Toward a complete description of Heavy Flavor Transport in Medium

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Outline

1. Introduction:

- Heavy quark probe for hot & dense matter

2. HQ probe: a strongly coupled framework

- Transport coefficient
- HQ diffusion in QGP: Langevin + hydro simulation
- Hadronization: coalescence vs fragmentation
- D-meson diffusion in hadronic phase

3. Heavy ion phenomenology

- RHIC: Non-photonic electrons, Ds vs D mesons
- LHC: D mesons

4. Summary

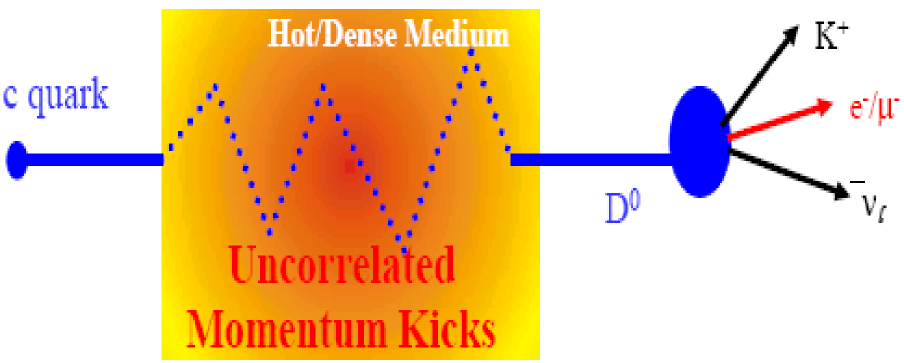
1.1 Introduction: HQ probe

- **primordial hard production + number conserved**
- **thermalization delayed** $$\tau_Q \approx \frac{m_Q}{T}\tau_q \approx 6 * \tau_q \geq \tau_{QGP}$$

➔ **Heavy quarks make a direct probe of the medium**

- **HQ diffusion in QGP: elastic scatterings with medium**

$$q_0 \sim \vec{q}^2 / 2m_Q << |\vec{q}|$$



Brownian motion:
Fokker-Planck Equation

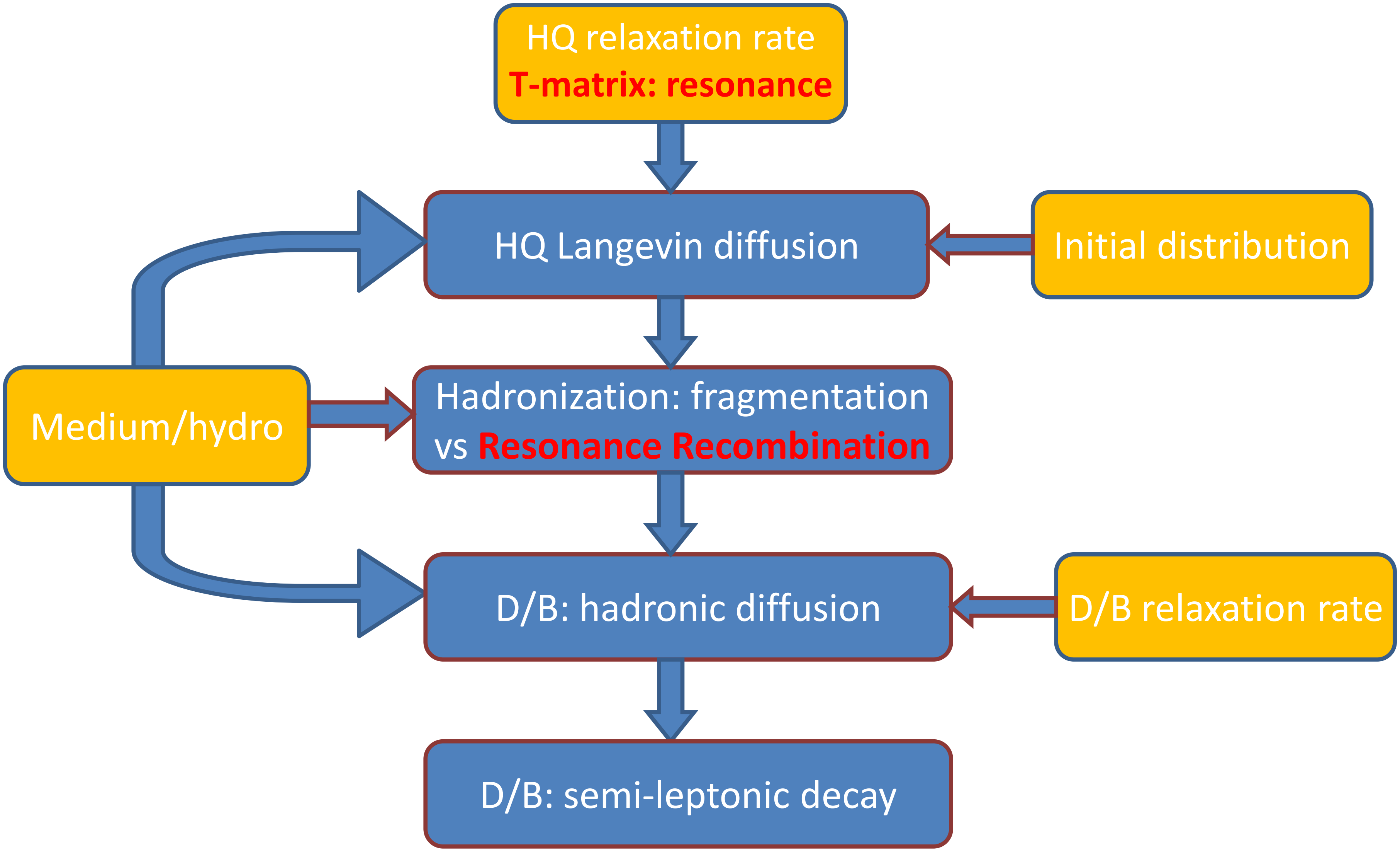
$$\frac{\partial f}{\partial t} = \gamma \frac{\partial (pf)}{\partial p} + D\frac{\partial^2 f}{\partial p^2}$$

thermalization rate **diffusion coefficient**

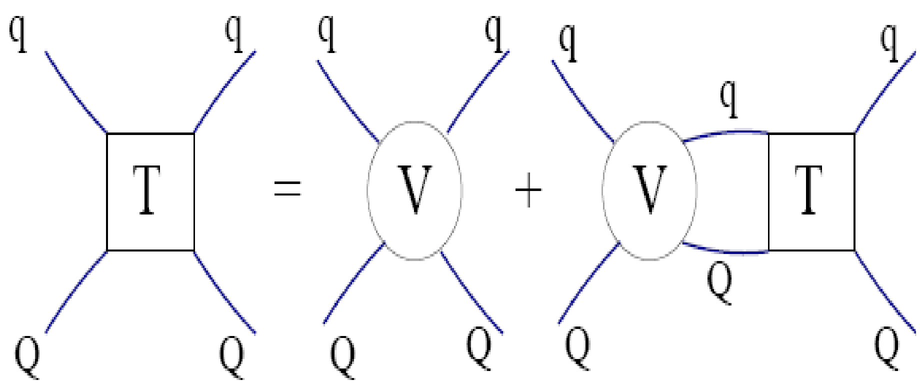
$$\gamma \sim \int |T_{Qq}|^2 (1-\cos\theta) f^q$$

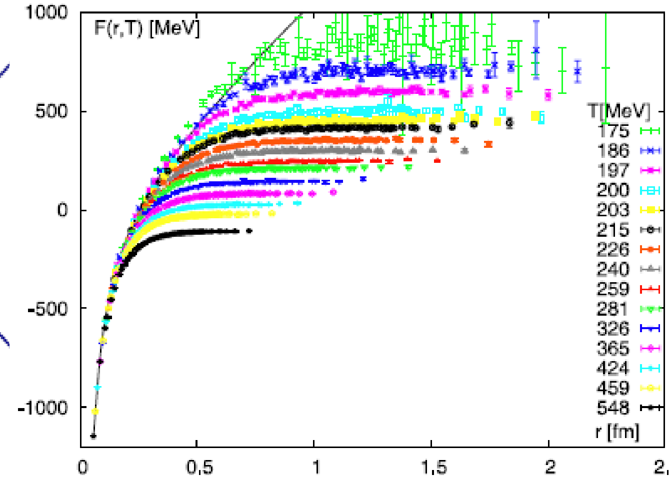
$$D = \gamma m_Q T$$

1.2 A strongly coupled framework: HQ



2.1.1 HQ relaxation rate: T-matrix



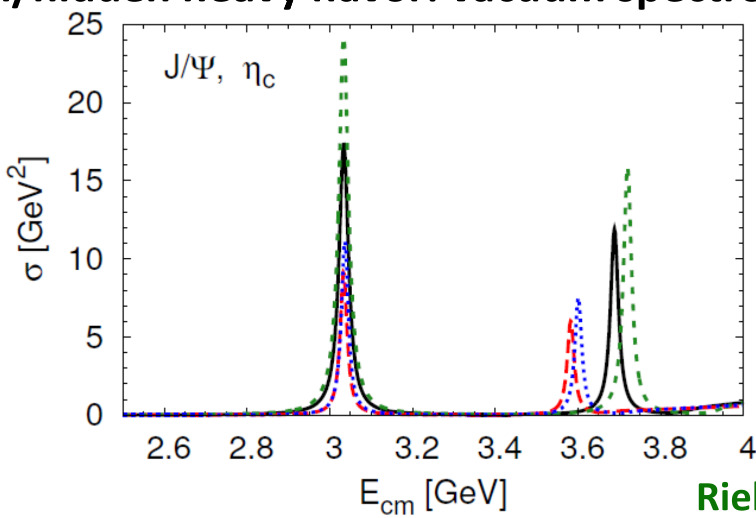


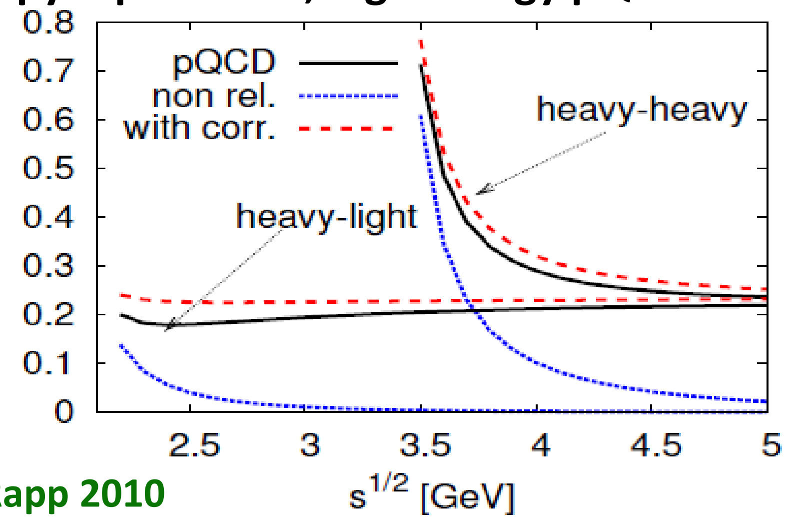
◆**lattice potential:** **Kaczmarek,2008**

$$U = F - T\frac{\partial F}{\partial T}$$

➔ **Resummation & Unitarization**

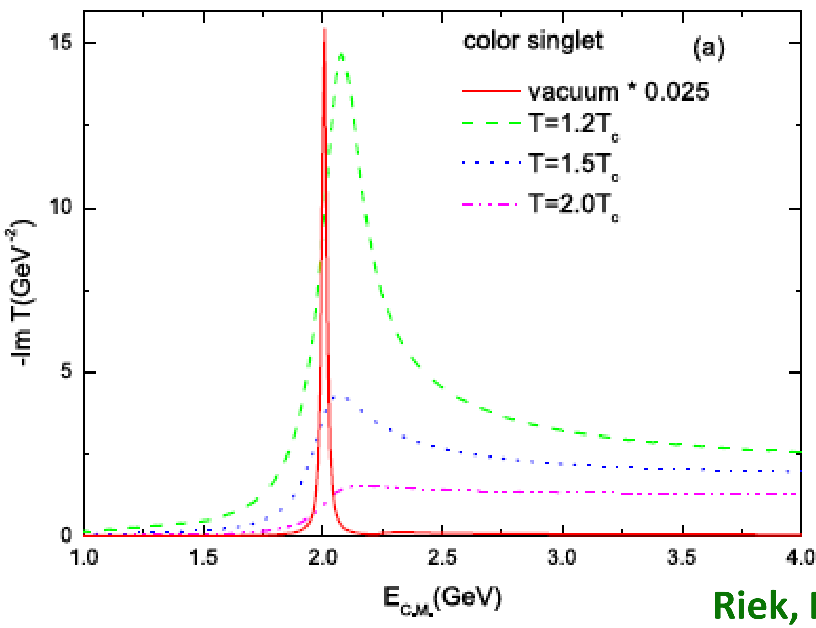
◆**Open/hidden heavy flavor: vacuum spectroscopy reproduced; high energy pQCD recovered**

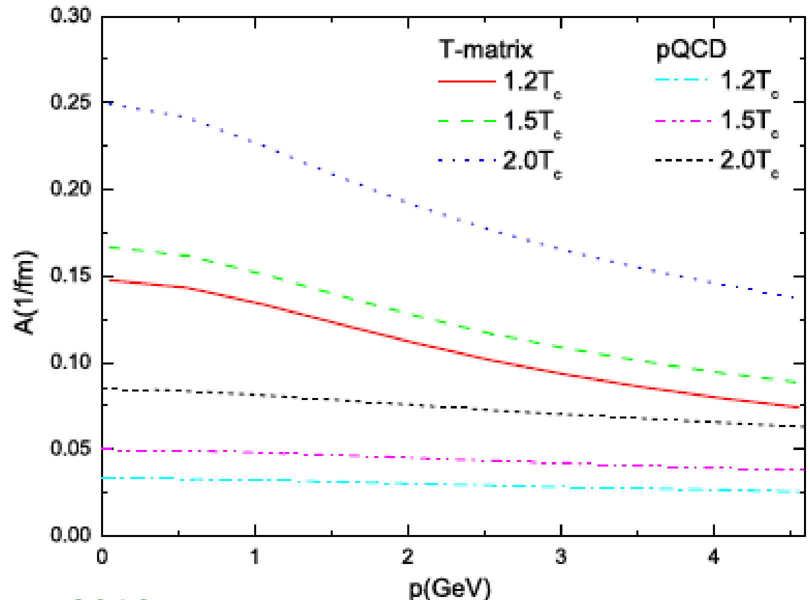




Riek, Rapp 2010

2.1.2 HQ relaxation rate: QGP





Riek, Rapp 2010

◆ T-matrix resummation ➔ color singlet and anti-triplet broad Feshbach resonances up to ~1.5 T_C

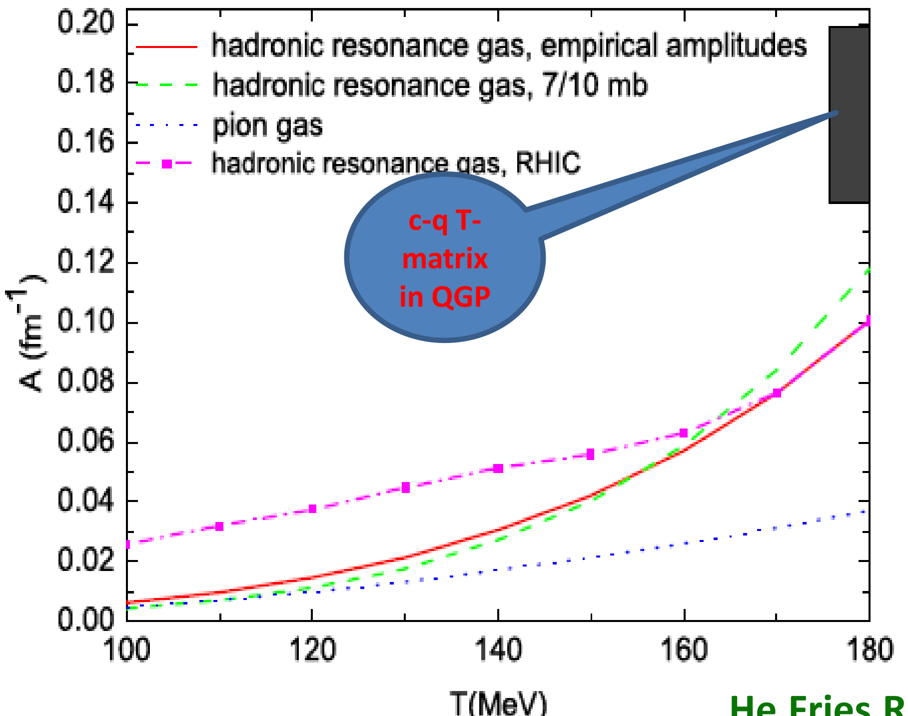
◆ this resonance correlation ➔ resonance recombination

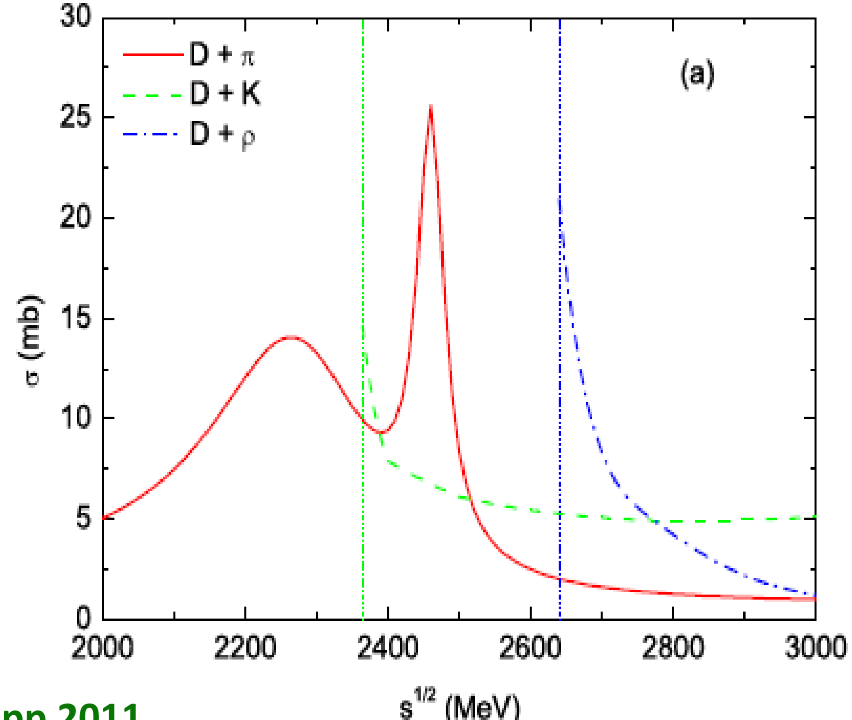
◆ T-matrix relaxation rate: a factor ~4-5 larger than LO pQCD at T=1.2 T_c

◆ T-dependence: screening potential; p-dependence: less contribution from Feshbach resonance as p increases

2.1.3 D-meson relaxation rate : HRG

- **D + pion, K,eta,rho,omega,K*,N,Delta, empirical s-wave cross sections from effective hadronic theory:** Lutz et al., 2004,2006; E.Oset et al. 2007



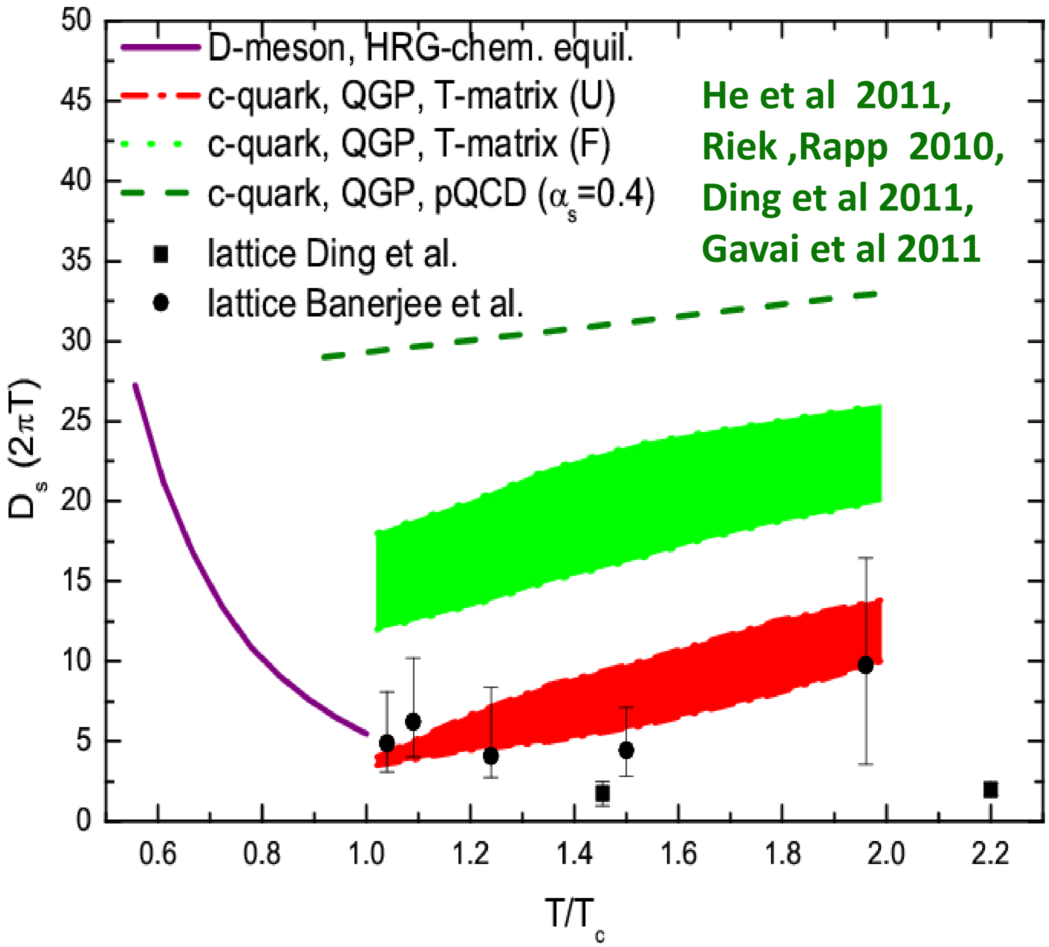


He,Fries,Rapp 2011

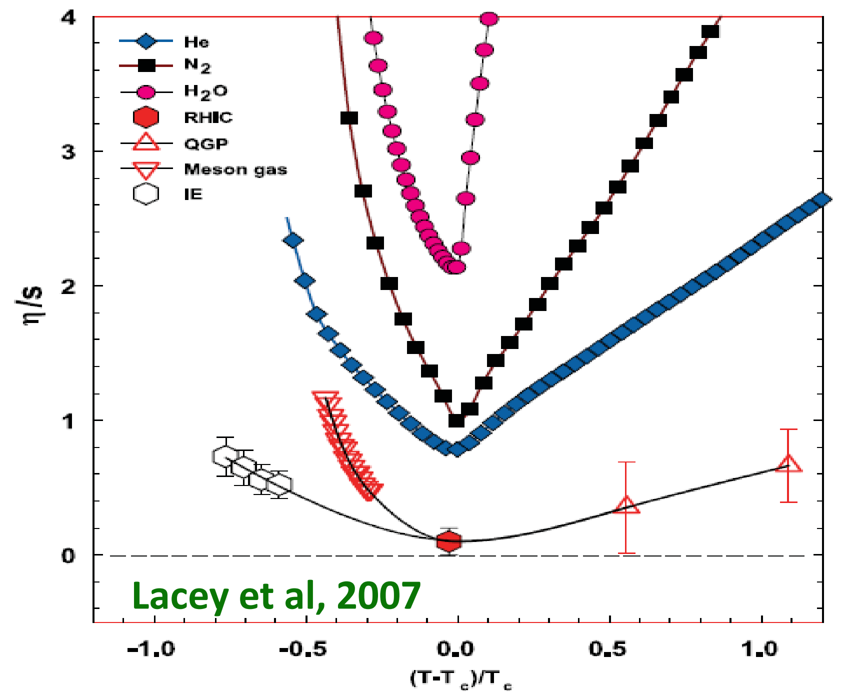
- **A~0.1 /fm at T=180 MeV, comparable to the non-perturbative T-matrix calculation of charm quark thermal relaxation rate in QGP**

2.1.4 Summarizing charm diffusion coeffi.

Hadronic Matter vs. QGP vs. Lattice QCD (quenched)



- **Transport coeffi.**: eta/s = (1/5 ~ 1/2)D_sT, Danielewicz&Gyulassy, 1985
- D_s translates into eta/s = (2-5)/4pi at T=180 MeV

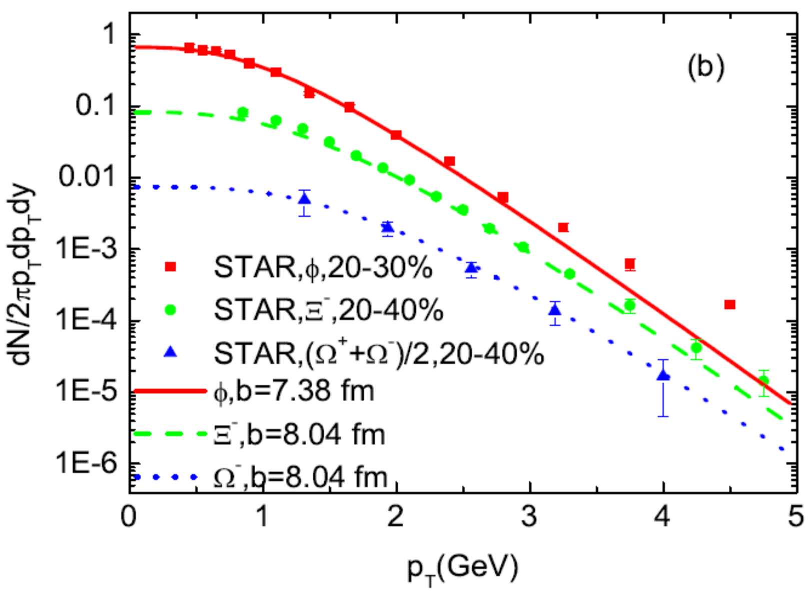


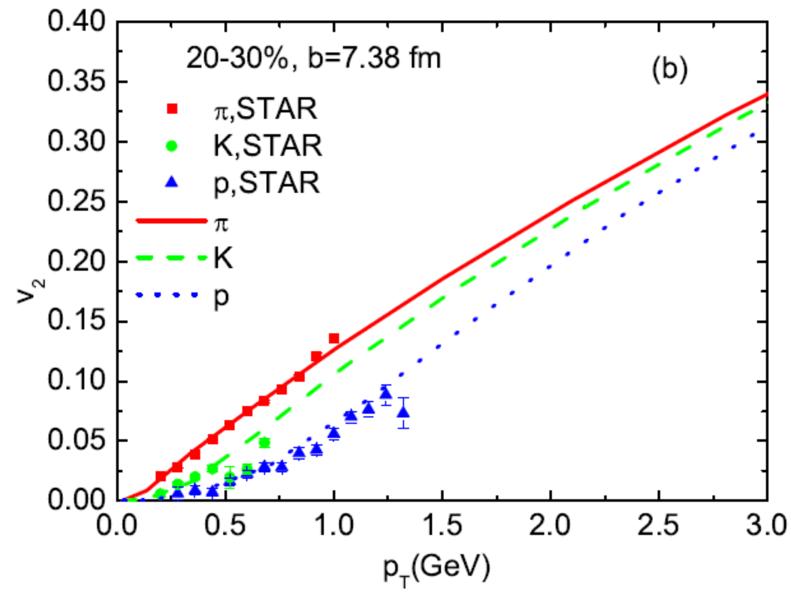
- Ds=T/(mA): T-matrix vs lattice; Minimum around Tc + Quark-hadron duality?!
- The charm diffusion: another perspective of looking into the transport properties of sQGP/dense matter

2.2.1 Medium evolution: hydro RHIC

- updated ideal 2+1 D hydro based on AZHYDRO Kolb + Heinz, 2003
- lattice/HRG-PCE EoS + pre-equilibrium flow + compact initial density s(x,y)~ n_{BC} (x,y)

  → fast build-up of radial flow + essential saturation of bulk v_2 around T_c

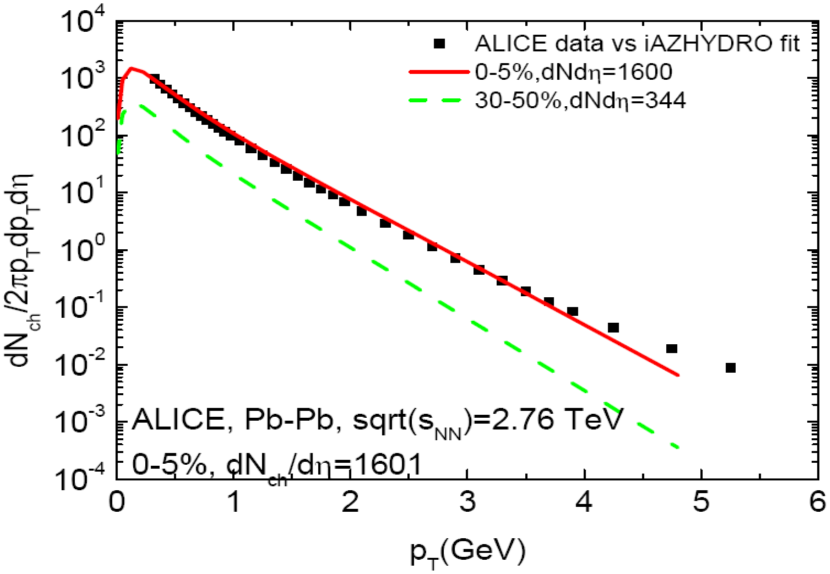


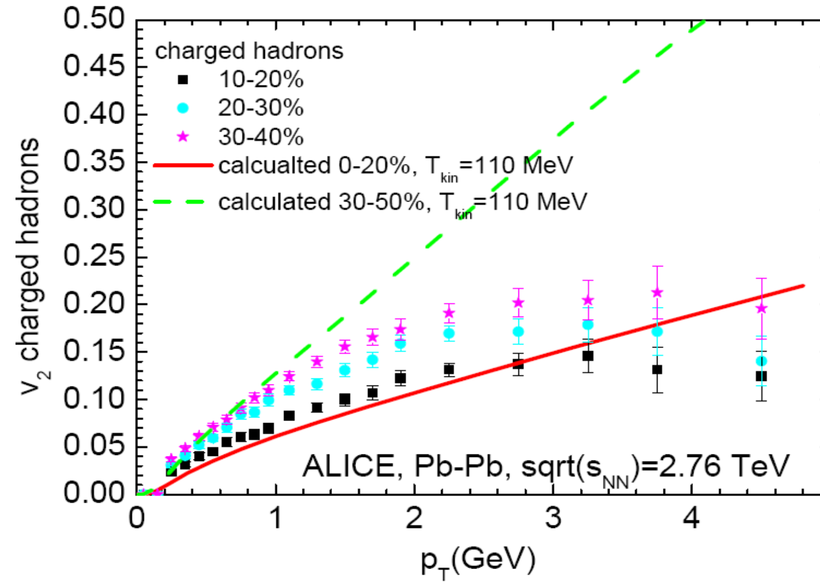


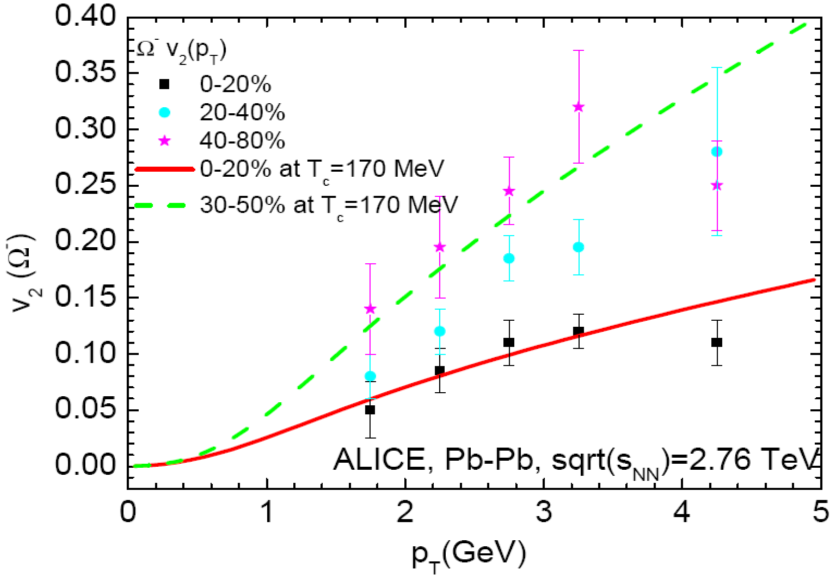
- multistrange hadrons ϕ, Ξ, Ω probably freeze out earlier STAR, PRC79,2009
- multi-strange particles' spectra and v_2 fitted at T_{ch} =160 MeV

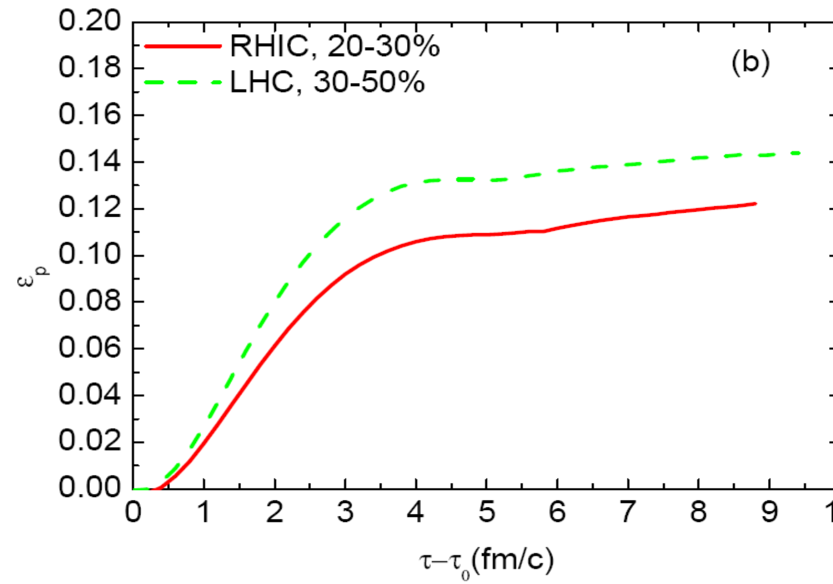
  bulk particles' spectra and v_2 fitted at T_{kin}=110 MeV He, Fries,Rapp, 2012

2.2.2 Medium evolution: hydro LHC







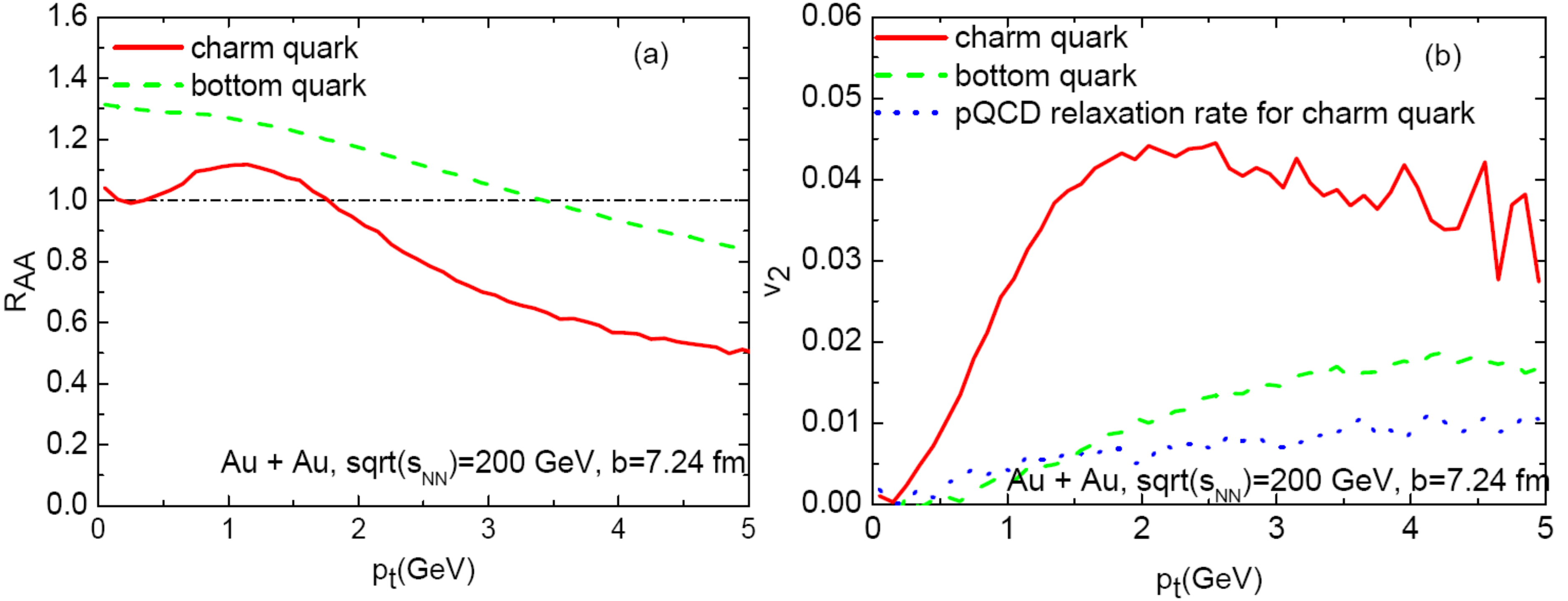


2.2.3 HQ diffusion: Langevin simulation

Langevin + hydro simulation down to T_c=170 MeV
fluid rest frame updates → boost to lab frame

$$d\mathbf{x} = \frac{\mathbf{p}}{E}dt,$$

$$d\mathbf{p} = -\Gamma(p)\mathbf{p}dt + \sqrt{2D(\mathbf{p}+d\mathbf{p})\,dt}\rho$$



- **initial HQ distribution: PYTHIA pp + Glauber n_{BC}**
- **quenching: early stage when medium particles' density is high**
- **v_2 : develops at later stage when the medium particles' v_2 is large**

2.3.1 Hadronization: Resonance Recombination

- **Hadronization = Resonance formation** $c\bar{q} \to D$

→ *consistent with T-matrix findings of resonance correlations towards T_c*

- **Realized by Boltzmann equation** Ravagli & Rapp,2007

$$p^\mu \partial_\mu f_M(t,\vec{x},\vec{p}) = -m\Gamma f_M(t,\vec{x},\vec{p}) + p^0 \beta(\vec{x},\vec{p})$$

gain term

$$\beta(\vec{x},\vec{p}) = \int \frac{d^3p_1 d^3p_2}{(2\pi)^6} f_q(\vec{x},\vec{p}_1) f_{\bar{q}}(\vec{x},\vec{p}_2) \times \sigma(s) v_{\rm rel}(\vec{p}_1,\vec{p}_2) \delta^3(\vec{p}-\vec{p}_1-\vec{p}_2)$$

Breit-Wigner

$$\sigma(s) = g_\sigma \frac{4\pi}{k^2} \frac{(\Gamma m)^2}{(s-m^2)+(\Gamma m)^2}$$

- **Equilibrium limit** $$f_M^{\rm eq}(\vec{p}) = \frac{E_M(\vec{p})}{m\Gamma} \int d^3x \beta(\vec{x},\vec{p})$$

- **Energy conservation + detailed balance**

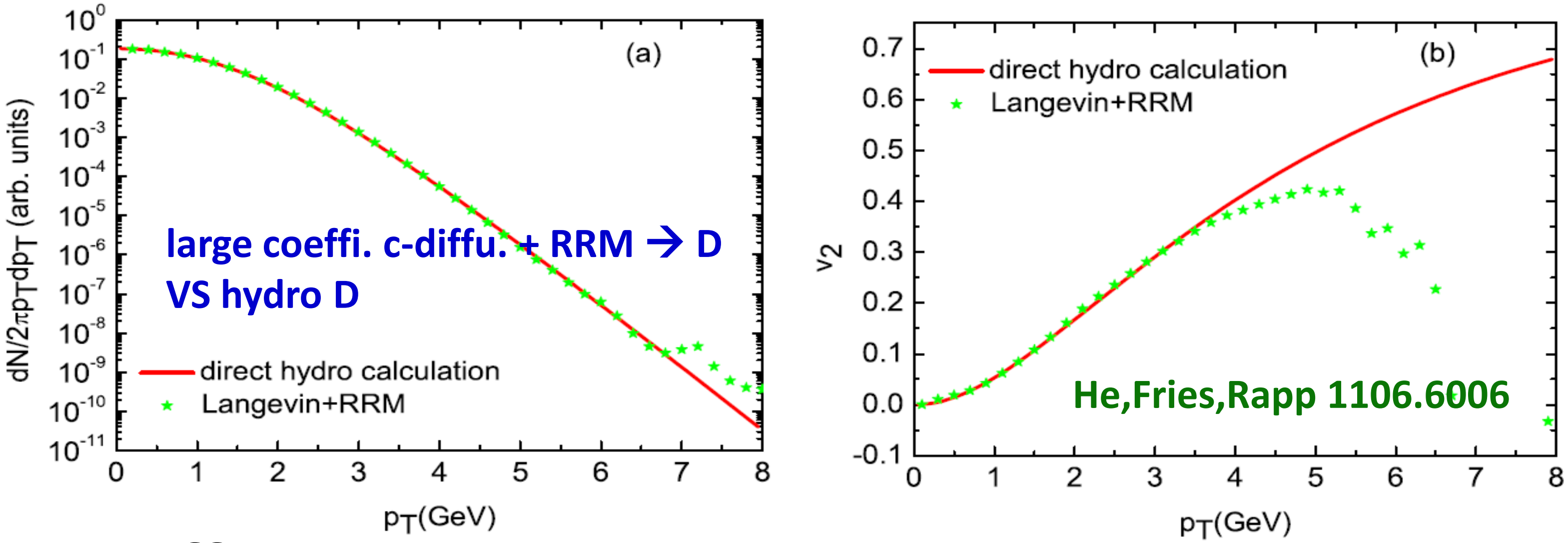
→ **equilibrium mapping**

2.3.2 Hadronization: coal. vs frag.

- **RRM coalescence:**

--- 4-mom. conservation, correct thermal equilibrium limit

--- implement on hydro freezeout hypersurface with full space-mom. correl.



- **Diffusion vs coalescence:** conceptually consistent

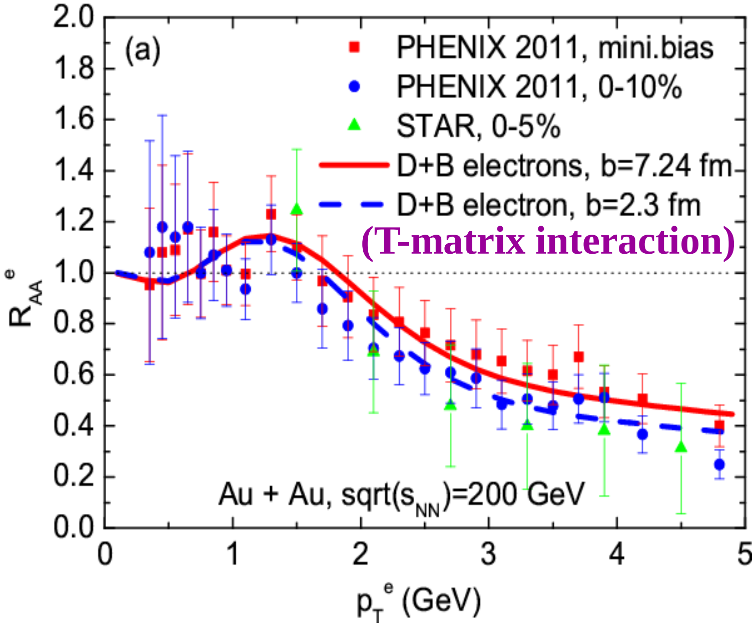
--- same interaction (T-matrix) underlying diffusion + hadronization

- **Fragmentation:** $D(z) = \delta(z-1)$ incompatible with thermalization

--- coal.proba. based on scattering rate: $P_{coal}(p_t) = \tau_{res}\gamma_Q(p_t)$

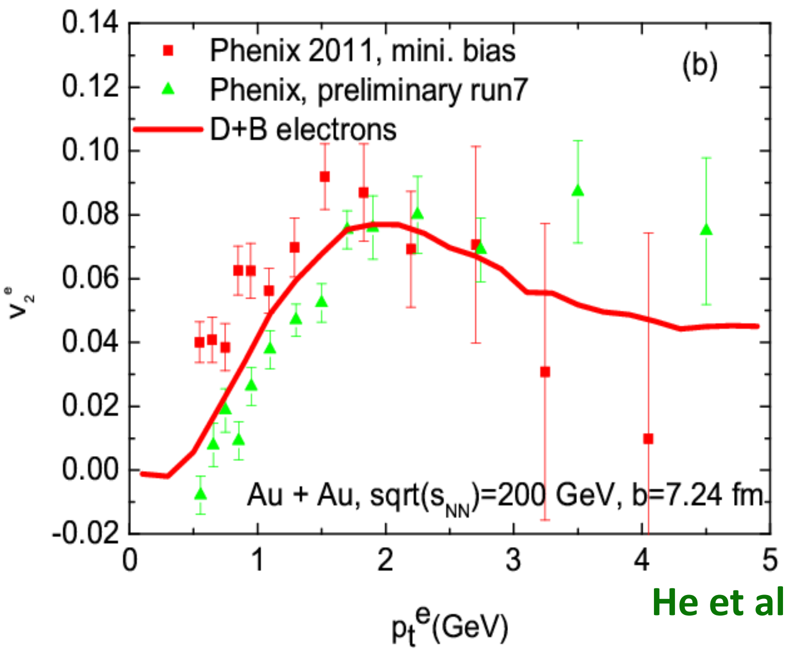
--- coal. dominates at low p_T; yields to frag. at higher p_T

3.1 Phenomenology: e± Spectra RHIC

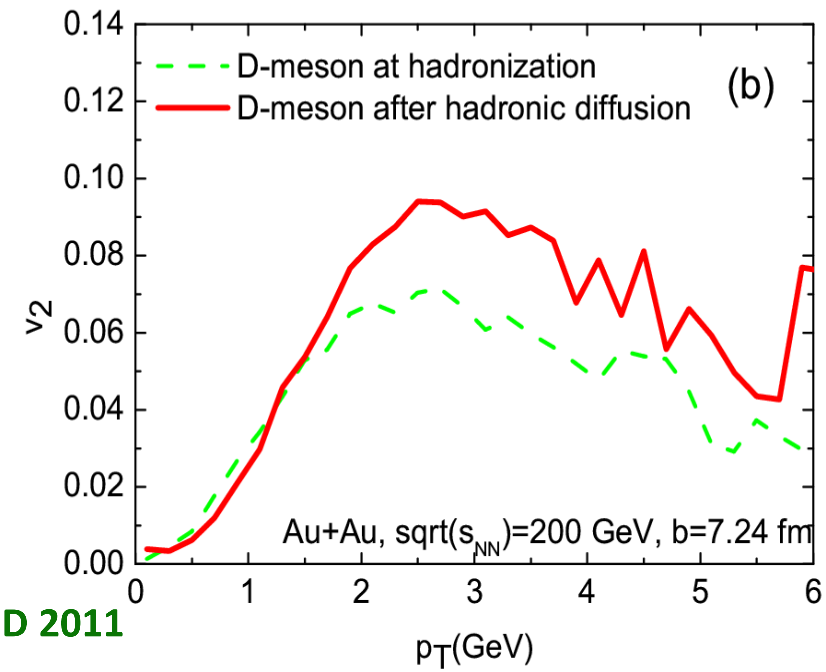


- medium modified D and B mesons: c/b diffusion + coal./frag. + hadronic diffusion
- semi-leptonic decays c(b) → s(c) + e + nu

$\langle|\mathcal{M}|^2\rangle \propto (p_s \cdot p_\nu)(p_c \cdot p_e)$ $\quad$ $\langle|\mathcal{M}|^2\rangle \propto (p_c \cdot p_e)(p_b \cdot p_\nu)$

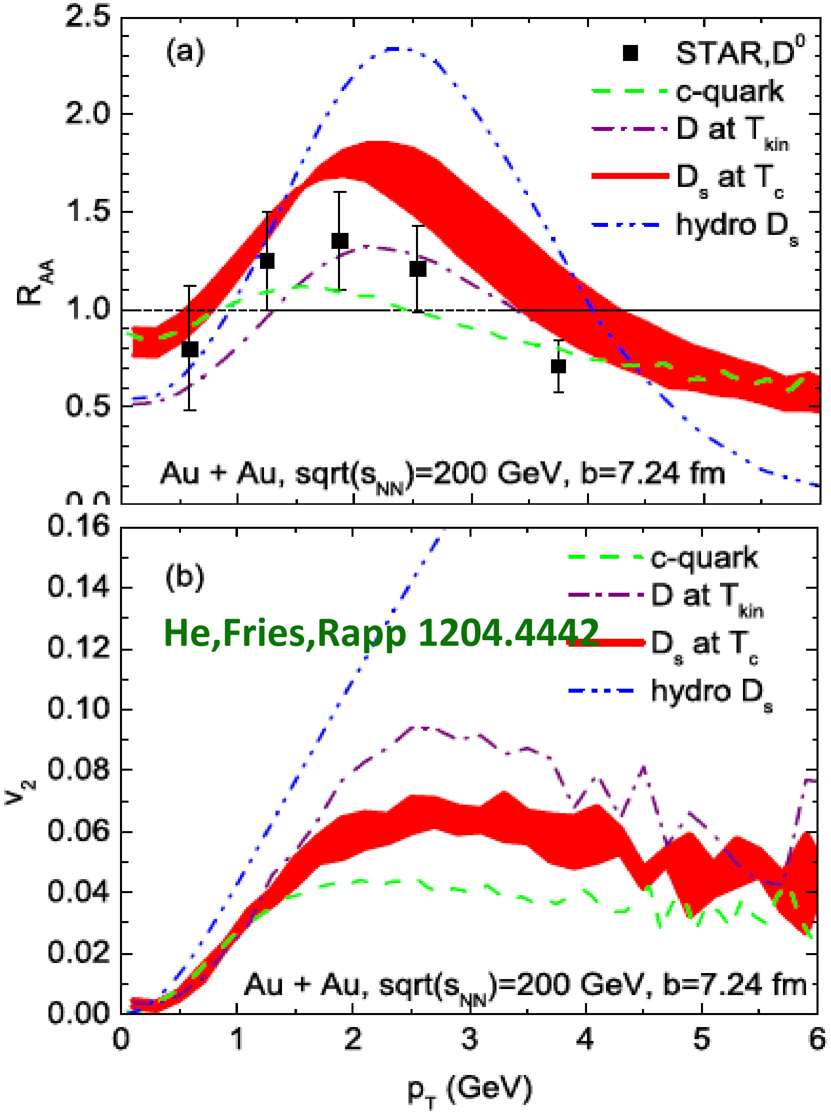


D Hadronic Diffusion



He et al., CPOD 2011

3.2 Phenomenology : D vs Ds mesons RHIC



◆ **pronounced D/Ds flow-bump?!**

RRM = an extra interaction, driving D closer to equilibrium

◆ **Ds R_{AA} ~ 1.5-1.8 at p_T~2 GeV**

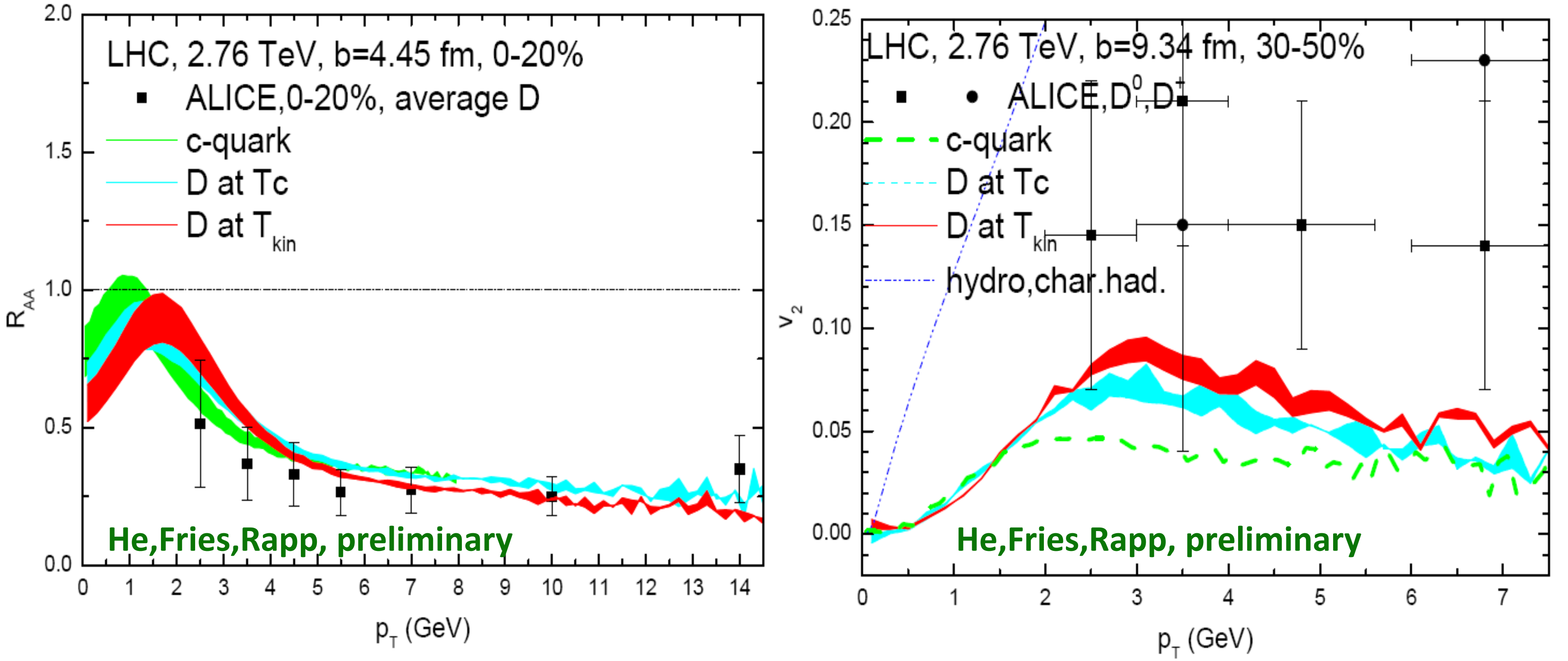
strong coupling c-QGP + coalescence + strangeness enhancement (unique valence quark content csbar)

◆ **Ds freezeout at T_c, D at T_{kin}**

D vs Ds v_2: quantitative measure of charm interaction in hadronic phase

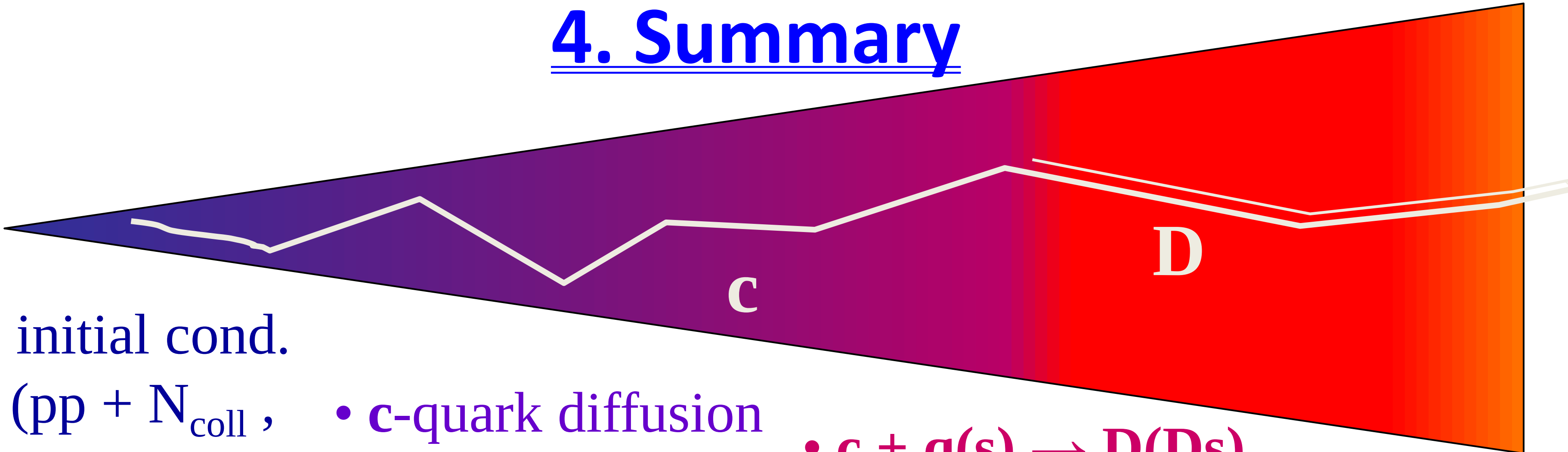
➔ **a unique pattern of R_{AA} and v_2 of Ds vs D mesons emerges**

3.3 Phenomenology: D-mesons LHC



- **initial charm distribution: fit to D-meson spectrum in pp@LHC + delta frag.**
- **background medium: ideal hydro tuned to fit charged hadrons and Omega data**
- **R_{AA}: considerable shadowing, MNR-EPS09, 66%-78% + observable flow bump**
- **v_2 : QGP diffu. + coalescence + HRG diffu. (coal.prob. 52% - 90%)**

4. Summary



- initial cond. (pp + N_{coll} , Cronin, shadowing)
- **c**-quark diffusion in QGP liquid (**T**-matrix, ***No K-factor***)
- **c + q(s) → D(Ds)** resonance recombination; Ds freezeout
- **D**-meson diffusion in hadron liquid

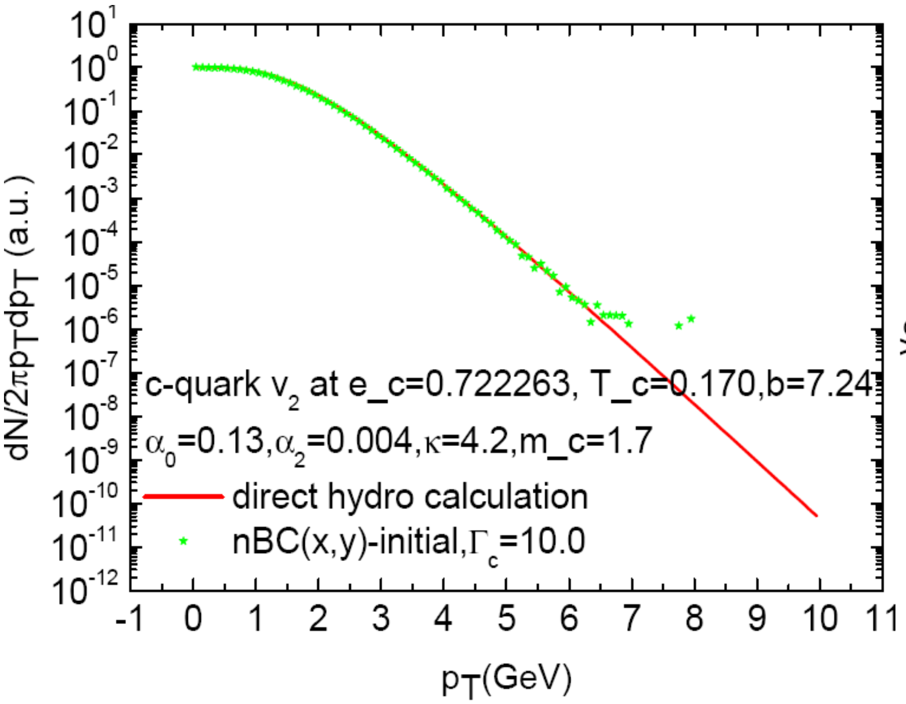
● Conceptual Consistency

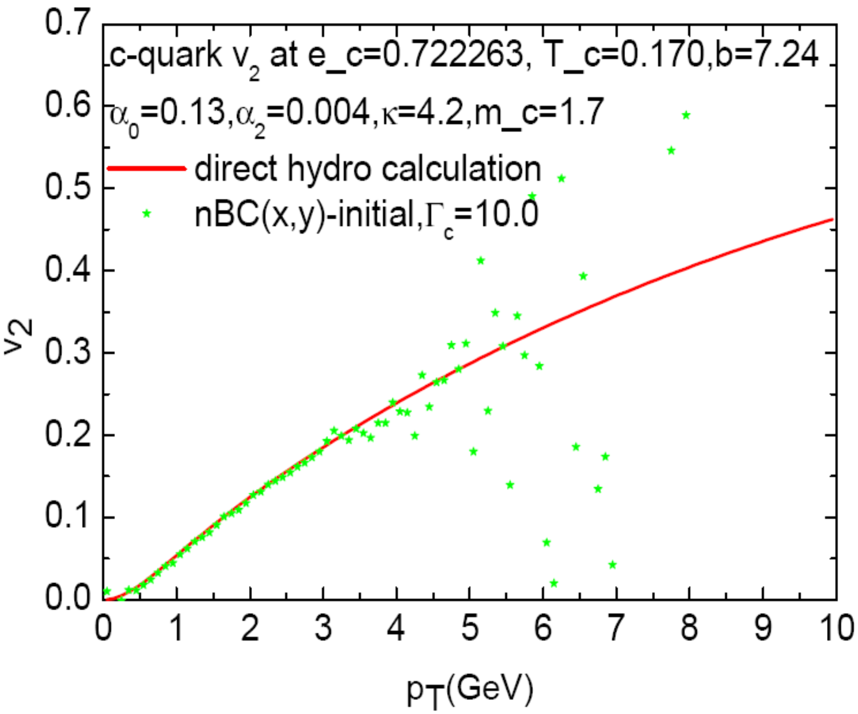
- **diffusion ↔ hadronization:**
  based on the same resonant interaction from T-matrix
- **diffusion ↔ bulk medium:**
  both based on strongly coupled QGP, **non-perturbative**

● Application: RHIC & LHC

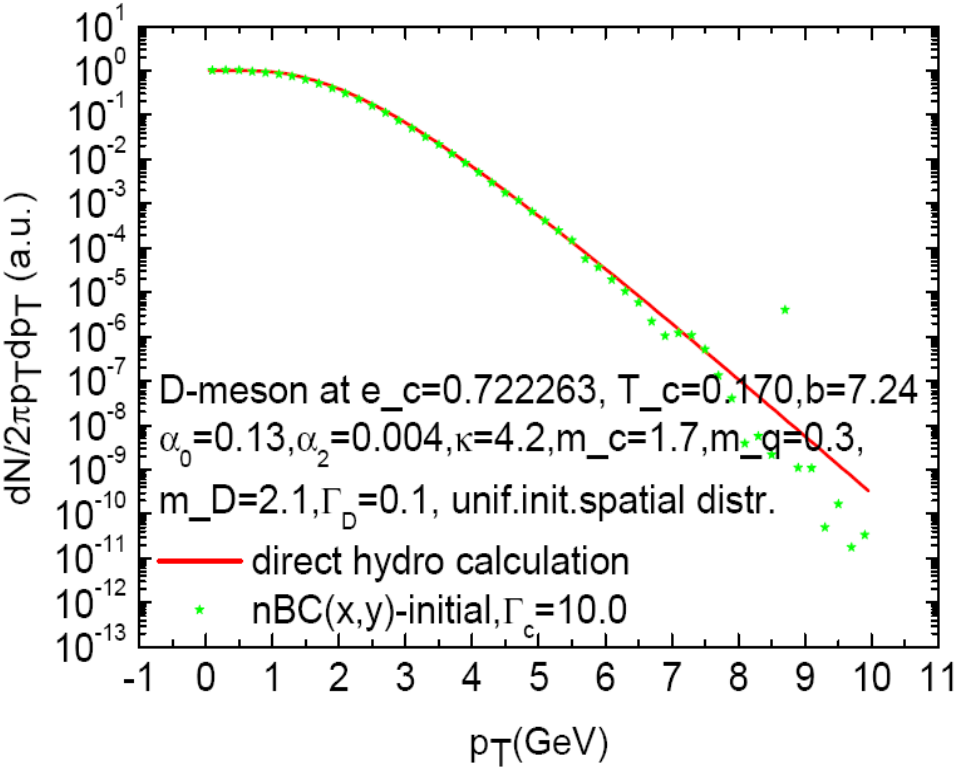
dynamical charm flow features emerge

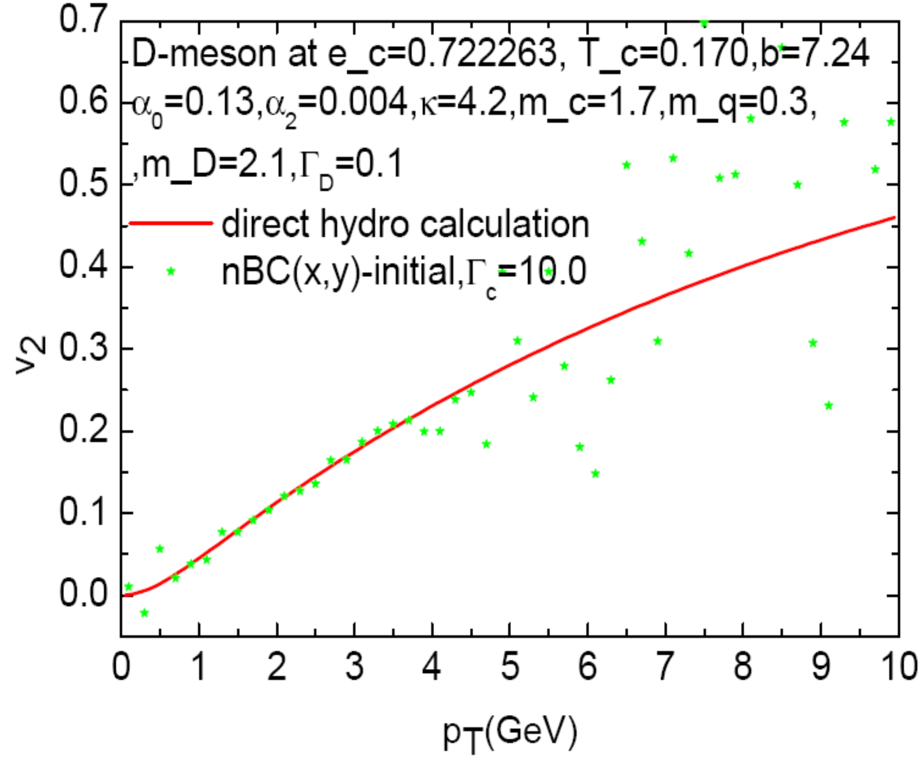
Backup 1: charm quark Langevin diffusion equilibrium



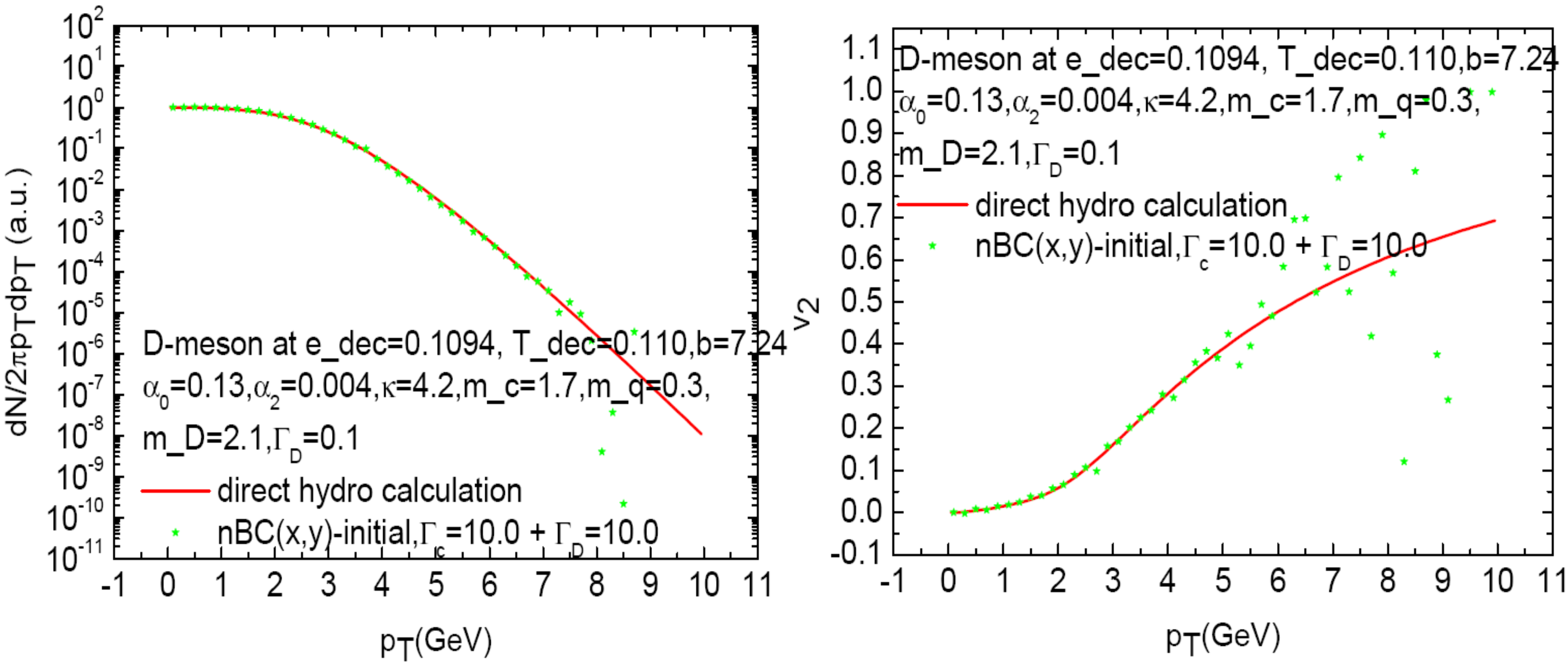


Backup 2: D-meson RRM equilibrium





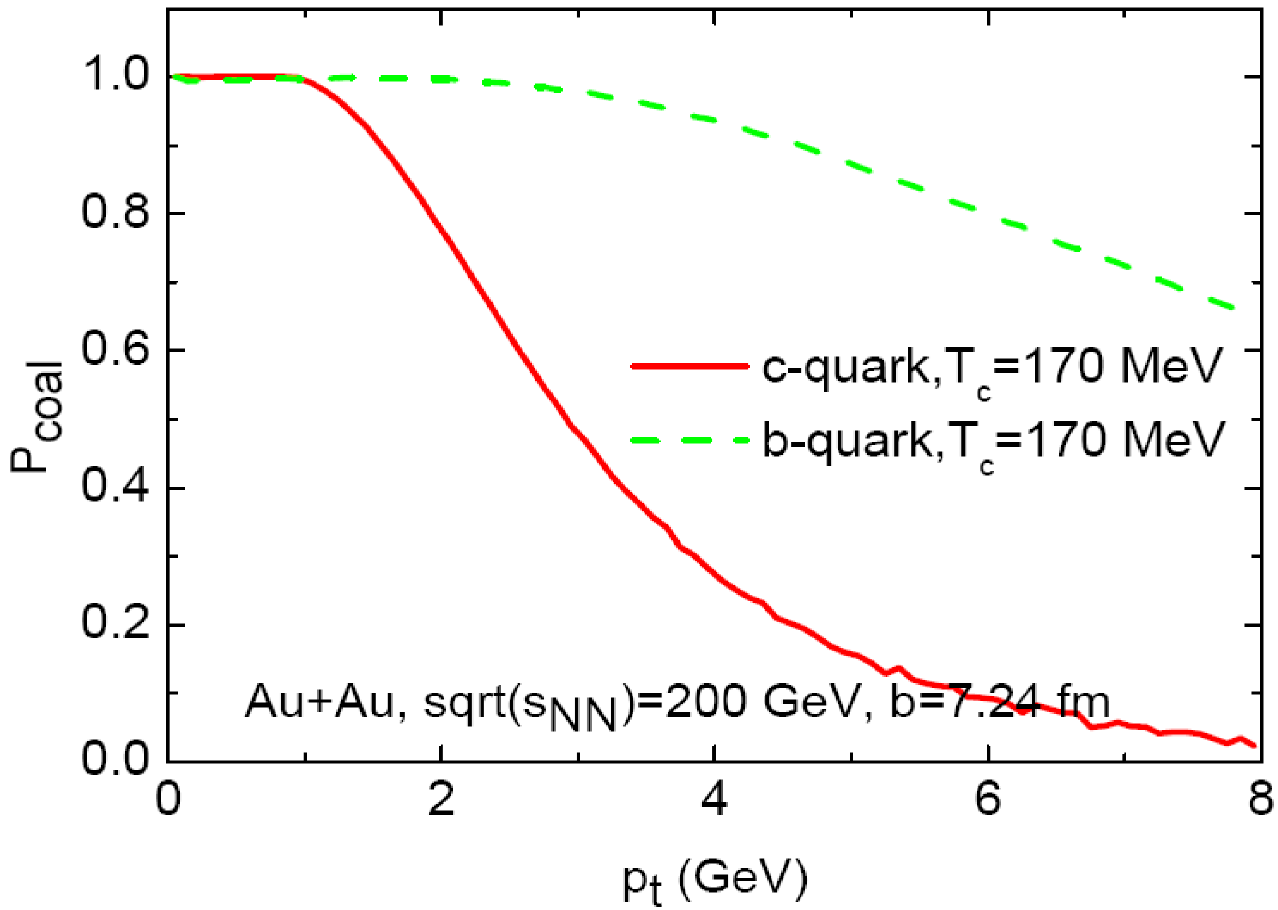
Backup 3: D-meson hadronic phase Langevin diffuison equilibrium



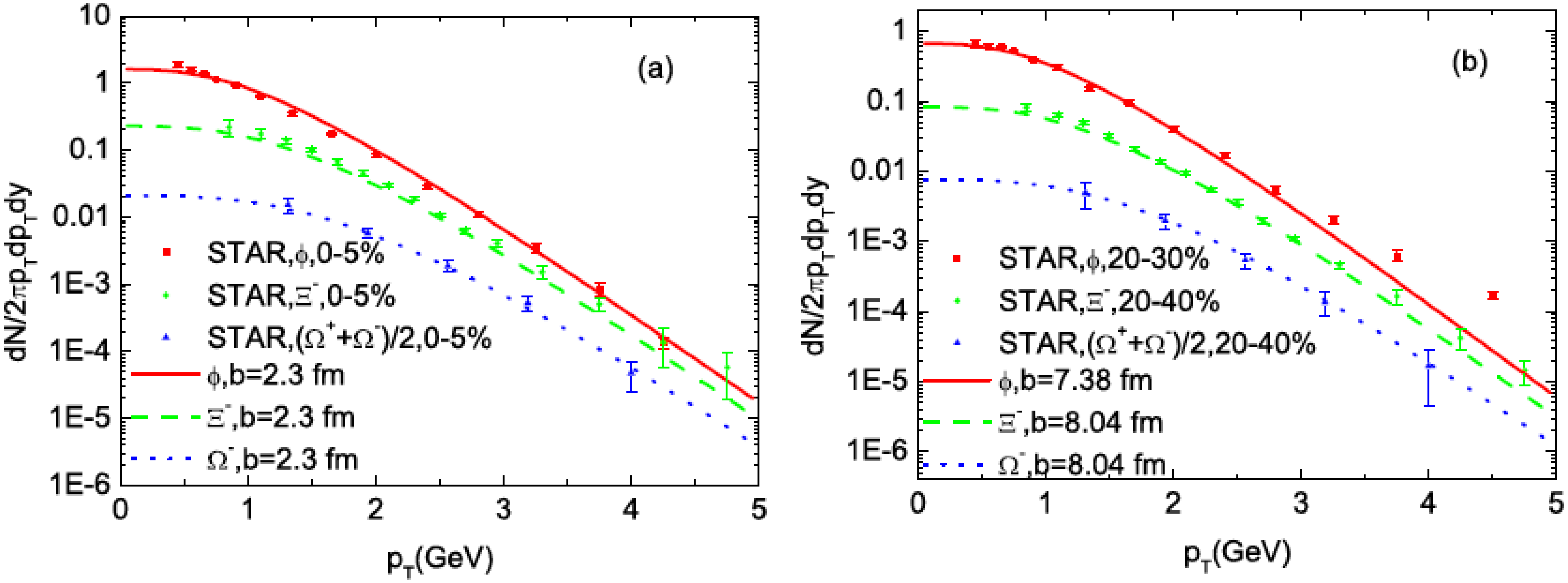
Backup 4: c/b coal.prob. based on scattering rate

- Aim: formulate coal.prob. consistent with RRM
- Quark scattering rate (vs thermal relaxation rate): $\gamma_Q = n < \sigma v_{rel} >$
  Breit-Wigner resonant cross section to reproduce color singlet contribution to relaxation rate ➔ scattering rate➔ boosted to lab frame at the end of Langevin simulation: $\gamma_Q = \gamma_Q(p_t)$
- Charm quark scattering time: $\tau_Q = 1/\gamma_Q$. Within this time duration, we can form a D-meson/resonance through c-qbar resonant scattering (RRM). If the resonance formation time allowed by the system evolution (mixed phase duration) $\tau_{res} > \tau_Q$, ➔ $P_{coal}(p_t) = 1$;otherwise, $P_{coal}(p_t) = \tau_{res}\gamma_Q(p_t)$

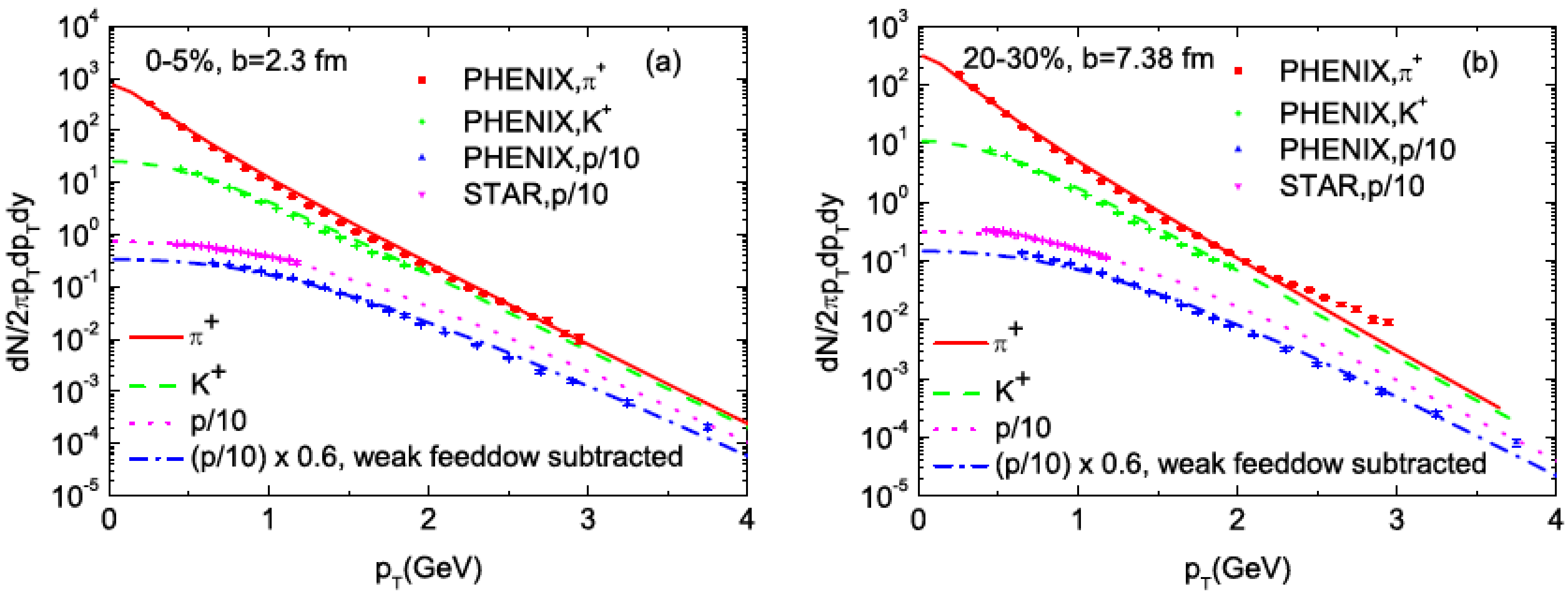
Backup 5: c/b coal.prob. based on scattering rate (continued)



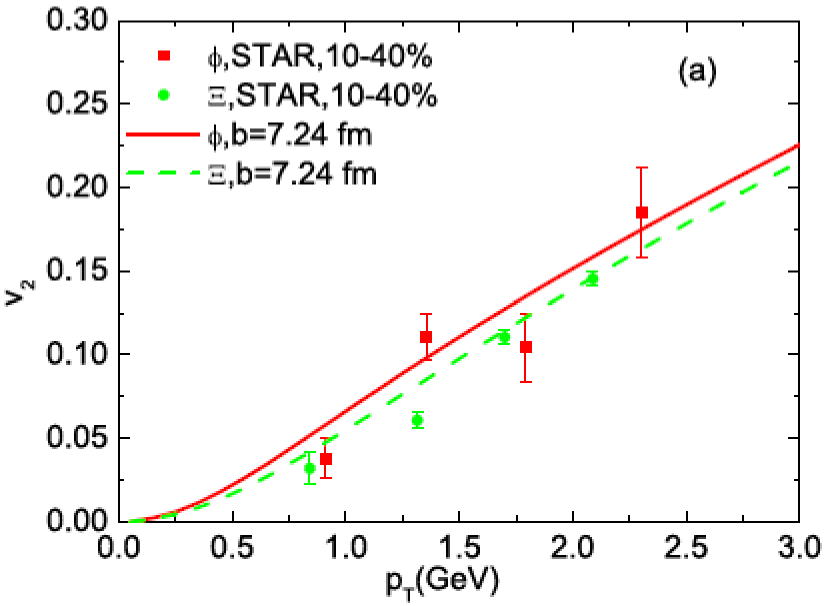
Backup 6:New hydro fits: multistrange particles' spectra

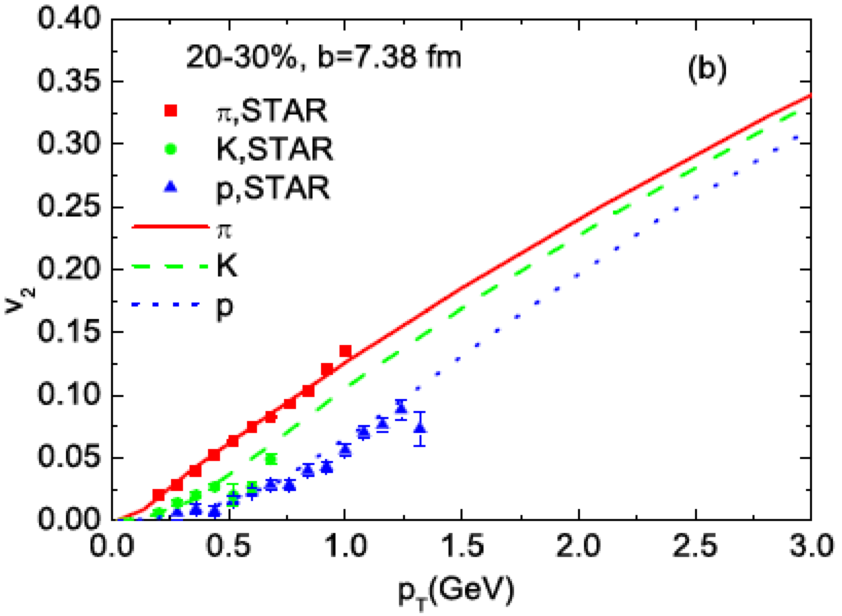


Backup 7:New hydro fits: bulk particles' spectra

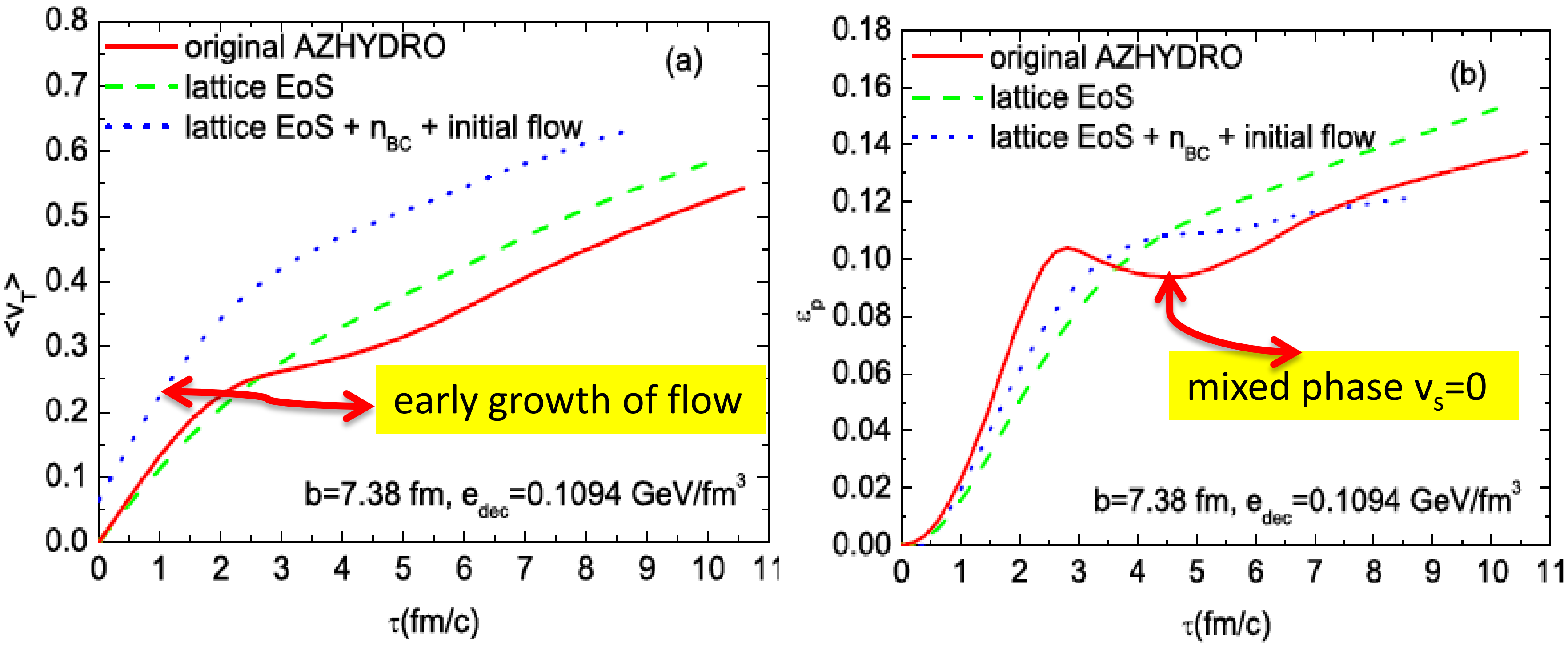


Backup 8:New hydro fits: multistrange and bulk particles' v2



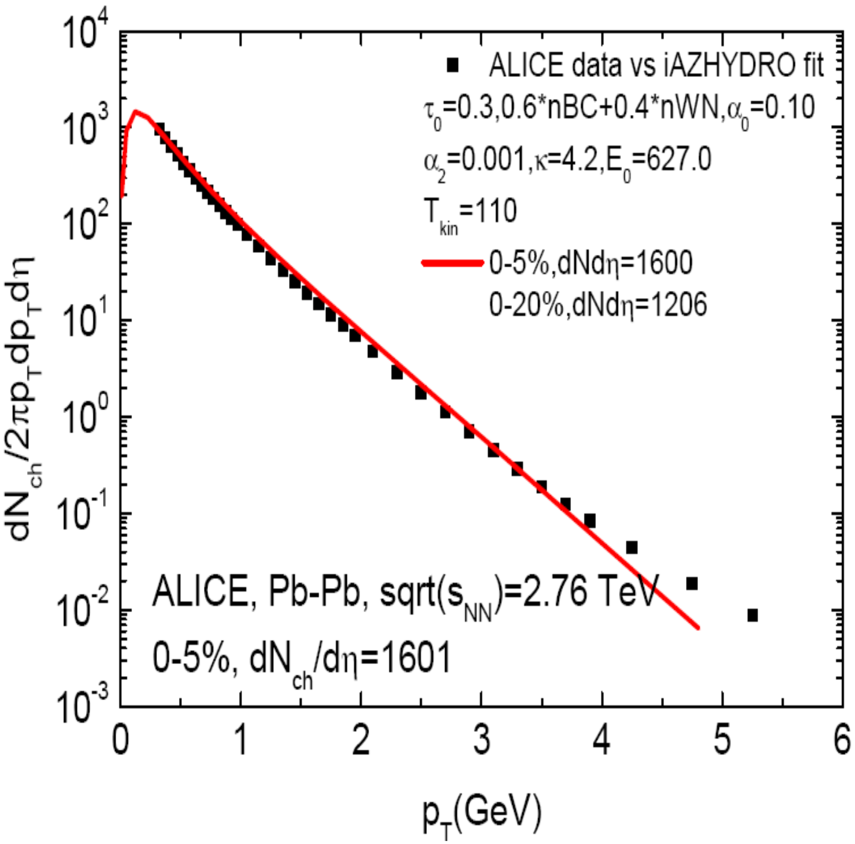


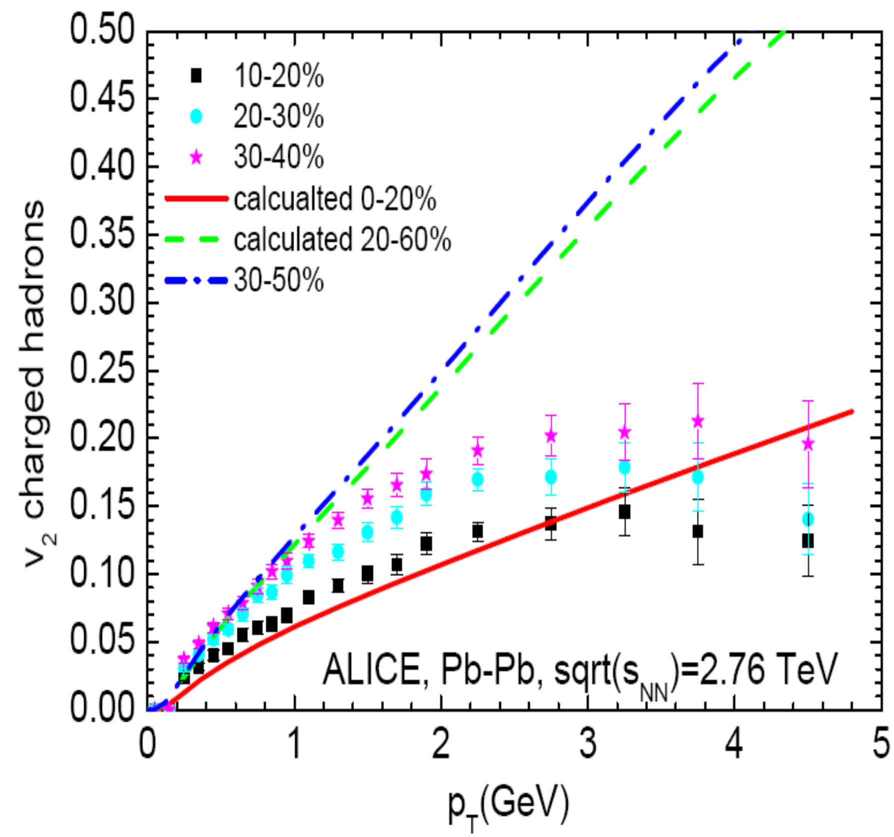
Medium evolution: improved AZHYDRO



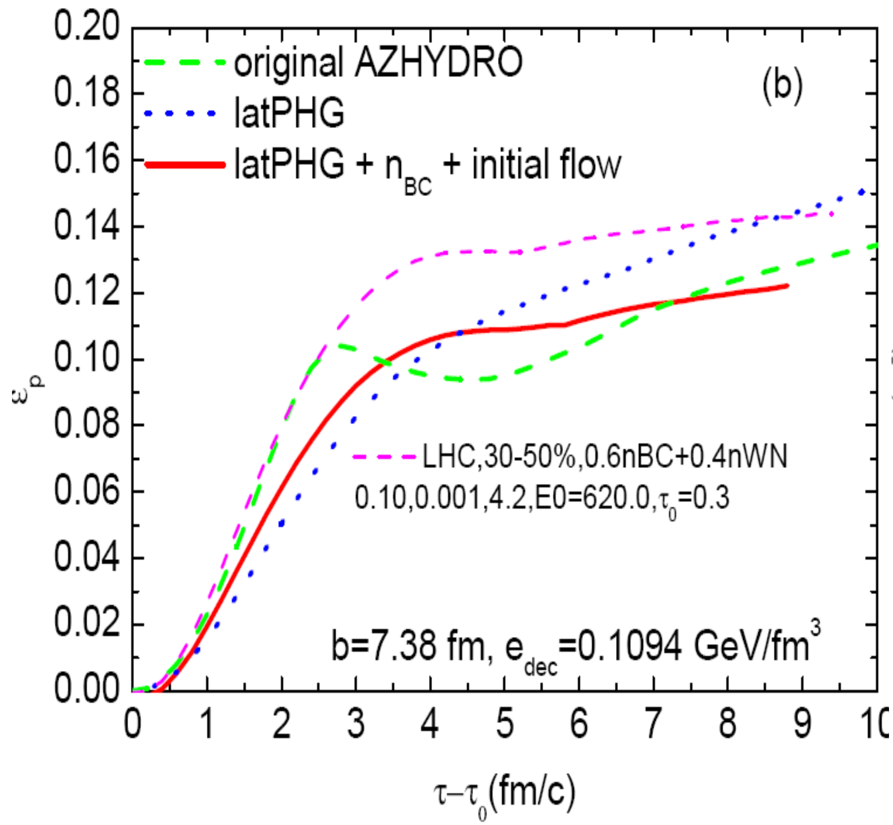
- **lattice EoS + pre-equilibrium flow + compact initial density profile s(x,y)~ n_{BC} (x,y)**
- **multistrange hadrons** ϕ, Ξ, Ω **probably freeze out earlier** STAR, PRC79,2009
- **multi-strange particles' spectra and v_2 fitted at T_{ch} =160 MeV**
  bulk particles' spectra and v_2 fitted at T_{kin}=110 MeV
  M. He, R.J.Fries, R. Rapp, in prepartion

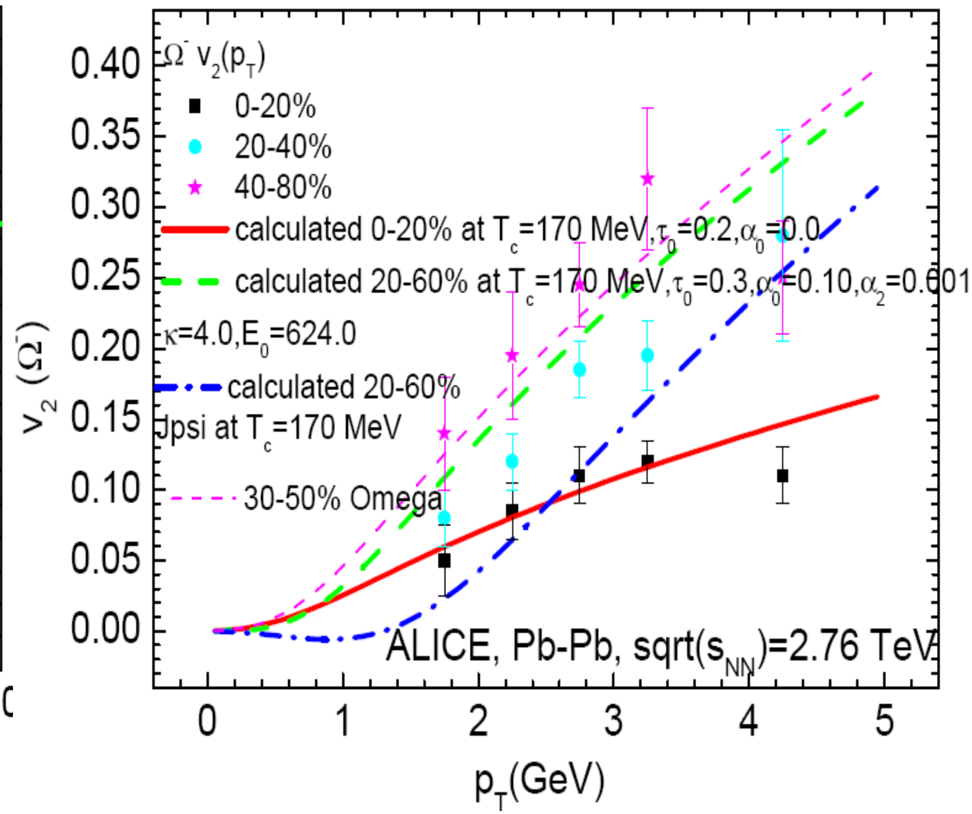
LHC: Hydro tuning (1)



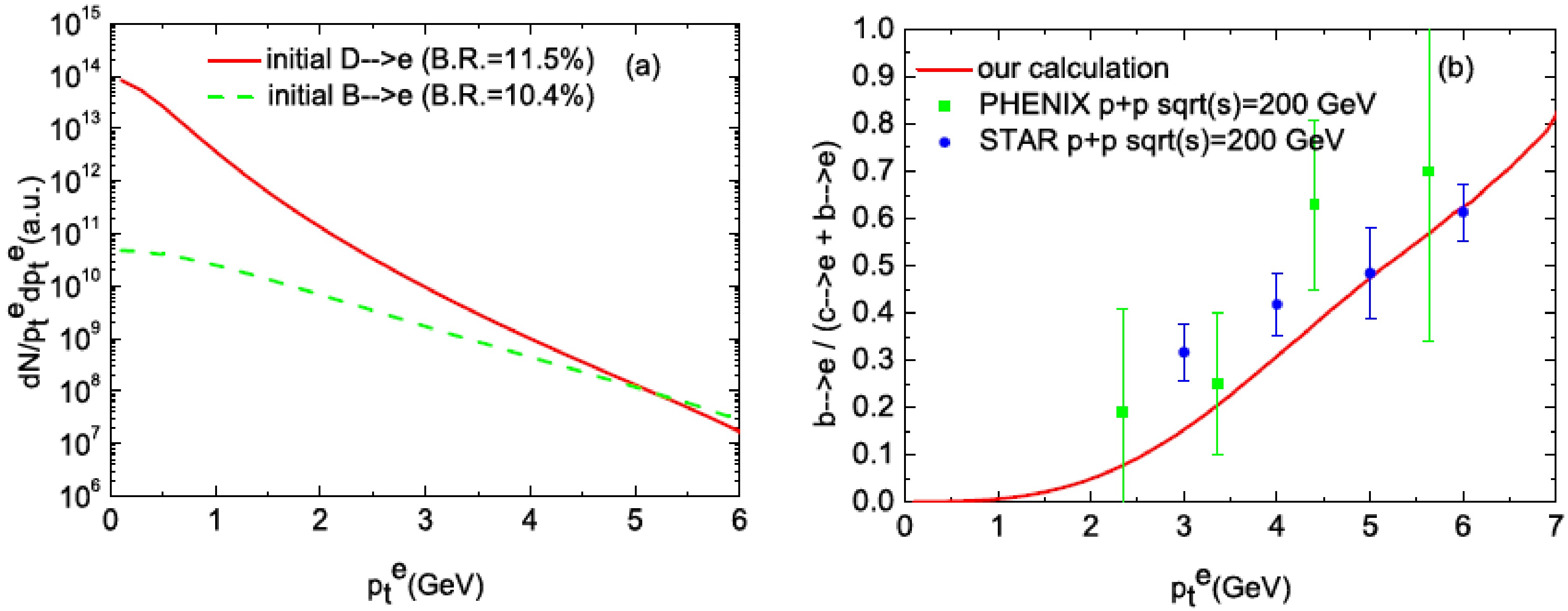


LHC: Hydro tuning (2)





HQ initial distribution



◆ initial p_t spectrum: PYTHIA parametrization $\frac{d^2N_c}{dp_T^2} = C\frac{(p_T + A)^2}{(1 + p_T/B)^{\alpha}}$

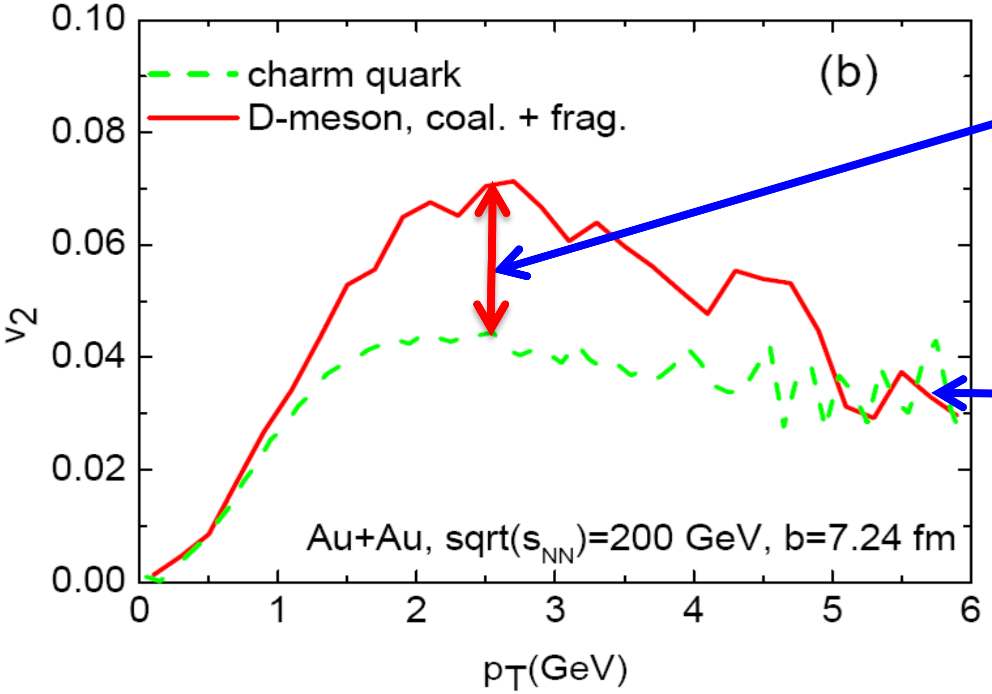
➔ B→e starts to dominate over D→e at p_t ~ 5 GeV, $\sigma_{b\bar{b}}/\sigma_{c\bar{c}} = 4.9\times10^{-3}$

◆Initial spatial distribution: Glauber binary collision density $n_{BC}(x,y)$

OLD Hadronization: coal. vs frag.

- coal. vs frag. :relatively normalized with the calculated coal. prob.

$$\frac{dN_D^{total}}{dyd^2p_T} = \frac{dN_D^{coal}}{dyd^2p_T} + \frac{dN_D^{frag}}{dyd^2p_T}$$



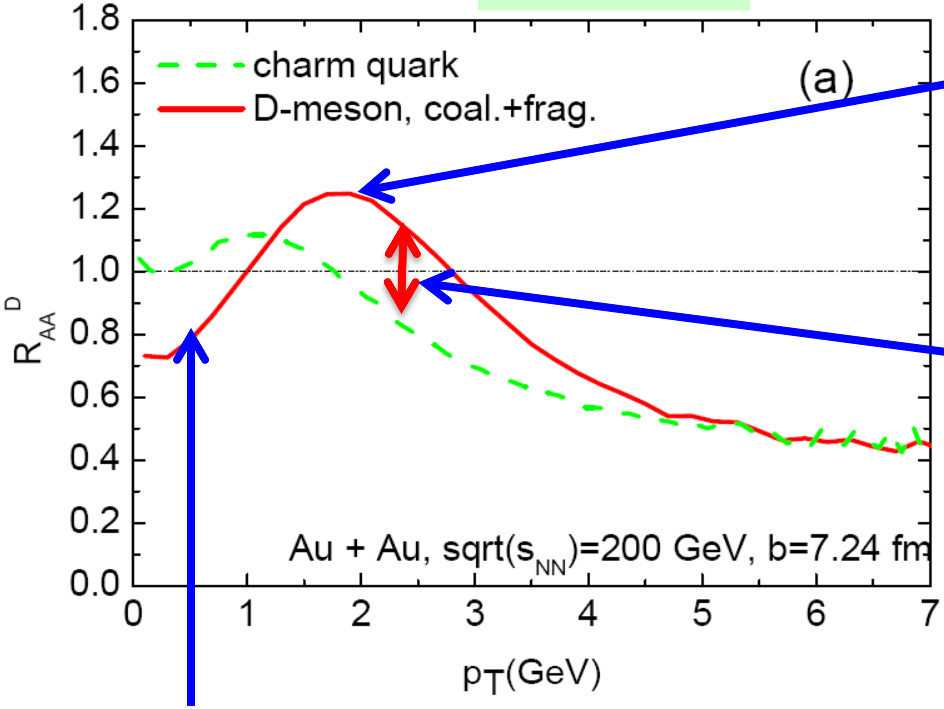
- coalescence: adds v_2 from the light quarks to D meson

- at higher p_T, coal. yields to frag.: preserves the HQ v_2 from c→ D

- **space-momentum correlation** built up via Langevin + hydro for HQ & q from hydro environment fully implemented in RRM
- RRM admits equilibrium mapping between quark and meson distributions, thus able to capture the remarkable flow effect via heavy-light coalescence

OLD Hadronization: coal. vs frag.

- charm quark coal. prob. based on scattering rate: $P_{coal}(p_t) = \tau_{res}\gamma_Q(p_t)$
- supplemented by $D(z) = \delta(z-1)$ fragmentation



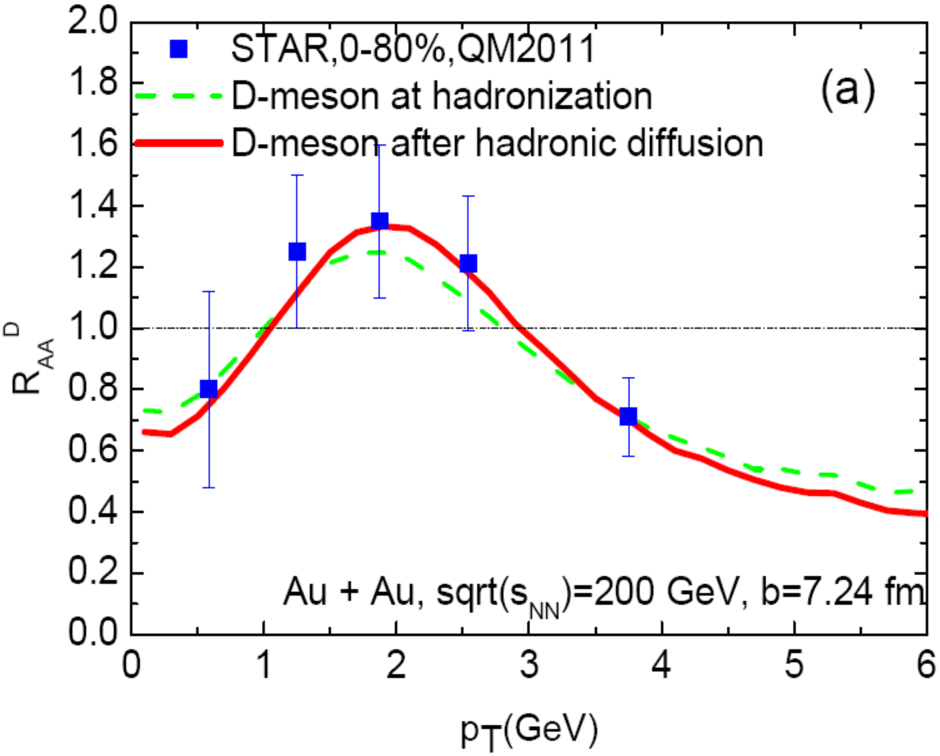
- **flow bump** more prominent from c to D & shifted to higher p_T

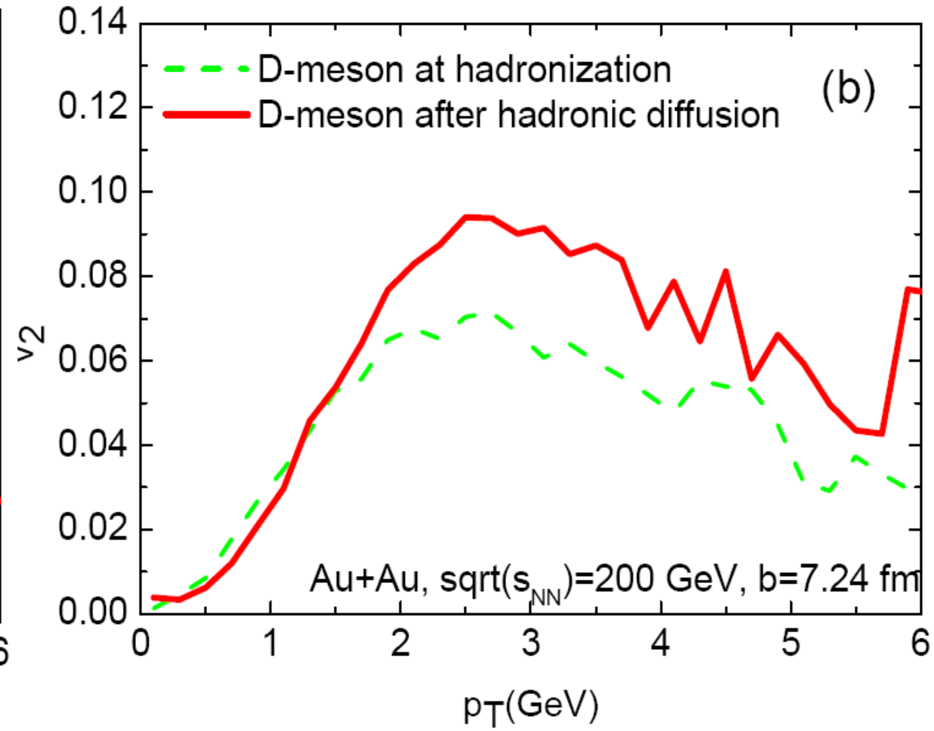
- At p_T~ 1.5-4.5 GeV, coalescence **adds momentum** to D, R_{AA} increases from c to D

- At low p_T, D-R_{AA} gets a larger dip, than charm; **flow depletion** on D, captured by **c-q RRM**

Coalescence acts as an **extra interaction,** driving D-spectrum closer to **equilibrium**

OLD D/B hadronic phase Langevin diffusion





◆ **flow bump somewhat shifted**

◆ **spectrum quenching continues, but largely counteracted by the hardening effect of large hadronic flow → R_{AA} not change much**

◆ **v_2 amplified by ~30%**

◆ **though bulk v_2 does not quite grow in hadronic phase, D-meson continues to thermalize and pick up v_2 from the medium**