Medium Modification of Heavy Flavor Hadron Production within a Boltzmann Transport Model

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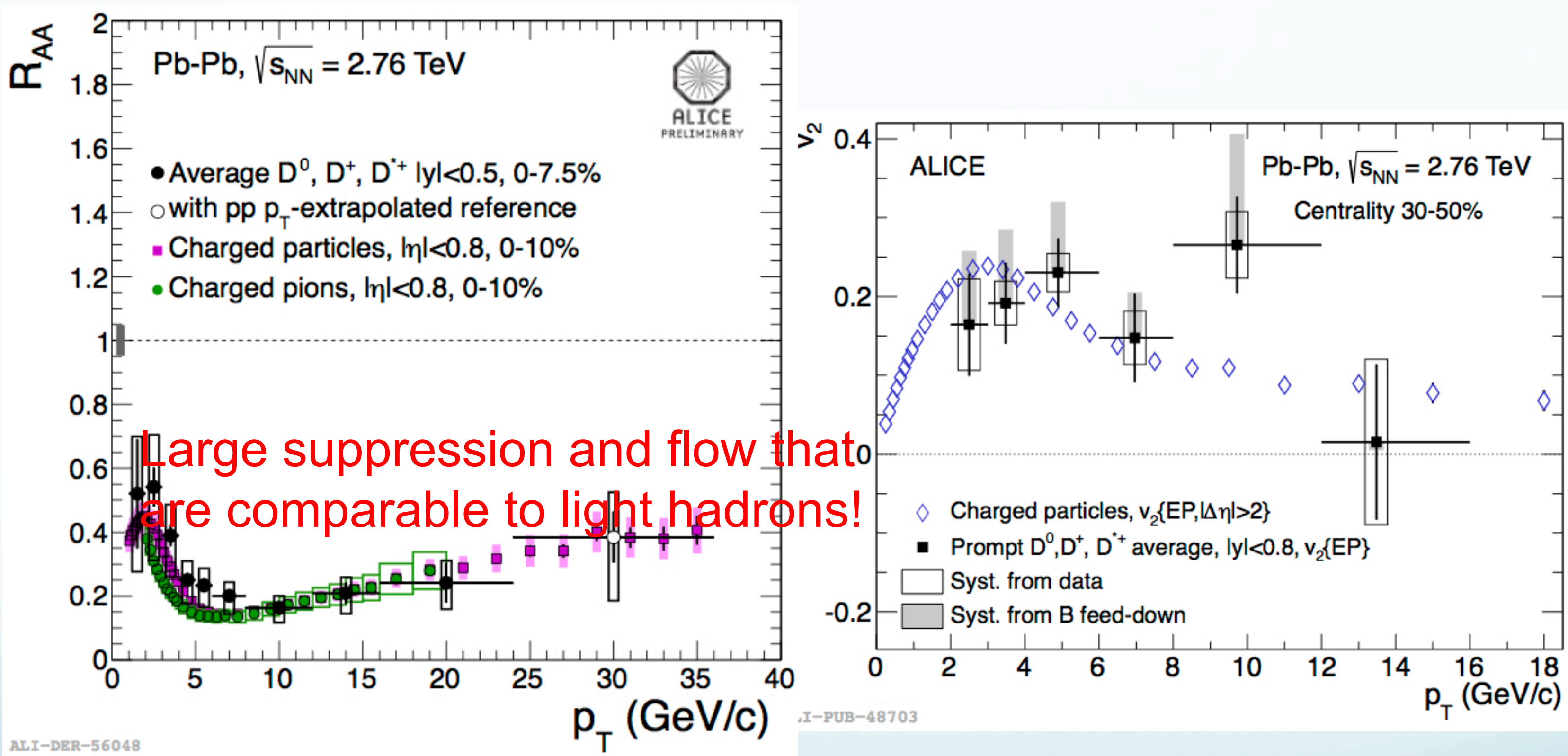
Outline

- Introduction
- Heavy flavor dynamics in heavy-ion collisions
  In-medium evolution: a Boltzmann Transport Model (col. + rad.)
  Hadronization: a hybrid frag. + coal. model
- Heavy meson suppression and flow (comparison with LHC/RHIC data)
- Simultaneous description of heavy and light flavor hadron spectra
- Summary and outlook

Why to Study Heavy Quarks?

- Heavy → produced at early stage: probe the full QGP history
- Heavy → thermal modification to mass is negligible: stable probe



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

Challenge: fully understand heavy flavor dynamics – whole evolution within the same framework of light partons

A Linearized Boltzmann Transport Model

Boltzmann equation for parton "1" distribution:

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

The collision term:

transition rate from p_1 to p_1-k

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

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

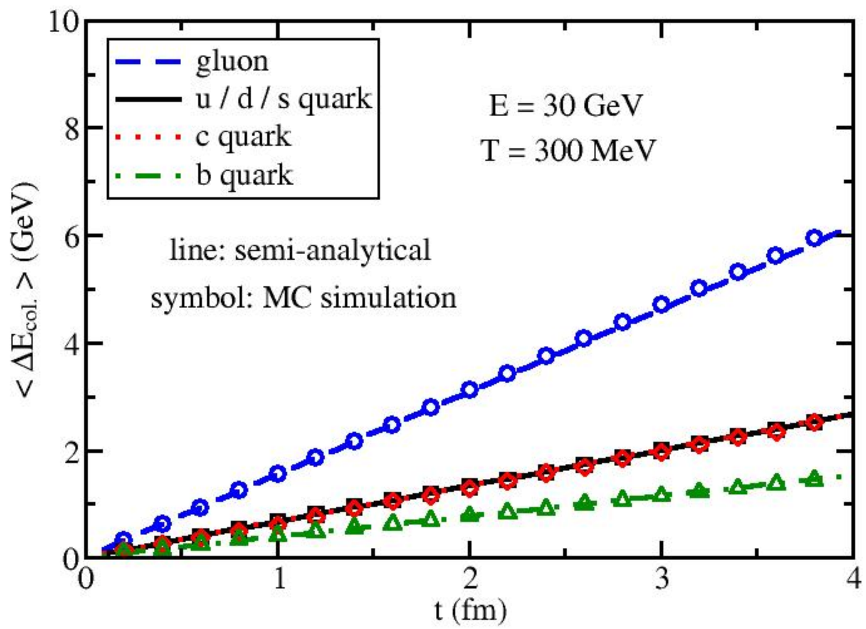
A Linearized Boltzmann Transport Model

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



$\Delta E_{\rm col.}$ 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:

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

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

A Linearized Boltzmann Transport Model

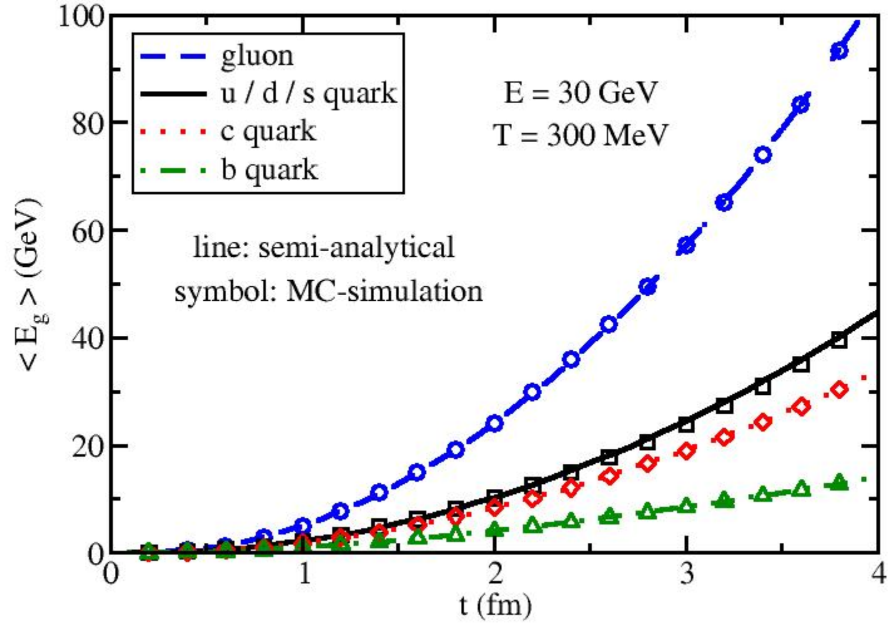
Number n of radiated gluons during Δt – Poisson distribution:

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

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

In model calculation:

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

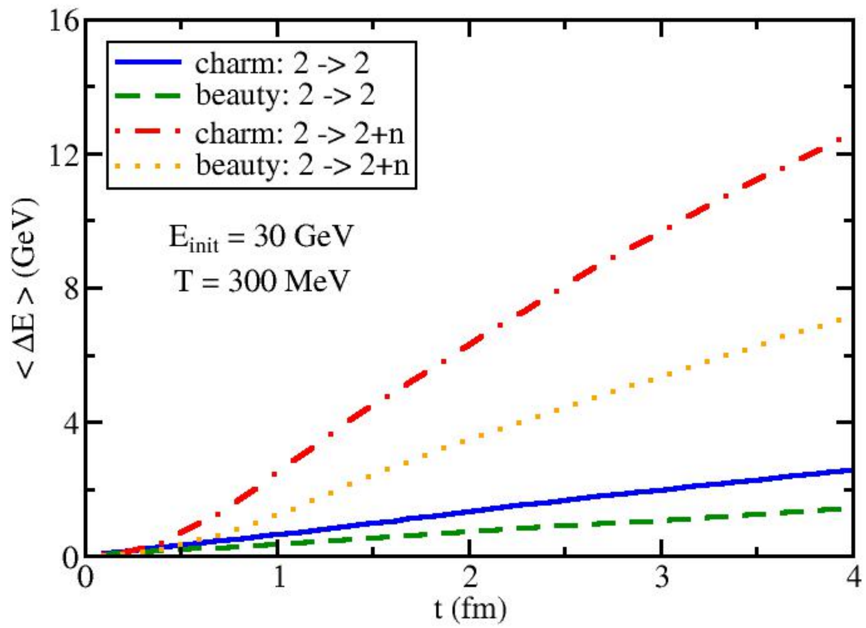
Divide scattering probability of jet parton into two regions:

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 of Heavy Quarks

Fragmentation + Heavy-Light 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)]

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 Boltzmann evolution

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

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

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

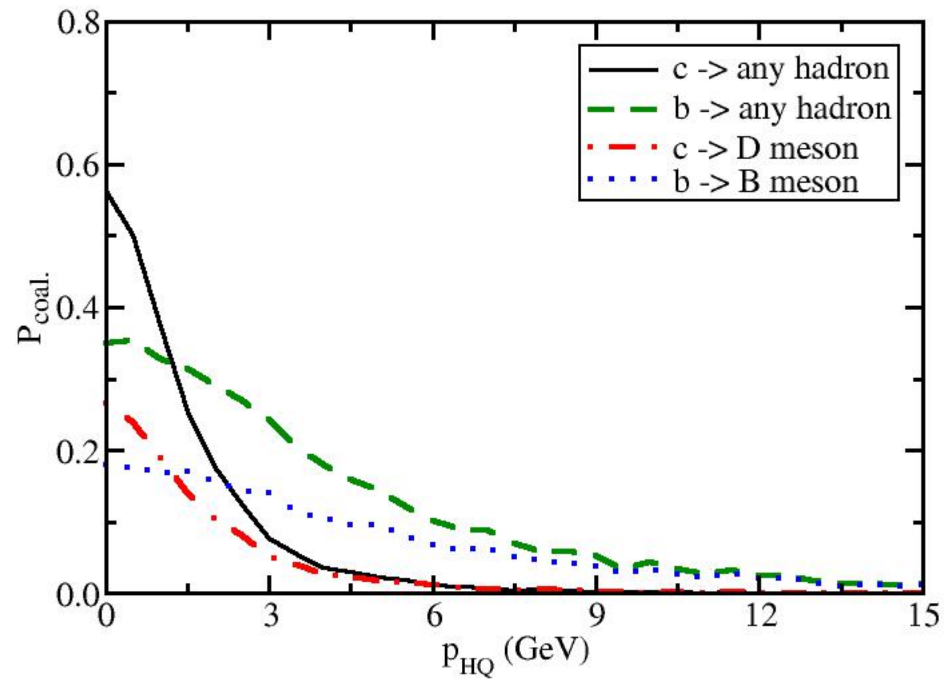
μ: reduced mass of the 2-particle system

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

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

Can be generalized to 3-particle recombination (baryon)

Hadronization of Heavy Quarks



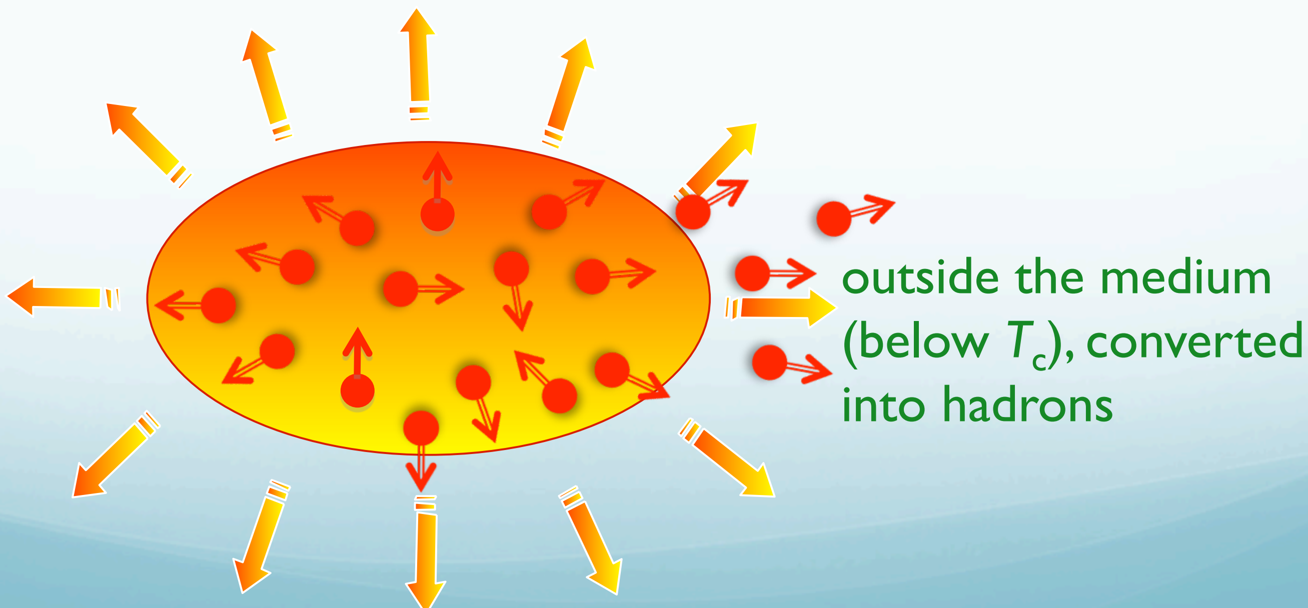
Use f^{W} to calculate $P_{coal.}(p_{HQ})$ for all channels ($D/B\ \Lambda\ \Sigma\ \Xi\ \Omega$) at T_c

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 Quark Evolution inside the QGP

- Generation of QGP medium: 2D viscous hydro from OSU group
- Initialization of heavy quarks: MC-Glauber for position space and pQCD calculation for momentum space (PDF: CTEQ5+EPS09)
- Simulation of heavy quark 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)]



Comment on the Transport Coefficient

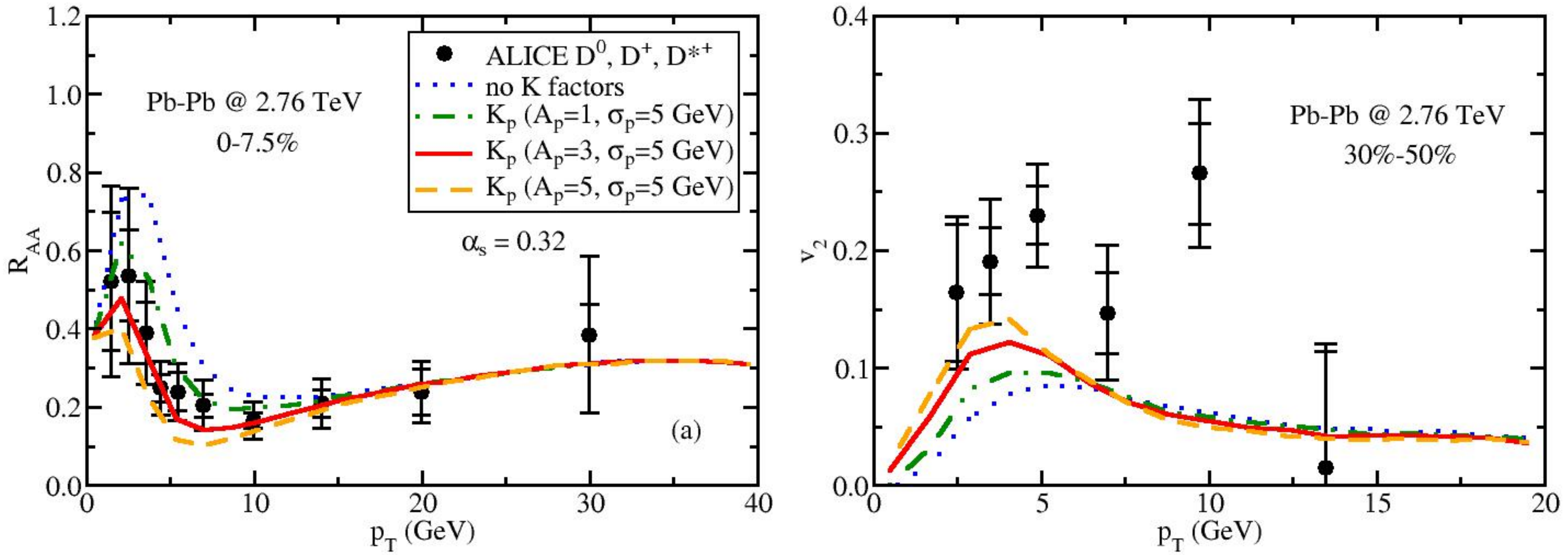
- Only one parameter α_s in our transport model which determines both the 2->2 rate and $\hat{q}$ that governs the 2->2+n process
- LO pQCD calculation fails at low *p* and *T* near T_c, and thus *p* and *T* dependent modification of transport coefficient is required in order to describe experimental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

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

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

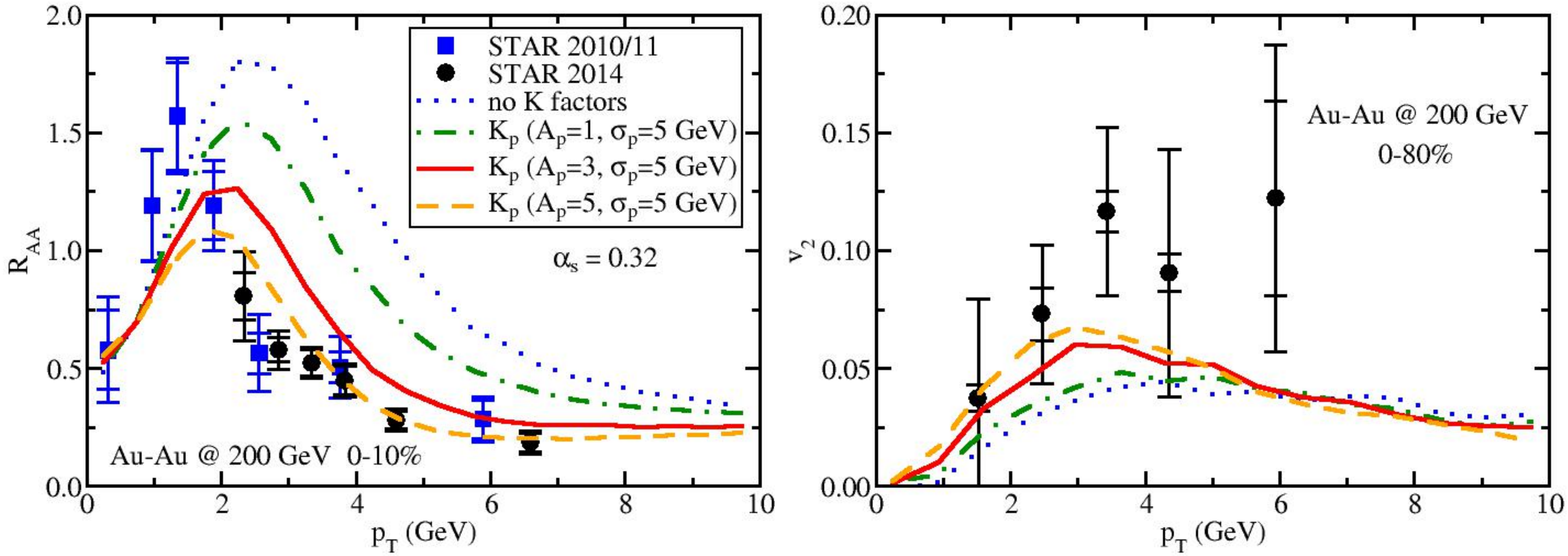
- At high *p* and *T*, LO pQCD calculation is respected, at low *p* and *T* near T_c, non-perturbative modification is introduced
- Only investigate possible phenomenological effects of K_p and K_T in this work; a precise extraction of these non-perturbative effects will be left for a future effort –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

Effect of K_p (LHC)



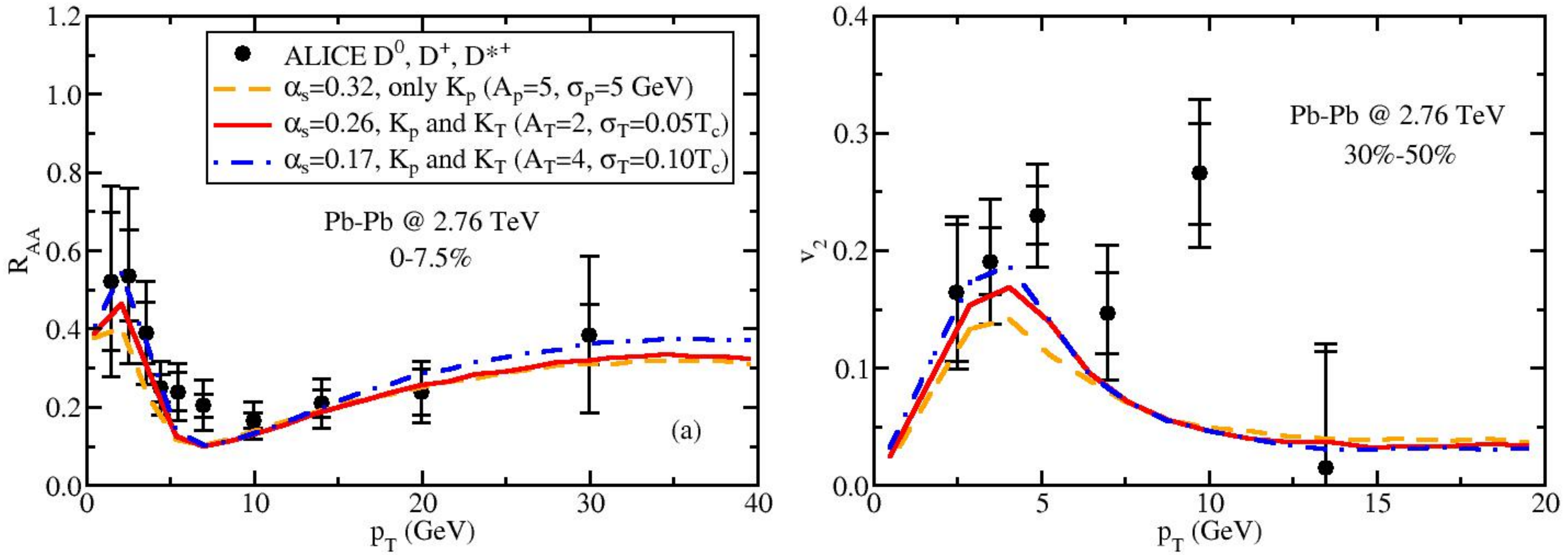
- Without K_p, *D* meson R_{AA} from LO pQCD calculation is consistent with data at high p_T, but is overestimated at low p_T
- With an enhancement of transport coefficient at low *p*, our model provides good p_T dependence of *D* meson R_{AA}
- *D* meson v_2 is still underestimated while its R_{AA} is fit to data

Effect of K_p (RHIC)



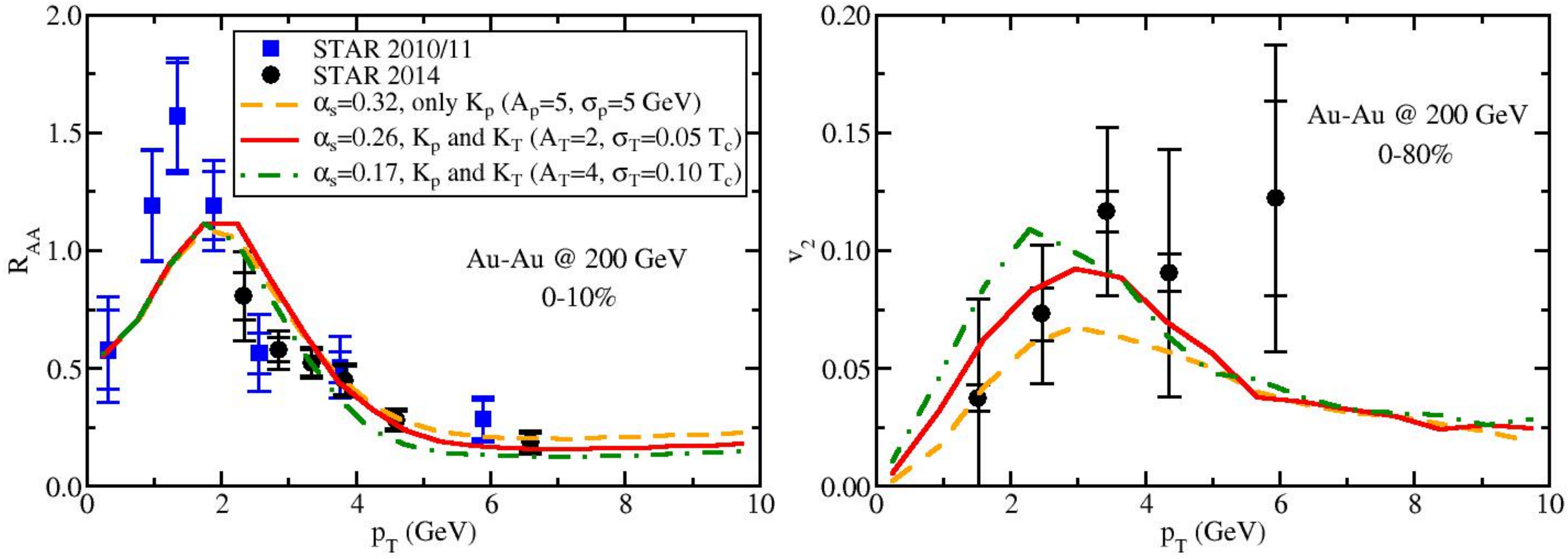
- Similar to the LHC scenario, an enhancement of transport coefficient at low *p* is necessary to describe *D* meson R_{AA} at low p_T
- *D* meson v_2 may be underestimated while its R_{AA} is fit to data

Effect of K_T (LHC)



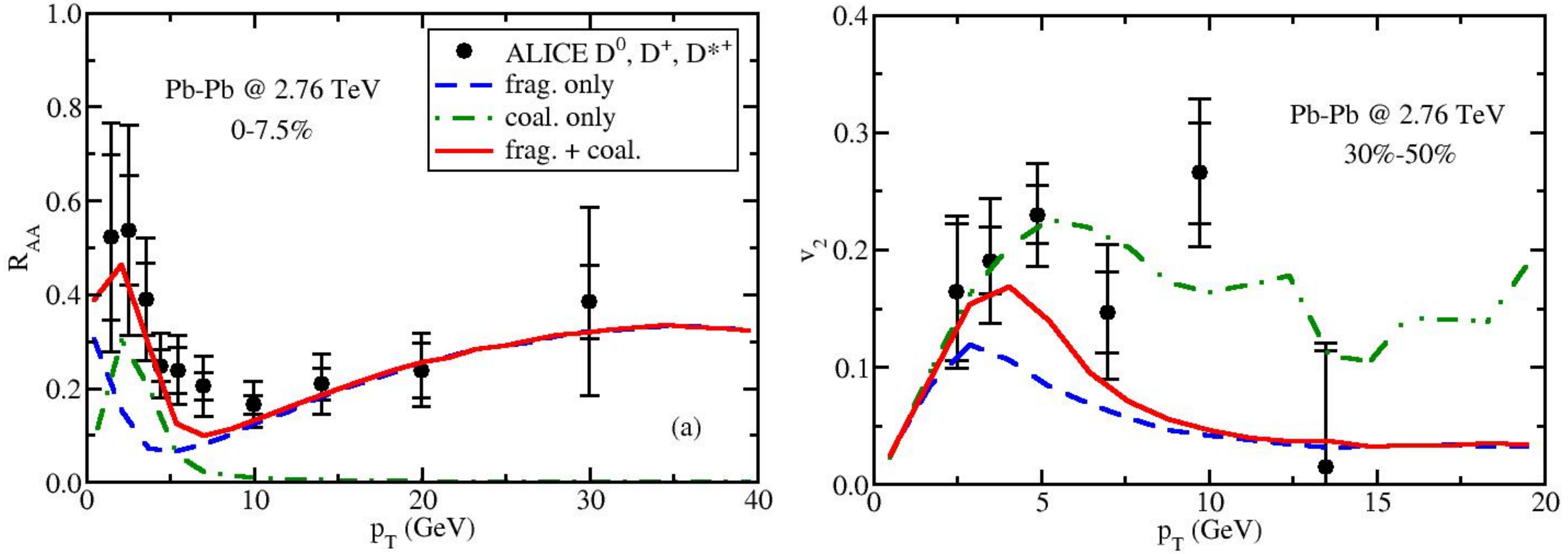
- Introduce different strength of enhancement of transport coefficient near T_c, adjust α_s so that R_{AA} is fixed
- The stronger K_T is near T_c, the larger D meson v_2 is obtained
- Reason: more energy loss of c quarks is shifted to the freeze-out hypersurface where both the geometric asymmetry and collective flow of the bulk matter is larger than average

Effect of K_T (RHIC)



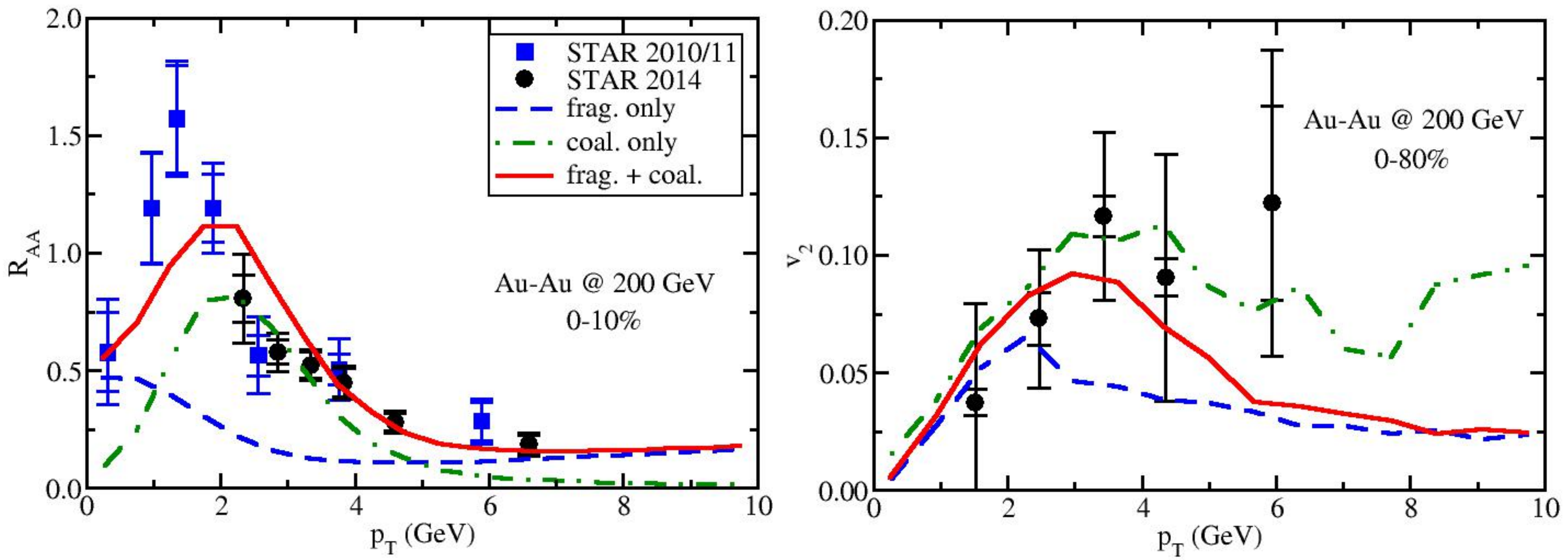
- Similar to the LHC scenario, while R_{AA} is fixed, the enhancement of transport coefficient near T_c increases D meson v_2
- Consistent with findings presented in
  Xu et. al., Chin. Phys. Lett. 32, 9 (2015)
  Das et. al., Phys. Lett. B747, 260 (2015)

Effect of Hadronization Process (LHC)



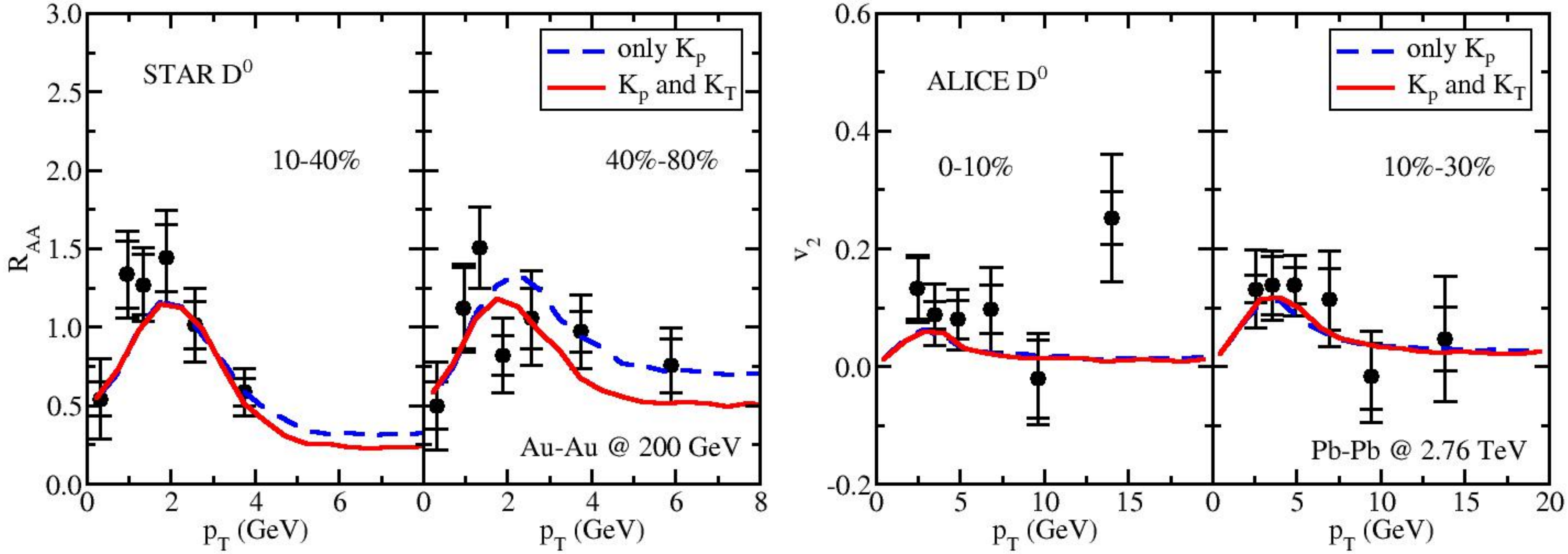
- Fragmentation dominates *D* meson production at high p_T; Coalescence enhances heavy meson production at medium p_T and forms a bump structure in R_{AA}
- Coalescence enhances heavy meson v_2 since it adds the *p*-space anisotropy of light partons from the bulk matter to heavy quarks

Effect of Hadronization Process (RHIC)



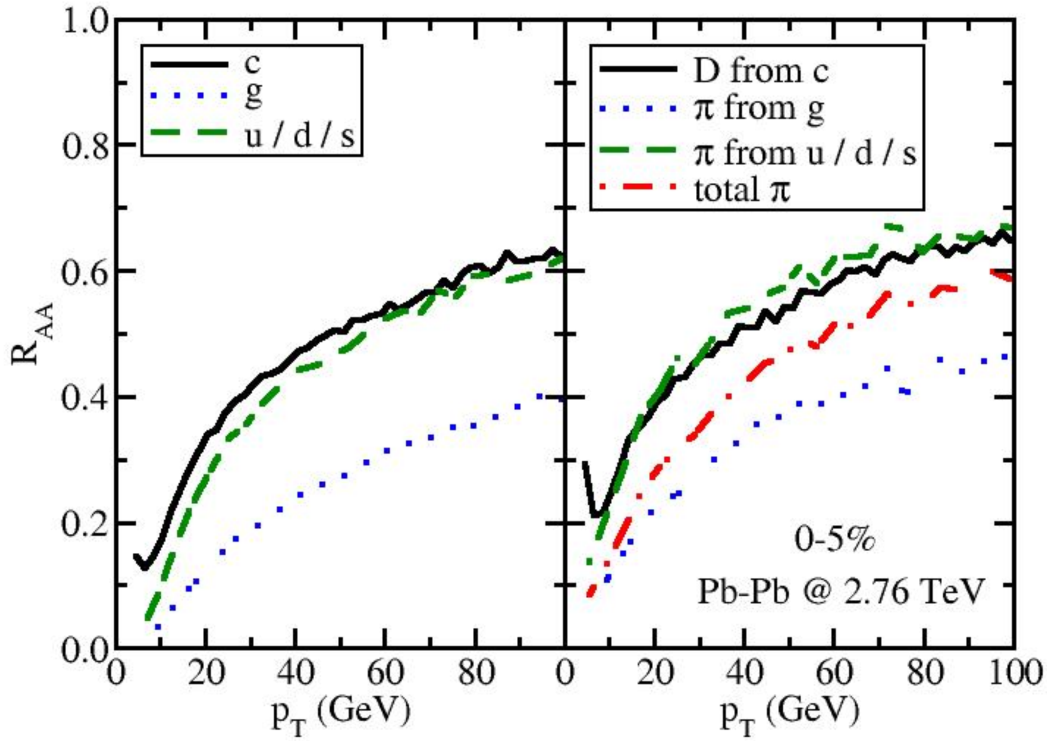
- Similar conclusions to the LHC scenario: coalescence enhances *D* meson R_{AA} and v_2 at medium p_T.

D meson R_{AA} and v_2 in other centrality bins at RHIC and LHC



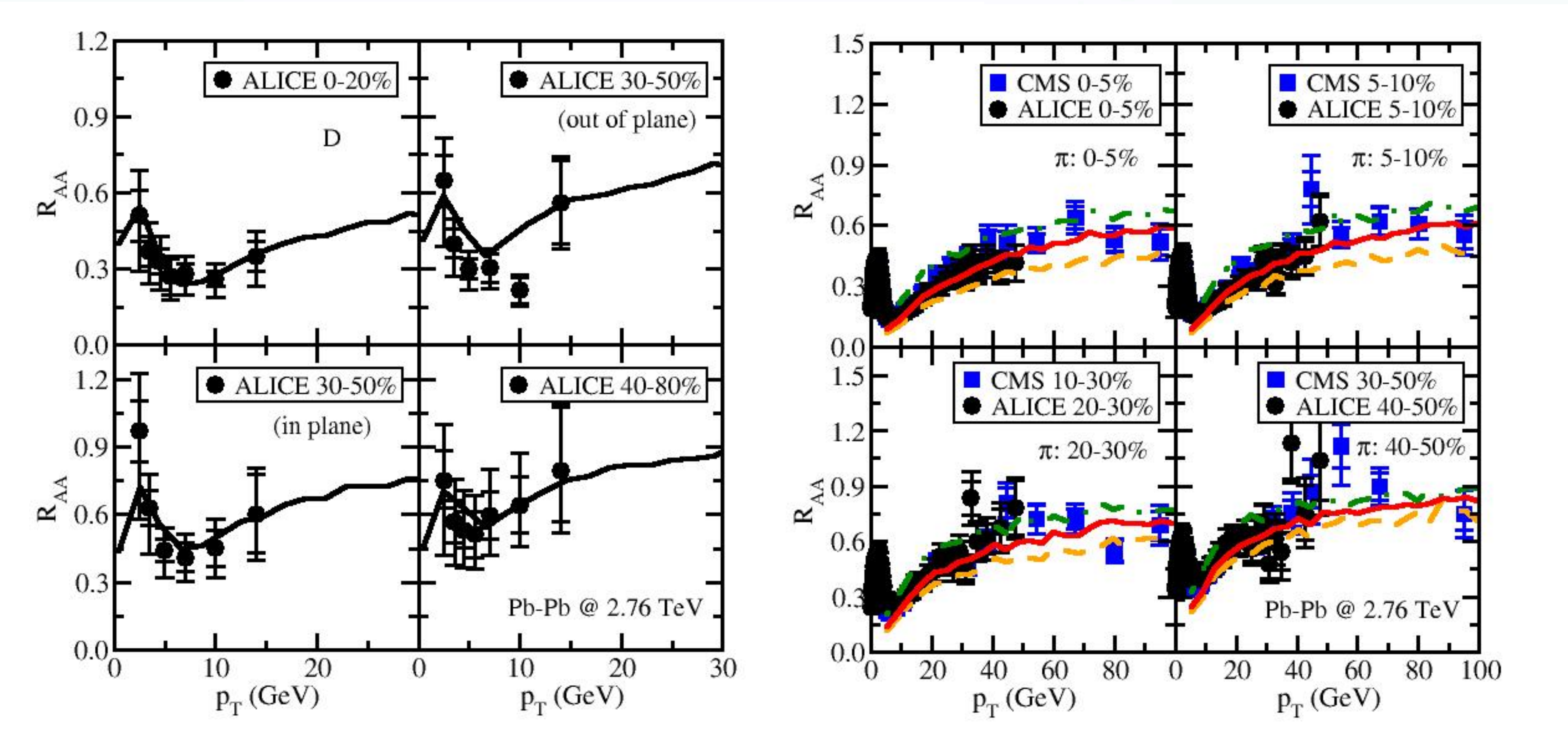
- With proper choices of K_p and K_T, our model provides good descriptions of heavy meson suppression and elliptic flow
- A global fit to experimental data using systematic statistic tool is necessary in the future to precisely extract the non-perturbative effects of heavy quark transport coefficient

Heavy vs. Light Hadron Suppression

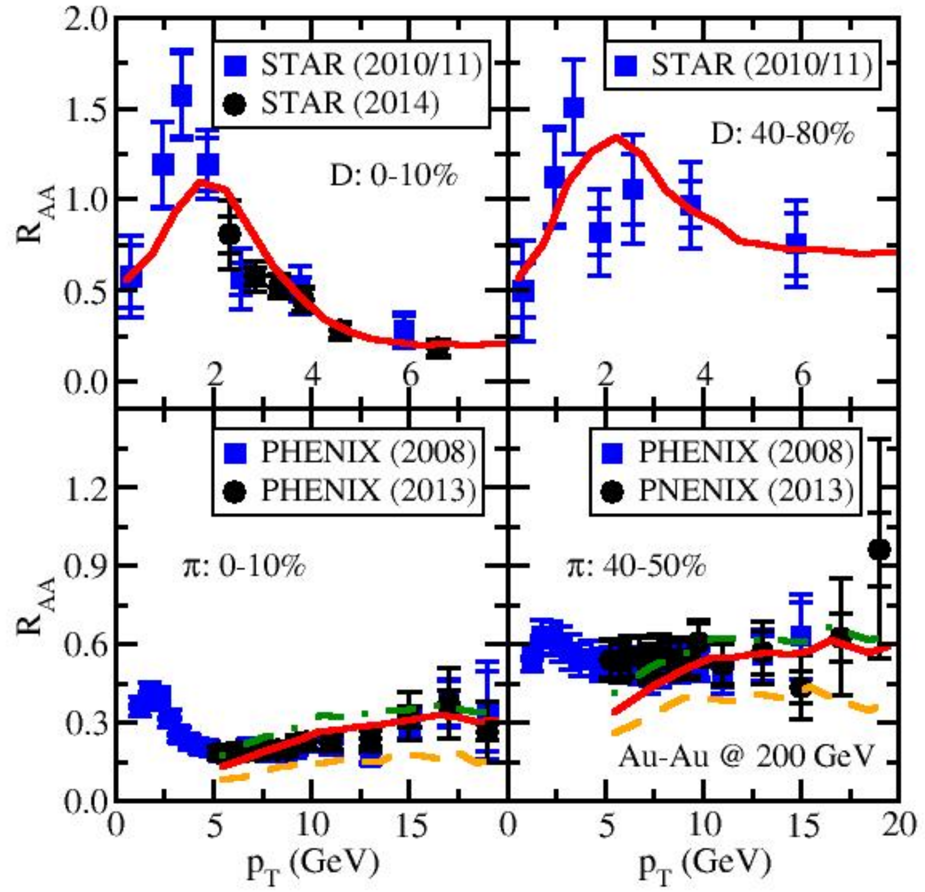


- *u*/*d*/*s* are more suppressed than *c* quark at low p_T but they have very similar R_{AA} at high p_T, *g* is significantly more suppressed
- Due to different fragmentation function (harder for *c* than for *u*/*d*/*s*), π from light quark is slightly less suppressed than *D*
- R_{AA} of mixed π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

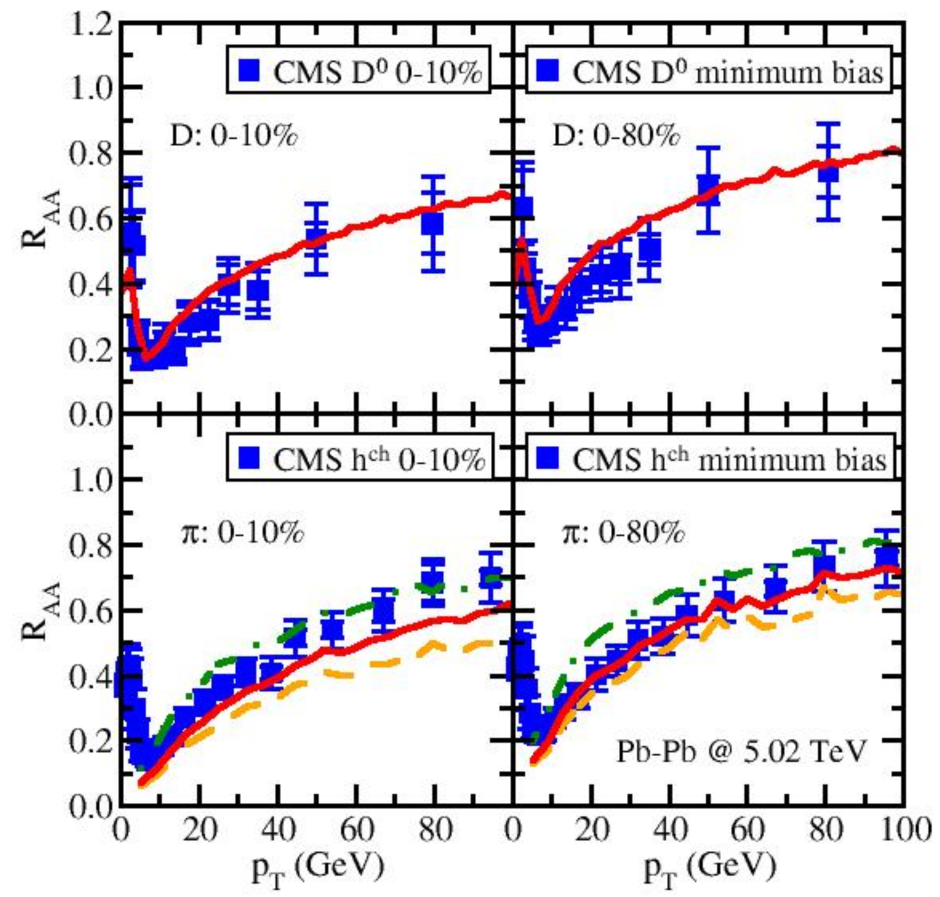
Simultaneous Description of *D* and *π* R_{AA} in 2.76 TeV Pb-Pb Collisions



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



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



Summary and Outlook

Established a Linearized Boltzmann Transport Model that simultaneously describes the elastic and inelastic scattering of hard partons in QGP

Provided good descriptions of the medium modification of both heavy and light flavor hadrons

Investigated the effects of different momentum and temperature dependence of transport coefficients on heavy meson suppression and flow; a precise extraction of non-perturbative effect from model-to-data comparison is expected in our future study

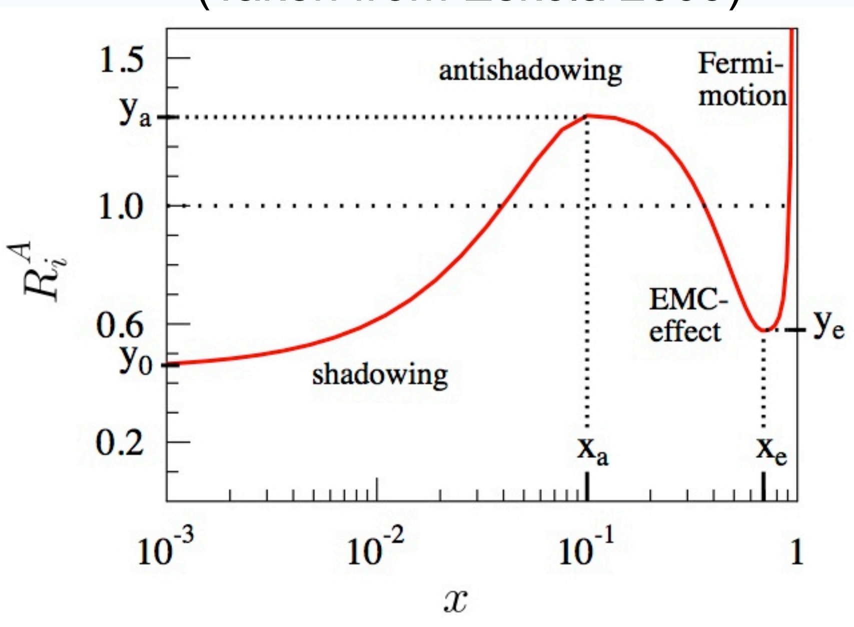
Heavy-light hadron correlation can be studied in the future which may provide more constraints on our understanding of the strongly interacting system

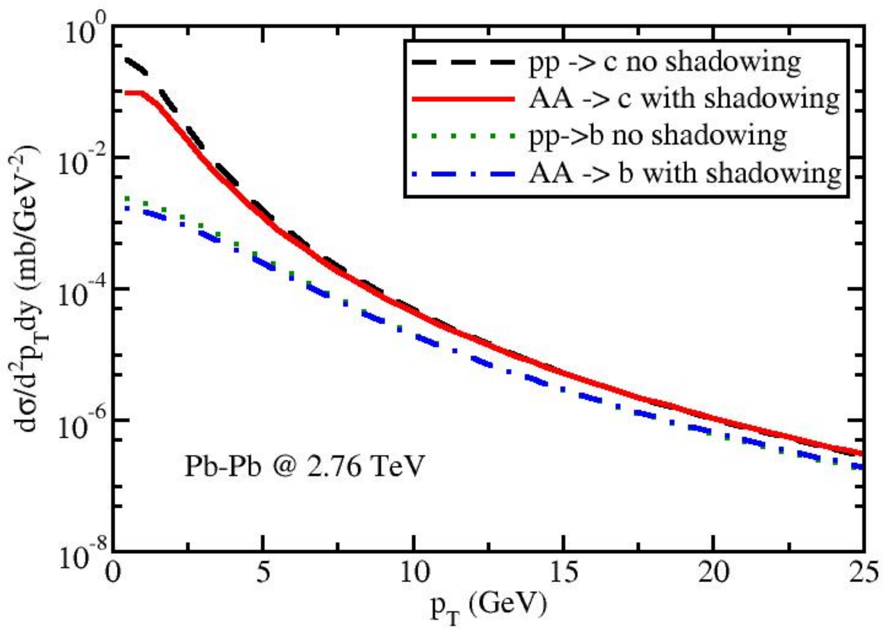
Thank you!

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}