Heavy quark energy loss in hot and dense nuclear matter

Shanshan Cao
In Collaboration with
G.Y. Qin, S.A. Bass and B. Mueller
Duke University

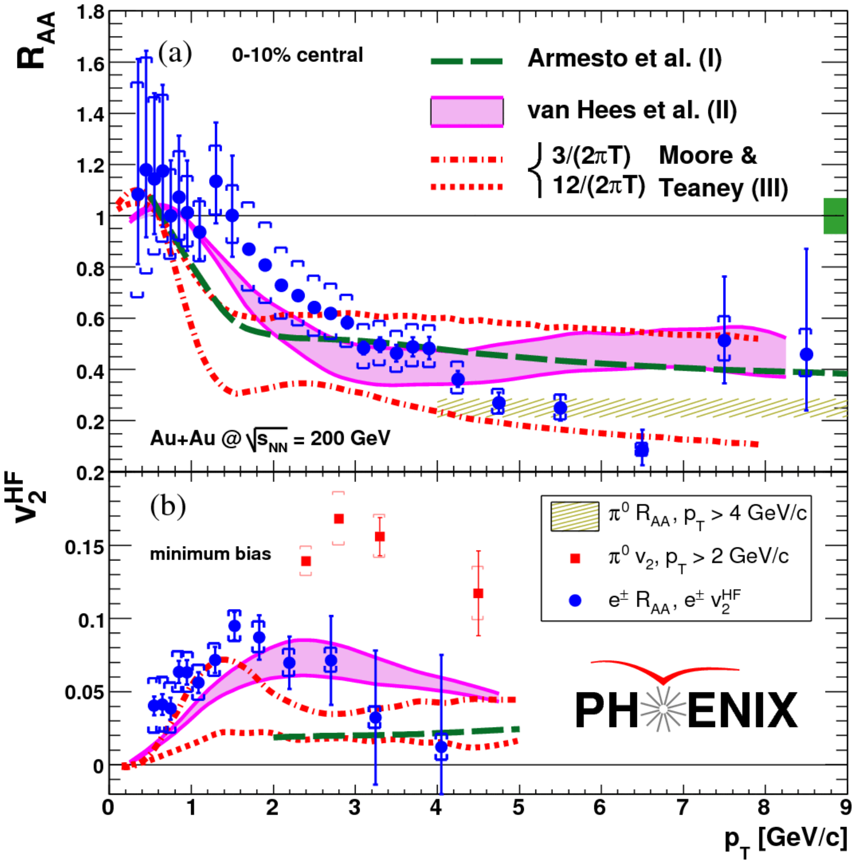
Outline

- Introduction and motivation
- Methodology

  Improved Langevin approach incorporating gluon radiation mechanism
- Results of heavy flavor suppression and flow and comparison with experimental data
- Heavy quark pair angular correlation
- Summary and outlook

Why to Study Heavy Quark

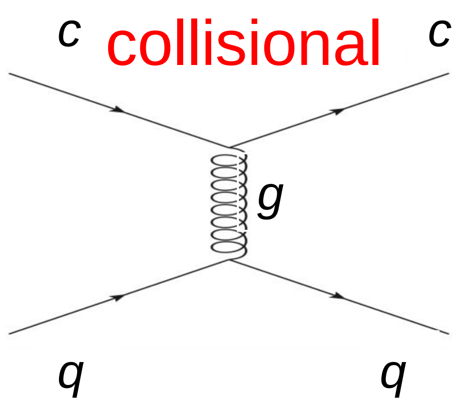
- Mainly produced at early stage: act as a hard probe
- Heavy: supposed to be influenced less by the medium
- Partially thermalized with medium – SC, Bass, *PRC 84, 064902*

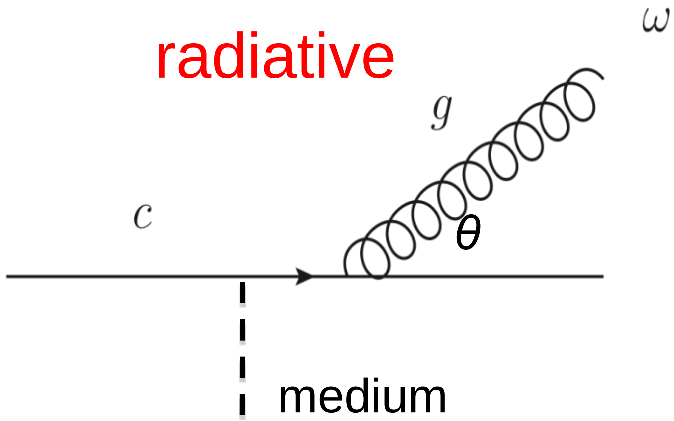


- Surprisingly small R_{AA} and large v_2 of non-photonic electrons
- Strong coupling between heavy quark and the medium
- **How to describe heavy quark energy loss process inside QGP?**

Energy Loss Mechanisms

- Two ways for heavy quarks to lose energy:





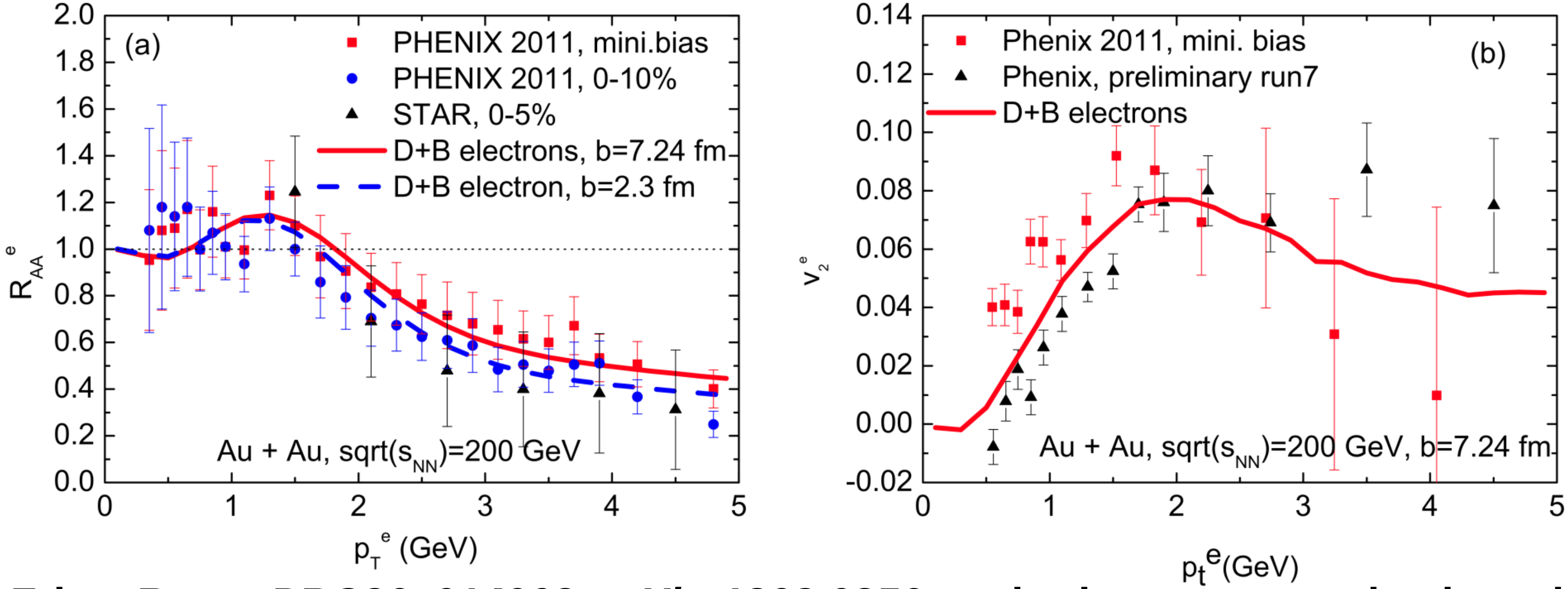
- Unless in the ultra-relativistic limit (*γv* >> 1/g), gluon radiation is suppressed by the "dead cone effect" → consider collisional energy loss as the dominant factor

- 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

Improved Langevin Approach Incorporating Gluon Radiation

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

Improved Langevin Approach Incorporating Gluon Radiation

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

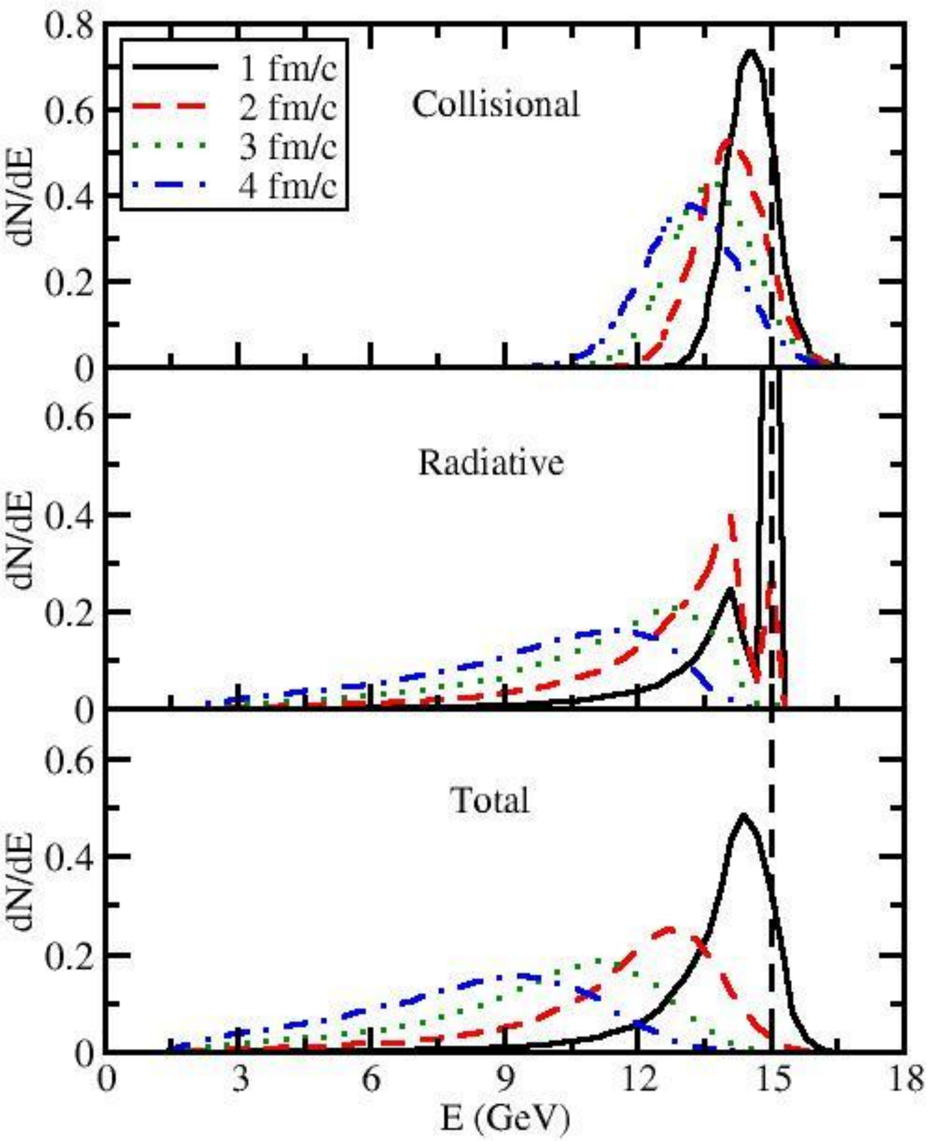
Thermal random force: $\langle \xi^i(t)\xi^j(t-n\Delta t)\rangle = \frac{\kappa}{\Delta t}\delta^{ij}\delta^{0n}$

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

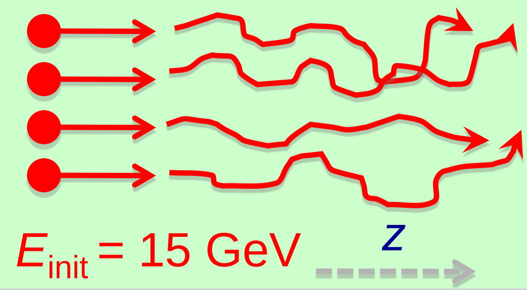
Lower cut for gluon radiation: *πT*

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

Charm Quark Evolution in Static Medium



T = 300 MeV, D=6/(2πT), i.e., qhat ~ 1.3 GeV^2/fm



Evolution of E distribution

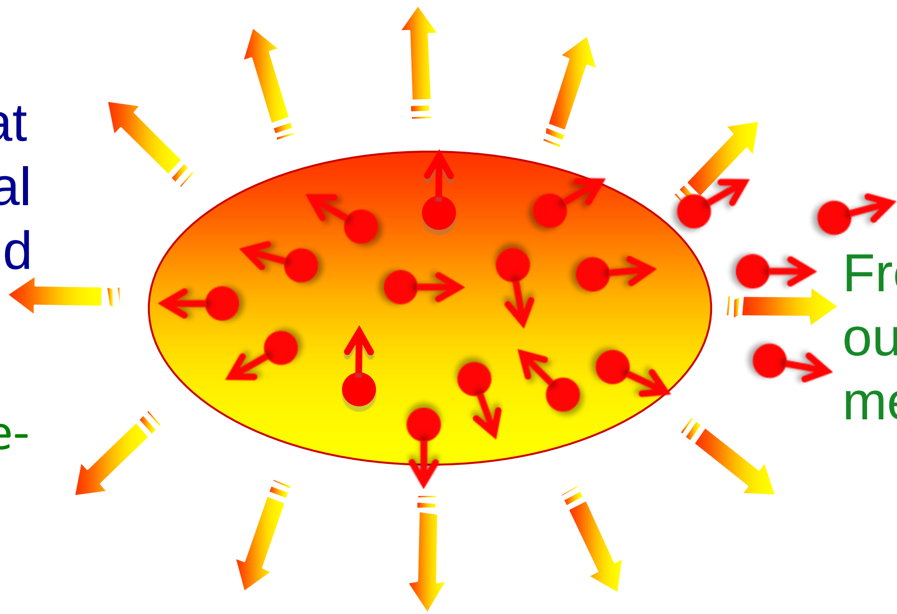
- Before 2 fm/c, collisional energy loss dominates; after 2 fm/c, radiative dominates;
- Collisional energy loss leads to Gaussian distribution, while radiative generates long tail.

Heavy Quark Evolution in LHC 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
- Fragmentation of HQ into heavy flavor mesons: PYTHIA 6.4

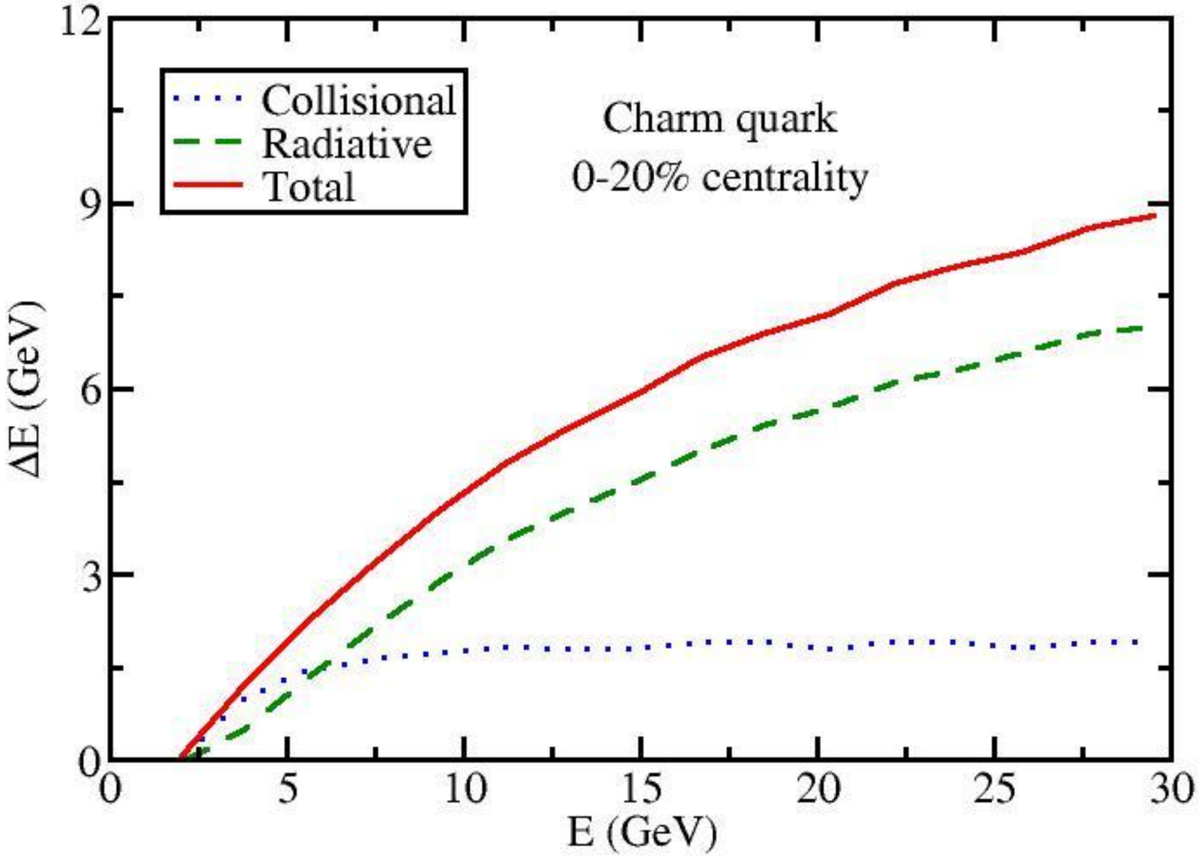
$D=6/(2\pi T)$, i.e., qhat ~ 3 GeV^2/fm at initial temperature (around 400 MeV)

After freeze-out: free-streaming



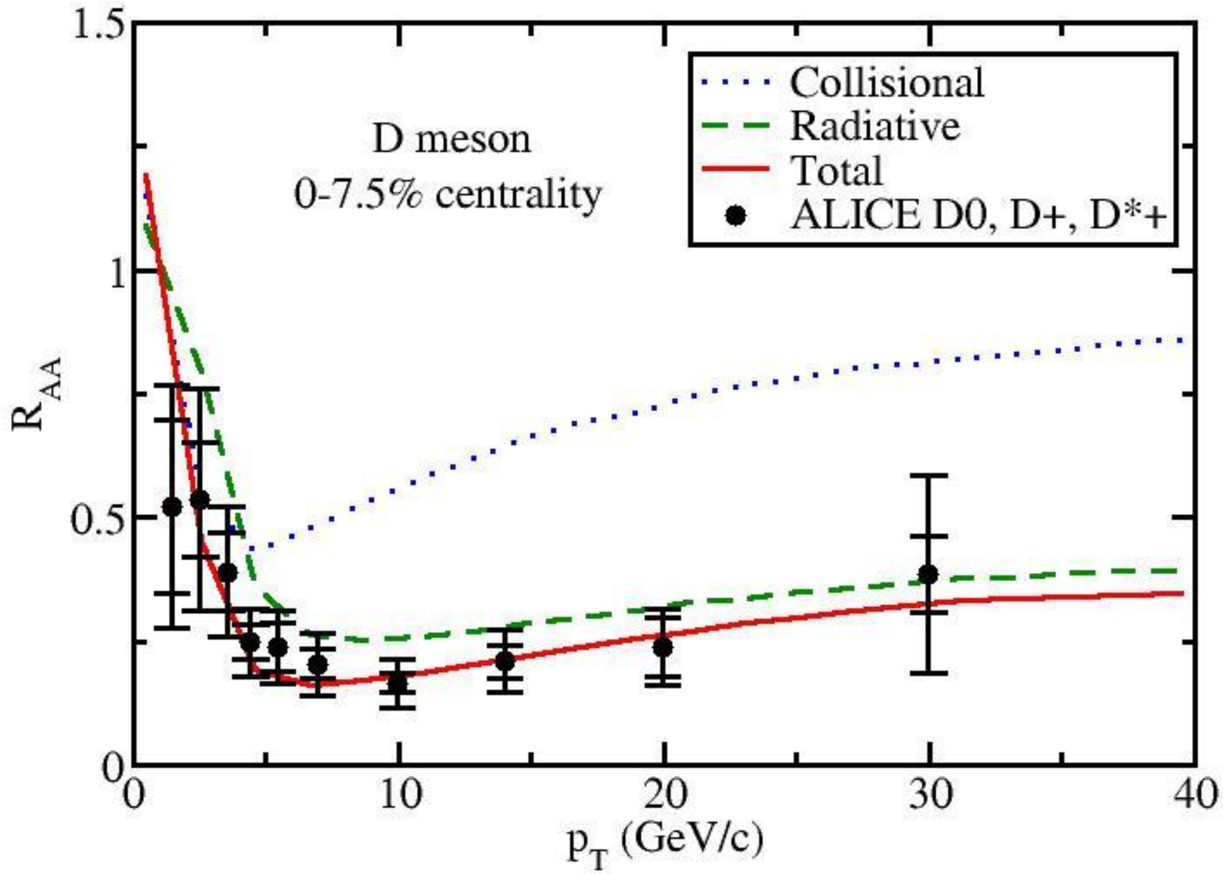
Free-streaming outside the medium

Heavy Quark Energy Loss



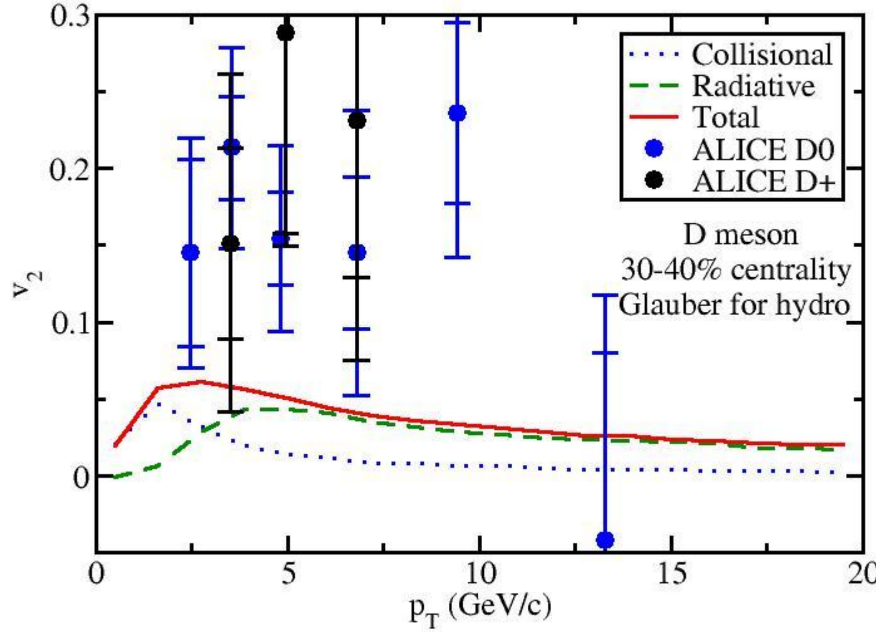
- Collisional energy loss dominates low energy region, while radiative dominates high energy region.
- Crossing point: around 6 GeV.

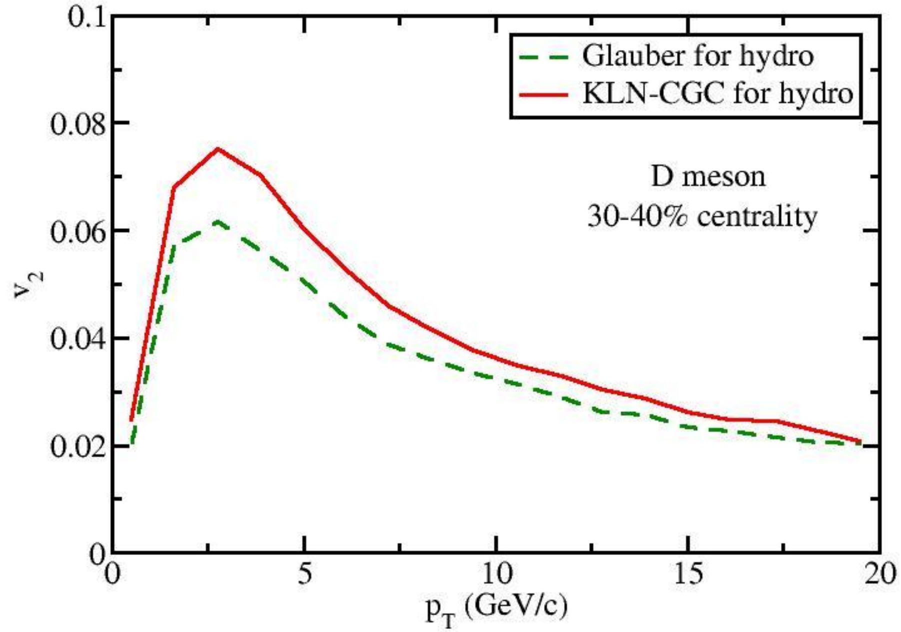
R_{AA} of D meson



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

v_2 of D meson





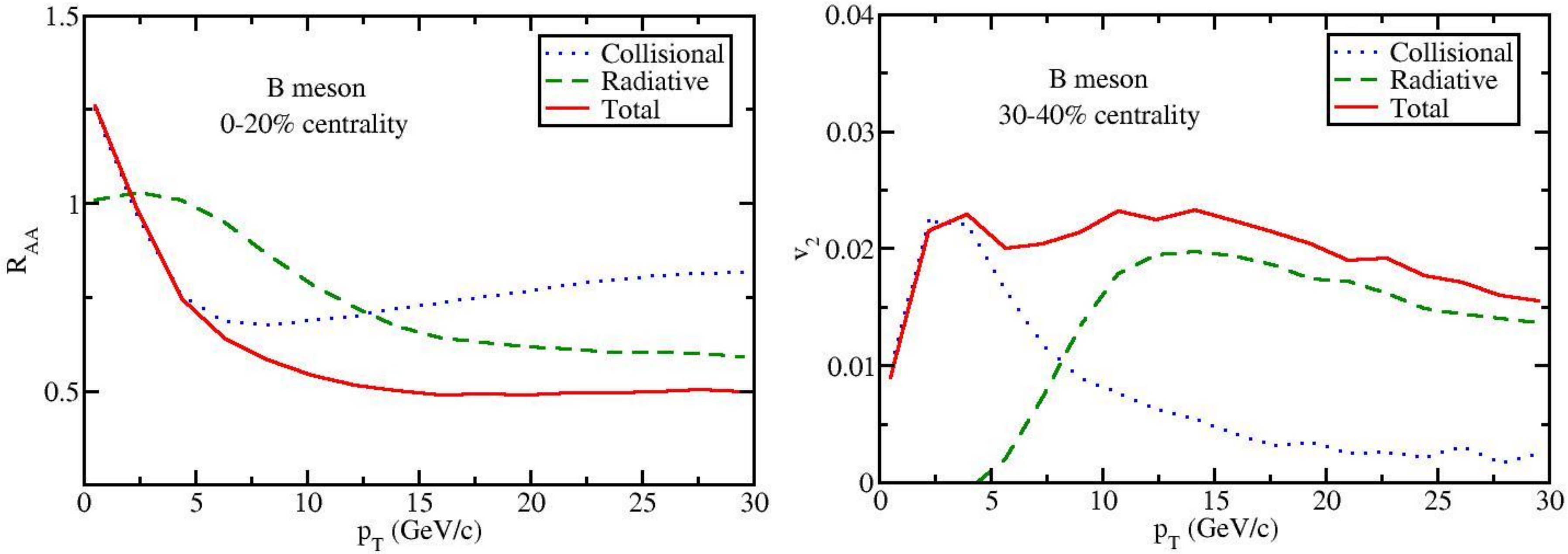
Similar trend of competition between the two energy loss mechanisms as revealed by R_{AA}

KLN provides larger eccentricity for the QGP profile than Glauber and therefore larger D meson v_2

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

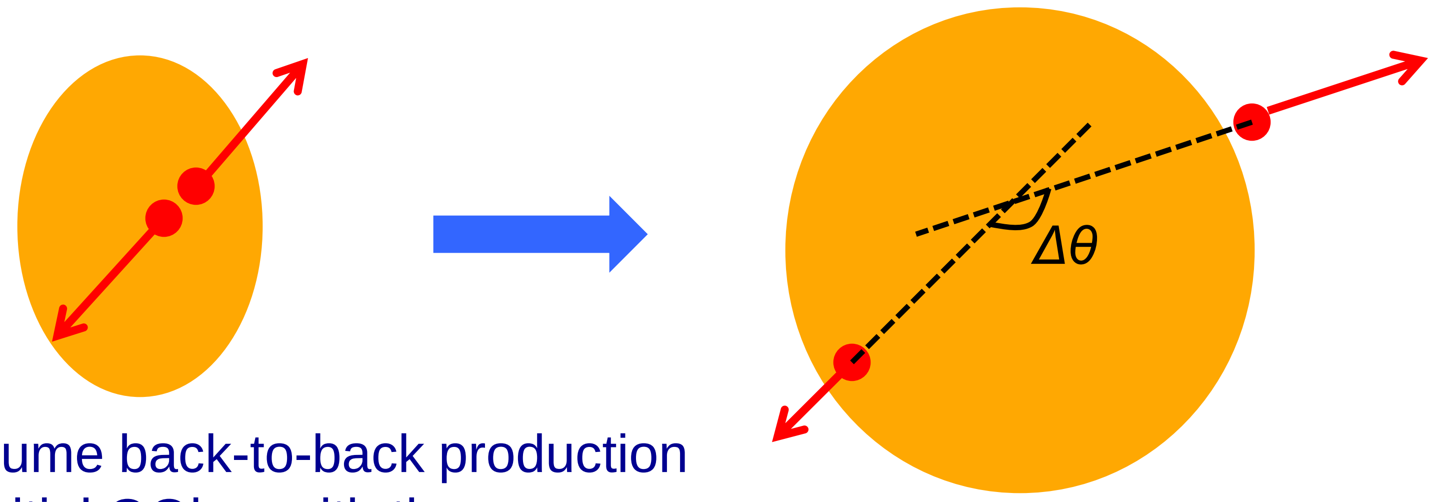
Influence of coalescence mechanism and hadronic interaction

Prediction for B Meson



- Similar behaviors as D meson – collisional energy loss dominates low p_T region, while radiative dominates high p_T.
- The crossing point is significantly higher because of the much larger mass of bottom quark than charm quark.
- B meson has larger R_{AA} and smaller v_2 than D meson.

Angular Correlation of QQbar

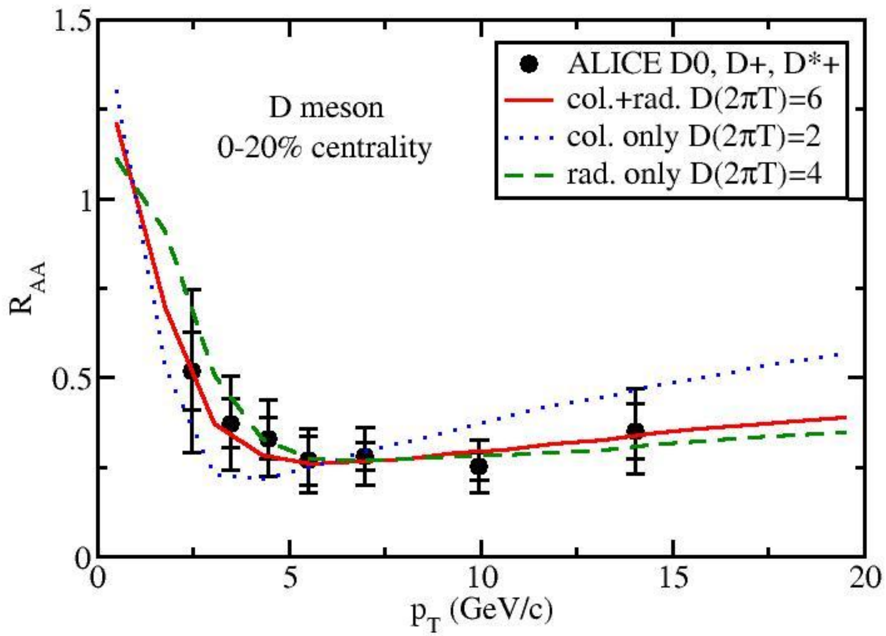


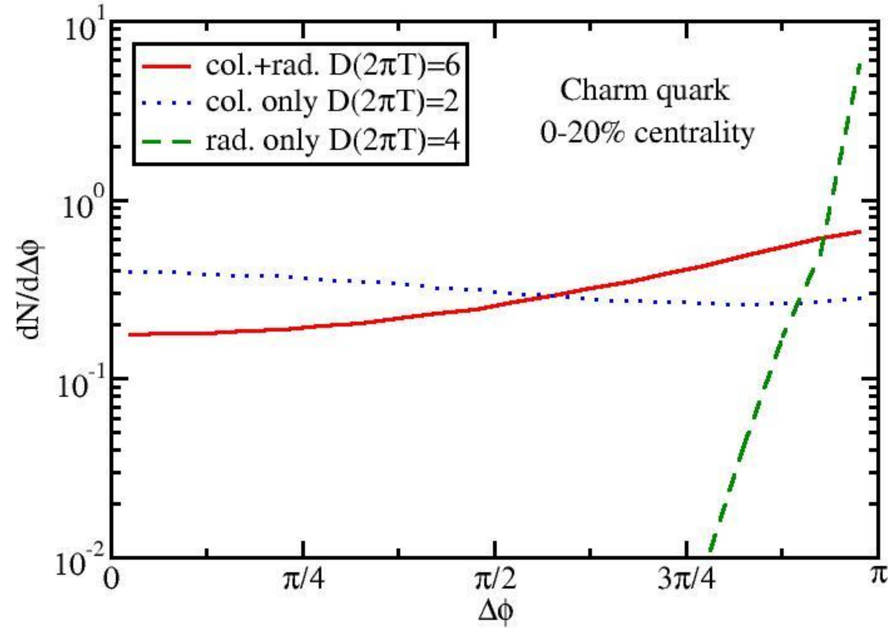
Assume back-to-back production of initial QQbar with the same magnitude of momentum

The angular correlation of the final state QQbar reveals:

- Momentum broadening of heavy quark
- How much do heavy quarks thermalize with the medium
- Coupling strength between heavy quark and QGP

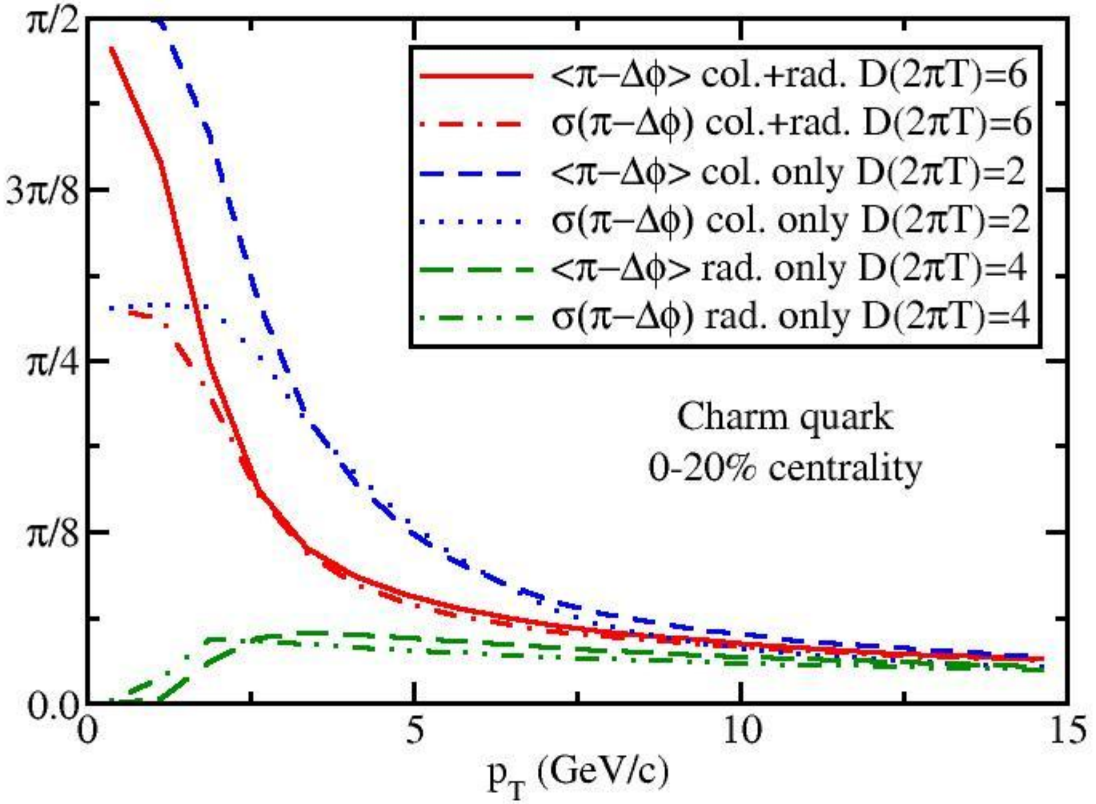
Angular De-correlation of CCbar

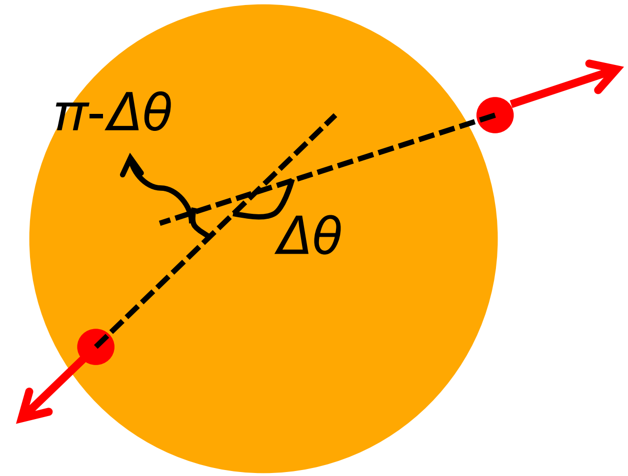




- Though each energy loss mechanism alone can fit R_{AA} with certain accuracy, they display very different behaviors of angular de-correlation.
- Experimental observations will help distinguish the energy loss mechanisms of heavy quark inside QGP.

p_T Dependence of Angular De-correlation





For the limit of uniform distribution between [0,π]:

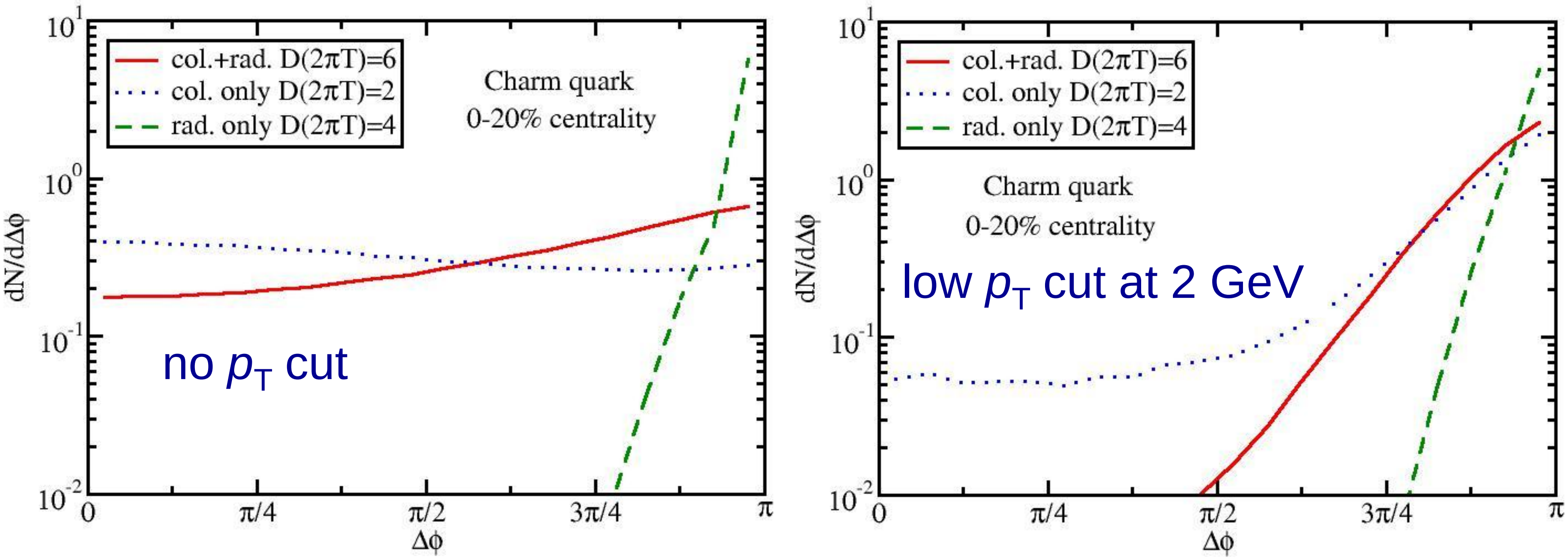
$$\langle \pi - \Delta\phi \rangle = \pi/2$$

$$\sigma(\pi - \Delta\phi) = \pi/2\sqrt{3}$$

- The de-correlation behavior strongly depends on HQ p_T.
- Collisional: charm quarks below 2 GeV are close to thermal, but above 2 GeV are off-equilibrium.
- Radiative: CCbar pair remains strongly correlated.

p_T Dependence of Angular De-correlation

Apply a 2 GeV p_T lower cut to the final state charm quarks:



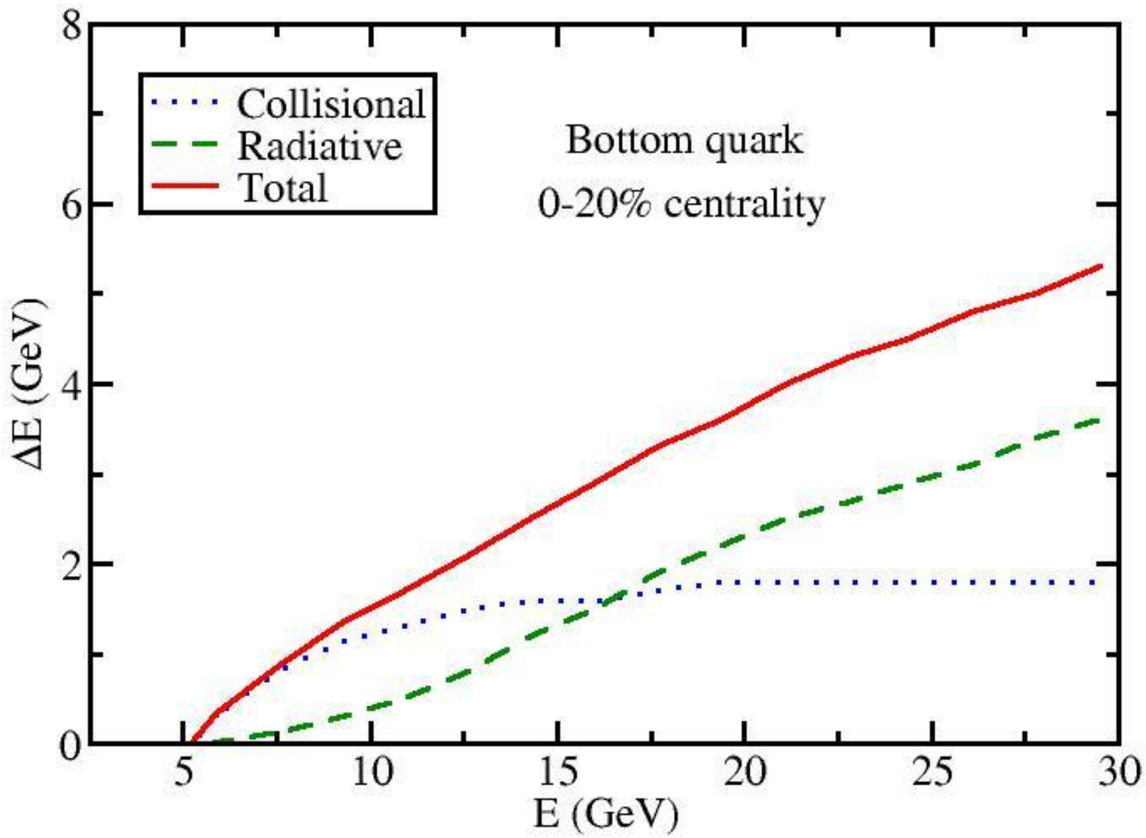
- The angular correlation function is sensitive to the p_T cut.
- The thermal pattern/de-correlation in the collisional energy loss scenario is contributed by the low p_T charm quarks.

Summary

- Study the heavy quark energy loss in hot and dense medium in the framework of the Langevin approach
- Improve the Langevin algorithm to incorporate radiative energy loss by treating gluon radiation as an extra force term
- Reveal the significant effect of radiative energy loss at the LHC energies and provide description of D meson suppression consistent with LHC data
- Propose a potential measurable quantity – QQbar pair correlation function – that may help distinguish the heavy quark energy loss mechanisms inside QGP

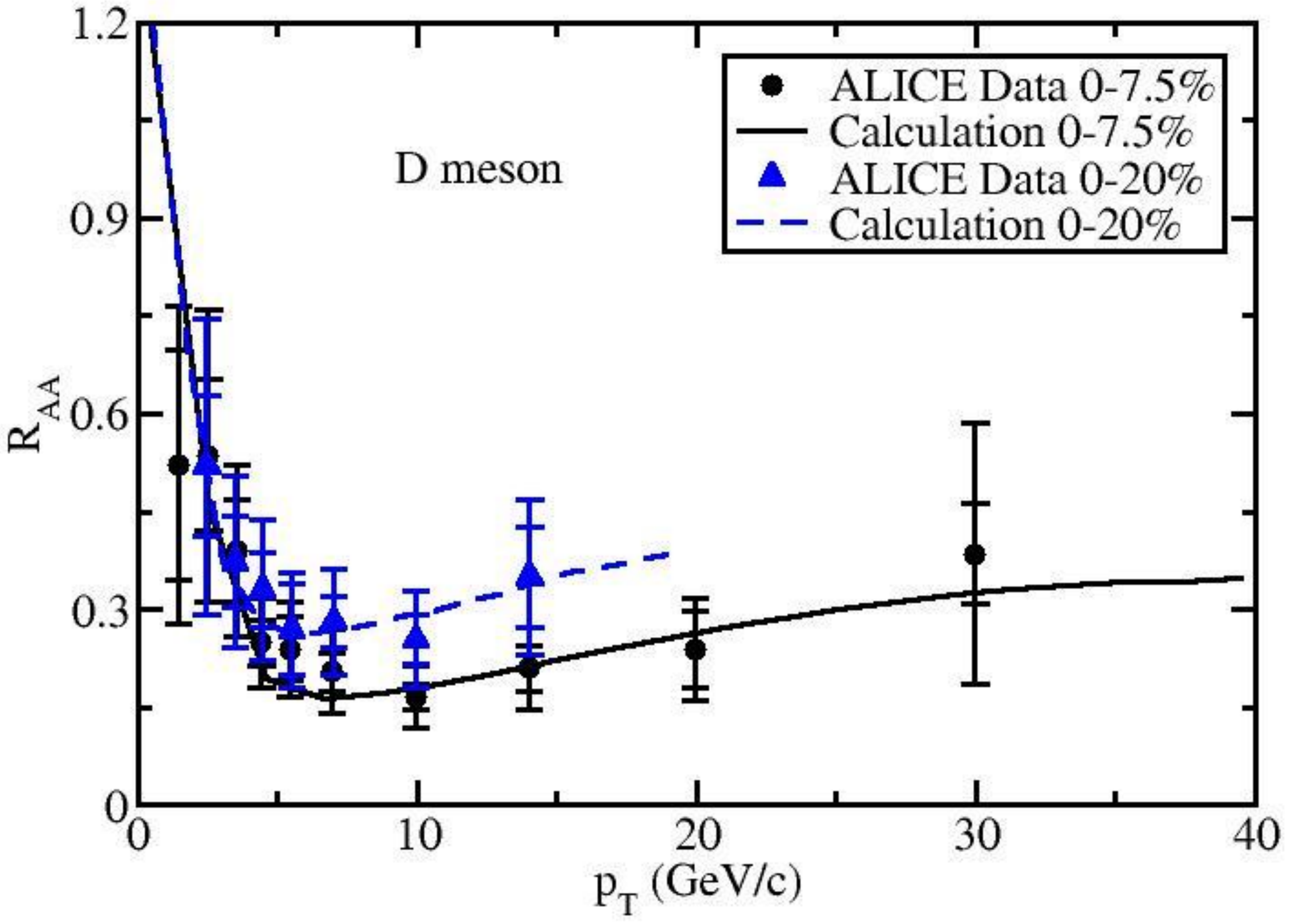
Thank you!

Backup: Bottom Quark Energy Loss



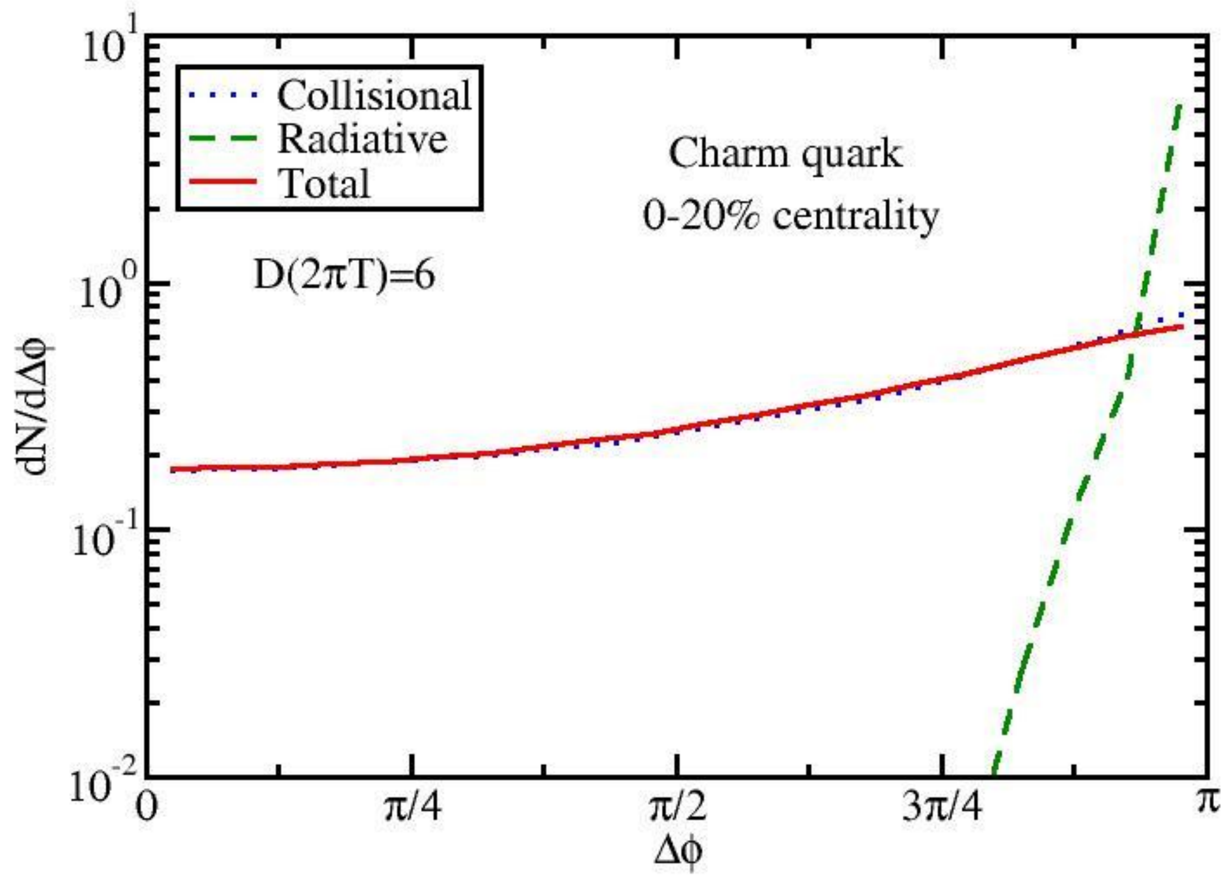
- Collisional energy loss dominates low energy region, while radiative dominates high energy region.
- Crossing point: around 17 GeV, much larger than charm quark because of heavier mass.

R_{AA} of D meson



Consistency between our calculation and the latest ALICE data from Quark Matter 2012

Angle De-correlation of Charm Quark



- The angle de-correlation of ccbar is majorly contributed by the collisional energy loss.
- Charm quarks do not entirely thermalize with QGP.

Outlook

We will further study:

- Anomalous transport of heavy quark in the pre-equilibrium stage after heavy-ion collisions
- Interaction between heavy mesons and hadron gas after QGP hadronizes
- Recombination mechanism of heavy flavor hadronization