Heavy Quark Energy Loss and Hadronization In a QGP Medium

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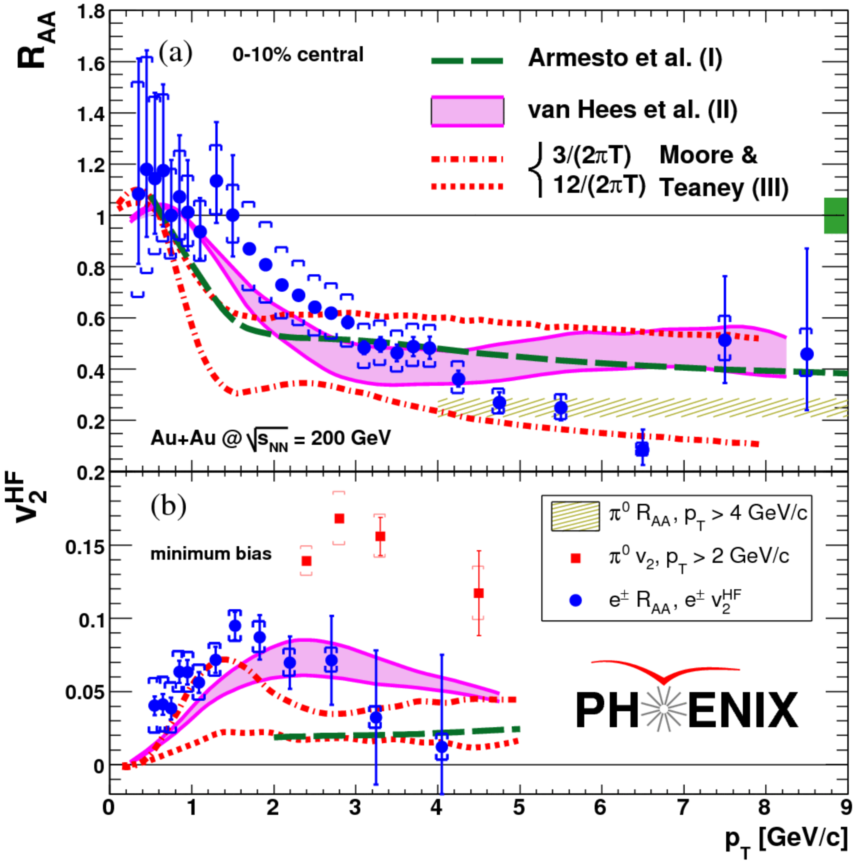
Outline

- Introduction and motivation
- Heavy flavor initial production: pQCD + shadowing
- Heavy flavor evolution inside QGP : Improved Langevin approach incorporating gluon radiation
- Heavy flavor hadronization: a hybrid coalescence plus fragmentation model
- Results of heavy flavor suppression and flow and comparison with LHC and RHIC data
- Summary and outlook

Why to Study Heavy Quark

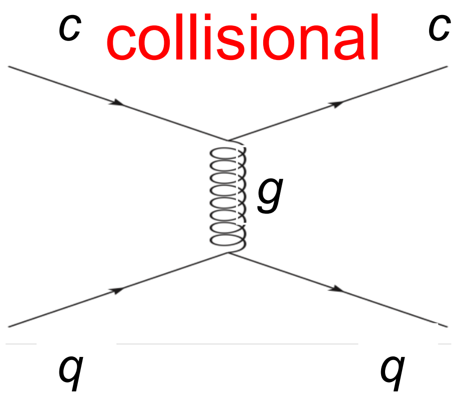
- Mainly produced at early stage: act as a hard probe
- Heavy: supposed to be influenced less by the medium
- Partially thermalized with medium – SC, Bass, *PRC 84, 064902*

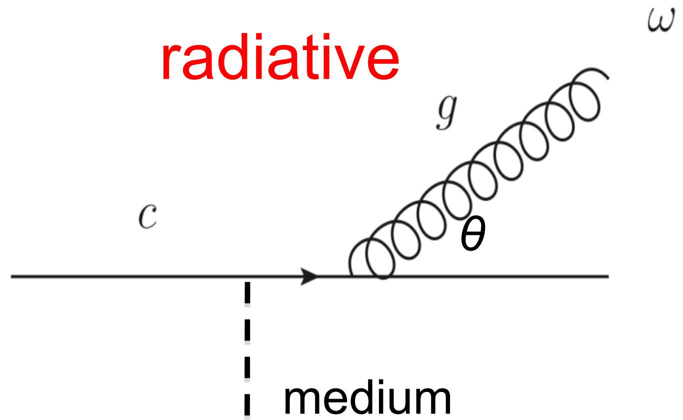


- Surprisingly small R_{AA} and large v_2 of non-photonic electrons
- Strong coupling between heavy quark and the medium
- **How to describe heavy quark energy loss process inside QGP?**

Energy Loss Mechanisms

- Two ways for heavy quarks to lose energy:

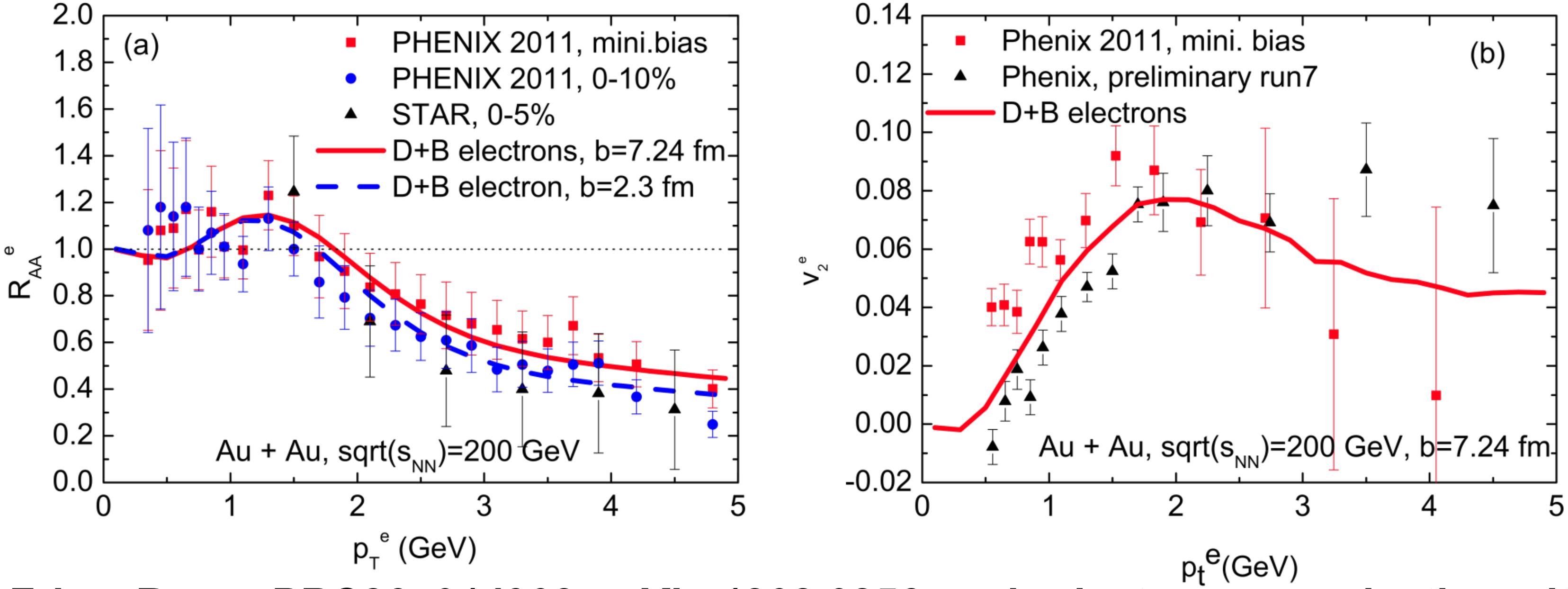




- Unless in the ultra-relativistic limit ($\gamma v >> 1/g$), gluon radiation is suppressed by the "dead cone effect" → consider collisional energy loss as the dominant factor
- Heavy quark inside QGP medium: Brownian motion
- Description: Langevin equation $$\frac{d\vec{p}}{dt} = -\eta_D(p)\vec{p} + \vec{\xi}$$

From RHIC to LHC

Successful description of RHIC data: Langevin for HQ + coal. & frag. for hadronization + heavy meson diffusion in hadron gas



He, Fries, Rapp, *PRC86, 014903*, *arXiv:1208.0256*, and private communication with He

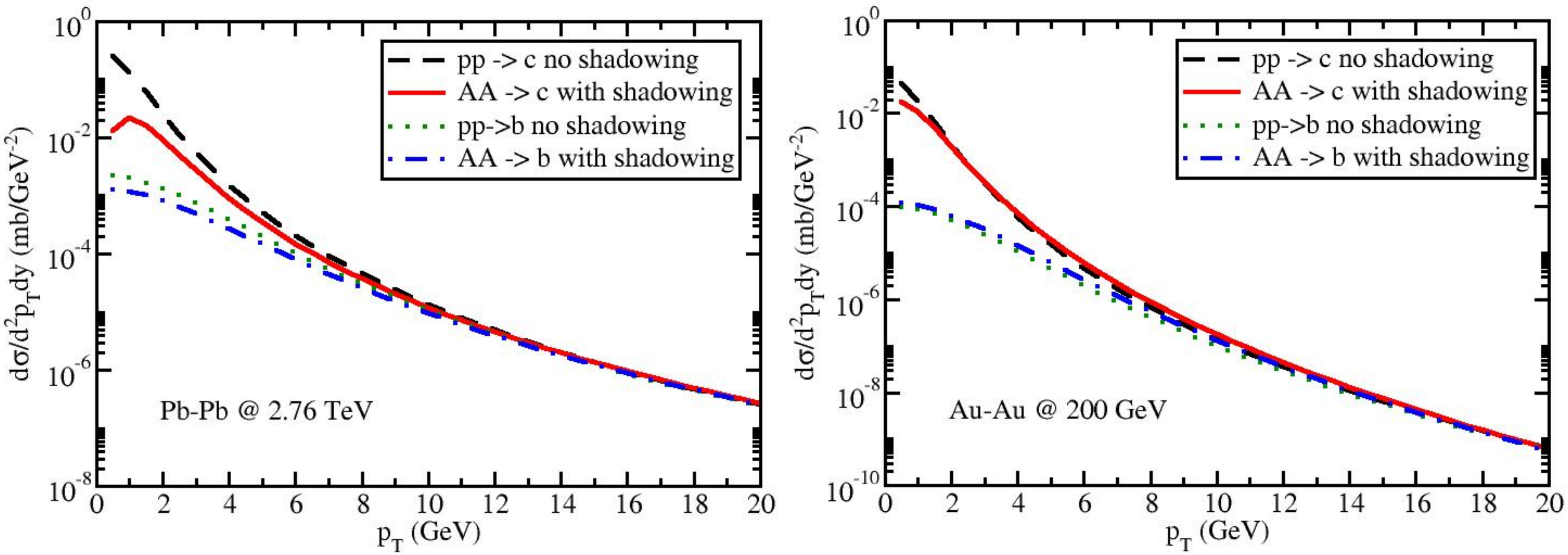
What shall we modify to go from RHIC to LHC?

- Even heavy quark is ultrarelativistic
  → radiative energy loss may not be ignored

Heavy Flavor Initial Production

- Initial production: MC-Glauber for the position space and leading-order pQCD calculation for the momentum space
- Shadowing effect: different PDF's of nucleon and nuclei lead to different production rate of HQ in pp and AA collisions

K. Eskola, et al., JHEP 0807 (2008) 102



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

Heavy Flavor Evolution inside QGP (Improved Langevin Approach)

Modified Langevin Equation: $$\frac{d\vec{p}}{dt} = -\eta_D(p)\vec{p} + \vec{\xi} + \vec{f}_g$$

Fluctuation-dissipation relation between drag and thermal random force: $$\eta_D(p) = \frac{\kappa}{2TE} \qquad \langle \xi^i(t)\xi^j(t')\rangle = \kappa\delta^{ij}\delta(t-t')$$

Force from gluon radiation: $$\vec{f}_g = -\frac{d\vec{p}_g}{dt}$$

Gluon distribution taken from Higher Twist calculation:

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

Guo and Wang, *PRL 85, 3591*; Majumder, *PRD 85, 014023*; Zhang, Wang and Wang, *PRL 93, 072301*.

Transport Coefficients: $$D = \frac{T}{M\eta_D(0)} = \frac{2T^2}{\kappa} \qquad \hat{q} = 2\kappa C_A/C_F$$

Heavy Flavor Evolution inside QGP
(Improved Langevin Approach)

Numerical Implementation (Ito Discretization)

$$\vec{p}(t+\Delta t) = \vec{p}(t) - \vec{d}_{\rm Ito}(\vec{p}(t))\Delta t + \vec{\xi}\Delta t - \Delta\vec{p}_{\rm gluon}$$

Drag force: $\vec{d}_{Ito}(\vec{p}) = \eta_D(p)\vec{p}$

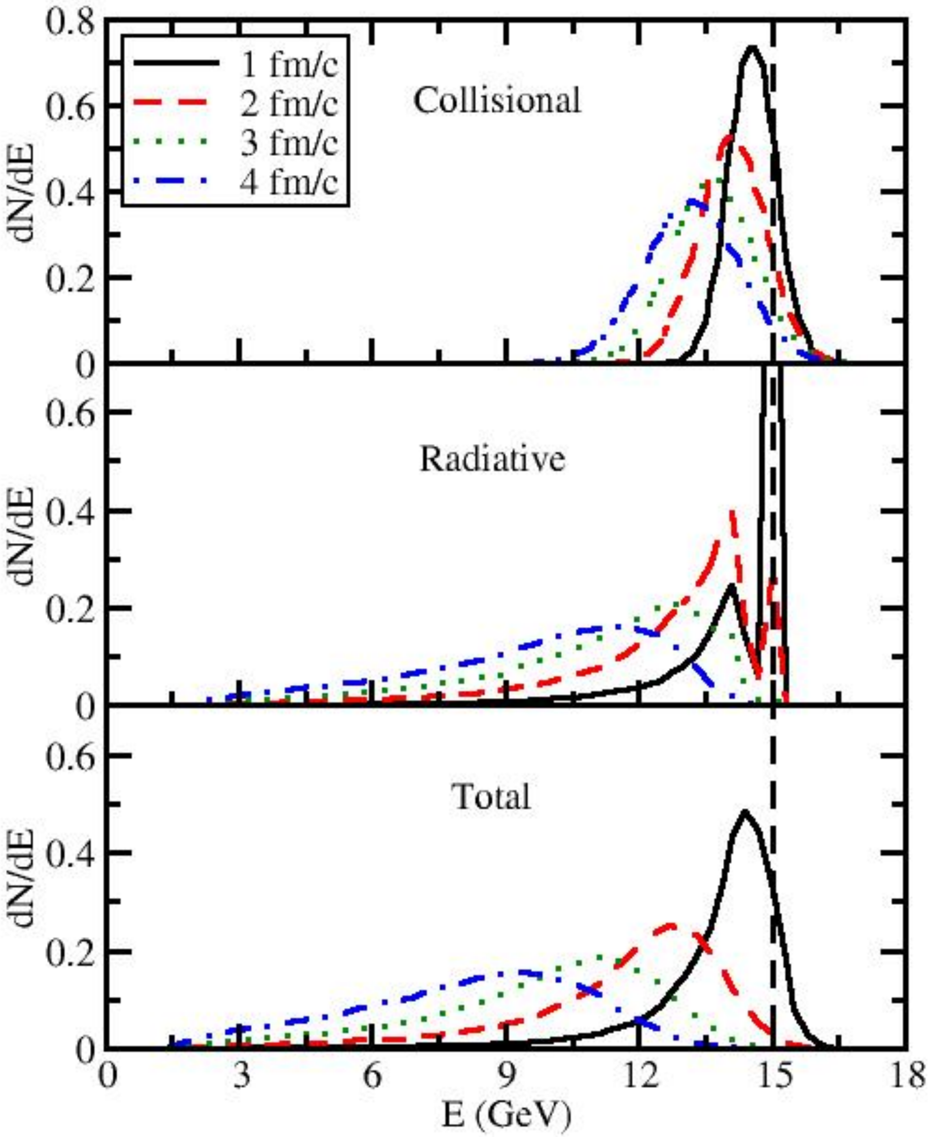
Thermal random force: $\langle\xi^i(t)\xi^j(t-n\Delta t)\rangle = \frac{\kappa}{\Delta t}\delta^{ij}\delta^{0n}$

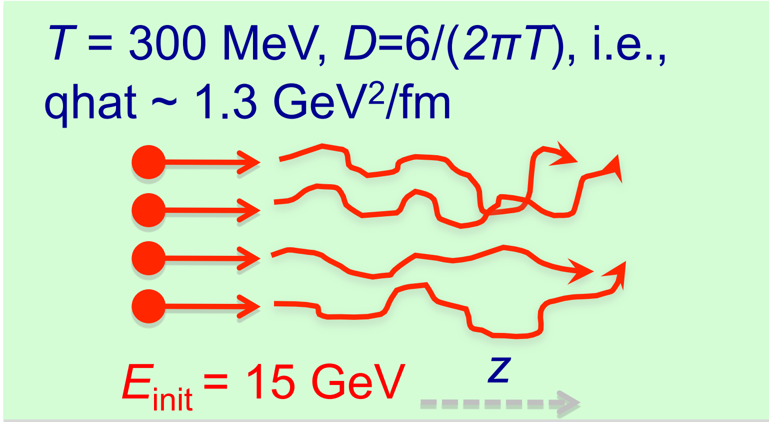
Momentum of gluon radiated during Δ*t*: $\Delta\vec{p}_{\rm gluon}$

Lower cut for gluon radiation: *πT*

- Balance between gluon radiation and absorption
- Guarantee equilibrium after sufficiently long evolution

Charm Quark Evolution in Static Medium

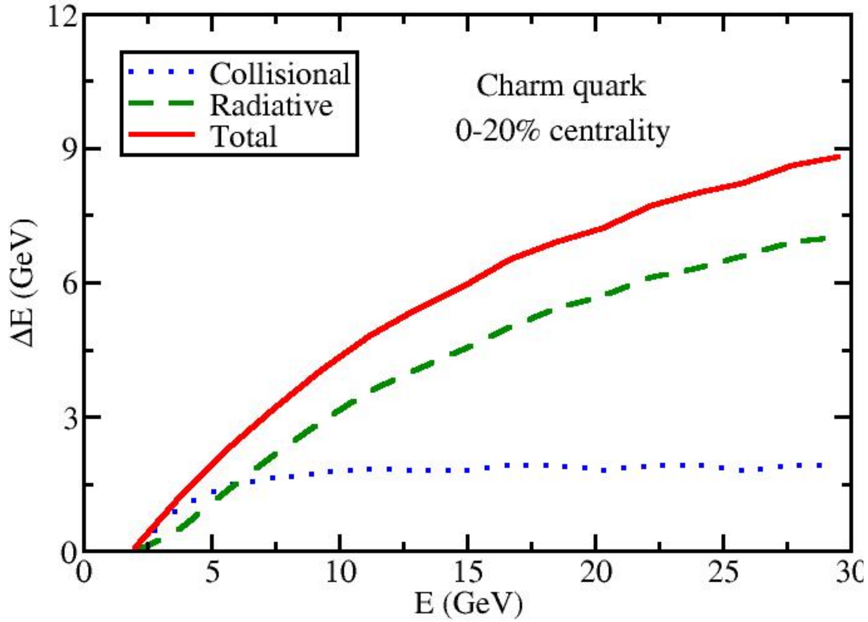


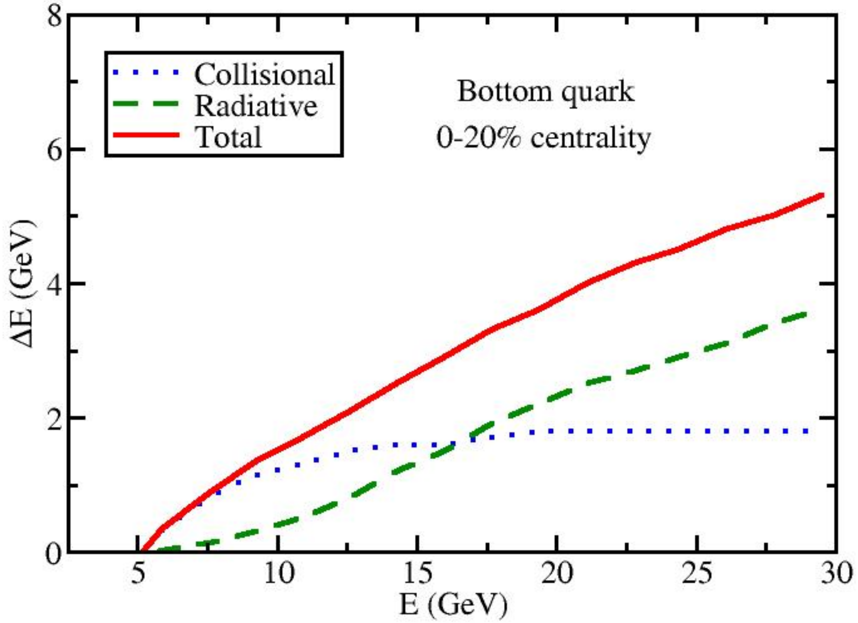


Evolution of E distribution

- Before 2 fm/c, collisional energy loss dominates; after 2 fm/c, radiative dominates;
- Collisional energy loss leads to Gaussian distribution, while radiative generates long tail.

Heavy Quark Energy Loss





- Collisional energy loss dominates low energy region, while radiative dominates high energy region.
- Crossing point: 6 GeV for *c* and 15 GeV for *b* quark.
- Collisional energy loss alone may work well to describe previous RHIC data but is insufficient for LHC.

Heavy Flavor Hadronization: Fragmentation + 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: use the sudden recombination model

Y. Oh, et al., PRC 79, 044905 (2009)

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: fermi-dirac distri. 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 recombine

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

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

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

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

The Sudden Recombination Model

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

N: normalization factor

g_M: statistics factor

e.g. 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 S.H.O.

Integrating over the position space leads to

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

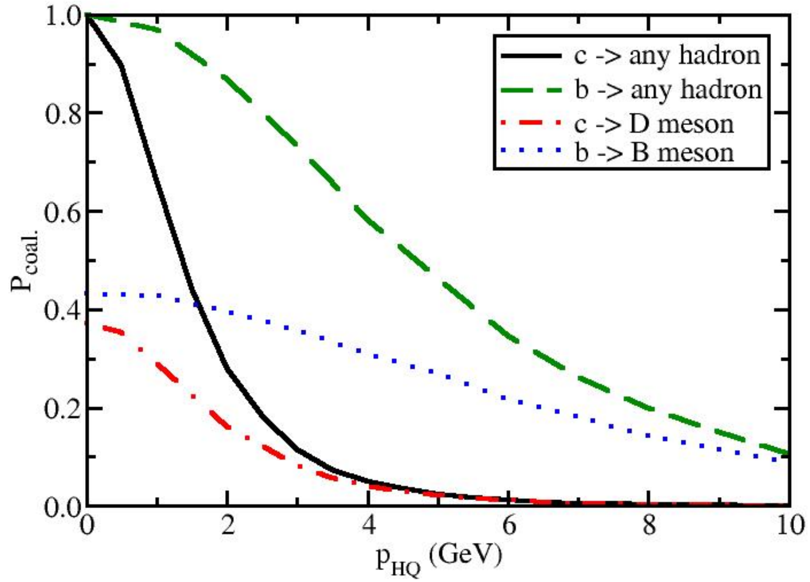
μ: reduced mass of the 2-particle system

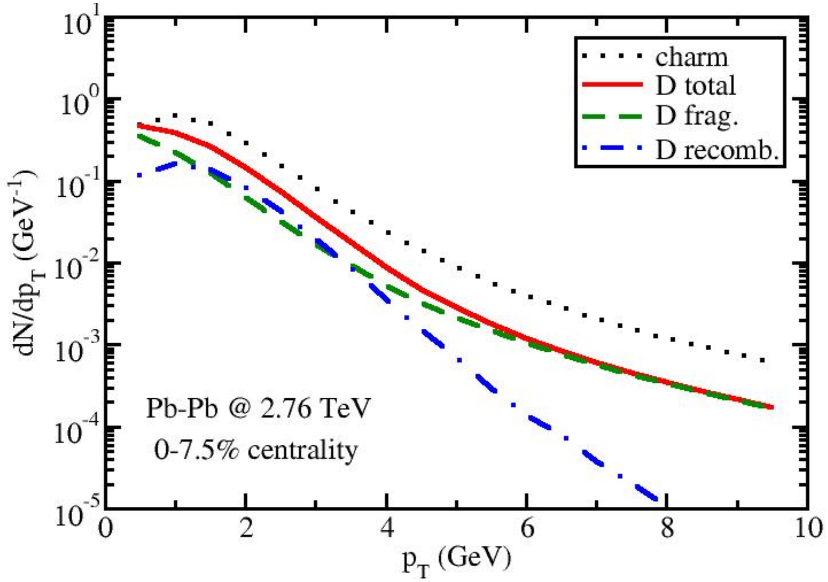
ω: S.H.O frequency – calculated by meson radius

0.106 GeV for *c*, and 0.059 GeV for *b*

Can be generalized to 3-particle recombination (baryon)

The Hybrid Coal. + Frag. Model





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

Normalization: $P_{coal.}(p_{HQ}=0) = 1$

Use Monte-Carlo to determine the hadronization channel of each HQ: frag. or recomb.? recomb. to *D*/*B* or a baryon?

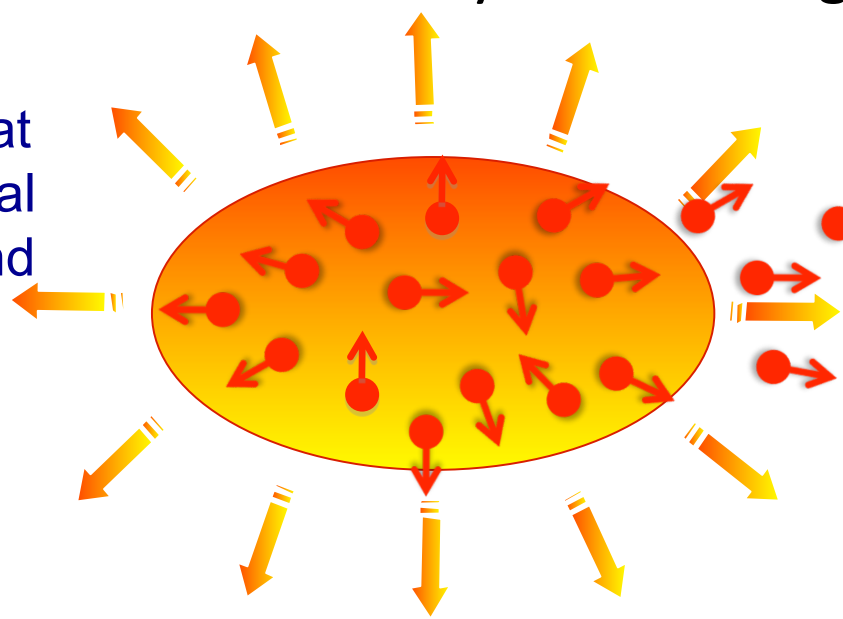
Fragmentation dominates *D* meson production at high p_T.

Recombination significantly enhances the *D* meson spectrum at intermediate p_T.

Sum up: Heavy Flavor inside QGP

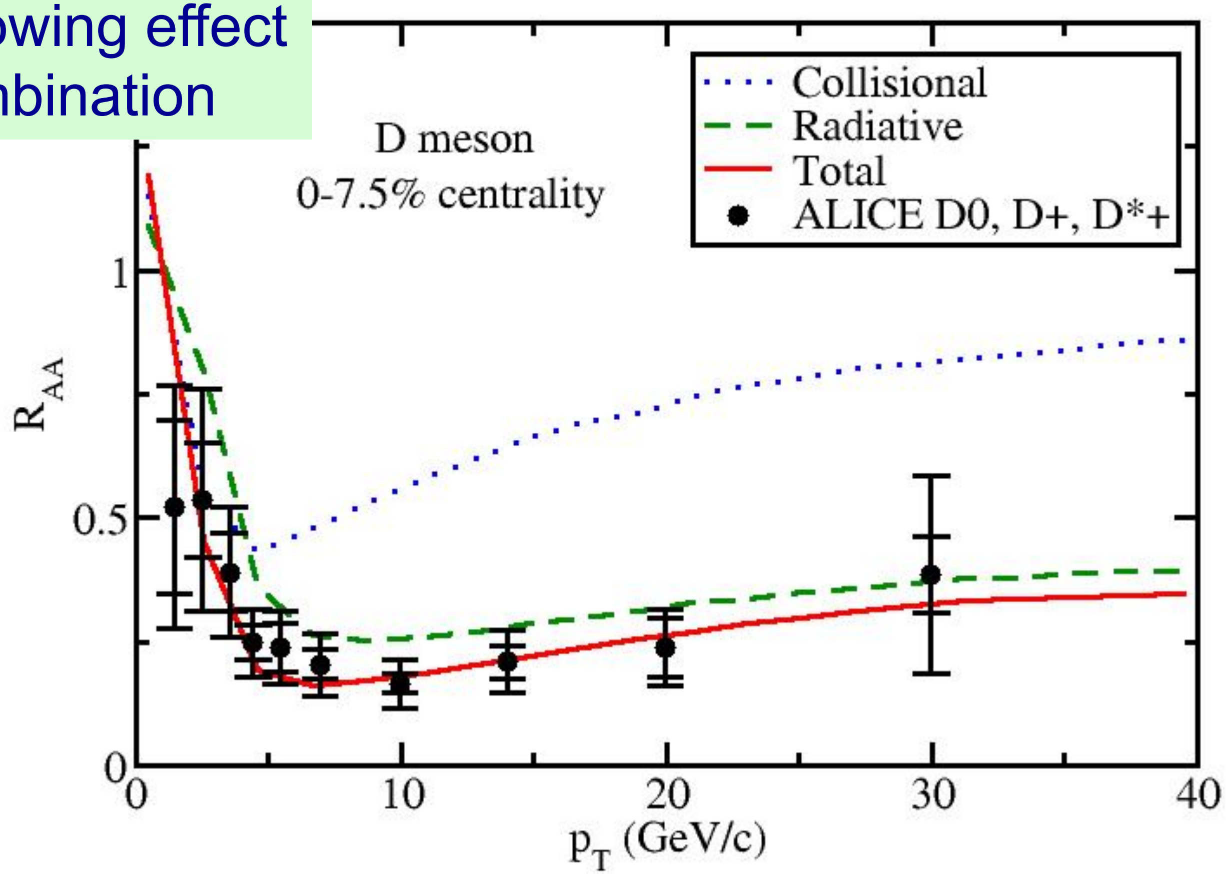
- Generation of QGP medium: 2D viscous hydro from OSU group (thanks to Qiu, Shen, Song, and Heinz)
- Initialization of heavy quarks: MC-Glauber for position space and pQCD calculation for momentum space
- Simulation of heavy quark evolution: the improved Langevin algorithm in the local rest frame of the medium
- Hadronization of HQ into heavy meson: frag. + recomb.

$D=6/(2\pi T)$, i.e., qhat ~ 3 GeV^2/fm at initial temperature (around 400 MeV)



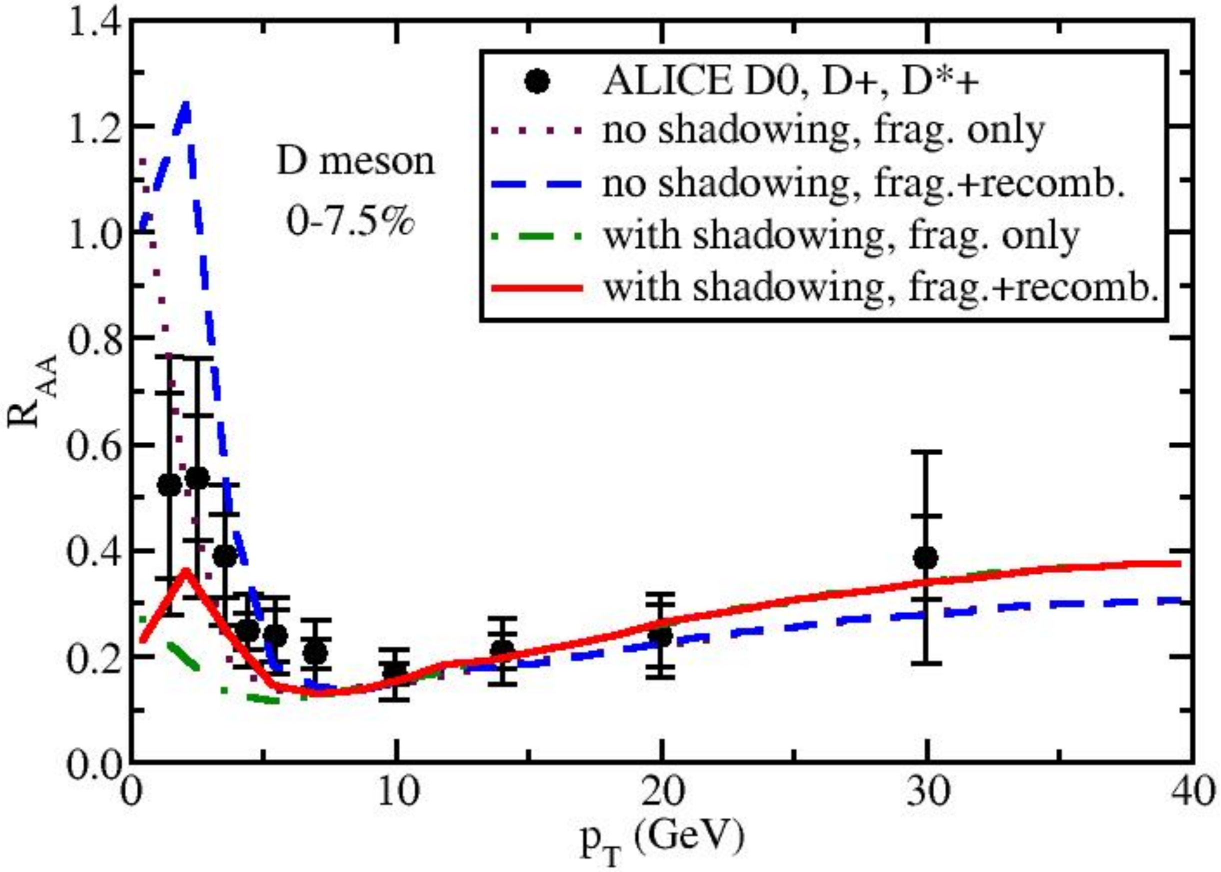
R_{AA} of LHC *D* meson

No shadowing effect
No recombination



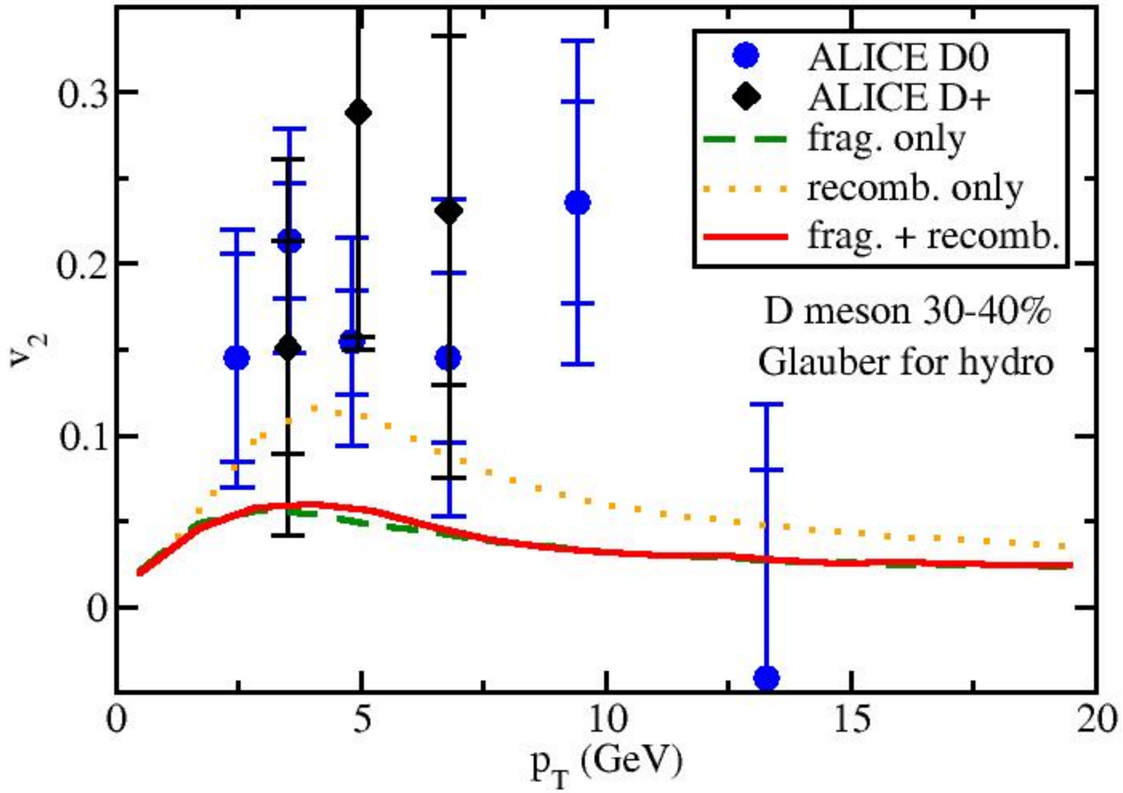
- Collisional dominates low p_T, radiative dominates high p_T.
- The combination of the two mechanisms provides a good description of experimental data.

R_{AA} of LHC *D* meson



- Shadowing effect reduce R_{AA} significantly at low p_T.
- Recombination mechanism raise R_{AA} at medium p_T.

v_2 of LHC *D* meson

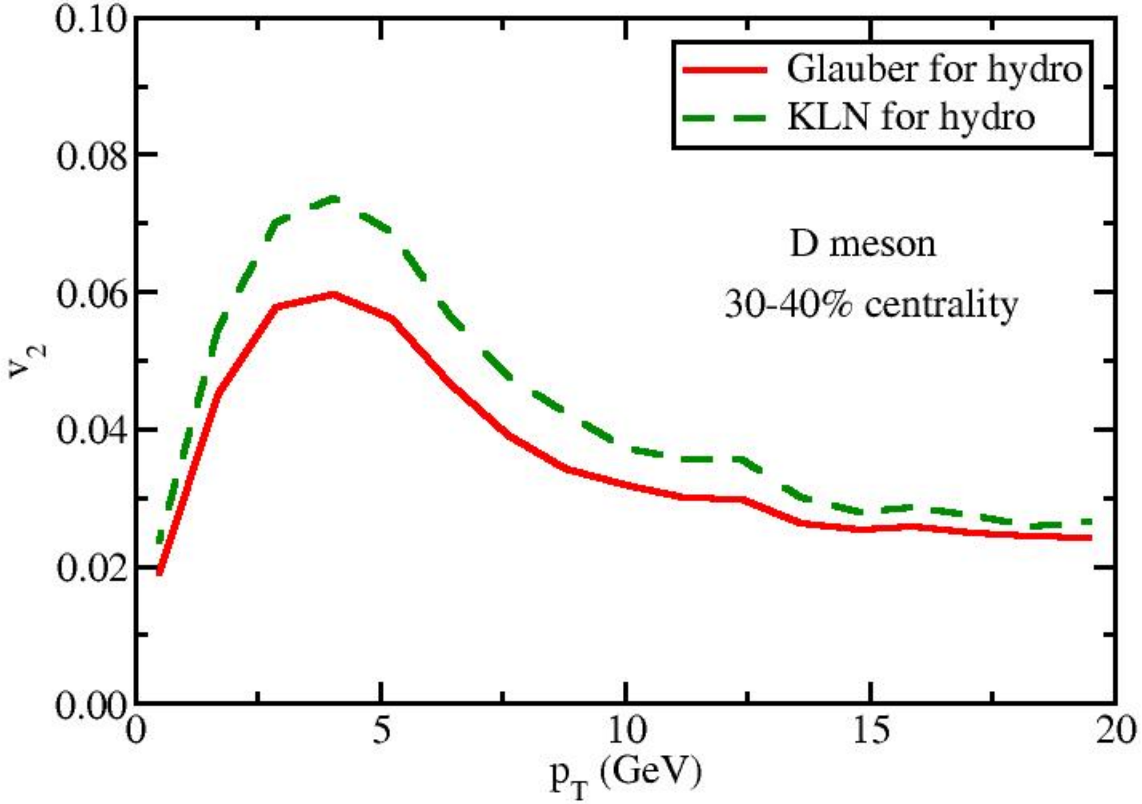


frag. only: force fragmentation, i.e., $f^W(q)=0$ for any q.

recomb. only: force combination, i.e., $f^W(q)=1$ for any q.

Recombination mechanism provides larger v_2 than fragmentation. However, due to the momentum dependence of the Wigner function, our combined mechanism only slightly raises the D v_2 at medium p_T.

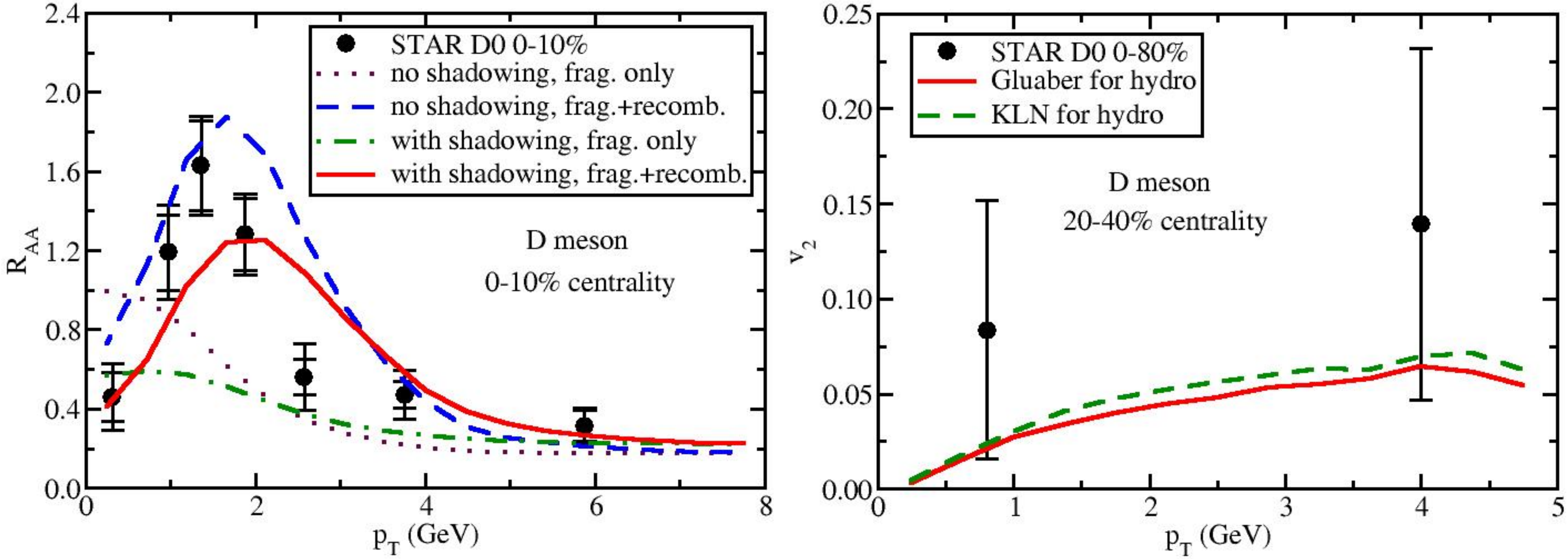
Uncertainties of v_2



Different geometries and flow behaviors of the QGP medium influence heavy flavor v_2 while does not significantly impact the overall suppression (SC, Qin and Bass, *arXiv:1205.2396*)

Currently use smooth initial condition for hydro evolution, an event-by-event study of HQ (more consistent with measurement) may result in different final state spectrum → future effeort

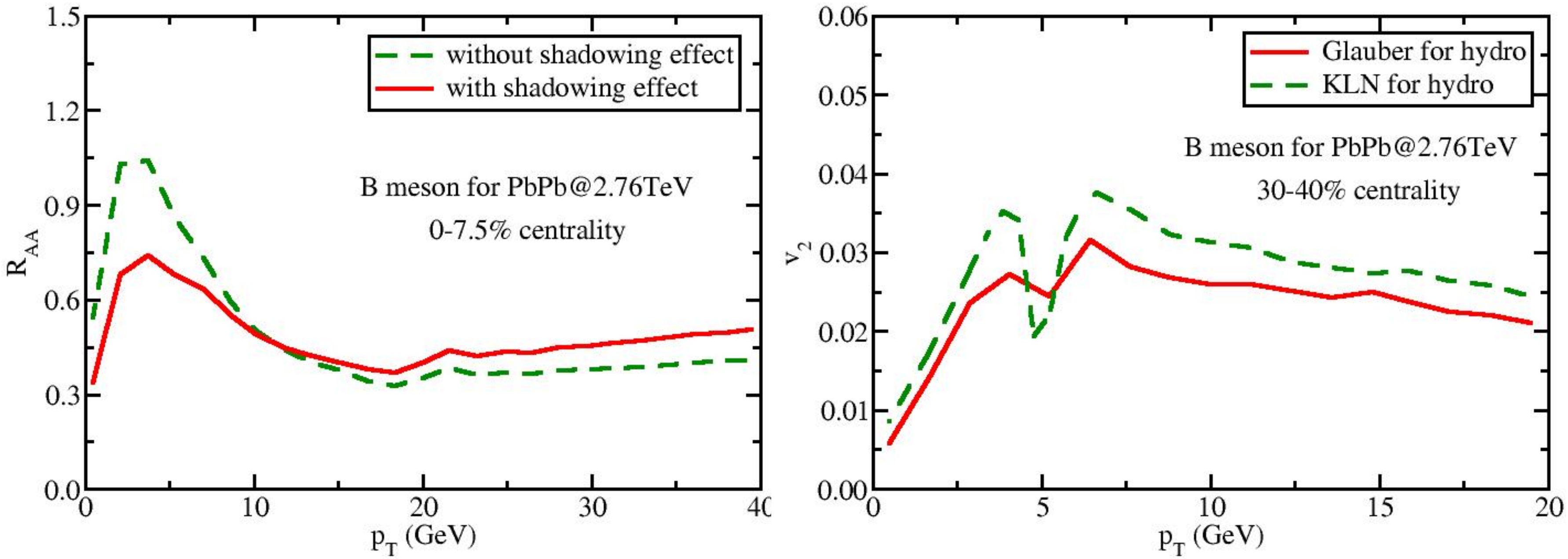
R_{AA} and v_2 of RHIC *D* Meson



Recombination mechanism has a significant contribution to R_{AA} at RHIC energy.

With the incorporation of the low energy effect (shadowing and recombination), our improved Langevin framework provides good descriptions of the RHIC data.

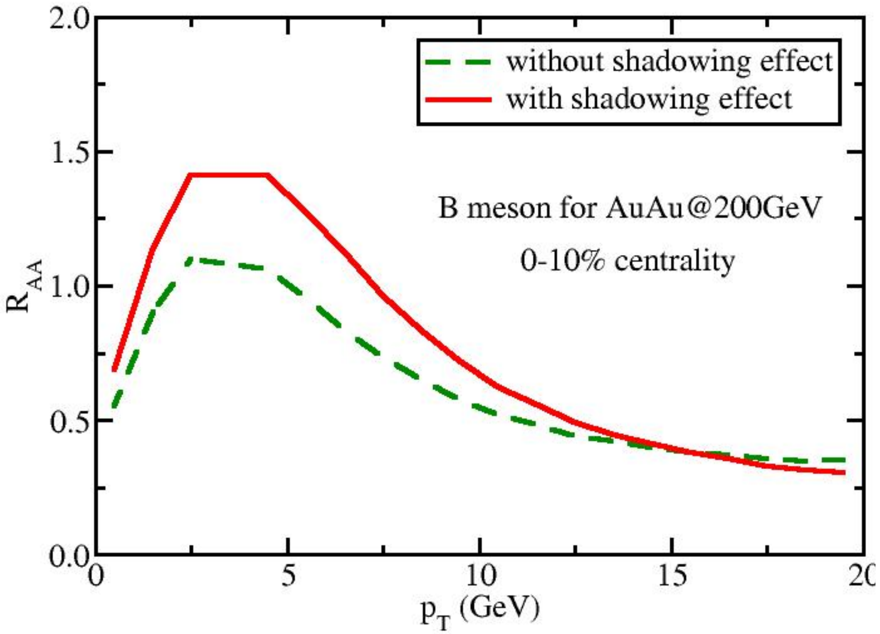
Prediction for LHC *B* Meson

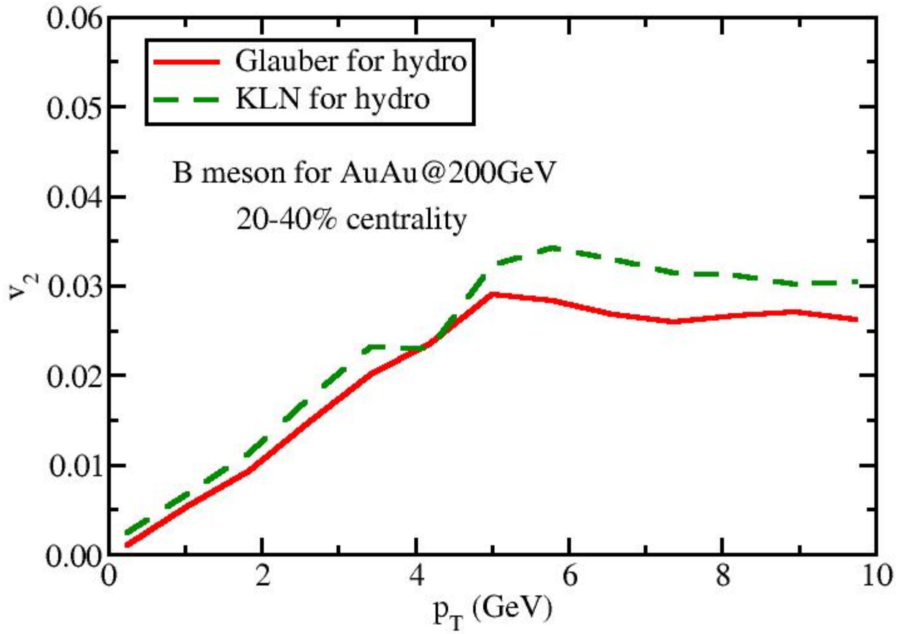


The shadowing effect for *b*-quark is not as significant as *c*-quark, but still non-negligible.

The dip of *B* meson v_2 around 5 GeV results from the transition behavior from the collisional dominating region to the radiative dominating region. See backup slides or *arXiv:1209.5410*.

Prediction for RHIC *B* Meson





Instead of "shadowing", RHIC *b*-quark has "anti-shadowing" effect at low p_T.

Summary and Outlook

- Study the heavy flavor evolution and hadronization in QGP in the framework of the Langevin approach
- Improve the Langevin algorithm to incorporate both collisional and radiative energy loss of heavy quark
- Construct a hybrid fragmentation plus recombination model to calculate heavy flavor hadronization
- Reveal the significant effect of gluon radiation at high energies and recombination at medium energies
- Provide good descriptions of *D* meson suppression and flow measured at both RHIC and LHC
- Will include hadronic interactions after the QGP phase and extend to an event-by-event study soon

Thank you!