

γ -hadron spectra in p + Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$

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[arXiv : 2003.02441]

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Hard Probes 2020

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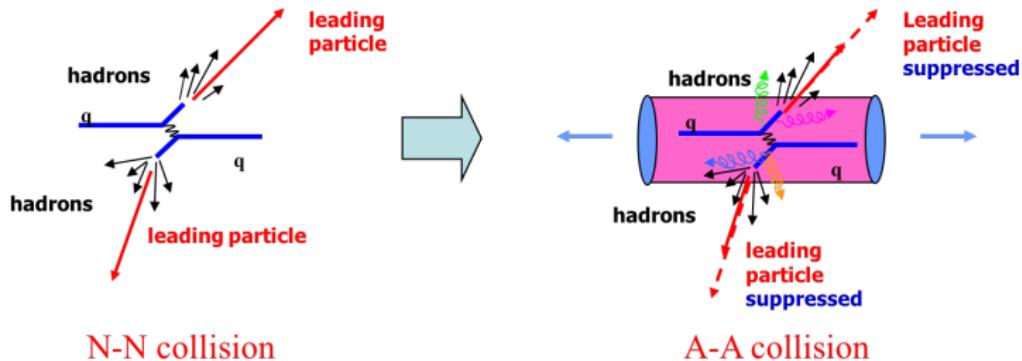


Outline

- Motivation
- pQCD parton model and JQ mFFs
- Direct photon production cross section
- CNM effect on direct photon and γ -hadron spectra
- γ -triggered hadron spectra in A + A and p + A collisions
- Summary and outlook

Introduction

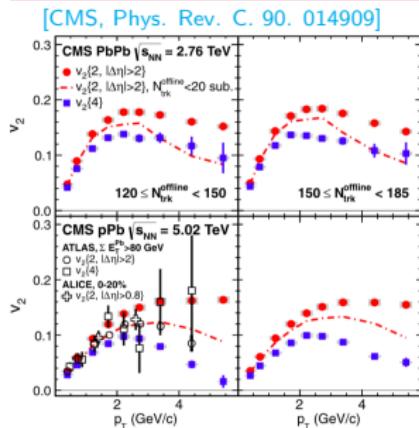
- Jet quenching: [X.-N. Wang and M. Gyulassy, Phys. Rev. Lett. 68, 1480 (1992)]
The energetic jet losses a large amount of its energy via radiating gluon induced by multiple scattering.



- 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.

Motivation

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



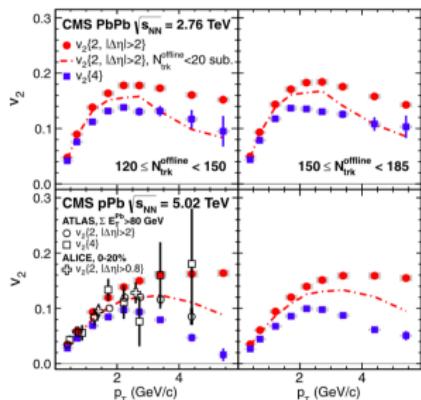
QGP is formed?

- $v_2\{2\}$ 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

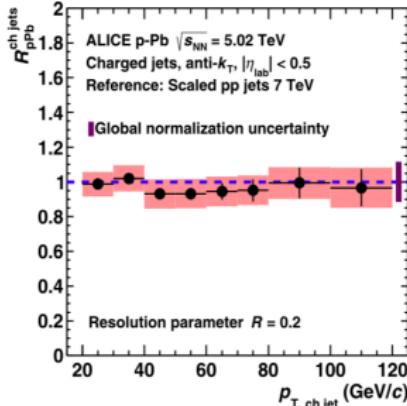
In $p + Pb$ collisions at $\sqrt{s_{NN}} = 5.02$ TeV:

[CMS, Phys. Rev. C. 90. 014909]



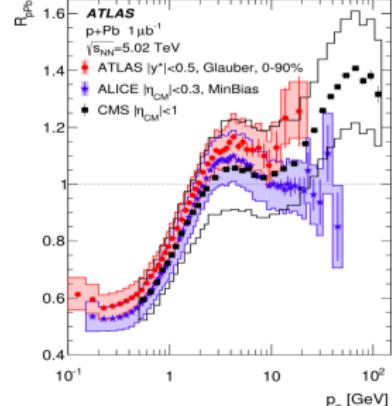
QGP is formed?

[ALICE, Phys. Lett. B 749, 68 (2015)]



QGP is not formed?

[ATLAS, Phys. Lett. B 763, 313 (2016)]

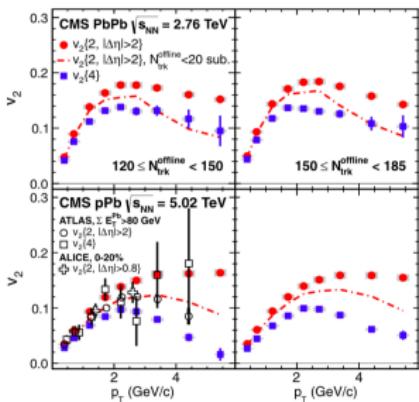


- $v_2\{2\}$ and $v_2\{4\}$ in 5.02 TeV $p + Pb$ collisions show a similar behavior of the collective flow as in $Pb + Pb$ collisions.
- Single jet and charged hadron spectra do not indicate strong JQ phenomena.

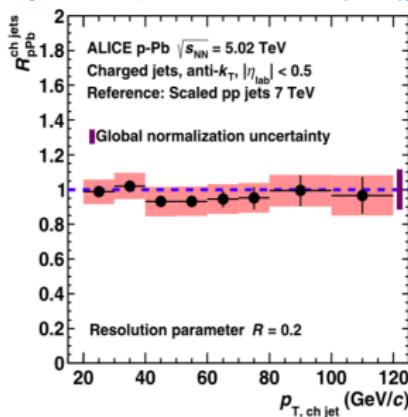
Motivation

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

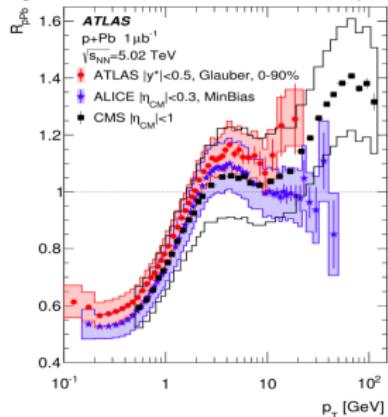
[CMS, Phys. Rev. C. 90. 014909]



[ALICE, Phys. Lett. B 749, 68 (2015)]



[ATLAS, Phys. Lett. B 763, 313 (2016)]



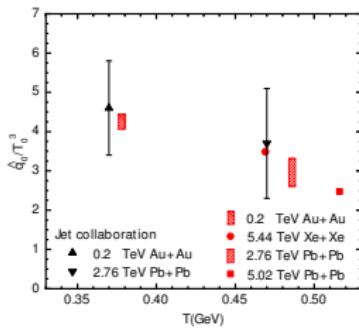
- For single hadron or jet: determining $\langle N_{\text{binary}} \rangle$ is problematic for $p + A$.
- For dihadron and dijet: they prefer surface and tangential emission.
- γ -jet production is a “golden probe” for studying ΔE_{loss} .

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.

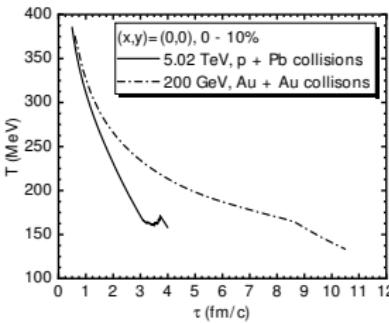
Jet energy loss, \hat{q} , hydrodynamic model

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

- Jet energy loss in QGP medium $\Delta E \propto \hat{q} \Rightarrow$ Jet transport coefficient:
 $\equiv \frac{d\langle q_T^2 \rangle}{dL}$: transverse momentum broadening squared per unit length.
[BDMPS, NPB 483 (1997) 291]
- \hat{q} depends on the local T in the jet trajectory: $\hat{q} = \hat{q}_0 \frac{T^3}{T_0^3} \frac{p \cdot u}{p_0}$.
[X. Chen, T. Hirano, E. Wang, X.-N. Wang, H. Z. Zhang, Phys. Rev. C84 (2011) 034902]
- 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)]



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



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

NLO pQCD parton model

In p + A collisions

- γ^{direct} : $qg \rightarrow q\gamma$ and $q\bar{q} \rightarrow g\gamma$;
- γ^{frag} : collinear fragmentation of final-state partons;
- γ^{prompt} : the combination of above sources.
- The invariant cross section of direct γ productions can be expressed as,

$$\frac{d\sigma_{pA}^{\gamma}}{dy d^2 p_T} = \sum_{abd} \int d^2 r \int_{x_{amin}}^1 dx_a t_A(\vec{r}) f_{a/A}(x_a, \mu^2) f_{b/p}(x_b, \mu^2) \times \frac{2}{\pi} \frac{x_a x_b}{2x_a - x_T e^y} \frac{d\sigma_{ab \rightarrow \gamma d}}{dt} + \mathcal{O}(\alpha_e \alpha_s^2). \quad (1)$$

- The invariant cross section of γ -triggered hadron productions can be written as,

$$\frac{d\sigma_{pA}^{\gamma h}}{dy^\gamma d^2 p_T^\gamma dy^h d^2 p_T^h} = \sum_{abd} \int d^2 r dz_d t_A(\vec{r}) f_{a/A}(x_a, \mu^2) f_{b/p}(x_b, \mu^2) \times \frac{x_a x_b}{\pi z_d^2} \frac{d\sigma_{ab \rightarrow \gamma d}}{dt} \tilde{D}_{h/d}(z_d, \mu^2, \Delta E) + \mathcal{O}(\alpha_e \alpha_s^2). \quad (2)$$

- CT14 PDF, EPPS16 nPDF, KKP FFs [Phys. Rev. D 95, no. 3, 034003 (2017), [Eur. Phys. J. C 77, no. 3, 163 (2017)], [Phys. Rev. D 62, 054001 (2000)]

Modified fragmentation functions — mFFs

- Modified fragmentation functions in QGP medium:

$$\begin{aligned}\tilde{D}_{h/d}(z_d, \mu^2, \Delta E_d) = & (1 - e^{-\langle N_g \rangle}) \left[\frac{z'_d}{z_d} D_{h/d}(z'_d, \mu^2) + \langle N_g \rangle \frac{z'_g}{z_d} D_{h/g}(z'_g, \mu^2) \right] \\ & + e^{-\langle N_g \rangle} D_{h/d}(z_d, \mu^2),\end{aligned}\quad (3)$$

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

[X.-N. Wang, PRC70 (2004) 031901], [H. Z. Zhang, J.F. Owens, Enke Wang, X.-N. Wang, Phys. Rev. Lett. 98, 212301 (2007)], and [H. Z. Zhang, J.F. Owens, Enke Wang, X.-N. Wang, Phys. Rev. Lett. 103, 032302 (2009)]

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

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

[W.T. Deng and X.-N. Wang, Phys. Rev. C 81, 024902 (2010)], [E. Wang and X.-N. Wang, Phys. Rev. Lett. 87, 142301 (2001); 89, 162301 (2002)]

Nuclear modification factor

In p + A collisions

- The nuclear modification factor of direct γ :

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

- The nuclear modification factor of γ -triggered fragmentation function:

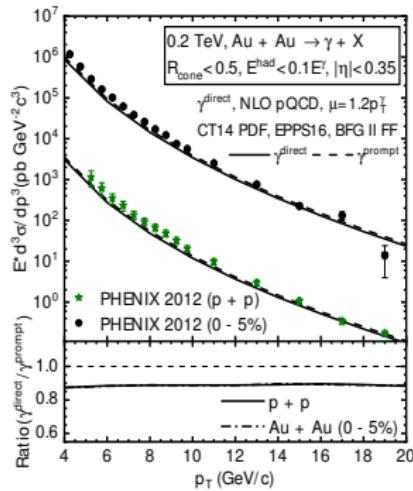
$$I_{pA}^{\gamma h}(z_T) = \frac{D_{pA}^{\gamma h}(z_T)}{D_{pp}^{\gamma h}(z_T)} \quad (6)$$

- The γ -triggered fragmentation function:

$$D_{pA}^{\gamma h}(z_T) = \frac{p_T^{\gamma} d\sigma_{pA}^{\gamma h}/dy^{\gamma} dp_T^{\gamma} dy^h dp_T^h d\phi}{d\sigma_{pA}^{\gamma}/dy^{\gamma} dp_T^{\gamma}} \quad (7)$$

Direct photon production cross section

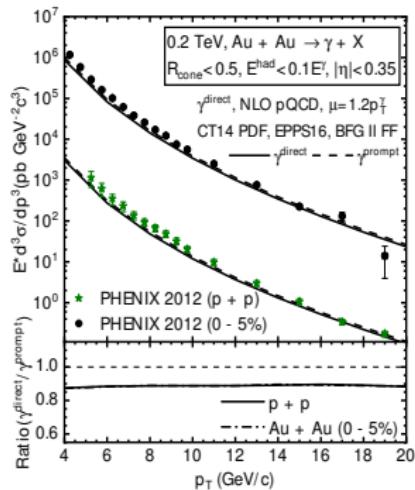
200 GeV Au + Au



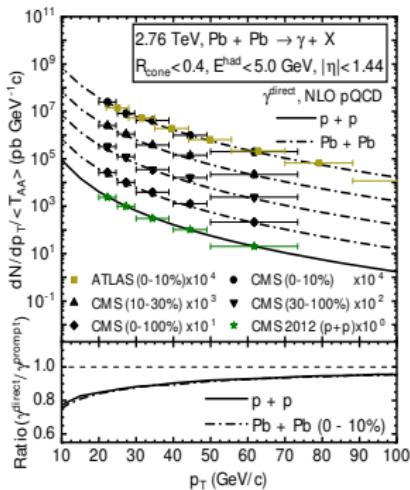
- The pQCD parton model can describe the experimental data well.
- With isolation cuts the contributions of fragmentation photon are about 10% in 200 GeV Au + Au collisions.

Direct photon production cross section

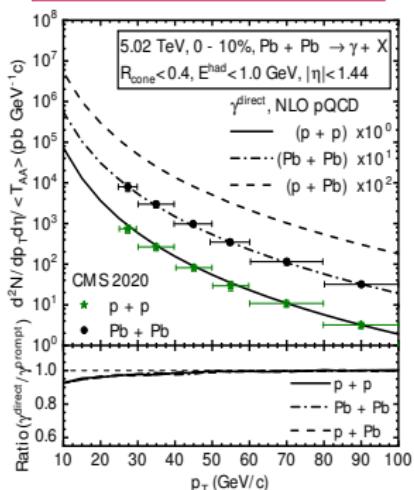
200 GeV Au + Au



2.76 TeV Pb + Pb



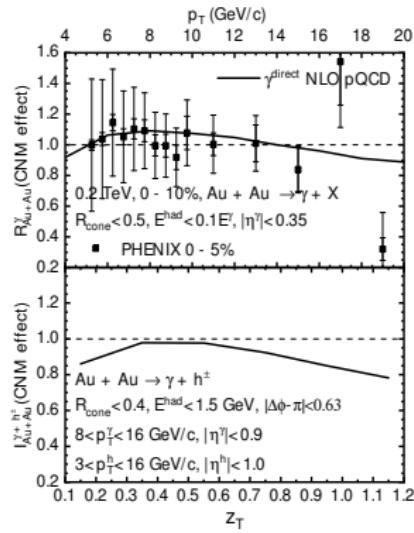
5.02 TeV p (Pb) + Pb



- 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.

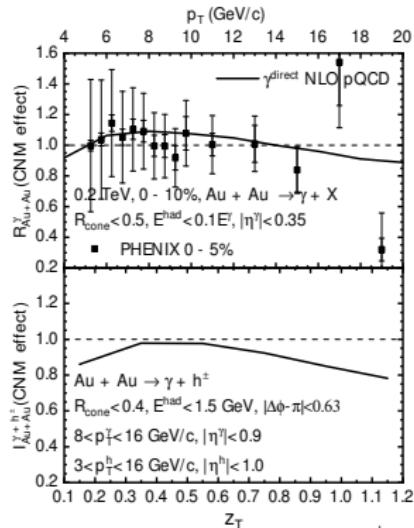
CNM effect on direct photon and γ -hadron spectra

200 GeV Au + Au

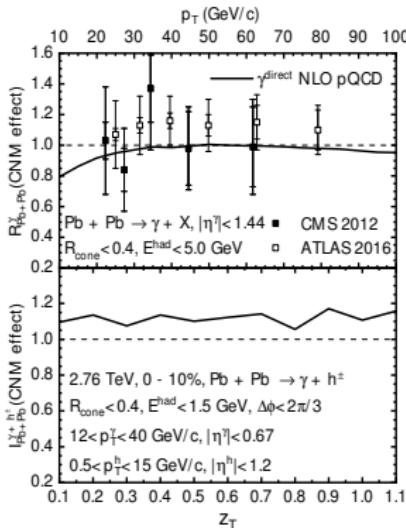


- $R^\gamma(\text{CNM})$ and $R^{\gamma+h^\pm}(\text{CNM})$ both are approximately equal to one in central Au + Au collisions at $\sqrt{s_{NN}} = 200 \text{ GeV}$.

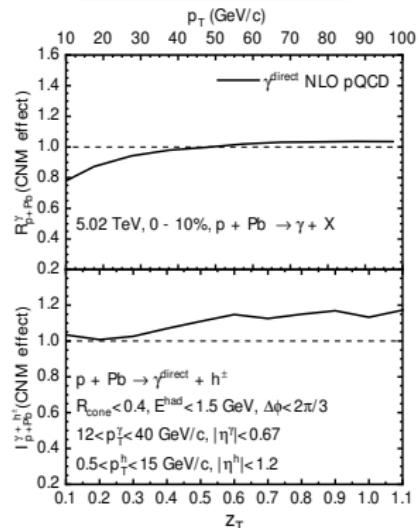
200 GeV Au + Au



2.76 TeV Pb + Pb

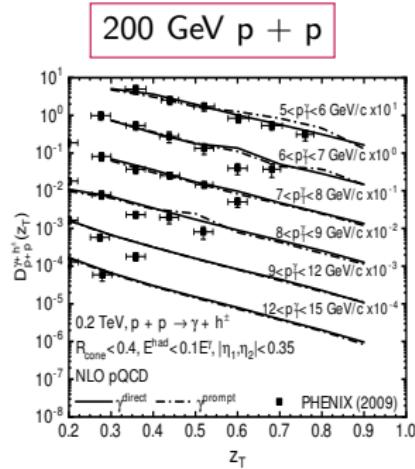


5.02 TeV p + Pb



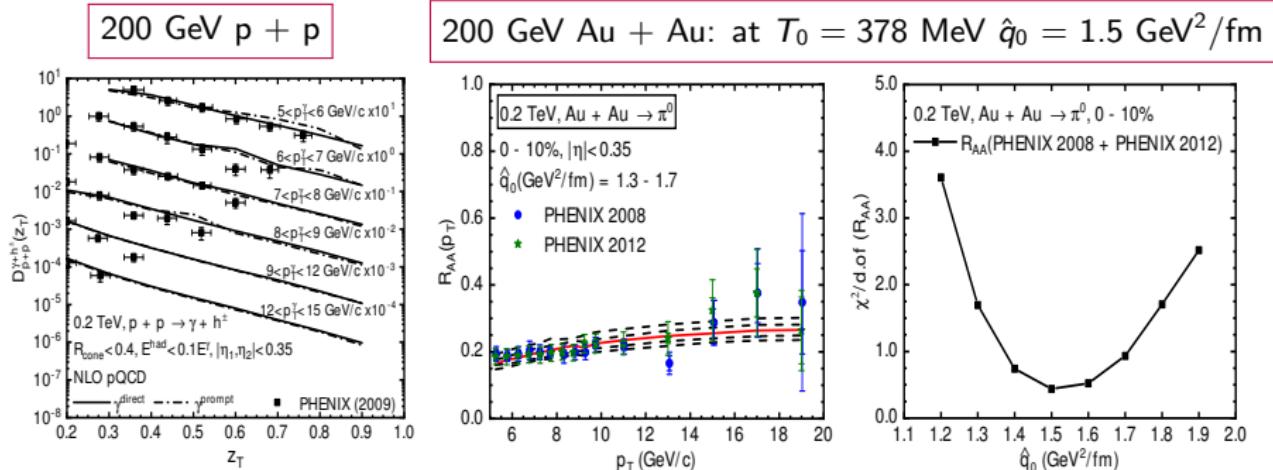
- $R^\gamma(\text{CNM})$ and $I^{\gamma+h^\pm}(\text{CNM})$ approximately equal to one in central Au + Au collisions.
- The CNM effect leads to a slight enhancement of the γ -hadron spectra $p_T^\gamma < 35$ GeV/c in central Pb + Pb and p + Pb collisions.
- The net suppressions of γ -triggered hadron spectra should be mainly caused by parton energy loss if it is observed in A + A or p + A collisions.

γ -triggered hadron spectra in 200 GeV Au + Au collisions



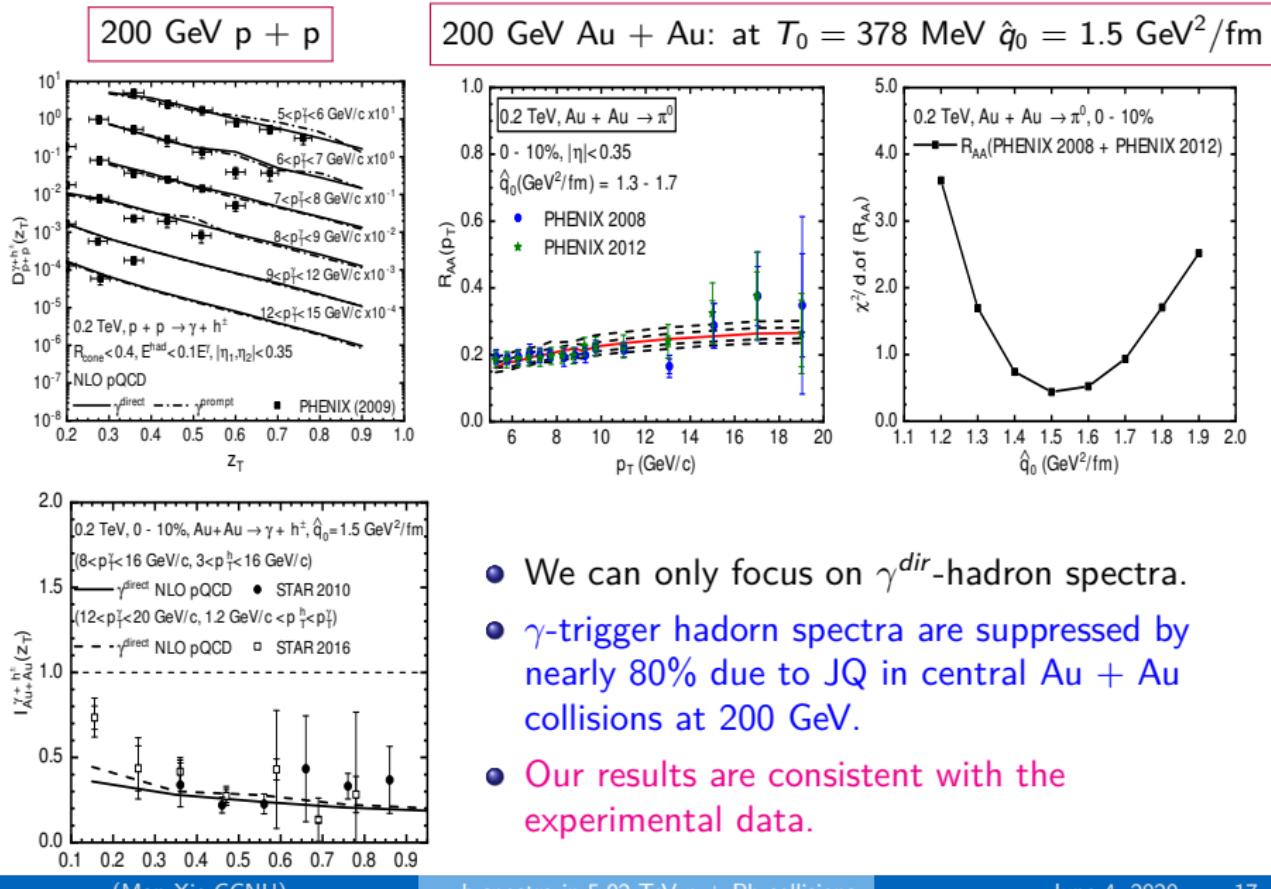
- Fragmentation functions triggered by γ^{prompt} is similar to that triggered by γ^{direct} with the isolation cuts.

γ -triggered hadron spectra in 200 GeV Au + Au collisions



- Fragmentation functions triggered by γ^{prompt} is similar to that triggered by γ^{direct} with the isolation cuts.

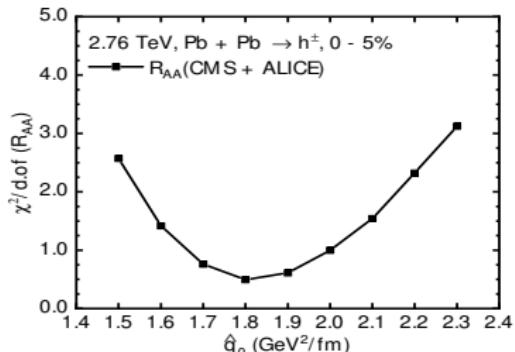
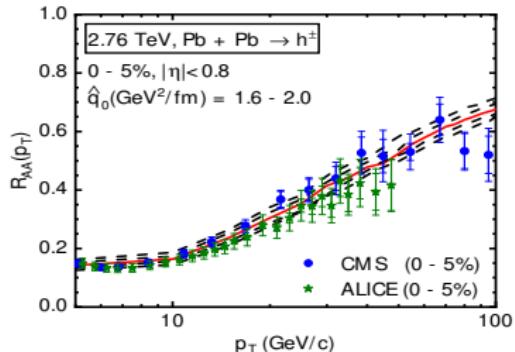
γ -triggered hadron spectra in 200 GeV Au + Au collisions



\hat{q}_0 via single hadron in Pb + Pb collisions

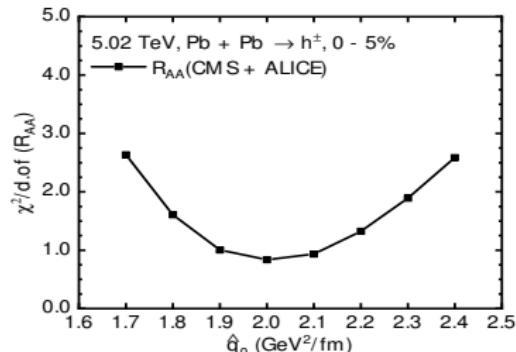
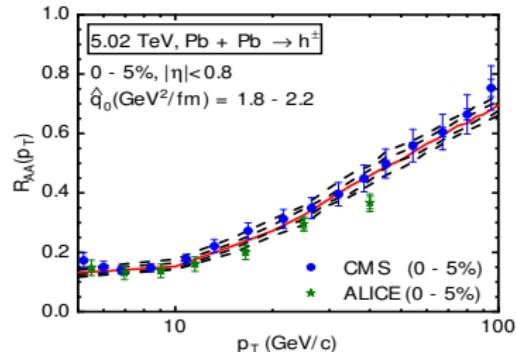
2.76 TeV Pb+Pb:

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

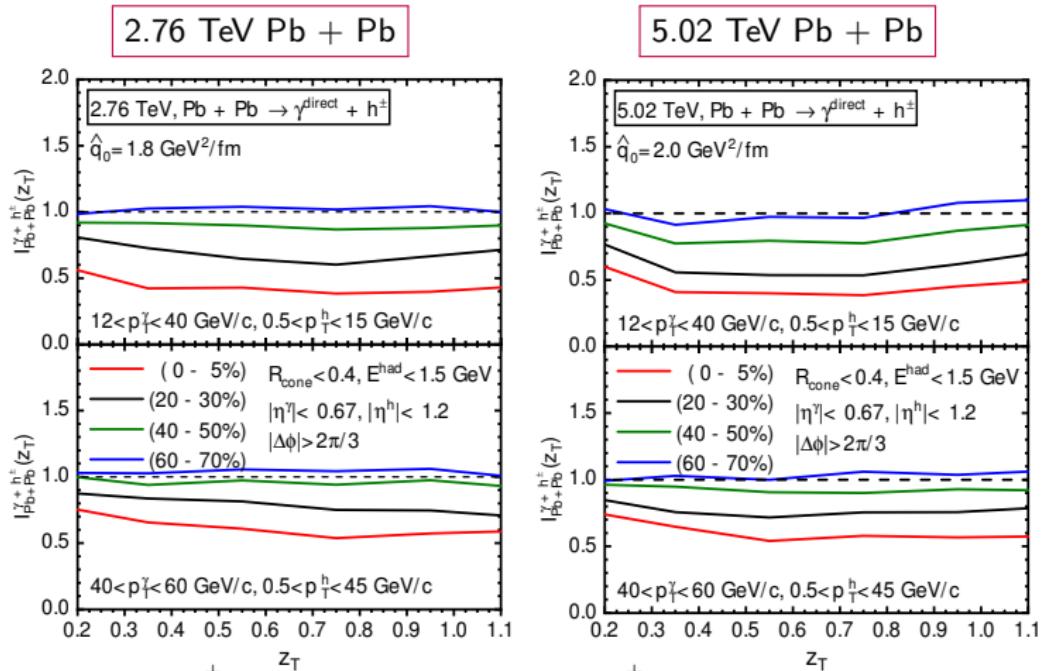


5.02 TeV Pb+Pb:

at $T_0 = 516$ MeV $\hat{q}_0 = 2.0$ GeV 2 /fm



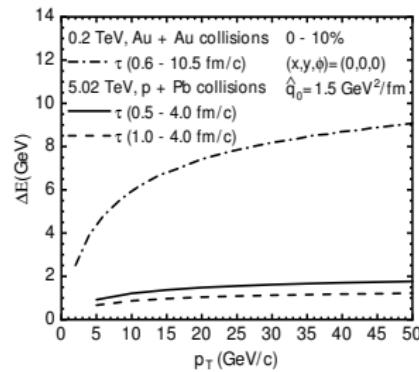
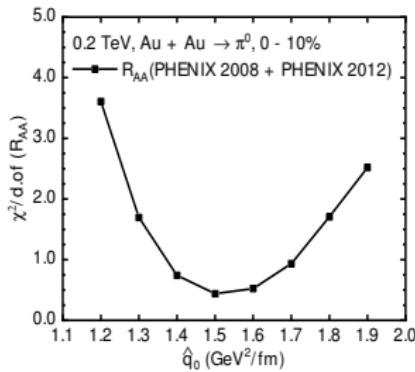
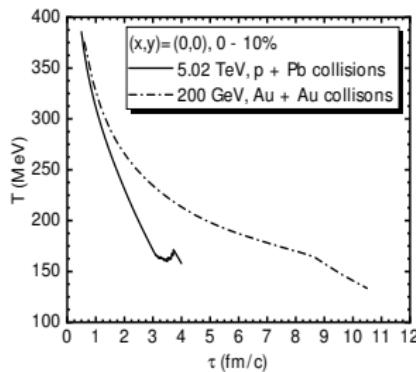
γ -triggered hadron spectra in Pb + Pb collisions



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

γ -triggered hadron spectra in p + Pb collisions

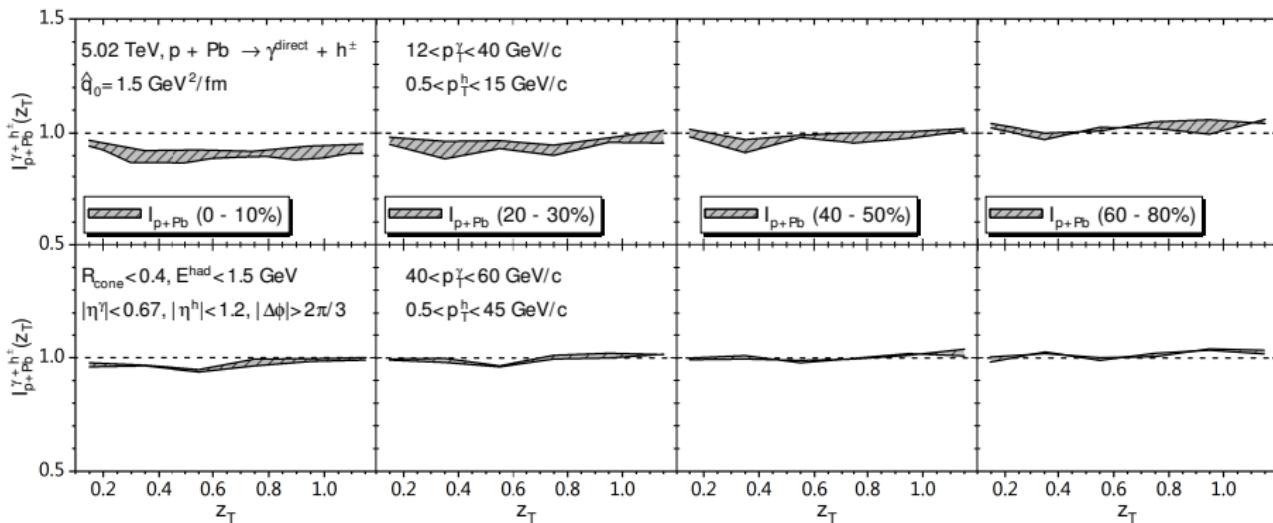
Assume: a small droplet QGP is formed in p + A collisions



- $T_0(p + \text{Pb}) \sim T_0(\text{Au} + \text{Au}) \implies \hat{q}_0(p + \text{Pb}) \sim \hat{q}_0(\text{Au} + \text{Au}) = 1.5 \text{ GeV}^2/\text{fm}$
- With the same \hat{q}_0 , the parton ΔE 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%.

γ -triggered hadron spectra in 5.02 TeV p + Pb collisions

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 $1.0 \text{ fm}/c$.

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

Summary and outlook

- Under the assumption that a QGP droplet is produced and its evolution can be described by hydrodynamics in p + A collisions, γ -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 ΔE in such a medium is described by the HT approach.
- The CNM effect is negligible and the net suppression of γ -hadron spectra is mainly caused by parton energy loss.
- γ -hadron spectra at $p_T^\gamma = 12 - 40$ GeV/c are suppressed by 5%~10% in the most central 0 - 10% p + Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.
- γ -hadron suppression in Pb + Pb collisions at $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV is also predicted.
- On going: we are working on single hadron, di-hadron spectra in p + Pb collisions ...

THANK YOU!