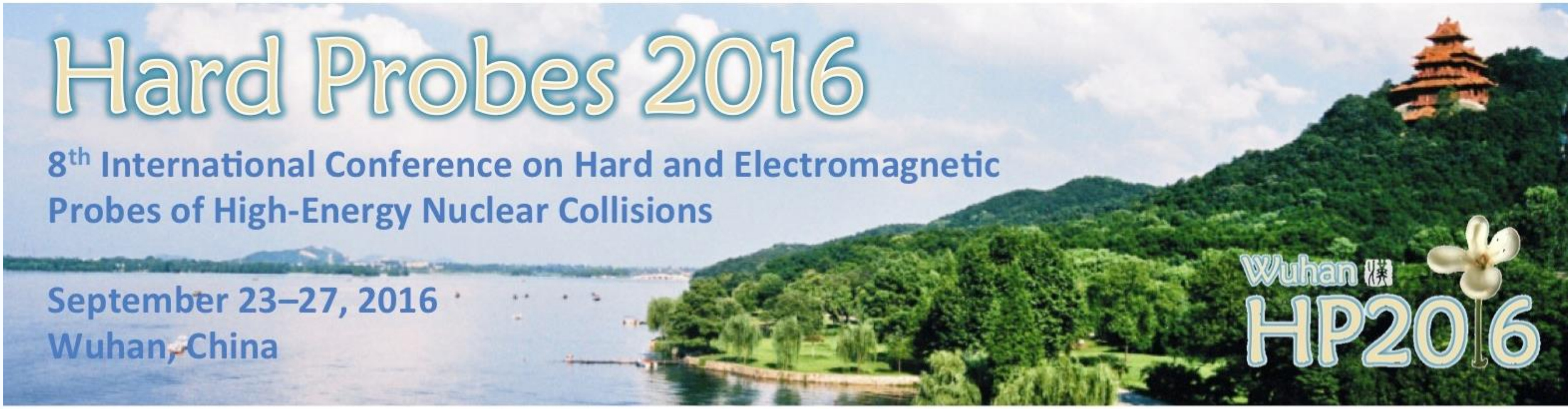
Heavy vs. light hadron production and medium modification at RHIC and the LHC



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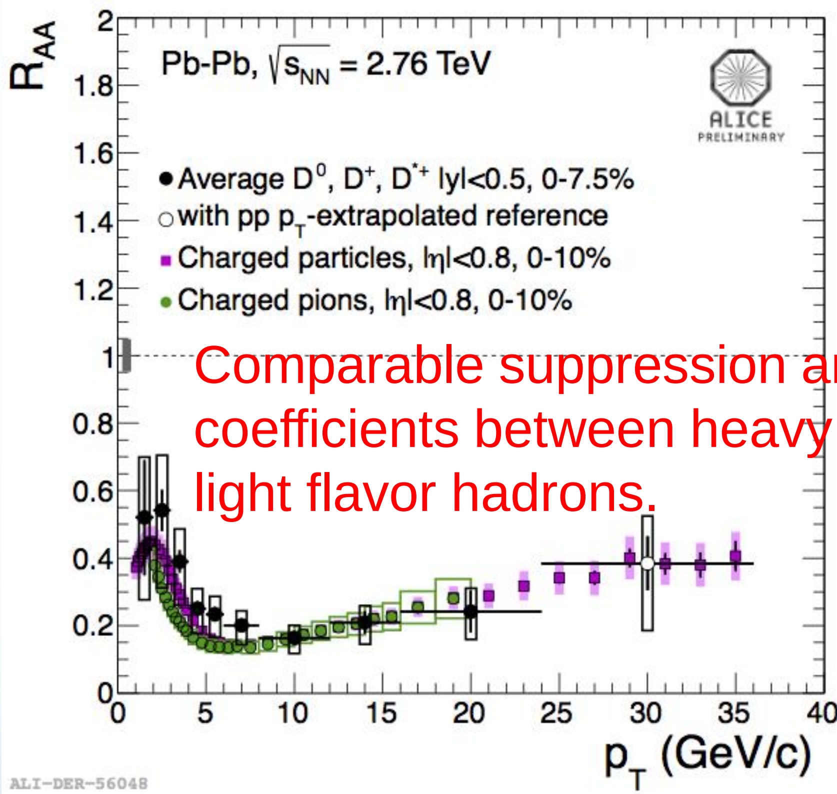
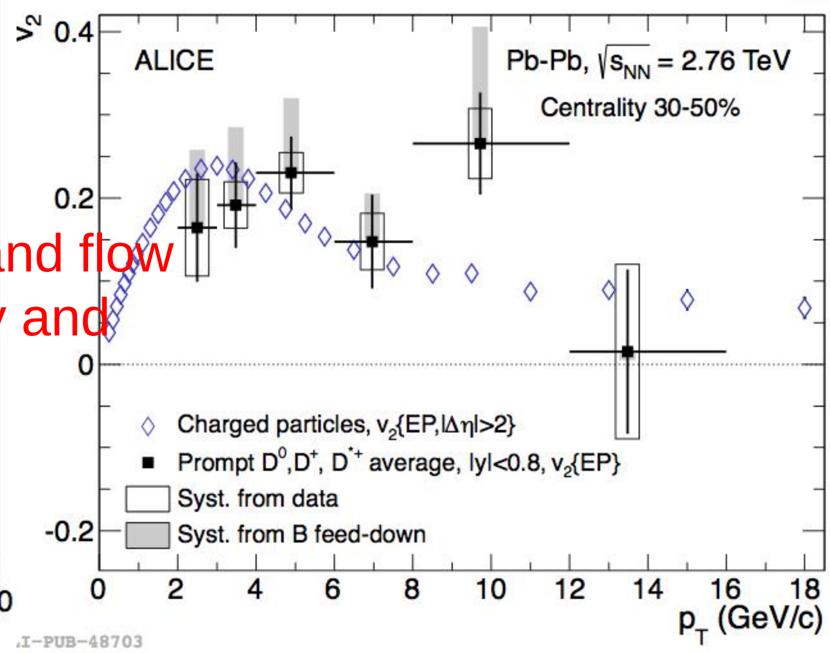
Outline

- Introduction
- A Linear Boltzmann Transport Model (LBT) for parton energy loss in QGP
- Heavy vs. light hadron suppression at RHIC and the LHC (the heavy vs. light flavor puzzle)
- Possible solutions to the R_{AA} vs. v_2 puzzle
- Summary and outlook

Motivation

High p_T 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 Linearized 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)

$$w(\vec{p}_1, \vec{k}) \equiv \sum_{2,3,4} w_{12\to 34}(\vec{p}_1, \vec{k})$$

$$w_{12\to 34}(\vec{p}_1, \vec{k}) = \gamma_2 \int \frac{d^3p_2}{(2\pi)^3} f_2(\vec{p}_2) \left[1 \pm f_3(\vec{p}_1 - \vec{k})\right] \left[1 \pm f_4(\vec{p}_2 + \vec{k})\right]$$
$$\times\, v_{\rm rel}\, d\sigma_{12\to 34}(\vec{p}_1, \vec{p}_2 \to \vec{p}_1 - \vec{k}, \vec{p}_2 + \vec{k})$$

microscopic cross section of 12->34

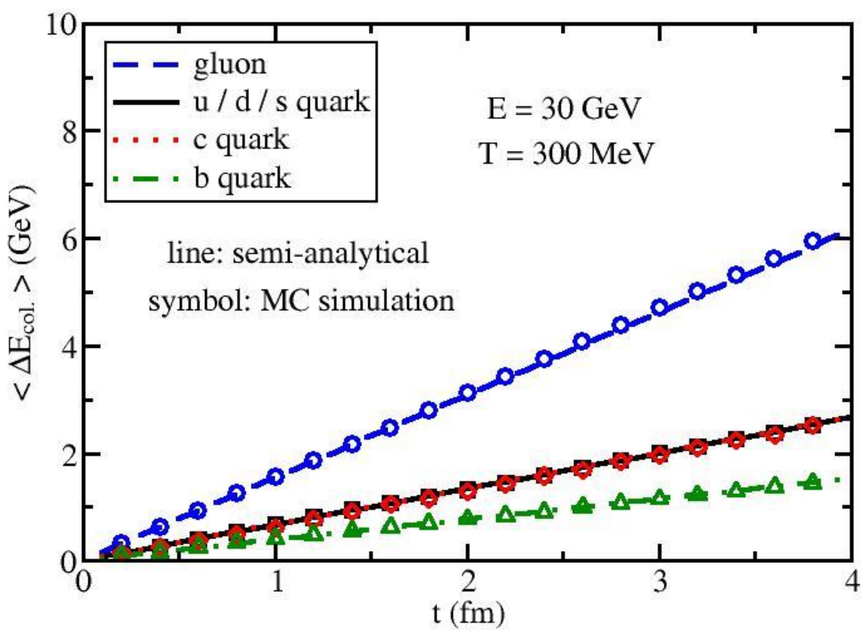
A Linearized Boltzmann Transport Model

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



$\Delta E_{col.}$ 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:

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

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

A Linearized Boltzmann Transport Model

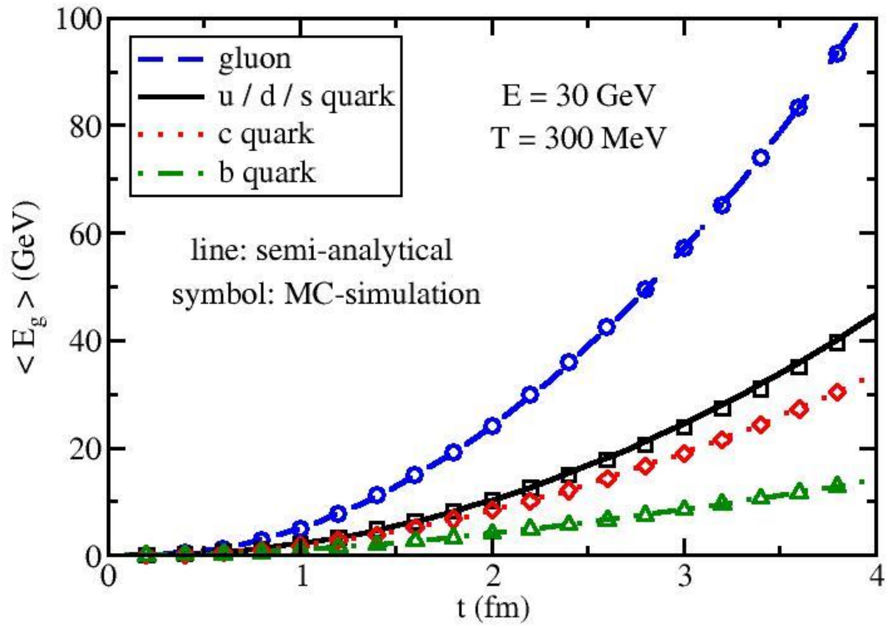
Number *n* of radiated gluons during *Δt* – Poisson distribution:

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

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



$\langle E_g \rangle$ from our MC simulation agrees with the semi-analytical result.

Elastic vs. Inelastic Energy Loss

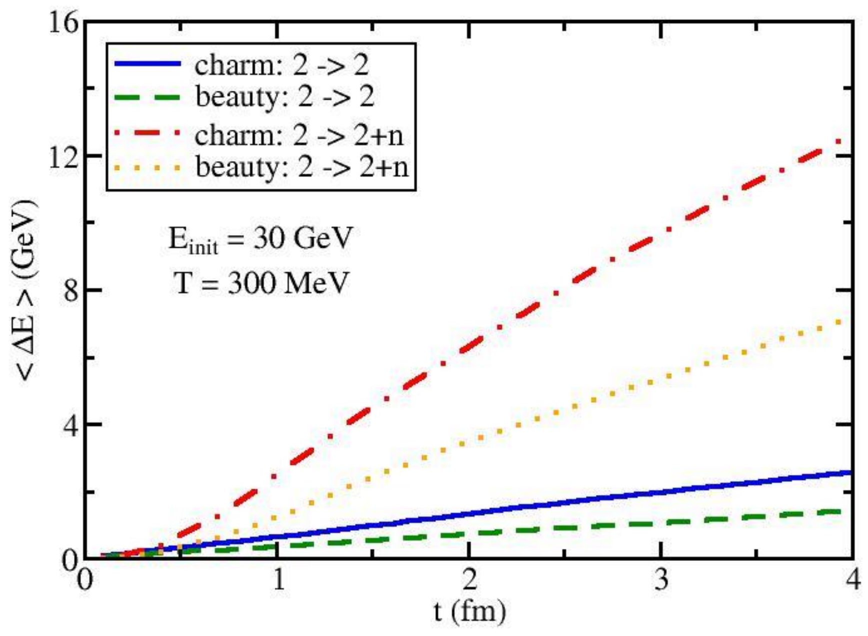
Divide scattering probability of jet parton into two regions:

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 (full p_T): Fragmentation + Coalescence

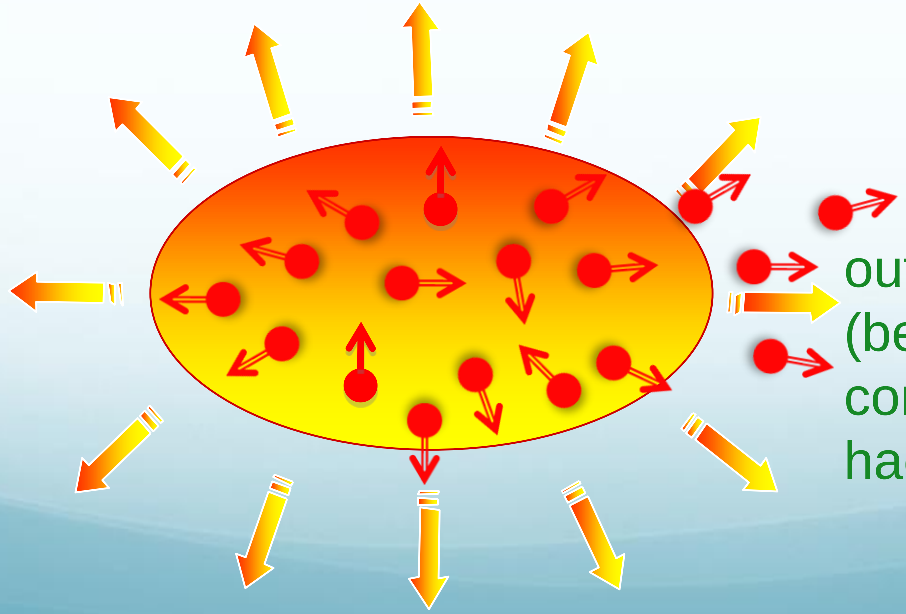
- Most high momentum heavy quarks fragment into heavy mesons: use PYTHIA 6.4
- Most low momentum heavy quarks hadronize to heavy mesons via recombination (coalescence) mechanism: use the instantaneous coalescence model [Oh (2009)]

Light flavor (high p_T only): Fragmentation

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

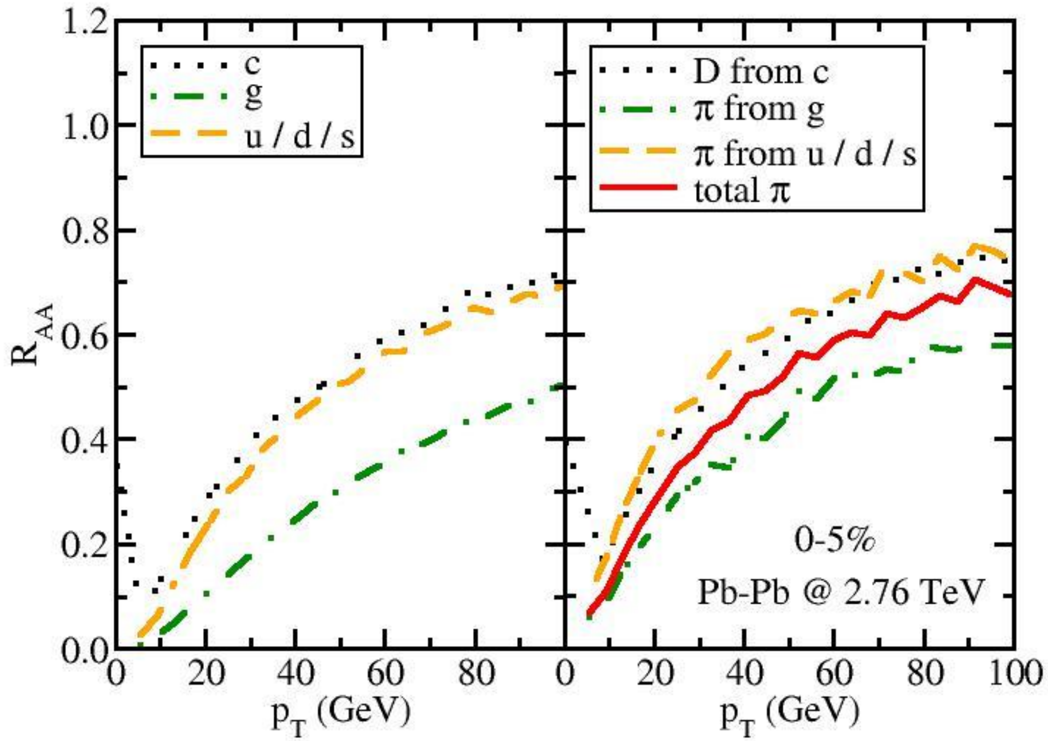
Framework Overview (Parton Evolution inside the QGP)

- 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 + coalescence model
- Hadronic rescattering: not included [ref: Phys. Rev. C92 (2015)]



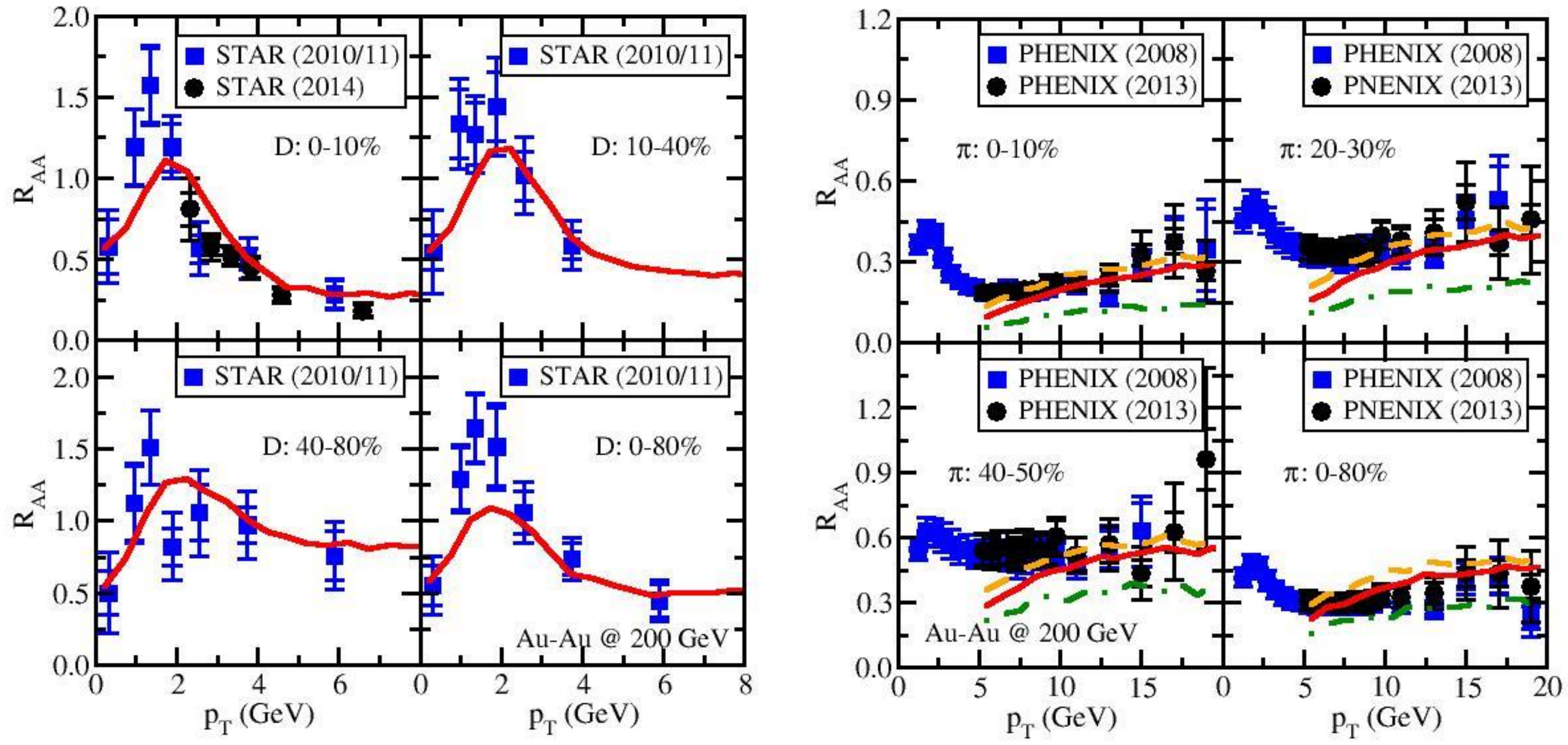
outside the medium (below T_c), converted into hadrons

Heavy vs. Light Hadron Suppression

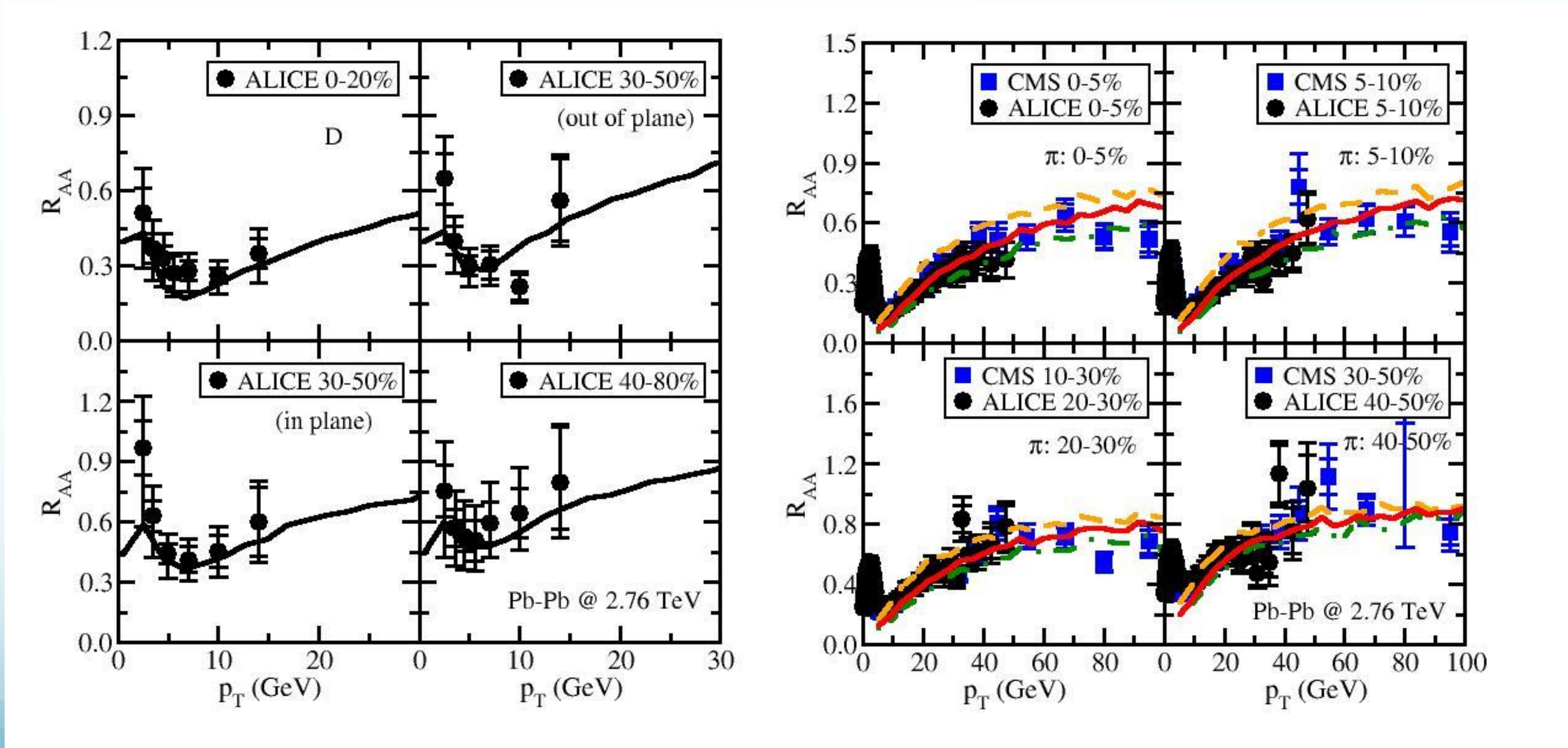


- *u*/*d*/*s* are more suppressed than *c* quark at low p_T but they have very similar R_{AA} at high p_T, *g* is significantly more suppressed
- Due to different fragmentation function (harder for *c* than for *u*/*d*/*s*), *π* from light quark is slightly less suppressed than *D*
- R_{AA} of mixed *π* is sensitive to fragmentation function of light quark vs. gluon [Chen et. al., J. Phys. 37 (2010) 015004]

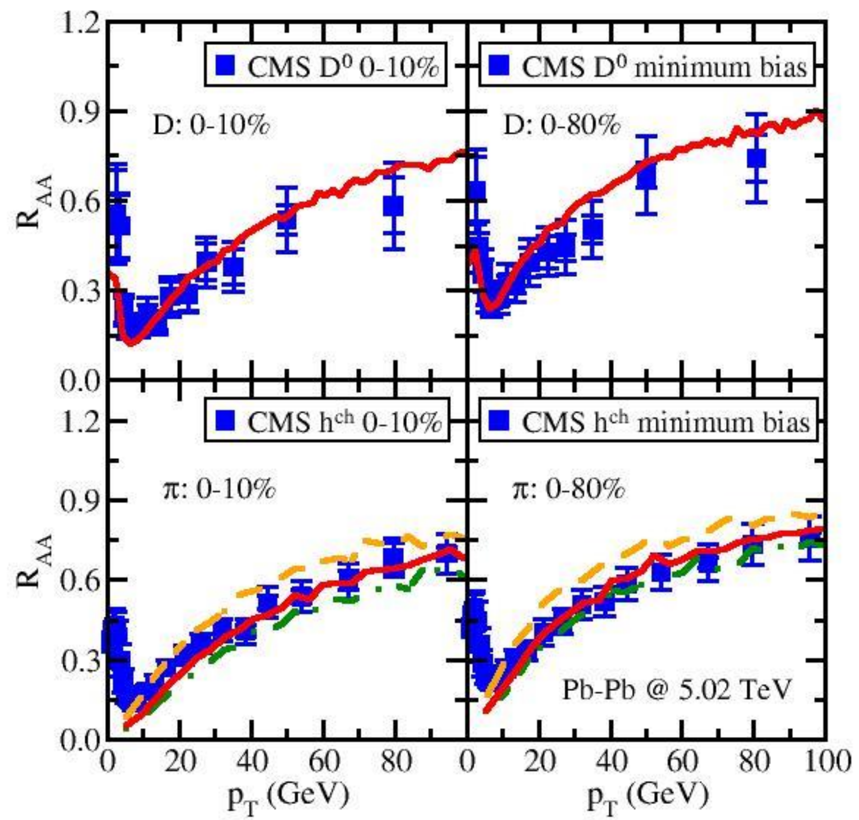
Simultaneous Description of *D* and *π* R_{AA} in 200 GeV Au-Au Collisions



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

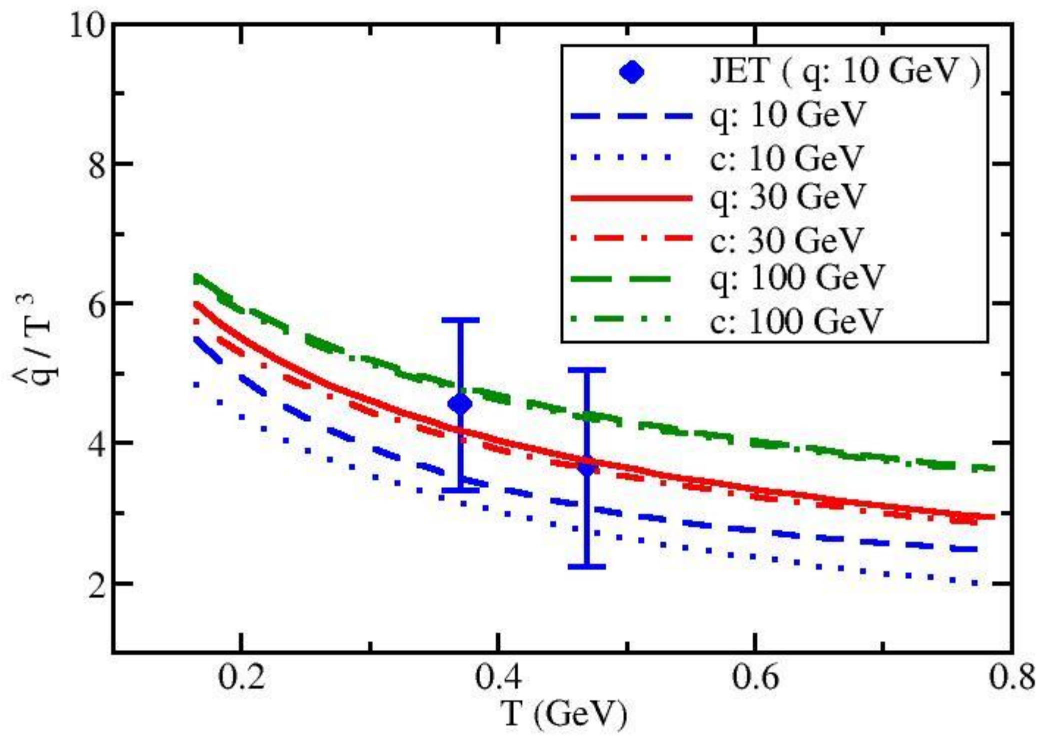


Simultaneous Description of *D* and *π* R_{AA} in 5.02 TeV Pb-Pb Collisions



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.

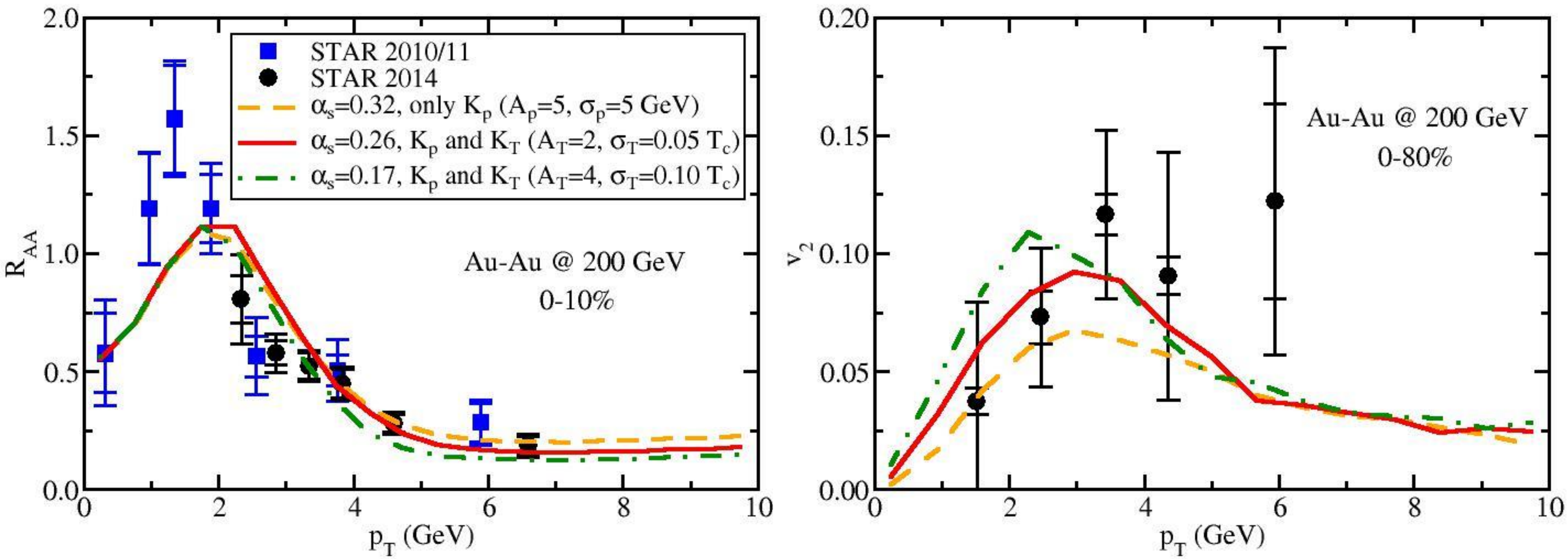
Quark Transport Coefficient: $\hat{q}$



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)].

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

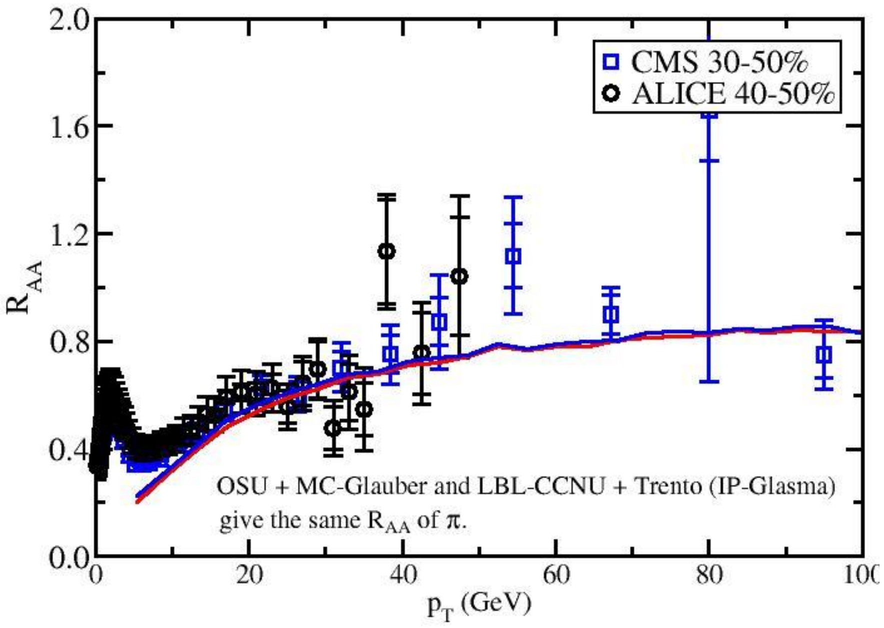
1. Near T_c enhancement of transport coefficient (arXiv: 1605.06447)

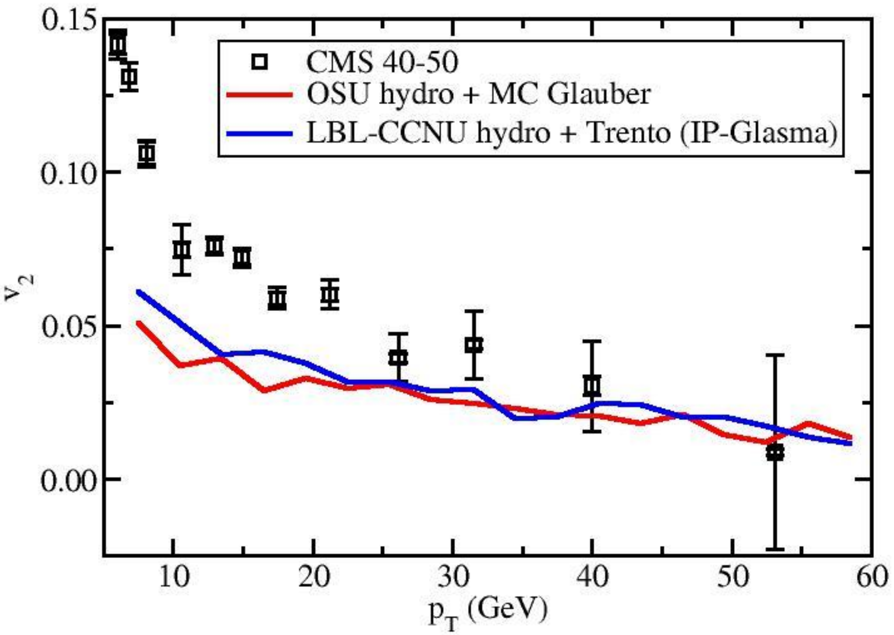


- While R_{AA} is fixed, the enhancement of transport coefficient near T_c increases *D* meson v_2
- Consistent with findings presented in
  - Xu et. al., Chin. Phys. Lett. 32, 9 (2015)
  - Das et. al., Phys. Lett. B747, 260 (2015)
- The detailed microscopic mechanism is still an open question

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

2. Different bulk evolutions





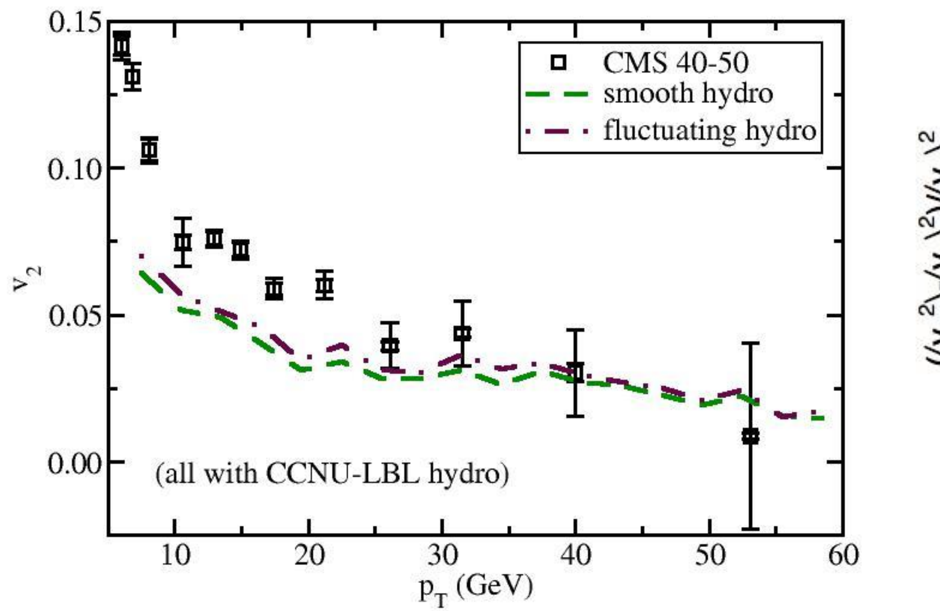
- Different bulk evolutions that provide same R_{AA} may lead to non-negligible difference in v_2
- KLN initial condition would give even larger v_2 due to its larger eccentricity [SC, G.-Y. Qin and S. Bass Phys .Rev. C92 (2015) no.5, 054909]

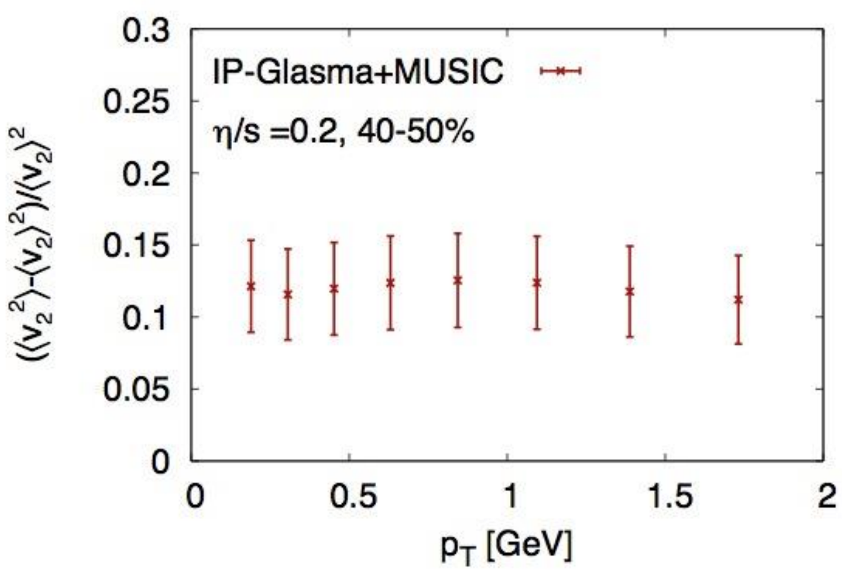
Possible Solutions to the R_{AA} vs. v_2 Puzzle

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 $(\delta v_2/\langle v_2\rangle)^2$ [soft] ~ 10% from our LBL-CCNU hydro + Trento (IP-Glasma), and also the value from MUSIC + IP-Glasma

Summary and Outlook

- Established a Linear Boltzmann Transport 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 at RHIC and the LHC
- Discussed several possible solutions to the "R_{AA} vs. v_2 puzzle", more systematic investigation will be implemented in our upcoming study
- Will explore heavy-light hadron correlation in the future, which may provide more constraints on our understanding of the strongly interacting system

Thank you!

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

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

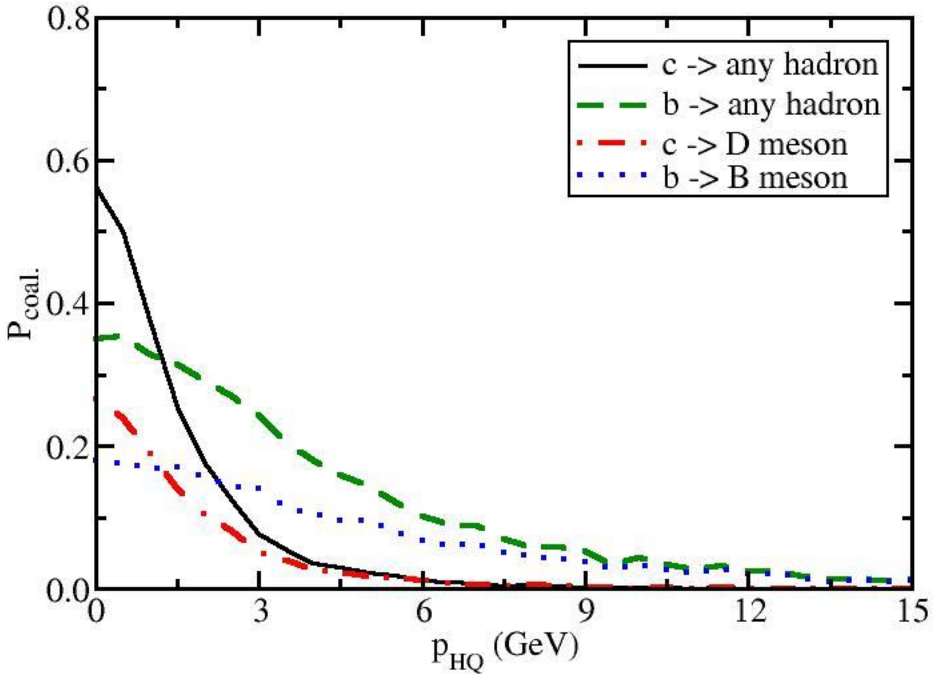
μ: reduced mass of the 2-particle system

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 ($D/B\ \Lambda\ \Sigma\ \Xi\ \Omega$) at T_c

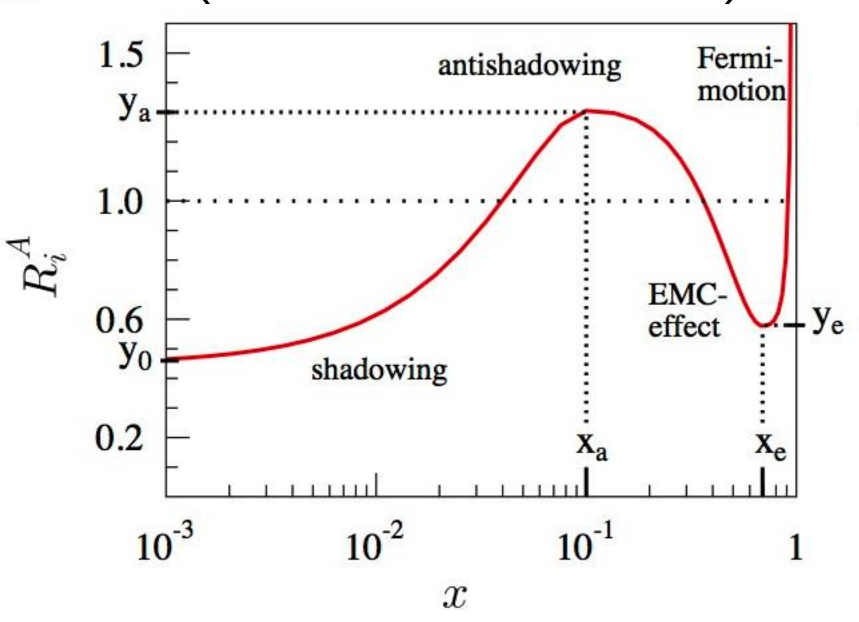
Three regions: recombination to *D*/*B* mesons, recombination to other hadrons, and fragmentation

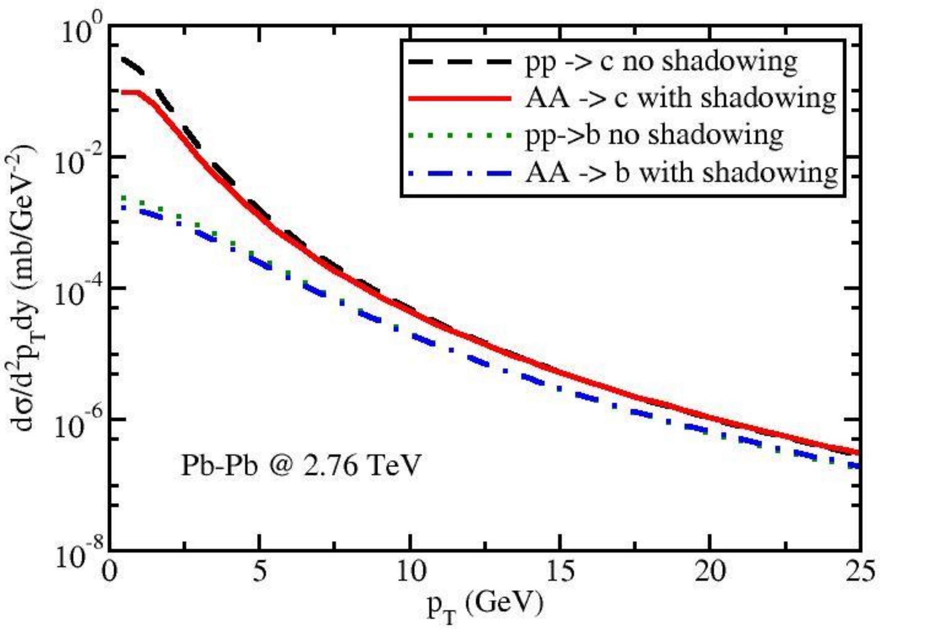
In model calculation: in the l.r.f of the freeze-out hypersurface, determine which region each HQ belongs to, and then use either recombination model or Pythia simulation to obtain *D*/*B* mesons

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:

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

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

- 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)]