Medium modification of heavy vs. light hadron production and *D*-hadron correlation

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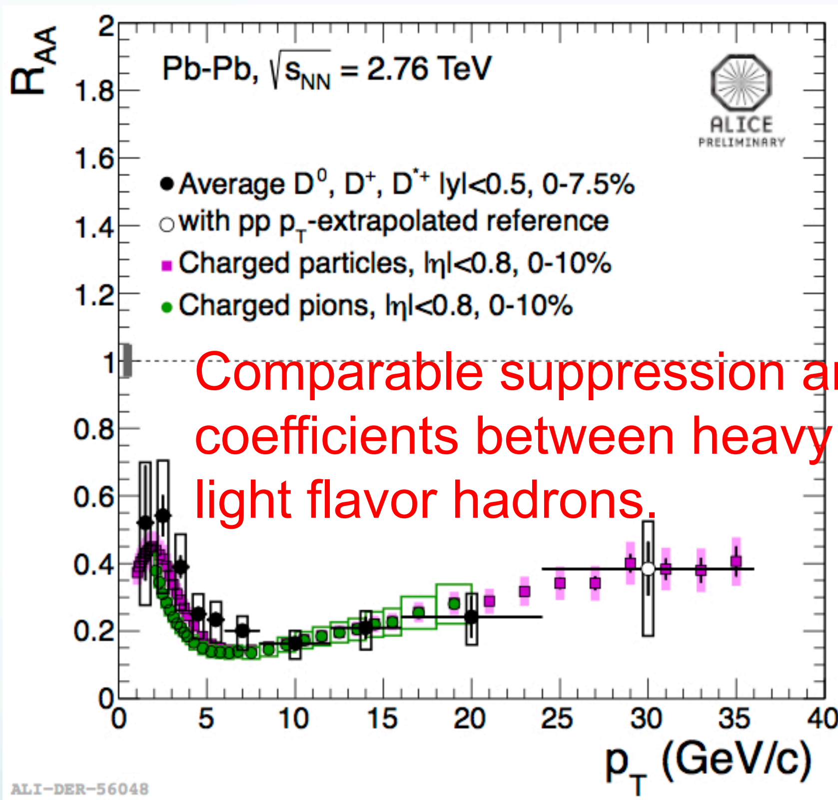
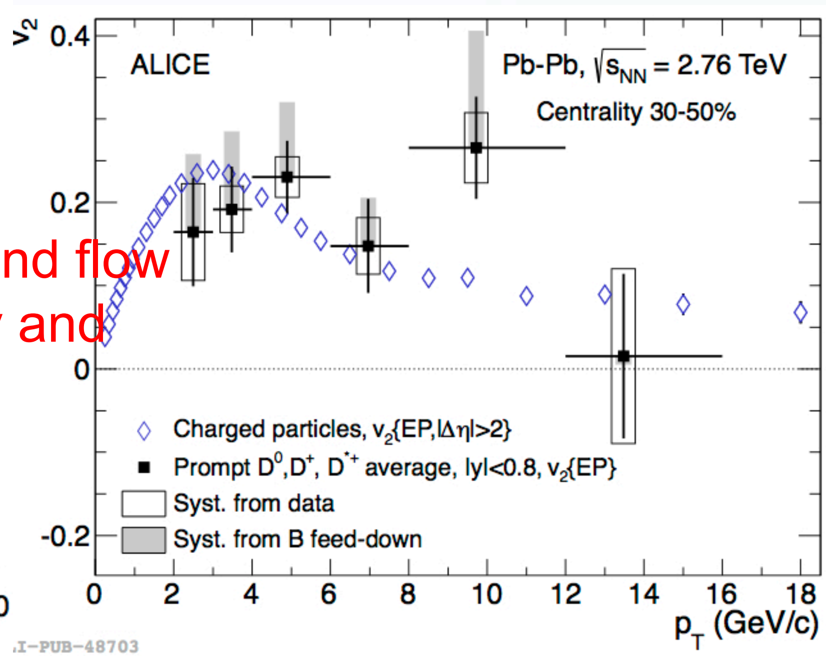
Outline

- Introduction
- A Linear Boltzmann Transport Model (LBT) for parton energy loss in QGP
- Heavy vs. light hadron suppression and anisotropic flow coefficients at RHIC and the LHC
- Medium modification of *D*-hadron correlation
- Summary and outlook

Motivation

Hard partons: produced early and probe the full QGP history





Comparable suppression and flow coefficients between heavy and light flavor hadrons.

"Heavy vs. light flavor puzzle": is $\Delta E_g > \Delta E_q > \Delta E_c > \Delta E_b$ still right?

"R_{AA} vs. v_2 puzzle": can we describe R_{AA} and v_2 simultaneously?

Goal: fully understand heavy and light parton dynamics within a unified theoretical/numerical framework

A Linear Boltzmann Transport Model

Boltzmann equation for parton "1" distribution:

$$p_1 \cdot \partial f_1(x_1, p_1) = E_1 C\left[f_1\right]$$

The collision term:

transition rate from p_1 to p_1-k

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

Elastic Scattering (2->2 process)

$$w(\vec{p}_1,\vec{k}) \equiv \sum_{2,3,4} w_{12\to34}(\vec{p}_1,\vec{k})$$

$$w_{12\to34}(\vec{p}_1,\vec{k}) = \gamma_2 \int \frac{d^3p_2}{(2\pi)^3} f_2(\vec{p}_2)\left[1 \pm f_3(\vec{p}_1-\vec{k})\right]\left[1 \pm f_4(\vec{p}_2+\vec{k})\right]$$
$$\times\, v_{\mathrm{rel}}\, d\sigma_{12\to34}(\vec{p}_1,\vec{p}_2 \to \vec{p}_1-\vec{k},\vec{p}_2+\vec{k})$$

microscopic cross section of 12->34

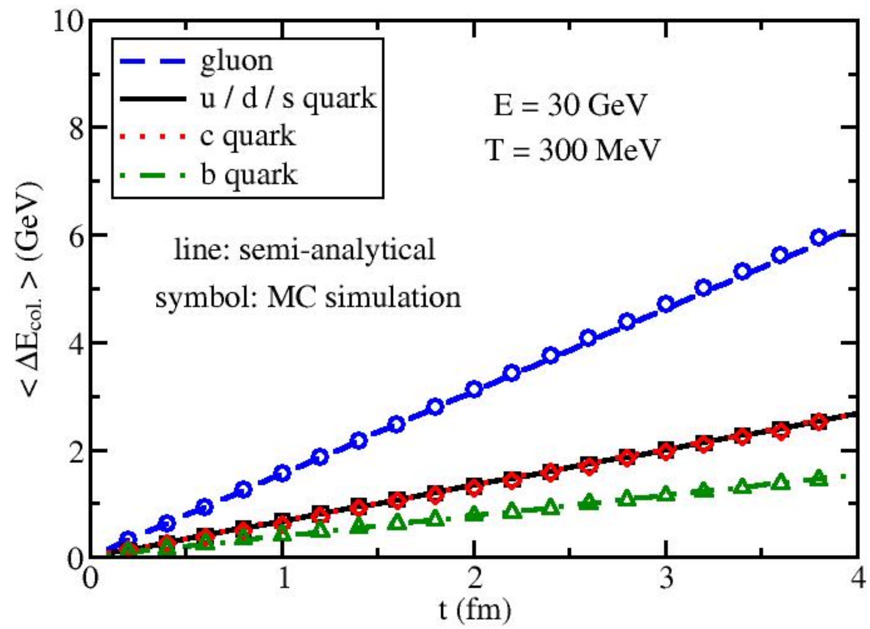
A Linearized Boltzmann Transport Model

Scattering rate:

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

In model calculation:

1. Use total rate $\Gamma = \sum_i \Gamma_i$ to determine the probability of elastic scattering $P_{\rm el} = \Gamma\Delta t$
2. Use branching ratios Γ_i/Γ to determine the scattering channel
3. Use the differential rate to sample the *p* space of the two outgoing partons



$\Delta E_{\rm col.}$ from our MC simulation agrees with the semi-analytical result.

A Linearized Boltzmann Transport Model

Inelastic Scattering (2->2+n process)

Average gluon number in Δt:

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

Spectrum of medium-induced gluon (higher-twist formalism):

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

[Guo and Wang (2000), Majumder (2012); Zhang, Wang and Wang (2004)]

$\hat{q}$: $dp_\perp^2/dt$ of quark/gluon due to 2->2 scatterings

Splitting time of radiated gluon: $\tau_f = 2Ex(1-x)/(k_\perp^2 + x^2 M^2)$

Splitting functions:

$$P_{q \to qg} = \frac{(1-x)(2-2x+x^2)}{x},$$

$$P_{g \to gg} = \frac{2(1-x+x^2)^3}{x(1-x)}.$$

g->q$\bar{q}$ not included – slight effect on single HM PRC 93 (2016), 024912

A Linearized Boltzmann Transport Model

Number *n* of radiated gluons during *Δt* – Poisson distribution:

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

Probability of inelastic scattering during *Δt*: $P_{\rm inel} = 1 - e^{-\langle N_g \rangle}$

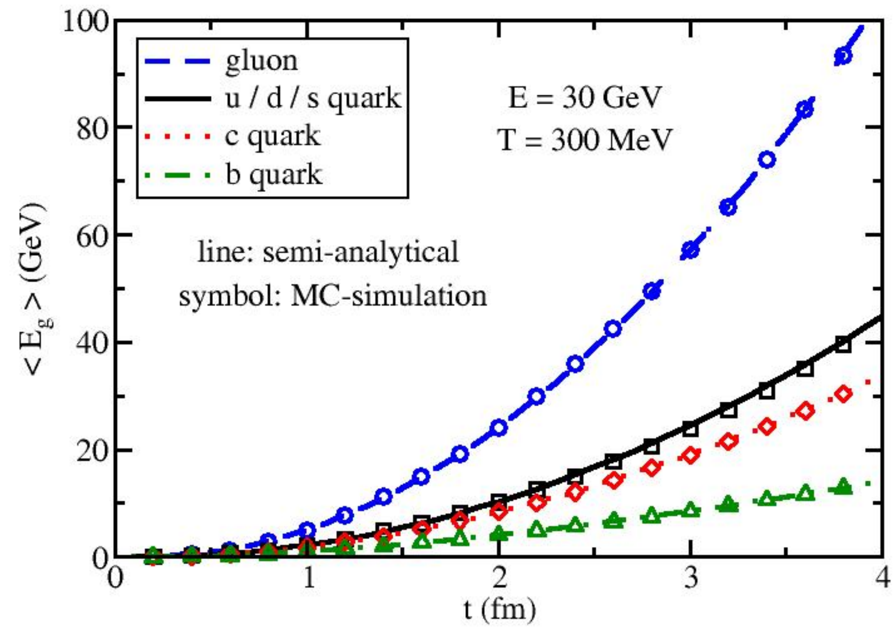
In model calculation:

1.Calculate $\langle N_g \rangle$and thus $P_{\rm inel}$

2.If gluon radiation happens, sample *n* from $P(n)$

3.Sample *E* and *p* of gluons using the differential spectrum

4.Assume 2->2 first and adjust *E* and *p* of the 2+n final partons together to guarantee *E-p* conservation of 2->2+n process



$<E_g>$ from our MC simulation agrees with the semi-analytical result.

Elastic vs. Inelastic Energy Loss

Divide scattering probability of jet parton into two regions:

1. Pure elastic scattering without radiated gluons: $P_{\rm el}(1-P_{\rm inel})$
2. Inelastic scattering: $P_{\rm inel}$

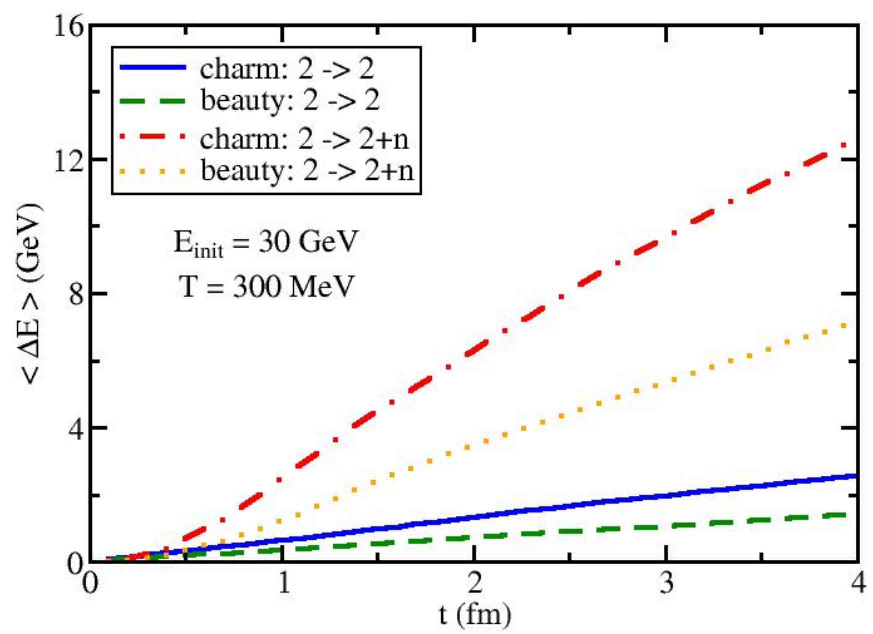
Total probability: $P_{\rm tot}=P_{\rm el}+P_{\rm inel}-P_{\rm el}P_{\rm inel}$

In model calculation:

1.Use $P_{\rm tot}$ to determine whether the jet parton scatter with the thermal medium

2.If so, we then determine whether this scattering is pure elastic or inelastic

3.Simulate the 2->2 or 2->2+n process



HQ energy loss due to elastic and inelastic processes are comparable at early time, but is dominated by the inelastic process at large *t*.

Hadronization

Heavy Flavor: fragmentation + HQ-thermal recombination

- Most high momentum heavy quarks fragment into heavy mesons: use PYTHIA 6.4
- Most low momentum heavy quarks hadronize to heavy mesons via recombination (coalescence) mechanism

[SC, Luo, Qin and Wang, Phys. Rev. C94 (2016) 014909]

Light flavor: jet fragmentation + jet-jet recombination

- Contribution from the bulk matter and jet-thermal recombination will be included in our future effort

[Han, Fries and Ko, Phys. Rev. C93 (2016) 045207]

Hadronization of Heavy Quarks

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 parton: thermal in the l.r.f of the hydro cell

Heavy quark: the distribution at T_c after Langevin evolution

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

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

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

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

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

Hadronization of Heavy Quarks

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

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

defined in the rest frame of the produced meson

g_M: color-spin degeneracy of the produced meson

Φ_M: meson wave function – approximated by S.H.O.

Averaging over the position space leads to

$$f_M^W(q^2) = g_M \frac{(2\sqrt{\pi}\sigma)^3}{V} e^{-q^2\sigma^2} \qquad \sigma = 1/\sqrt{\mu\omega}$$

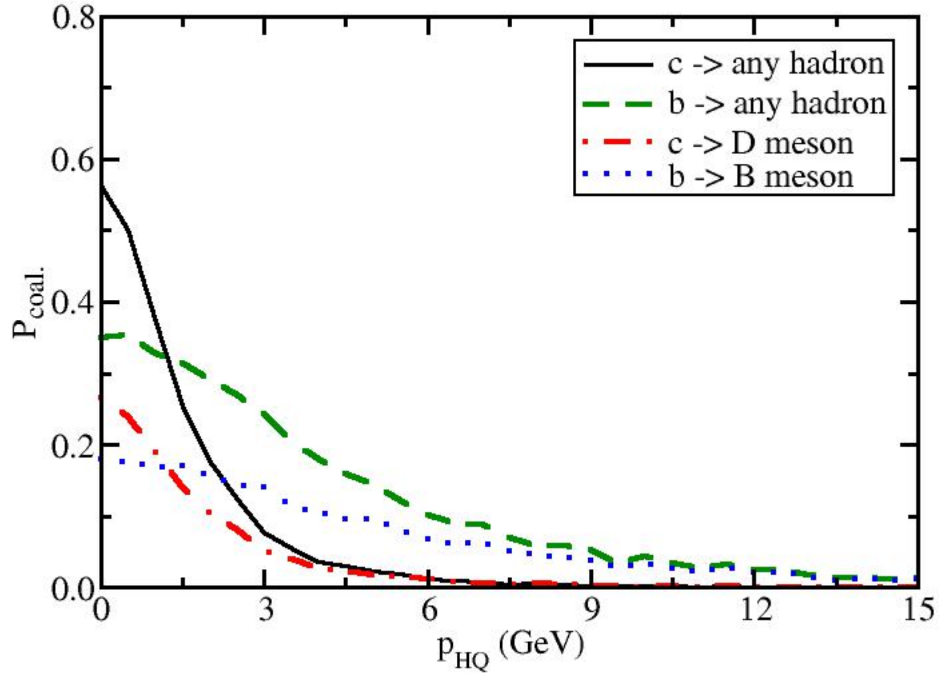
μ: reduced mass of the 2-particle system

ω: S.H.O frequency – related meson charge radius (parameter free)

$$\langle r_M^2 \rangle_{\mathrm{ch}} = \frac{3}{2\omega} \frac{1}{(m_1+m_2)(Q_1+Q_2)}$$

Can be generalized to 3-particle recombination (baryon)

Hadronization of Heavy Quarks



Use f^{W} to calculate $P_{coal.}(p_{HQ})$ for all channels (D/B Λ Σ Ξ Ω) at T_c

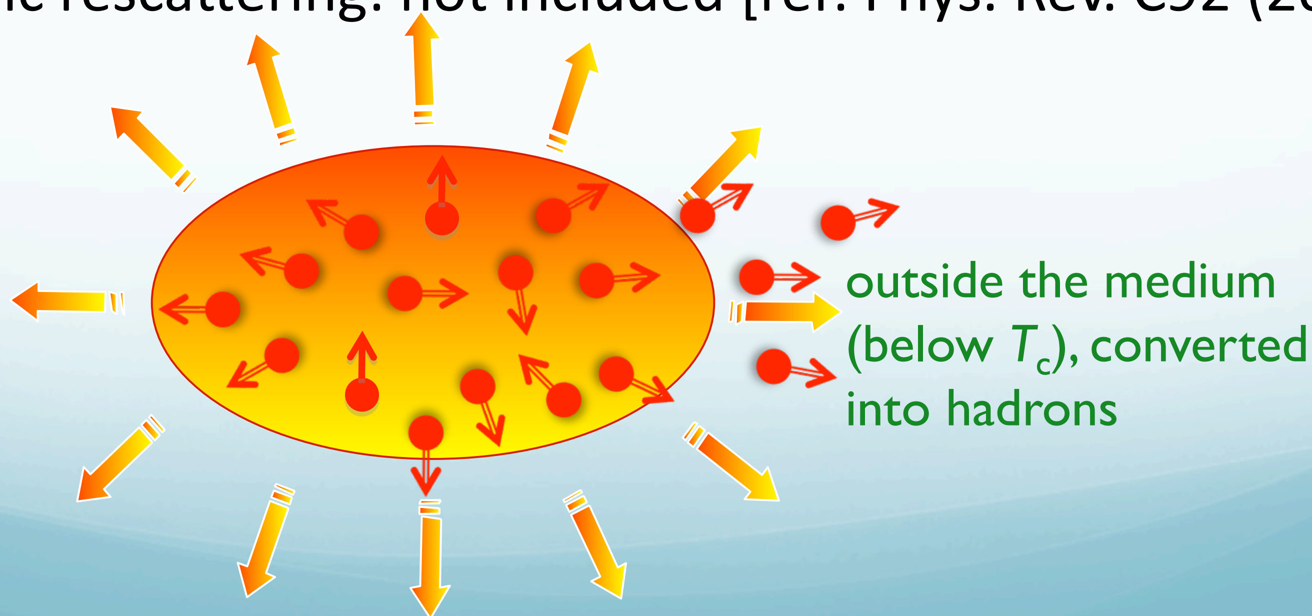
Three regions: recombination to *D*/*B* mesons, recombination to other hadrons, and fragmentation

In model calculation: in the l.r.f of the freeze-out hypersurface, determine which region each HQ belongs to, and then use either recombination model or Pythia simulation to obtain *D*/*B* mesons

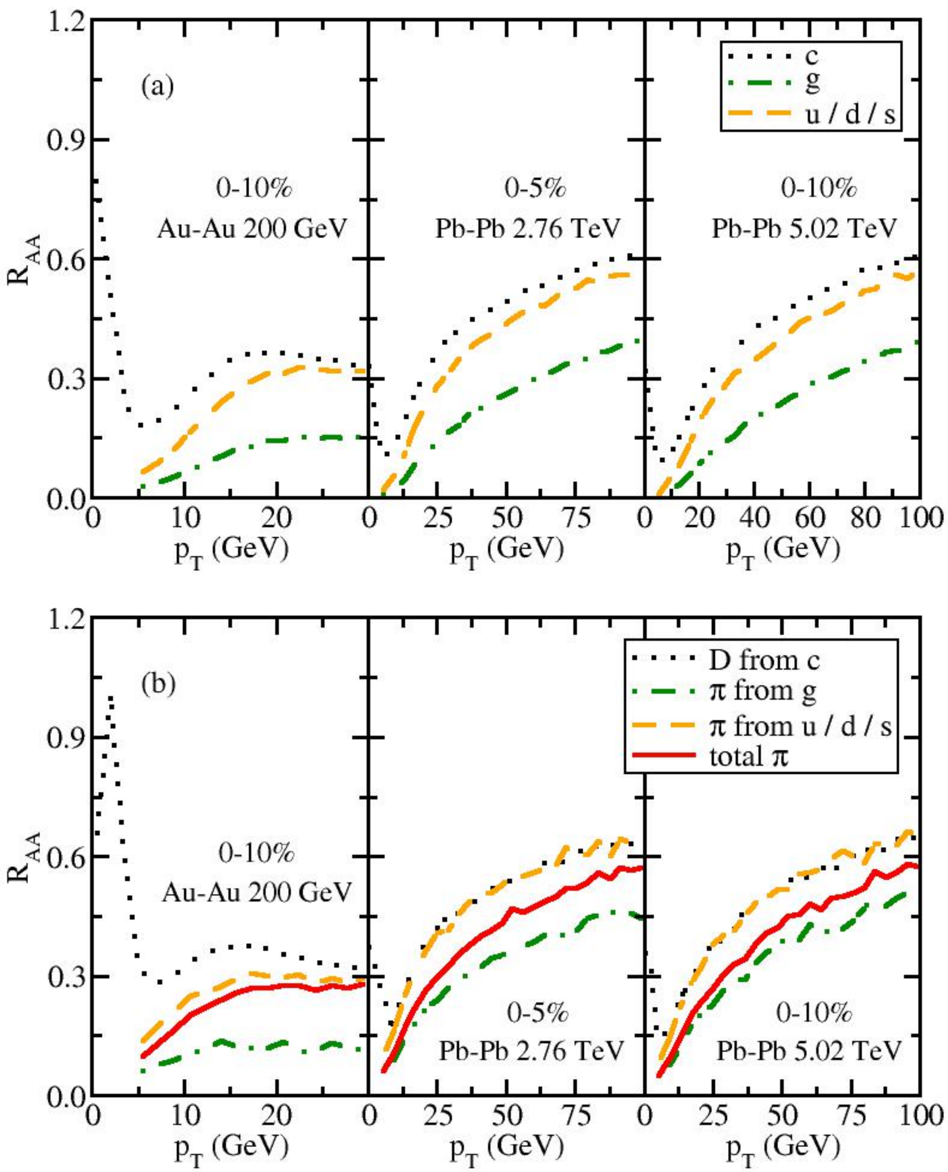
Framework Overview

(Parton Evolution inside the QGP)

- Generation of QGP medium: viscous hydro from OSU (2+1 D) or LBL-CCNU (3+1 D) group
- Initialization of hard partons: MC-Glauber for position space and pQCD calculation for momentum space (PDF: CTEQ5+EPS09)
- Simulation of parton evolution: the Boltzmann transport model in the local rest frame of the medium
- Hadronization: fragmentation + recombination model
- Hadronic rescattering: not included [ref: Phys. Rev. C92 (2015)]

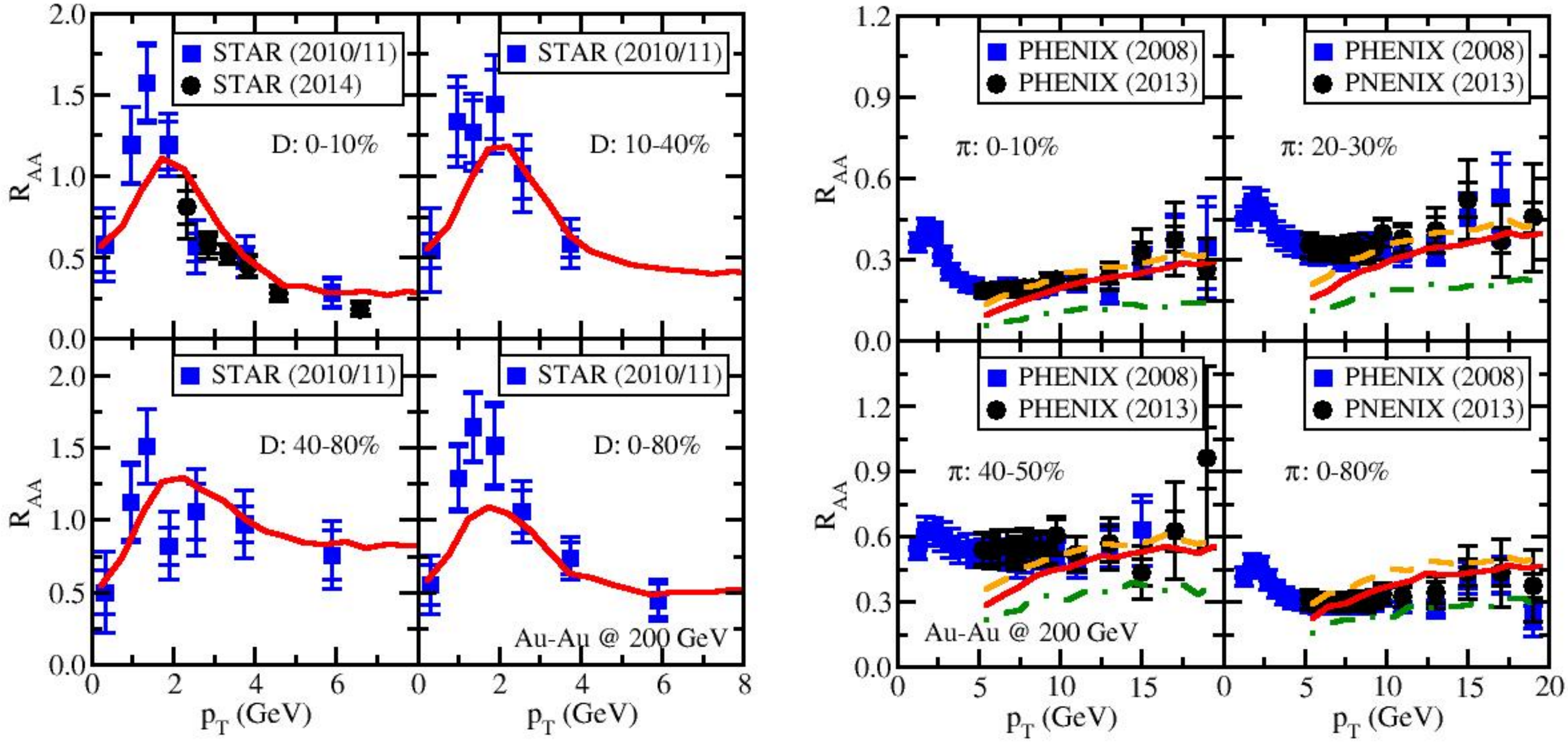


Heavy vs. Light Hadron Suppression

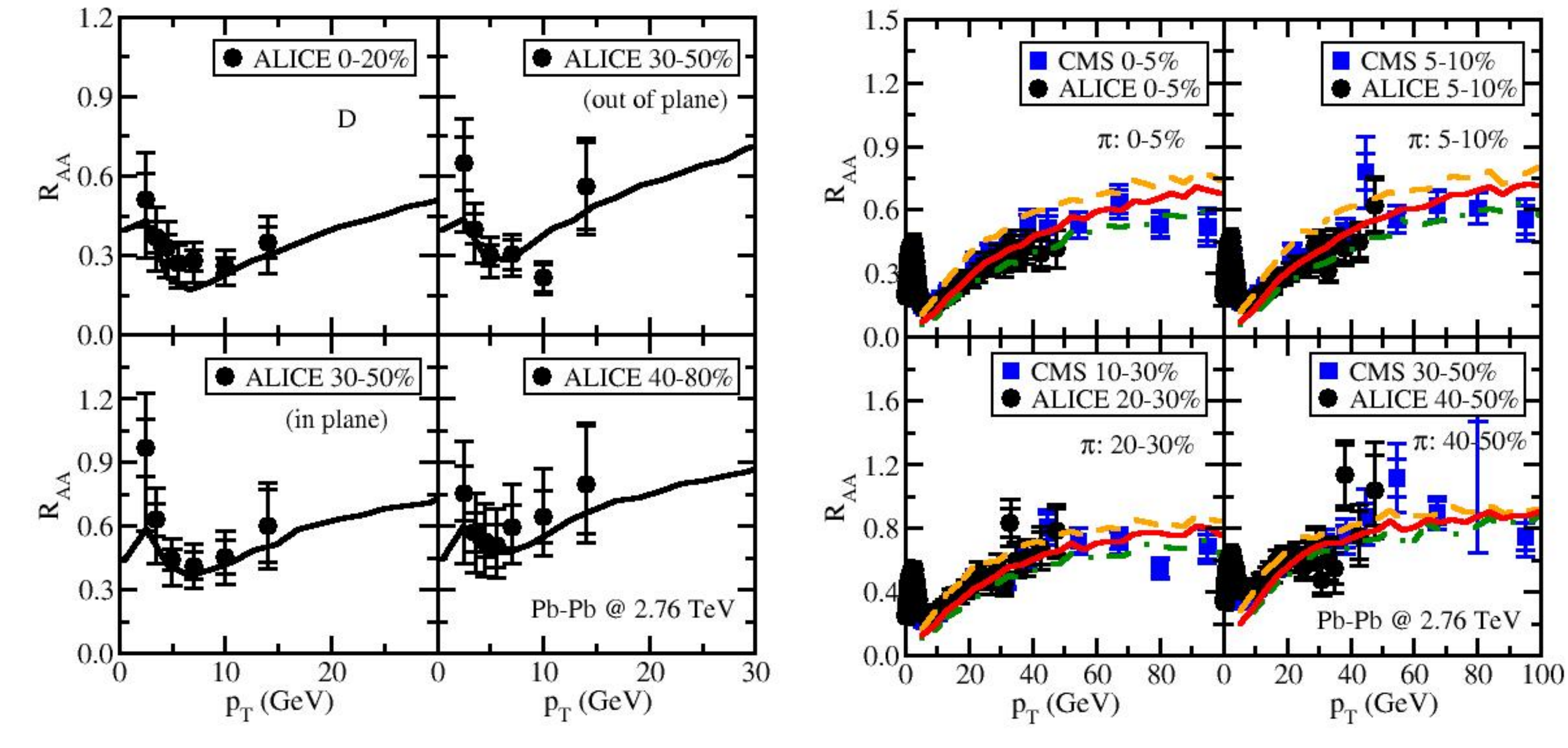


- *u/d/s* are slightly more suppressed than *c* quark, *g* is significantly more suppressed
- Due to different fragmentation function (harder for *c* than for *u/d/s*), *π* from light quark has similar R_{AA} *to D*, *π* from gluon is still more suppressed
- Final *π* is dominated by contribution from quark jet at small $\sqrt{s_{NN}}$, but is dominated by gluon jet at large $\sqrt{s_{NN}}$

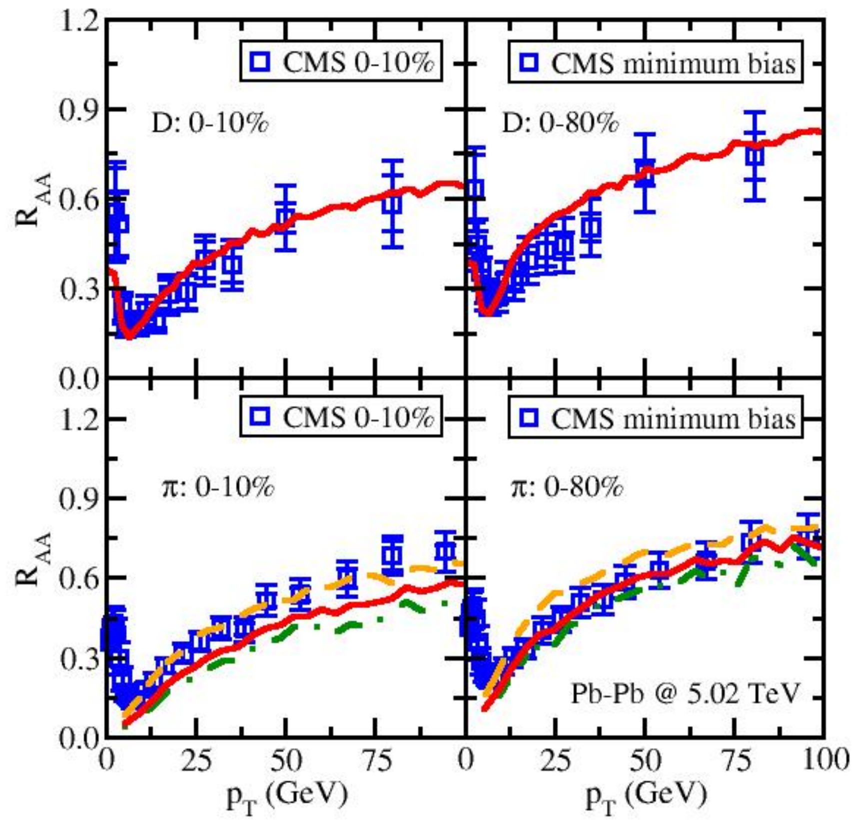
Simultaneous Description of D and π R_{AA} in 200 GeV Au-Au Collisions



Simultaneous Description of *D* and *π* R_{AA} in 2.76 TeV Pb-Pb Collisions

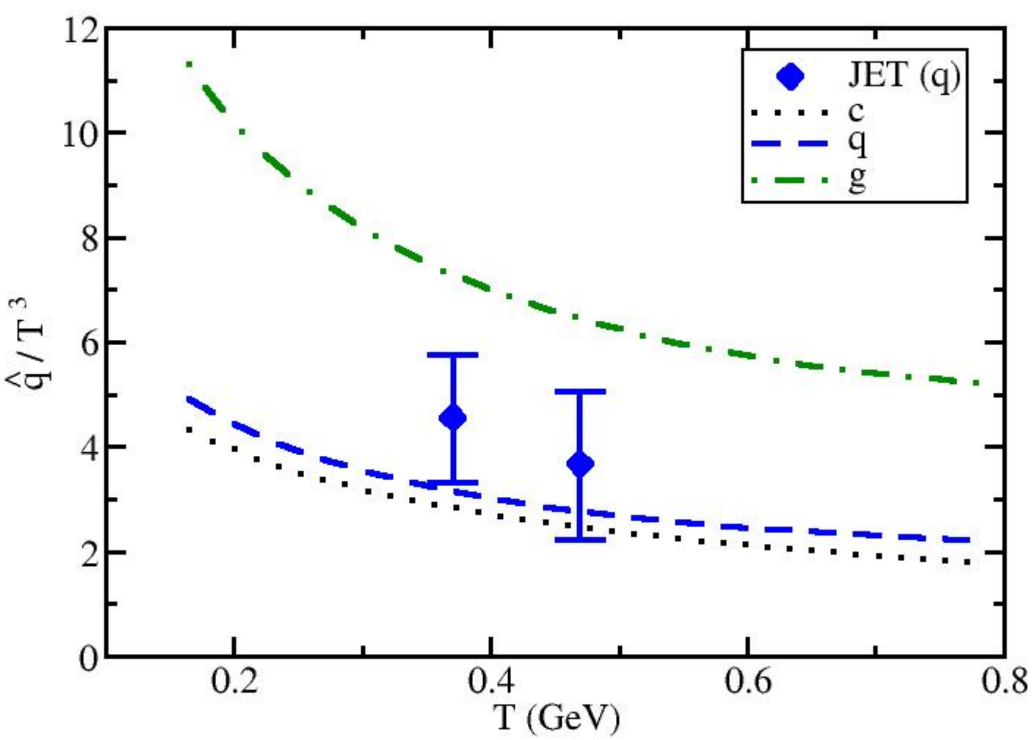


Simultaneous Description of *D* and *π* R_{AA} in 5.02 TeV Pb-Pb Collisions



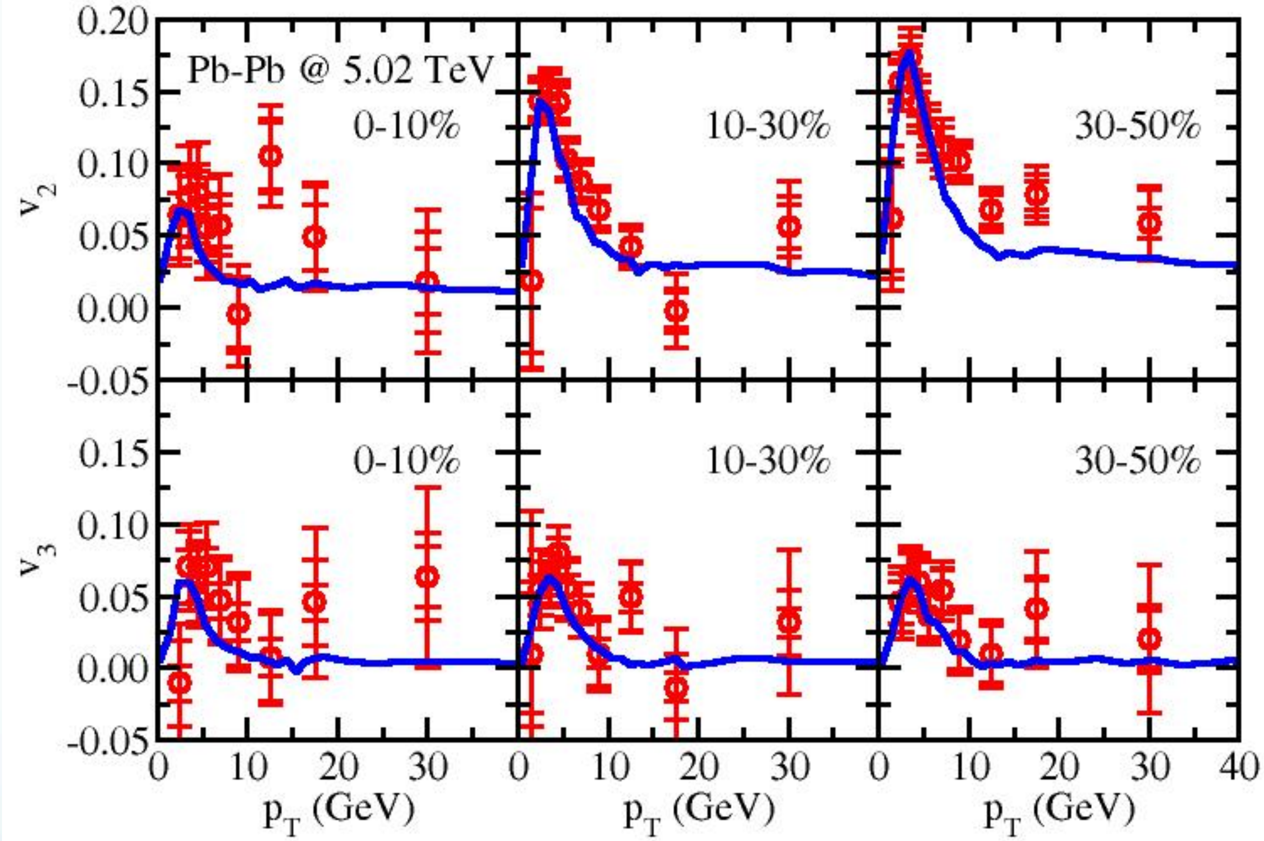
With a delicate treatment of heavy and light parton in-medium evolution and their hadronization, one may provide reasonable description of heavy and light hadron suppression simultaneously.

Quark and Gluon Transport Coefficient: $\hat{q}$



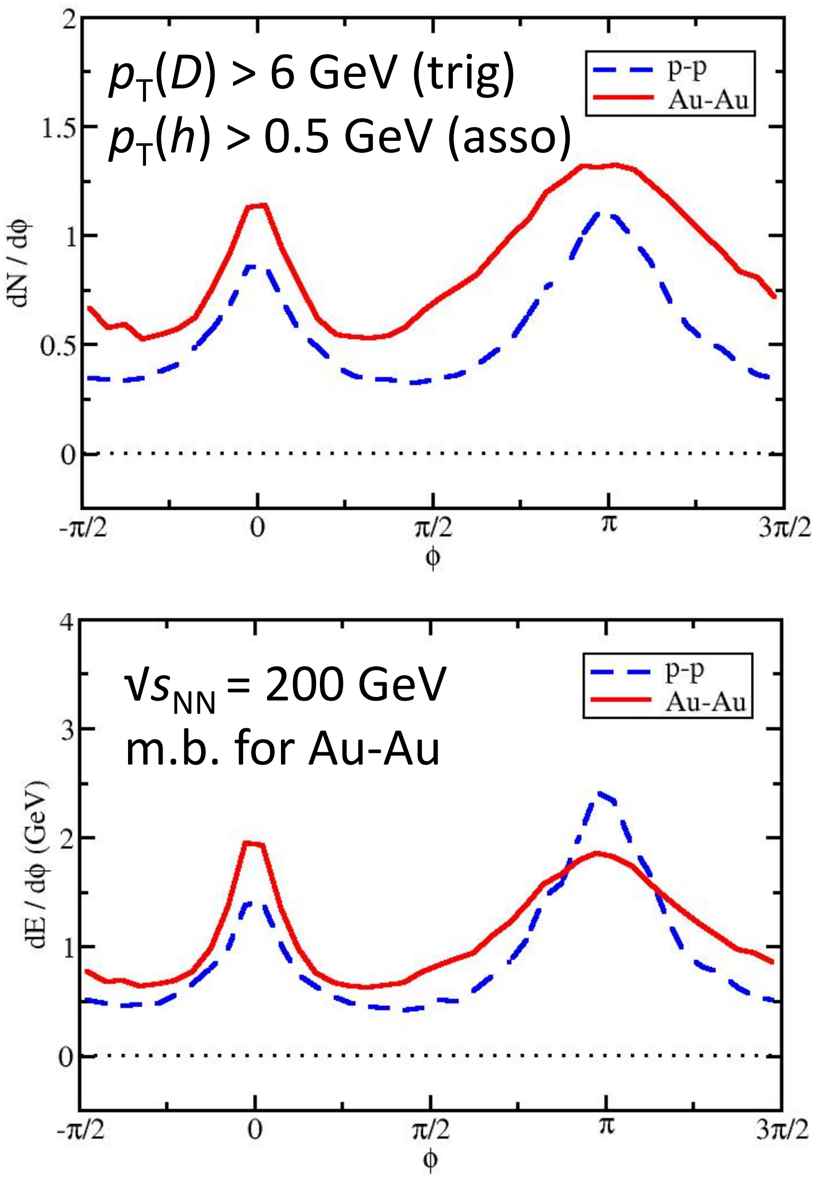
The extracted $\hat{q}$ from model to data comparison within our LBT framework is consistent with the value constrained by the earlier work by the JET Collaboration [Phys. Rev. C90, 014909 (2014)].

Anisotropic Flow (v_2 and v_3) of *D* Mesons



- Predictions of v_2 and v_3 are consistent with CMS data at 5.02 TeV.
- Strong v_2 is observed for the full p_T range.
- Strong v_3 is observed at low p_T, but it is consistent with 0 at high p_T.

D-hadron Correlation Functions



- Single hadron observables quantify the amount of parton energy loss; *D*-hadron correlation reveals how the lost energy is re-distributed.
- p-p baseline: Pythia
- Au-Au: all charged hadrons from heavy and light parton shower, recoiled parton from and back reaction to the medium (thermal hadrons emitted by QGP are not included)
- $dN/d\Phi$ is increased at all Φ due to parton shower in Au-Au
- $dE/d\Phi$ is enhanced at 0 due to *c* energy loss in Au-Au; and broadened at π due to parton shower and scattering in QGP
- Will quantify energy loss and jet broadening in upcoming work

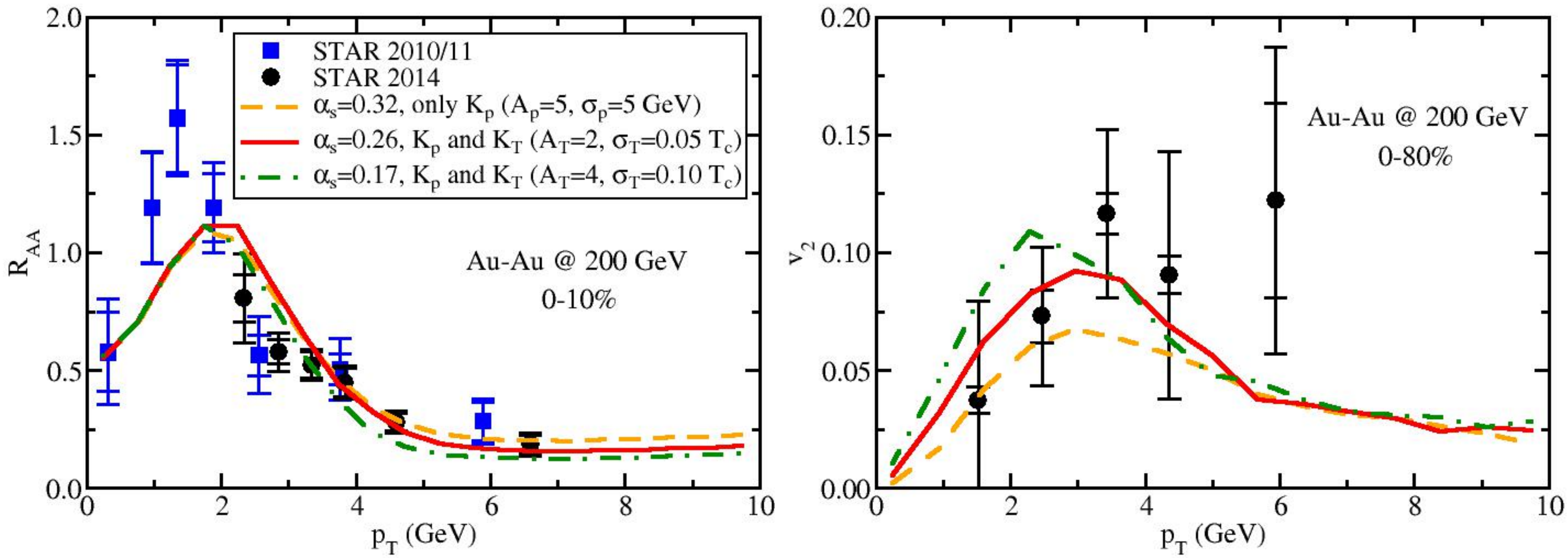
Summary and Outlook

- Established a Linear Boltzmann Transport (LBT) Model that treats heavy and light parton evolution on the same footing and simultaneously incorporates their elastic and inelastic scattering inside QGP
- Provided reasonable descriptions of both heavy and light hadron suppression and flow at RHIC and the LHC
- Discussed *D*-hadron correlation functions for the first time: not only quantify the amount of energy loss of heavy quarks, but also reveal how the lost energy is re-distributed inside the parton shower; more detailed quantitative study will be released soon

Thank you!

Possible Solutions to the R_{AA} vs. v_2 Puzzle

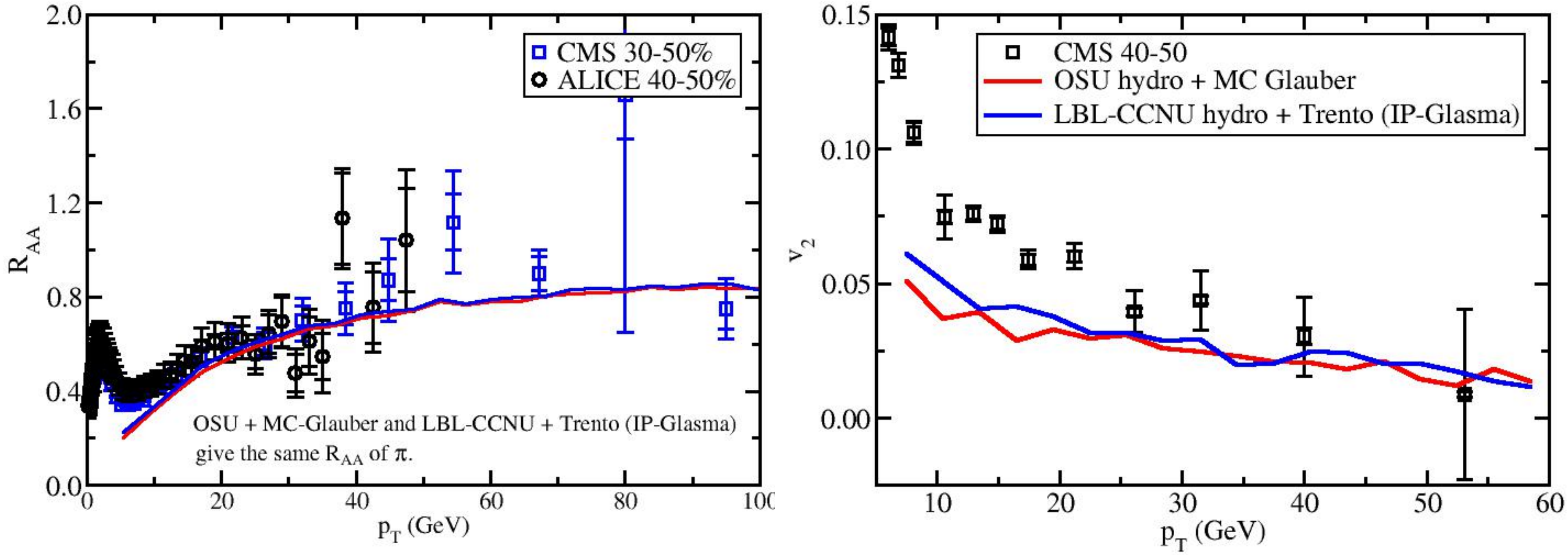
1. Near T_c enhancement of transport coefficient (arXiv: 1605.06447)



- While R_{AA} is fixed, the enhancement of transport coefficient near T_c increases *D* meson v_2
- Consistent with findings presented in
  - Xu et. al., Chin. Phys. Lett. 32, 9 (2015)
  - Das et. al., Phys. Lett. B747, 260 (2015)
- The detailed microscopic mechanism is still an open question

Possible Solutions to the R_{AA} vs. v_2 Puzzle

2. Different bulk evolutions



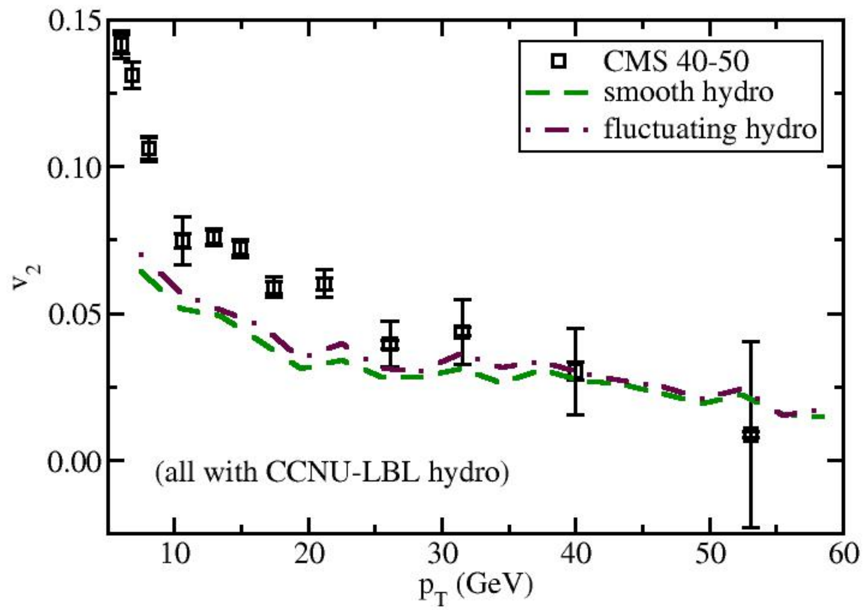
- Different bulk evolutions that provide same R_{AA} may lead to non-negligible difference in v_2
- KLN initial condition would give even larger v_2 due to its larger eccentricity [SC, G.-Y. Qin and S. Bass Phys .Rev. C92 (2015) no. 5, 054909]

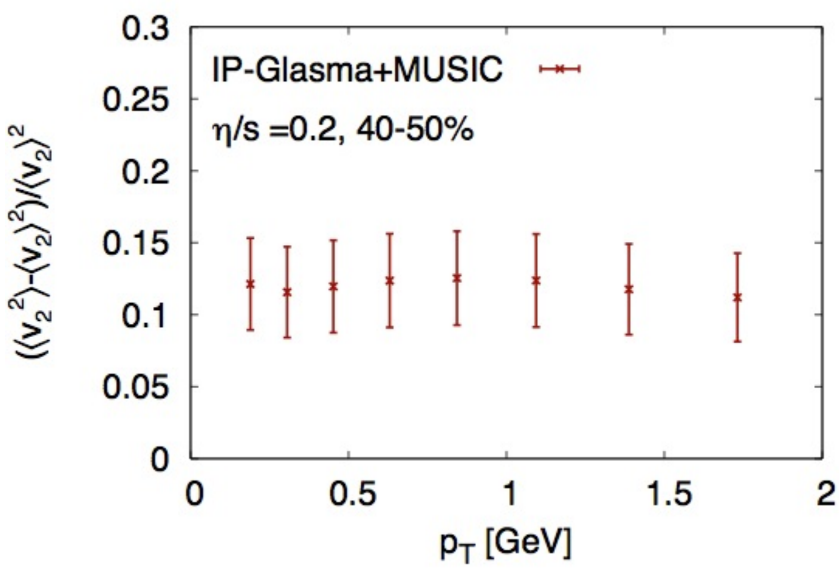
Possible Solutions to the R_{AA} vs. v_2 Puzzle

3. Effect of the initial state fluctuation of the bulk matter

$$v_2^{\rm hard}(p_{\rm T}) \sim \langle v_2^{\rm hard}(p_{\rm T})\rangle \left[1+\left(\frac{\delta v_2^{\rm soft}}{\langle v_2^{\rm soft}\rangle}\right)^2\right]$$

Noronha-Hostler et. al. PRL 116 (2016), 252301





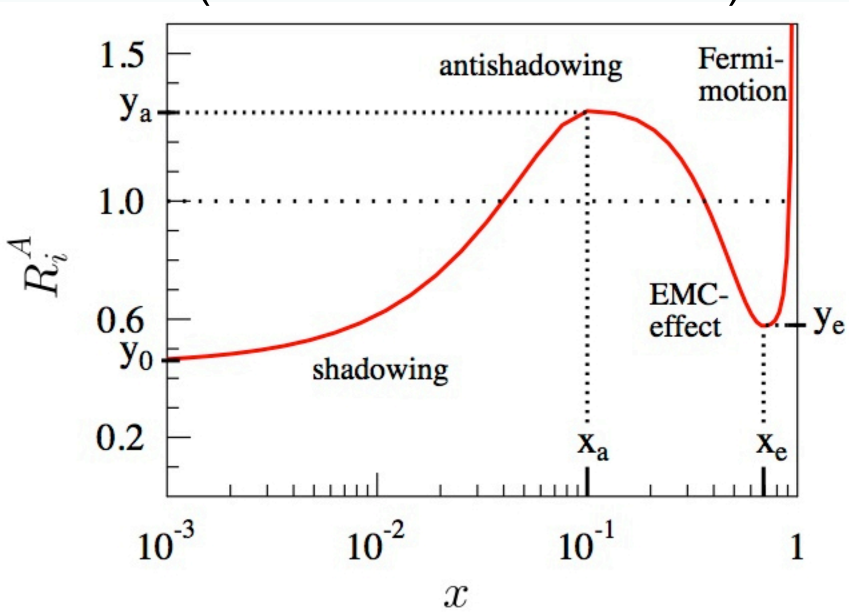
[Courtesy of B. Schenke]

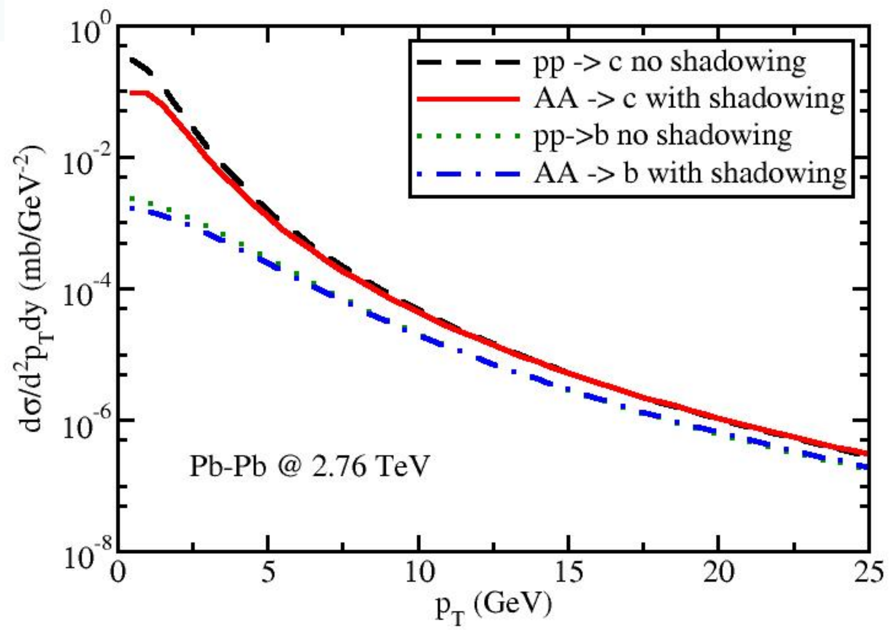
- Only around 10% larger v_2 (hard) is observed in our calculation after the inclusion of the fluctuation of the bulk matter
- Consistent with $(\delta v_2/<v_2>)^2$ [soft] ~ 10% from our LBL-CCNU hydro + Trento (IP-Glasma), and also the value from MUSIC + IP-Glasma

Heavy Flavor Initial Production

- Initial production: MC-Glauber for the position space and LO pQCD calculation (Combridge,1979) for the momentum space
- Parton distribution functions: CTEQ5 (Lai, 2000)
- Nuclear shadowing effect: EPS09 (Eskola, 2009)

(Taken from Eskola 2009)





Significant shadowing effect for heavy quark production at low p_T (especially at the LHC energy) → impact on R_{AA}

Comment on the Transport Coefficient

- Only one parameter α_s in our transport model which determines both the 2->2 rate and $\hat{q}$ that governs the 2->2+n process
- LO pQCD calculation fails at low *p* and *T* near T_c, and thus *p* and *T* dependent modification of transport coefficient is required in order to describe experimental data:

$$\tilde{\alpha}_s = K_T \alpha_s, \;\; \tilde{\hat{q}} = K_p \hat{q}$$

$$K_p = 1 + A_p e^{-|\vec{p}|^2/2\sigma_p^2}, \;\; K_T = 1 + A_T e^{-(T-T_c)^2/2\sigma_T^2}$$

- At high *p* and *T*, LO pQCD calculation is respected, at low *p* and *T* near T_c, non-perturbative modification is introduced
- Only investigate possible phenomenological effects of K_p and K_T in this work; a precise extraction of these non-perturbative effects will be left for a future effort – global fit to experimental data with a Bayesian method [Bernhard et. al., PRC 91 (2015)]