Extracting jet transport coefficient via single hadron and dihadron productions in high-energy HIC

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Outline

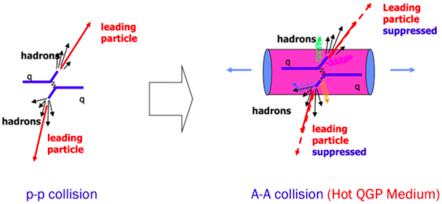
- Motivation
- NLO pQCD, JQ mFFs, and Hydro models
- Extracting $\hat{q}_0$ via single and dihadron suppressions

  Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV;
  Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.
- Predictions for dihadron suppression factors

  Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV;
  Xe+Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV.
- Summary and outlook

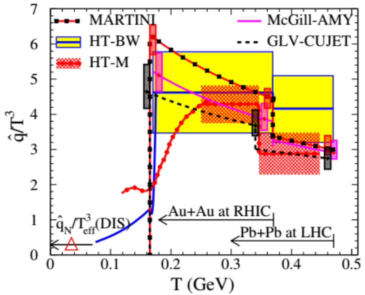
Introduction

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



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

Motivation



[The JET collaboration, Phys. Rev. C. 90. 014909]

For a 10 GeV quark, the values of $\hat{q}$ temperatures available have been obtained as:

$$\frac{\hat{q}}{T^3} \approx \begin{cases} 4.6 \pm 1.2 & \textit{at RHIC} \\ 3.7 \pm 1.4 & \textit{at the LHC}. \end{cases}$$

The corresponding absolute values for $\hat{q}$ at an initial time $\tau_0 = 0.6$ fm/c,

$$\hat{q} \approx \begin{cases} 1.2 \pm 0.3 \text{ GeV}^2/\text{fm} & \textit{at } 370\textit{MeV} \\ 1.9 \pm 0.7 \text{ GeV}^2/\text{fm} & \textit{at } 470 \textit{ MeV}. \end{cases}$$

- Extracting $\hat{q}_0$ via single hadron and dihadron suppression in HIC.
- Whether the dihadron $\hat{q}_0$ is consistent with the single hadron? Whether the non-central collisions $\hat{q}_0$ is consistent with the central collisions?
- Predicting the dihadron suppression factors in Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV and in Xe+Xe collisions at $\sqrt{s_{\mathrm{NN}}} = 5.44$ TeV.

NLO pQCD parton model

- In A+A collisions, the yield of dihadron productions can be given by

$$\frac{dN_{AB}^{h_1 h_2}}{dy^{h_1} d^2 p_T^{h_1} dy^{h_2} d^2 p_T^{h_2}} = \sum_{abcd} \int \frac{dz_c}{z_c^2} \frac{dz_d}{z_d^2} d^2 r t_A(\vec{r}) t_B(\vec{r}+\vec{b})$$
$$\times x_a f_{a/A}(x_a, \mu^2, \vec{r}) x_b f_{b/B}(x_b, \mu^2, \vec{r}+\vec{b})$$
$$\times \frac{1}{\pi} \frac{d\sigma_{ab\to cd}}{d\hat{t}} \tilde{D}_c^{h_1}(z_c, \mu^2, \Delta E_c) \tilde{D}_d^{h_2}(z_d, \mu^2, \Delta E_d)$$
$$\times \delta^2\left(\frac{\vec{p}_T^{h_1}}{z_c} + \frac{\vec{p}_T^{h_2}}{z_d}\right) + O(\alpha_s^3), \quad (1)$$

- $t_A(\vec{r}) \rightarrow$ thickness function: Woods-Saxon
  $f_{a/A} \rightarrow$ PDFs: CT14, EPPS16 [Phys. Rev. D 95, no. 3, 034003 (2017)], [Eur. Phys. J. C 77, no. 3, 163 (2017)]
  $\frac{d\sigma}{d\hat{t}} \rightarrow$ hard scattering cross section
  $D_c^h(z_c, \mu^2) \rightarrow$ FFs in vacuum: Kretzer [Phys. Rev. D 62, 054001 (2000)]

Modified fragmentation functions — mFFs

- Modified fragmentation functions in QGP medium:

$$\tilde{D}_c^h(z_c,\mu^2,\Delta E_c) = (1-e^{-\langle N_g\rangle})\left[\frac{z_c'}{z_c}D_c^h(z_c',\mu^2)\langle N_g\rangle\frac{z_g{}'}{z_c}D_g^h(z_g{}',\mu^2)\right] + e^{-\langle N_g\rangle}D_c^h(z_c,\mu^2), \qquad (2)$$

where $z_c{}' = p_T/(p_{Tc}-\Delta E_c)$, $z_g{}' = \langle N_g\rangle p_T/\Delta E_c$.

[X.-N. Wang, PRC70 (2004) 031901], [H. Z. Zhang, J.F. Owens, Phys. Rev. Lett. 98.212301 (2007)], and [H. Z. Zhang, J.F. Owens, Phys. Rev. Lett. 103, 032302 (2009)]

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

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

[W.T. Deng and X.-N. Wang, Phys. Rev. C81,024902(2010], [E. Wang and X.-N. Wang, Phys. Rev. Lett. 87, 142301 (2001); 89, 162301 (2002)]

2+1D hydrodynamics medium model

- $\hat{q}$ depends on the local T in the jet trajectory:

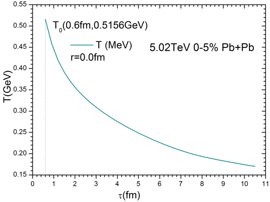
$$\hat{q}(\tau, r) = \hat{q}_0 \frac{\rho_g(\tau, r)}{\rho_g(\tau_0, 0)} \frac{p^\mu u_\mu}{p_0}(1 - f), \rho_g \propto T^3 \rightarrow \frac{\hat{q}}{T^3} = \frac{\hat{q}_0}{T_0^3} \qquad (4)$$

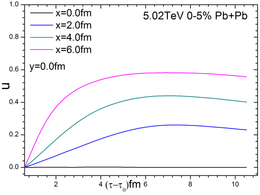
- hadron phase fraction: $f(\tau, r) = \begin{cases} 0 & when T \geq 170 MeV \\ 1 & when T < 170 MeV \end{cases}$

[X. Chen, T. Hirano, E. Wang, X.-N. Wang, H. Z. Zhang, Phys. Rev. C84 (2011) 034902]

- T, u are given by 2+1D hydro to describe the medium evolution

[Z. Qiu, C. Shen and U. Heinz, Phys. Lett. B 707, 151 (2012)]





Nuclear modification factor

- Single hadron nuclear modification factor:

$$R_{AA} = \frac{dN_{AA}/dyd^2p_T}{\langle T_{AA}\rangle d\sigma_{pp}/dyd^2p_T} \tag{5}$$

- Dihadron nuclear modification factor:

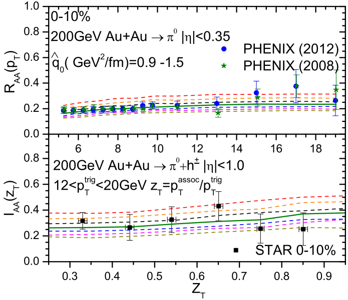
$$I_{AA}(z_T) = \frac{D_{AA}(z_T)}{D_{pp}(z_T)} = \frac{D_{AA}(p_T^{assoc})}{D_{pp}(p_T^{assoc})} \tag{6}$$

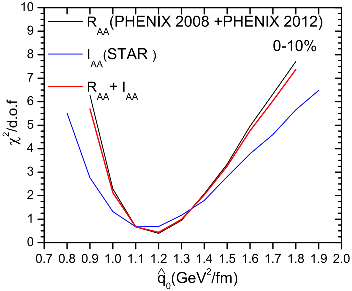
where $z_T = \frac{p_T^{assoc}}{p_T^{trig}}$.

$$D_{AA}(z_T) = p_T^{trig} \frac{dN_{AA}^{h_1 h_2}/dy^{trig}dp_T^{trig}dy^{assoc}dp_T^{assoc}}{\langle T_{AA}\rangle d\sigma_{AA}^{h_1}/dy^{trig}dp_T^{trig}} \tag{7}$$

Extracting $\hat{q}_0$ via single and di-hadron productions in HIC

- Extracting $\hat{q}_0$ in central Au+Au collisions at $\sqrt{s_{NN}}$= 200 GeV.

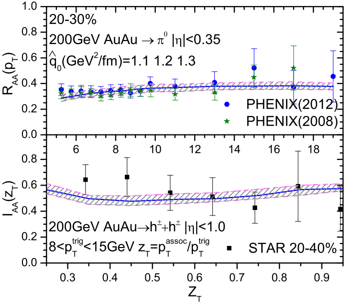




At T_0=378 MeV, $\hat{q}_0 = 1.1 \sim 1.2\ \mathrm{GeV}^2/\mathrm{fm}$

Data from [[PHENIX Collaboration], [Phys. Rev. C 87, no. 3,034911(2013), Phys. Rev. Lett. 101, 232301(2008)], and [[STAR], [Phys. Rev. Lett. 97, 162301 (2006)]]

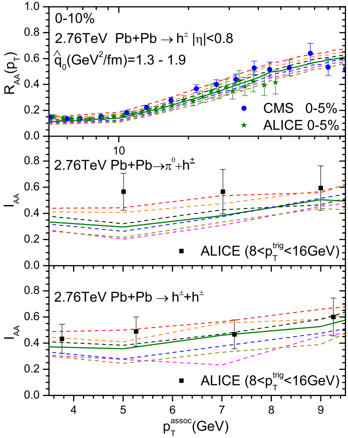
R_{AA} and I_{AA} in mid-central Au+Au collisions at 200 GeV

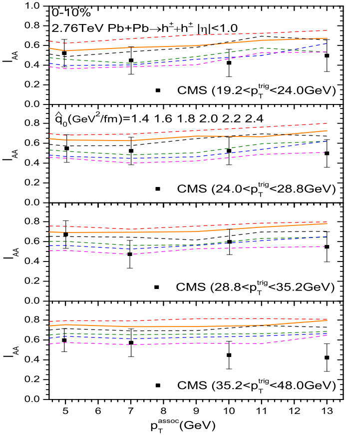


- Dihadron $\hat{q}_0$ is consistent with single hadron.
- Mid-central collisions results is consistent with central collisions at RHIC.

Data from [[PHENIX Collaboration], [Phys. Rev. C 87, no. 3,034911(2013), Phys. Rev. Lett. 101, 232301(2008)], and [[STAR], [Phys. Rev. Lett. 97, 162301 (2006)]]

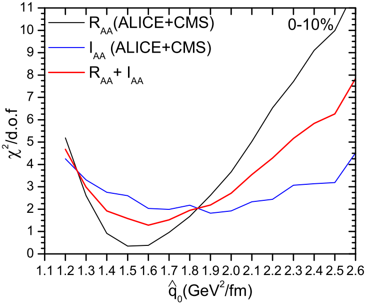
Extracting $\hat{q}_0$ in central Pb+Pb collisions at 2.76 TeV





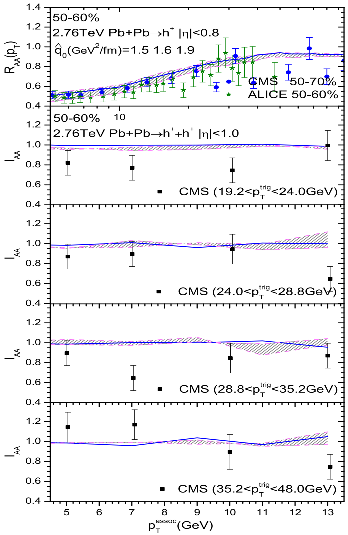
Data from [[ALICE Collaboration], [Phys. Lett. B 720 52-62(2013), Phys. Lett. B 763 238-250(2016)], [CMS Collaboration], [Nuclear. Phys. A 904-905 451c-454c(2013), and [Eur. Rhys. J. C 72, 1945(2012)]]

Extracting $\hat{q}_0$ in central Pb+Pb collisions at 2.76 TeV



- At $T_0 = 486$ MeV
  $\hat{q}_0 = 1.5 \sim 1.9$ GeV^2/fm
- With the similar values of $\hat{q}_0$, our jet energy loss model can provide a consistent description of both R_{AA} and I_{AA}.

R_{AA} and I_{AA} in non-central Pb+Pb collisions at 2.76 TeV



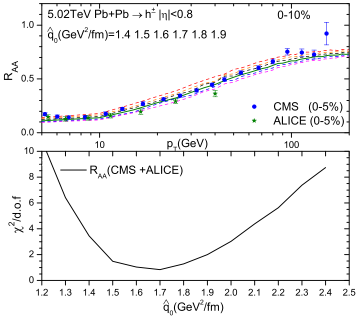
- Our model can provide a consistent description for R_{AA} and I_{AA} in central and non-central A-A collisions at RHIC and the LHC energies.
- Interesting phenomenon: $I_{AA} > R_{AA}$. High p_T single hadrons mainly come from surface bias emission jets, while high p_T dihadrons come from a combination of surfacial and tangential jets as well as punching-through jets.

  [H. Zhang, J. F. Owens, E. Wang and X. N. Wang, Phys. Rev. Lett. 98, 212301 (2007), J. Phys. G 35, 104067 (2008)]

Extracting $\hat{q}_0$ via single hadron R_{AA} at 5.02 and 5.44 TeV

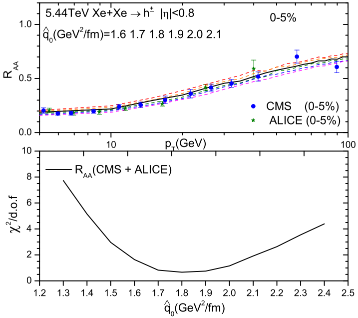
Pb+Pb collisions

5.02 TeV, 0 - 10%



Xe+Xe collisions

5.44 TeV, 0 - 5%



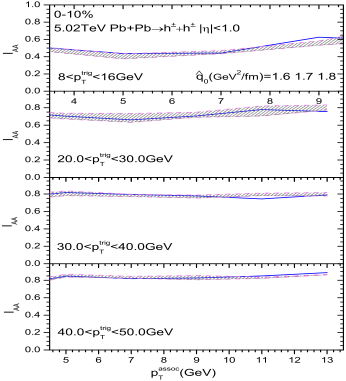
- At $T_0 = 516$ MeV $\hat{q}_0 = 1.7$ GeV^2/fm
- At $T_0 = 469$ MeV $\hat{q}_0 = 1.8$ GeV^2/fm

Data from [[CMS Collaboration], [JHEP 1704, 039 (2017), JHEP 1810, 138 (2018)], [ALICE Collaboration], [JHEP 1811, 013 (2018), and Phys. Lett. B 788, 166 (2019)]]

Predicting I_{AA} at 5.02 and 5.44 TeV

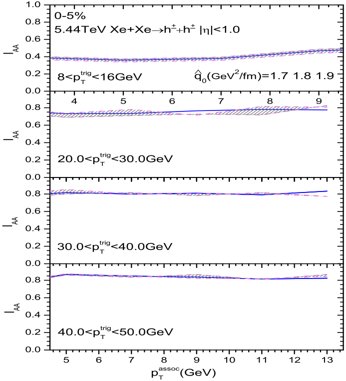
Pb+Pb collisions

5.02 TeV, 0 - 10%



Xe+Xe collisions

5.44 TeV, 0 - 5%

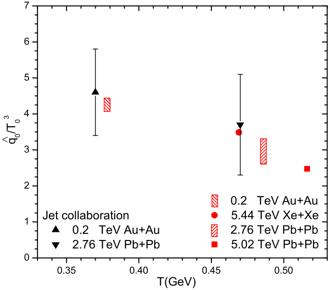


- Interesting observation: the values of I_{AA} also increase as one increases p_T^{trig}.

  With increasing p_T^{trig}, the contribution from punching-through jets increases, thus the average total energy loss of jets decreases.

  [H. z. Zhang, J. F. Owens, E. Wang and X.- N. Wang, J. Phys. G 35, 104067 (2008)]

$\hat{q}_0$ from single hadron and dihadron nuclear suppressions at RHIC and the LHC



$$\frac{\hat{q}}{T^3} = 4.1 \sim 4.4,\ T = 378\ \mathrm{MeV},\ \mathrm{Au{+}Au}\ 0.2\mathrm{A\ TeV};$$

$$\frac{\hat{q}}{T^3} = 3.5,\quad T = 469\ \mathrm{MeV},\ \mathrm{Xe{+}Xe}\ 5.44\mathrm{A\ TeV};$$

$$\frac{\hat{q}}{T^3} = 2.6 \sim 3.3,\ T = 486\ \mathrm{MeV},\ \mathrm{Pb{+}Pb}\ 2.76\mathrm{A\ TeV};$$

$$\frac{\hat{q}}{T^3} = 2.5,\quad T = 516\ \mathrm{MeV},\ \mathrm{Pb{+}Pb}\ 5.02\mathrm{A\ TeV}.$$

- The scaled jet quenching parameter $\hat{q}/T^3$ has some temperature dependence:
  it decreases as one increases the temperature, which can be understood as decreasing jet-medium interaction strength with increasing temperature.

Summary and outlook

- Large p_T hadrons are studied in a NLO pQCD parton model in heavy-ion collisions with mFFs due to jet quenching.
- First, we quantitatively extract the jet quenching parameter $\hat{q}$ for four different collisions systems via a global χ^2 analysis.
- Second, our model can provide a consistent description for the nuclear modification factors of single hadron R_{AA} and dihadron I_{AA}, not only in central but also in non-central A-A collisions at RHIC and the LHC energies.
- Third, here are some other interesting results: the dihadron $I_{AA} > R_{AA}$ in the same collision system and the values of I_{AA} also increase as one increases p_T^{trig}.
- Finally, we find $\hat{q}/T^3$ decreases as one increases the temperature.
- On going: we are calculating the $\gamma - h$ correlations to study QGP, and studying the additional temperature dependence of $\hat{q}/T^3$...

THANK YOU!