gamma \) is smaller than one with \( p_T^\gamma < 35 \text{ GeV/c} \) both in \( \text{Pb + Pb} \) and \( p + \text{Pb} \) collisions. At an average value of photon trigger transverse momentum \( p_T^\gamma = 26 \text{ GeV/c} \), the direct photon spectrum has a suppression of about 10% which causes the \( \gamma \)-hadron suppression factor \( I^{\gamma h} \) becoming a little larger than one. One can conclude that the medium modification factors \( I^\gamma_{\text{PbPb}} \) and \( I^\gamma_{\text{PbPb}} \) for the hadron spectra per trigger photon will be slightly enhanced at small \( p_T^\gamma \) by the CNM effects. At very high \( p_T^\gamma \), the CNM effect has no influence on \( \gamma \)-hadron spectra in mid-rapidity [69] in both \( A + A \) and \( p + A \) collisions.

From the above numerical calculations, the effect of cold nuclear matter only leads to a slight enhancement of the \( \gamma \)-hadron spectra at intermediate \( p_T^\gamma = 26 \text{ GeV/c} \). The suppressions of \( \gamma \)-triggered hadron spectra should be mainly caused by parton energy loss if it is observed in \( A + A \) or in \( p + A \) collisions.

V. \( \gamma \)-TRIGGERED HADRON SPECTRA IN A + A COLLISIONS

In this section we will focus on the medium modification of \( \gamma \)-triggered hadron spectra in \( A + A \) collisions due to parton energy loss in our pQCD parton model. The dynamical evolution of the QGP medium is obtained using the (2+1)-dimensional viscous hydrodynamic model VISH2+1 with Monte-Carlo Glauber (MC-Glauber) initial conditions [78][81]. Shown in Fig. 6 are the calculated \( \gamma^{\text{dir}} \) (or \( \gamma^{\text{prompt}} \))-triggered fragmentation function in \( p + \text{Pb} \) collisions at \( \sqrt{s_{\text{NN}}} = 2.76 \text{ TeV} \) which agrees well with the PHENIX data [27]. We note that the fragmentation functions triggered by \( \gamma^{\text{prompt}} \) is similar to that triggered by \( \gamma^{\text{dir}} \) with the isolation cuts. Therefore, we only focus on \( \gamma^{\text{dir}} \)-hadron spectra in the following discussions.

The corresponding medium modification factor \( I^\gamma_{\text{AuAu}} \) for \( \gamma \)-triggered hadron spectra in 0 - 10% \( \text{Au + Au} \) collisions at 0.2 TeV with \( 8 < p_T^\gamma < 16 \text{ GeV/c} \), \( 3 < p_T^\gamma < 16 \) GeV/c (solid line) or \( 12 < p_T^\gamma < 20 \text{ GeV/c} \), 1.2 GeV/c/\( \Delta\phi \) (dashed line) are compared with STAR experimental data [29][30] in Fig. 8. In pQCD model calculations the initial jet transport coefficient \( \hat{c} = 1.5 \text{ GeV}^2/\text{fm} \) is used which is extracted from the suppression of single hadron spectra in central \( \text{Au + Au} \) collisions at 0.2 TeV shown in Fig. 7. One can see that \( \gamma \)-triggered hadron spectra are suppressed by nearly 80% due to jet quenching in central \( \text{Au + Au} \) collisions at \( \sqrt{s_{\text{NN}}} = 0.2 \text{ TeV} \).
except the last data point at small $z_T = 0.15$ where contrib-
tions from hadronization of radiated gluons and jet-
induced medium recoil partons [72] become important.
Our current pQCD model for medium modification needs
to be extended to include these effects.

We note that the modification factor $I_{\gamma/h}^{AA}$ as a func-
tion of $z_T$ increases slightly with $p_T^\gamma$ especially at inter-
mediate and small $z_T$. This is because the parton energy
loss has an energy dependence that is weaker than a lin-
ar dependence. The fraction of punch-through jets that
come out and fragment into hadrons without energy loss
also increases with $p_T^\gamma$ and leads to an increase of $I_{\gamma/h}^{AA}$.
Similarly, we can extract the initial jet transport coeffi-
cient $\hat{q}_0=1.8$ GeV$^2$/fm in Pb + Pb collisions at 2.76 TeV
and $\hat{q}_0=2.0$ GeV$^2$/fm in Pb + Pb collisions at 5.02 TeV
from the experimental data on the suppression of single
inclusive hadron spectra in 0 - 5% Pb + Pb collisions at these
two energies, respectively, as shown in Fig. 8. Note that
the initial jet transport coefficient in the center of the
most central Pb+Pb collisions at 5.02 TeV is almost
same as at 2.76 TeV, even though the charged hadron
rapidity density is about 20% higher at 5.02 TeV [76]. This
indicates that the ratio $\hat{q}_0/T_0^3$ decreases slightly with $T_0$
as indicated by the values extracted by the JET Collab-
oration [77].

Using these values of the initial jet transport coefficient
$\hat{q}_0$, we can predict the medium modification factors for $\gamma$
triggered hadron spectra in Pb + Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV
and 5.02 TeV for different (0 - 5%, 20 - 30%, 40 - 50%, 60 - 70%) centralities as shown in Fig. 10.

Two different ranges of $p_T^\gamma$ and $q_0$ are used: $12 < p_T^\gamma < 40$ GeV/c, $0.5 < p_T^\gamma < 15$ GeV/c for the results in the
upper panels and $40 < p_T^\gamma < 60$ GeV/c, $0.5 < p_T^\gamma < 45$ GeV/c in the lower panels.

FIG. 6. $\gamma^{\text{dir}} (\gamma^{\text{prompt}})$-triggered FFs with six different $p_T^\gamma$
ranges in p + p collisions at $\sqrt{s_{NN}} = 0.2$ TeV compared with
PHENIX data [27].

FIG. 7. The single hadron suppression factor (upper panel)
in 0 - 10% Au + Au collisions at $\sqrt{s_{NN}} = 0.2$ TeV compared with
PHENIX [70, 71] data and the corresponding $\chi^2/d.o.f$
of the fit as a function of the initial jet transport coefficient
$\hat{q}_0$ (lower panel).

FIG. 8. $\gamma^{\text{dir}}$-hadron suppression factors with $\hat{q}_0 = 1.5$
GeV$^2$/fm in 0 - 10% Au + Au collisions at $\sqrt{s_{NN}} = 0.2$ TeV
with 8 < $p_T^\gamma < 16$ GeV/c, 3 < $p_T^\gamma < 16$ GeV/c (solid) and
12 < $p_T^\gamma < 20$ GeV/c, 1.2 GeV/c < $p_T^\gamma < 1.8$ GeV (dashed) as compared with STAR data [29, 30].
From the left panel in Fig. 10 we see that $I_{PbPb}^{h}$ is about 0.4 in 0 - 5% central Pb + Pb collisions at 2.76 TeV and it increases with centrality. In 60 - 70% peripheral collisions, there is almost no suppression of $\gamma$-triggered hadron spectra. Similarly as at the RHIC energy, the suppression of $\gamma$-triggered hadron spectra becomes weaker at larger $p_T$. The results of $\gamma$-triggered hadron suppression at 5.02 TeV are almost the same as
at 2.76 TeV, similar to the situation for single charged hadron suppression [74].

VI. γ-TRIGGERED HADRON SPECTRA IN P + Pb COLLISIONS

In order to predict γ-triggered hadron spectra in p + Pb collisions in our pQCD model under the assumption that a small droplet QGP is formed, one only needs to provide the value of the initial jet transport coefficient $\hat{q}_0$. The dynamical evolution of the QGP droplet in p + Pb collisions is provided by superSONIC hydrodynamic model averaged over 200 Glauber initial conditions [12] per centrality. The centrality class is determined by the charged particle rapidity density $dN_{ch}/dγ$ for each event. Compared with Pb + Pb collisions [78–81], the hot medium in p + Pb collisions simulated by hydrodynamic model has a shorter evolution time and a lower central temperature [12]. From the superSONIC hydrodynamic model, the initial highest temperature at the center of the most central p + Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV is about the same as that in the most central Au + Au collisions at $\sqrt{s_{NN}} = 0.2$ TeV. We then assume $\hat{q}_0$ will also be similar and take $\hat{q}_0 = 1.5$ GeV$^2$/fm.

Even with the same initial jet transport coefficient, the total parton energy in p + Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV is still significantly smaller than that in the central Au + Au collisions at $\sqrt{s_{NN}} = 0.2$ TeV due to the much shorter lifetime of the QGP as shown in Fig. 11 where we plot the total energy loss of a quark that originates from the center of the hot medium in central p + Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV (solid) and central Au + Au collisions at $\sqrt{s_{NN}} = 0.2$ TeV (dot-dashed). The suppression of γ-triggered hadron spectra in p + Pb collisions should be significantly smaller than in Pb + Pb collisions.

To study the sensitivity of the total parton energy loss on the initial time $\tau_0$, we also vary $\tau_0$ in the calculation.
when a parton starts interacting with the hot medium and losing energy. We set the default (solid line) initial time $\tau_0 = 0.5$ fm/$c$ in p+Pb collisions as provided by the superSONIC hydrodynamic model. Plotted as the dashed line is the quark energy loss when we set the initial time. The variation of the total parton energy loss in this case is about 30%.

Shown in Fig. [12] are the predictions of the suppression factor for $\gamma$-triggered hadron spectra in 5.02 TeV p + Pb collisions with four different centralities for two different ranges of the transverse momentum of the trigger photon and hadron. For $12 < p_T^{\gamma} < 40$ GeV/$c$, $0.5 < p_T^h < 15$ GeV/$c$ in the upper panel, the $\gamma$-triggered hadron spectra in the most 0 - 10% central p + Pb collisions is suppressed by about 5% ~ 10%. The suppression becomes smaller in more peripheral collisions and disappears in the most 60 - 80% peripheral collisions. The shaded bands in these results indicate variations of the results when one varies the initial time for parton energy loss between $\tau_0 = 0.5$ and 1.0 fm/$c$.

For a large transverse momentum of the triggered photon, $40 < p_T^{\gamma} < 60$ GeV/$c$, $0.5 < p_T^h < 45$ GeV/$c$ (the lower panels), the suppression factor for $\gamma$-triggered hadron spectra is close but smaller than 1 in the most central p + Pb collisions. And the effect of varying initial time from $\tau_0 = 0.5$ to 1.0 fm/$c$ on the suppression factor is almost indistinguishable when $p_T^{\gamma}$ is larger.

Overall, if we assume QGP droplet is formed and can be described by hydrodynamic evolution in p + Pb collisions, $\gamma$-hadron spectra will be suppressed by about 5%~10% due to jet quenching and the suppression becomes weaker with for increasing $p_T^{\gamma}$.

VII. SUMMARY

In this paper, under the assumption that a QGP droplet is produced in p + Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV and its evolution can be described by hydrodynamics, we study the suppression of $\gamma$-triggered hadron spectra within NLO perturbative QCD parton model with medium modified fragmentation function due to parton energy loss. The evolution of the medium and its temperature profile is simulated event-by-event using the superSONIC model, while the parton energy loss is calculated within the high-twist formalism. We have taken into account and illustrated the CNM effect on $\gamma$-hadron spectra which is negligible on the $\gamma$-triggered hadron spectra (hadron yield per trigger) and the net suppression of $\gamma$-hadron spectra is mainly caused by parton energy loss. With the effect of jet quenching, we predict that $\gamma$-triggered hadron spectra are suppressed by about 5% ~ 10% for $12 < p_T^{\gamma} < 60$ GeV/$c$ in the most 0 - 10% central p + Pb collisions at 5.02 TeV, with the initial jet transport coefficient $q_0$ extracted from the suppression of single hadron spectra in A + A collisions. The suppression is shown to decrease with increasing $p_T^{\gamma}$. We also provided prediction of $\gamma$-hadron suppression in Pb + Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ and 5.02 TeV which are similar because similar values of $q_0$ as extracted from the suppression of single hadron spectra in Pb + Pb collisions at these two energies. The experimental measurements of such suppression could provide much stringent constraints on the formation of QGP droplets in p + A collisions without the complication of the determination of number of binary collisions in any given class of centrality.

ACKNOWLEDGMENTS

We would like to thank Jamie Nagle, Jeffrey Ouellette and Paul Romatschke for providing the superSONIC hydro profiles of p+Pb collisions used in this study. This work is supported by National Natural Science Foundation of China under grant Nos. 11935007, 11221504 and 11890714, the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Division of Nuclear Physics, of the U.S. Department of Energy under grant No. DE-AC02-05CH11231, the National Science Foundation (NSF) under grant No. ACI-1550228 within the framework of the JETSCAPE Collaboration.

[1] M. Gyulassy and M. Plumer, Phys. Lett. B 243, 432 (1990). doi:10.1016/0370-2693(90)91409-5
[2] X. N. Wang and M. Gyulassy, Phys. Rev. Lett. 68, 1480 (1992). doi:10.1103/PhysRevLett.68.1480
[3] G. Y. Qin and X. N. Wang, Int. J. Mod. Phys. E 24, no. 11, 1530014 (2015) [arXiv:1511.0090] [hep-ph].
[4] A. Adare et al. [PHENIX Collaboration], Phys. Rev. Lett. 105, 142301 (2010) doi:10.1103/PhysRevLett.105.142301 [arXiv:1006.3740] [nucl-ex].
[5] S. Chatrchyan et al. [CMS Collaboration], Phys. Rev. Lett. 109, 022301 (2012) doi:10.1103/PhysRevLett.109.022301 [arXiv:1204.1850] [nucl-ex].
[6] B. Abelev et al. [ALICE Collaboration], Phys. Lett. B 719, 18 (2013) doi:10.1016/j.physletb.2012.12.066 [arXiv:1205.5761] [nucl-ex].
[7] G. Aad et al. [ATLAS Collaboration], Phys. Lett. B 707, 330 (2012) doi:10.1016/j.physletb.2011.12.056 [arXiv:1108.6018] [hep-ex].
[8] A. M. Sirunyan et al. [CMS Collaboration], Phys. Lett. B 776, 195 (2018) doi:10.1016/j.physletb.2017.11.041 [arXiv:1702.00630] [hep-ex].
[9] S. Chatrchyan et al. [CMS Collaboration], Phys. Lett. B 718, 795 (2013) doi:10.1016/j.physletb.2012.11.025 [arXiv:1210.5482] [nucl-ex].
