

γ -hadron spectra in p + Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV
and in O + O collisions at $\sqrt{s_{NN}} = 7$ TeV

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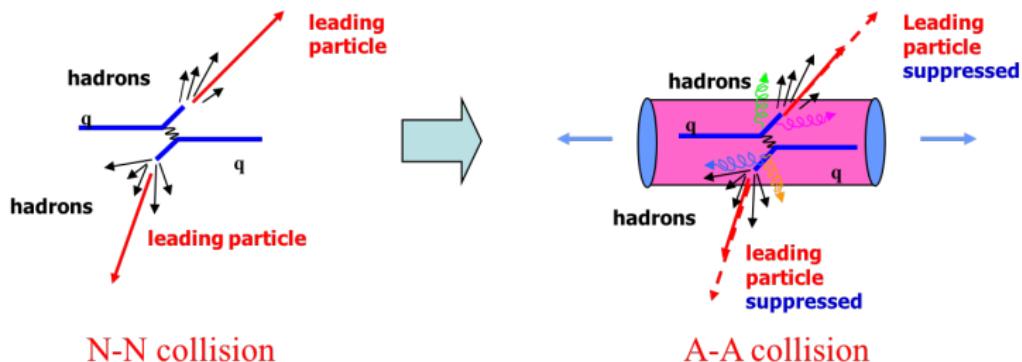


Outline

- Motivation
- pQCD parton model and JQ mFFs
- Numerical simulation results
 - * Direct γ production cross section
 - * Extracting jet transport parameter \hat{q}_0/T_0^3
- γ -hadron spectra and jet quenching
 - * in Pb + Pb collision at $\sqrt{s_{\text{NN}}} = 2.76$ and 5.02 TeV
 - * in p + Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV [[arXiv : 2003.02441](#)]
 - * in O + O collisions at $\sqrt{s_{\text{NN}}} = 7$ TeV
- Summary and outlook

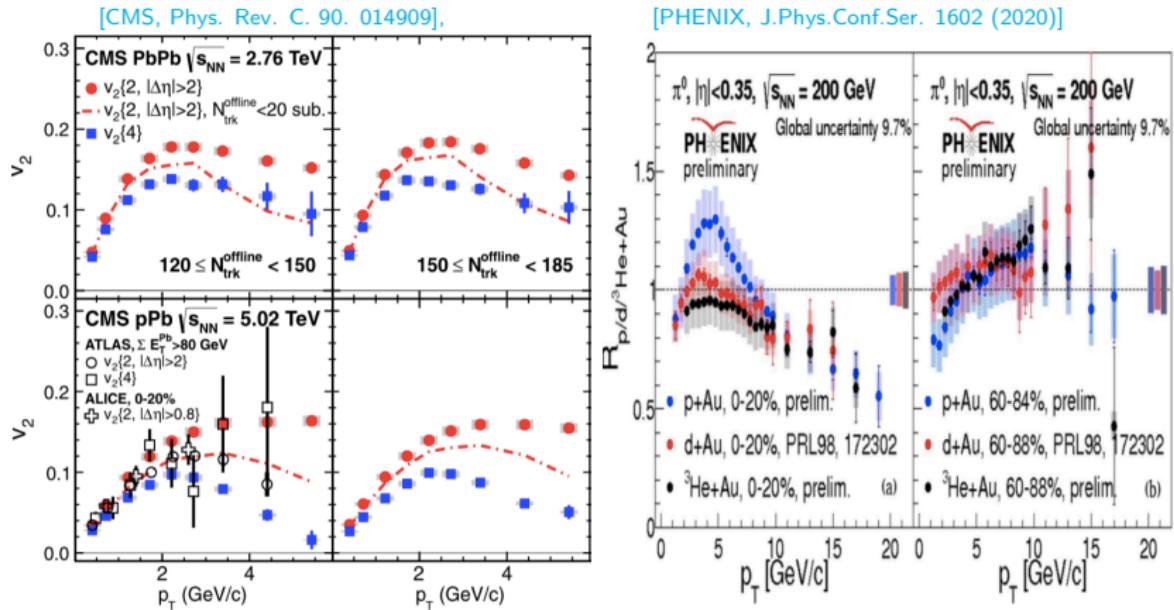
Introduction

- 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 $R_{AB}(p_T)$ and $v_2(p_T)$ of high p_T hadron spectra are two key evidences for the formation of QGP in HIC.

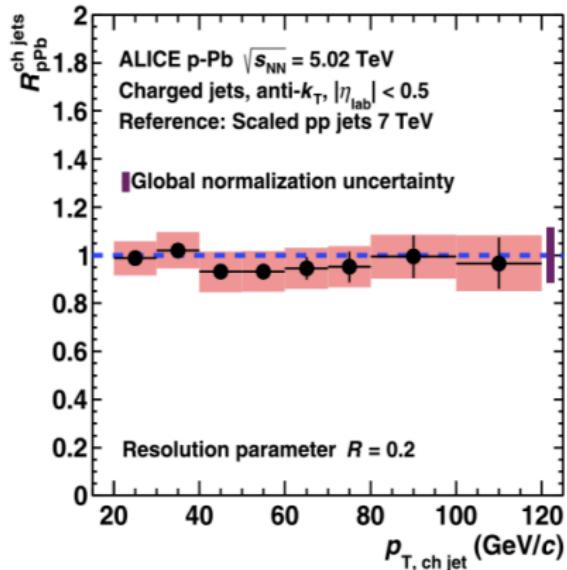
Motivation



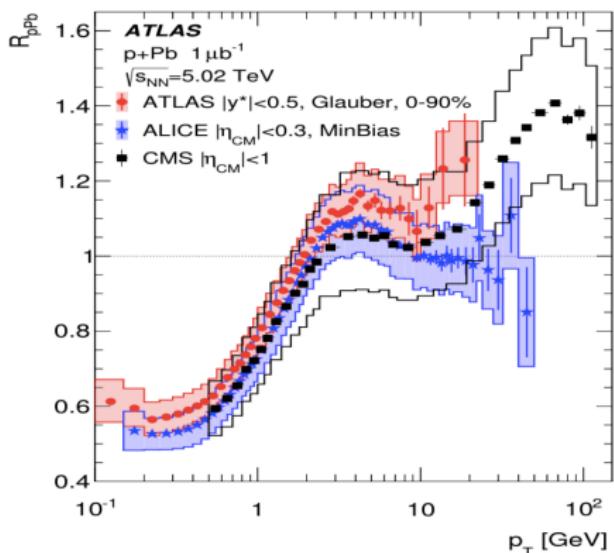
- $v_2\{2\}$ and $v_2\{4\}$ in 5.02 TeV $p + \text{Pb}$ collisions show a similar behavior of the collective flow as in $\text{Pb} + \text{Pb}$ collisions.
- R_{AB} at high p_T in $p+\text{Au}$, $d+\text{Au}$, $\text{He}+\text{Au}$ collisions show a comparable suppression.

Motivation

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



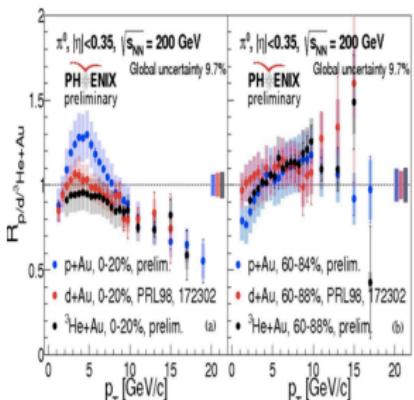
[ATLAS, Phys. Lett. B 763, 313 (2016)]



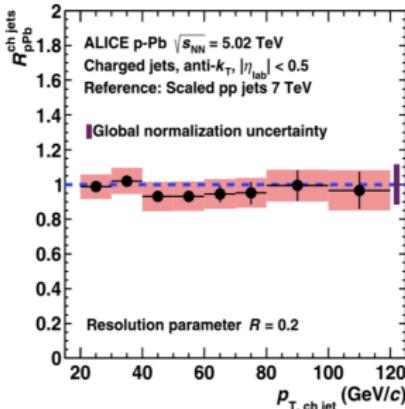
- Single jet and charged hadron spectra seemingly do not indicate strong JQ phenomena in p + Pb collisions.

Motivation

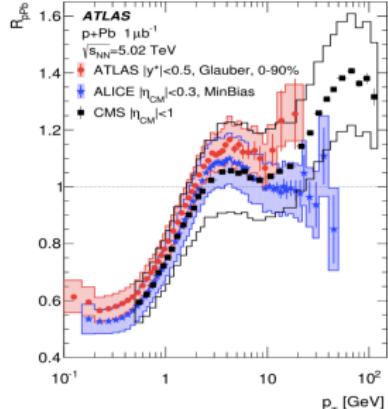
[PHENIX, J.Phys.Conf.Ser. 1602 (2020)]



[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 small systems.
- 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 medium and can be used to best approximate the transverse momentum of the accompanying jet in the hard processes of LO. And using it as the coincidence trigger dose not lead to biases in the geometrical configuration of the initial production.

NLO pQCD parton model

In p + A collisions for examples:

- 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, [J. F. Owens, Rev. Mod. Phys. 59, 465 (1987)]

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

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

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

- 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

Assume: parton will lose energy in small systems

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

$$\frac{\Delta E_d}{E} = \frac{2C_A\alpha_s}{\pi} \int d\tau \int \frac{d\beta_T^2}{\beta_T^4} \int dz [1 + (1 - z)^2] \hat{q}_d \sin^2\left(\frac{\beta_T(\tau - \tau_0)}{4z(1 - z)E}\right) \quad (3)$$

[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)]

- Modified fragmentation functions in QGP medium:

$$\begin{aligned} \tilde{D}_{h/d}(z_d, \mu^2, \Delta E_d) &= (1 - e^{-\langle N_g \rangle}) \left[\frac{z'_d}{z_d} D_{h/d}(z'_d, \mu^2) + \langle N_g \rangle \frac{z'_g}{z_d} D_{h/g}(z'_g, \mu^2) \right] \\ &\quad + e^{-\langle N_g \rangle} D_{h/d}(z_d, \mu^2), \end{aligned} \quad (4)$$

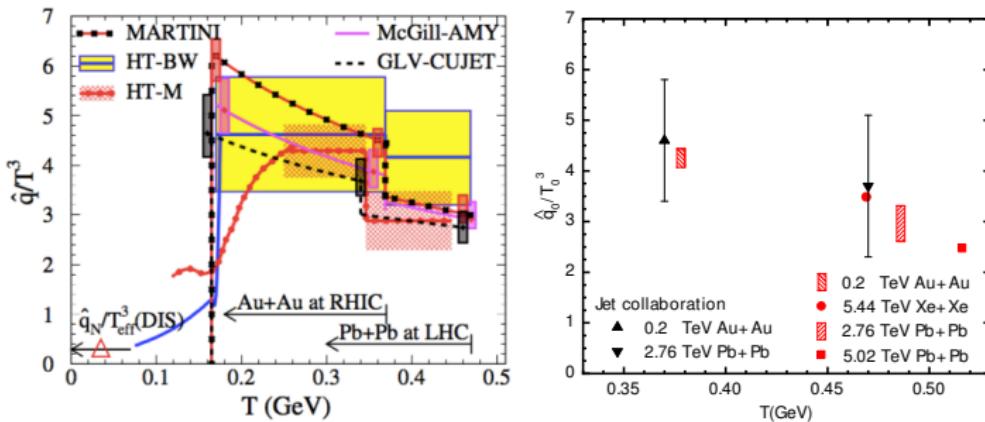
where $z'_d = p_T / (p_{Td} - \Delta E_d)$, $z'_g = \langle N_g \rangle p_T / \Delta E_d$.

[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)]

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

Assume: parton will lose energy in small systems

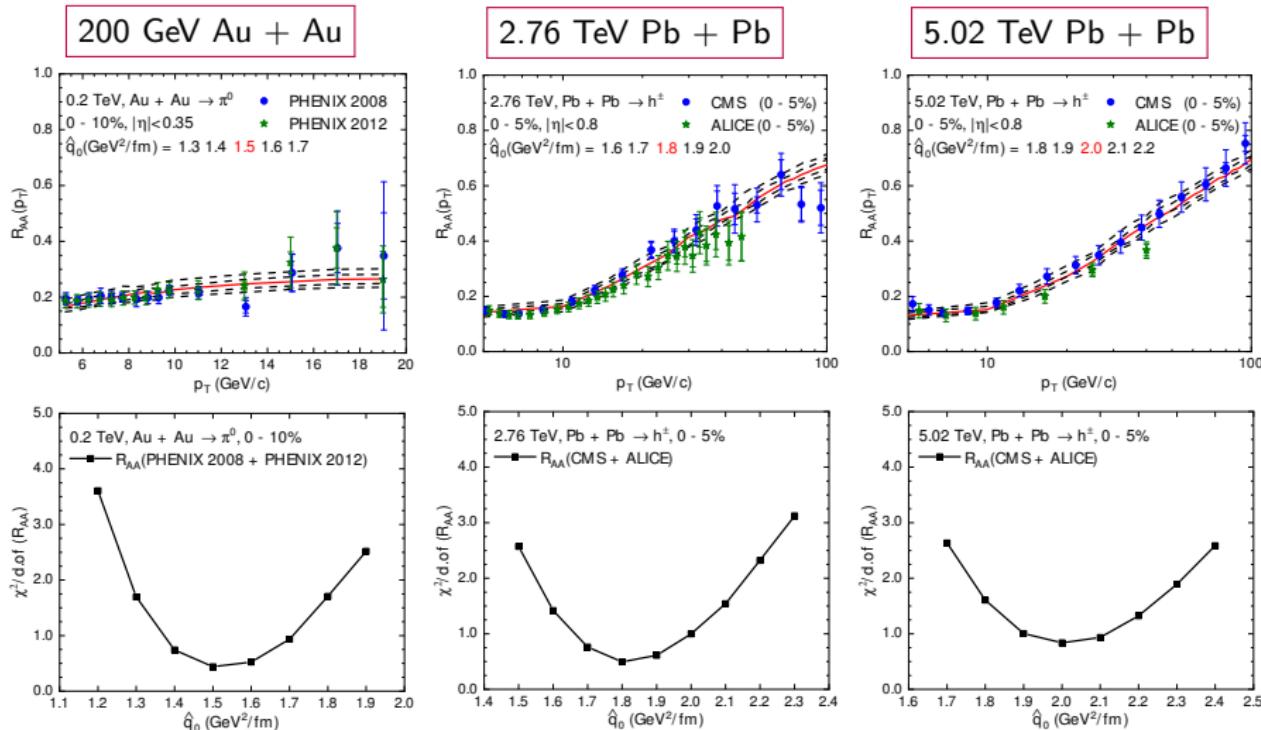
- Jet energy loss in QGP medium $\Delta E \propto \hat{q} \Rightarrow$ Jet transport coefficient:
 $\equiv \frac{d\langle q_T^2 \rangle}{dL}$: transverse momentum broadening squared per unit length.
[BDMPS, NPB 483 (1997) 291]
- \hat{q} depends on the local T in the jet trajectory: $\frac{\hat{q}}{T^3}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



[The JET collaboration, PRC PRC 90. 014909] [Man Xie, S. Y. Wei, G. Y. Qin, H. Z. Zhang, EPJC 79, no. 7, 589 (2019)]

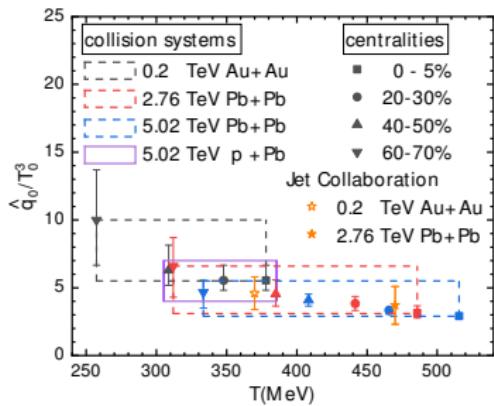
$$T_0(\text{small}) \sim T_0(\text{large}) \Rightarrow \hat{q}_0(\text{small}) \sim \hat{q}_0(\text{large})$$

\hat{q}_0 / T_0^3 from R_{AA} of single inclusive h^\pm in central collisions



$$\hat{q}_0 / T_0^3 = 5.5 \text{ at } T_0 = 380 \text{ MeV}; \hat{q}_0 / T_0^3 = 3.1 \text{ at } T_0 = 486 \text{ MeV}; \hat{q}_0 / T_0^3 = 2.9 \text{ at } T_0 = 516 \text{ MeV}$$

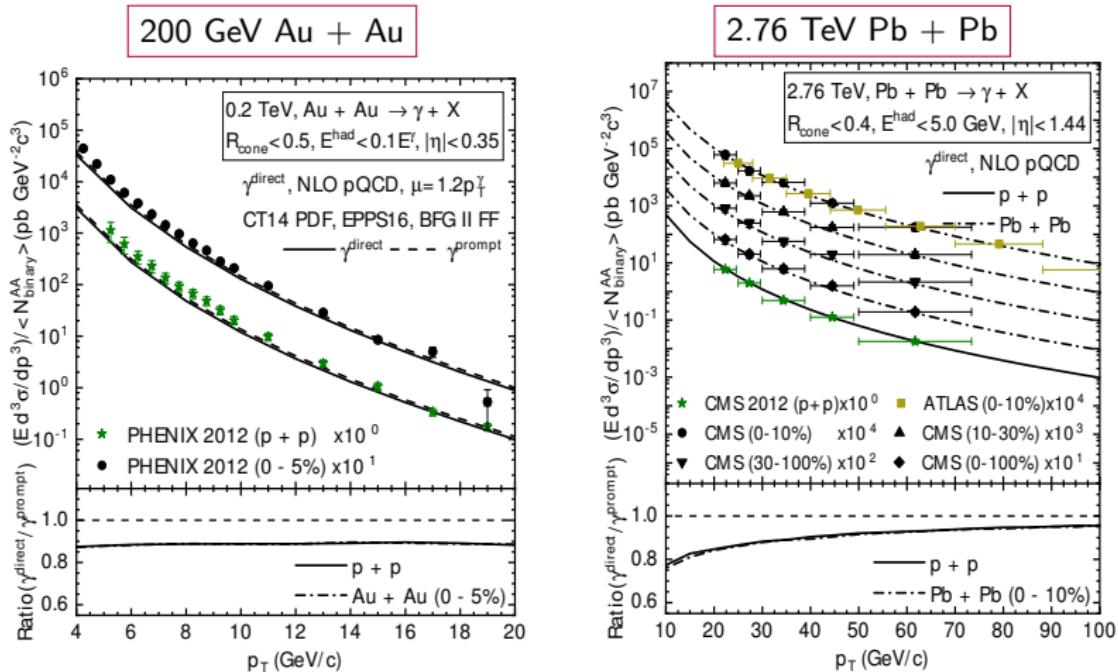
Extending the extractions of \hat{q}_0/T_0^3 to non-central collisions



- 3 collision energies: Au+Au at 0.2 TeV; Pb+Pb at 2.76 and 5.02 TeV;
- 4 centralities: 0-5%, 20-30%, 40-50%, 60-70%;
- for p + Pb collisions:
$$\frac{\hat{q}_0}{T_0^3} = 4 - 7 \text{ at } T_0 = 385 - 300 \text{ MeV};$$
- for O + O collisions:
$$\frac{\hat{q}_0}{T_0^3} = 4 - 7 \text{ at } T_0 = 380 - 300 \text{ MeV}.$$

- A clear but small temperature dependence for the temperature range achieved in heavy-ion collisions.
- The hydrodynamic evolution of the medium created in p + Pb collisions as provided by the superSONIC hydrodynamic model. [P. Romatschke, EPJC 75, no.7 305 (2015)], [R. D. Weller, P. Romatschke, PLB 774, 351 (2017)]
- For O + O collisions at 7 TeV, it provided by the CLVisc hydrodynamic model. [L.-G. Pang, X.-N. Wang, etc. Phys.Rev.C 97 (2018) 6, 064918]

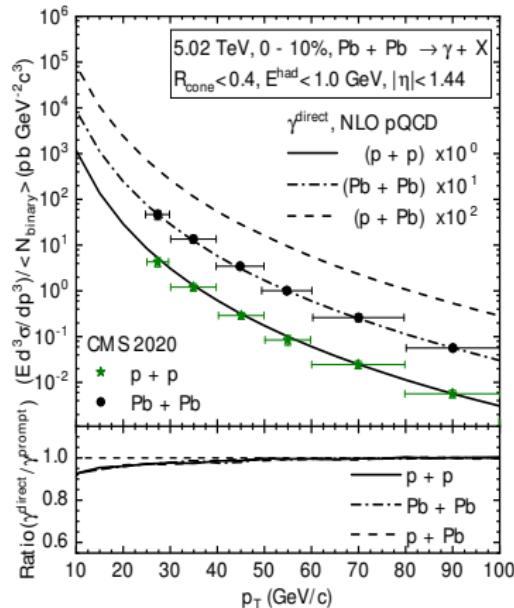
Direct photon production cross section



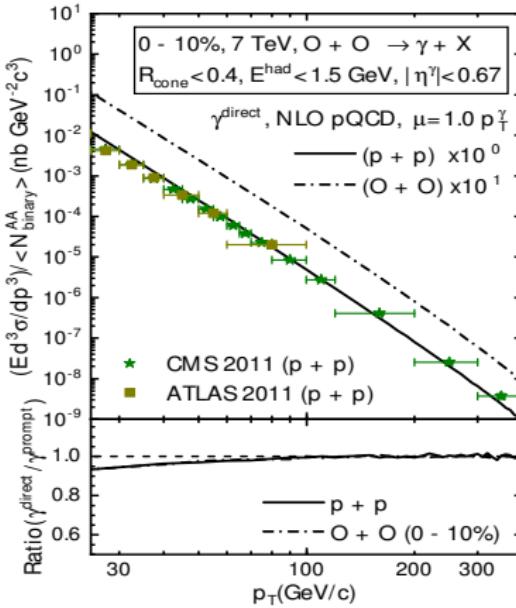
- The pQCD parton model can describe the experimental data well.
- With isolation cuts the contributions of fragmentation photons are about or less than 10%.

Direct photon production cross section

5.02 TeV p (Pb) + Pb

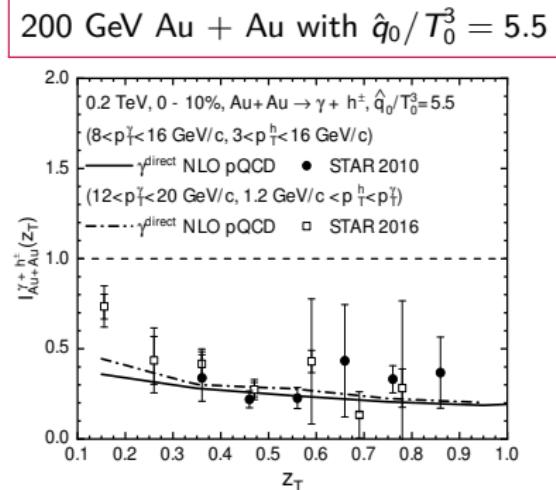
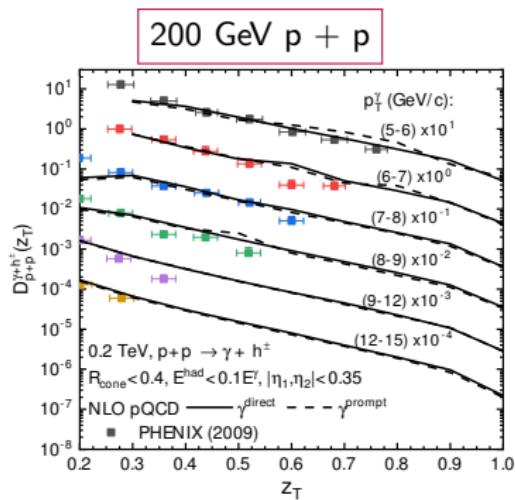


7 TeV O + O



- 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.

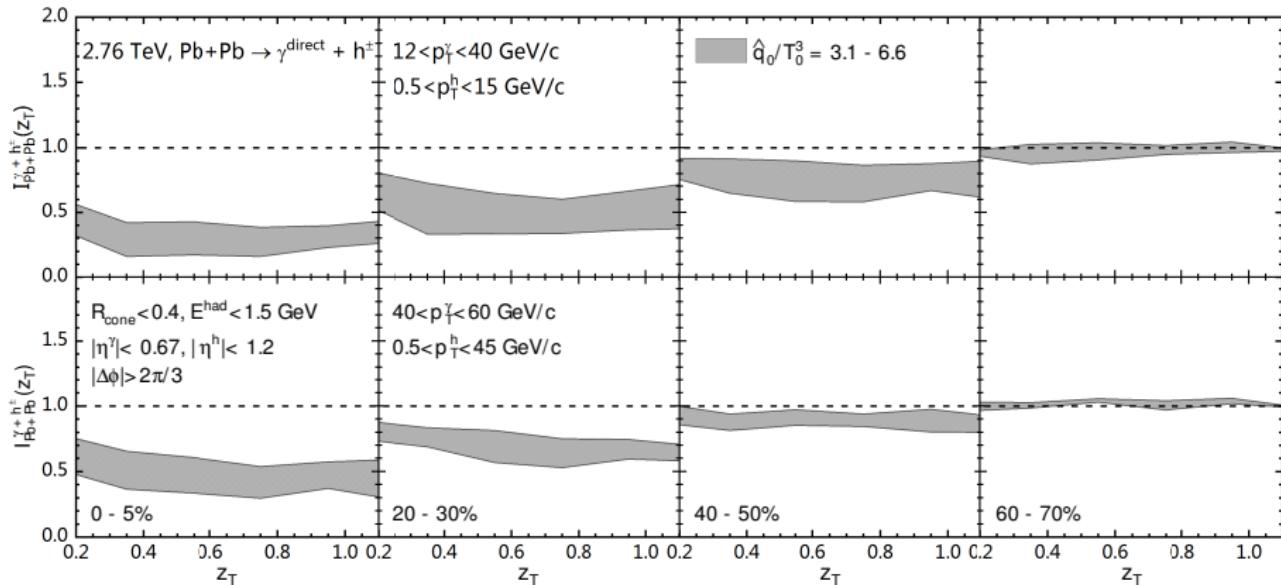
γ -triggered hadron spectra in 200 GeV Au + Au collisions



- Our results are consistent with the experimental data.
- γ -trigger hadron spectra are suppressed by nearly 80% due to JQ in central Au + Au collisions at 200 GeV.

γ -triggered hadron spectra in Pb + Pb collisions

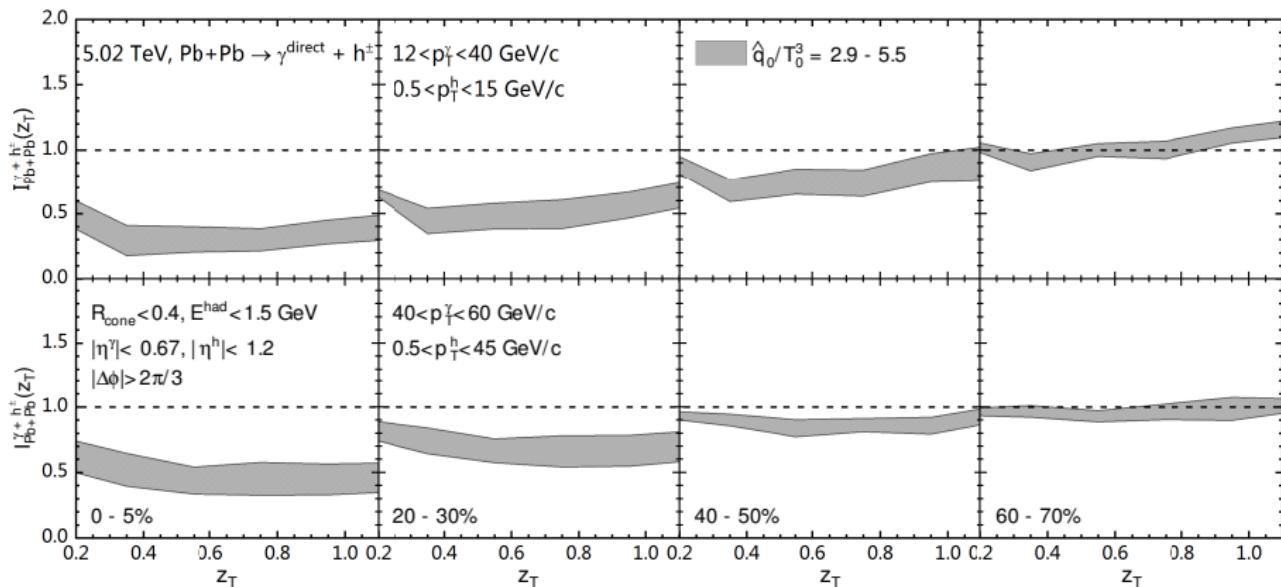
2.76 TeV Pb + Pb with $\hat{q}_0/T_0^3 = 3.1 - 6.6$



- In 0 - 5%, $I_{\text{Pb+Pb}}^{\gamma+h^\pm} \approx 0.2 \sim 0.4$; In 60 - 70%, $I_{\text{A+A}}^{\gamma+h^\pm} \approx 1$
- The suppression becomes weaker at larger p_T^γ .

γ -triggered hadron spectra in Pb + Pb collisions

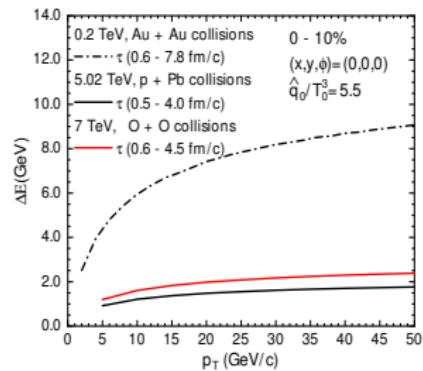
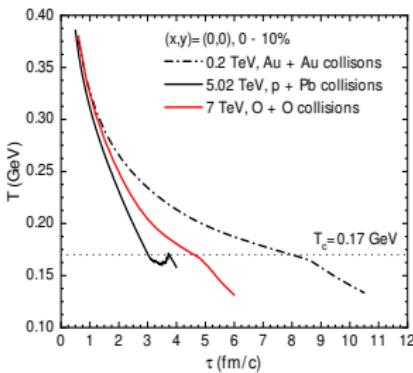
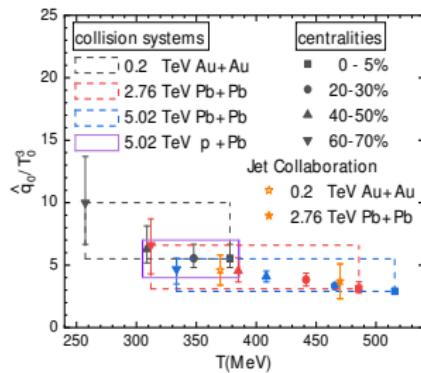
5.02 TeV Pb + Pb with $\hat{q}_0/T_0^3 = 2.9 - 5.5$



- The results of γ -triggered hadron suppression in Pb + Pb collisions 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 small systems

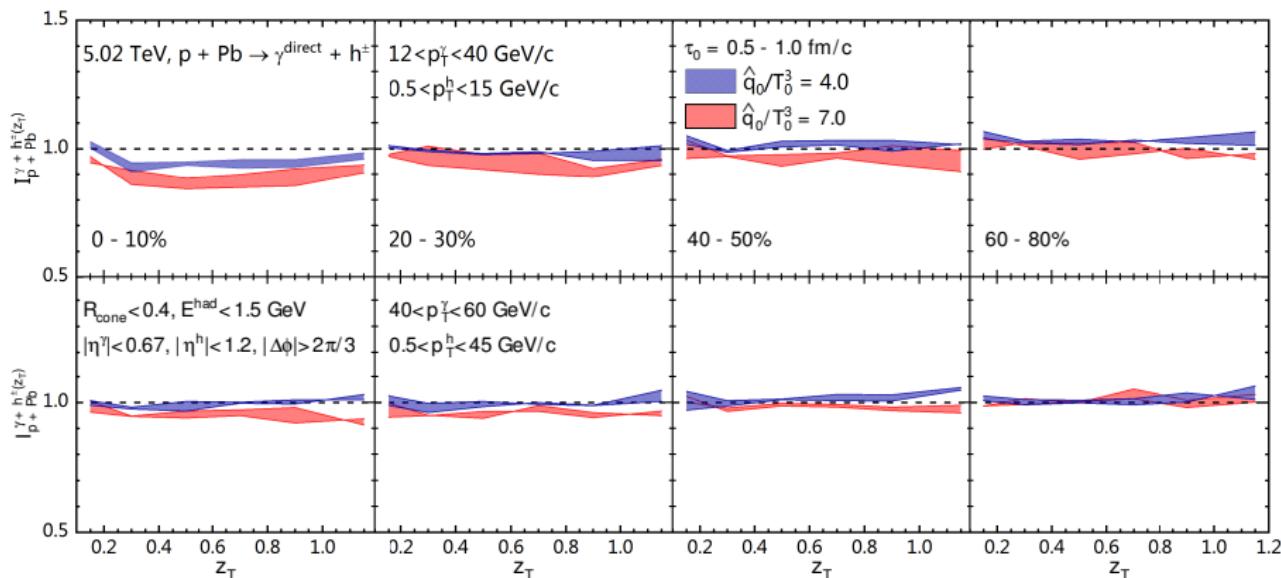
Assume: a small droplet QGP is formed in small systems



- $T_0 \sim 380 - 300$ MeV $\implies \hat{q}_0/T_0^3 \sim 4.0 - 7.0$.
- With the same \hat{q}_0/T_0^3 , 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.
- With the same \hat{q}_0/T_0^3 , the parton ΔE in central 7 TeV O + O collisions is a little larger than that in the central 5.02 TeV p + Pb collisions.

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

γ -hadron spectra will be suppressed by about 5%-15% in central 5.02 TeV p+Pb collisions due to JQ and the suppression becomes weaker with increasing p_T^γ .

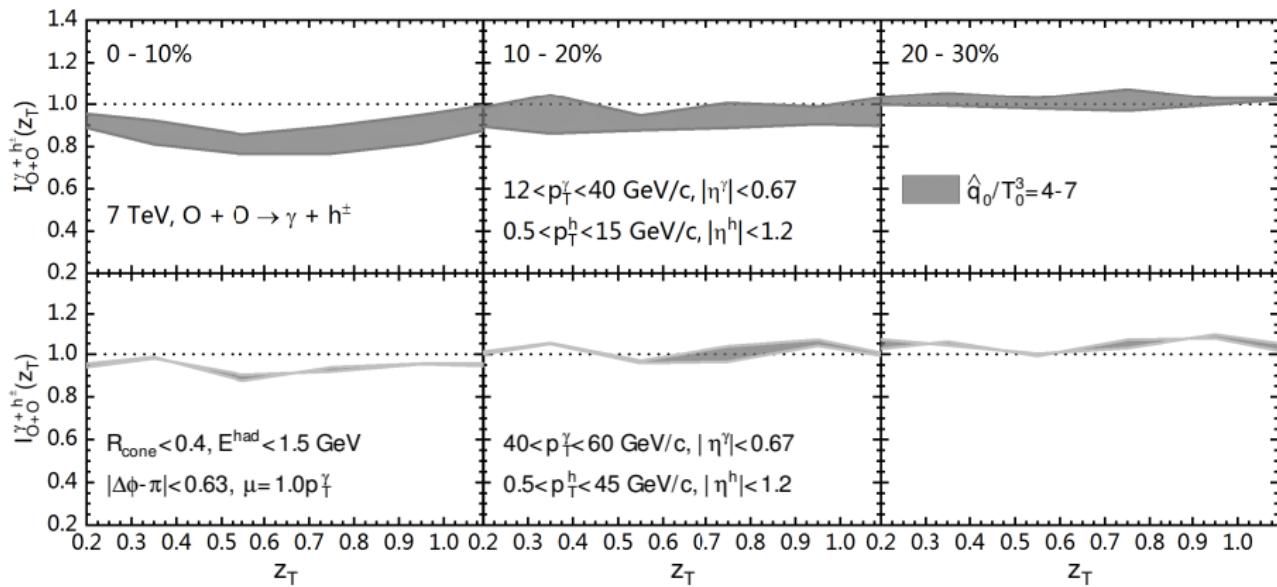


The shaded bands indicate variations of the results when one changes the initial time for parton-medium interaction between $\tau_0 = 0.5$ and $1.0 \text{ fm}/c$.

γ -triggered hadron spectra in 7 TeV O + O collisions

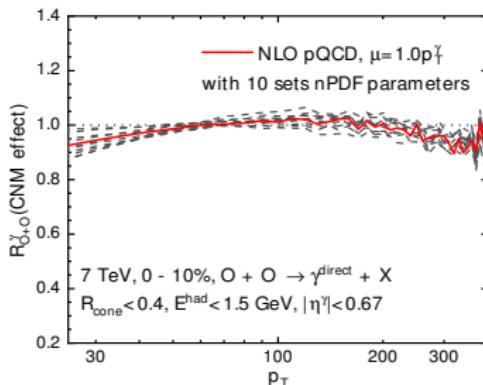
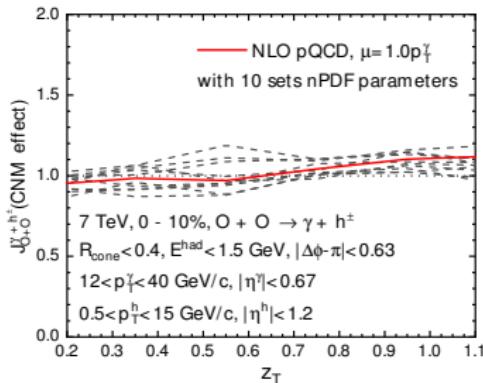
Assume: a small QGP droplet is formed in O + O collisions

γ -hadron spectra will be suppressed by about 10%-20% in central 7 TeV O + O collisions due to JQ and the suppression becomes weaker with increasing p_T^γ .



γ -triggered hadron spectra in 7 TeV O + O collisions

Taking the nPDFs uncertainties into account: without jet energy loss



- $I_{AA}^{\gamma h}(z_T) = \frac{J_{AA}^{\gamma h}(z_T)}{R_{AA}^{\gamma}(p_T)}$

- $J_{AA}^{\gamma h}(z_T) = \frac{d\sigma_{AA}^{\gamma h}/dy^{\gamma} dp_T^{\gamma} dy^h dp_T^h}{\langle N_{binary}^{AA} \rangle d\sigma_{pp}^{\gamma h}/dy^{\gamma} dp_T^{\gamma} dy^h dp_T^h}$:

γ -triggered hadron nuclear modification factor without normalization by the production cross section of the trigger photon.

- $R_{AA}^{\gamma}(p_T) = \frac{d\sigma_{AA}^{\gamma}/dy^{\gamma} dp_T^{\gamma}}{\langle N_{binary}^{AA} \rangle d\sigma_{pp}^{\gamma}/dy^{\gamma} dp_T^{\gamma}}$:

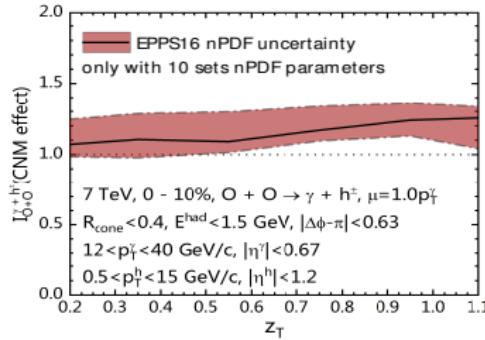
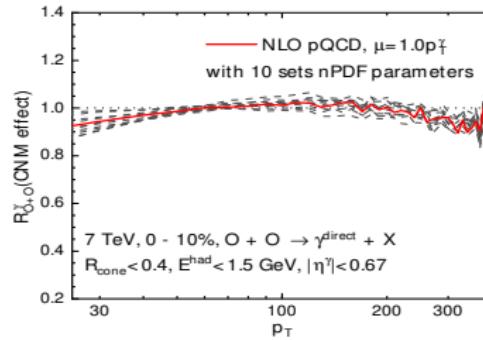
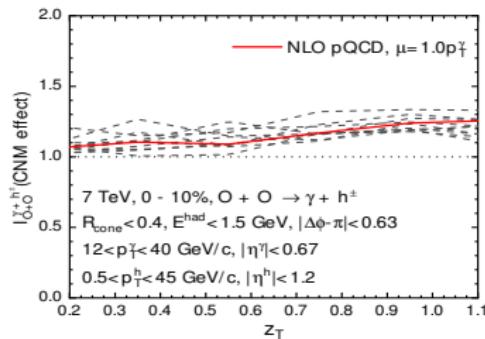
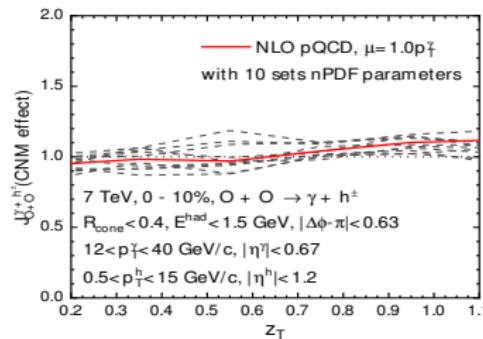
- If $R^{\gamma}(p_T) = 1$, then $I^h(z_T) = J^h(T)$

- Methods for estimating the propagation of nPDF uncertainties are provided by EPPS16 nPDFs [[Eur. Phys. J. C 77, no. 3, 163 \(2017\)](#)]

$$(\Delta X^+)^2 \approx \sum_k [\max \{X(S_k^+) - X(S^0), X(S_k^-) - X(S^0), 0\}]^2$$

$$(\Delta X^-)^2 \approx \sum_k [\max \{X(S^0) - X(S_k^+), X(S^0) - X(S_k^-), 0\}]^2,$$

γ -triggered hadron spectra in 7 TeV O + O collisions



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$$(\Delta X^-)^2 \approx \sum_k [\max \{X(S^0) - X(S_k^+), X(S^0) - X(S_k^-), 0\}]^2,$$

Summary and outlook

- Under the assumption that a QGP droplet is produced and its evolution can be described by hydrodynamics in small systems, 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 in O + O collisions is from CLVisc hydrodynamic model and parton ΔE in such a medium is described by the HT approach.
- γ -hadron spectra at $p_T^\gamma = 12 - 40 \text{ GeV}/c$ are suppressed by 5%-15% in the most central 0 - 10% p + Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$.
- γ -hadron spectra at $p_T^\gamma = 12 - 40 \text{ GeV}/c$ are suppressed by 10%-20% in the most central 0 - 10% O + O collisions at $\sqrt{s_{\text{NN}}} = 7 \text{ TeV}$.
- γ -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 small systems; taking the nPDFs uncertainties into our calculations...

THANK YOU!