Heavy and light flavor jet quenching at RHIC and the LHC

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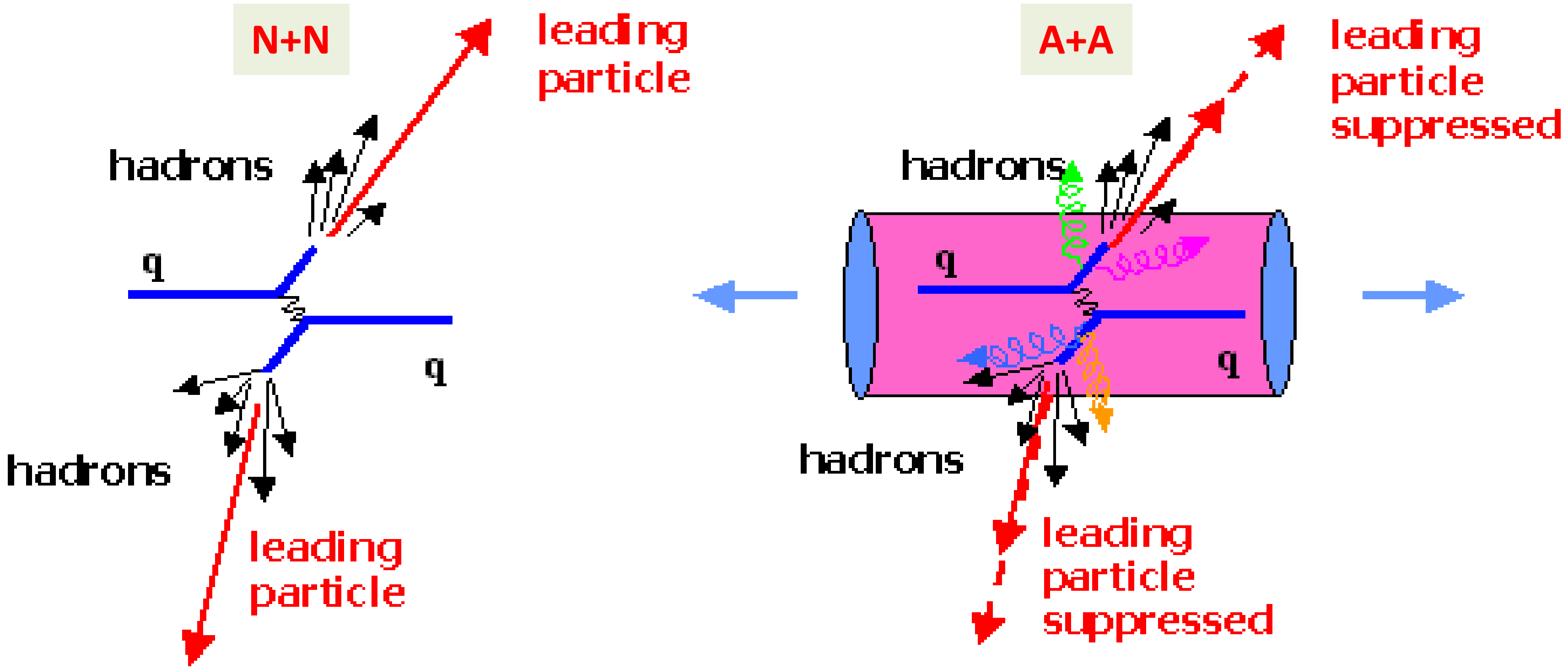
S. Cao, T. Luo, GYQ, X.N. Wang, PRC 2016; arXiv:1703.00822

Outline

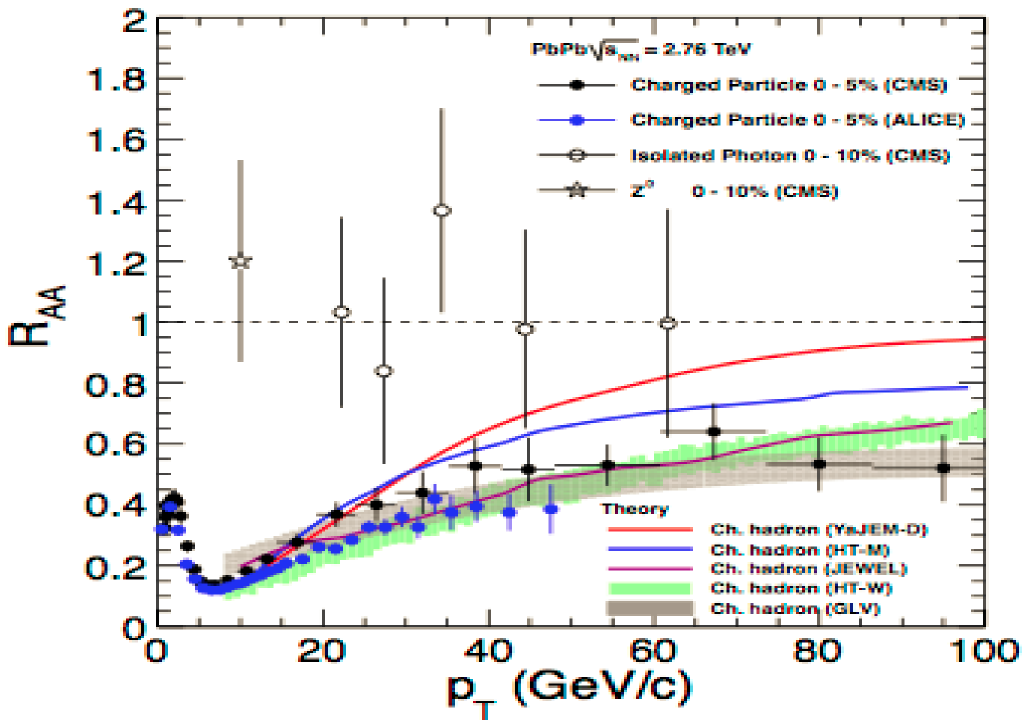
- Introduction
- A Linear Boltzmann Transport (LBT) approach for heavy and light flavor jet quenching
- Some numerical results
- Summary

Jet quenching in heavy-ion collisions



Jet quenching in quark-gluon plasma

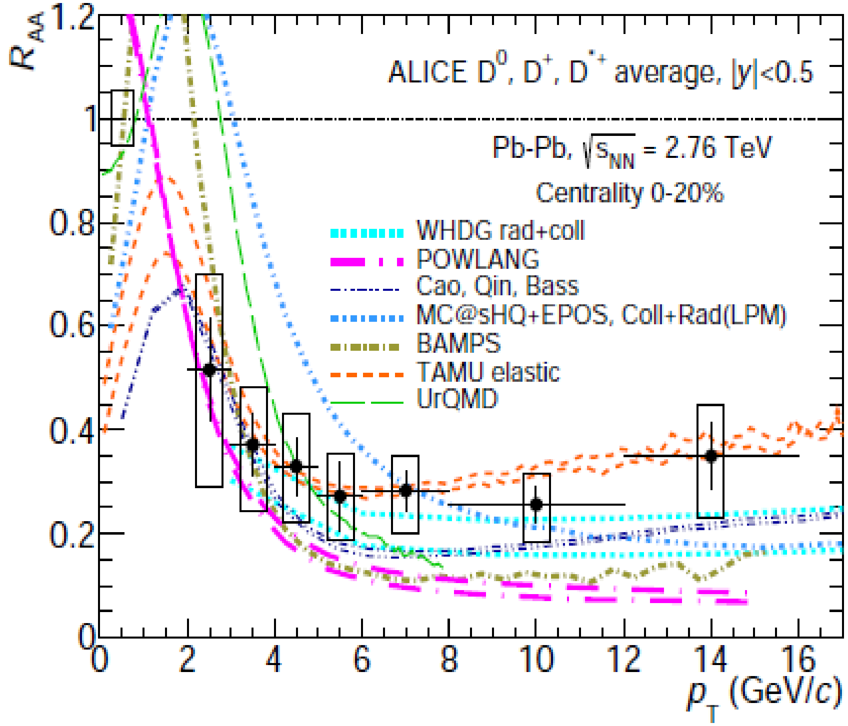
Large transverse momentum hadrons

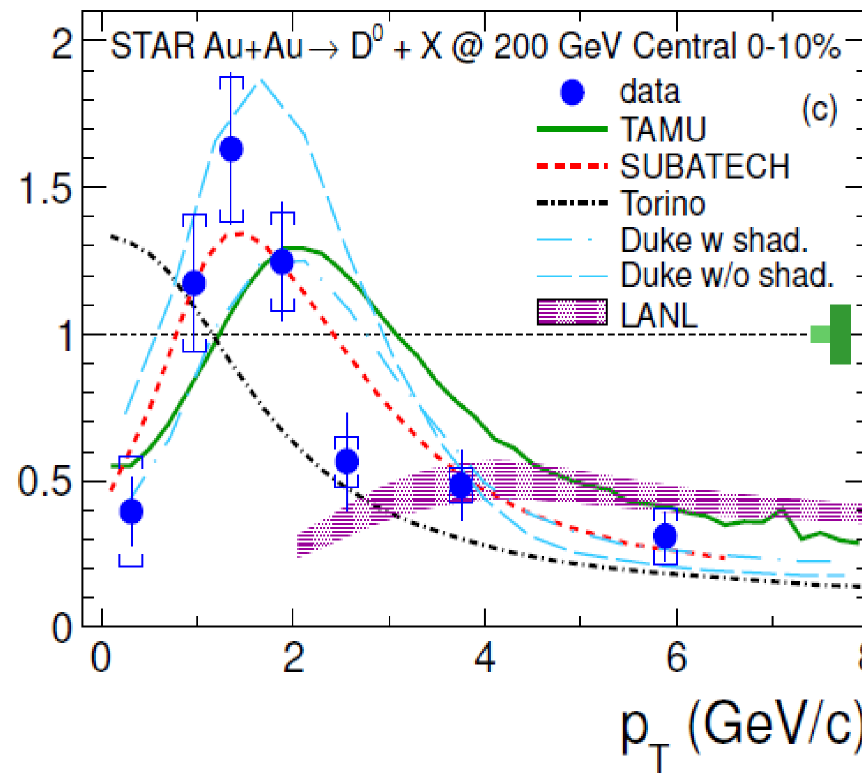


$$R_{AA} = \frac{dN^{AA} / d^2 p_T dy}{N_{\mathrm{coll}} dN^{pp} / d^2 p_T dy}$$

- If A+A collisions are just simple combination of many N+N collisions, then R_{AA}=1
- Photon & Z boson: R_{AA}=1
- Large p_T hadron: R_{AA}<1 (due to final state jet-medium interaction and parton energy loss in QGP)
- **Jet quenching is mainly a final state effect**

Heavy flavor hadrons

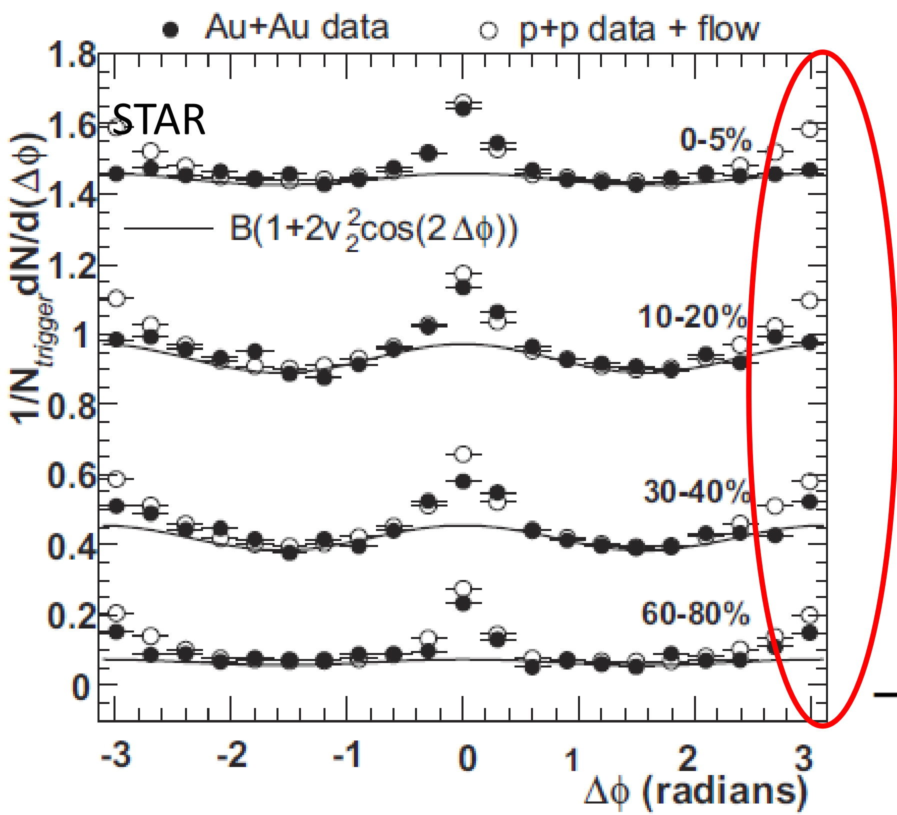


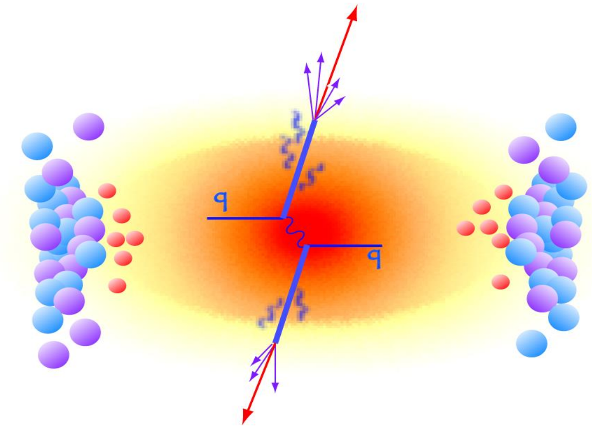


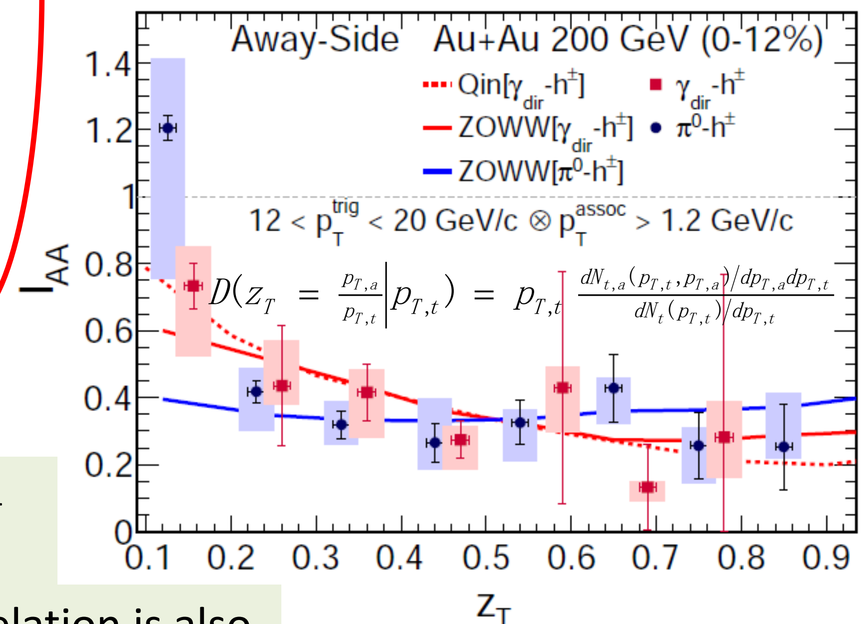
Strong nuclear modification (R_{AA}) for heavy flavor mesons comparable to light flavors

Different models vary in a few aspects: Radiative & collisional energy loss of HQ in QGP; Full Boltzmann & Fokker-Planck (Langevin) transport approaches for HQ evolution; Fragmentation & recombination for HQ hadronization; Partonic & hadronic interactions for heavy flavors; Shadowing; …

Jet-related dihadron & γ-hadron correlations



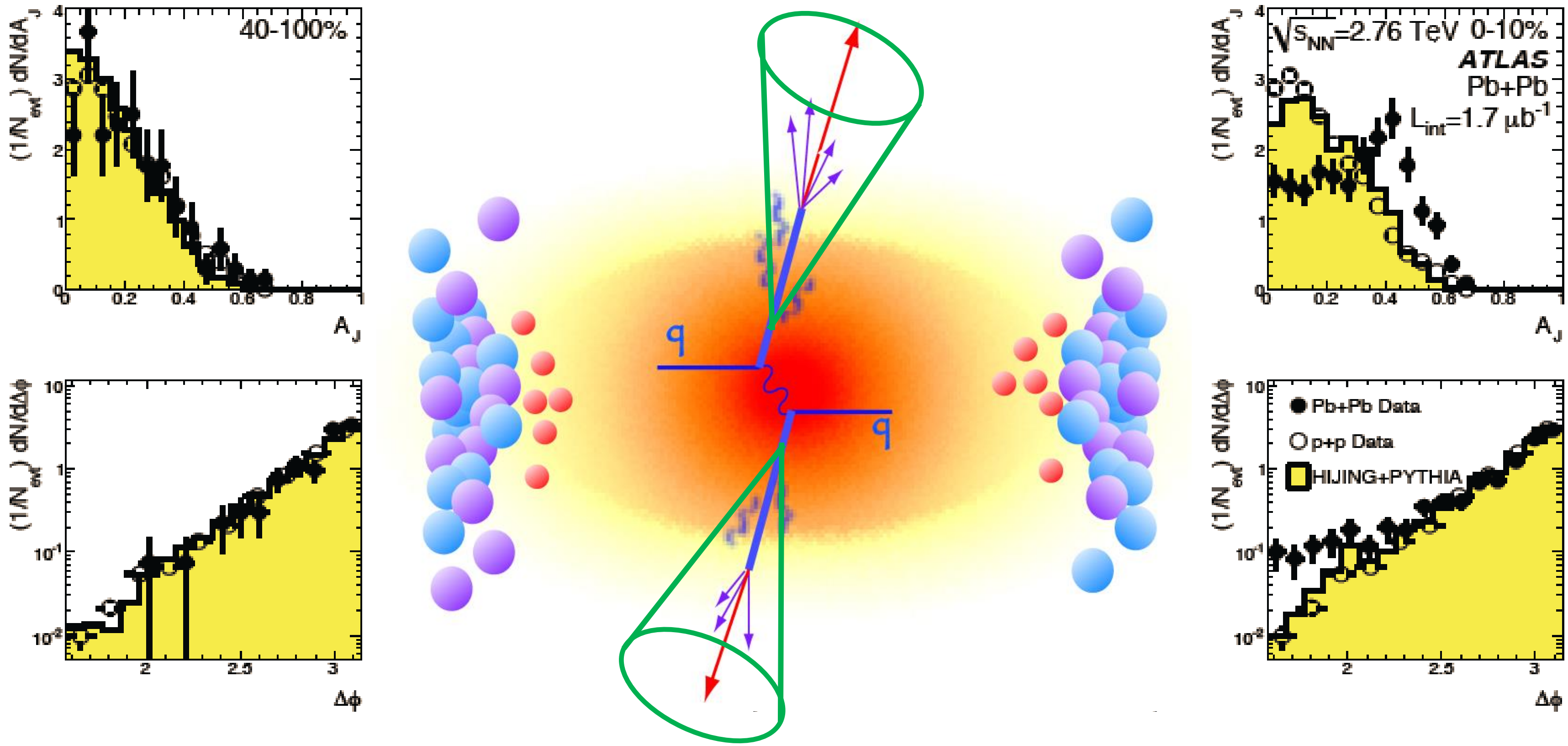




The away-side per-trigger yield at large z_T is suppressed due to parton energy loss

The shape of the away-side angular correlation is also changed due to transverse momentum broadening

Dijet asymmetry and correlations

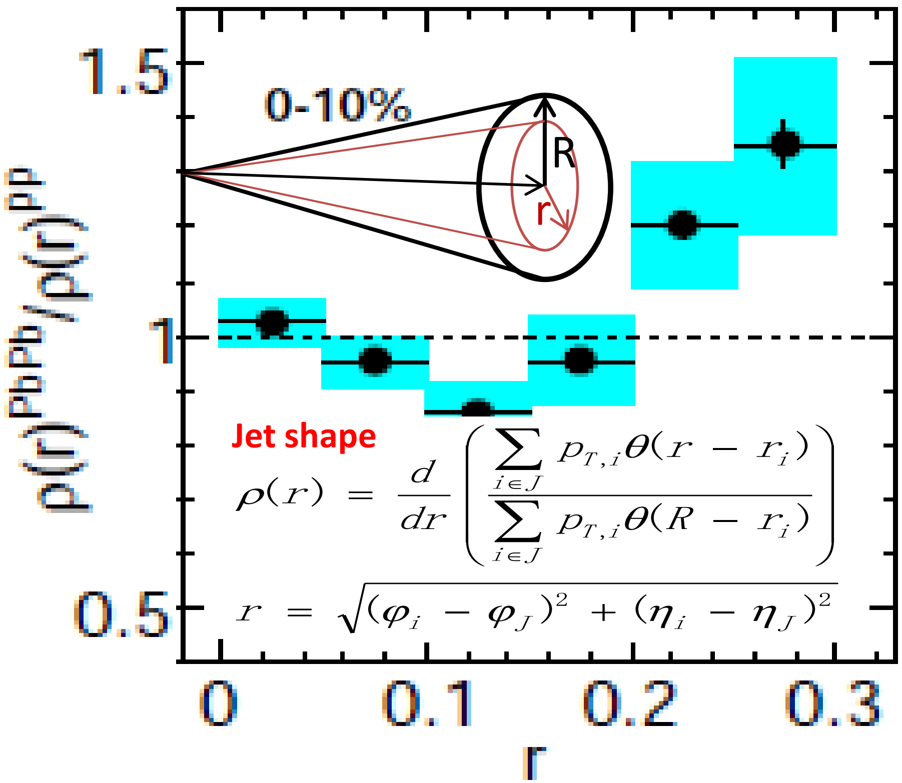


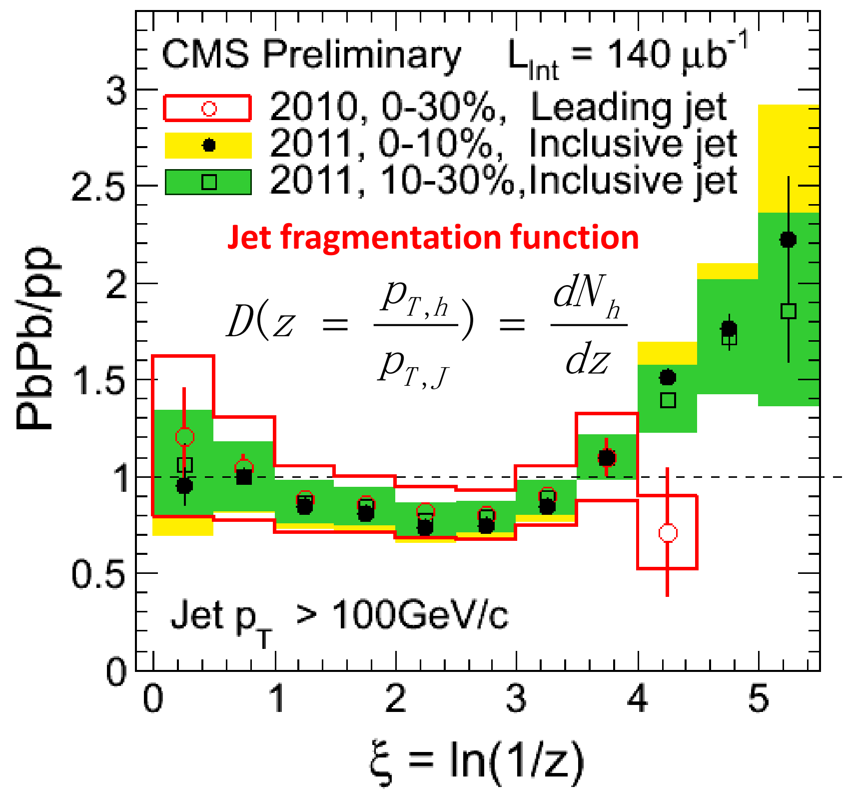
$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

$$\Delta\phi = \left|\phi_1 - \phi_2\right|$$

Strong modification of momentum imbalance distribution
=> Significant energy loss experienced by the subleading jets
Largely-unchanged angular distribution
=> medium-induced broadening is quite modest

Jet internal structure





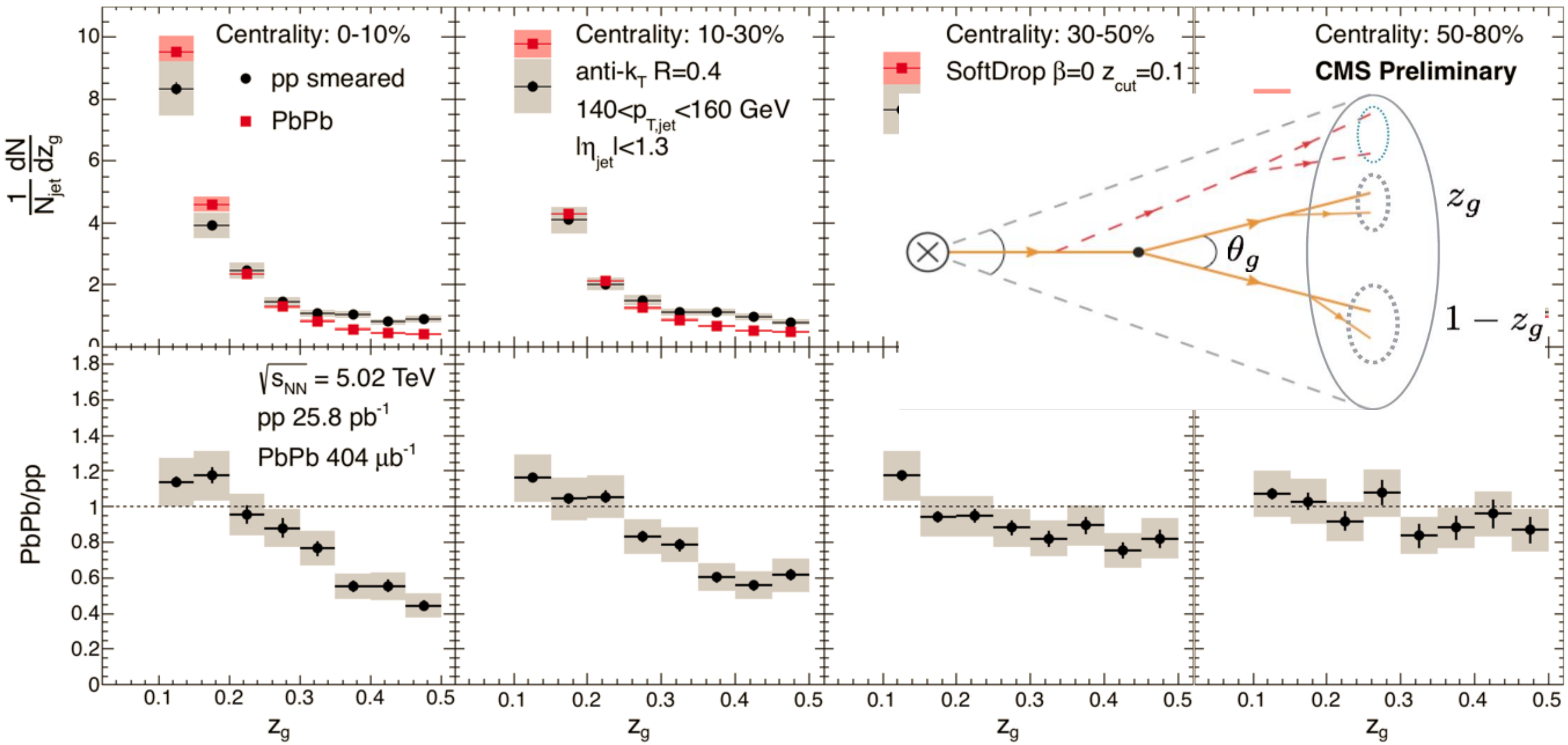
The enhancement at large r is consistent with jet broadening (& medium-induced radiation)

The enhancement at low z is expected from medium-induced radiation

The soft outer part of the jet is easier to modify, while changing the inner hard cone is more difficult

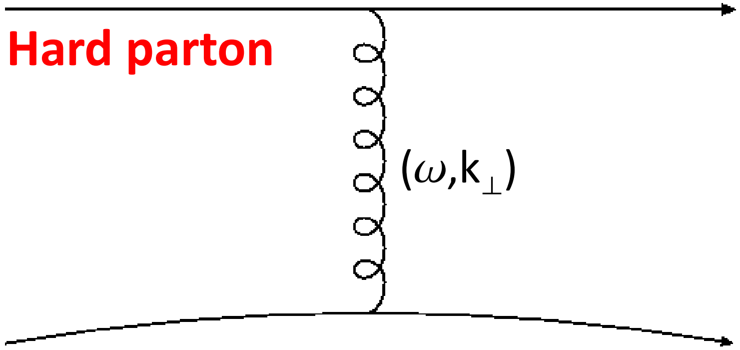
Groomed jet splitting

The momentum sharing z_g distribution for soft-drop groomed jets provides an opportunity to probe the medium-modified splitting function



CMS: more imbalanced splitting (branching) in more central PbPb collisions.

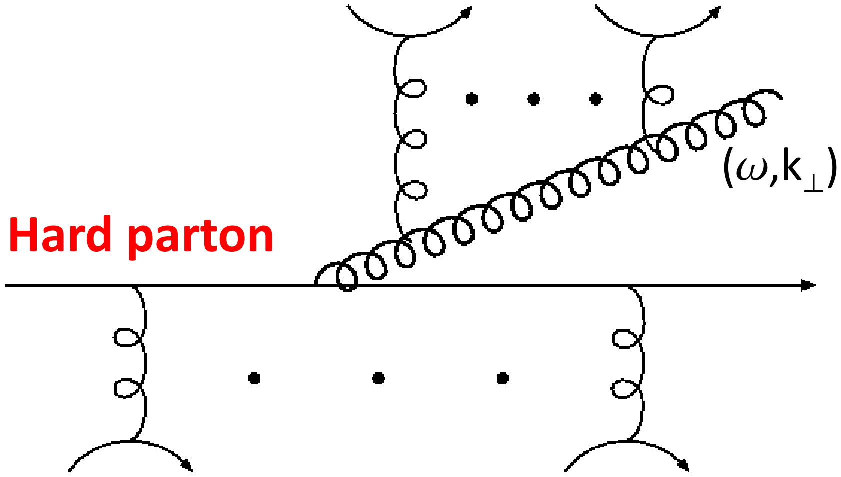
Jet-medium interaction



Elastic (collisional)

$$\frac{d\Gamma_{coll}}{d\omega dk_{\perp}^{2} dt}(T, E, \ldots) = ?$$

Bjorken 1982; Bratten, Thoma 1991; Thoma, Gyulassy, 1991; Mustafa, Thoma 2005; Peigne, Peshier, 2006; Djordjevic (GLV), 2006; Wicks et al (DGLV), 2007; GYQ et al (AMY), 2008; GYQ, Majumder, 2013…



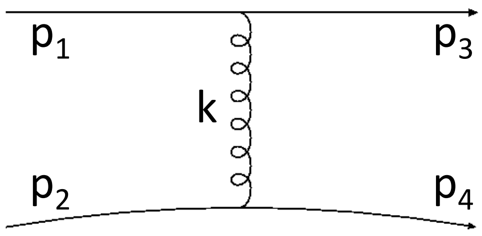
Inelastic (radiative)

$$\frac{d\Gamma_{rad}}{d\omega dk_{\perp}^{2} dt}(T, E, \ldots) = ?$$

BDMPS-Z: Baier-Dokshitzer-Mueller-Peigne-Schiff-Zakharov
ASW: Amesto-Salgado-Wiedemann
AMY: Arnold-Moore-Yaffe
DGLV: Djordjevic-Gyulassy-Levai-Vitev
HT: Wang-Guo-Majumder
Caron-Huot, Gale 2010; Djordjevic, Heinz, 2008; Djordjevic, Djordjevic, 2012; Majumder 2012…

A Linearized Boltzmann Transport (LBT) approach for heavy & light flavor jet quenching

- **Boltzmann equation:** $p_1 \cdot \partial f_1(x_1, p_1) = E_1 C[f_1]$



- **The collision term is the sum of gain and loss contributions**

$$C[f_1] \equiv \int d^3k \left[w(\vec{p}_1 + \vec{k}, \vec{k}) f_1(\vec{p}_1 + \vec{k}) - w(\vec{p}_1, \vec{k}) f_1(\vec{p}_1) \right]$$

- **For *elastic* (1+2->3+4) process, the transition rate is related to the cross section as:**

$$w(\vec{p}_1, \vec{k}) = \gamma_2 \int \frac{d^3p_2}{(2\pi)^3} f_2(\vec{p}_2) \left[1 \pm f_3(\vec{p}_1 - \vec{k})\right] \times \left[1 \pm f_4(\vec{p}_2 + \vec{k})\right] v_{\rm rel} d\sigma(\vec{p}_1, \vec{p}_2 \to \vec{p}_1 - \vec{k}, \vec{p}_2 + \vec{k})$$

- **The *elastic* scattering rate for (1+2->3+4) process:**

$$\Gamma_{12\to 34}(\vec{p}_1) = \int d^3k\, w(\vec{p}_1, \vec{k})$$

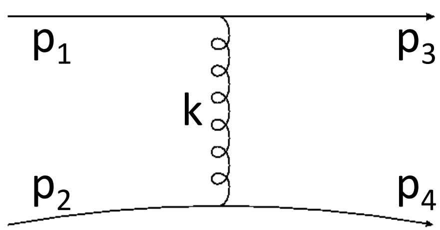
Cao, Luo, GYQ, Wang, PRC 2016 ; arXiv:1703.00822, etc.

A Linearized Boltzmann Transport (LBT) approach for heavy & light flavor jet quenching

- **Boltzmann equation:** $p_1 \cdot \partial f_1(x_1, p_1) = E_1 C\,[f_1]$

- **Elastic collisions:**

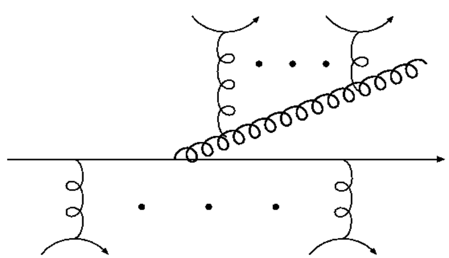
$$\Gamma_{12\to 34} = \frac{\gamma_2}{2E_1}\int \frac{d^3p_2}{(2\pi)^3 2E_2}\int \frac{d^3p_3}{(2\pi)^3 2E_3}\int \frac{d^3p_4}{(2\pi)^3 2E_4}$$
$$\times f_2(\vec{p}_2)\left[1 \pm f_3(\vec{p}_1 - \vec{k})\right]\left[1 \pm f_4(\vec{p}_2 + \vec{k})\right] S_2(s,t,u)$$
$$\times (2\pi)^4 \delta^{(4)}(p_1 + p_2 - p_3 - p_4)|\mathcal{M}_{12\to 34}|^2$$



$$P_{el} = 1 - e^{-\Gamma_{el}\Delta t}$$

- **Inelastic collisions:**

$$\langle N_g\rangle(E, T, t, \Delta t) = \Delta t \int dx dk_\perp^2 \frac{dN_g}{dx dk_\perp^2\, dt}$$



$$P(n) = \frac{\langle N_g\rangle^n}{n!} e^{-\langle N_g\rangle}$$

$$P_{inel} = 1 - e^{-\langle N_g\rangle}$$

- **Elastic + Inelastic:** $P_{tot} = P_{el} + P_{inel} - P_{el}P_{inel}$

Cao, Luo, GYQ, Wang, PRC 2016 ; arXiv:1703.00822; etc.

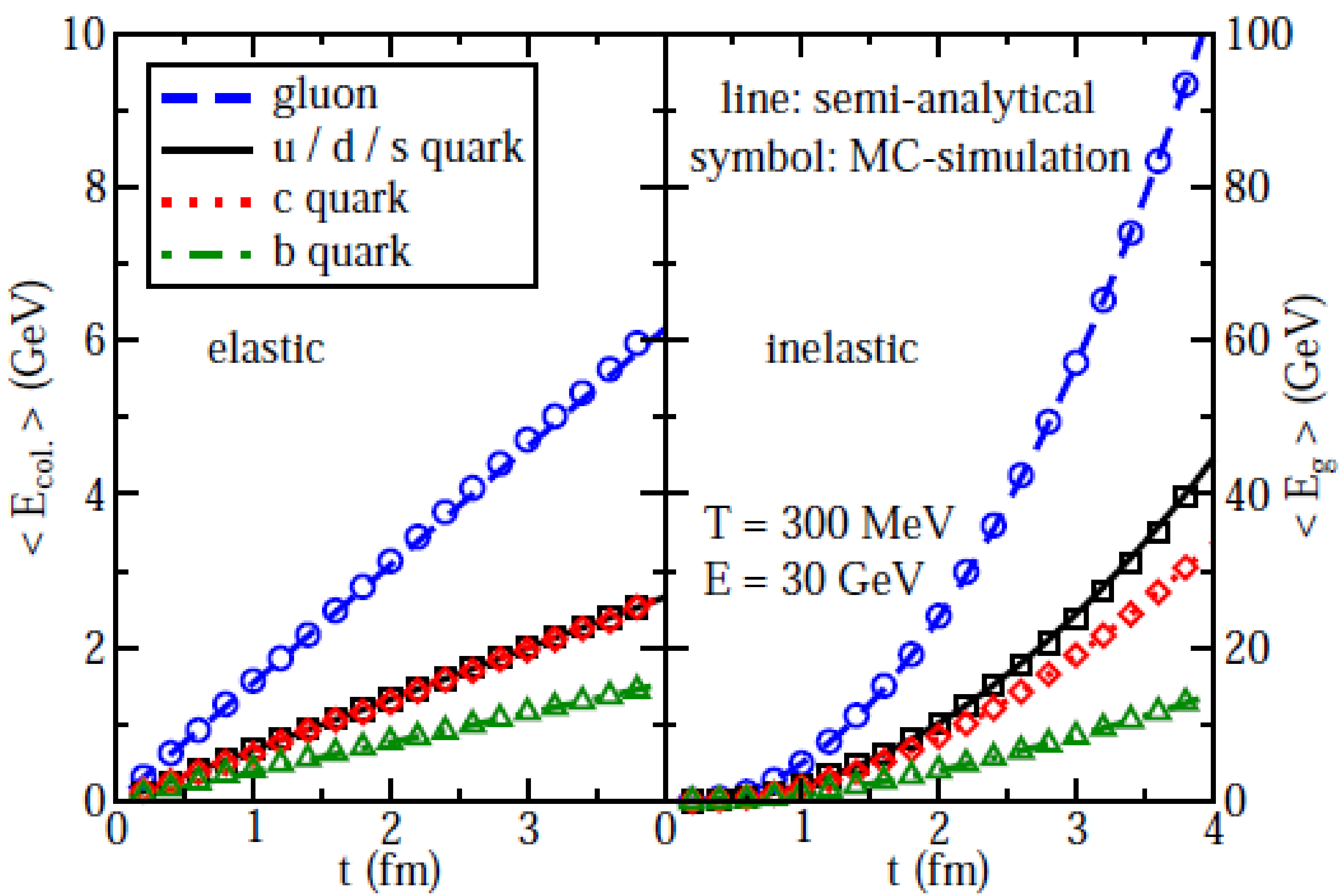
A Linearized Boltzmann Transport (LBT) approach for heavy & light flavor jet quenching

- **Elastic:**
  - Use total scattering rate to determine the probability of elastic scattering $P_{el}=1-e^{-\Gamma_{el}\Delta t}$
  - Use branching ratios Γ_i/Γ to determine the scattering channel
  - Use the differential rate to sample the momenta of two outgoing partons

- **Inelastic:**
  - Calculate $\langle N_g\rangle = \Gamma_{inel}\Delta t$ and $P_{inel}=1-e^{-\langle Ng\rangle}$
  - Sample *n* gluons from Poisson distribution $P(n) = \langle N_g\rangle^{-n}/n!\ e^{-\langle Ng\rangle}$
  - Sample *E* and *p* of gluons using the differential radiation spectrum

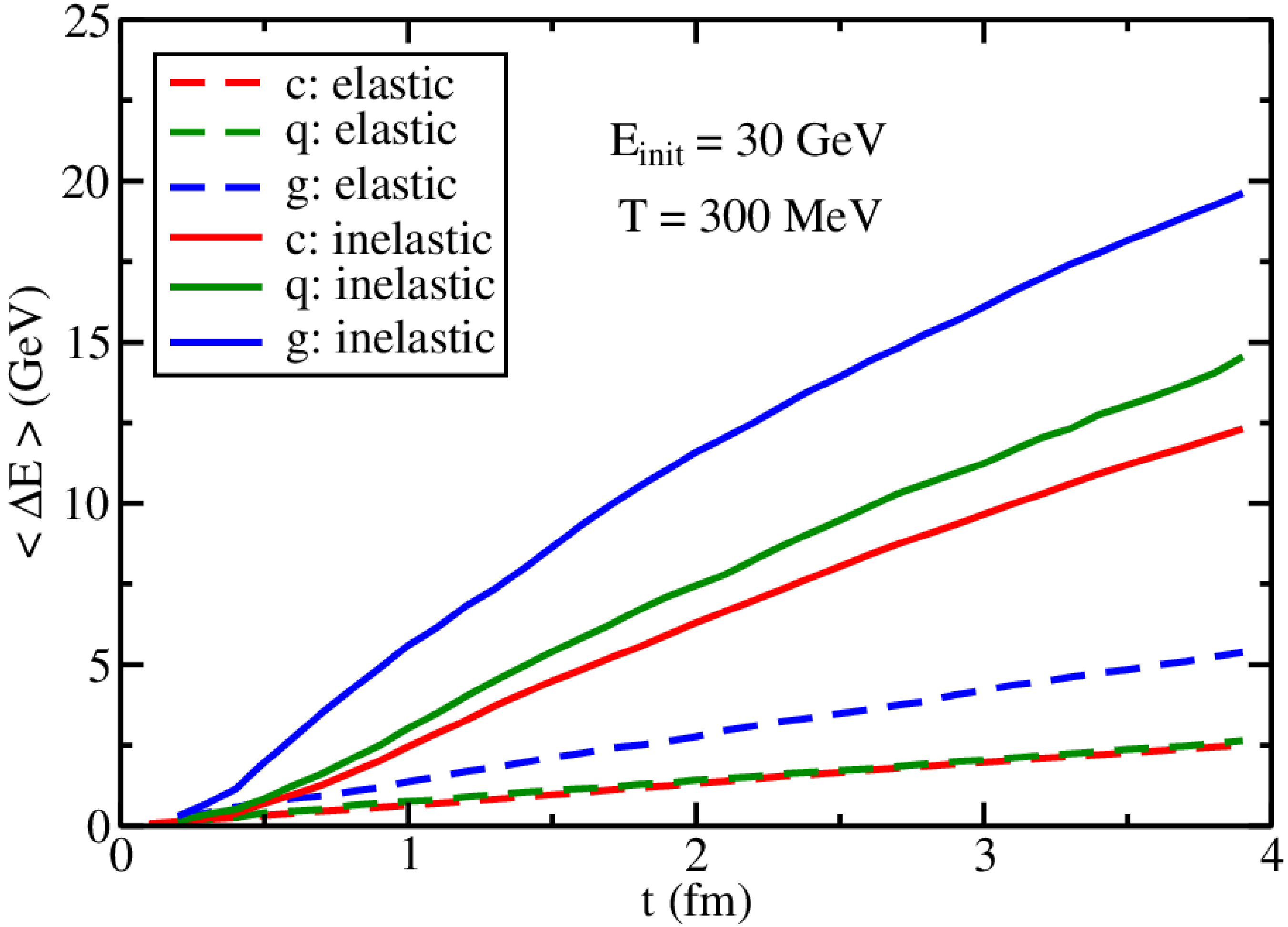
- **Elastic + Inelastic:**
  - Pure elastic: $P_{el}(1-P_{inel})$, Inelastic: P_{inel}, total: $P_{tot}=P_{el}+P_{inel}-P_{el}P_{inel}$
  - Use P_{tot} to determine whether jet parton interacts with thermal medium
  - If an interaction happens, then determine whether it is pure elastic $P_{el}(1-P_{inel})$ or inelastic P_{inel}
  - Simulate pure elastic (2->2) or inelastic (2->2+n) processes

LBT model validation



Cao, Luo, GYQ, Wang, PRC 2016; arXiv:1703.00822

Realistic simulation in LBT: parton energy loss



Cao, Luo, GYQ, Wang, PRC 2016; arXiv:1703.00822

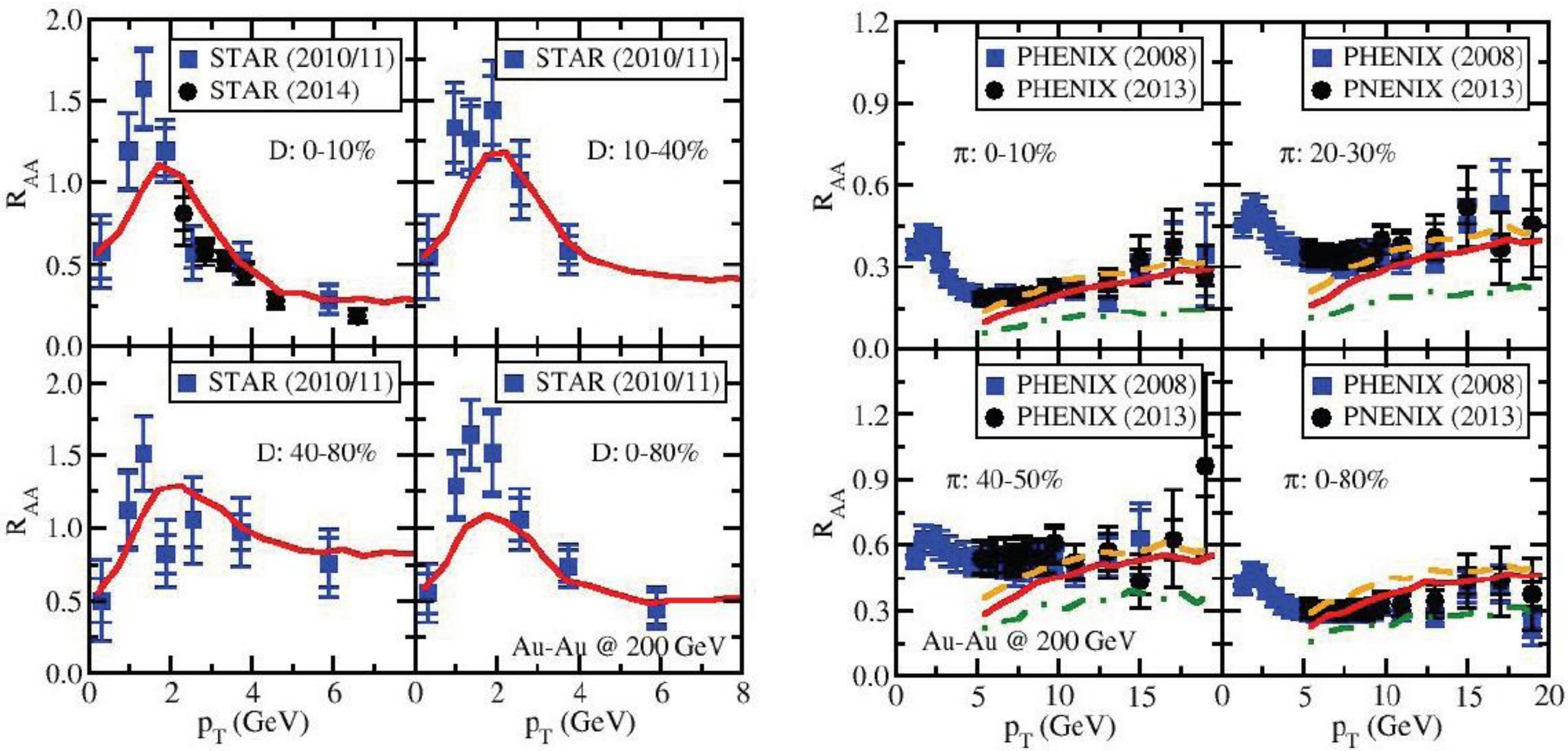
Realistic simulation in LBT: nuclear modification of hadrons

- **Initial condition**
  - Glauber model for *space* distribution
  - LO pQCD for *momentum* distribution

- **QGP background**
  - Relativistic hydrodynamic simulation provides the space-time evolution profiles of the QGP (the local temperature and flow of the medium that jet traverse)

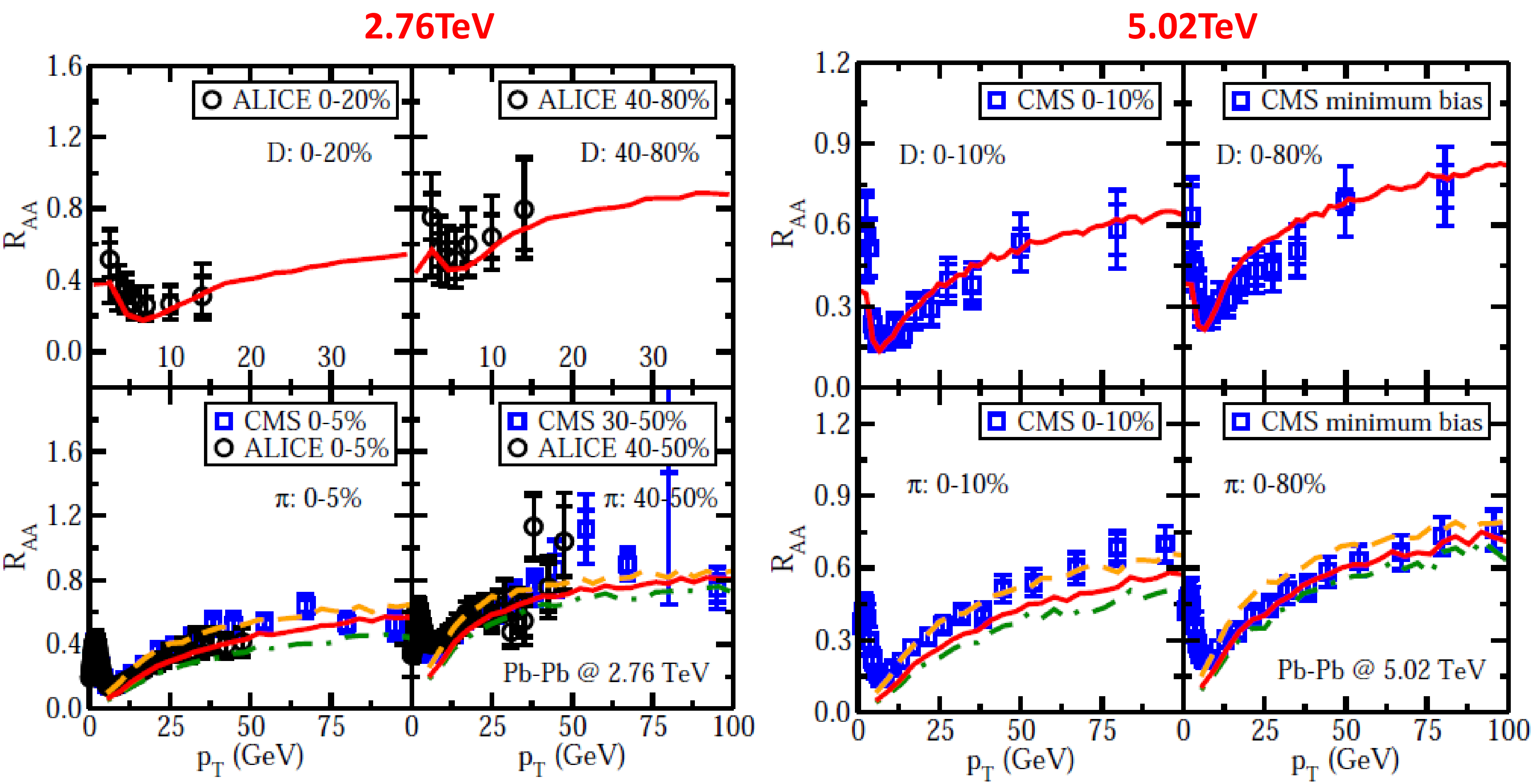
- **Hadronization:**
  - High momentum light flavor hadrons (fragmentation via PYTHIA)
  - Heavy flavor mesons (low & high momentum):
    - Most high momentum heavy quarks fragment into heavy mesons (via PYTHIA)
    - Most low momentum heavy quarks hadronize to heavy mesons via heavy-light quark coalescence mechanism

Heavy and light flavor jet quenching at RHIC



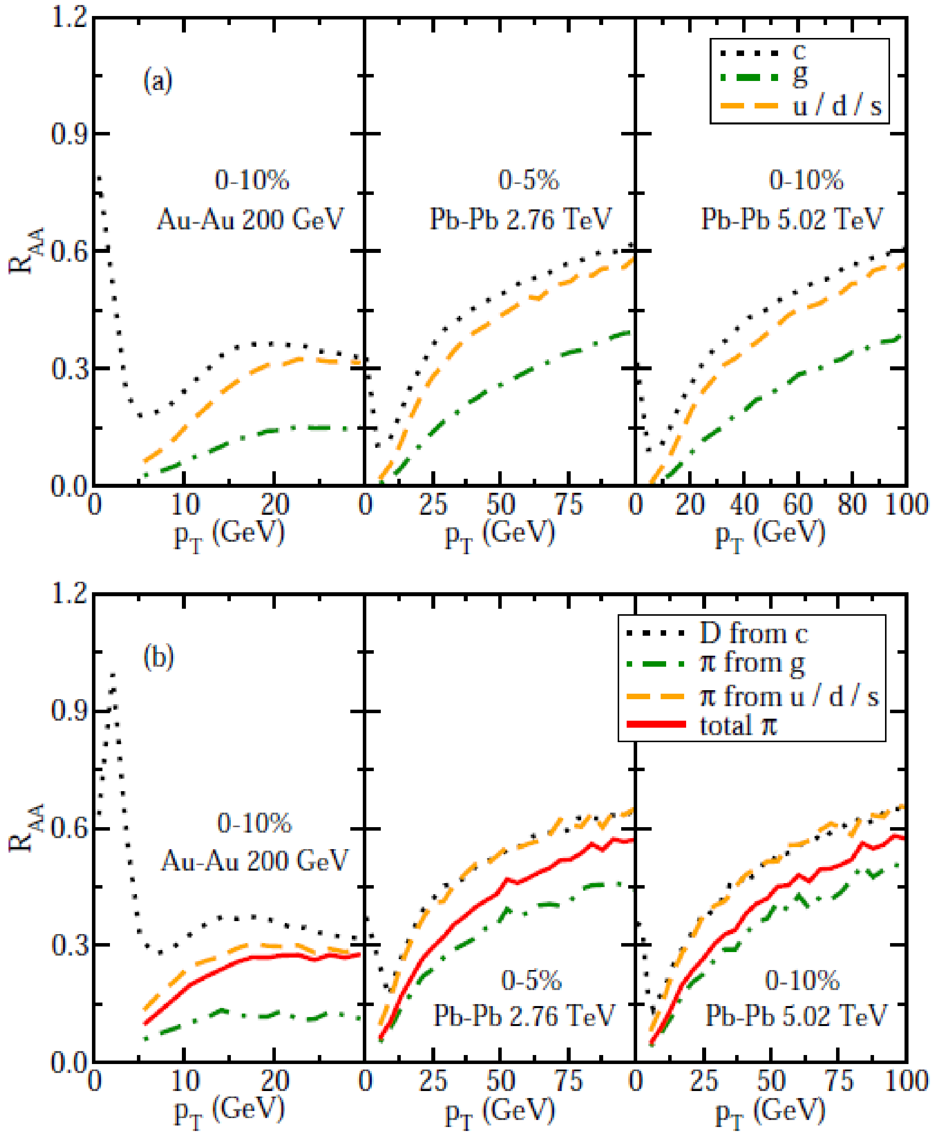
Cao, Luo, GYQ, Wang, PRC 2016; arXiv:1703.00822

Heavy and light flavor jet quenching at the LHC



Cao, Luo, GYQ, Wang, PRC 2016; arXiv:1703.00822

Flavor dependence of jet quenching



$R_{AA}(g) < R_{AA}(u,d,s) < R_{AA}(c)$

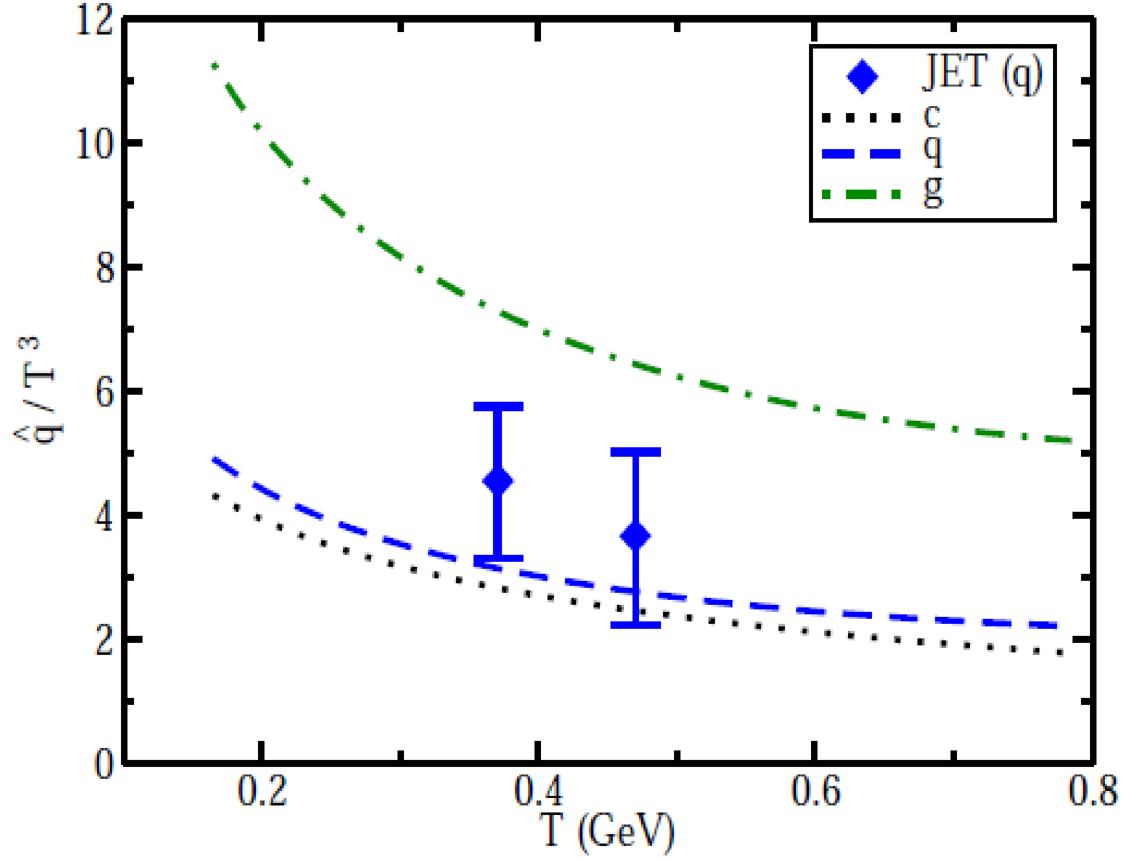
The rising of R_{AA} at the LHC due to harder initial parton spectra

$R_{AA}(\pi/u,d,s)$ ~ $R_{AA}(D)$ at the LHC due to deeper FF for light flavors (=> the same p_T hadrons probe higher energy partons)

From RHIC to the LHC, the *gluon contribution to light hadrons at the same p_T is increasing =>* the splitting of π and D meson R_{AA} at high p_T is larger

Cao, Luo, GYQ, Wang, PRC 2016; arXiv:1703.00822

Extract $\hat{q}$ from parton energy loss (by LBT)



Cao, Luo, GYQ, Wang, PRC 2016; arXiv:1703.00822

Linear-Boltzmann Transport approach: $p^{\mu}\partial_{\mu}f(\vec{x},\vec{p},t) = E\left(C_{col}[f] + C_{rad}[f]\right)$

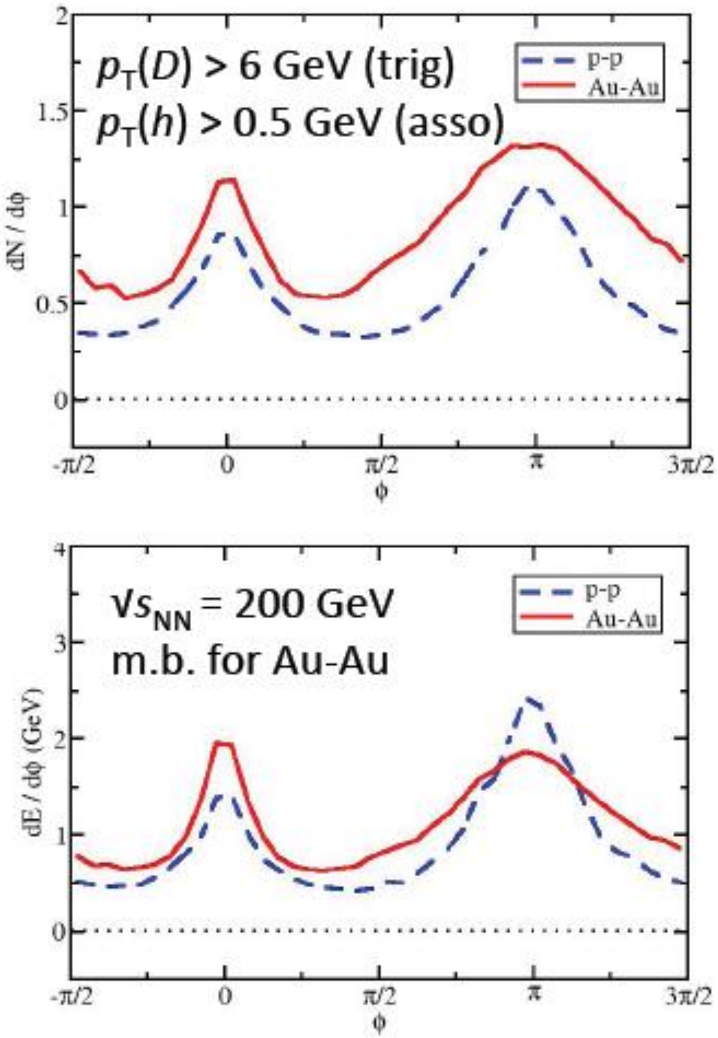
Summary

- A linear Boltzmann transport (LBT) model: Heavy and light flavor jet quenching on the same footing

- Both initial parton spectra and fragmentation functions are important for understanding the detailed difference between the nuclear modifications of light and heavy flavor hadrons

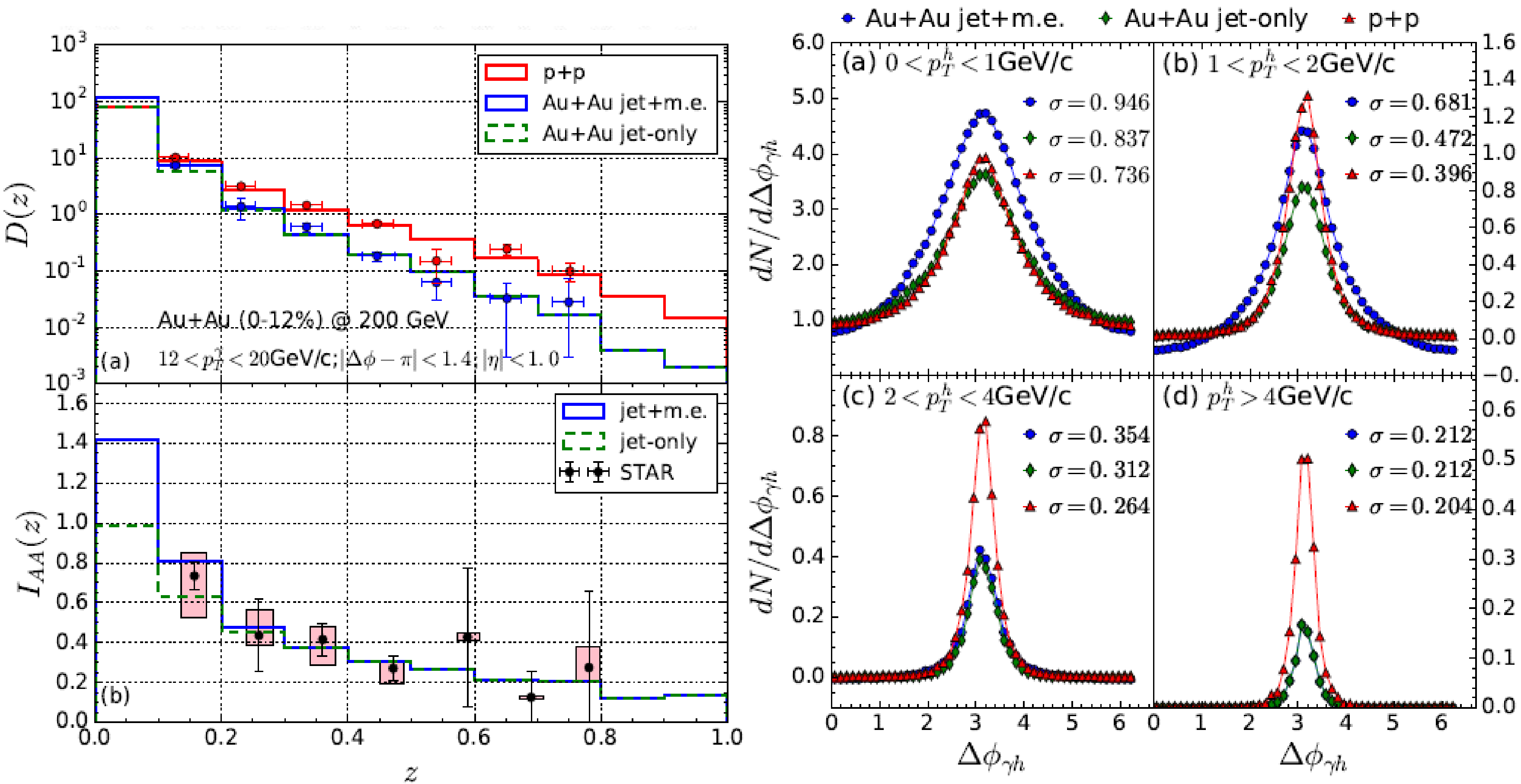
- Future: heavy flavor jets, heavy-light correlations, medium response, hadronization, …

D-hadron correlations



- Single hadron observables only probe parton energy loss
- D-hadron correlations can tell how the lost energy is redistributed, thus probe both parton energy loss and medium-induced broadening
- **pp baseline: PYTHIA**
- Include all charged hadrons from heavy and light parton shower and the recoiled partons from back reaction to the medium
- The background from thermal hadrons emitted by QGP are removed
- dN/dϕ is increased at all ϕ due to parton shower in Au-Au
- dE/dϕ is enhanced at 0 due to c energy loss in Au-Au, and broadened at π due to parton shower and scattering in QGP

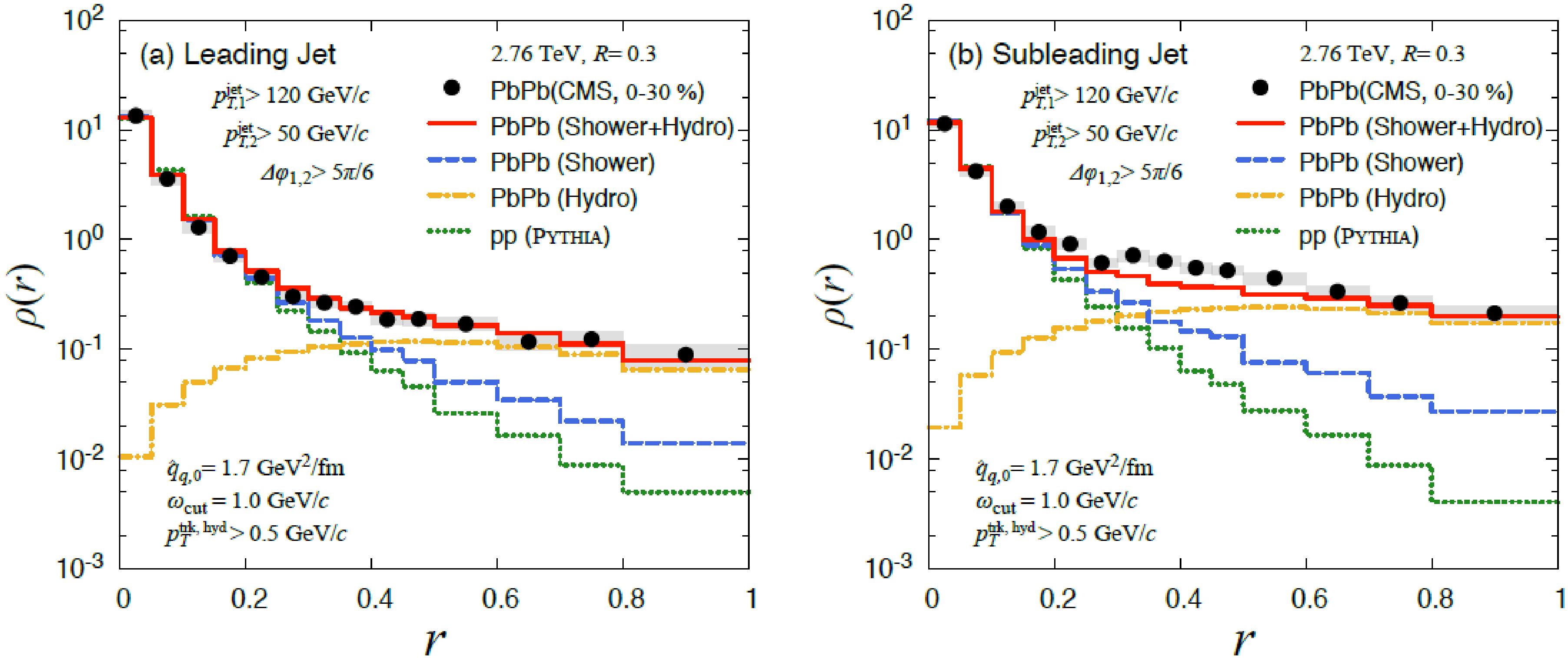
γ-hadron correlations from CoLBT-Hydro



Chen, Cao, Luo, Pang, Wang, arXiv:1704.03648

Thank you!

Jet shape from a jet-fluid model



The contribution from the hydro part is quite flat and finally dominates over the shower part in the region with r > 0.5.

Jet shape function for subleading jets is broader than leading jets due to more jet-medium interaction

Y. Tachibana, N. B. Chang, GYQ, PRC 2017

Elastic collisions

$$\Gamma_{12\to34} = \frac{\gamma_2}{2E_1}\int\frac{d^3p_2}{(2\pi)^3 2E_2}\int\frac{d^3p_3}{(2\pi)^3 2E_3}\int\frac{d^3p_4}{(2\pi)^3 2E_4}$$
$$\times f_2(\vec{p}_2)\left[1\pm f_3(\vec{p}_1-\vec{k})\right]\left[1\pm f_4(\vec{p}_2+\vec{k})\right]S_2(s,t,u)$$
$$\times (2\pi)^4\delta^{(4)}(p_1+p_2-p_3-p_4)|\mathcal{M}_{12\to34}|^2$$

$$S_2(s,t,u) = \theta(s\geq 2\mu_{\rm D}^2)\theta(-s+\mu_{\rm D}^2\leq t\leq -\mu_{\rm D}^2)$$

$$\Gamma_{12\to34}(\vec{p}_1,T) = \frac{\gamma_2}{16E_1(2\pi)^4}\int dE_2 d\theta_2 d\theta_4 d\phi_4$$
$$\times f_2(E_2,T)\left[1\pm f_4(E_4,T)\right]S_2(s,t,u)|\mathcal{M}_{12\to34}|^2$$
$$\times\frac{E_2E_4\sin\theta_2\sin\theta_4}{E_1-|\vec{p}_1|\cos\theta_4+E_2-E_2\cos\theta_{24}}$$

$\vec{p}_1$ in the $+z$ direction

$\vec{p}_2$ in the $x-z$ plane

$$\hat{q} = \langle\langle(\vec{p}_3-\hat{p}_1\cdot\vec{p}_3)^2\rangle\rangle$$
$$\hat{e} = \langle\langle(E_1-E_3)\rangle\rangle$$

$$\cos\theta_{24} = \sin\theta_2\sin\theta_4\cos\phi_4+\cos\theta_2\cos\theta_4$$
$$E_4 = \frac{E_1E_2-p_1E_2\cos\theta_2}{E_1-p_1\cos\theta_4+E_2-E_2\cos\theta_{24}}$$

Inelastic radiation

$$\frac{dN_g}{dx dk_\perp^2 dt} = \frac{2\alpha_s C_A P(x)}{\pi k_\perp^4} \hat{q} \left(\frac{k_\perp^2}{k_\perp^2 + x^2 M^2} \right)^4 \sin^2 \left(\frac{t - t_i}{2\tau_f} \right)$$

$$\tau_f = 2Ex(1-x)/(k_\perp^2 + x^2 M^2)$$

$$\langle N_g \rangle (E, T, t, \Delta t) = \Delta t \int dx dk_\perp^2 \frac{dN_g}{dx dk_\perp^2 dt}$$

Heavy quark hadronization

- **Most high momentum heavy quarks fragment into heavy mesons**
  - Use PYTHIA 6.4 "independent fragmentation model"
- **Most low momentum heavy quarks hadronize to heavy mesons via recombination (coalescence) mechanism**
  - use sudden recombination model based on Y. Oh, et al., PRC 79, 044905 (2009)

$$\frac{dN_M}{d^3p_M} = \int d^3p_1 d^3p_2 \frac{dN_1}{d^3p_1}\frac{dN_2}{d^3p_2} f_M^W(\vec{p}_1,\vec{p}_2)\delta(\vec{p}_M - \vec{p}_1 - \vec{p}_2)$$

$$\frac{dN_B}{d^3p_B} = \int d^3p_1 d^3p_2 d^3p_3 \frac{dN_1}{d^3p_1}\frac{dN_2}{d^3p_2}\frac{dN_3}{d^3p_3} f_B^W(\vec{p}_1,\vec{p}_2,\vec{p}_3)\delta(\vec{p}_M - \vec{p}_1 - \vec{p}_2 - \vec{p}_3)$$

  - Inputs: heavy quark/anti-quark distribution after evolution, light quark/ anti-quark distribution from QGP, and Wigner function f^W
  - f^W is obtained from hadron wave functions (approximated by S.H.O.)

$$f_M^W(\vec{r},\vec{q}) \equiv N g_M \int d^3r' e^{-i\vec{q}\cdot\vec{r}'}\phi_M(\vec{r}+\frac{\vec{r}'}{2})\phi_M^*(\vec{r}-\frac{\vec{r}'}{2})$$

The Sudden Recombination Model

Two-particle recombination:

$$\frac{dN_M}{d^3p_M} = \int d^3p_1 d^3p_2 \frac{dN_1}{d^3p_1}\frac{dN_2}{d^3p_2} f_M^W(\vec{p}_1, \vec{p}_2)\delta(\vec{p}_M - \vec{p}_1 - \vec{p}_2)$$

$\frac{dN_i}{d^3p_i}$ Distribution of the *i* th kind of particle

Light quark: FD distribution in the LRF of the hydro cell

Heavy quark: the distribution at T_c after in-medium evolution

$f_M^W(\vec{p}_1, \vec{p}_2)$ Probability for two particles to recombine

$$f_M^W(\vec{r}, \vec{q}) \equiv g_M \int d^3r' e^{-i\vec{q}\cdot\vec{r}'} \phi_M(\vec{r}+\frac{\vec{r}'}{2})\phi_M^*(\vec{r}-\frac{\vec{r}'}{2})$$

$$\vec{r} = \vec{r}_1' - \vec{r}_2'$$

$$\vec{q} = \frac{1}{E_1' + E_2'}(E_2'\vec{p}_1' - E_1'\vec{p}_2')$$

Variables on the R.H.S. are defined in the CM frame of the two-particle system.

The Sudden Recombination Model

$$f_M^W(\vec{r},\vec{q}) \equiv g_M \int d^3r' e^{-i\vec{q}\cdot\vec{r}'} \phi_M(\vec{r}+\frac{\vec{r}'}{2})\phi_M^*(\vec{r}-\frac{\vec{r}'}{2})$$

g_M: statistics factor

D ground state: 1/(2*3*2*3)=1/36 – spin and color

D*: 3/(2*3*2*3)=1/12 – spin of D* is 1

Φ_M: meson wave function–approximated by ground state of QM SHO

$$\phi_M(\vec{r}) = \left(\frac{1}{\pi\sigma^2}\right)^{3/4} e^{-r^2/(2\sigma^2)} \qquad \sigma = 1/\sqrt{\mu\omega}$$

μ: reduced mass of the 2-particle system (m_q=300MeV, m_s=475MeV)

ω: SHO frequency – calculated by meson radius:

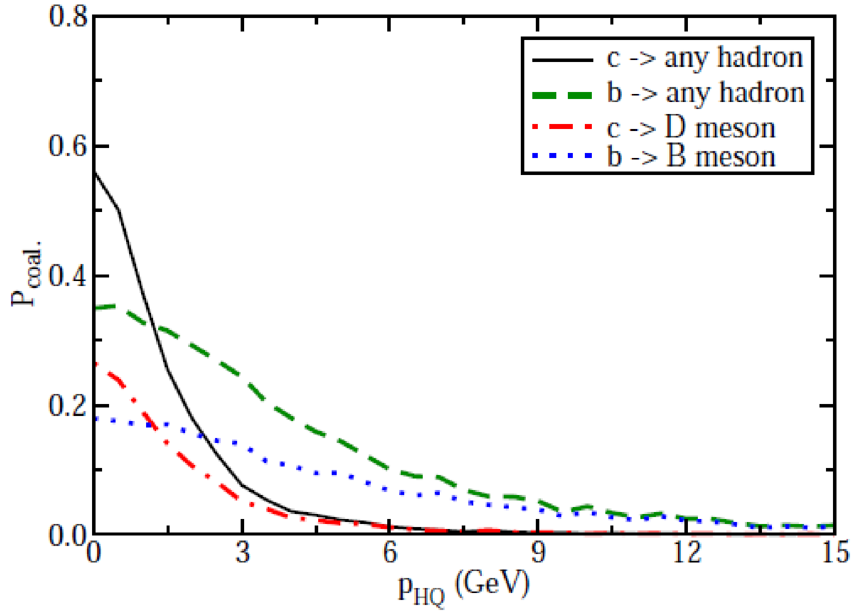
0.33GeV for c/b meson, 0.43GeV for c baryon, 0.41GeV for b baryon

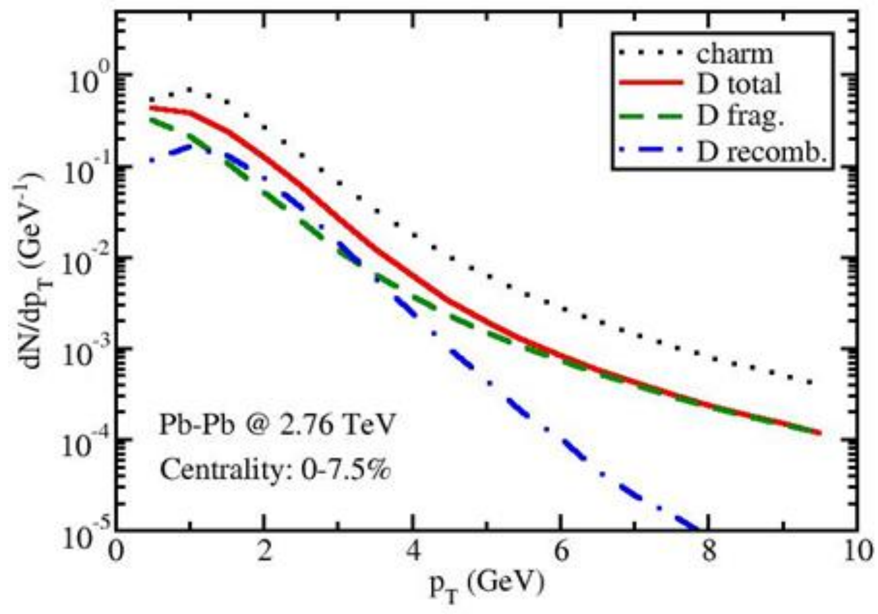
Integrating over the position space:

$$f_M^W(q^2) = g_M \frac{(2\sqrt{\pi}\sigma)^3}{V} e^{-q^2\sigma^2}$$

$$f_B^W(q_1^2, q_2^2) = g_B \frac{(2\sqrt{\pi})^6(\sigma_1\sigma_2)^3}{V^2} e^{-q_1^2\sigma_1^2 - q_2^2\sigma_2^2}$$

Heavy quark hadronization





- Use Wigner function f^{W} to calculate the rec. probability $P_{coal.}(p_{HQ})$ for all meson & baryon channels: D/B, Λ_Q, Σ_Q, Ξ_Q, Ω_Q
- For each HQ, determine the channel: frag. or recomb.? recomb. to *D/B* or a baryon?
- b quark recomb. probability is smaller than c quark at p=0, but decreases slower with increasing p
- Fragmentation dominates D/B meson production at high p_T
- Recombination greatly increases D/B yield at intermediate p_T
- At same p_T, bottom quarks have larger recomb. probability than charm to produce heavy flavor hadrons due to larger masses (not shown)