Heavy quark diffusion and hadronization in dense matter

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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: Langevin + hydro simulation
- Hadronization: coalescence vs fragmentation
- R_{AA} & v_2: thermalization & quenching

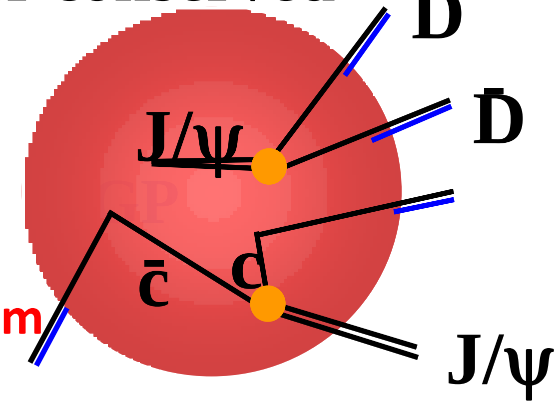
3. Charm diffusion: hadronic phase

- Transport coefficient: quark-hadron duality?!

4. Summary

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 for the medium

- **HQ energy loss:**

  gluon radiation:dead cone $\theta \leq m_Q / E$ **+ DGLV HQ puzzle**

  elastic scattering: $-\frac{dE}{dx} = \gamma p$ **uncorrelated momenta kick**

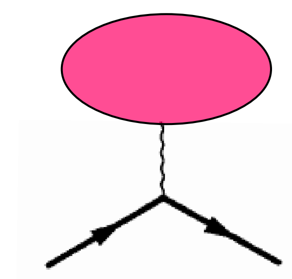
$$\frac{\partial f}{\partial t} = \gamma \frac{\partial (pf)}{\partial p} + D \frac{\partial^2 f}{\partial p^2}$$

$$p_{th} \sim \sqrt{3 m_Q T} \gg T \sim q_{tr}$$

thermalization rate; diffusion coefficient

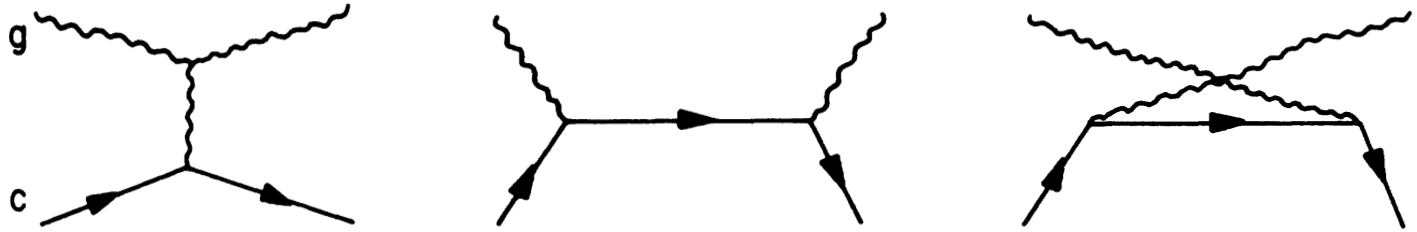
$$\gamma \sim \int |T_{Qq}|^2 (1-\cos\theta) f^q$$

$$D = \gamma m_Q T$$



Introduction: HQ probe (continued)

- **pQCD elastic collisions** B. Combridge,1978

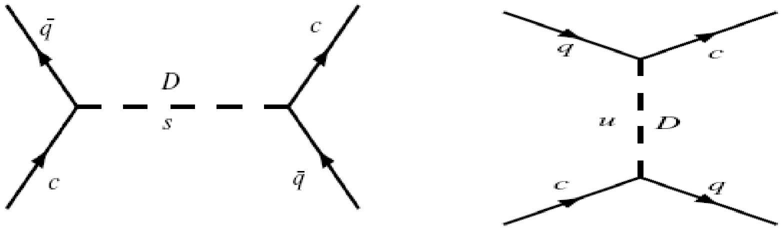


various **weakly coupled** (pQCD) scenarios for HQ transport:

Moore & Teaney, 2005; Gossiaux & Aichelin, 2008; Alberico et al., 2011; J.Uploff et al., 2010; …

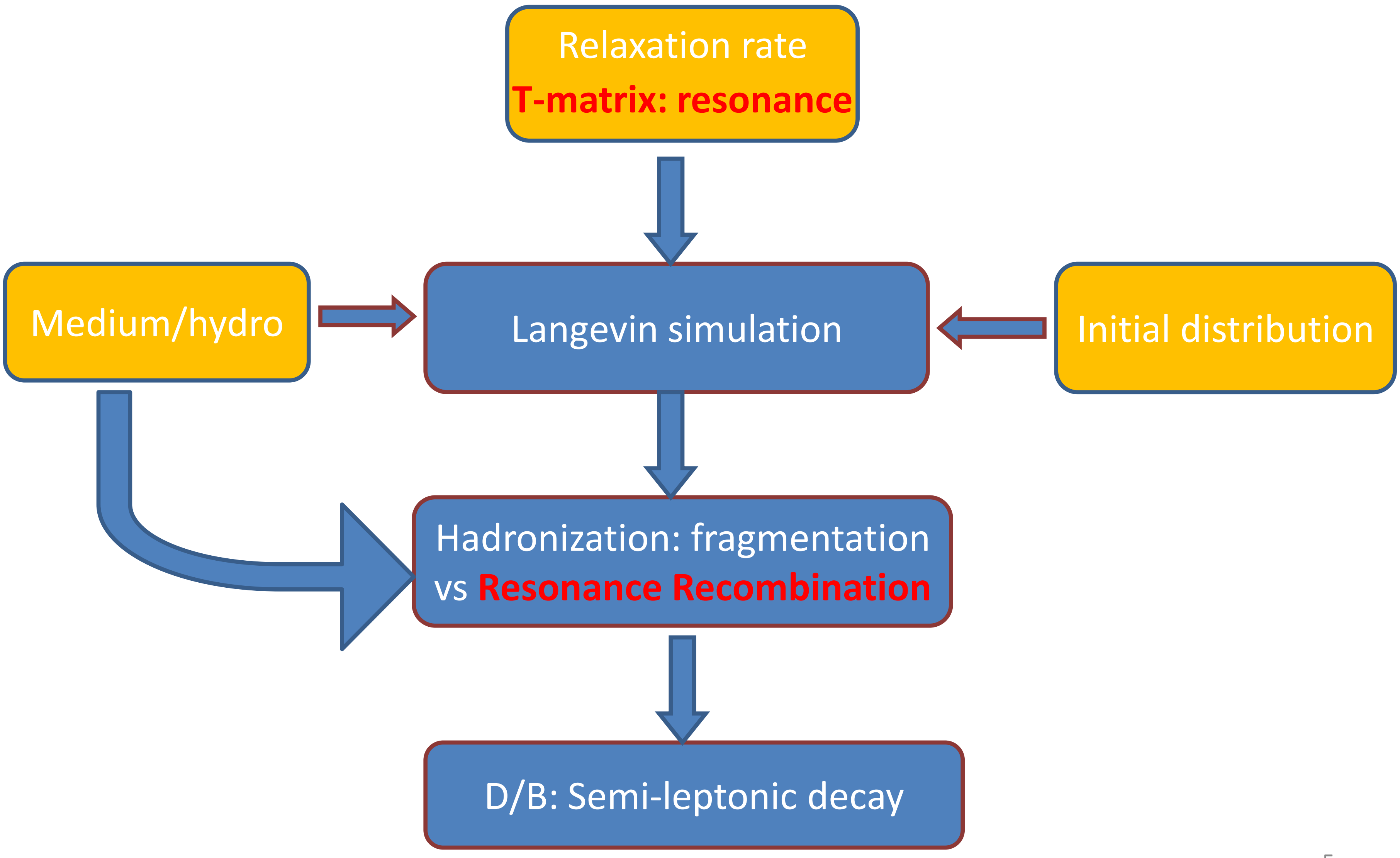
running coupling, Debye screening, K-factor?

- **Resonant scattering: non-perturbative** van Hees, Greco & Rapp, 2005,2006

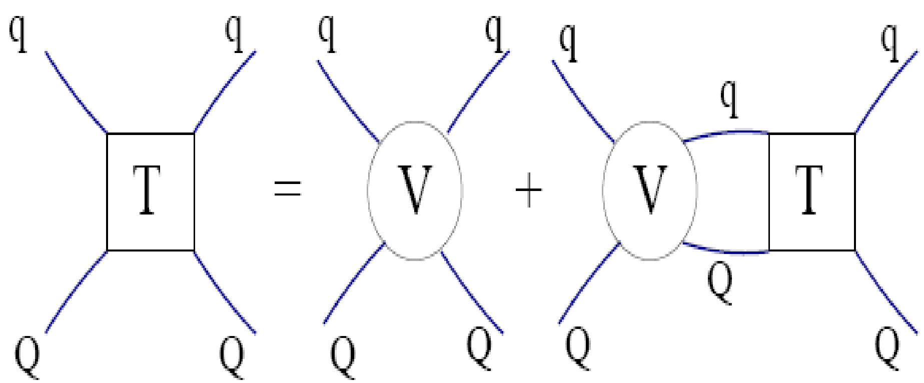


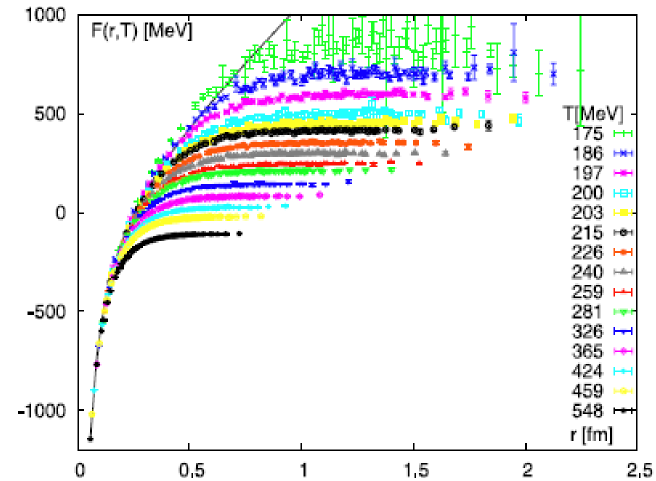
strongly coupled scenario

A strongly coupled framework: HQ



Relaxation rate: T-matrix





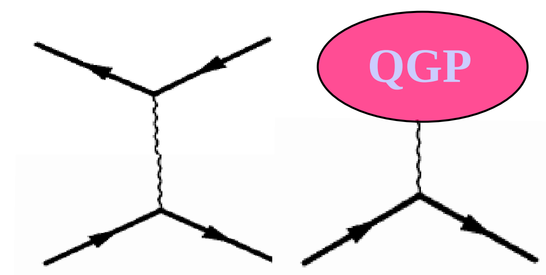
◆**static approximation** $q_0 \simeq \vec{q}^2 / 2m_Q \ll |\vec{q}|$

◆**lattice potential:** Kaczmarek,2008 $U = F - T\frac{\partial F}{\partial T}$ → **Resummation !!!**

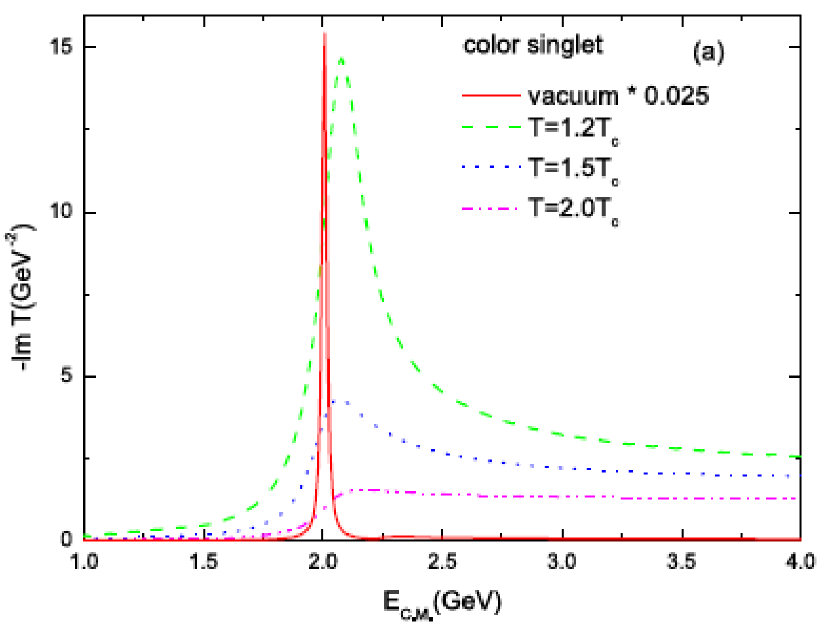
◆ **open/hidden heavy flavor vacuum spectroscopy reproduced:** Riek & Rapp,2010

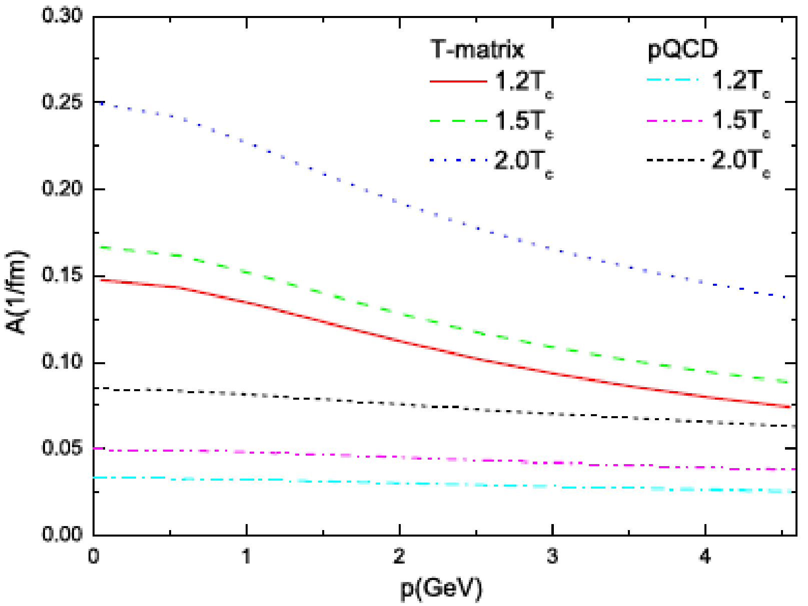
◆**heavy quarkonia (bound states)**
◆**heavy quark transport (scattering states)**

Common basis & mutual constraints



Relaxation rate: T-matrix (continued)

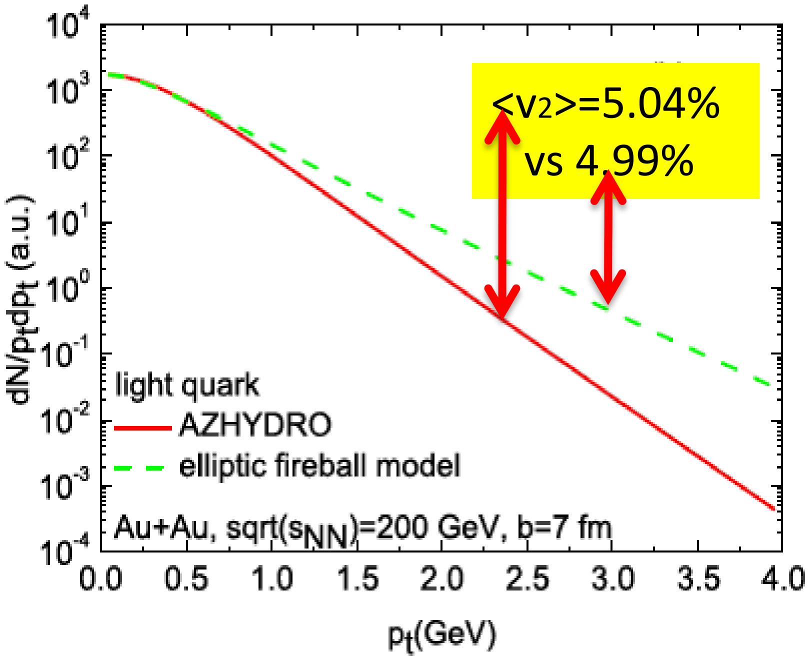


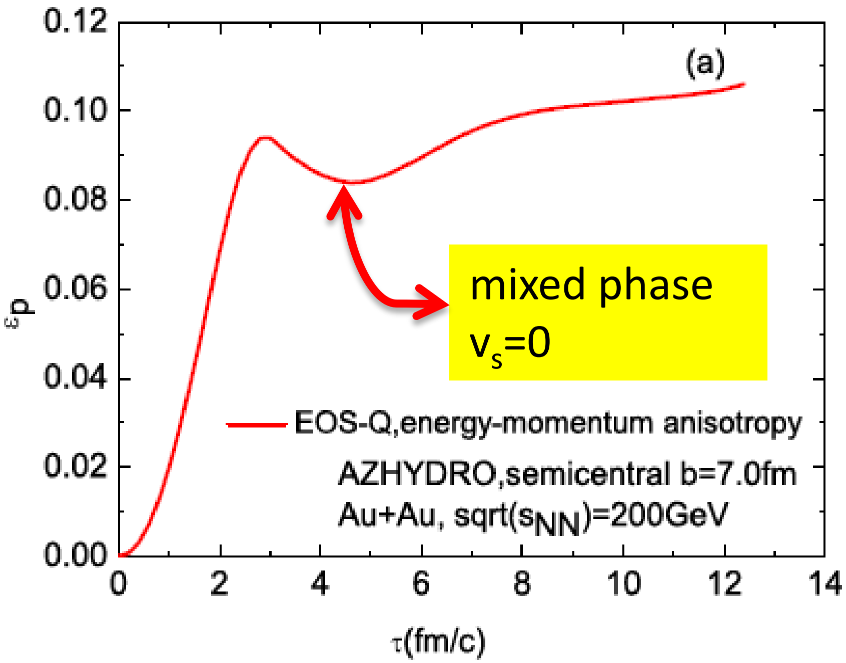


- T-matrix resummation ➔ color singlet and anti-triplet broad Feshbach resonances up to ~1.5 T_C
- this resonance correlation will be reiterated in our hadronization-coalescence model

- T-matrix relaxation rate: a factor ~4-5 larger than LO pQCD at T=1.2 T_c
- T-dependence: screening potential vs light parton density; p-dependence: less contribution from threshold Feshbach resonance as p increases

QGP medium: AZHYDRO vs fireball

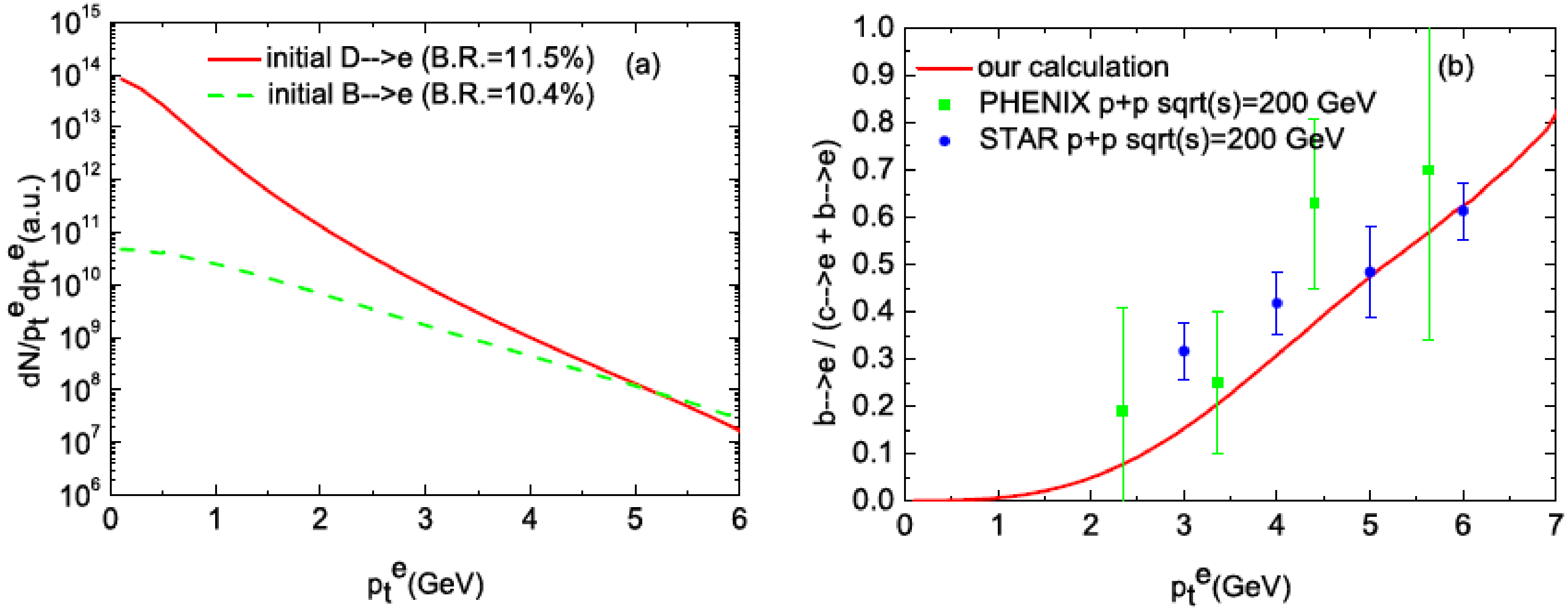




◆ **AZHYDRO:initialization time** $\tau_0 = 0.6\, fm/c$ **,boost invariant**
Cooper-Frye freezeout: the end of mixed phase e_{dec} **=0.445 GeV/fm³ ,**T_{dec}**=165 MeV**

◆ **Elliptic fireball: tune to fit to multi-strange particles' spectra and** v_2 **at** T_c
c.f. M.He, R.Fries & R.Rapp, 2010 , harder than AZHYDRO, larger flow

HQ initial distribution



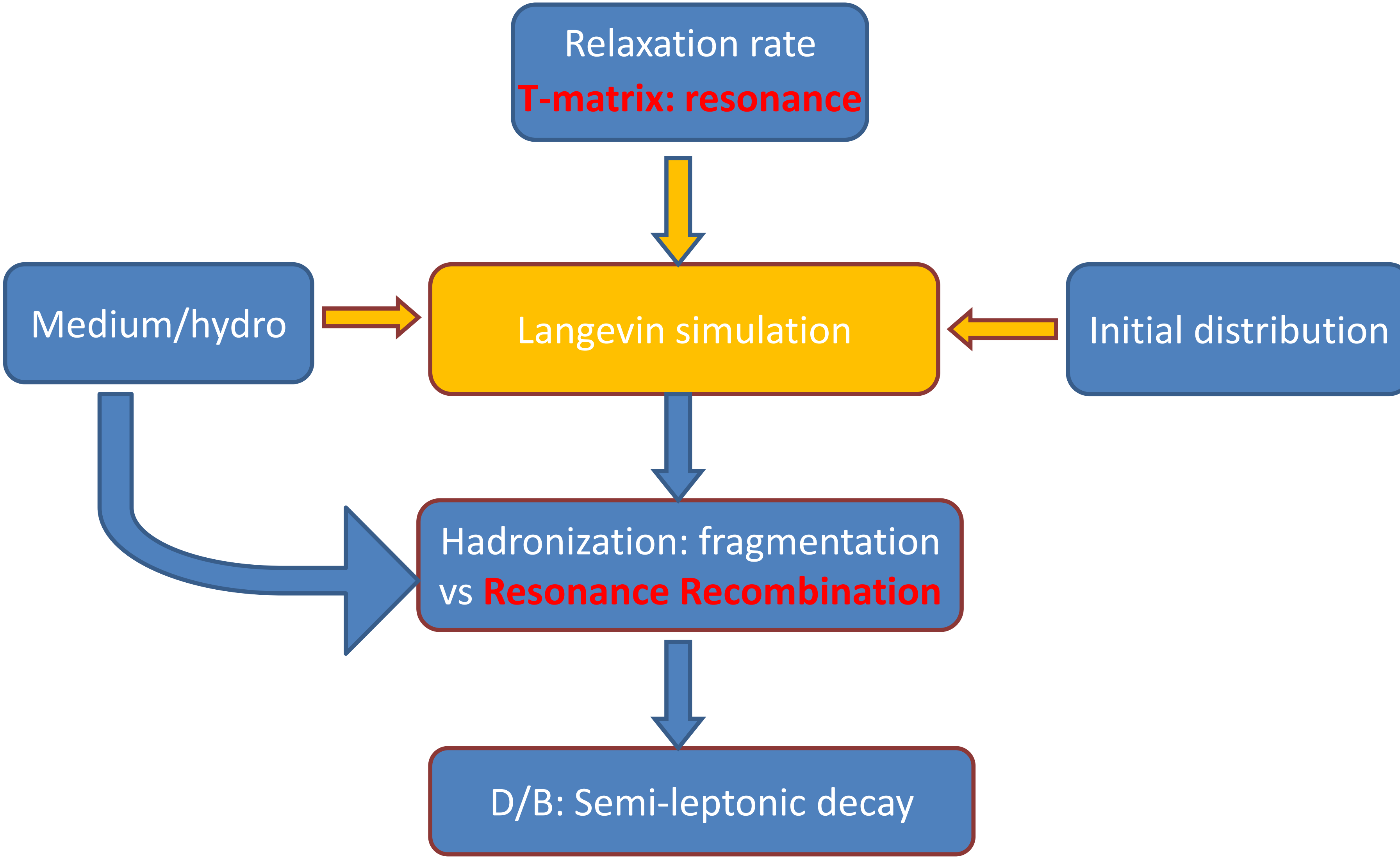
◆ initial p_t spectrum: PYTHIA parametrization

$$\frac{d^2N_c}{dp_T^2} = C\frac{(p_T + A)^2}{(1 + p_T/B)^\alpha}$$

➔ B→e starts to dominate over D→e at p_t ~ 5 GeV

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

A strongly coupled framework: HQ

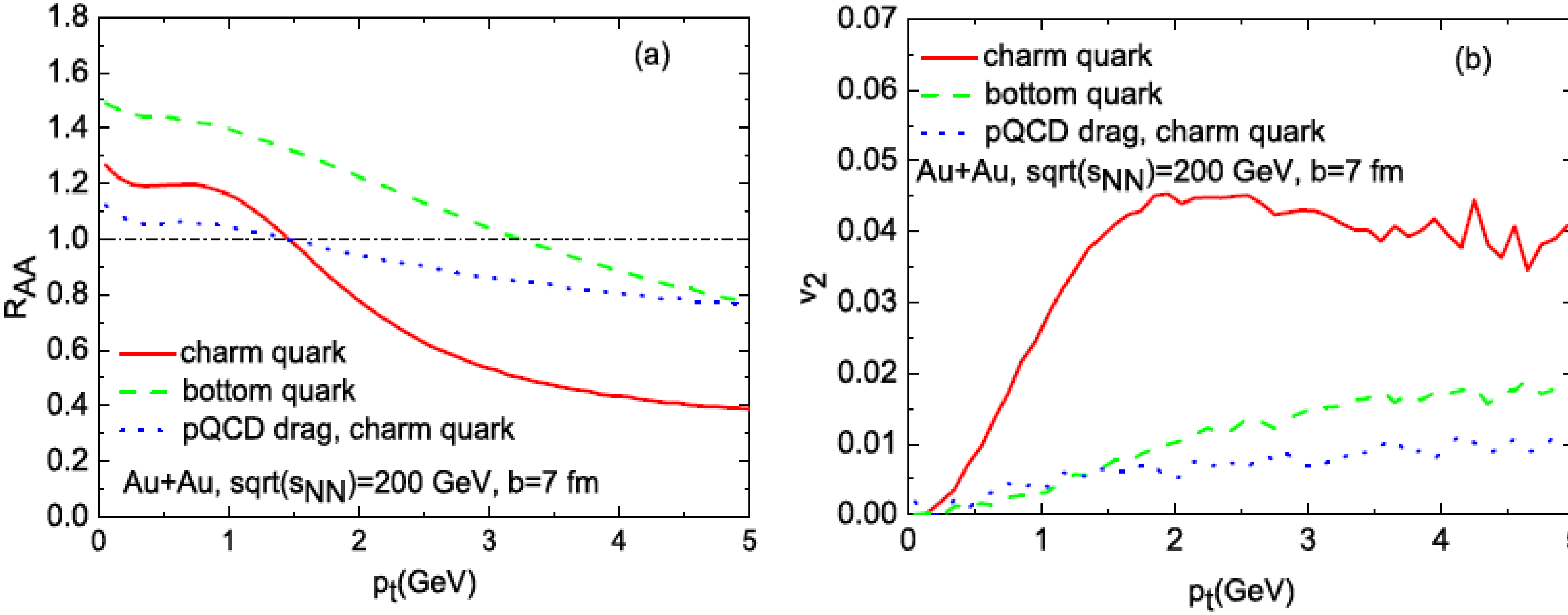


Langevin simulation of HQ diffusion

- **Langevin + AZHYDRO simulation**
  fluid rest frame updates → boost to lab frame

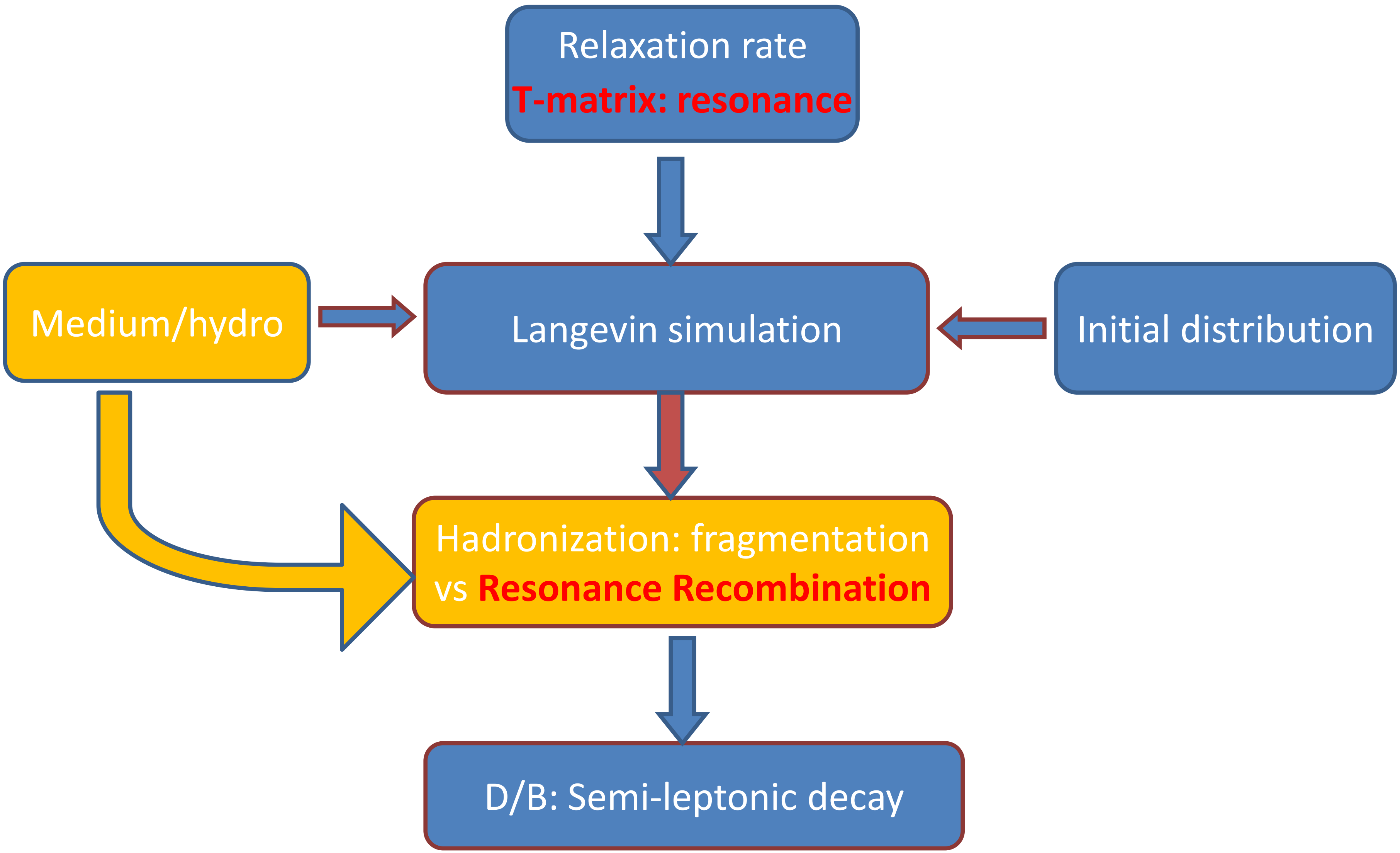
$$d\mathbf{x} = \frac{\mathbf{p}}{E}dt,$$

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



- **quenching: early stage when medium particles' density is high**
- **v_2 : develops at later stage when the medium particles' v_2 is large**

A strongly coupled framework: HQ



Hadronization: Resonance Recombination

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

→ *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

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

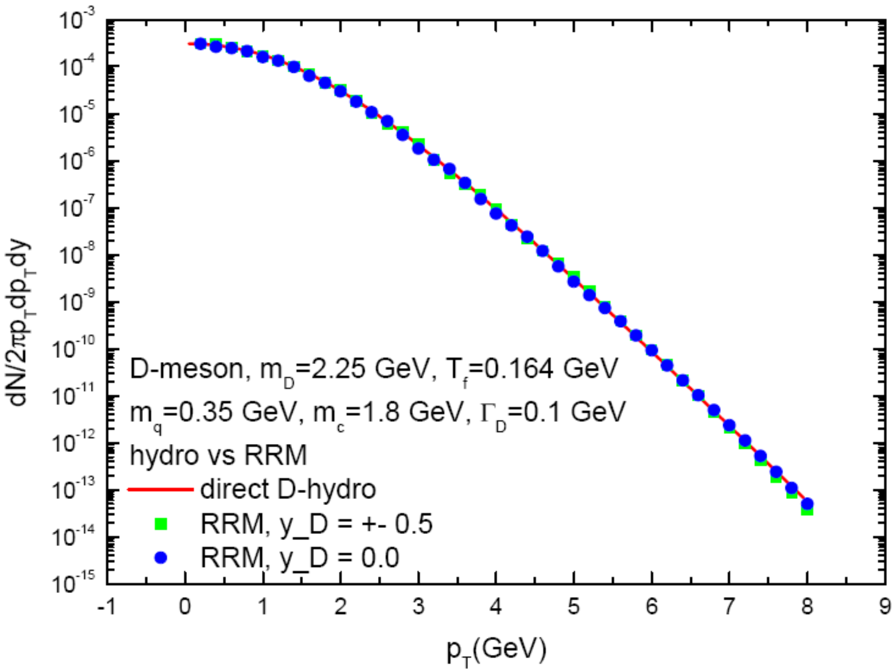
- **Equilibrium limit**

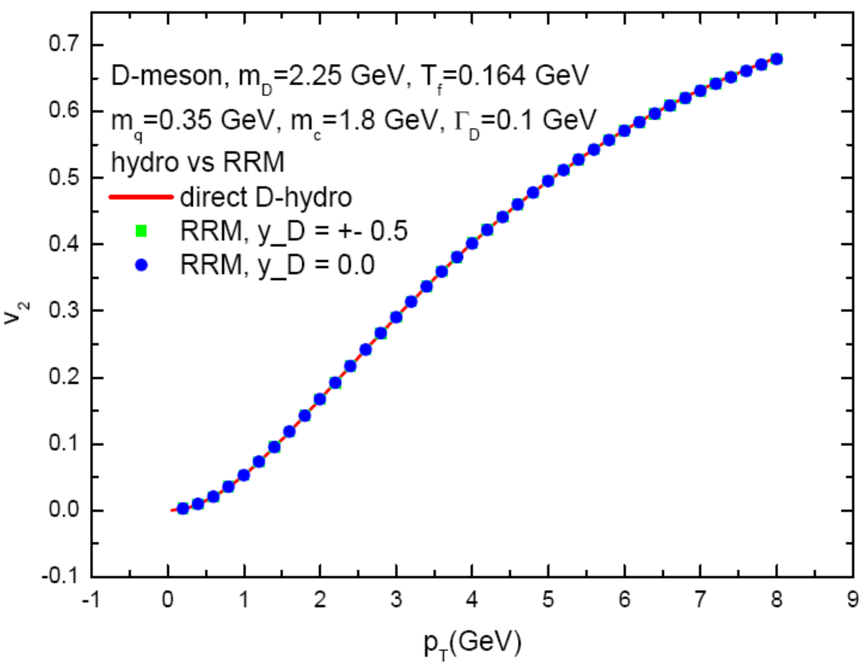
$$f_M^{\rm eq}(\vec{p}) = \frac{E_M(\vec{p})}{m\Gamma} \int d^3x \beta(\vec{x},\vec{p})$$

- **Energy conservation + detailed balance**

→ **equilibrium mapping**

Equilibrium Quark → Equilibrium Meson





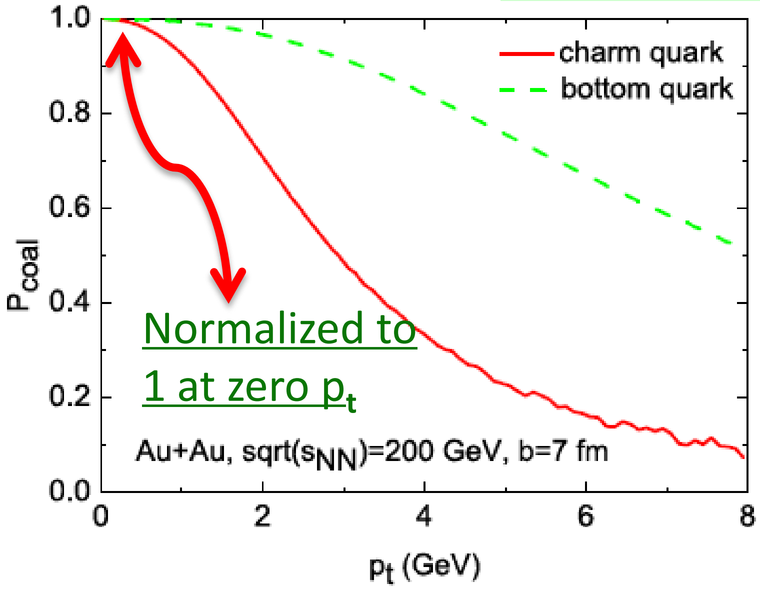
◆ **Kolb-Heinz AZHYDRO: space-momentum correlation at freezeout included, excellent equilibrium mapping achieved; boost invariance preserved**

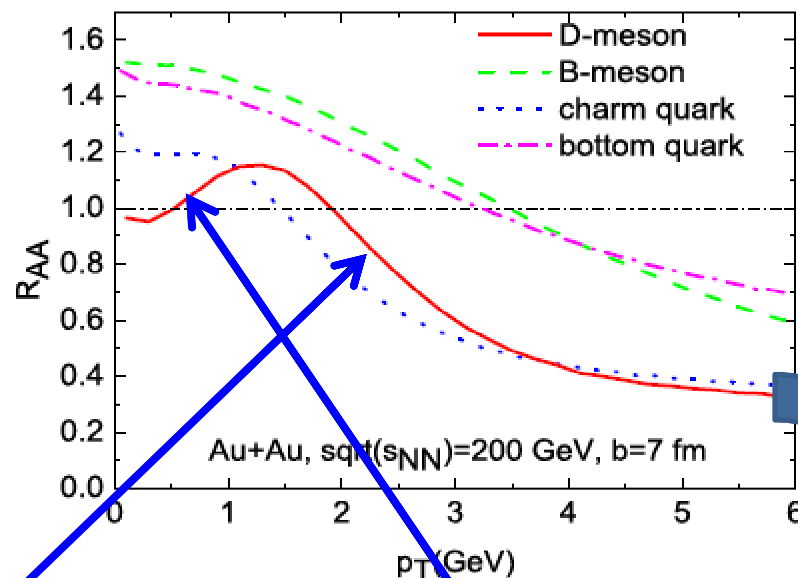
c.f. M. He, R. J. Fries & R. Rapp, 2010

➔RRM (compared to instantaneous coalescence models) quite facilitates the description of the transition from low p_T (equilibrium) to intermediate p_T (kinetic) region in heavy-light quark recombination

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



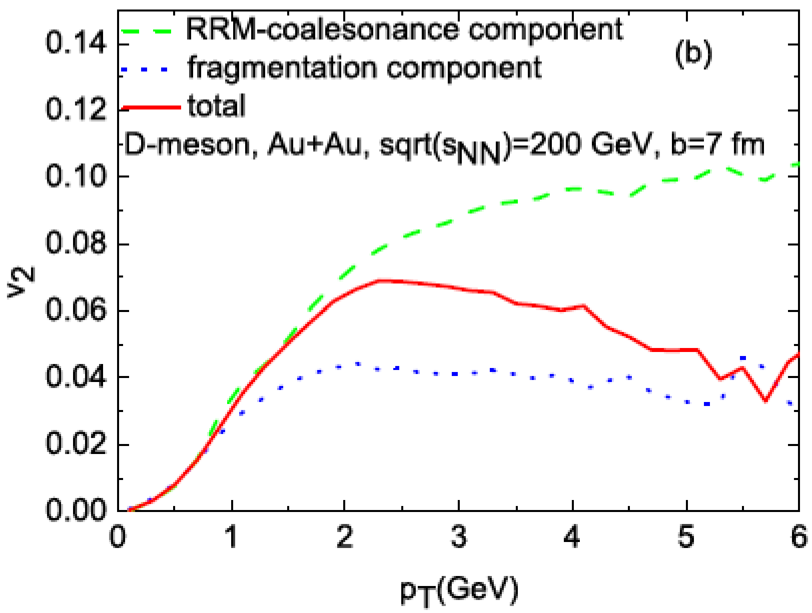


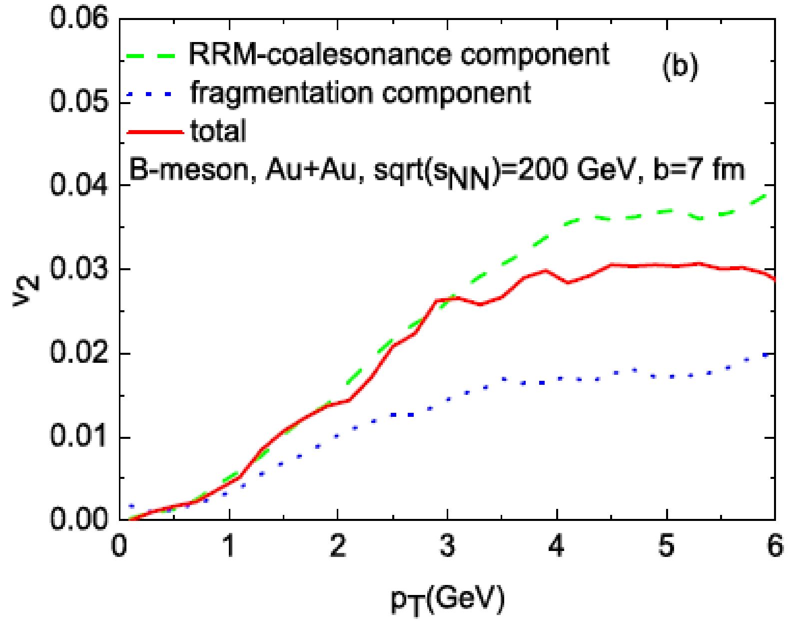
◆At p_T~ 1.5-4.0 GeV, coalescence adds momentum to D, R_{AA} increases from c to D

◆At low p_T, D-R_{AA} gets a dip, not present for charm; flow depletion on D, captured by c-q RRM

Coalescence acts as an extra interaction, driving D-spectrum closer to equilibrium, which also explains D-spectrum slightly below c at high p_T

Hadronization: coal. vs frag.(cond.)





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

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

- **fragmentation: preserves the HQ v_2 from c/b→ D/B**
  coalescence: adds v_2 from the light quarks to D/B mesons

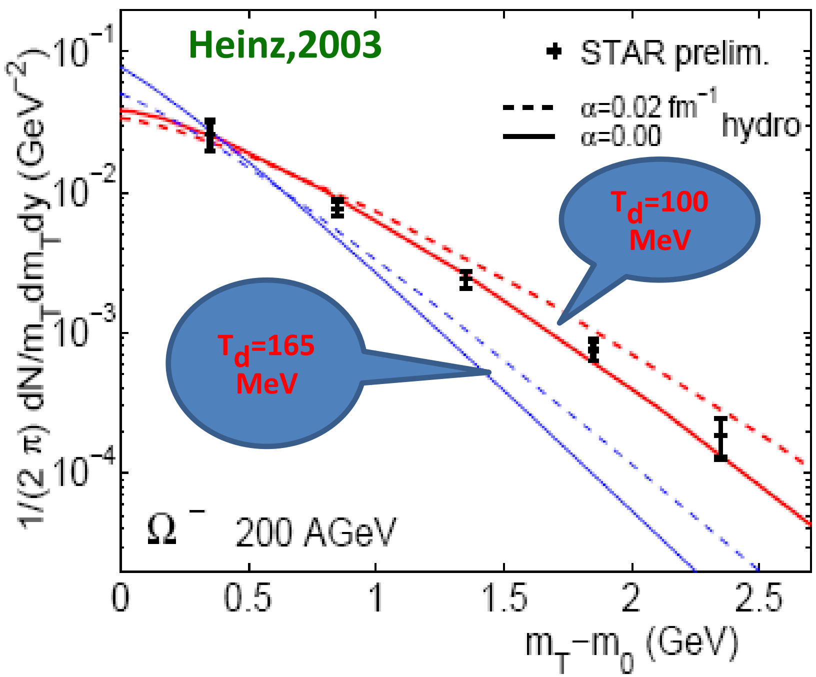
- **RRM properly accounts for space-momentum correlation built up via Langevin + hydro for HQ + q ➔ enables us to analyze medium flow effect**

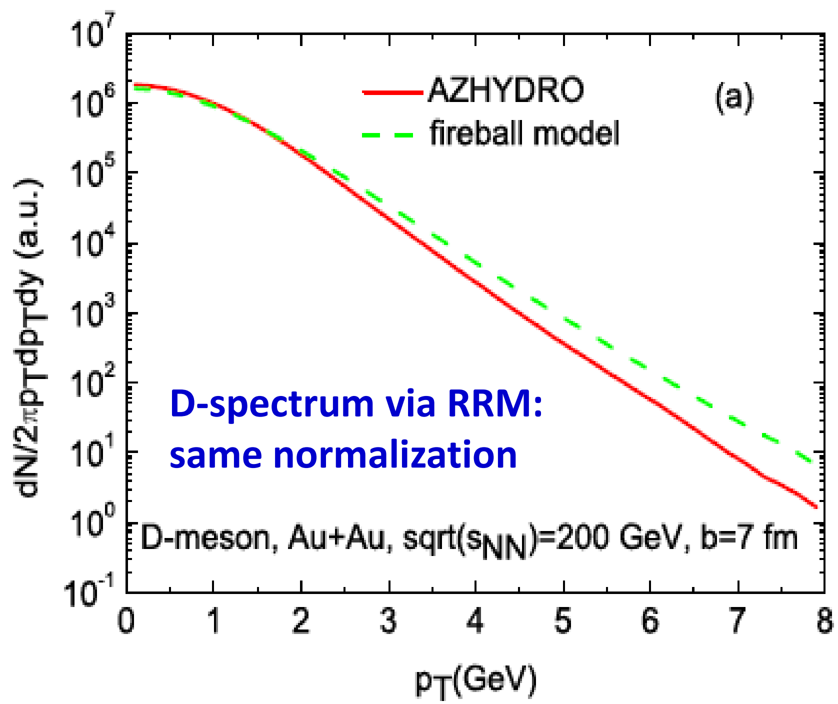
What’s missing: medium flow

- multi-strange hadrons ϕ, Ω, Ξ decouple close to T_c

  STAR, 2005; Mohanty & Xu, 2009; M.He, R.Fries & R.Rapp, 2010

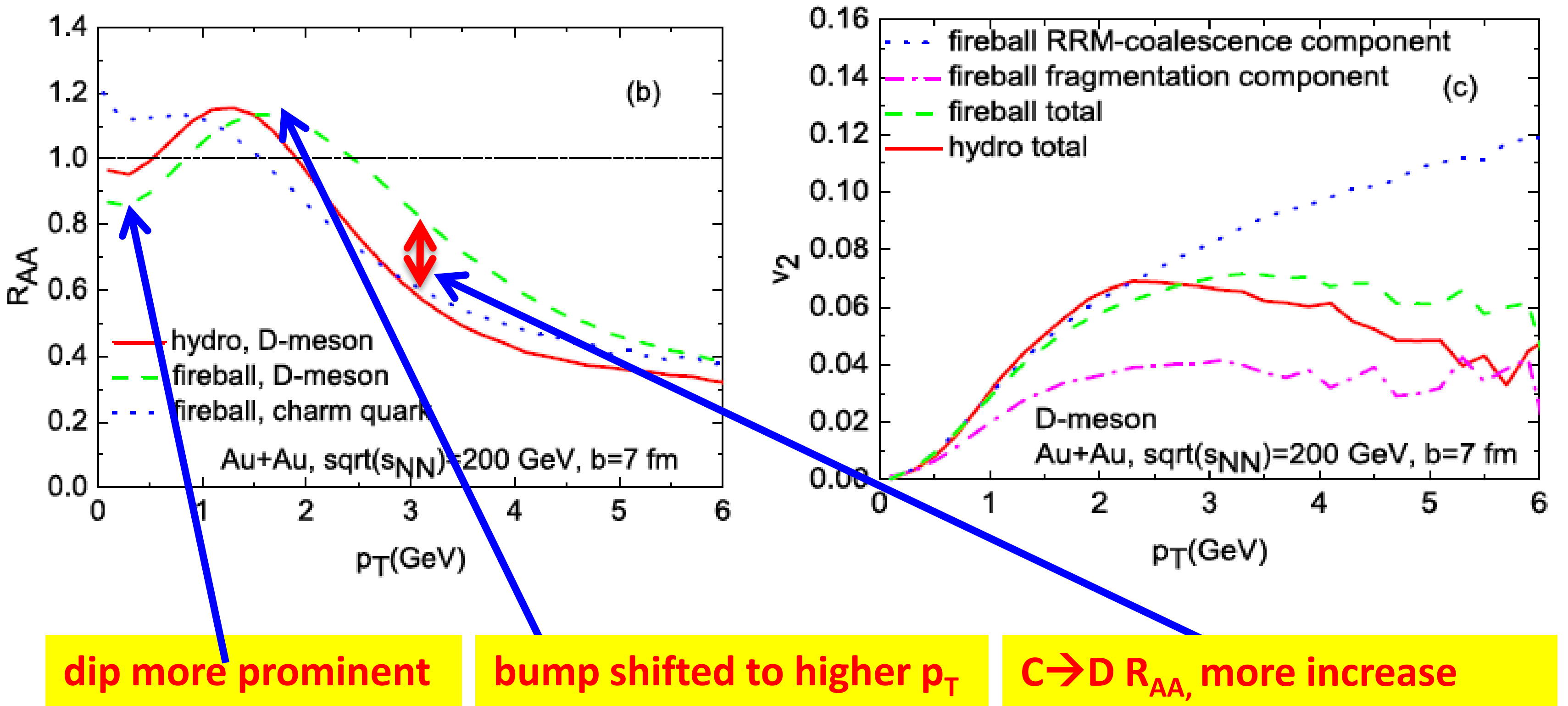
➔ Important to tune hydro flow to fit to multi-strange hadrons’ spectra at T_c





- AZHYDRO underestimates the flow close to $T_{c\,;}$ mixed phase $v_s=0$ → lattice EOS
- fireball model (Page8): tuned to fit to multistrange hadrons’ spectra and v_2 at T_c → light quark spectrum harder → D spectrum via RRM harder !!!

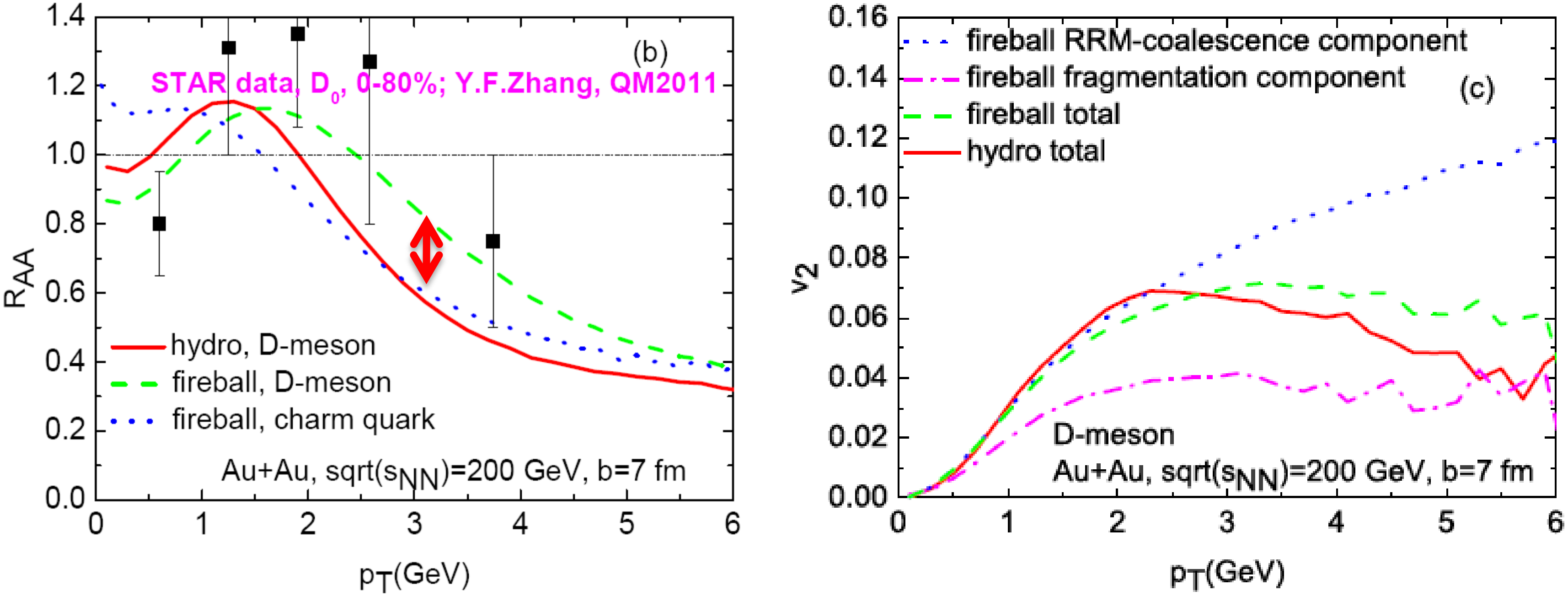
Medium flow effect via RRM (continued)



◆ **RRM admits equilibrium mapping between quark and meson distributions, thus able to capture the remarkable flow effect via heavy-light coalescence**

◆ **D-meson v2 receives a modest increase at p_T>2.5 GeV, also due to larger flow**

Medium flow effect via RRM (continued)

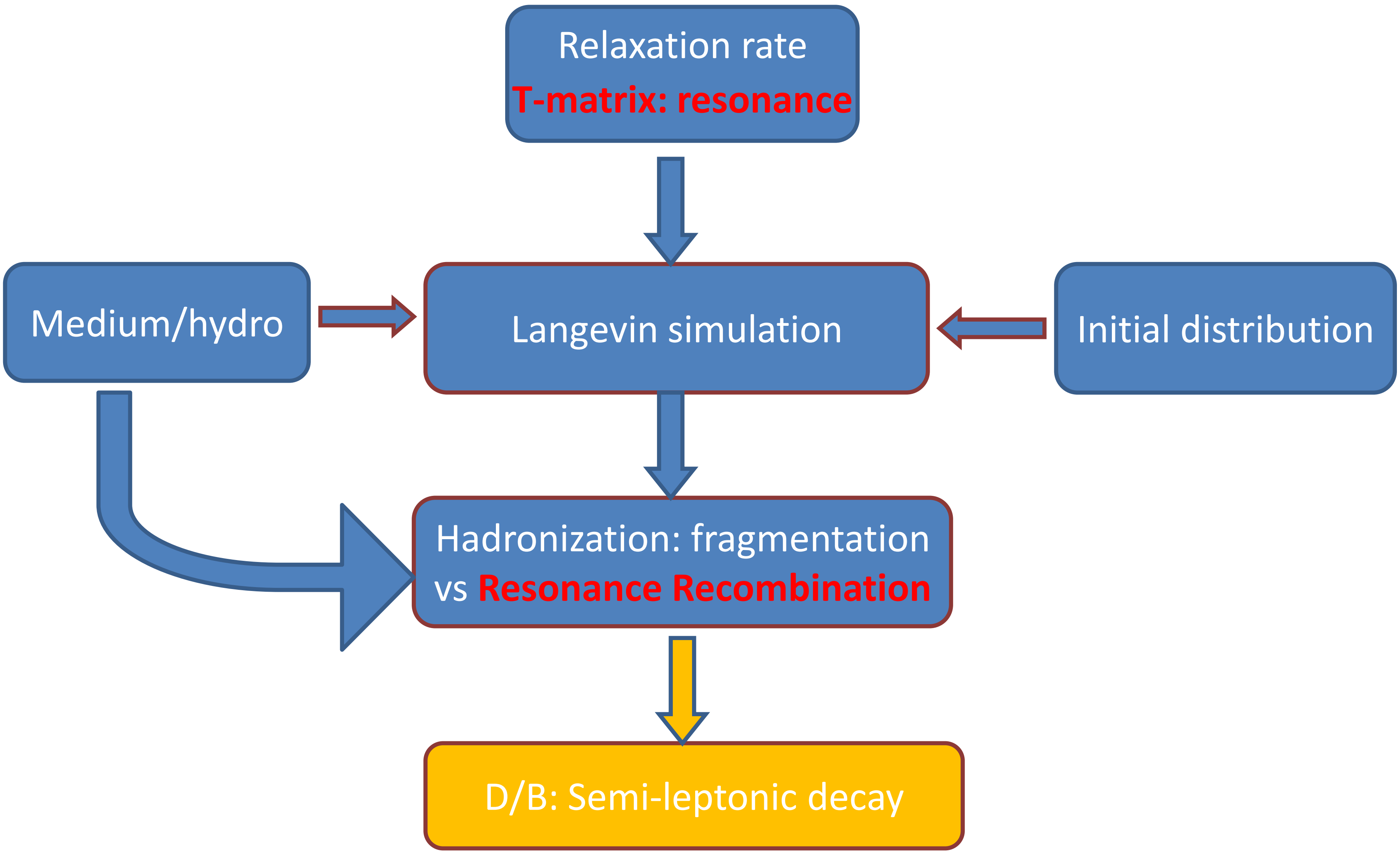


dip more prominent | **bump shifted to higher p_T** | **C→D $R_{AA,}$ more increase**

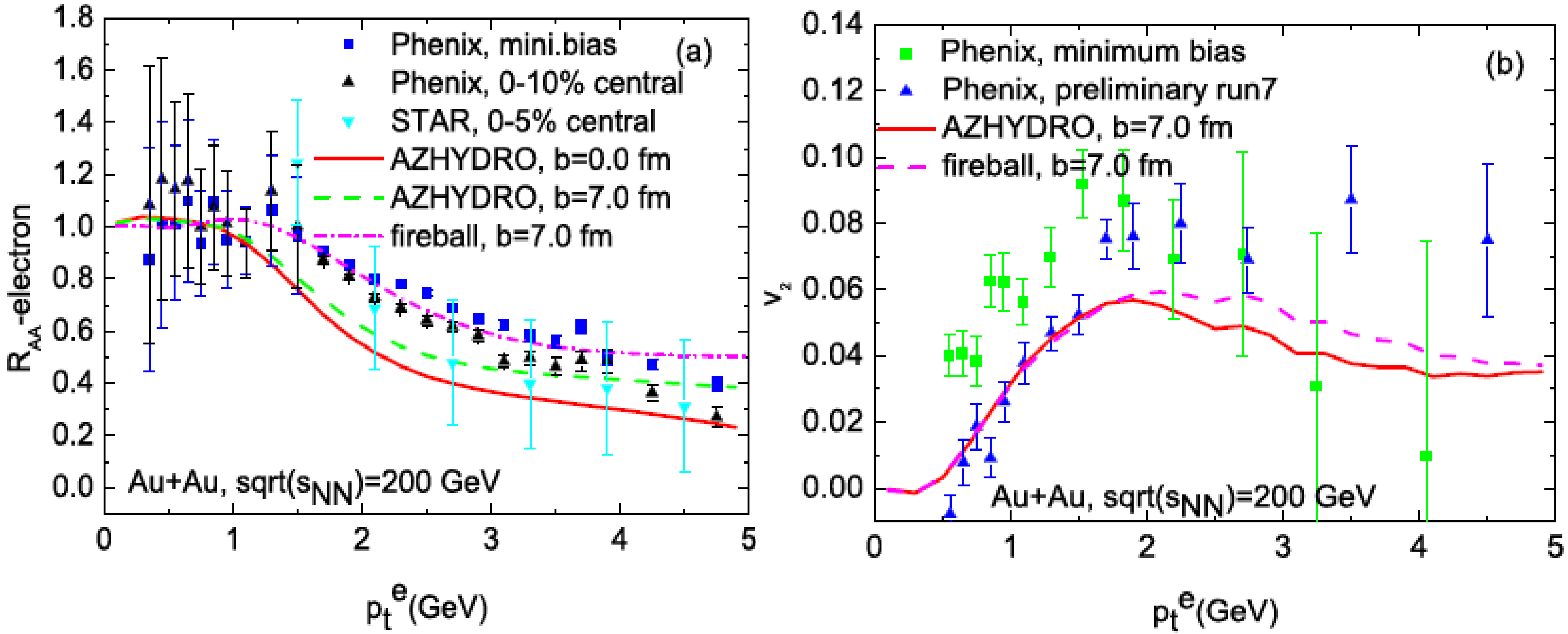
- **qualitatively/semi-quantitatively reproduce the data behavior: dip, bump**
- **fireball model with larger medium flow gets better agreement with data**

➔ correct flow at T_c important!

A strongly coupled framework: HQ

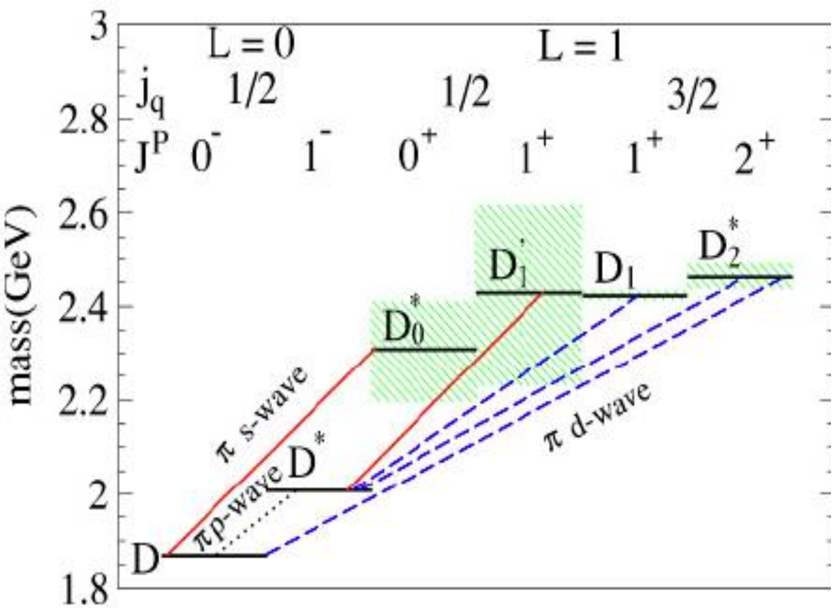


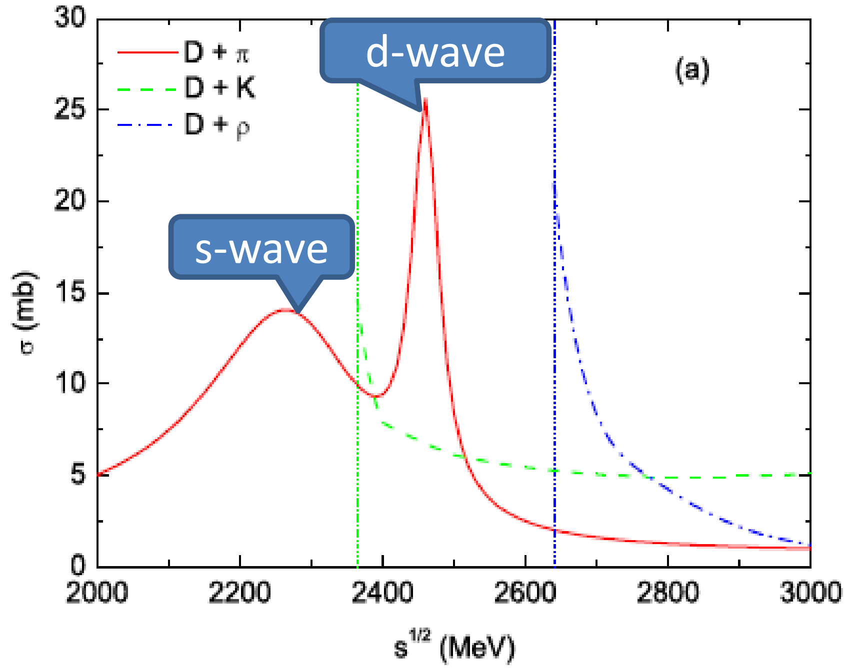
Non-photonic decay electrons



- Monte-Carlo simulation, free quark decay c(b) → s(c) + e + nu, m_b=5.28, m_c=1.87, m_s=0.5, m_e=0.0005 GeV; inclusive branching ratios: c:11.5% ; b: 10.4%
- matrix elements $\langle|\mathcal{M}|^2\rangle \propto (p_s \cdot p_\nu)(p_c \cdot p_e)$ and $\langle|\mathcal{M}|^2\rangle \propto (p_c \cdot p_e)(p_b \cdot p_\nu)$
  hadronic form factors little effect, checked
- fireball model: better agreement of R_{AA} → correct medium flow important!
  v_2 smaller → hadronic phase diffusion?

Charm diffusion: pion gas



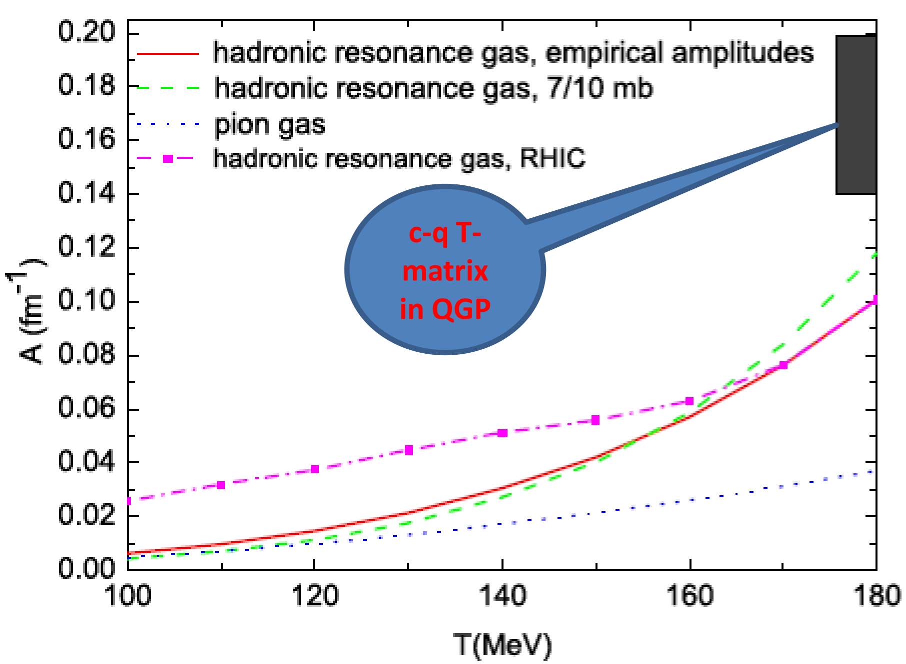


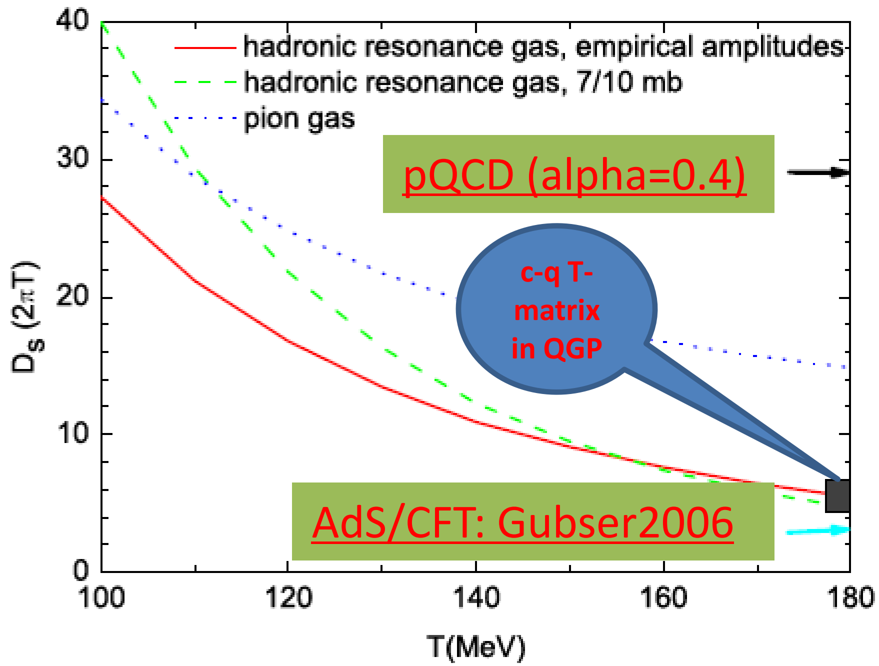
- D&D_0*, D*&D_1' : chiral partners, large pion s-wave decay width ~300 MeV, Fuchs, et al., 2006; BELLE Colla., 2004; also verified by Chiral Unitarized Approach

- D + pion →resonance→ D + pion: $A_{1/2} = \sum_{j=0,1,2} \frac{8\pi\sqrt{s}}{k} \frac{(2j+1)}{(2j_1+1)(2j_2+1)} \frac{-\sqrt{s}\Gamma_j^{D\pi}}{s - M_j^2 + i\sqrt{s}\Gamma_j^{\rm tot}}$,

Charm diffusion: hadronic resonance gas

- D + K,eta,rho,omega,K*,N,Delta, empirical s-wave cross sections based on ChUA: Lutz et al., 2004,2006; E.Oset et al., 2007

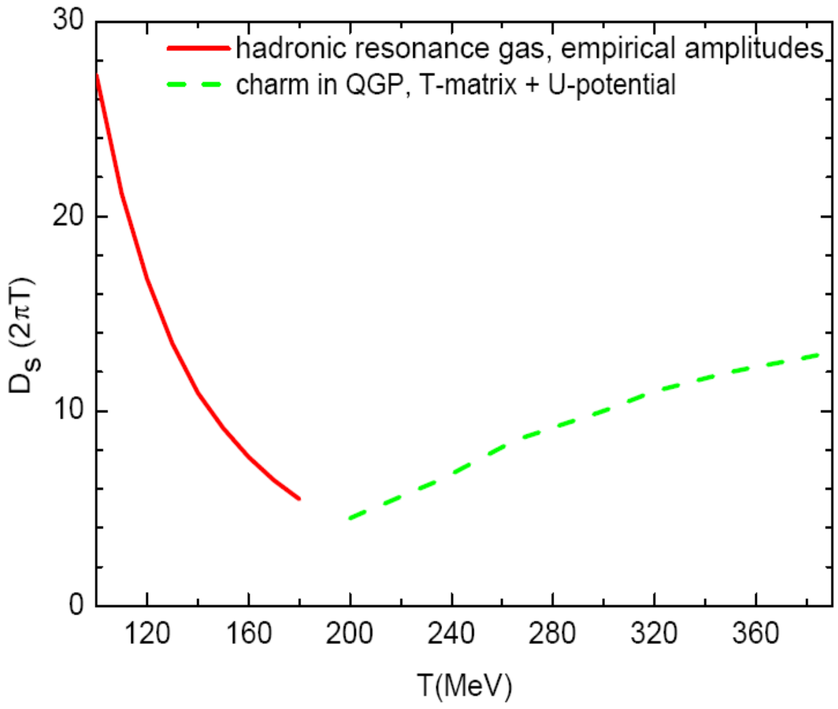


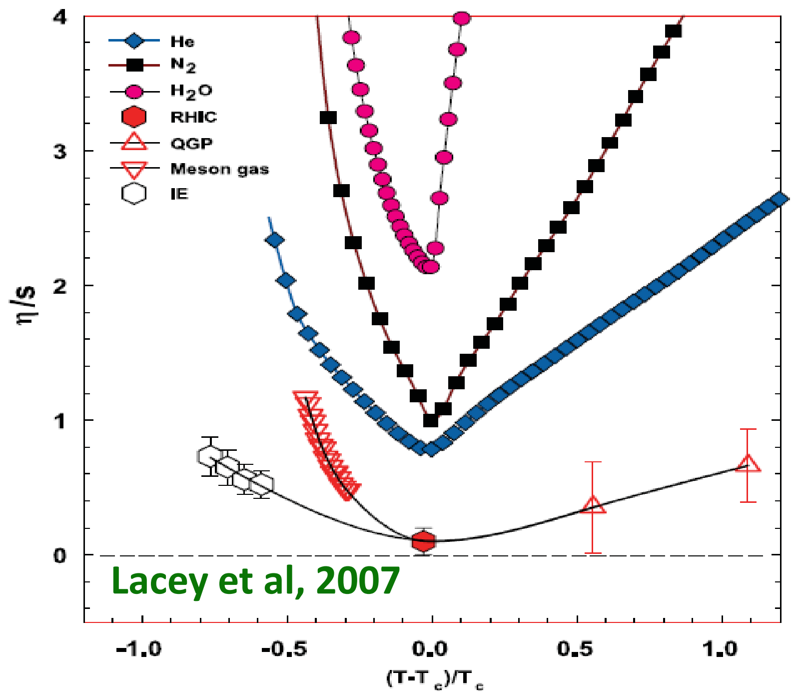


- A~0.1 /fm at T=180 MeV, comparable to the non-perturbative T-matrix calculation of charm quark thermal relaxation rate in QGP
- expected modification of D-spectrum at RHIC: $1-\exp(-A\Delta\tau_{had}) \approx 20\%$
- spatial diffusion coefficient D_s=T/(mA), surprisingly close to T-matrix result for charm quark in QGP: quark-hadron duality?!

Charm diffusion: HRG ➔ eta/s

- Transport coefficient: eta/s = (1/5 ~ 1/2)D_s; Danielewicz&Gyulassy, 1985
- D_s translates into eta/s = (2-5)/4pi at T=180 MeV, comparable to J.N-Hostler 2009





- Both exhibit a minimum across the quark-hadron transition ➔ duality?!
- The charm diffusion coeffi. provides us with another perspective of looking into the transport properties of sQGP/dense matter

Summary & Conclusion

- A strongly coupled framework for HQ diffusion + hadronization (Hydro + Langevin + RRM) presented
- The role of resonance correlation emphasized:

  (a). resonance contribution (Q-q T-matrix calculation) to heavy quark thermal relaxation

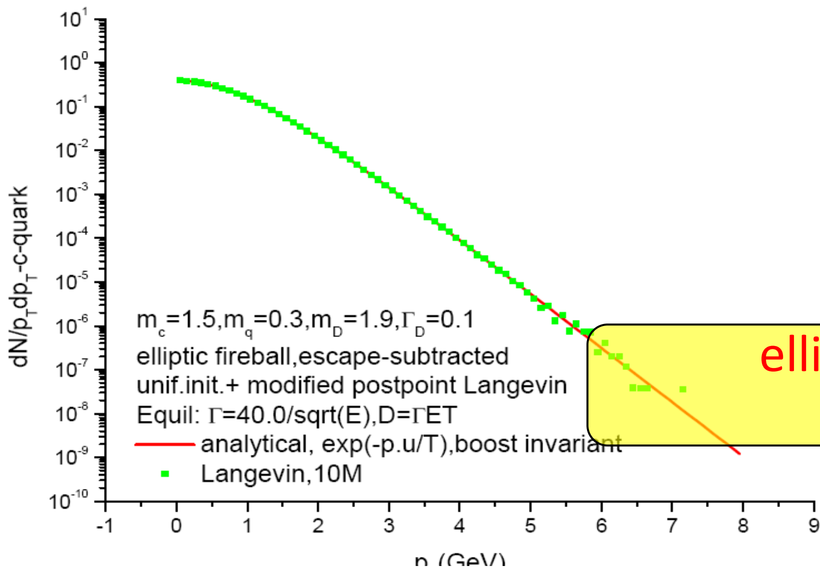
  (b). c-q Resonance Recombination to describe the coalescence hadronization
- Medium flow's effect (via RRM) on heavy-meson observables highlighted

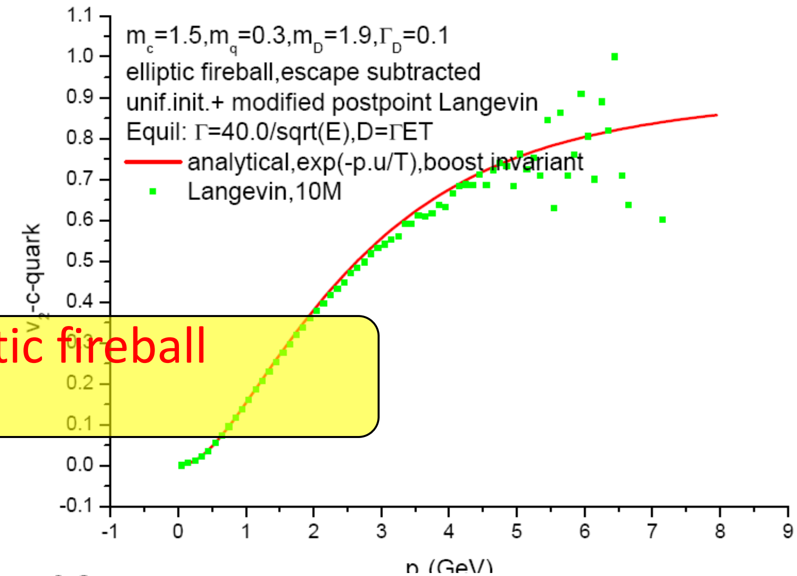
  Reference: M. He, R. J. Fries & R. Rapp, arXiv: 1106.XXXX[nucl-th]
- charm hadronic diffusion: quark-hadron duality?!

  Reference: M. He, R. J. Fries & R. Rapp, PLB, in press

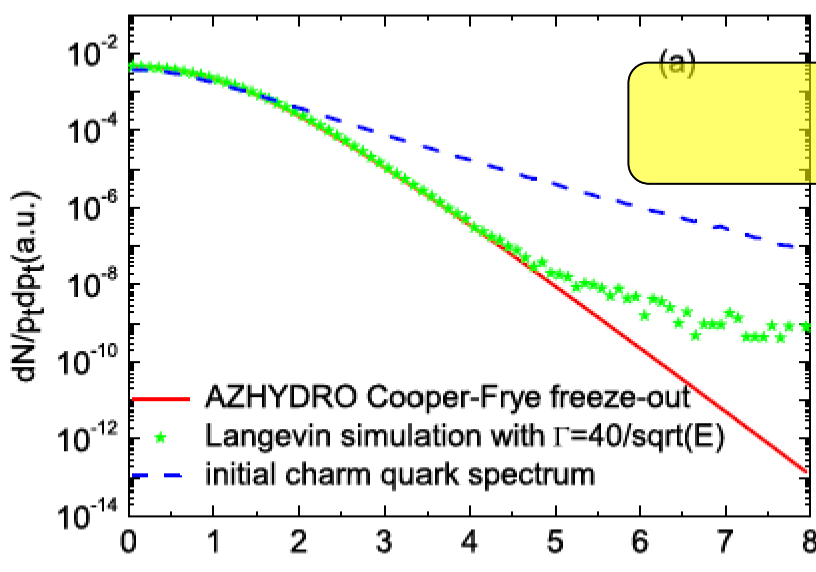
Thanks for attention!

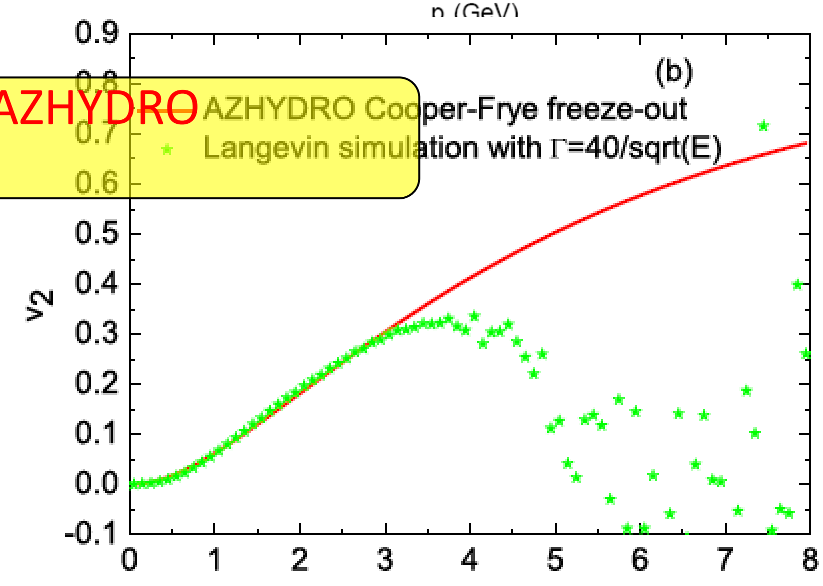
Backup 1: Langevin equilibrium





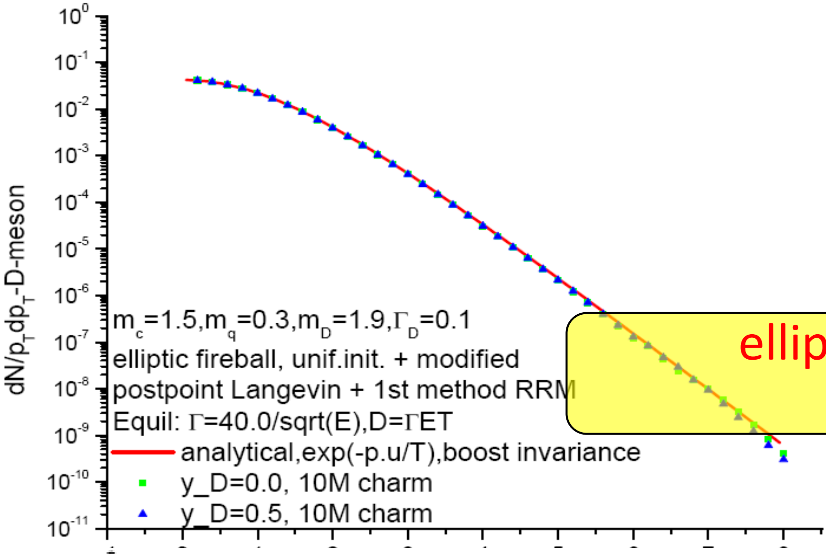
elliptic fireball

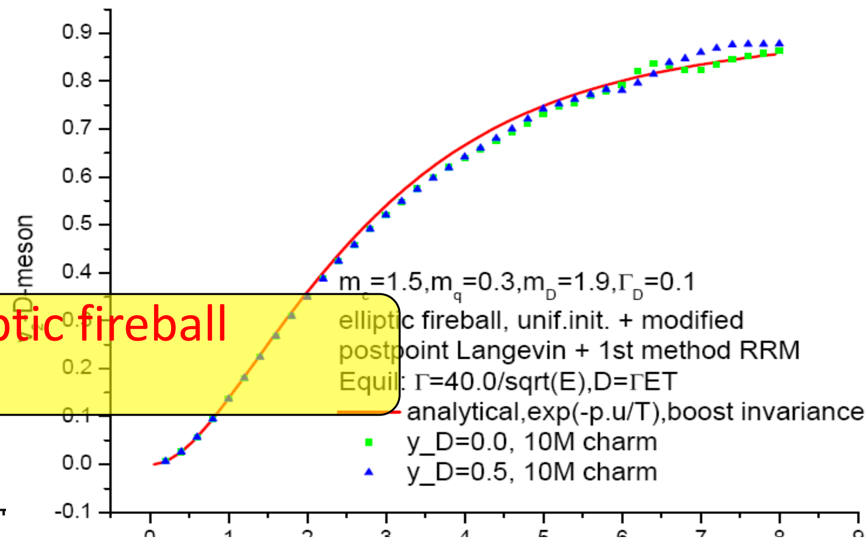




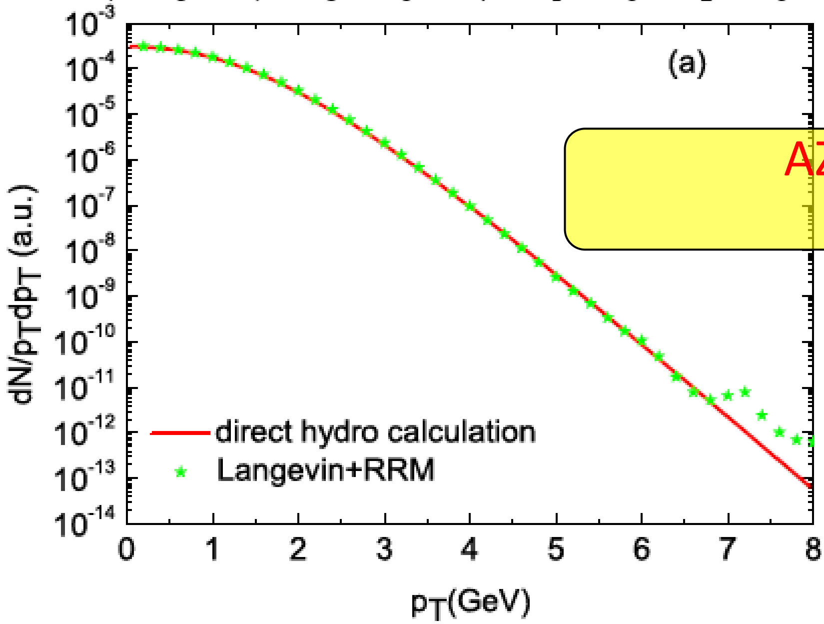
AZHYDRO

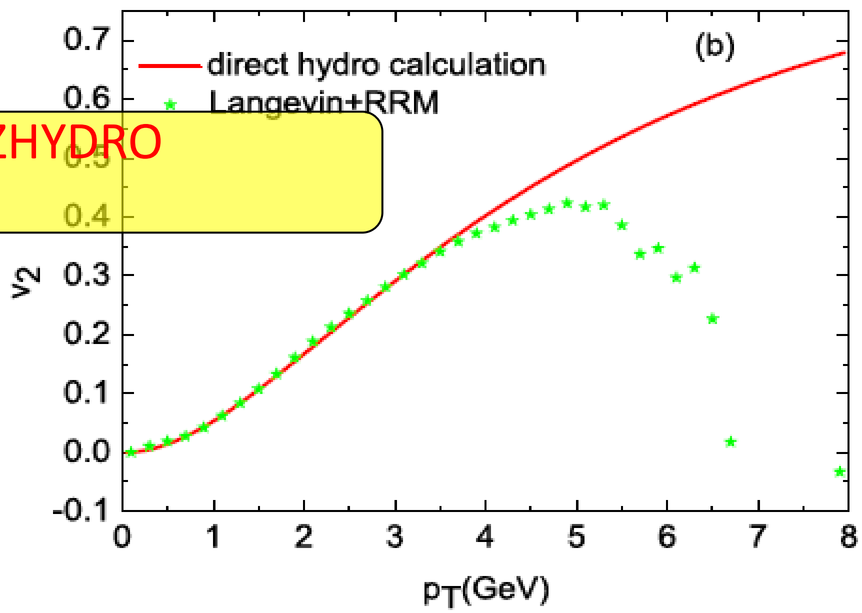
Backup 2: RRM equilibrium





elliptic fireball





AZHYDRO

Backup 3: 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, $P_{coal}(p_t) = \tau_{res}\gamma_Q(p_t)$