Heavy Flavor Dynamics in Relativistic Heavy-ion Collisions

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Outline

- Introduction
- Heavy flavor dynamics in QGP and Hadron Gas

  Initial production: Glauber + pQCD;

  In-medium evolution: an improved Langevin approach (col. + rad.)

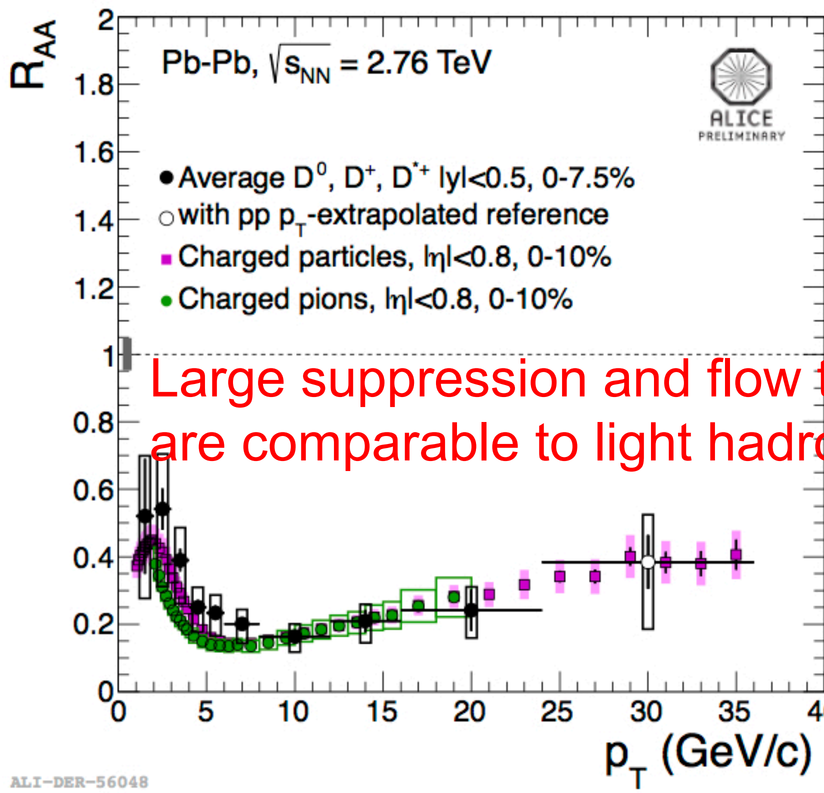
  Hadronization: a hybrid frag. + coal. model

  Hadronic interaction: the UrQMD model

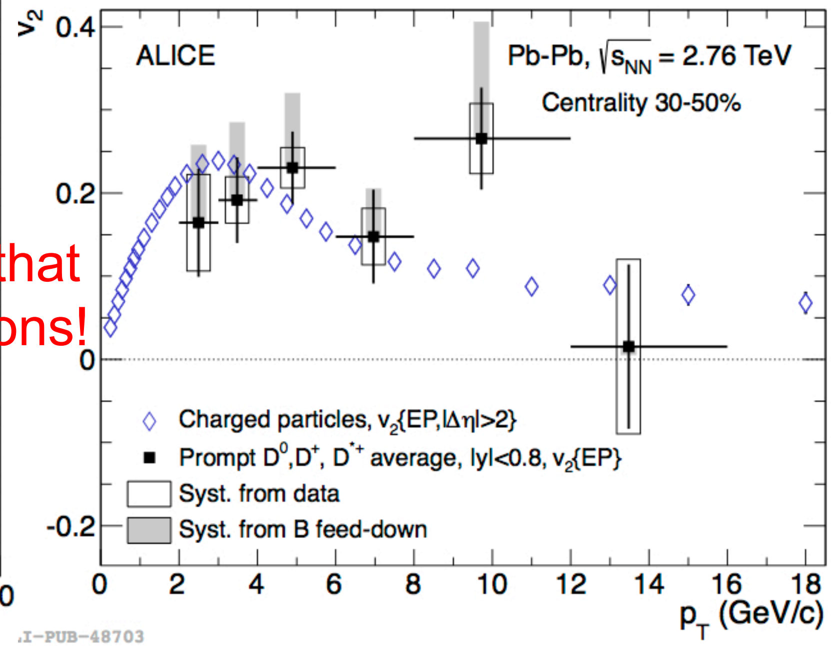
- Heavy flavor suppression and flow (comparison with LHC/RHIC data)
- Angular correlation function of Heavy Flavor
- Summary

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 → supposed to be influenced less by the medium



(Hard Probes 2013)



Large suppression and flow that are comparable to light hadrons!

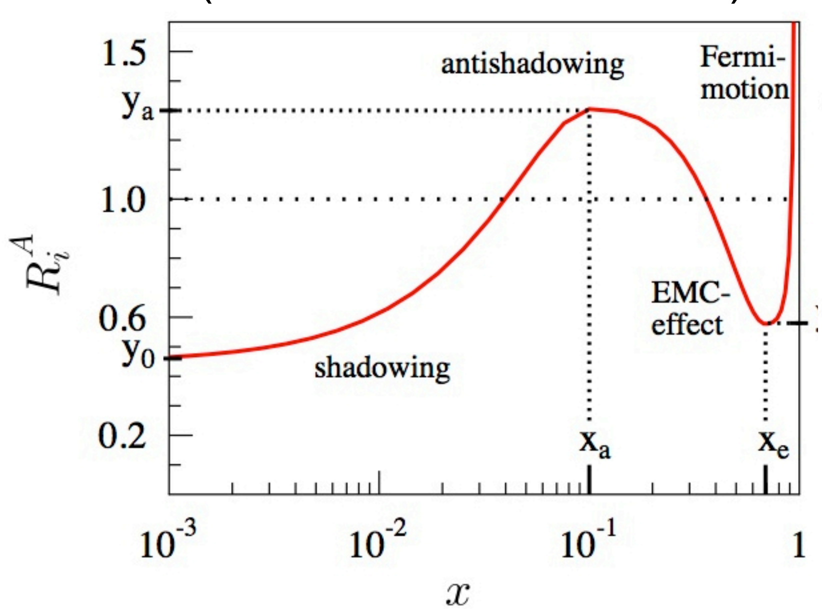
"Heavy flavor puzzle": is $\Delta E_g > \Delta E_q > \Delta E_c > \Delta E_b$ still right?

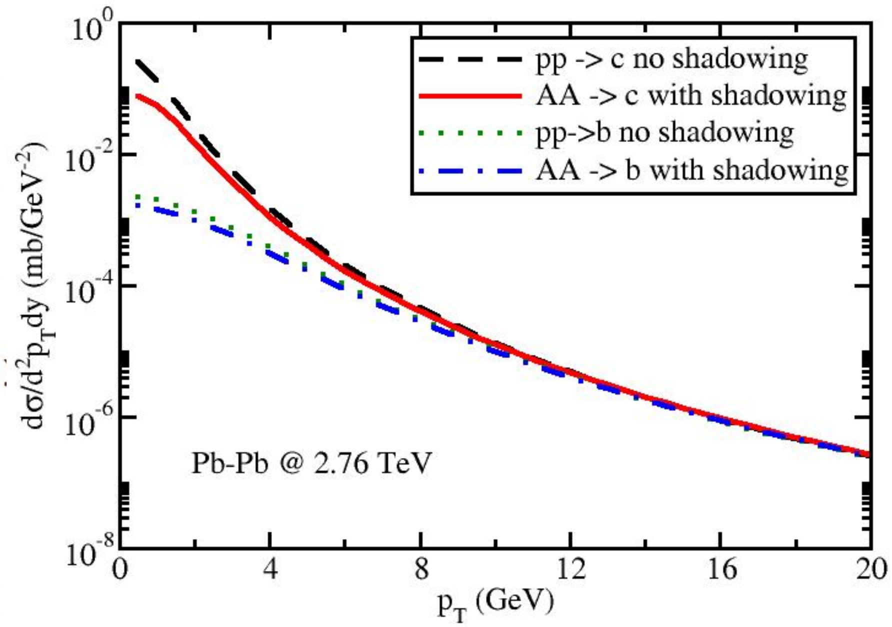
Challenge: fully understand heavy flavor dynamics – whole evolution

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)



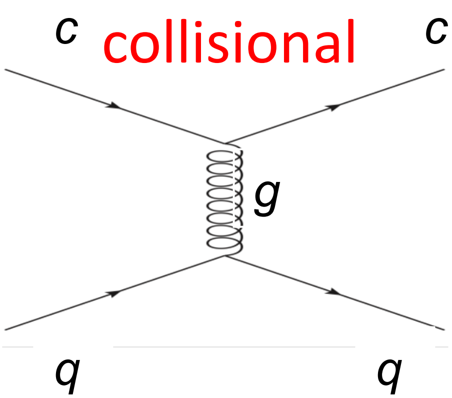


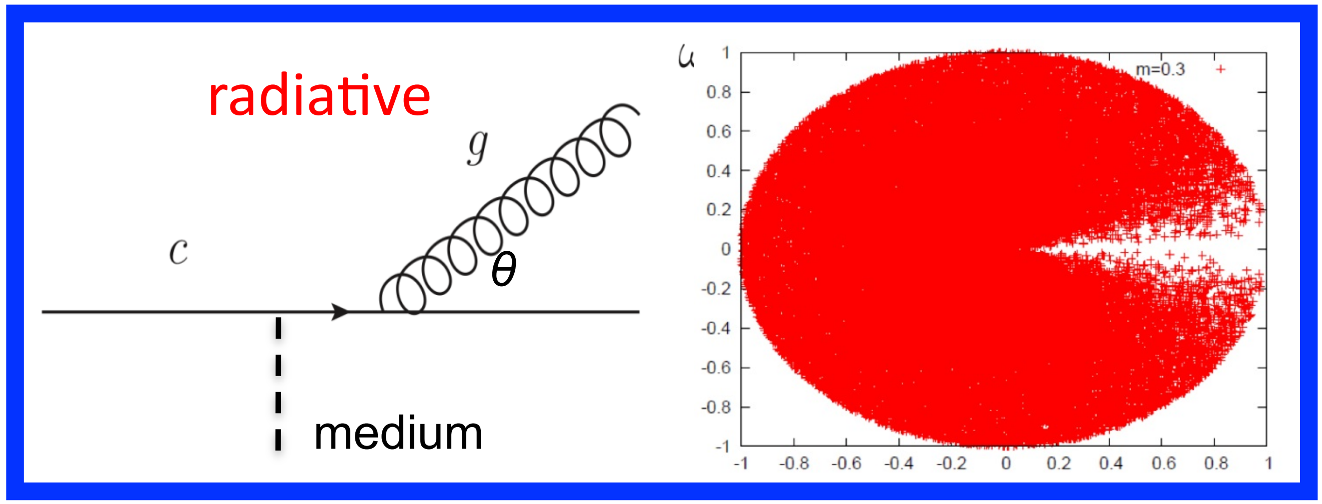
Significant shadowing effect for heavy quark production at low p_T (especially at the LHC energy) → impact on R_{AA}

Energy Loss Mechanisms

Two ways for heavy quarks to lose energy:

Abir et al. PLB 715 183





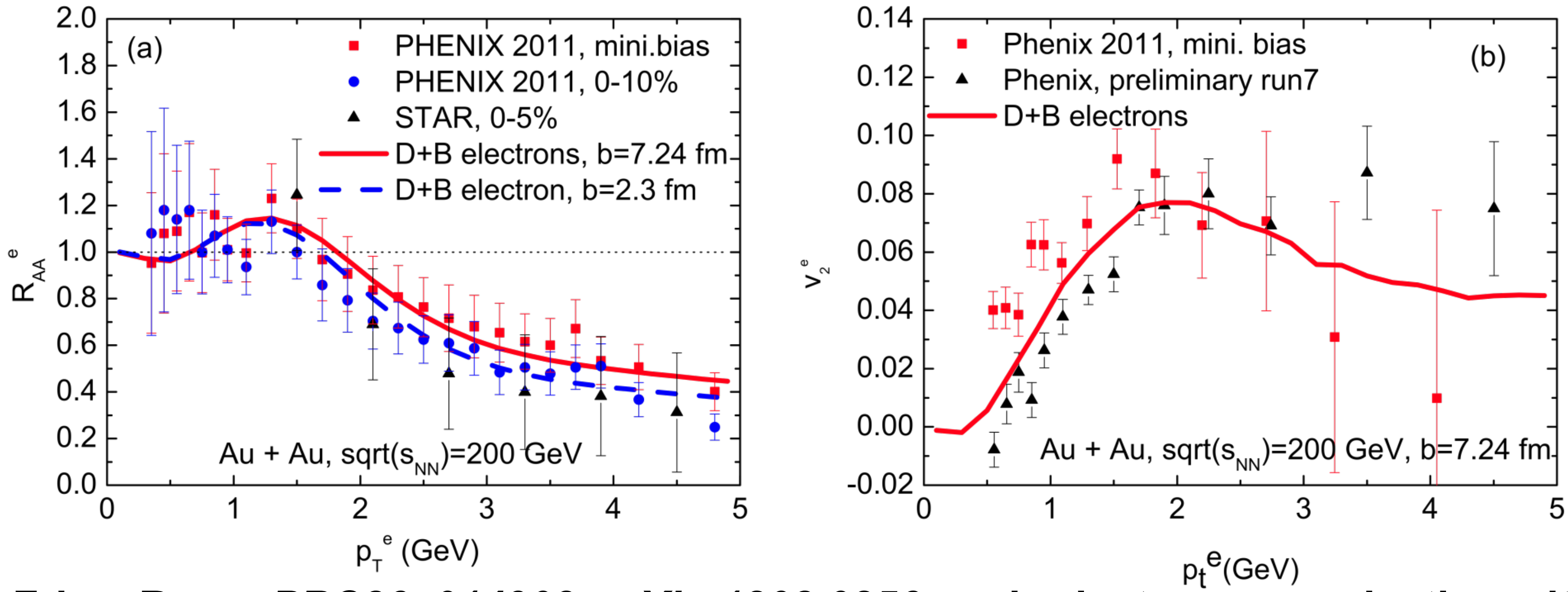
"Dead cone effect": Unless in an ultrarelativistic limit, gluon radiation is suppressed by the large mass of heavy quark
→ consider collisional energy loss as the dominant factor

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

Going from RHIC to LHC?

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

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: $\eta_D(p) = \frac{\kappa}{2TE}$ $\quad \langle \xi^i(t)\xi^j(t')\rangle = \kappa\delta^{ij}\delta(t-t')$

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

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

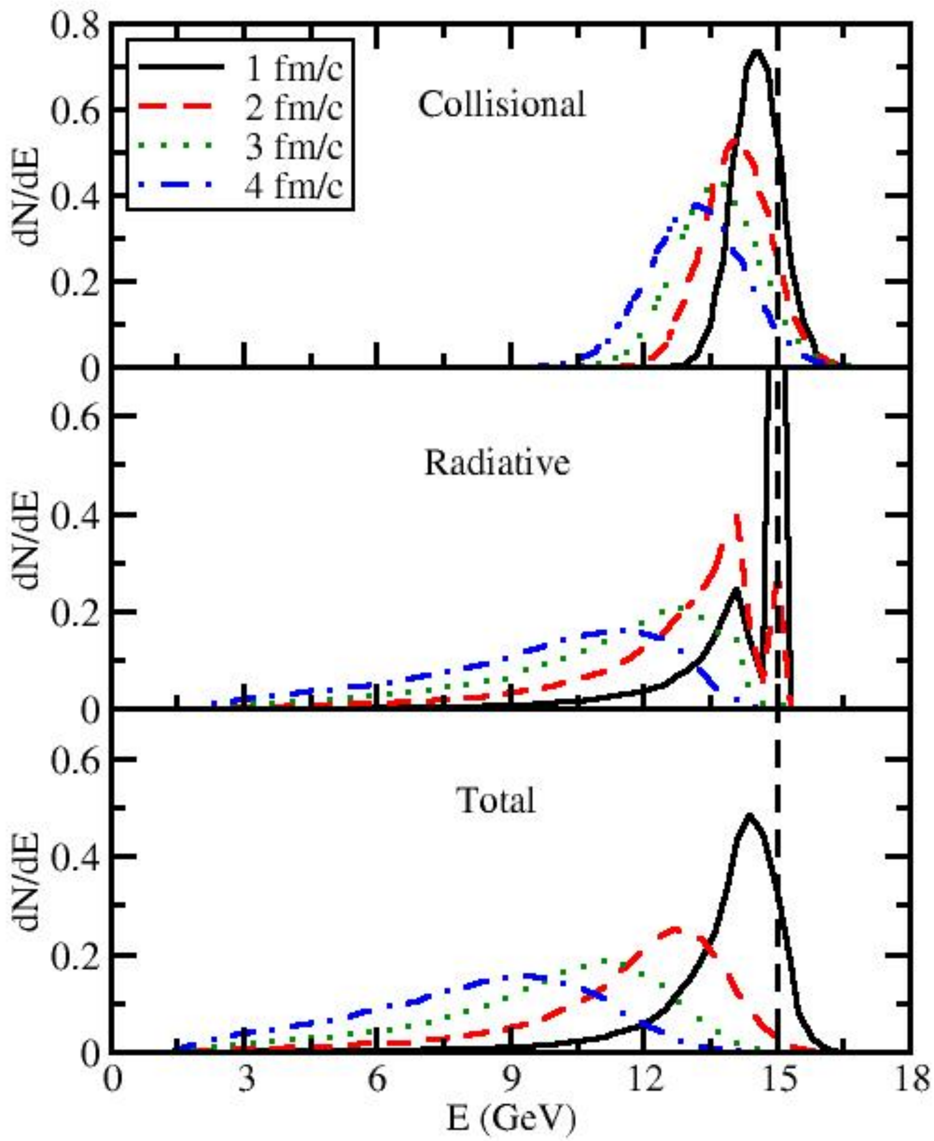
Thermal random force: $\langle \xi^i(t)\xi^j(t-n\Delta t)\rangle = \frac{\kappa}{\Delta t}\delta^{ij}\delta^{0n}$

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

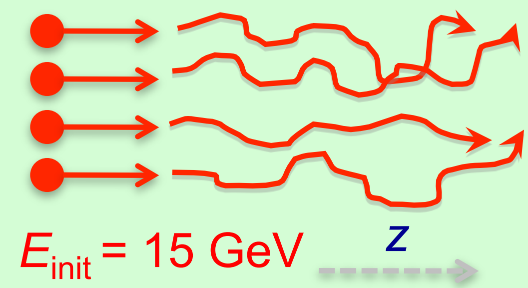
Lower cut for gluon radiation: *πT*

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

Charm Quark Evolution in Static Medium



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



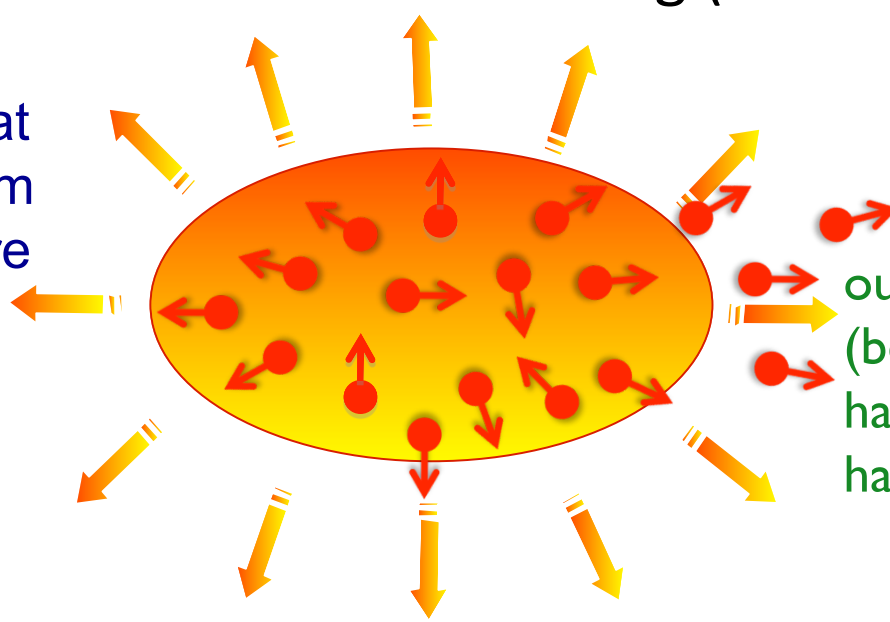
Evolution of E distribution

- 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.

Charm Quark Evolution inside the 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 and hadronic scattering (discuss later)

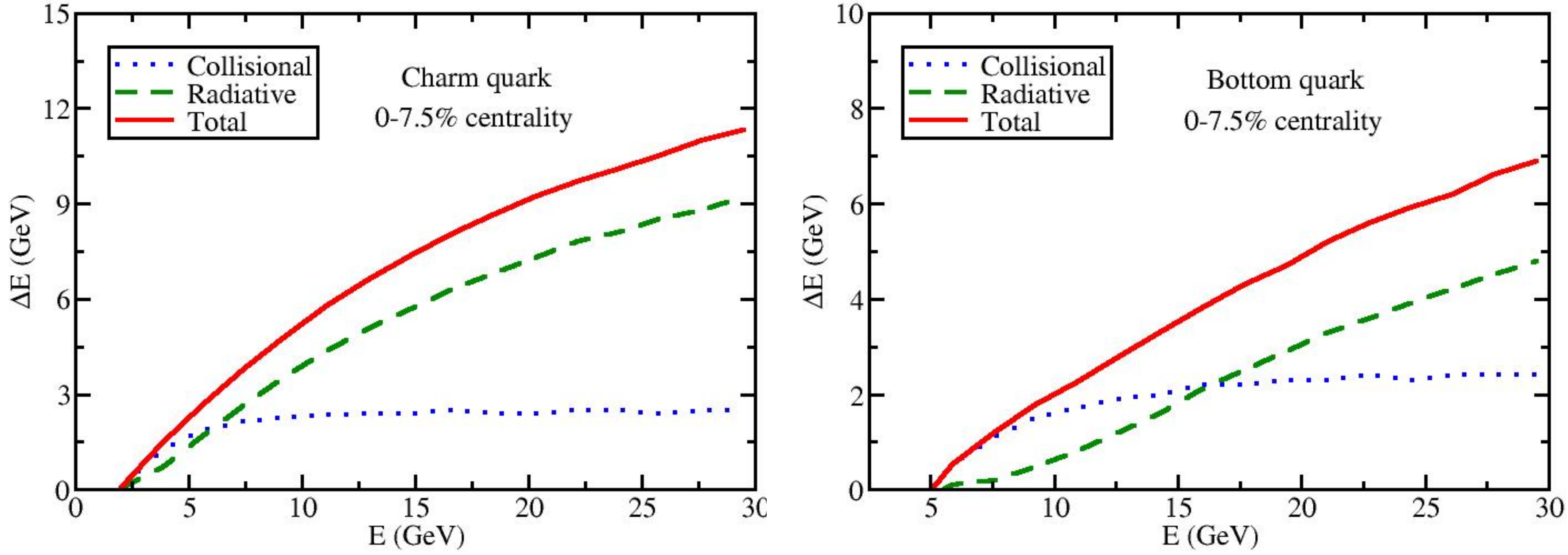
$D=6/(2\pi T)$, i.e., qhat around 2~3 GeV^2/fm at initial temperature (around 350~400 MeV)



outside the medium (below T_c) hadronize and hadronic scattering

Heavy Quark Energy Loss

(SC, Qin and Bass, PRC 88 (2013) 044907)



- Collisional energy loss dominates low energy region, while radiative dominates high energy region.
- Crossing point: 6 GeV for *c* and 16 GeV for *b* quark.
- ➔ Collisional energy loss alone may work well to describe previous RHIC data but is insufficient for LHC.

Hadronization

QGP: Cooper-Frye Freeze-out (OSU iSS)

$$E\frac{dN}{d^3p} = \int_\sigma f(x,p)p^\mu d\sigma_\mu$$

- $f(x,p)$: thermal distribution of soft hadrons
- σ : hypersurface of freeze-out

HQ: 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 instantaneous coalescence model (Oh, 2009)

The Instantaneous Coalescence 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: 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

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

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

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

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

The Instantaneous Coalescence 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

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

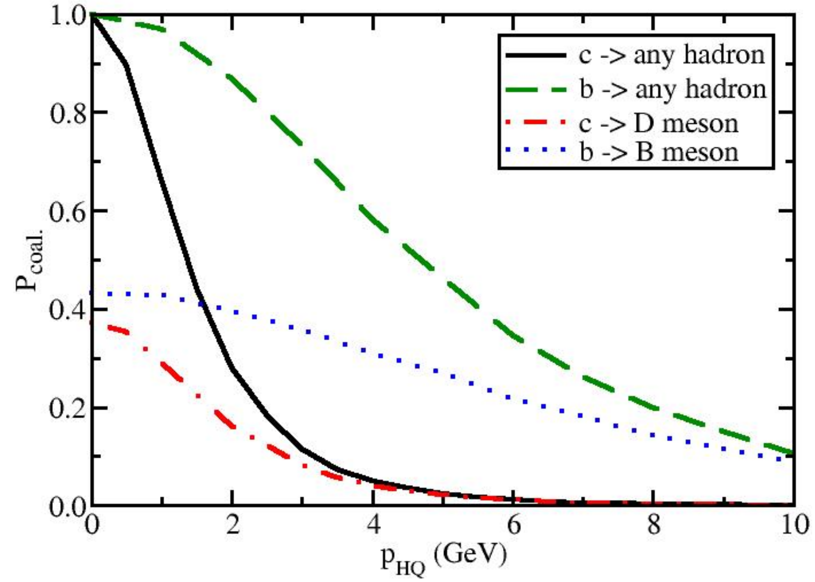
μ: reduced mass of the 2-particle system

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)

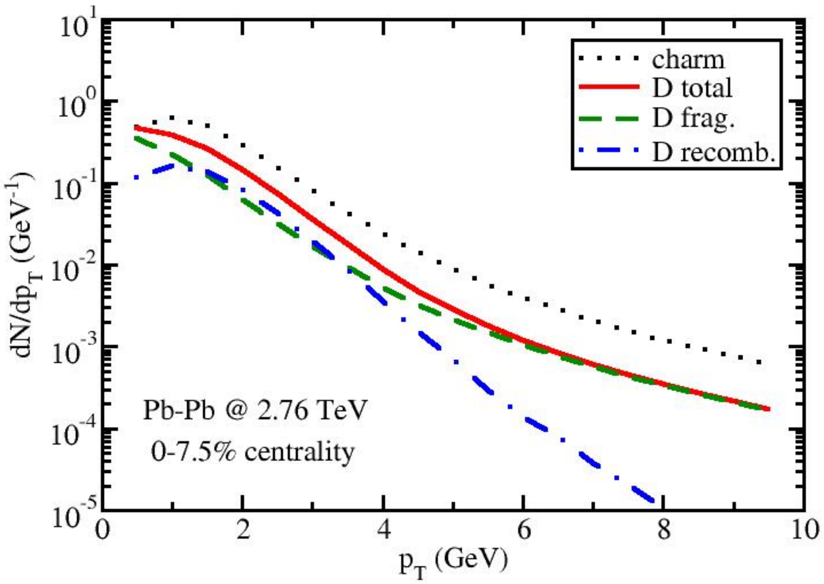
The Hybrid Coal. + Frag. Model



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.

Hadronic Interactions

Soft hadrons from QGP

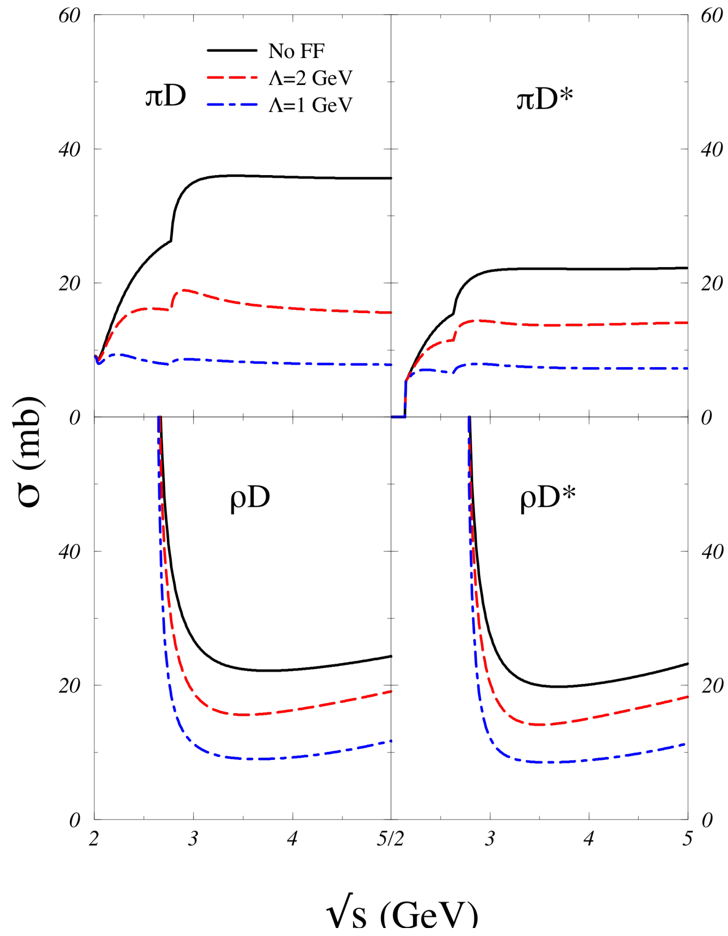
Heavy mesons from heavy quarks

} UrQMD

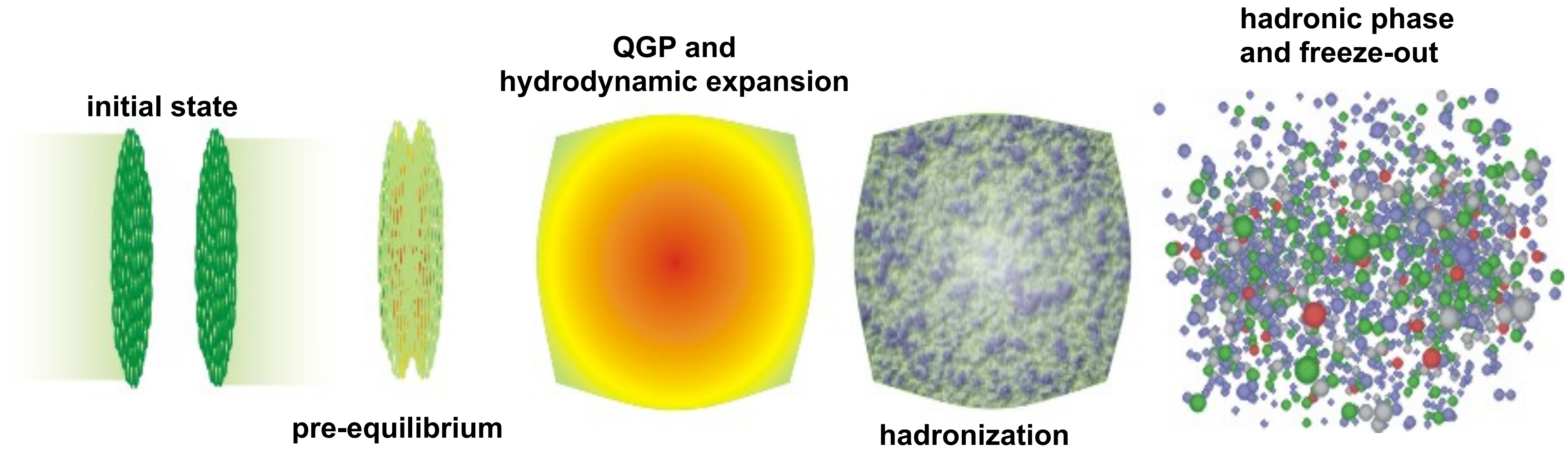
Charm Meson Scattering Cross Sections:
(Lin and Ko, 2001)

Consider scatterings with
π and *ρ* mesons

Λ: cutoff parameter in hadron form factors

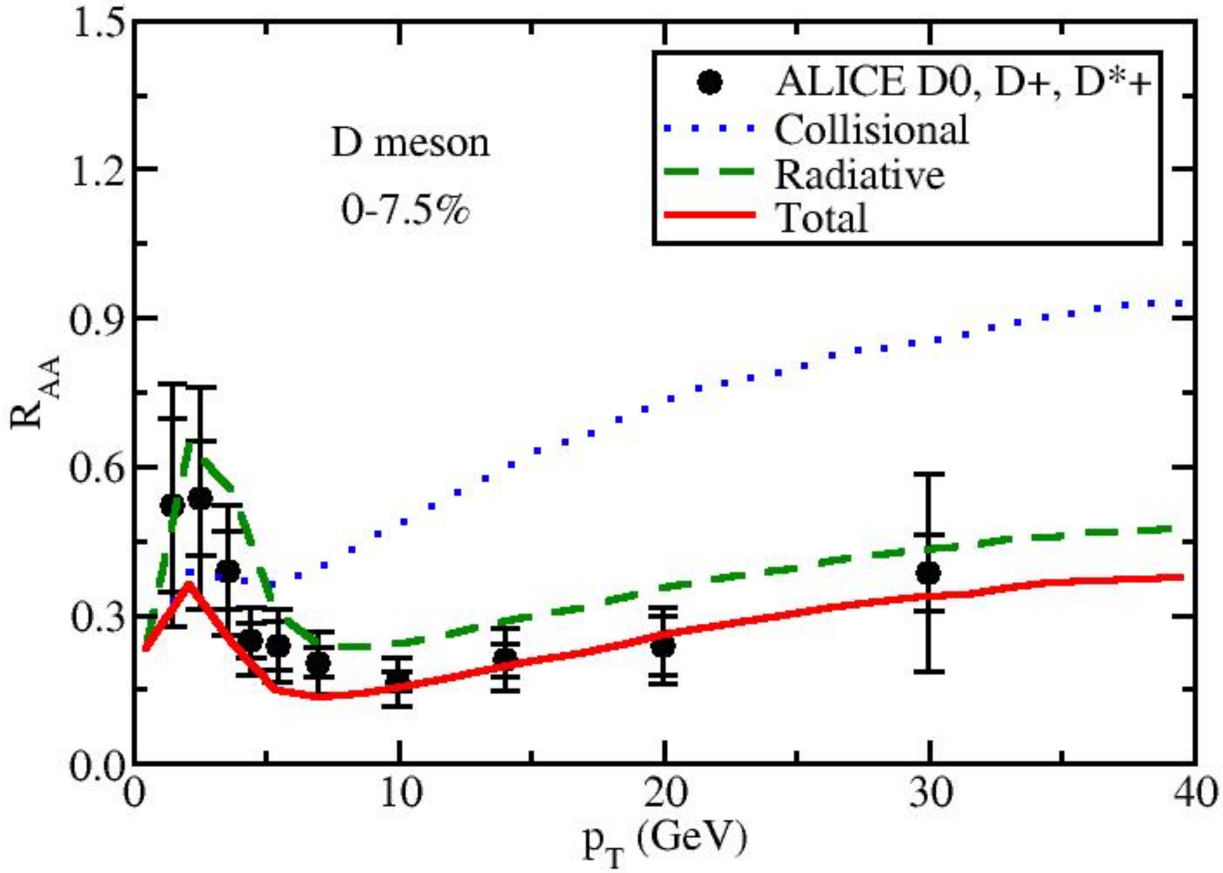


Interim Summary of HF Dynamics



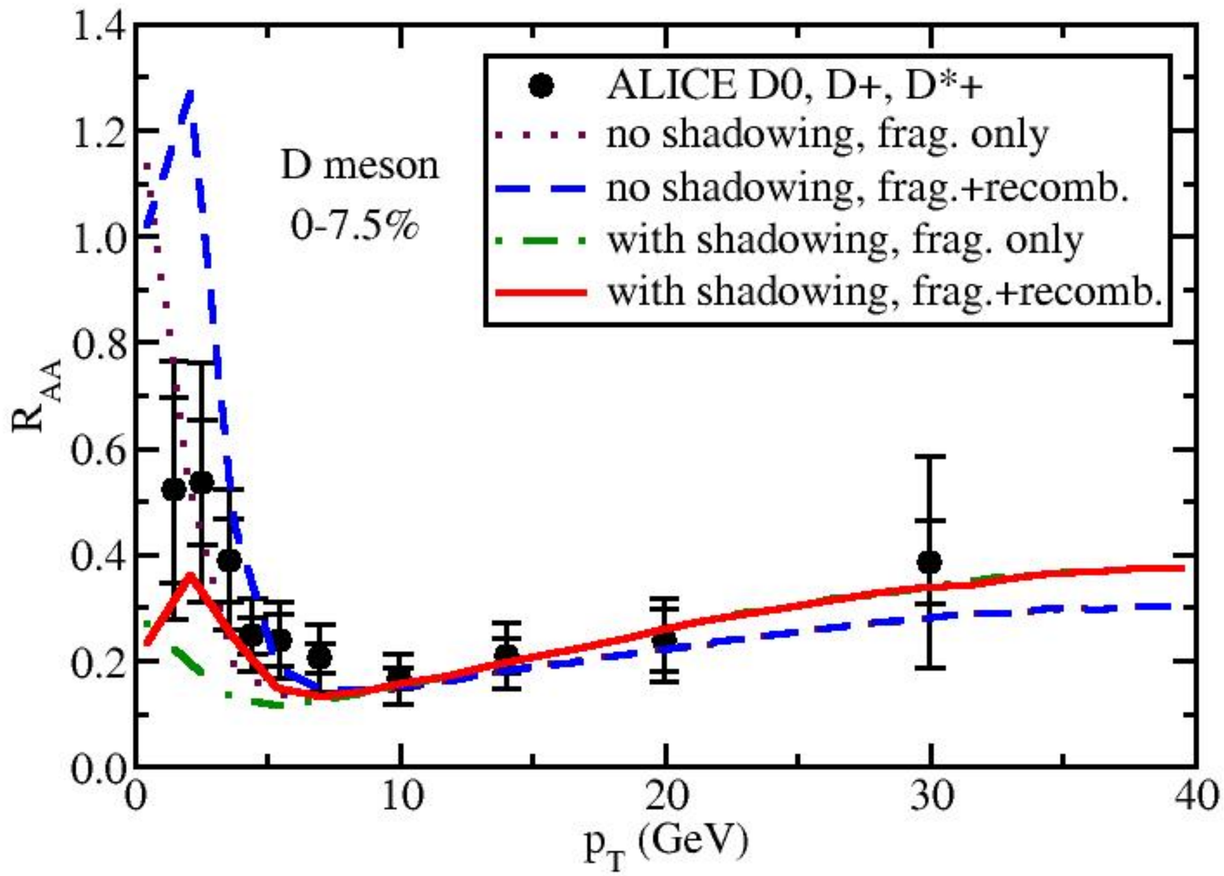
Bulk Matter:	Glb/KLN initial condition	(2+1)-d viscous hydro (OSU)	Cooper-Frye (OSU iSS)	UrQMD
Heavy Flavor:	Glauber for *x* LOpQCD+CTEQ +EPS09 for *p*	Improved Langevin col.+rad.	Hybrid model of frag.+coal.	UrQMD

R_{AA} of LHC *D* meson



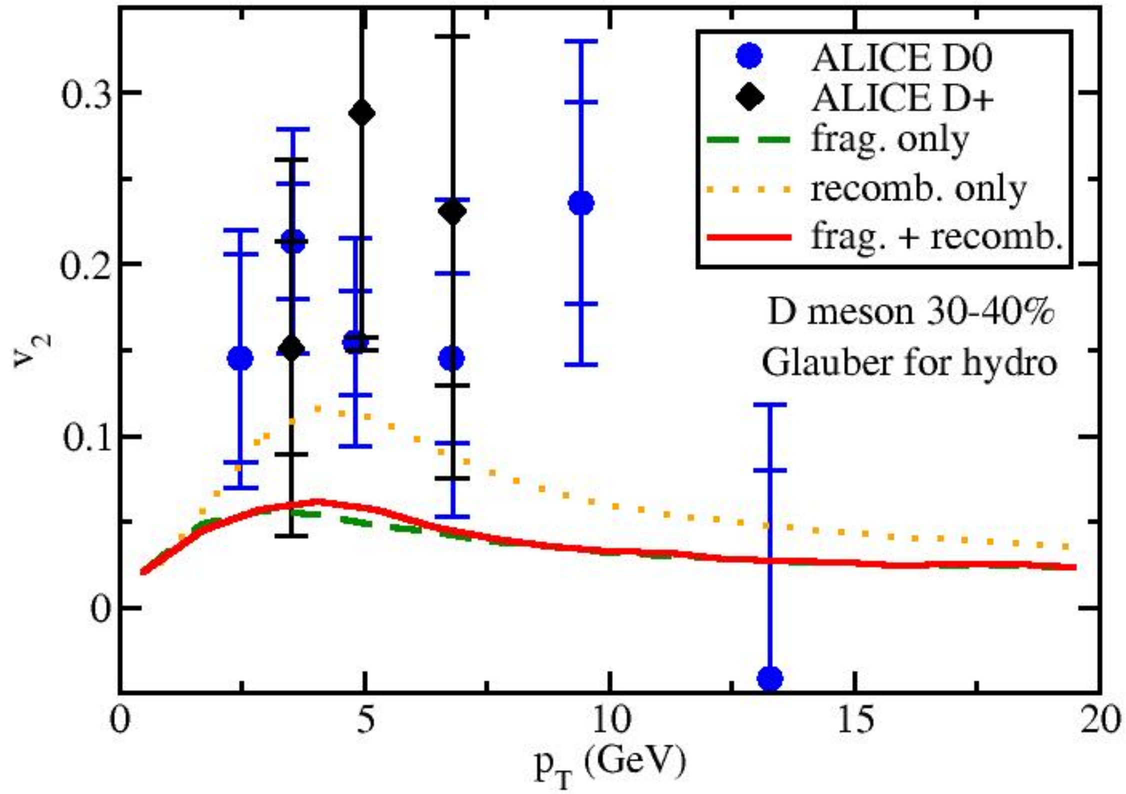
- Collisional dominates low p_T, radiative dominates high p_T.
- The combination of the two mechanisms provides a good description of experimental data.

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

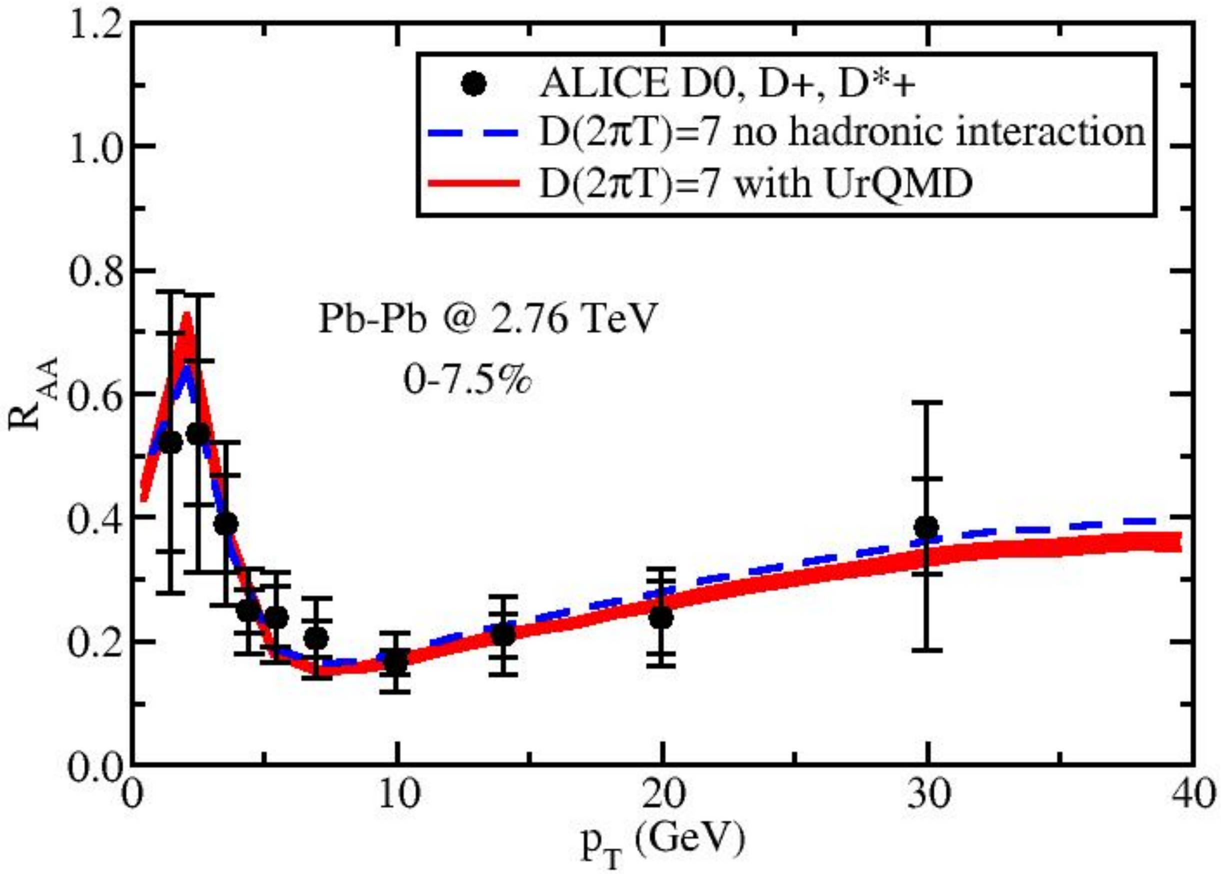


frag. only: force fragmentation, i.e., $f^W(q)$=0 for any q.

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

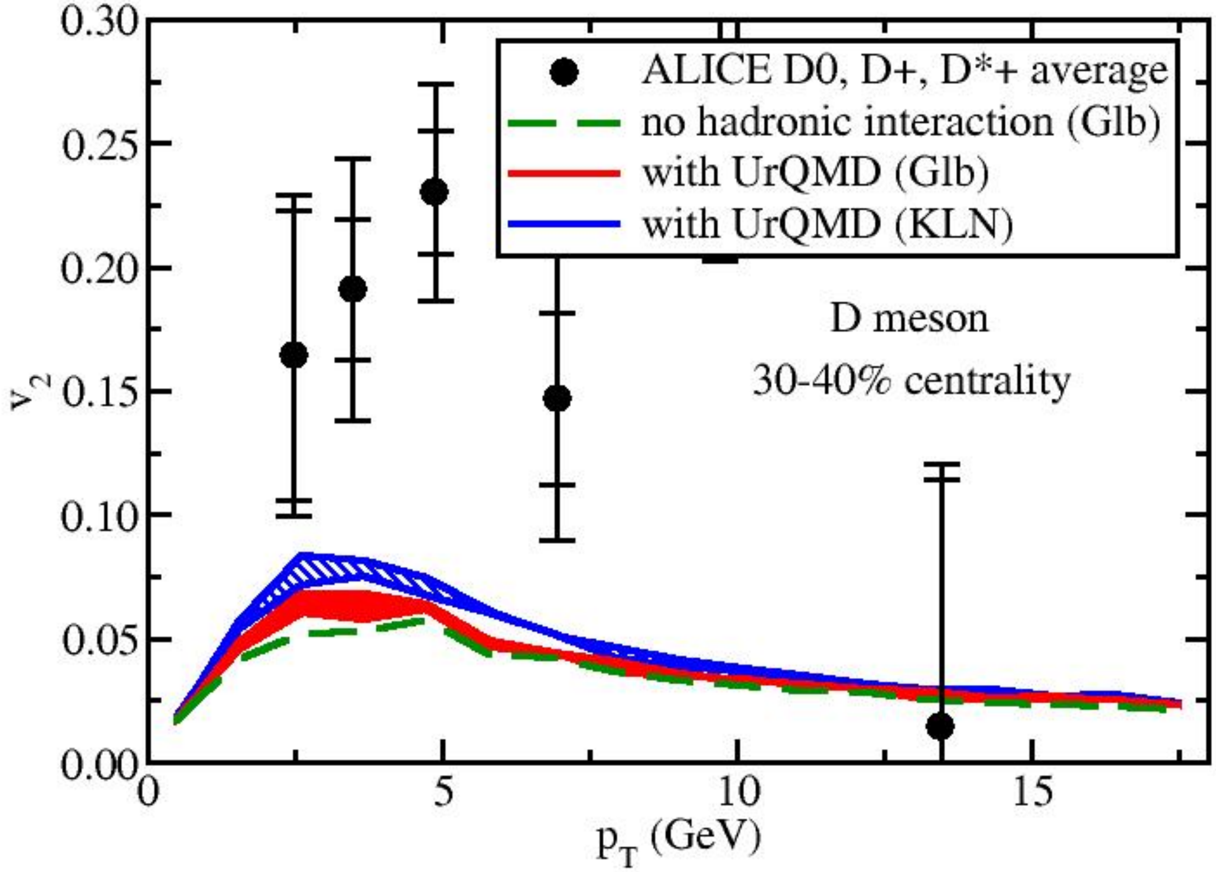
Recombination mechanism provides larger v_2 than fragmentation. However, due to the momentum dependence of the Wigner function, our combined mechanism only slightly raises the *D* v_2 at medium p_T.

R_{AA} of LHC *D* meson



- Hadronic interaction further suppresses R_{AA} at large p_T but slightly enhances it at low p_T
- Good description of the experimental data

v_2 of LHC *D* meson

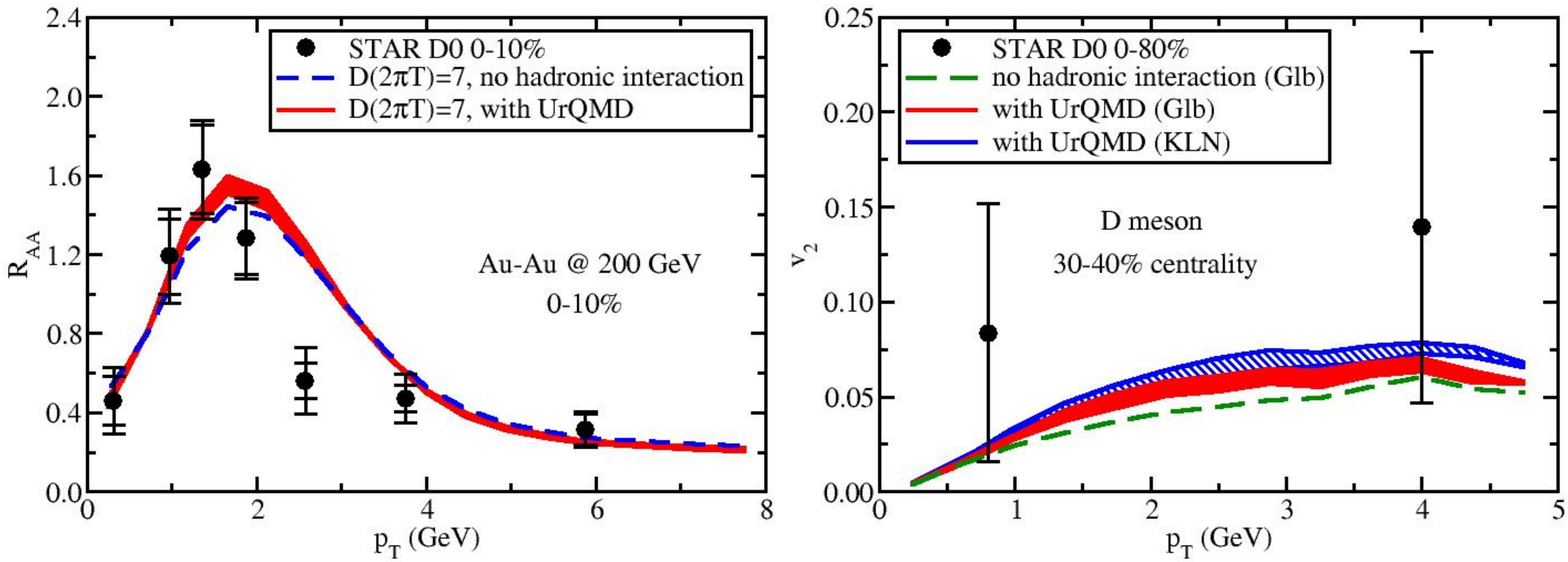


Hadronic interaction enhances *D* meson v_2 by over 30%

Difference between the Glb to KLN initial condition for hydro leads to another 30% uncertainties in *D* meson v_2

Still under-estimate *D* meson v_2 as measured by ALICE

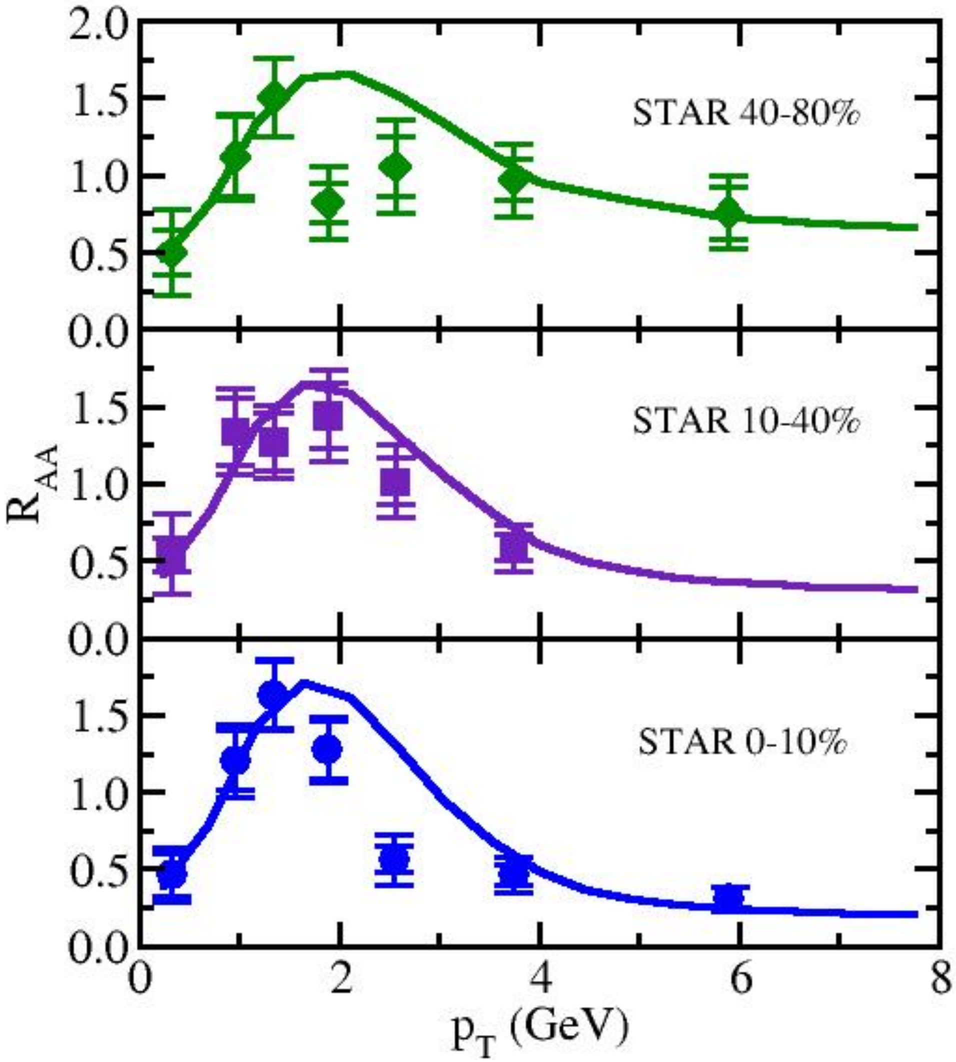
R_{AA} and v_2 of RHIC *D* Meson

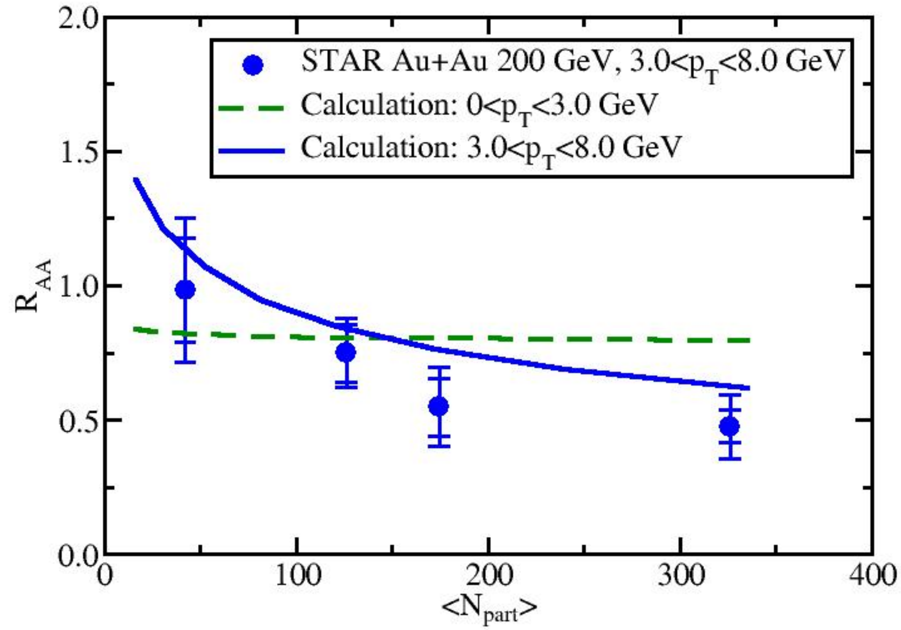


Hadronic interaction suppresses R_{AA} at large p_T and enhances v_2

Our calculations are consistent with the RHIC data

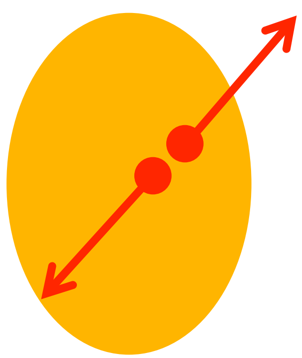
More R_{AA} results for RHIC

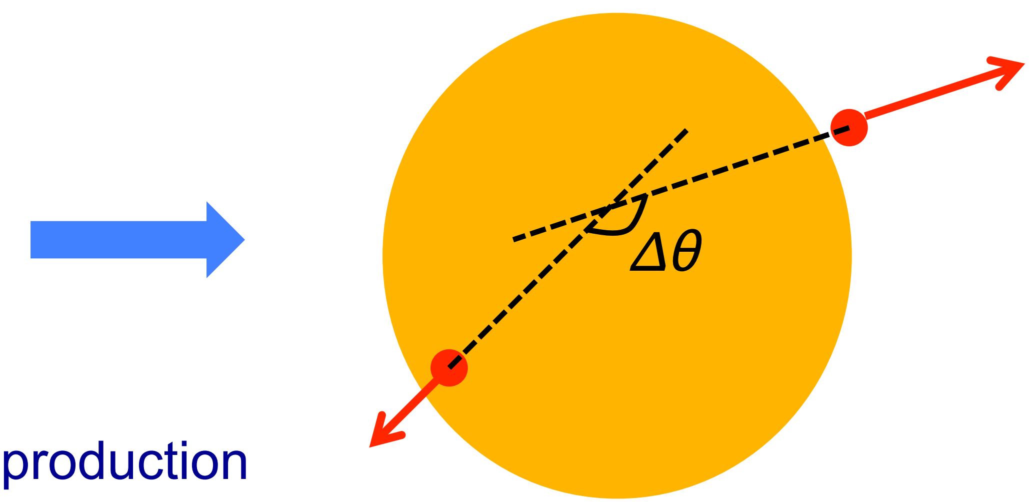




Centrality and participant number dependence are also consistent with RHIC observations.

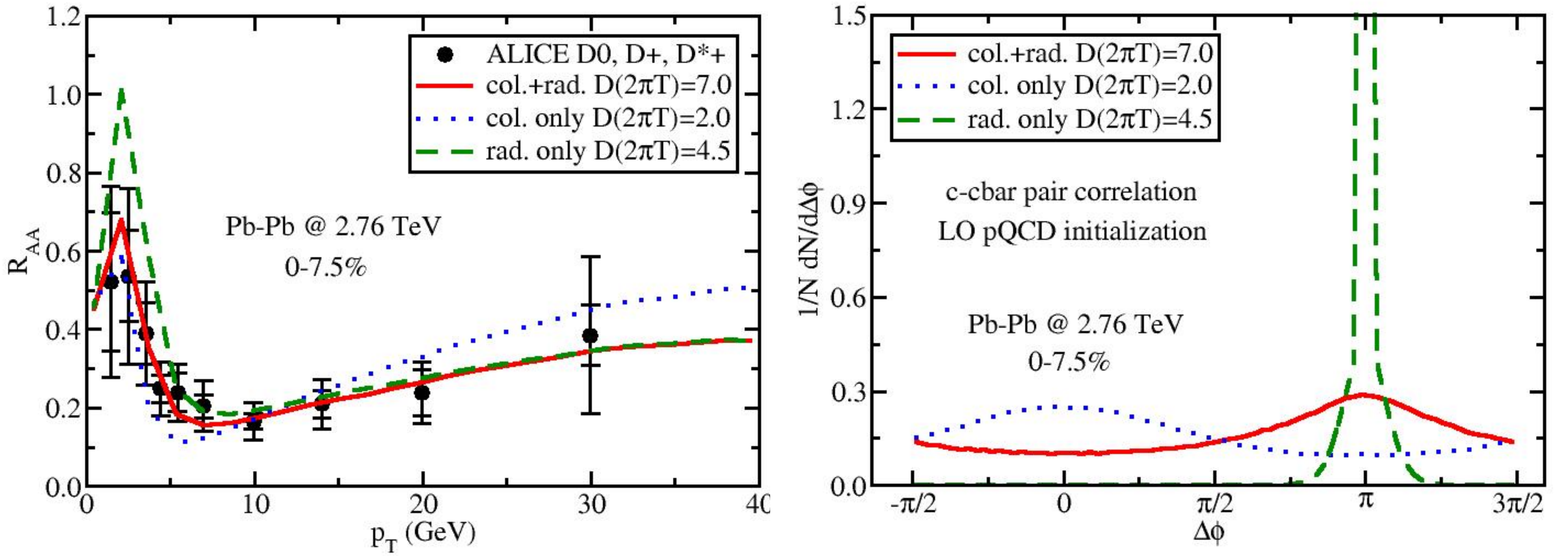
From Single to Double Particle Spectra (Angular Correlation of Heavy Flavor)





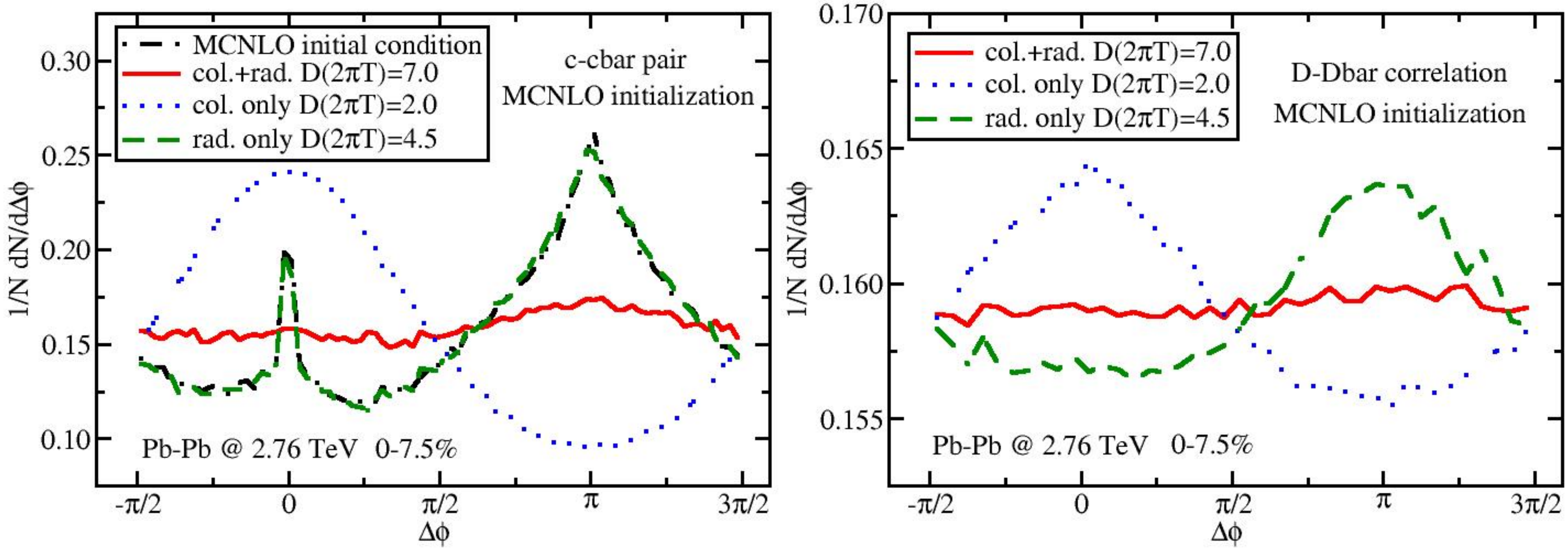
At LO: Back-to-back production of initial QQbar with the same magnitude of momentum

Angular De-correlation of CCbar



- Though each energy loss mechanism alone can fit R_{AA} to certain accuracy, they display very different behaviors of angular de-correlation.
- Pure radiative energy loss does not influence the angular correlation significantly; pure collisional leads to peak at collinear distribution because of the QGP flow.

More Realistic Analysis



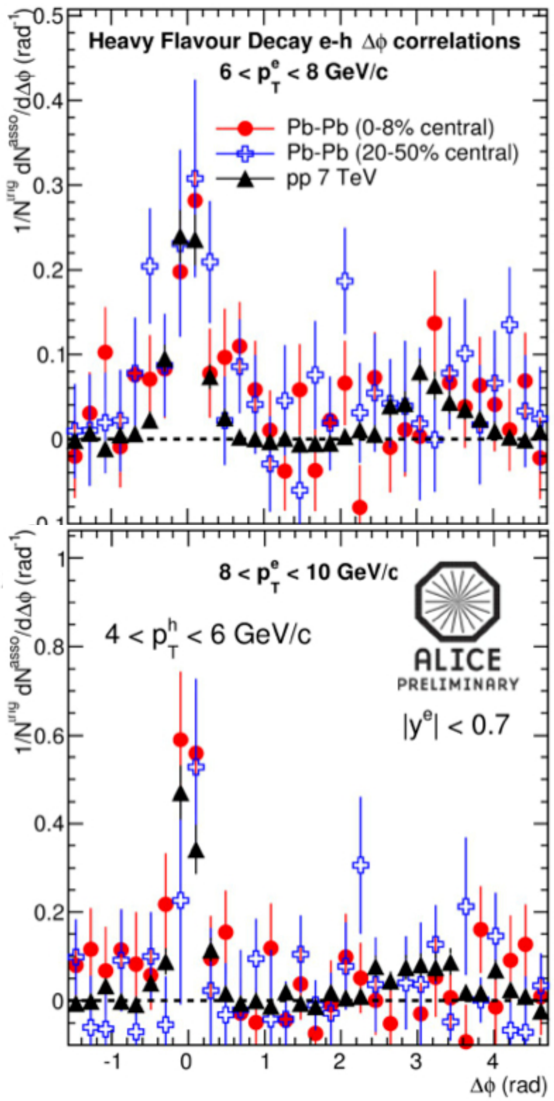
- MCNLO + Herwig radiation for HQ initial production
- Angular correlation function of final state ccbar pairs

- Within each event, loop each D with all Dbar's
- Similar shape as ccbar pairs, but on top of a large background

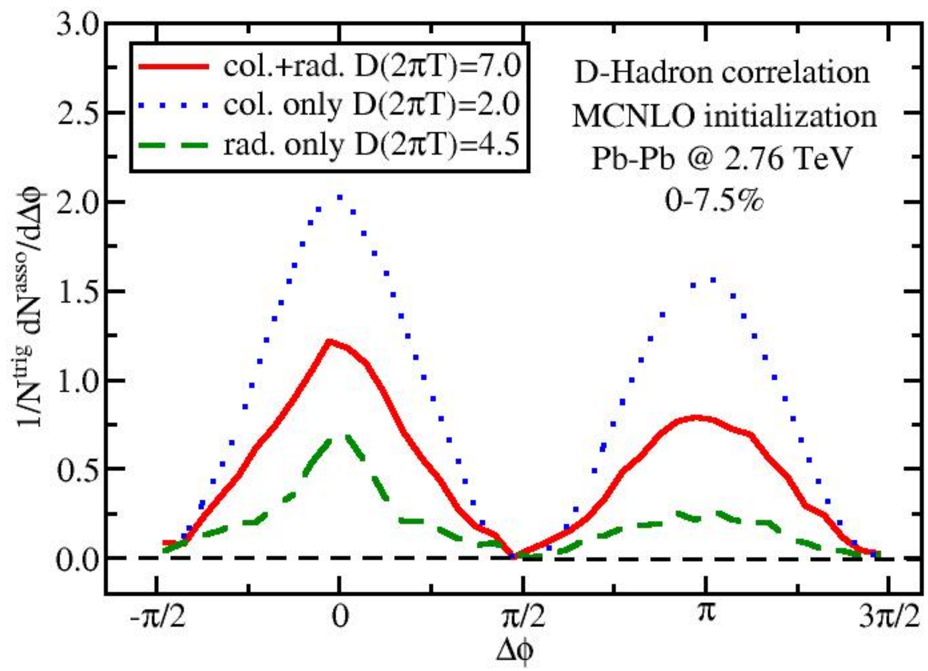
Experimental observations will help distinguish the energy loss mechanisms of heavy quark inside QGP.

Current Experiments (HF-Hadron Correlation)

(e from c, b) - h correlation
(talk by Pereira at HP2013)



Calculation of D-hadron correlation



Peaks around 0 and π

Complication introduced by the medium flow to the correlation function

Differences between various energy loss mechanisms depend on *y* and p_T cut (should be investigated later)

Summary

- Established a comprehensive framework of heavy flavor dynamics in relativistic heavy-ion collisions, including initial production, energy loss inside QGP, hadronization process and hadronic interaction in hadron gas
- Revealed the significant effect of gluon radiation at high energies and recombination at medium p_T, The hadronic interaction further suppresses *D* meson R_{AA} at large p_T and enhances its v_2
- Provided descriptions of *D* meson suppression and flow consistent with most of the data at both RHIC and LHC
- Discussed about the heavy-flavor tagged correlation functions – may help distinguish between different energy loss mechanisms of heavy quarks inside QGP

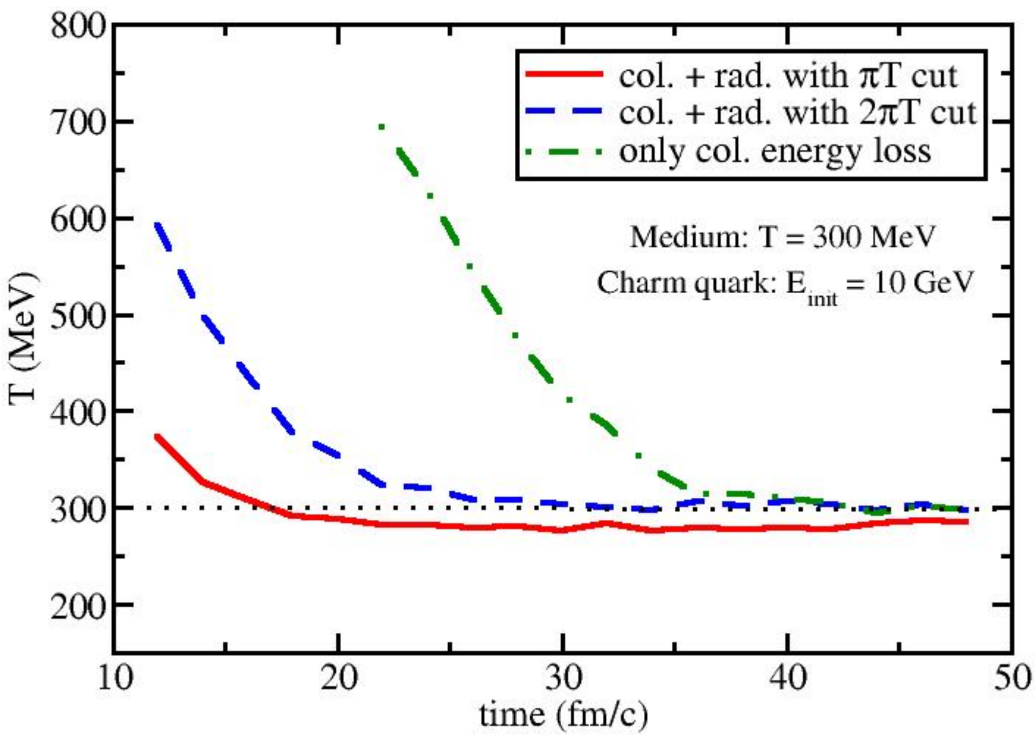
Thank you!

Check of Detail Balance

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

$\vec{f}_g$ Gluon radiation only, may break the detail balance

$$\eta_D(p) = \frac{\kappa}{2TE} \qquad \langle \xi^i(t)\xi^j(t')\rangle = \kappa\delta^{ij}\delta(t-t')$$

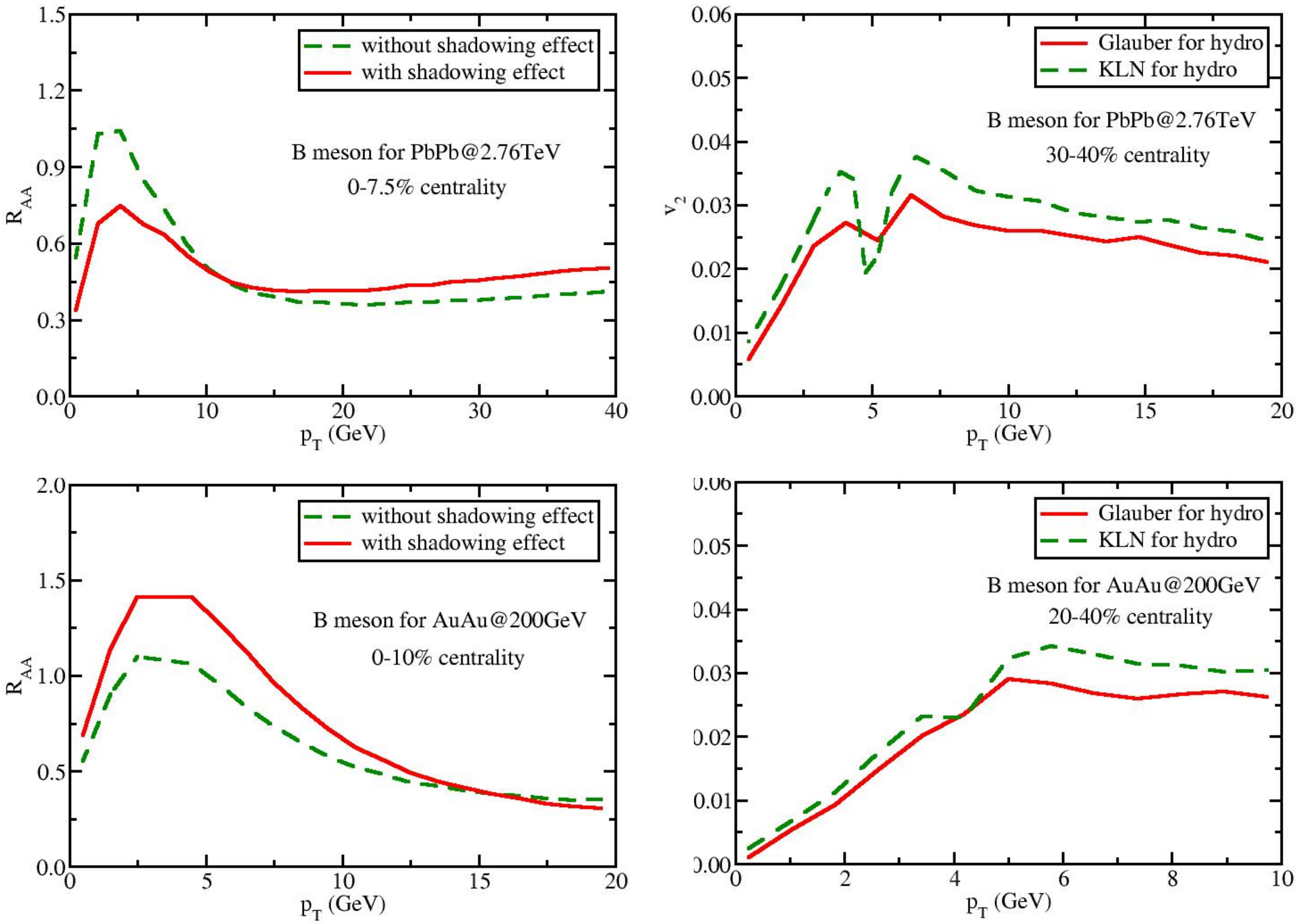


Cut off gluon radiation at low energies where collisional energy loss dominates and detail balance is preserved.

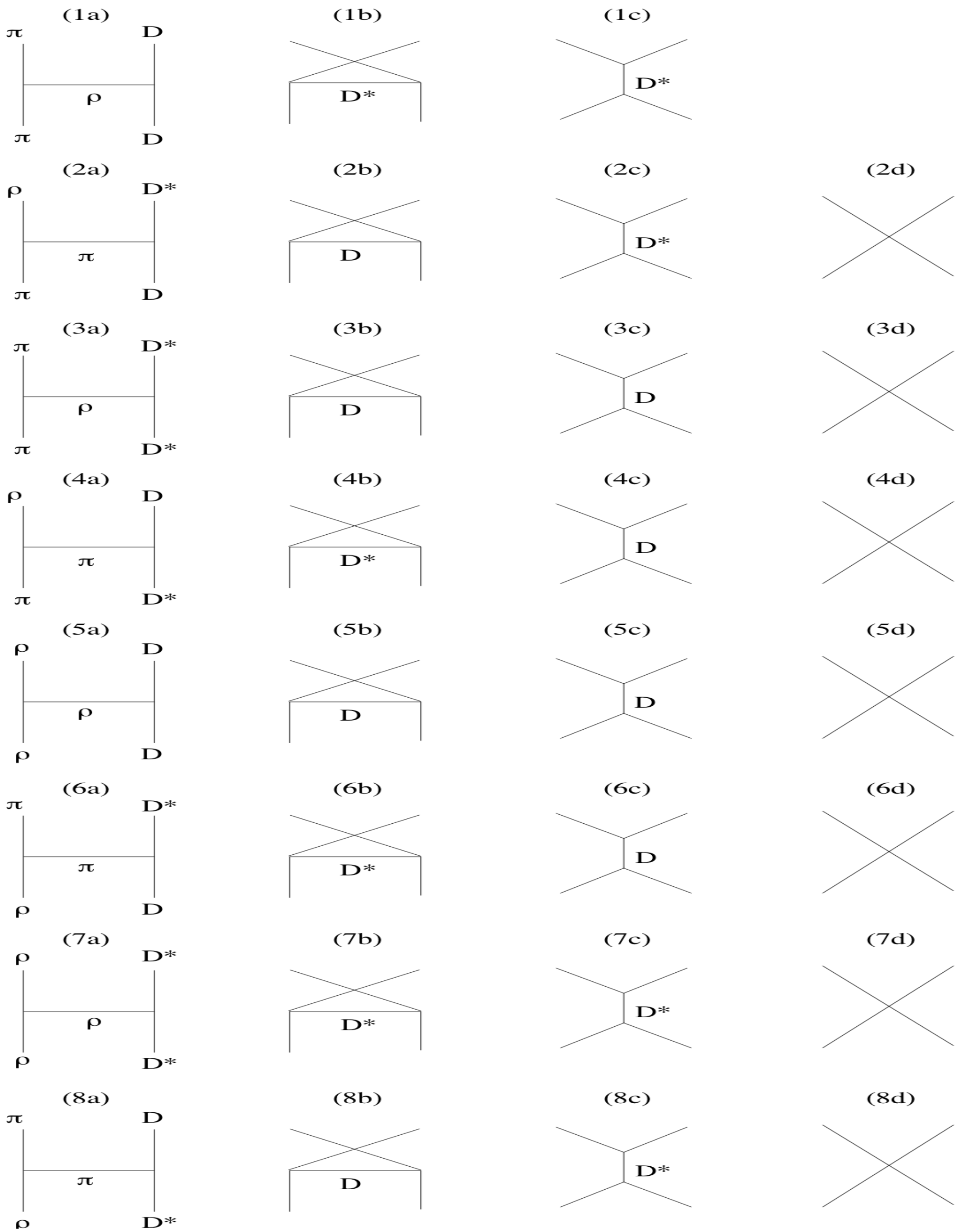
Large enough cut reproduces charm quark thermalization behavior.

More rigorous solution: include gluon absorption term into the higher-twist formalism directly and recalculate $\vec{f}_g$ term.

Prediction for *B* Meson Measurements



The shadowing effect for *b*-quark is not as significant as *c*-quark, but still non-negligible. "Anti-shadowing" at RHIC energy.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