# Open Heavy Flavors in QGP and HG in heavy-ion collisions

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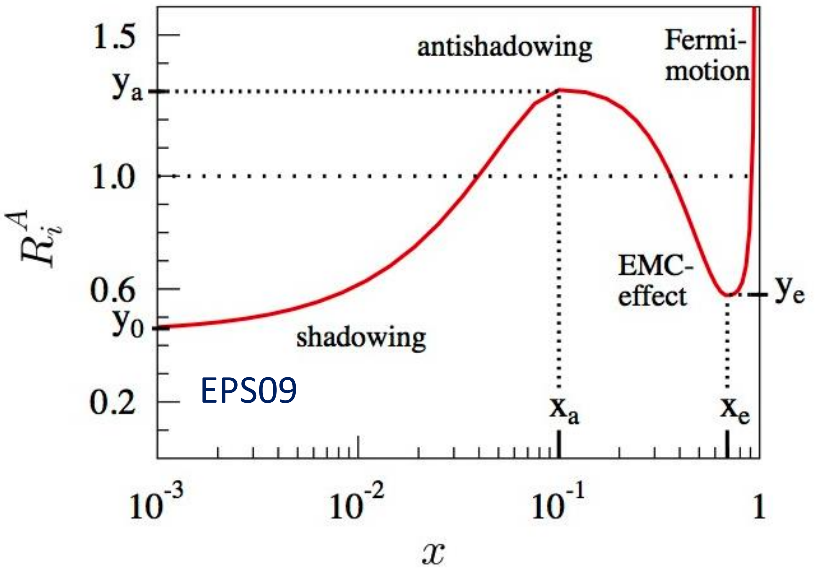
# Heavy flavors

- **p-p collisions: test pQCD, reference for p-A and A-A collisions**

$$d\sigma_H = \sum_{abQ} f_{a/A} \otimes f_{b/B} \otimes d\sigma_{ab \to QX} \otimes h_{H/Q}$$

- **p-A collisions: study cold nuclear effect (shadowing …), reference for A-A collisions**

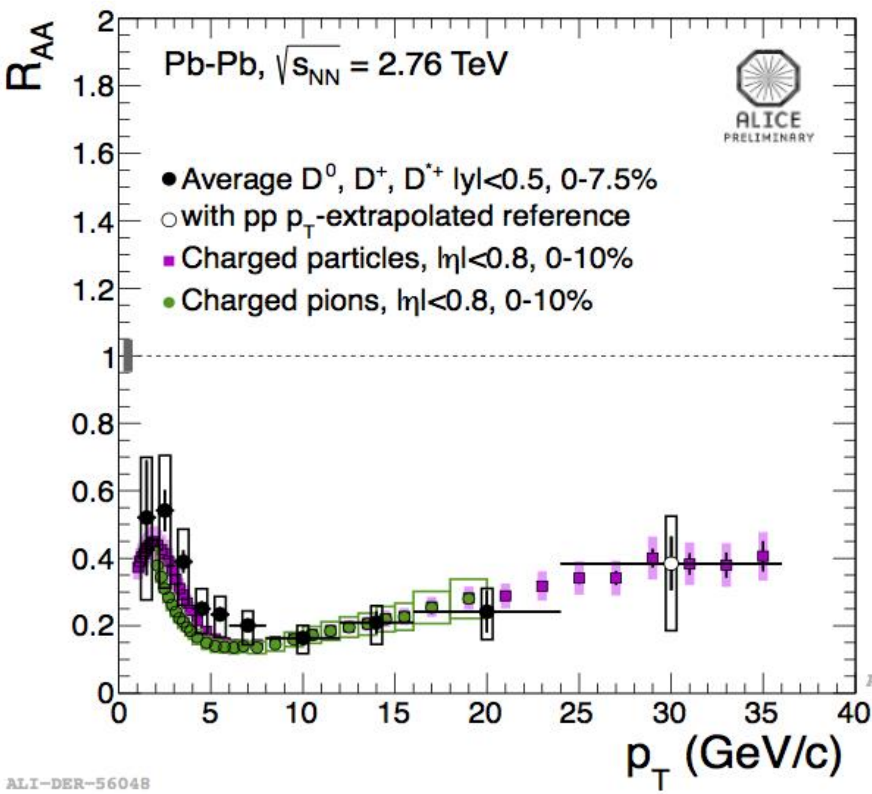
$$R_i^A(x, Q^2) = f_{a/A}(x, Q^2) \,/\, f_{a/p}(x, Q^2)$$

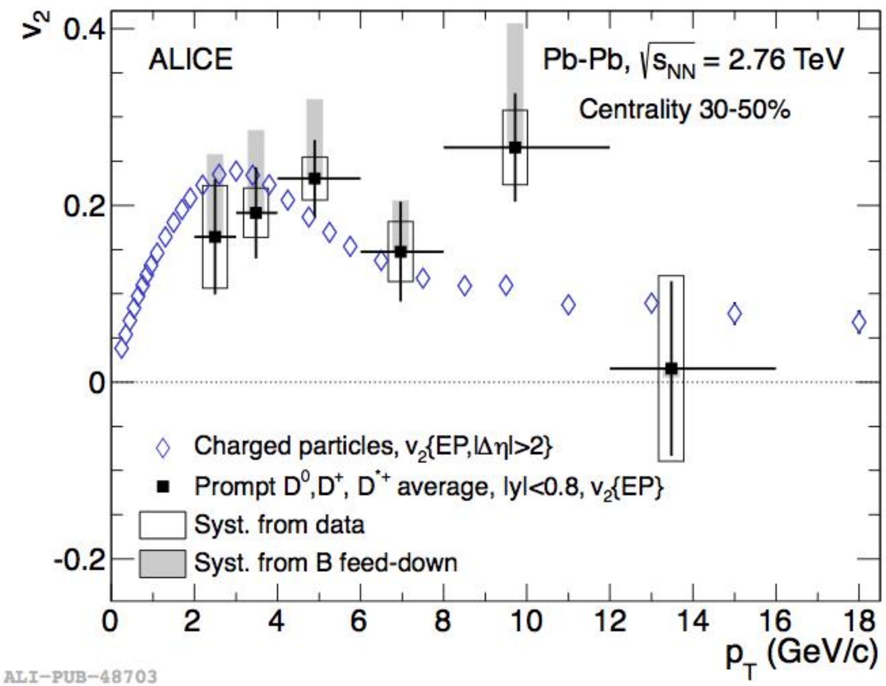



- **A-A collisions: study medium effect on heavy flavors (energy loss…)**
  - Produced at early stage, serve as hard probes of QGP
  - Expected to be influenced less by the QGP medium compared to light flavors
  - Can be utilized to study flavor and mass dependences of parton-medium interaction

$$\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$$

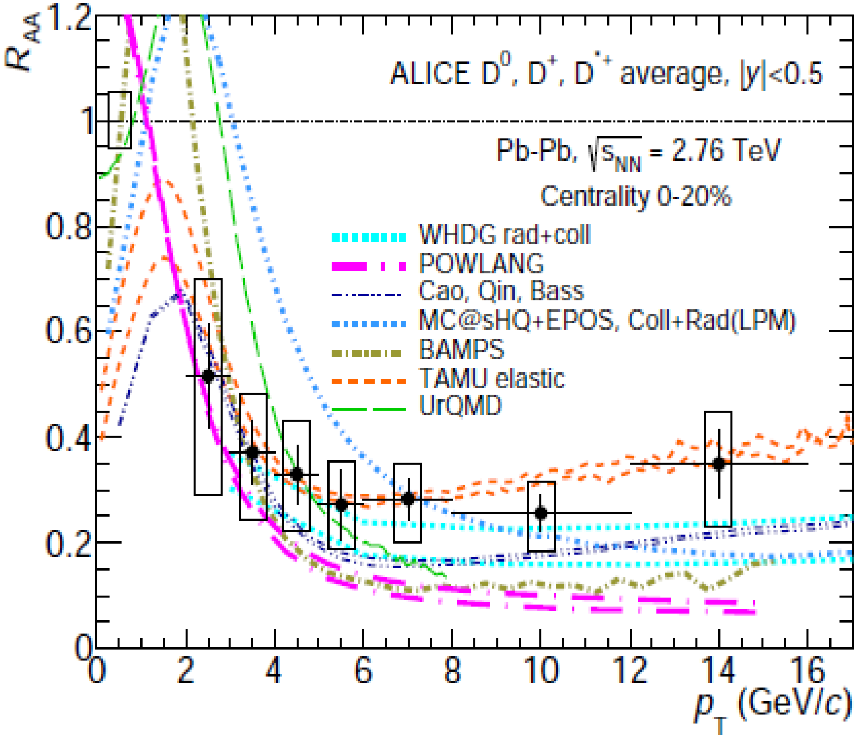
# Experimental observations

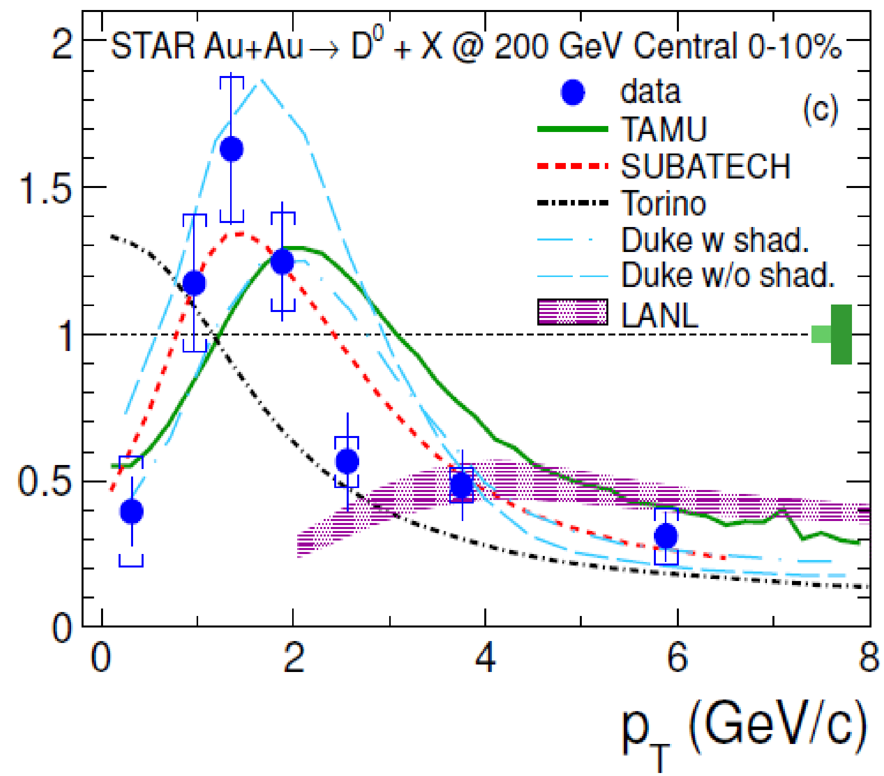



**Strong nuclear modification ($R_{AA}$) and large elliptic anisotropy $v_2$ for heavy flavor mesons comparable to light flavors**

# Data vs. models

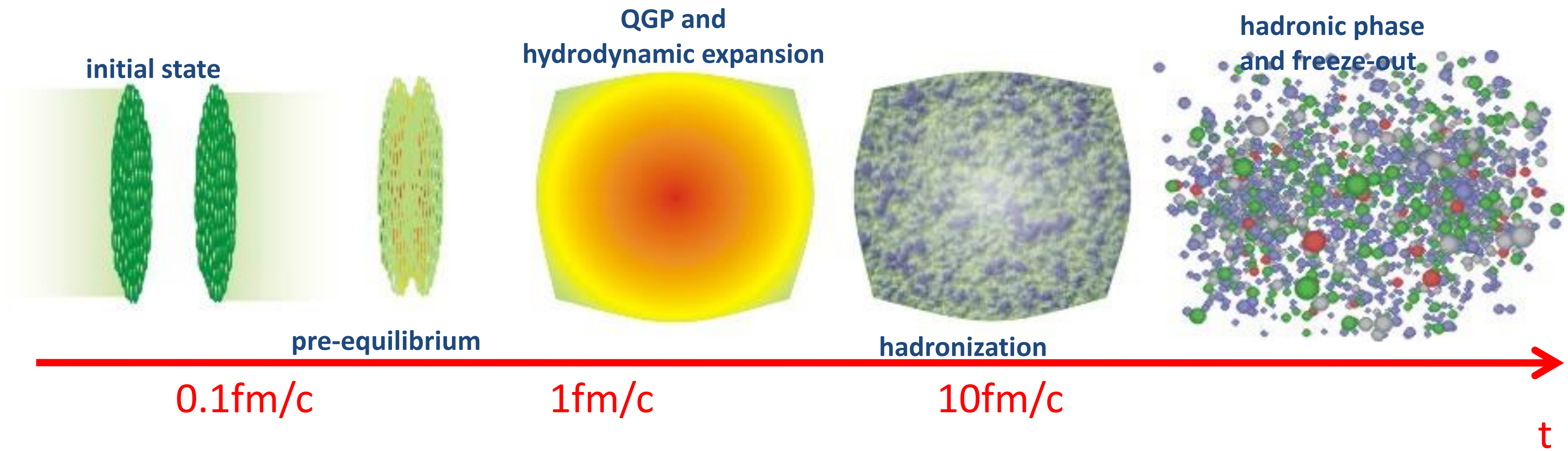



**Different models vary in a few aspects:**

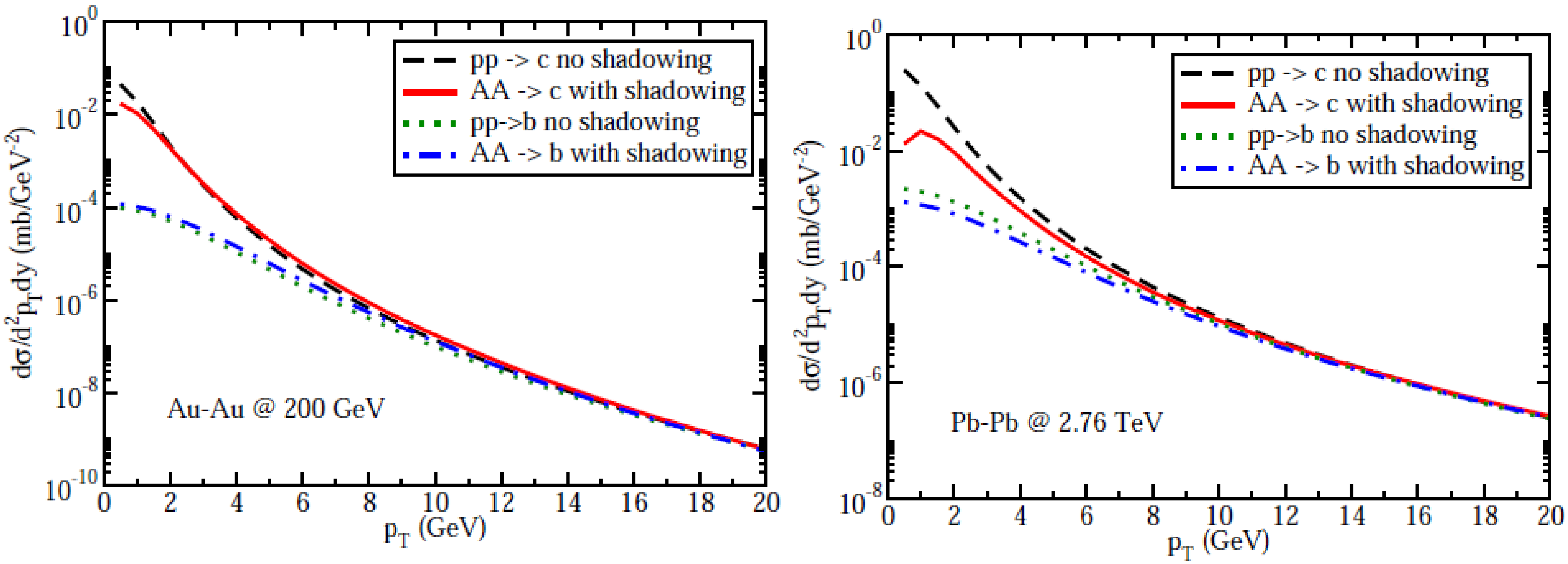
- **Radiative & collisional energy loss of heavy quarks in QGP**
- **Full Boltzmann & Fokker-Planck (Langevin) transport approaches for HQ evolution**
- **Fragmentation & recombination for heavy quark hadronization**
- **Partonic & hadronic interactions for heavy flavors**
- **Shadowing, Cronin, …**

# Short summary of our model




- **Soft sector (bulk matter):**
  - **Initial conditions: Glauber/KLN-CGC for energy/entropy density distribution**
  - **Space-time evolution: (2+1)-d viscous hydrodynamics (OSU)**
  - **Hadronization: cooper-Frye formula => hadron gas**
- **Hard Sector (heavy quark):**
  - **Initial conditions: Glauber for space distribution and pQCD for momentum distribution**
  - **Heavy quark evolution in QGP: Langevin approach with collisional and radiative energy loss**
  - **Hadronization: fragmentation plus coalescence/recombination => heavy meson**
- **Heavy mesons evolution in hadron gas: UrQMD model**

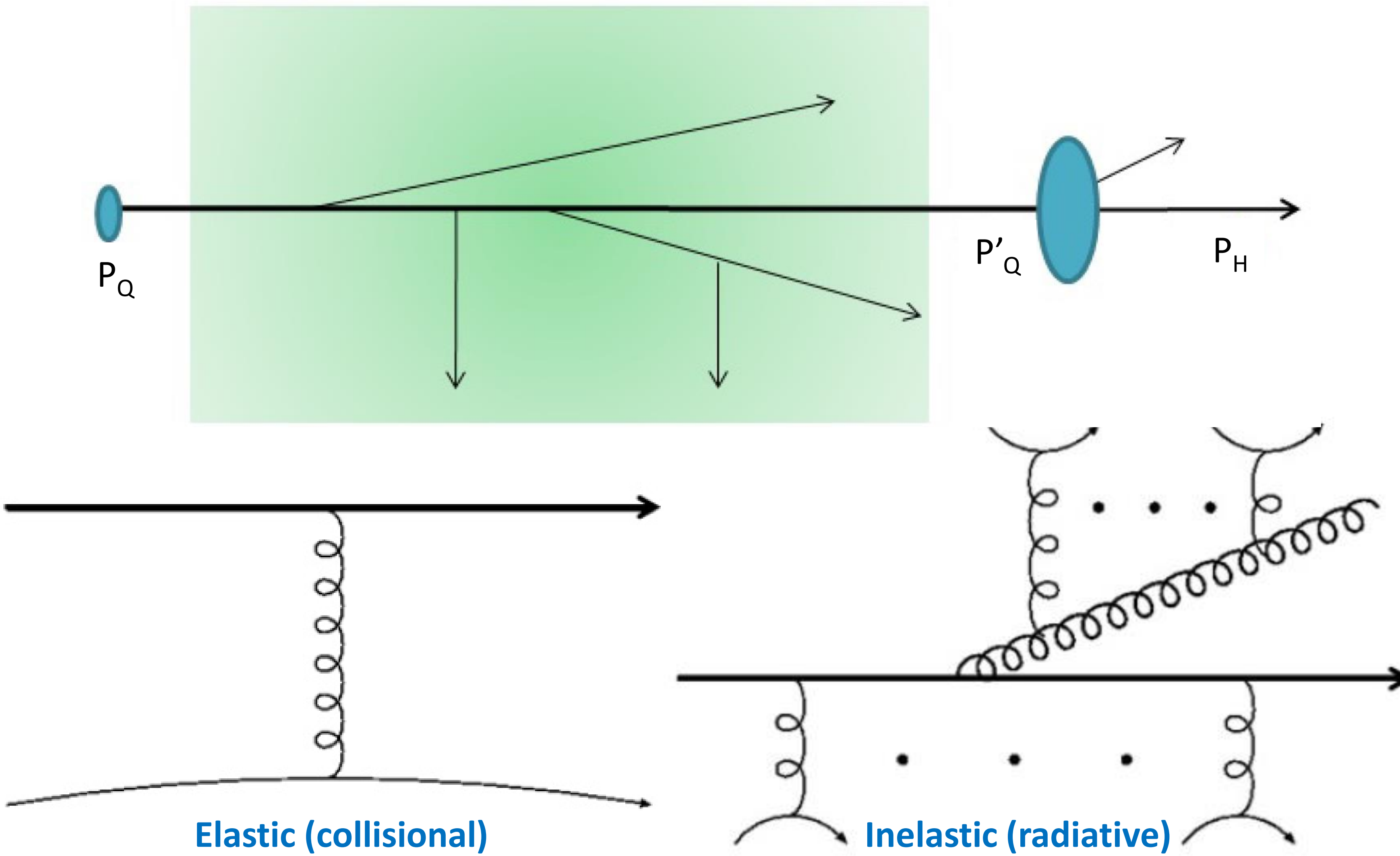
# Initial production of heavy quarks




- **Spatial distribution: Glauber model (binary collisions)**
- **Momentum distribution: perturbative QCD calculation**
  - **Parton distribution functions taken from CTEQ5 (Lai et al, 2000)**
  - **Nuclear shadowing effect taken from EPS09 (Eskola et al, 2009)**
- **Shadowing affects heavy quark production at low $p_T$ (more influence at the LHC)**
- **Shadowing has impact on final $R_{AA}$**

Cao, GYQ, Bass, PRC 2013; JPG 2013

# Heavy quark energy loss in QGP



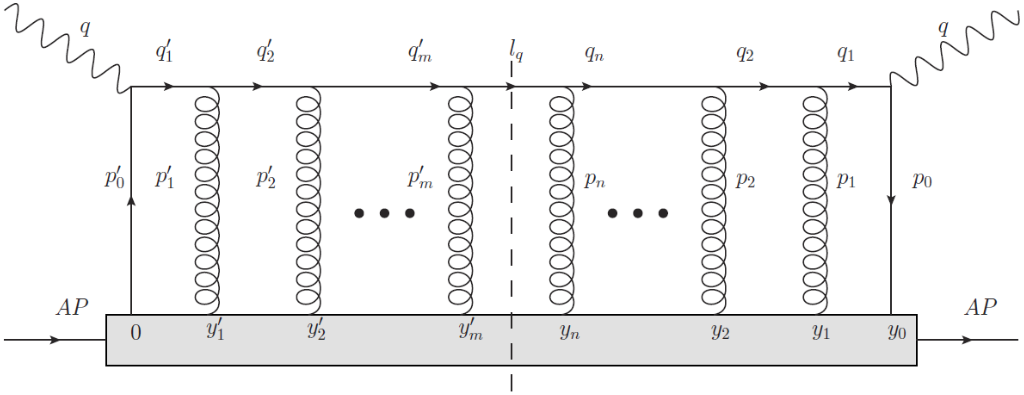
# Elastic collisions

- **At low $p_T$, heavy quark energy loss is more dominated by collisional component**
- **Langevin approach has been widely utilized at RHIC for heavy quark evolution**
  (Moore, Teaney, PRC 2005; He, Fries, Rapp, PRC 2012; Young, Schenke, Jeon, Gale, PRC 2012 …)

$$\frac{d\vec{p}}{dt} = -\eta_D(p)\vec{p} + \vec{\xi} \qquad \langle \xi^i(t)\xi^j(t')\rangle = \kappa\delta^{ij}\delta(t-t')$$

- **Einstein relation (detailed balance)**

$$\eta_D(p) = \frac{\kappa}{2TE} \qquad D = \frac{T}{M\eta_D(0)} = \frac{2T^2}{\kappa}$$



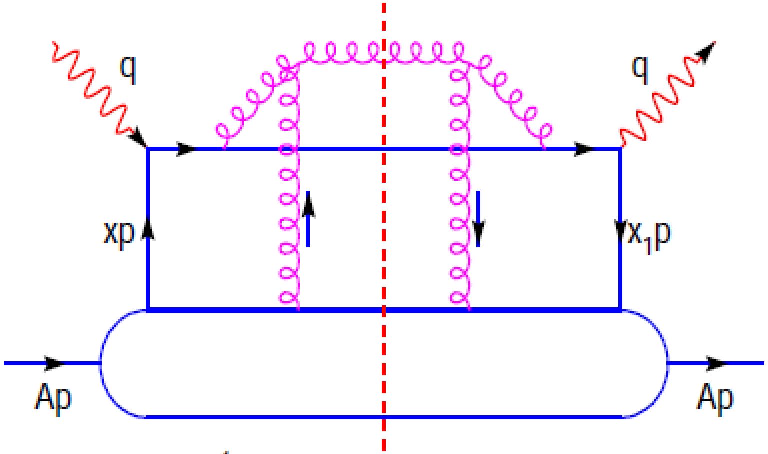

$$\frac{\partial f}{\partial L^-} = \left[D_{L1}\frac{\partial}{\partial l_q^-} + \frac{1}{2}D_{L2}\frac{\partial^2}{\partial^2 l_q^-} + \frac{1}{2}D_{T2}\nabla^2_{\vec{l}_{q\perp}}\right] f(L^-, l_q^-, \vec{l}_{q\perp})$$

$$D_{T2} \approx \frac{4\pi\alpha_s C_R}{N_c^2-1}\int dy^- \left\langle F^{\mu+}(0)F^+_\mu(y^-)\right\rangle$$

Keeping up to the second order in a momentum gradient expansion: **longitudinal drag & longitudinal diffusion & transverse diffusion due to multiple scatterings**
(GYQ, Majumder, PRC 2013; Abir, Kaur, Majumder, arXiv:1407.1864)

# Radiative energy loss

- **At high $p_T$, more dominated by radiative component (similar to light flavors), necessary to include it at the LHC**
- **A number of parton energy loss formalisms for medium-induced gluon radiation**
  (BDMPS-Z, ASW, DGLV, AMY, HT)
- **Utilize higher twist (HT) energy loss formalism**
  (Guo, Wang, PRL 2000; Majumder, PRC 2012)
- **HT model for heavy quark radiative energy loss**
  (Zhang, Wang, Wang, PRL 2004)



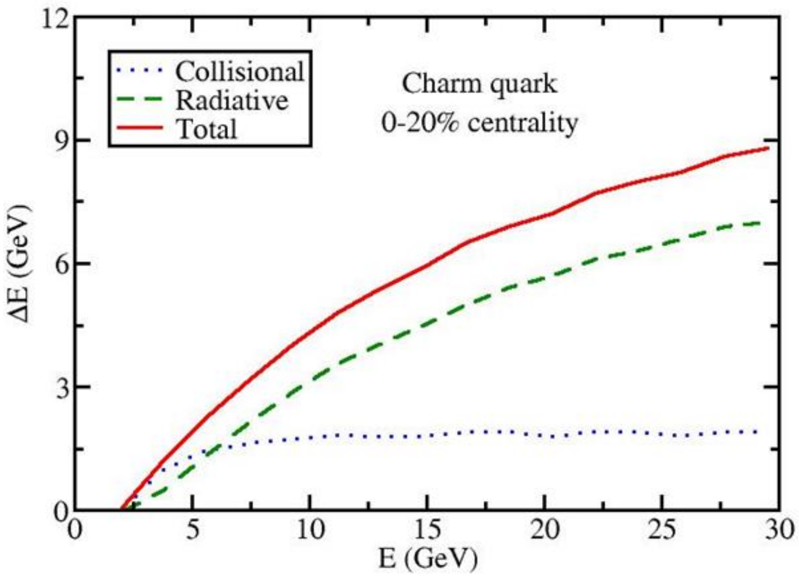

$$\frac{dN_g}{dx dk_\perp^2 dt} = \frac{2\alpha_s P(x)\hat{q}}{\pi k_\perp^4} \sin^2\left(\frac{t-t_i}{2\tau_f}\right)\left(\frac{k_\perp^2}{k_\perp^2 + x^2 M^2}\right)^4$$

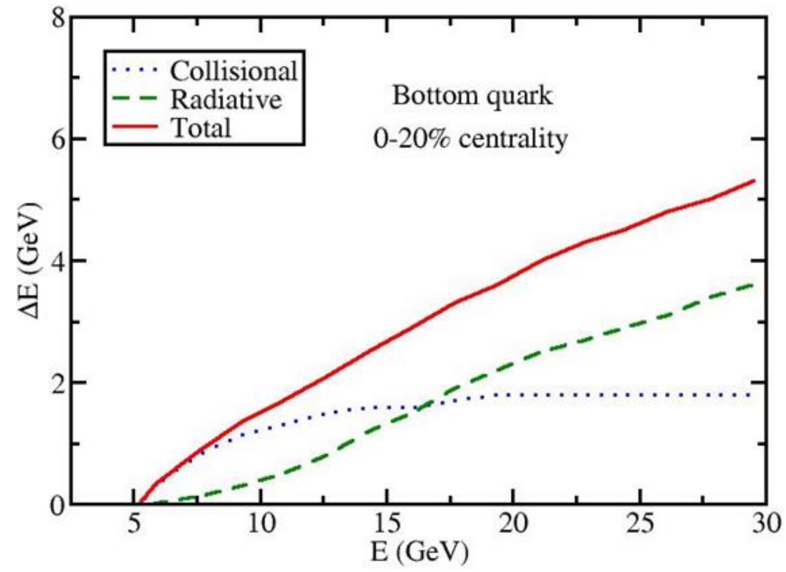
- **Also contribution from longitudinal momentum exchange to medium-stimulated radiation**
  (GYQ, Majumder, arXiv:1411.5642 for photon radiation; for gluon radiation, GYQ, in progress)
- **Include gluon radiation contribution as a recoil force exerted on the heavy quark**

$$\frac{d\vec{p}}{dt} = -\eta_D \vec{p} + \vec{\xi} - \vec{f}_g$$

$$\vec{p}(t+\Delta t) = \vec{p}(t) - \eta_D \vec{p}\Delta t + \vec{\xi}\Delta t - \vec{k}_g$$

# Heavy quark energy loss in QGP (LHC)




- **QGP medium: (2+1)-D viscous hydrodynamics (OSU)**
- **D=6/(2πT), i.e., $\hat{q}$ ~ 2 $GeV^2$/fm at a temperature around 350 MeV**
- **Collisional energy loss dominates at low energy, while radiative energy loss dominates at high energy**
- **The crossing point is larger for bottom than charm quarks due to the mass effect**

Cao, GYQ, Bass, PRC 2013; JPG 2013

# Heavy quark hadronization

- **Most high momentum heavy quarks fragment into heavy mesons**
  - Use PYTHIA 6.4 “independent fragmentation model”
- **Most low momentum heavy quarks hadronize to heavy mesons via recombination (coalescence) mechanism**
  - use sudden recombination model based on Y. Oh, et al., PRC 79, 044905 (2009)

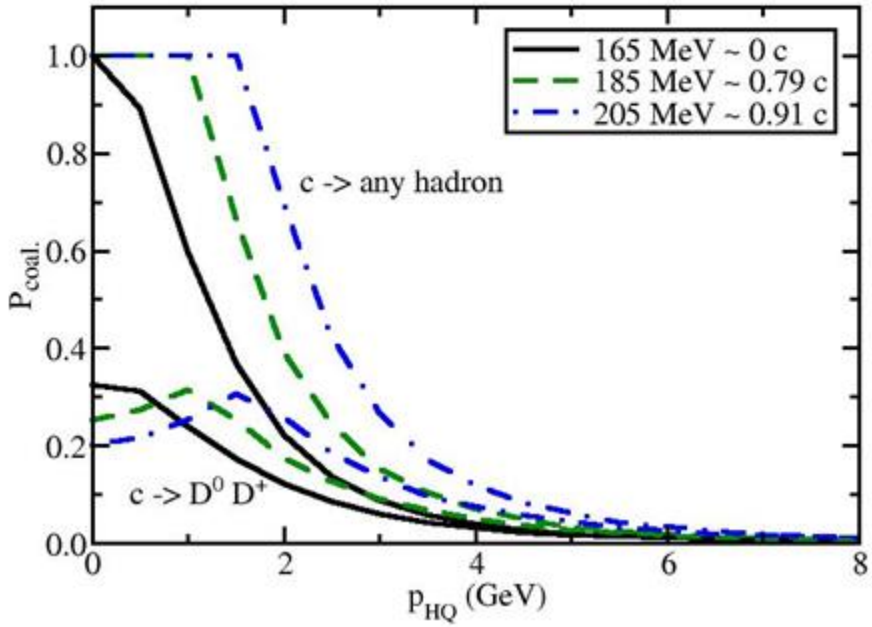
$$\frac{dN_M}{d^3p_M} = \int d^3p_1 d^3p_2 \frac{dN_1}{d^3p_1}\frac{dN_2}{d^3p_2} f_M^W(\vec{p}_1, \vec{p}_2)\delta(\vec{p}_M - \vec{p}_1 - \vec{p}_2)$$

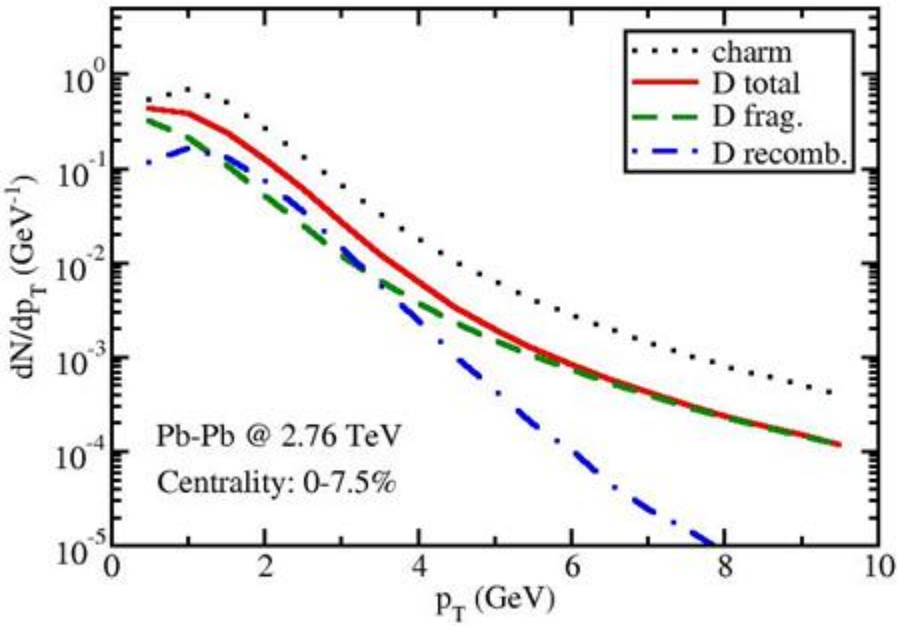
$$\frac{dN_B}{d^3p_B} = \int d^3p_1 d^3p_2 d^3p_3 \frac{dN_1}{d^3p_1}\frac{dN_2}{d^3p_2}\frac{dN_3}{d^3p_3} f_B^W(\vec{p}_1, \vec{p}_2, \vec{p}_3)\delta(\vec{p}_M - \vec{p}_1 - \vec{p}_2 - \vec{p}_3)$$

  - Inputs: heavy quark/anti-quark distribution after evolution, light quark/ anti-quark distribution from QGP, and Wigner function $f^W$
  - $f^W$ is obtained from hadron wave functions (approximated by S.H.O.)

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

# Heavy quark hadronization

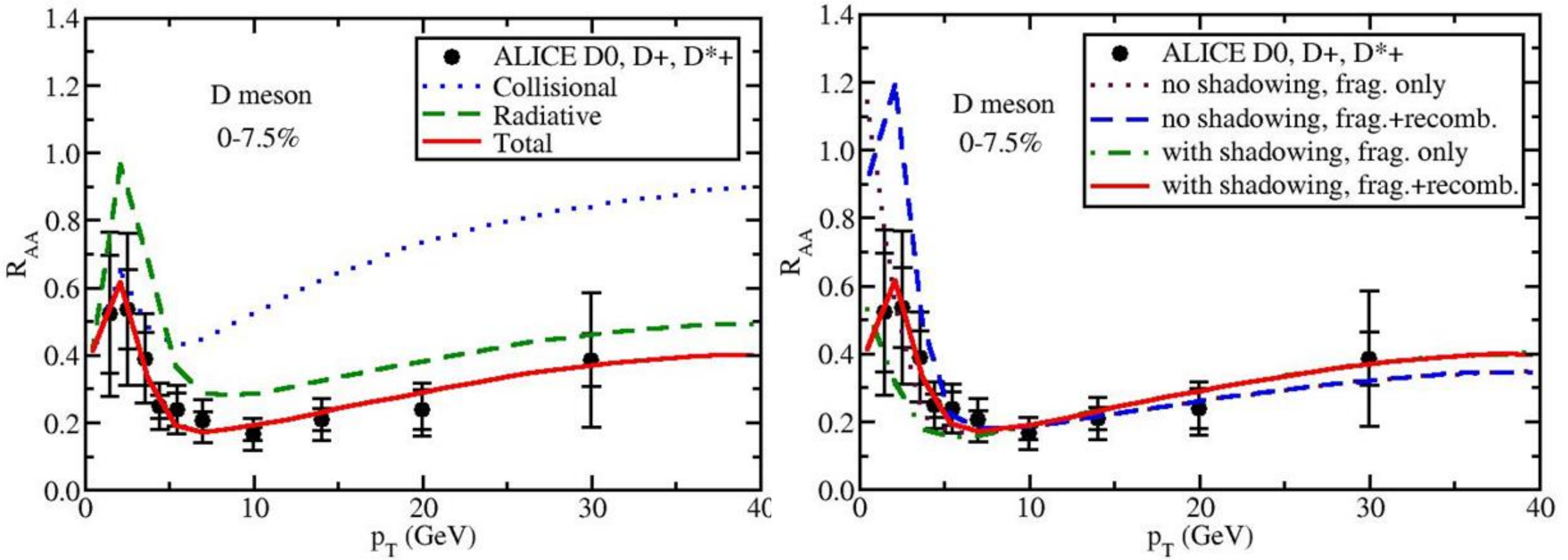



- Use Wigner function $f^{W}$ to calculate the rec. probability $P_{coal.}(p_{HQ})$ for all meson & baryon channels: $D/B$, $\Lambda_Q$, $\Sigma_Q$, $\Xi_Q$, $\Omega_Q$
- Normalization: $P_{coal.}(p_{HQ}=0) = 1$ for T=165MeV, $v_{flow} = 0$
- For each HQ, determine the channel: frag. or recomb.? recomb. to *D/B* or a baryon?

- Fragmentation dominates D/B meson production at high $p_T$
- Recombination greatly increases D/B yield at intermediate $p_T$
- At same $p_T$, bottom quarks have larger recomb. probability than charm to produce heavy flavor hadrons due to larger masses (not shown)

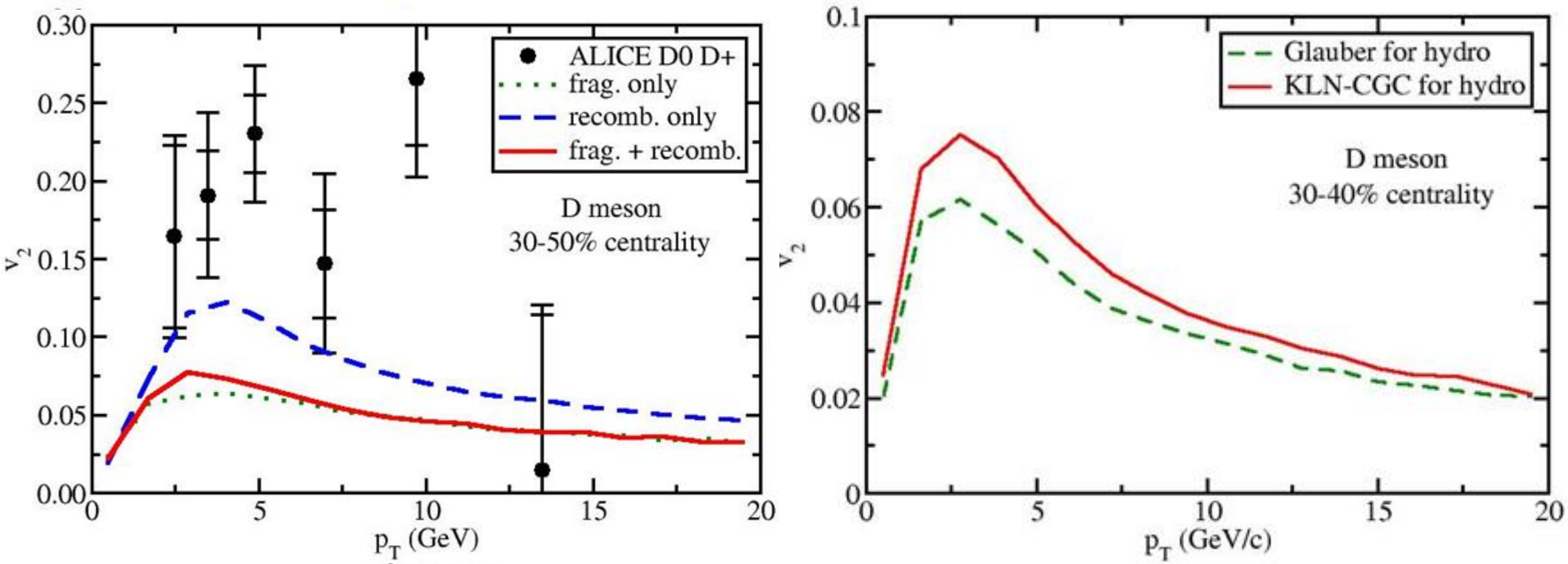
# Heavy meson $R_{AA}$ after QGP (LHC)




- **Collisional energy loss dominates at low $p_T$, while radiative energy loss dominates at high $p_T$**
- **Fragmentation is sufficient to describe heavy quark hadronization above 8 GeV, but at low and intermediate $p_T$, recombination becomes important**
- **Shadowing effect: a decrease in D $R_{AA}$ at low $p_T$, while a mild increase at high $p_T$**

Cao, GYQ, Bass, PRC 2013; JPG 2013

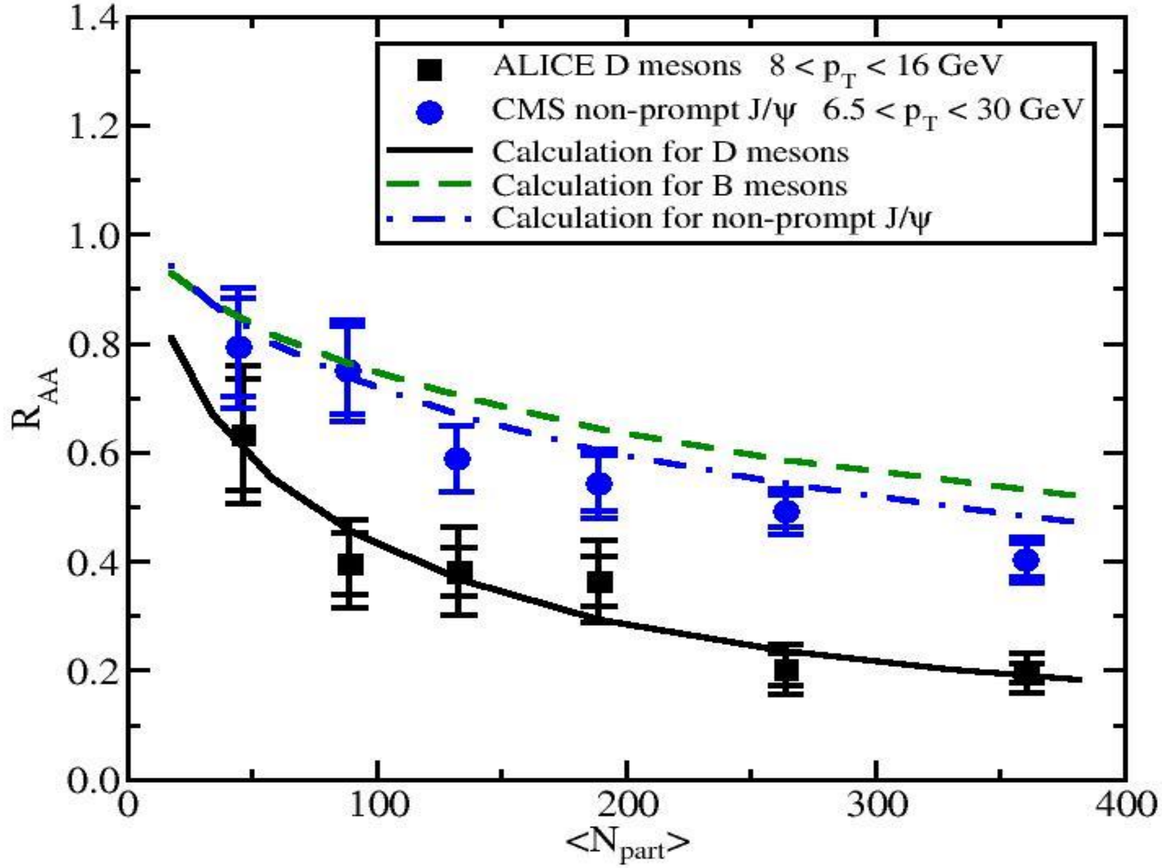
# Heavy meson $v_2$ after QGP (LHC)




- Competition between recombination and fragmentation: larger $v_2$ from recombination
- KLN-CGC provides larger eccentricity for the QGP than Glauber => larger D meson $v_2$
- Different geometries and flow behaviors of the QGP does not significantly influence the overall suppression (not shown), they may have large impact on heavy flavor $v_2$

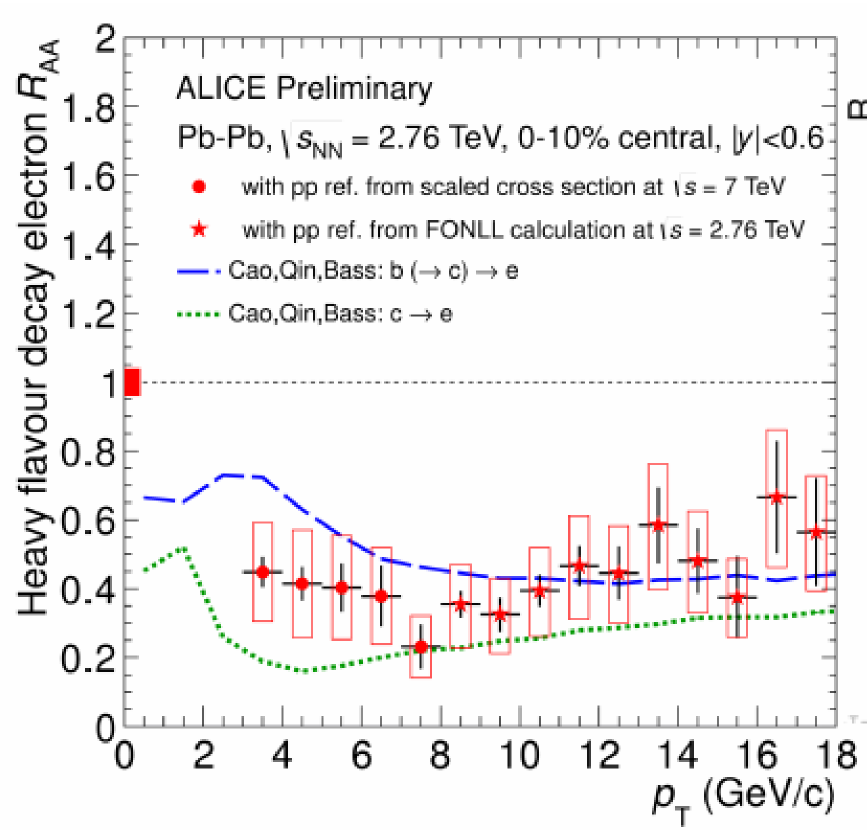
Cao, GYQ, Bass, PRC 2013; JPG 2013

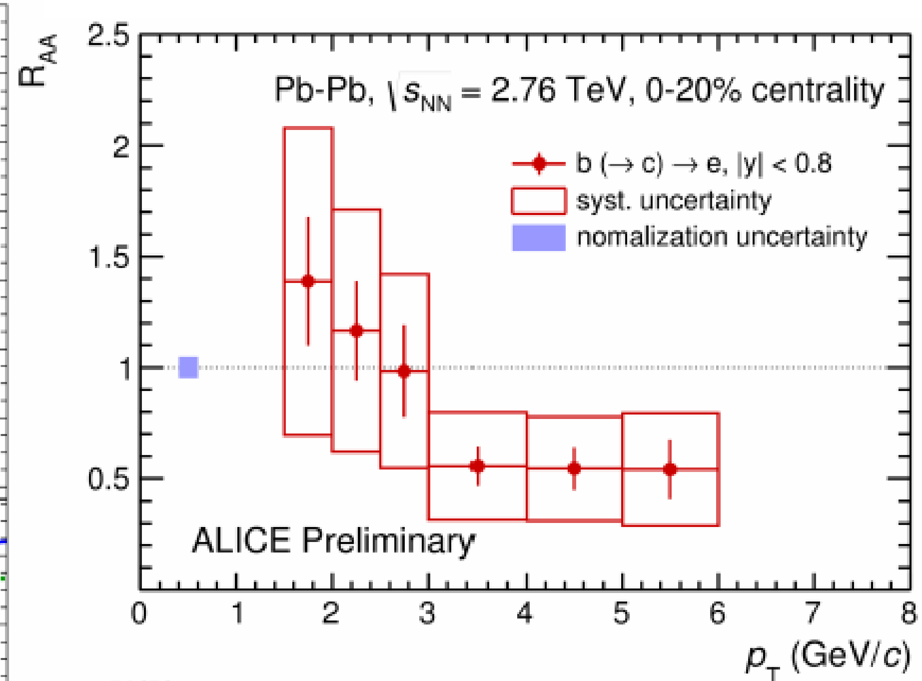
# $R_{AA}$ for non-prompt J/ψ (LHC)



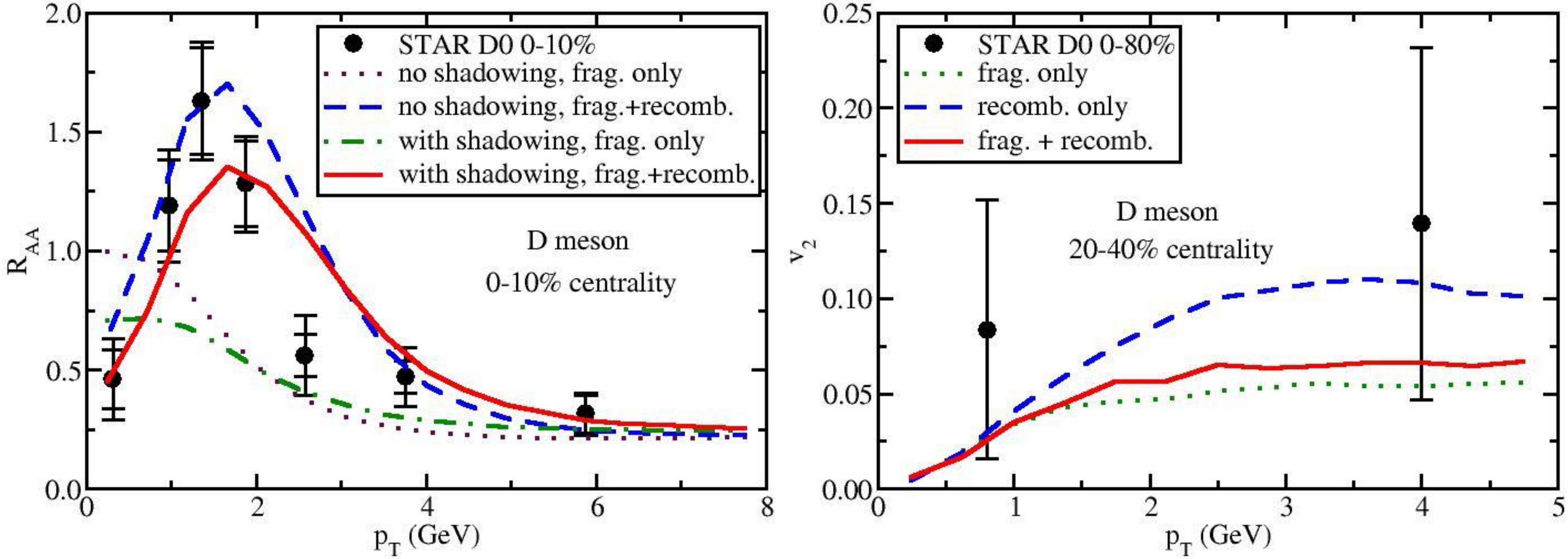

- **Model gives a good description of $N_{part}$ dependence of $D$ $R_{AA}$**
- **Using the same transport coefficients for *c* and *b* quarks, we obtain reasonable description of non-prompt $J/\psi$ $R_{AA}$**
- **Mass ordering of heavy quark energy loss: $\Delta E_c > \Delta E_b$**

# $R_{AA}$ for HF decay electrons (LHC)



# $R_{AA}$ and $v_2$ of *D* mesons at RHIC




- **Recombination enhances $R_{AA}$ at intermediate $p_T$ & produces the bump structure**
- **Recombination increases $v_2$**
- **With the incorporation of radiative & collisional energy loss, recombination & fragmentation function, shadowing, hadronic interactions, our model calculations are consistent with the RHIC data**

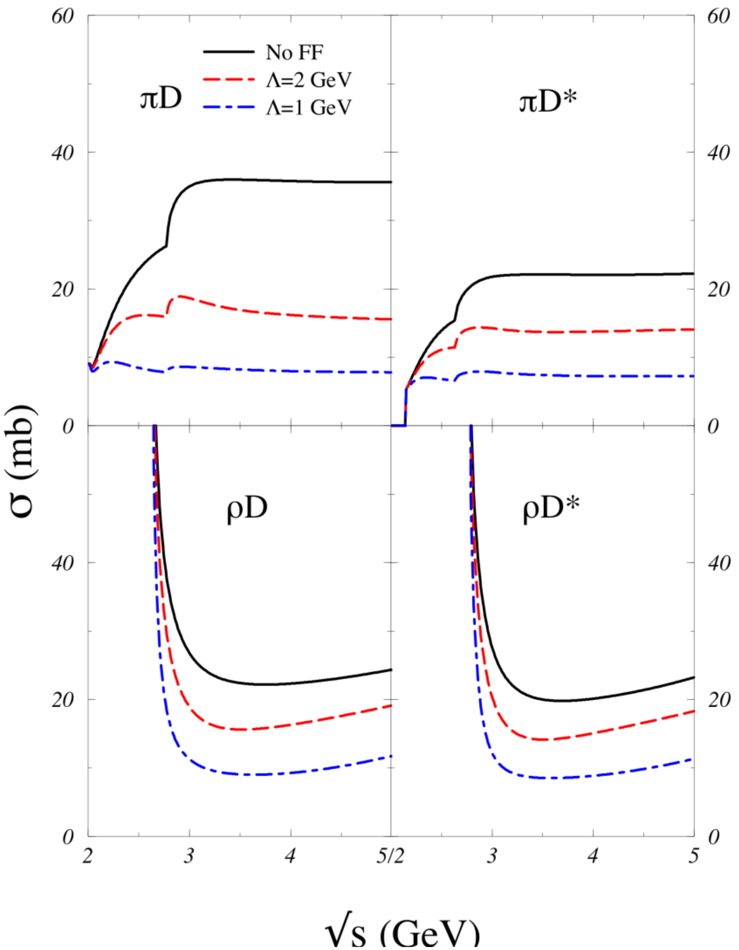
# Hadronic interactions of heavy flavor mesons

- **Hadron gas: soft hadrons from QGP**
- **Heavy flavor mesons: fragmentation and recombination from heavy quarks**

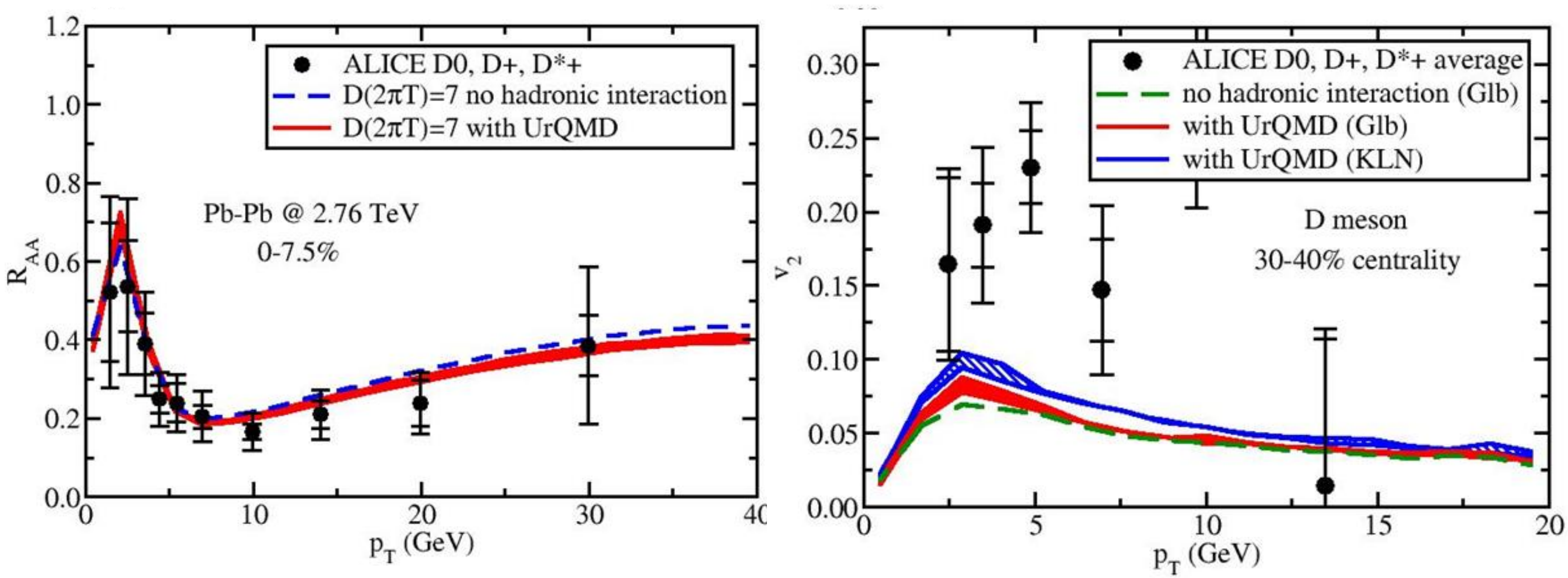
- **Evolution of heavy flavor mesons in hadron gas: use UrQMD model**
- **Processes: D mesons scattering with π & ρ**

$$\pi D \leftrightarrow \rho D^*,\ \pi D \rightarrow \pi D,\ \pi D^* \rightarrow \pi D^*,$$
$$\pi D^* \leftrightarrow \rho D,\ \rho D \rightarrow \rho D,\ \rho D^* \rightarrow \rho D^*.$$

- **D meson scattering cross sections including π, ρ & D exchange and 4-vertex diagrams** (Lin and Ko, NPA, 2001)
- **Λ is the cutoff parameter in hadron form factors (taken to be 1 & 2 GeV)**



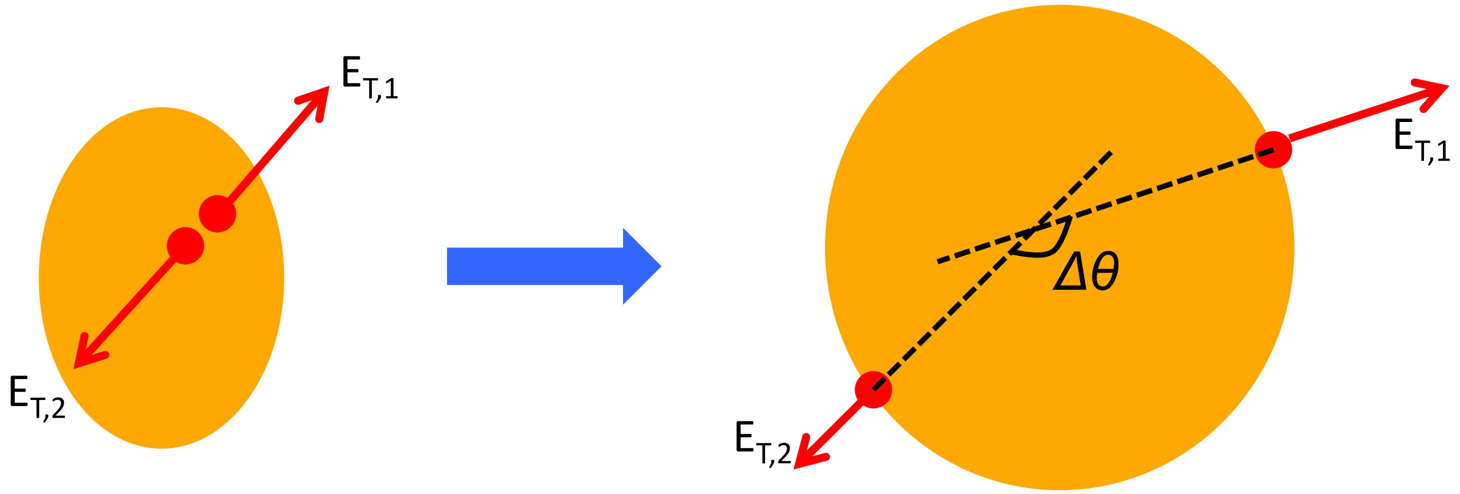
# Effect of hadronic interaction (LHC)




- **Rescatterings of D mesons in hadron gas increases a little bit quenching at high $p_T$ and there is some enhancement at low $p_T$**
- **Hadronic interaction further increases D meson $v_2$**

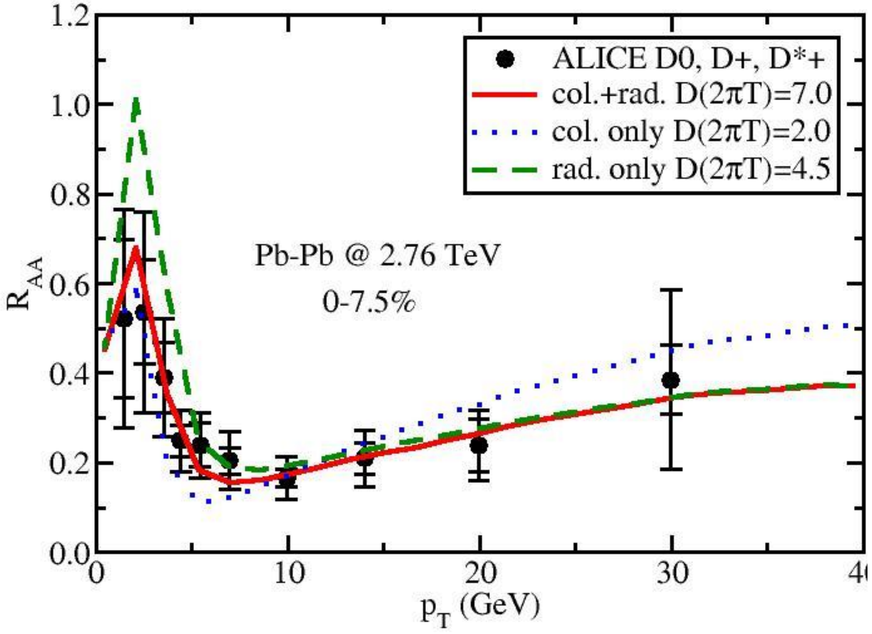
# Correlation measurements

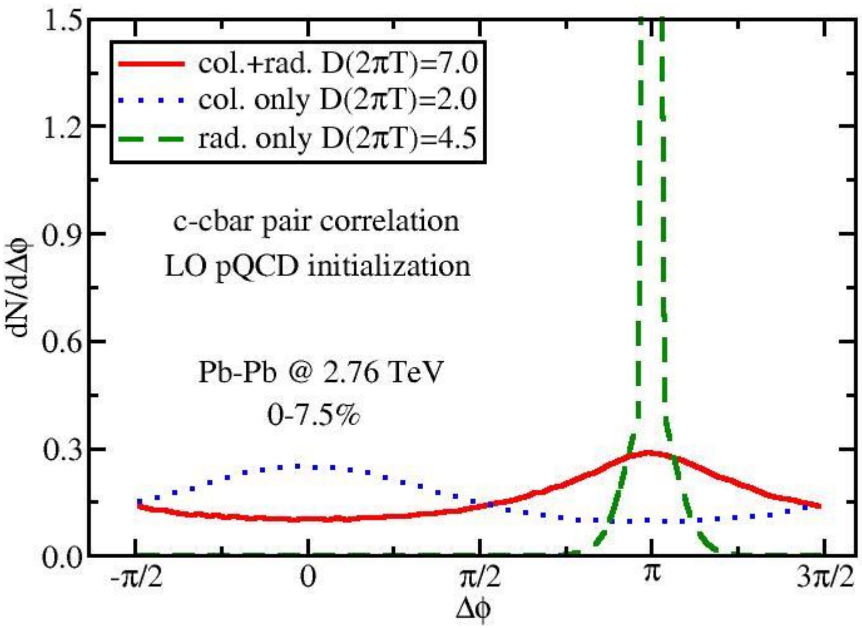
- **At LO: back-to-back production of initial $QQ^{bar}$**




- **The momentum correlation (imbalance) of the final state HF pairs:**
  - **Energy loss of heavy quarks**
- **The angular correlation of the final state HF pairs:**
  - **Degree of deflection (momentum broadening) of heavy quarks**

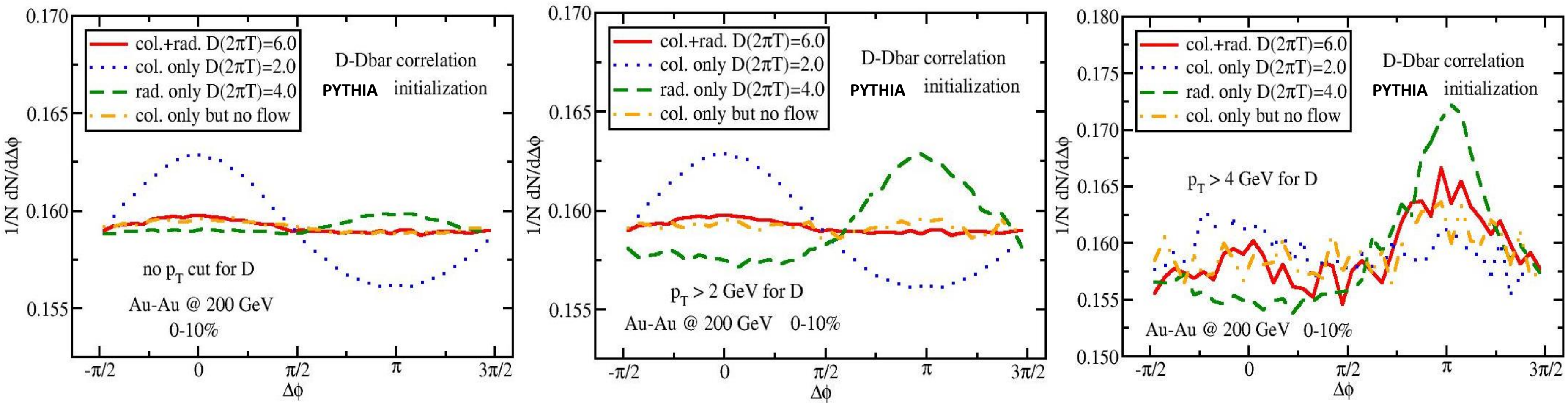
# Angular correlation of cc$^{bar}$




- **Each energy loss mechanism alone can fit $R_{AA}$ to certain accuracy, but has very different behaviors for angular correlation**
- **Radiative energy loss does not influence the angular correlation significantly; Collisional energy loss leads to a peak at near side because of the QGP flow**
- **Experimental observations may help to distinguish different energy loss mechanisms of heavy quarks inside QGP**

# Angular correlation of $DD^{bar}$




- **For each event, take all $DD^{bar}$ pairs**
- **Without $p_T$ cut (low $p_T$ dominated), there is near-side peak for pure collisional energy loss**
- **The near-side peak disappears when the QGP flow is turned off**
- **With higher $p_T$ cuts, near-side peak becomes smaller and away-side peak becomes larger**
- **With higher $p_T$ cuts, differences between various energy loss mechanisms tend to become smaller**

**For 1 event, we may take all $DD^{bar}$ pairs, one $D(D^{bar})$ paring with all $D^{bar}(D)$, or only one $DD^{bar}$ pair**

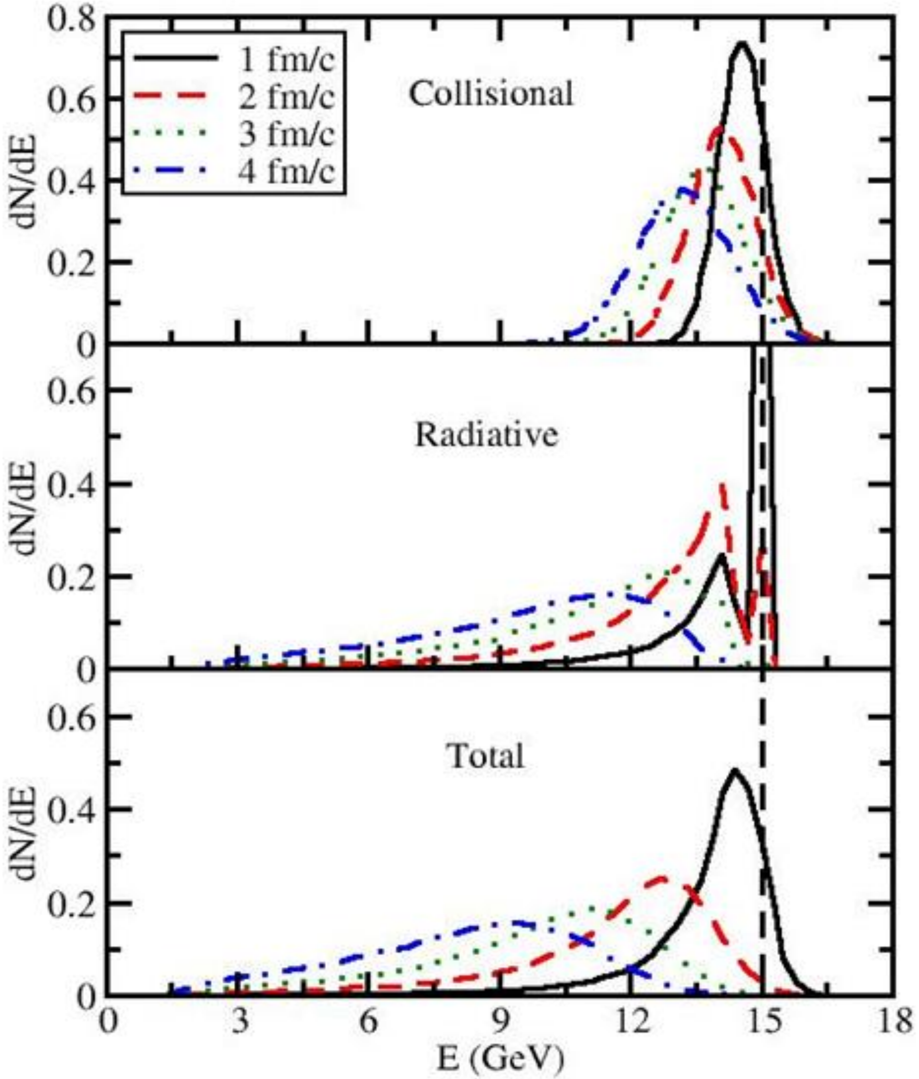
# Summary

- **Full time evolution of heavy flavors in heavy-ion collisions**
  - Initial production (nuclear shadowing), evolution in QGP (radiative and collisional energy loss), hadronization (fragmentation & recombination), and hadronic interaction in hadron gas
- **Reasonable descriptions of nuclear modification of heavy flavors at RHIC and the LHC**
- **Significant contribution from medium-induced gluon radiation to heavy quark energy loss at high energies**
- **Recombination is important for heavy flavor meson production at intermediate energies**
- **Hadronic rescatterings suppress D meson $R_{AA}$ at large $p_T$ and enhances $v_2$**
- **Heavy-flavor tagged correlations**

# Heavy quark evolution in a static QGP

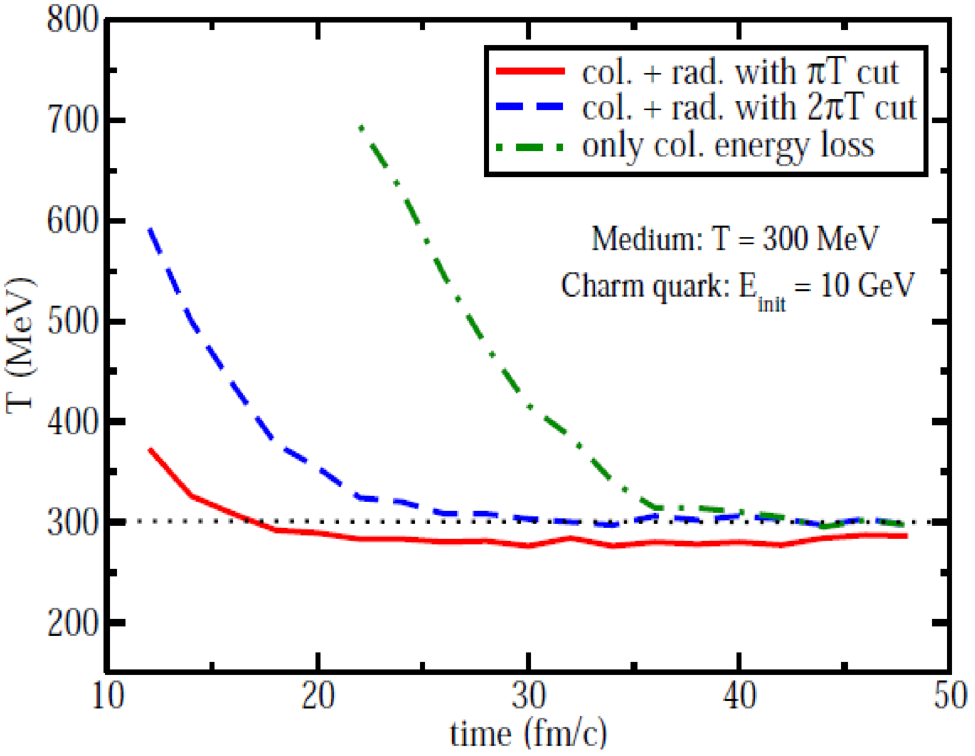
- ***T* = 350 MeV, *D*=6/(2*πT*), i.e., $q^{hat}$ ~ 2 GeV²/fm**
- **Collisional energy loss leads to Gaussian distribution, while radiative energy loss has long tails**
- **Before 2fm/c, collisional component dominates; after 2fm/c, radiative component dominates**

Cao, GYQ, Bass, Muller, NPA 2013



# Thermalization & detailed balance

- If there is only collisional energy loss, the temperature parameter of the charm quarks evolves to the medium temperature
- Gluon radiation alone may break the detail balance
- Large enough cut-off: charm quark thermalization behavior reproduced
- Lower cut-off: equilibrium still achieved but the equilibrium temperature is shifted by a small amount
- Collisional energy loss dominates at low energies, so detail balance is preserved
- More rigorous solution: include gluon absorption into formalism directly



# 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

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

$\Phi_M$: meson wave function–approximated by ground state of QM SHO

$$\phi_M(\vec{r}) = \left(\frac{1}{\pi\sigma^2}\right)^{3/4} e^{-r^2/(2\sigma^2)} \qquad \sigma = 1/\sqrt{\mu\omega}$$

μ: reduced mass of the 2-particle system

ω: SHO frequency – calculated by meson radius:

0.106 GeV for c, and 0.059 GeV for b

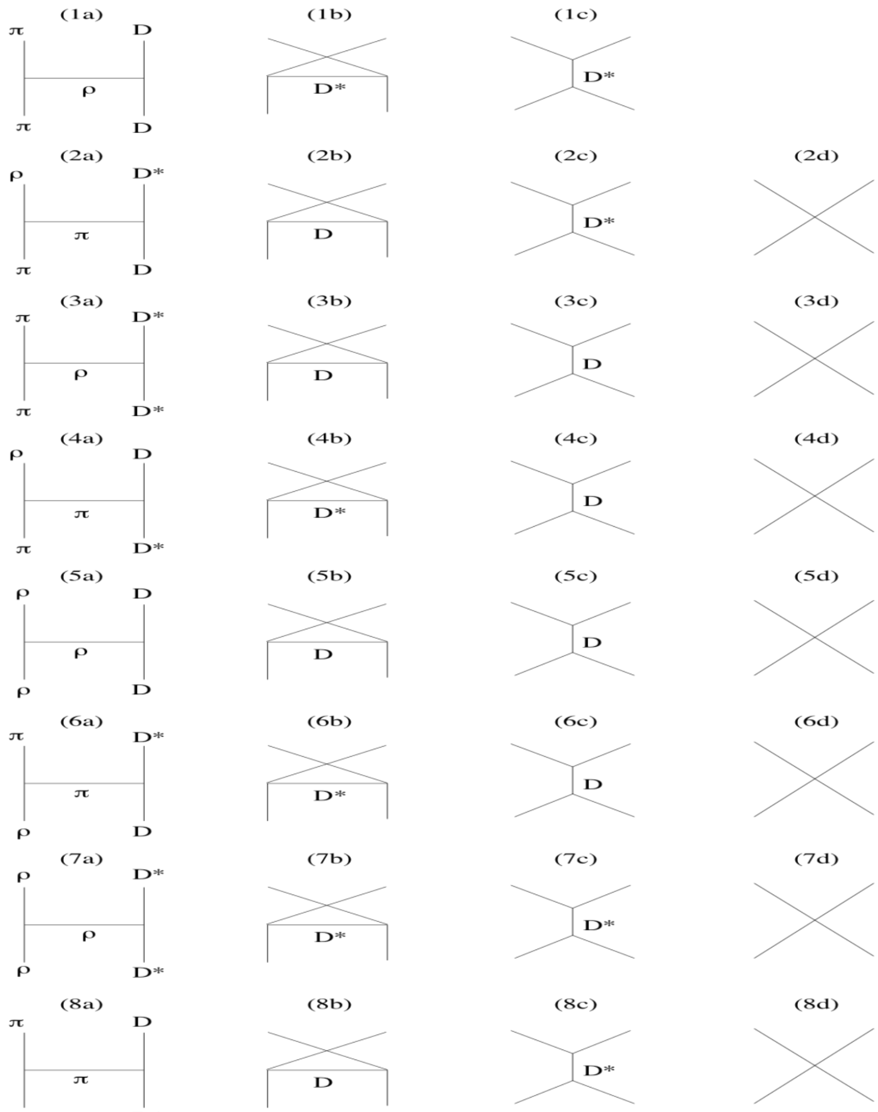
Integrating over the position space:

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

Can be generalized to 3-particle recombination (baryon)

$$\mathcal{L}_0 = \mathrm{Tr}\left(\partial_\mu P^\dagger \partial^\mu P\right) - \frac{1}{2}\mathrm{Tr}\left(F^\dagger_{\mu\nu} F^{\mu\nu}\right)$$

$$\mathcal{L} = \mathcal{L}_0 + ig\mathrm{Tr}\left(\partial^\mu P\left[P, V_\mu\right]\right) - \frac{g^2}{4}\mathrm{Tr}\left(\left[P, V_\mu\right]^2\right) + ig\mathrm{Tr}\left(\partial^\mu V^\nu\left[V_\mu, V_\nu\right]\right) + \frac{g^2}{8}\mathrm{Tr}\left(\left[V_\mu, V_\nu\right]^2\right)$$




$$g_{\rho\pi\pi} = 6.1$$

$$g_{\pi DD^*} = 4.4$$

$$g_{\rho DD} = g_{\rho D^* D^*} = 2.52$$

$$g_{\rho\rho\rho} = g_{\rho\pi\pi}$$

$$g_{\pi\rho DD^*} = g_{\pi DD^*} g_{\rho DD}$$

$$g_{\pi\pi D^* D^*} = 2\ g^2_{\pi DD^*}$$

$$g_{\rho\rho DD} = 2\ g^2_{\rho DD}$$

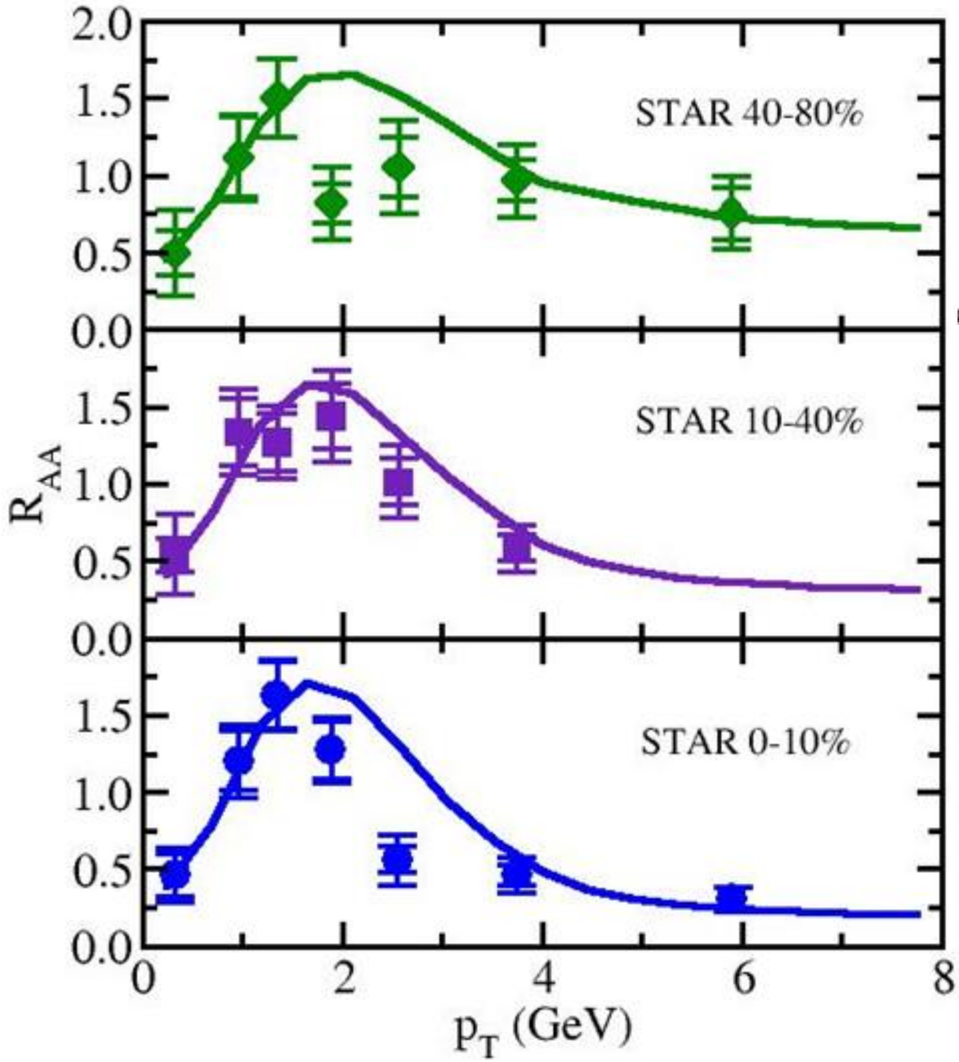
$$g_{\rho\rho D^* D^*} = g^2_{\rho D^* D^*}$$

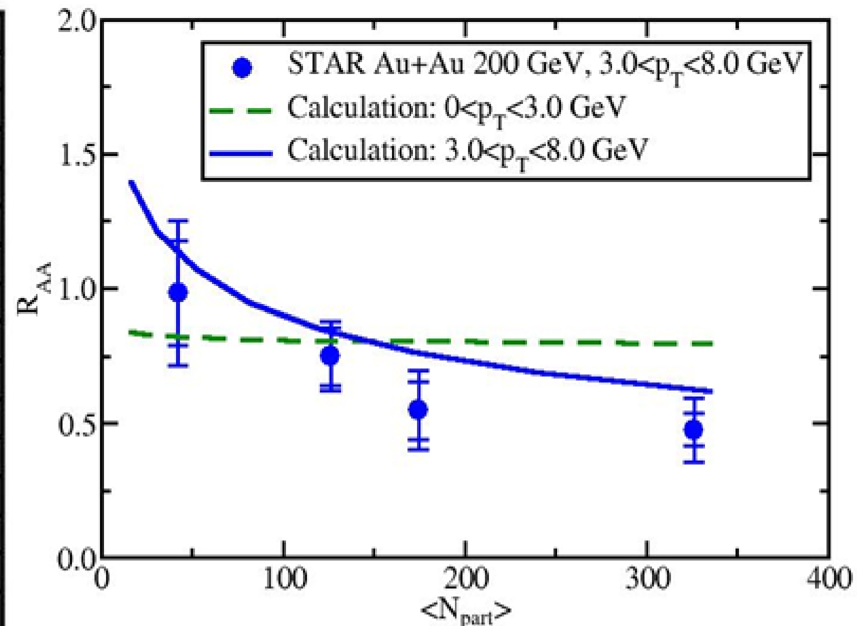
SU(4) symmetry gives following relations:

$$\frac{g_{\rho\pi\pi}}{2}(3.0) = g_{\pi DD^*}(4.4) = g_{\rho DD}(2.5)$$

Lin and Ko, NPA, 2001

# *D* meson $R_{AA}$ at RHIC




**$R_{AA}$ for different centralities at RHIC is consistent with observations.**