\( \gamma \)-hadron spectra in \( p + Pb \) collisions at \( \sqrt{s_{NN}} = 5.02 \) TeV

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Outline

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The energetic jet loses a large amount of its energy via radiating gluon induced by multiple scattering.

JQ as reflected in $R_{AA}(p_T)$ and $v_2(p_T)$ of hadron spectra are two key evidences for the formation of QGP in HIC.
In $p + Pb$ collisions at $\sqrt{s_{NN}} = 5.02$ TeV:

QGP is formed?

- $v_2\{2\}$ and $v_2\{4\}$ in 5.02 TeV $p + Pb$ collisions show a similar behavior of the collective flow as in Pb + Pb collisions.
Motivation

In \( p + \text{Pb} \) collisions at \( \sqrt{s_{NN}} = 5.02 \) TeV:

- QGP is formed?
- QGP is not formed?

\( v_2 \{2\} \) and \( v_2 \{4\} \) in 5.02 TeV \( p + \text{Pb} \) collisions show a similar behavior of the collective flow as in \( \text{Pb} + \text{Pb} \) collisions.

- Single jet and charged hadron spectra do not indicate strong JQ phenomena.
Motivation

In $p + Pb$ collisions at $\sqrt{s_{NN}} = 5.02$ TeV:

- For single hadron or jet: determining $\langle N_{binary} \rangle$ is problematic for $p + A$.
- For dihadron and dijet: they prefer surface and tangential emission.
- $\gamma$-jet production is a “golden probe” for studying $\Delta E_{loss}$.

The color-neutral photon does not interact strongly with the QGP matter and can be used to best approximate the $p_T$ of the accompanying jet.
Jet energy loss, $\hat{q}$, hydrodynamic model

Assume: parton will lose energy in $p + A$ collisions

- Jet energy loss in QGP medium $\Delta E \propto \hat{q} \Rightarrow$ Jet transport coefficient:
  \[
  \equiv \frac{d\langle q^2 \rangle}{dL} : \text{transverse momentum broadening squared per unit length.}
  \]
  [BDMPS, NPB 483 (1997) 291]

- $\hat{q}$ depends on the local $T$ in the jet trajectory:
  \[
  \hat{q} = \hat{q}_0 \frac{T^3}{T_0^3} \frac{p \cdot u}{p_0}.
  \]

- The dynamic evolution of the matter created in $p + Pb$ collisions at $\sqrt{s_{NN}} = 5.20$ TeV is from event-by-event simulations of the superSONIC hydrodynamic model. [R. D. Weller, P. Romatschke, Phys. Lett. B 774, 351 (2017)]

\[\text{(Man Xie CCNU)}\]

\(\gamma\)-h spectra in 5.02 TeV $p + Pb$ collisions

\[T_0(p + Pb) \sim T_0(Au + Au) \Rightarrow \hat{q}_0(p + Pb) \sim \hat{q}_0(Au + Au)\]

[M. Xie, S. Y. Wei, G. Y. Qin, H. Z. Zhang, EPJC 79, no. 7, 589 (2019)]
NLO pQCD parton model

In p + A collisions

- \( \gamma^{\text{direct}} \): \( qg \rightarrow q\gamma \) and \( q\bar{q} \rightarrow g\gamma \);
- \( \gamma^{\text{frag}} \): collinear fragmentation of final-state partons;
- \( \gamma^{\text{prompt}} \): the combination of above sources.

The invariant cross section of \( \gamma \) productions can be expressed as,

\[
\frac{d\sigma_{\gamma pA}}{dyd^2p_T} = \sum_{abcd} \int d^2r \int_{x_{\text{amin}}}^{1} dx_a t_A(\vec{r}) f_a/A(x_a, \mu^2) f_b/p(x_b, \mu^2) \\
\times \frac{2}{\pi} \frac{x_ax_b}{2x_a - x_T e^y} \frac{d\sigma_{ab\rightarrow\gamma d}}{d\hat{t}} + O(\alpha_e \alpha_s^2). \tag{1}
\]

The invariant cross section of \( \gamma \)-triggered hadron productions can be written as,

\[
\frac{d\sigma_{\gamma h pA}}{dy \gamma d^2p_T dy^h d^2p_T} = \sum_{abcd} \int d^2rdz_d t_A(\vec{r}) f_a/A(x_a, \mu^2) f_b/p(x_b, \mu^2) \\
\times \frac{x_ax_b}{\pi z_d^2} \frac{d\sigma_{ab\rightarrow\gamma d}}{d\hat{t}} \tilde{D}_{h/d}(z_d, \mu^2, \Delta E) + O(\alpha_e \alpha_s^2). \tag{2}
\]


(Man Xie CCNU)  \( \gamma \)-h spectra in 5.02 TeV p + Pb collisions June 4, 2020 8 / 23
Modified fragmentation functions — mFFs

- Modified fragmentation functions in QGP medium:

\[
\tilde{D}_{h/d}(z_d, \mu^2, \Delta E_d) = (1 - e^{-\langle N_g \rangle}) \left[ \frac{Z_d'}{Z_d} D_{h/d}(z_d', \mu^2) + \langle N_g \rangle \frac{Z_g'}{Z_d} D_{h/g}(z_g', \mu^2) \right] + e^{-\langle N_g \rangle} D_{h/d}(z_d, \mu^2),
\]

where \( z_d' = p_T/(p_{Td} - \Delta E_d) \), \( z_g' = \langle N_g \rangle p_T/\Delta E_d \).


- Total energy loss of jet in high-twist method:

\[
\frac{\Delta E_d}{E} = 2C_A\alpha_s \frac{1}{\pi} \int d\tau \int \frac{dl_T^2}{l_T^4} \int dz \left[ 1 + (1 - z)^2 \right] \hat{q} \sin^2 \left( \frac{l_T^2(\tau - \tau_0)}{4z(1 - z)E} \right)
\]

The nuclear modification factor of direct $\gamma$:

$$R_{pA}^{\gamma}(p_T) = \frac{d\sigma_{pA}^{\gamma}/dyd^2p_T}{\langle N_{\text{binary}} \rangle d\sigma_{pp}^{\gamma}/dyd^2p_T}$$  \hspace{1cm} (5)$$

The nuclear modification factor of $\gamma$-triggered fragmentation function:

$$I_{pA}^{\gamma h}(z_T) = \frac{D_{pA}^{\gamma h}(z_T)}{D_{pp}^{\gamma h}(z_T)}$$  \hspace{1cm} (6)$$

The $\gamma$-triggered fragmentation function:

$$D_{pA}^{\gamma h}(z_T) = \frac{p_Td\sigma_{pA}^{\gamma h}/dy^\gamma dp_T^{\gamma h}dy^h dp_T^h d\phi}{d\sigma_{pA}^{\gamma}/dy^\gamma dp_T^{\gamma}}$$  \hspace{1cm} (7)$$
The pQCD parton model can describe the experimental data well.

With isolation cuts the contributions of fragmentation photon are about 10% in 200 GeV Au + Au collisions.
Direct photon production cross section

**200 GeV Au + Au**

- $0.2 \text{ TeV, } \text{Au} + \text{Au} \rightarrow \gamma + X$
- $R_{\text{cone}} < 0.5, E_{\text{had}} < 0.1E_{\gamma}, |\eta| < 0.35$
- $\gamma_{\text{direct}}, \text{NLO pQCD}, \mu = 1.2p$
- CT14 PDF, EPPS16, BFG II FF

**2.76 TeV Pb + Pb**

- $2.76 \text{ TeV, } \text{Pb} + \text{Pb} \rightarrow \gamma + X$
- $R_{\text{cone}} < 0.4, E_{\text{had}} < 5.0 \text{ GeV}, |\eta| < 1.44$
- $\gamma_{\text{direct}}, \text{NLO pQCD}$
- $p + p$
- $\text{Pb} + \text{Pb}$

**5.02 TeV p (Pb) + Pb**

- $5.02 \text{ TeV, } 0 - 10\%, \text{Pb} + \text{Pb} \rightarrow \gamma + X$
- $R_{\text{cone}} < 0.4, E_{\text{had}} < 1.0 \text{ GeV}, |\eta| < 1.44$
- $\gamma_{\text{direct}}, \text{NLO pQCD}$
- $(p + p) \times 10^{4}$
- $(\text{Pb} + \text{Pb}) \times 10^{4}$

- $(p + \text{Pb}) \times 10^{3}$

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- One can neglect the contributions of fragmentation photons with isolation cuts.
- The pQCD parton model can describe the experimental data well at any collisions energies.
$R^{\gamma}(\text{CNM})$ and $I^{\gamma+h^\pm}(\text{CNM})$ both are approximately equal to one in central Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV.
Without jet energy loss!

- $R_\gamma$ (CNM) and $I_{\gamma+h^\pm}$ (CNM) approximately equal to one in central Au + Au collisions.

- The CNM effect leads to a slight enhancement of the $\gamma$-hadron spectra $p_T^{\gamma} < 35$ GeV/c in central Pb + Pb and p + Pb collisions.

- The net suppressions of $\gamma$-triggered hadron spectra should be mainly caused by parton energy loss if it is observed in A + A or p + A collisions.
Fragmentation functions triggered by $\gamma^{prompt}$ is similar to that triggered by $\gamma^{direct}$ with the isolation cuts.
Fragmentation functions triggered by $\gamma^{\text{prompt}}$ is similar to that triggered by $\gamma^{\text{direct}}$ with the isolation cuts.
We can only focus on $\gamma^{\text{dir}}$-hadron spectra.

- $\gamma$-trigger hadron spectra are suppressed by nearly 80% due to JQ in central Au + Au collisions at 200 GeV.

- Our results are consistent with the experimental data.
$\hat{q}_0$ via single hadron in Pb + Pb collisions

2.76 TeV Pb+Pb:

at $T_0 = 486$ MeV $\hat{q}_0 = 1.8$ GeV$^2$/fm

5.02 TeV Pb+Pb:

at $T_0 = 516$ MeV $\hat{q}_0 = 2.0$ GeV$^2$/fm
γ-triggered hadron spectra in Pb + Pb collisions

**2.76 TeV Pb + Pb**

- $\hat{q}_0 = 1.8 \text{ GeV}^2/\text{fm}$
- $12 < p_\gamma \leq 40 \text{ GeV}/c$, $0.5 < p_h \leq 15 \text{ GeV}/c$
- $q_0 = 1.8 \text{ GeV}$
- $T < 1.2 \text{ fm}$
- $|\eta_\gamma| < 0.67$, $|\eta_h| < 1.2$
- $|\Delta\phi| > \frac{2\pi}{3}$

In 0 - 5%, $I_{A+A}^{\gamma+h^\pm} \approx 0.4$; In 60 - 70%, $I_{A+A}^{\gamma+h^\pm} \approx 1$

The suppression becomes weaker at larger $p_\gamma^\pm$.

The suppression at 5.02 TeV are almost the same as at 2.76 TeV, similar to the situation for single charged hadron suppression.

**5.02 TeV Pb + Pb**

- $\hat{q}_0 = 2.0 \text{ GeV}^2/\text{fm}$
- $12 < p_\gamma \leq 40 \text{ GeV}/c$, $0.5 < p_h \leq 15 \text{ GeV}/c$
- $q_0 = 2.0 \text{ GeV}$
- $T < 1.5 \text{ GeV}$
- $|\eta_\gamma| < 0.67$, $|\eta_h| < 1.2$
- $|\Delta\phi| > \frac{2\pi}{3}$

(Man Xie CCNU)
Assume: a small droplet QGP is formed in p + A collisions

- $T_0(p + Pb) \sim T_0(Au + Au) \rightarrow \hat{q}_0(p + Pb) \sim \hat{q}_0(Au + Au) = 1.5 \text{ GeV}^2/\text{fm}$
- With the same $\hat{q}_0$, the parton $\Delta E$ in central 5.02 TeV p + Pb collisions is still significantly smaller than that in the central 200 GeV Au + Au collisions.
- The variation of the total parton energy loss with $\tau_0 = 0.5 \text{ fm}/c$ or with 1.0 $\text{ fm}/c$ in this case is about 30%.
Assume: a small QGP droplet is formed in p + A collisions

The shaded bands indicate variations of the results when one changes the initial time for parton-medium interaction between $\tau_0 = 0.5$ and $1.0 \text{ fm}/c$.

$\gamma$-hadron spectra will be suppressed by about $5\% \sim 10\%$ in central 5.02 TeV p+Pb collisions due to JQ and the suppression becomes weaker with for increasing $p_T^\gamma$. 

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Under the assumption that a QGP droplet is produced and its evolution can be described by hydrodynamics in p + A collisions, \( \gamma \)-triggered hadron spectra are studied within a NLO pQCD parton model with the medium-modified parton FFs.

The dynamical evolution of the matter created in p+Pb collisions is from e-b-e simulations of the superSONIC hydrodynamic model and parton \( \Delta E \) in such a medium is described by the HT approach.

The CNM effect is negligible and the net suppression of \( \gamma \)-hadron spectra is mainly caused by parton energy loss.

\( \gamma \)-hadron spectra at \( p_\perp^\gamma = 12 - 40 \) GeV/c are suppressed by 5%\textasciitilde10% in the most central 0 - 10% p + Pb collisions at \( \sqrt{s_{\text{NN}}} = 5.02 \) TeV.

\( \gamma \)-hadron suppression in Pb + Pb collisions at \( \sqrt{s_{\text{NN}}} = 2.76 \) and 5.02 TeV is also predicted.

On going: we are working on single hadron, di-hadron spectra in p + Pb collisions ...
THANK YOU!