Open Heavy Flavor

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Date: Wednesday, June 18, 2014
Organizers: Rachid Nouicer, Yifei Zhang
Time: 9:00am to 12:15pm
Location: Biosciences Department John Dunn Seminar Room, Building 463

Agenda

Session I:		
9:00 - 9:30	Theoretical Overview of Open Heavy Flavor results from RHIC and LHC	Ralph Rapp, Texas A& M University
9:30 - 10:00	Experimental Overview of Open heavy Flavor Results from RHIC and LHC	Wei Xie, Purdue University
10:00 -10:30	Recent Open heavy Flavor Results from STAR Experiment at RHIC	Mustafa Mustafa for the STAR Collaboration
10:30 -10:45	**Coffee Break/End of Session I**	
Session II:		
10:45 -11:15	Recent Open Heavy Flavor Results from PHENIX Experiment at RHIC	Maki Kurosawa for the PHENIX Collaboration
11:15 -11:45	Recent Open Heavy Flavor Results from ALICE Experiment at LHC	Jeremy Wilkinson, University of Heidelberg
11:45 -12:15	Recent Open Heavy Flavor results from ATLAS and CMS Experiment at LHC	Yen-Jie Lee, Massachusetts Institute of Technology

Theoretical Overview of Open Heavy-Flavor at RHIC and LHC

Ralf Rapp
Cyclotron Institute +
Dept of Phys & Astro
Texas A&M University
College Station, USA

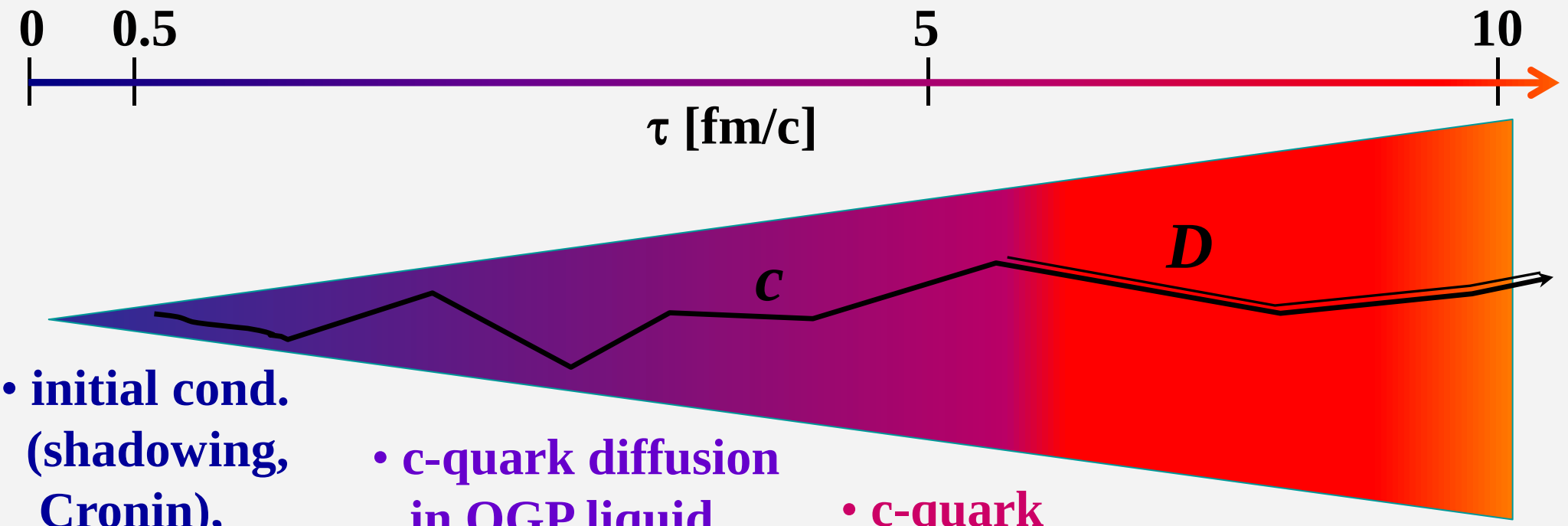
Workshop on "Open Heavy Flavor"
RHIC & AGS Annual Users' Meeting
BNL (Upton, NY), 17.-20.06.14

1.) Introduction: Why Heavy Quarks in URHICs?

"Large" scale $m_Q >> \Lambda_{QCD}, T$ (Q = c, b):

- pair production in primordial NN collisions
  → well defined initial condition, flavor conserved
- thermal relaxation time $\tau_Q \sim m_Q/T \sim 5\text{-}20 \geq \tau_{fireball}$
  → incomplete thermalization, **"gauge" of interaction strength**
- simplifications in theoretical treatment
  → diffusion: **Brownian markers of QGP**
  → access to **soft** interactions in QGP / hadronization
  → **potential** theory
  → quantitative connections to **lattice QCD**
  → direct window on QGP **transport coefficient**

1.2 Heavy-Quark Evolution in URHICs



- **initial cond. (shadowing, Cronin), pre-equil. fields**
- **c-quark diffusion in QGP liquid**
- **c-quark hadronization**
- **D-meson diffusion in hadron liquid**

- **Consistency**
  - **weak coupling:** pQCD + fragmentation
  - **strong coupling:** non-pert. diffusion + recombination

Outline

1.) Introduction

2.) Heavy-Quark Transport in QGP

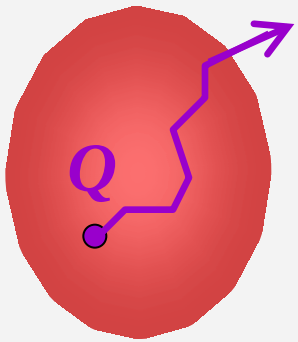
3.) D-Meson Transport in Hadronic Matter

4.) Hadronization

5.) Heavy-Ion Phenomenology

6.) Conclusions

2.) Heavy-Quark Transport Coefficient



- $p^2 \sim m_Q T >> k^2 \sim T^2 \Rightarrow$ Brownian Motion:

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

Fokker Planck Eq.

thermalization rate

$$\gamma p = \int d^3k \, w_Q(k,p) \, k$$

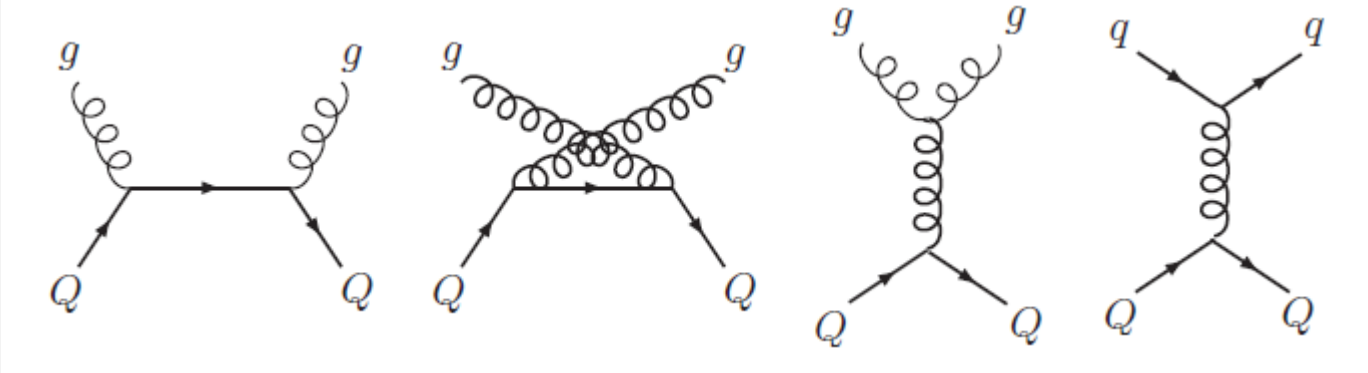
$$\sim \int |T_{Qq}|^2 (1 - \cos\theta) \, f^{q,g}$$

diffusion coefficient

$$D_p = \frac{1}{2} \int d^3k \, w_Q(k,p) \, k^2$$

- thermal relaxation time $\tau_Q = 1/\gamma$
- Einstein relation: $T = D_p / \gamma m_Q$ $\rightarrow$ check FP approximation
- spatial diffusion constant: $D_s = T / \gamma m_Q$
- relation to bulk medium: $D_s (2\pi T) \sim \eta / s$

2.1 Leading-Order Perturbative QCD



- gluon exchange regularized by Debye mass**:**

$$G(t) = \frac{1}{t} \rightarrow \frac{1}{t - \mu_D^2}\ , \quad \mu_D = gT$$

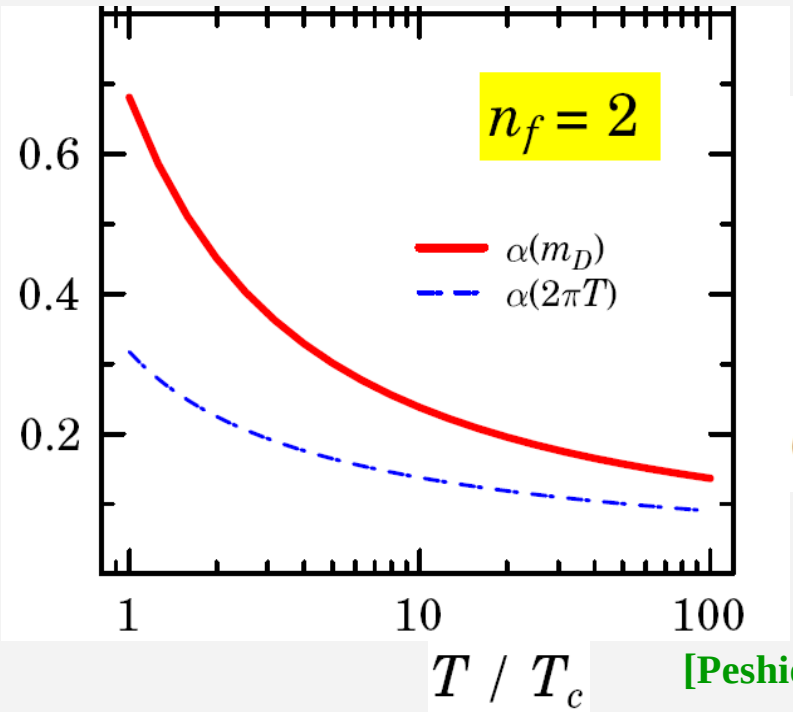
[Svetitsky '88, Mustafa et al '98, Molnar et al '04, Zhang et al '04, Hees+RR '04, Teaney+Moore'04]

- dominated by forward scattering off gluons
- thermalization time $\gamma^{-1} = \tau_c \geq 20$ **fm/c** long (**T≤ 300MeV,** α_s**=0.4**)

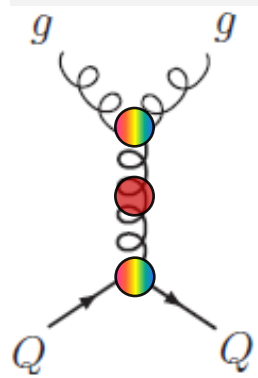
2.2 Perturbative QCD with Running Coupling

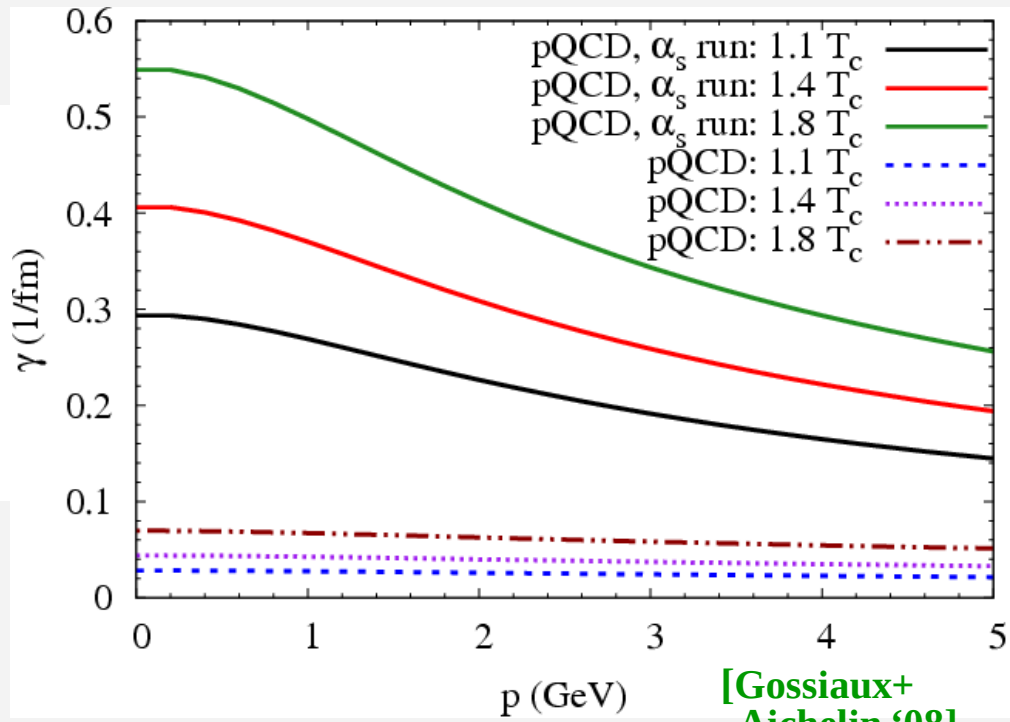
- run α_s to $\mu_D \sim gT$, rather than $2\pi T$
- reduced Debye mass $\tilde{\mu}^2 = \frac{1}{5}\mu_D^2$

$$G(t) = \frac{\alpha}{t} \rightarrow \frac{\alpha_{\rm eff}(t)}{t - \tilde{\mu}^2}$$



[Peshier '07]



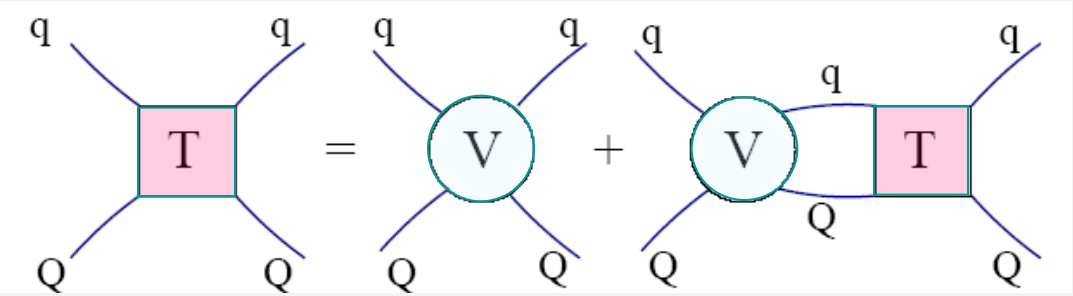


[Gossiaux+ Aichelin '08]

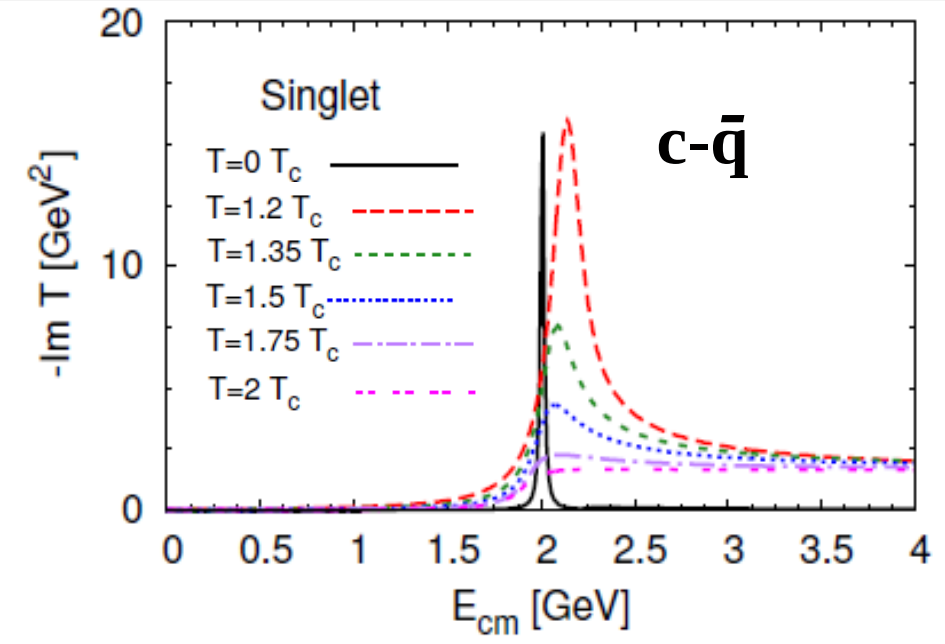
- factor ~10 faster thermalization: $\tau_c \approx$ 2-3 fm/c
- perturbative regime? Need to resum large diagrams…

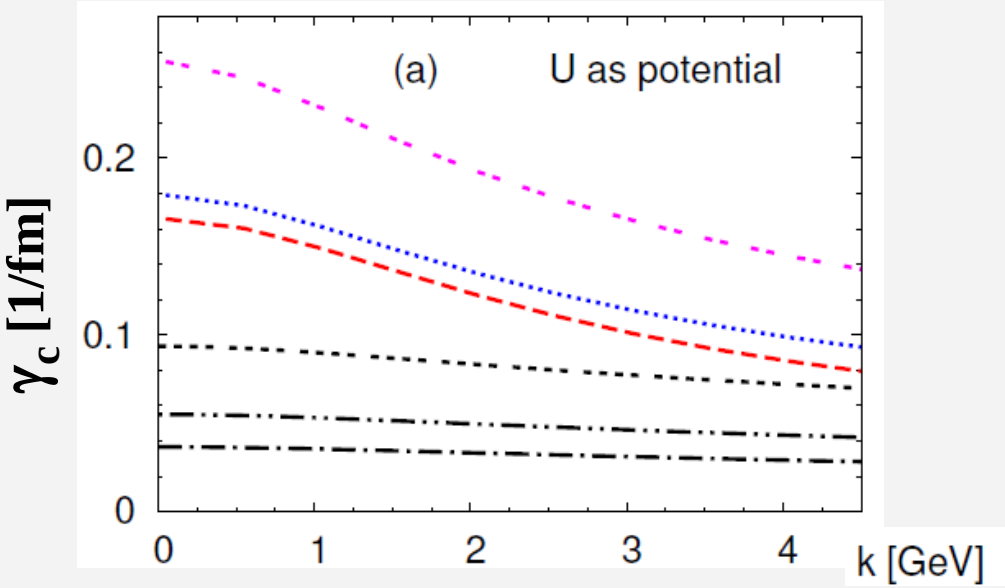
2.3 T-Matrix Approach

- **In-medium scattering amplitude**



$$T_{Qq}(E;p,p') = V_{Qq}(p,p') + \int k^2 dk\, V_{Qq}(p,k)\, G^0_{Qq}(E,k)\, T_{Qq}(E;k,p')$$





- "Feshbach" resonances near T_c

[Riek+RR '10]

- enhanced thermalization rate
- 3-momentum dependence!

3.) D-Meson Transport in Hadronic Matter

$$\gamma_D = \int |\mathcal{M}_{Dh}|^2 (1-\cos\theta)\, f^h$$

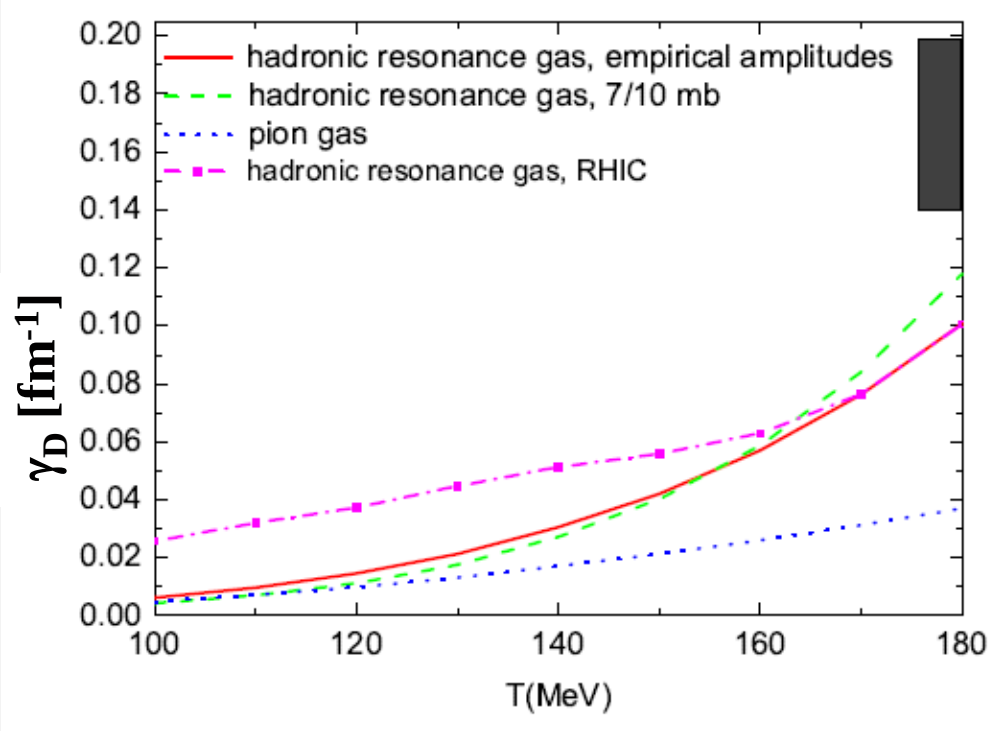
- effective ***D-h*** scattering amplitudes

[He,Fries+RR '11, Tolos+Torres-Rincon '13]

Hadrons	$L_{I,2J}$	γ_D [fm^{-1}]
π	$S_{1/2,0},\ P_{1/2,2},\ D_{1/2,4},\ S_{3/2,0}$	0.0371
$K+\eta$	$S_{0,0},\ S_{1,0}$	0.0236
$\rho+\omega+K^*$	$S_{1/2,2},\ S_{0,2},\ S_{1,2}$	0.0129
$N+\bar{N}$	$S_{0,1},\ S_{1,1}$	0.0128
$\Delta+\bar{\Delta}$	$S_{1,3}$	0.0144

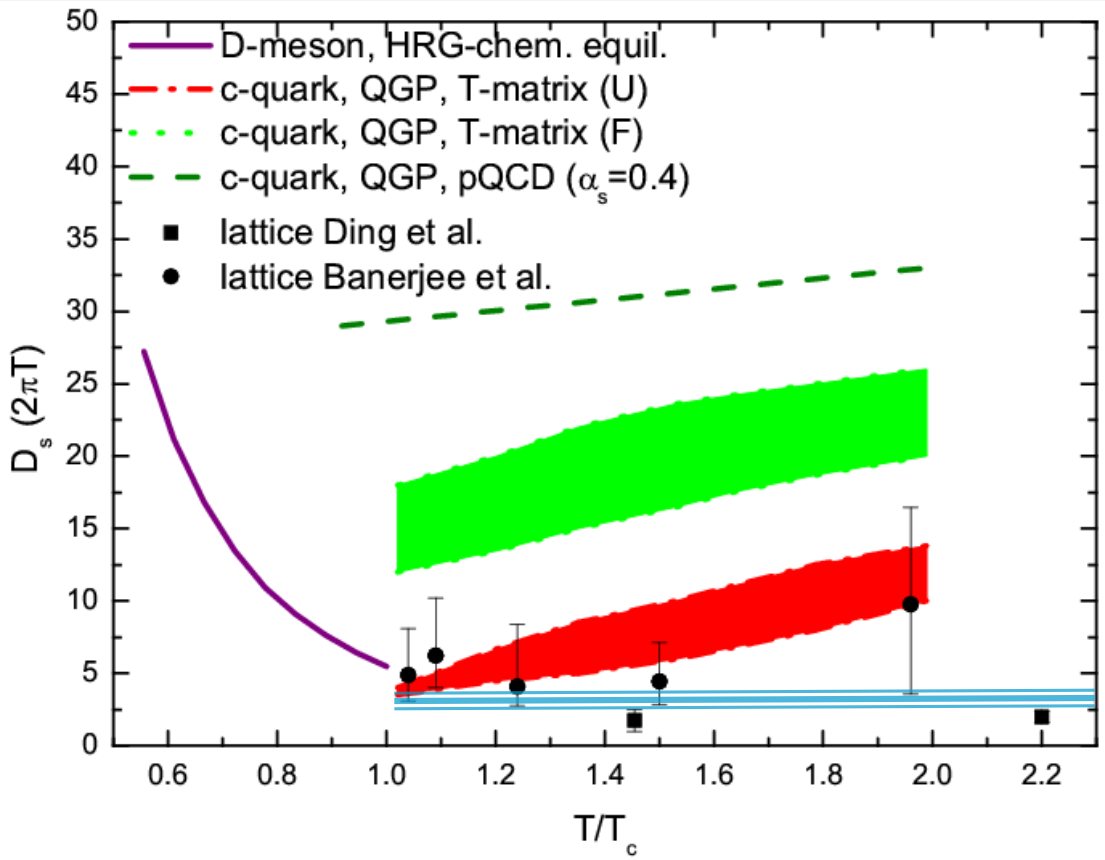
- **D**-meson in pion gas:
  - consistent with unitarized HQET [Cabrera et al '11]
  - factor **~10** larger in heavy-meson χPT [Laine '11]

- hadron gas at **~T_c**: $\tau_D \approx$ **10fm/c**



Summary of Charm Diffusion in Matter

Hadronic Matter vs. QGP vs. Lattice QCD



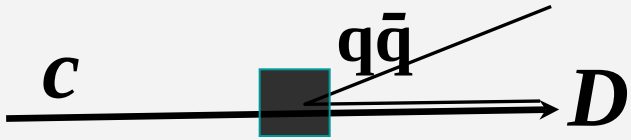
[He et al '11, Riek+RR '10, Ding et al '11, Gavai et al '11]

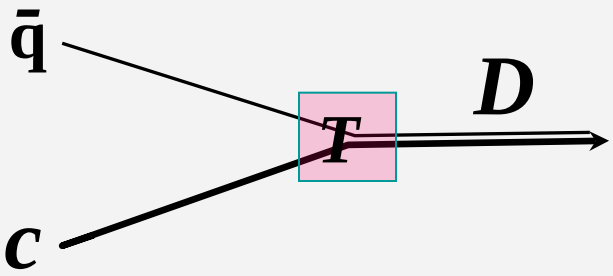
AdS/QCD [Gubser '07]

- Shallow minimun around T_c !?
- Quark-Hadron Continuity!?

4.) Heavy-Flavor Hadronization

- **Hadronization is an interaction!**
- High $\mathbf{p_T}$: pQCD with fragmentation
- Low + Intermediate $\mathbf{p_T}$
  - resonant **Qq** recombination:
    same interaction as in non-pert. diffusion,
    contributes to equilibration!

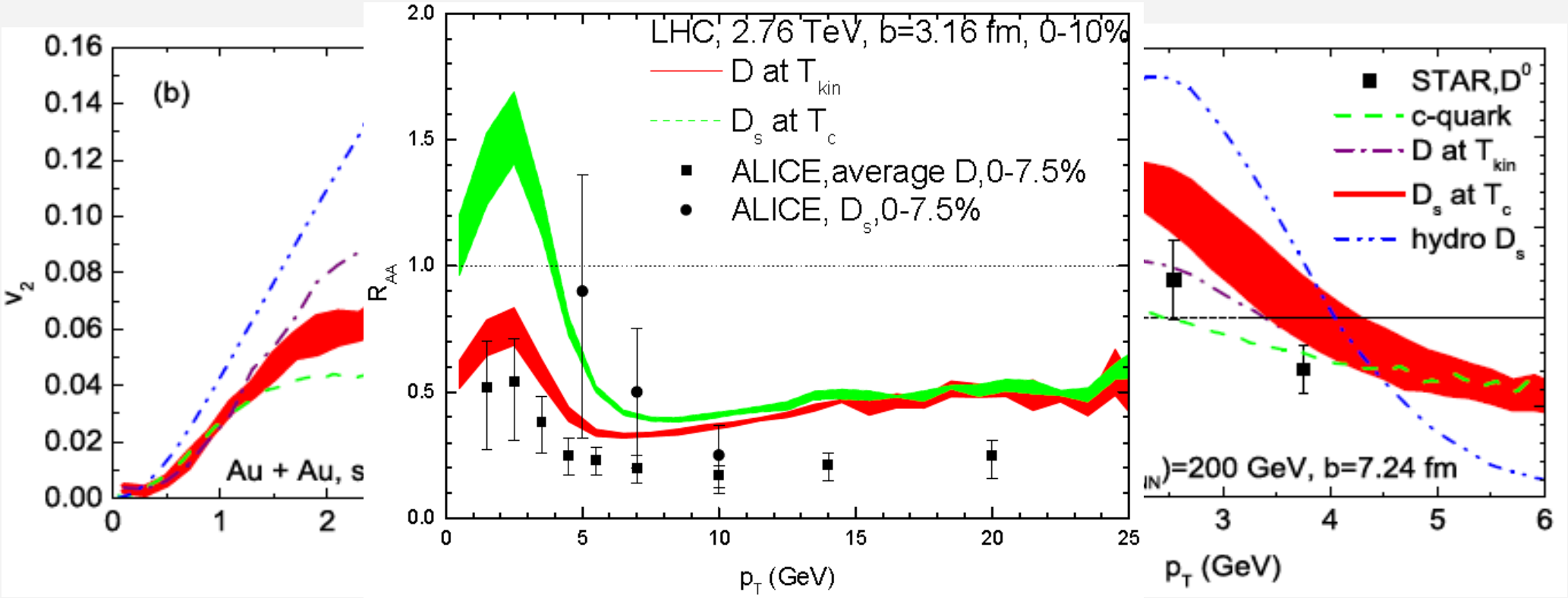




[Ravagli+RR '07]

5.) Charm Transport at RHIC + LHC

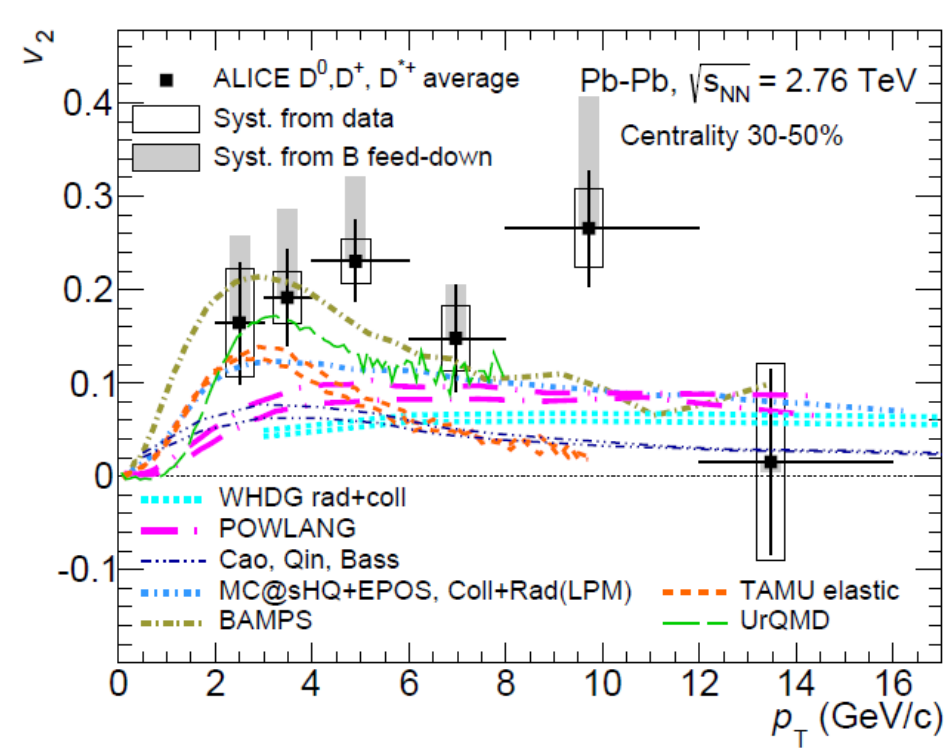
5.1 QGP – Hadronization – Hadronic Matter

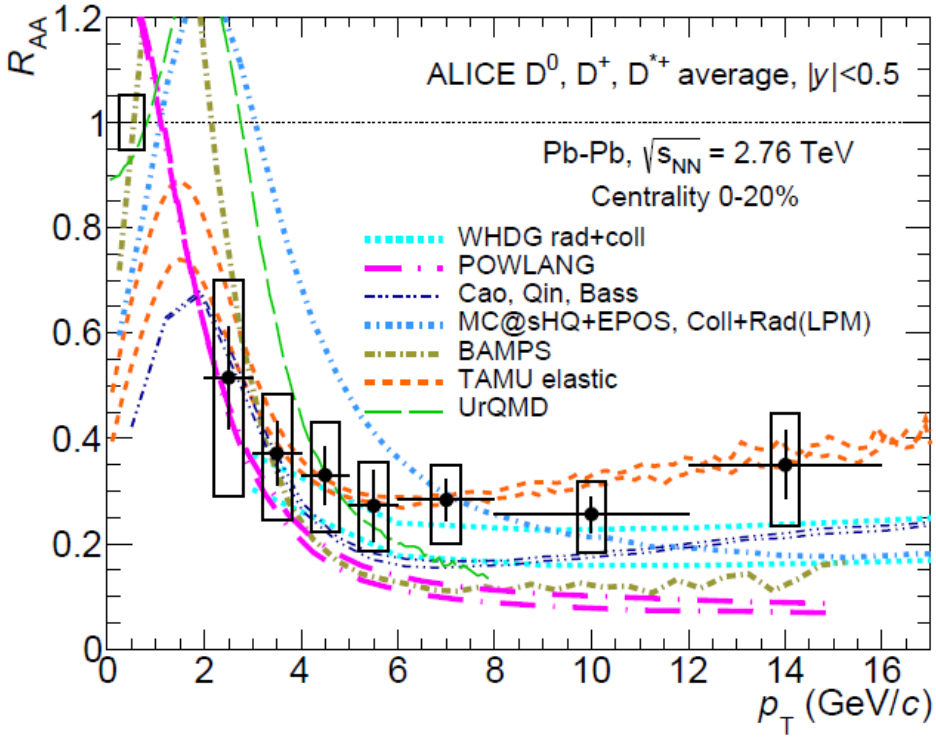


- increased QGP-$\mathbf{v_2}$ from recombination + hadronic diffusion
- $\mathbf{R_{AA}}$ "bump" sensitive to medium flow
- enhanced $\mathbf{D_s}$-$\mathbf{R_{AA}}$ from strangeness enhancement

[He et al '12]

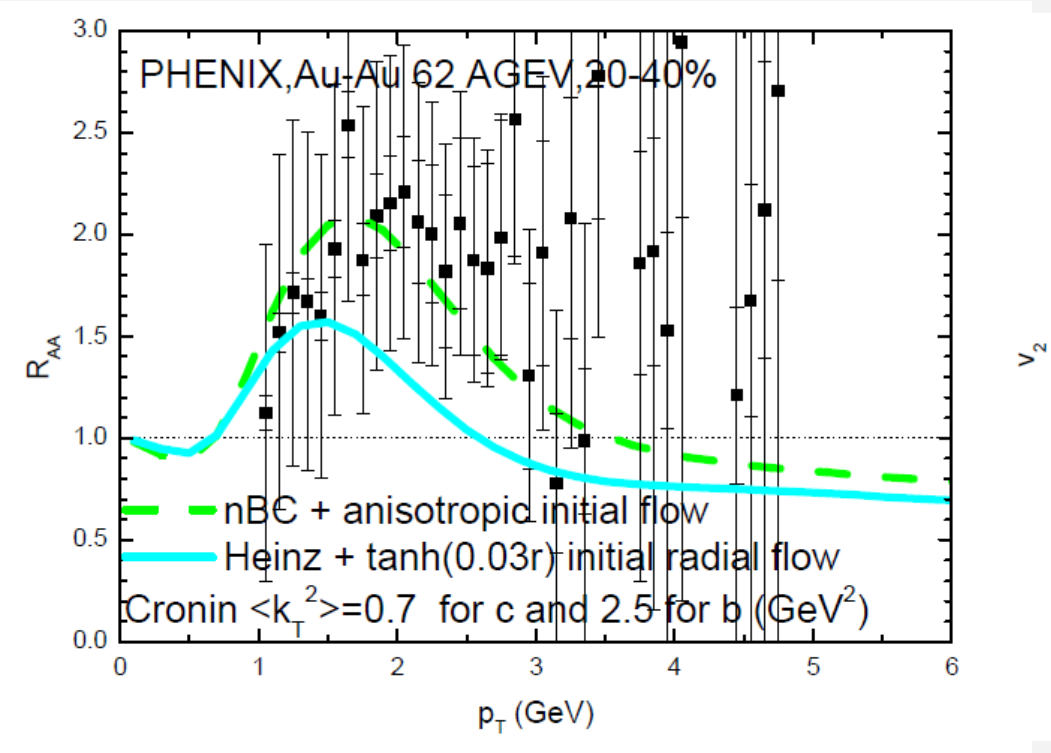
5.2 D-mesons at LHC

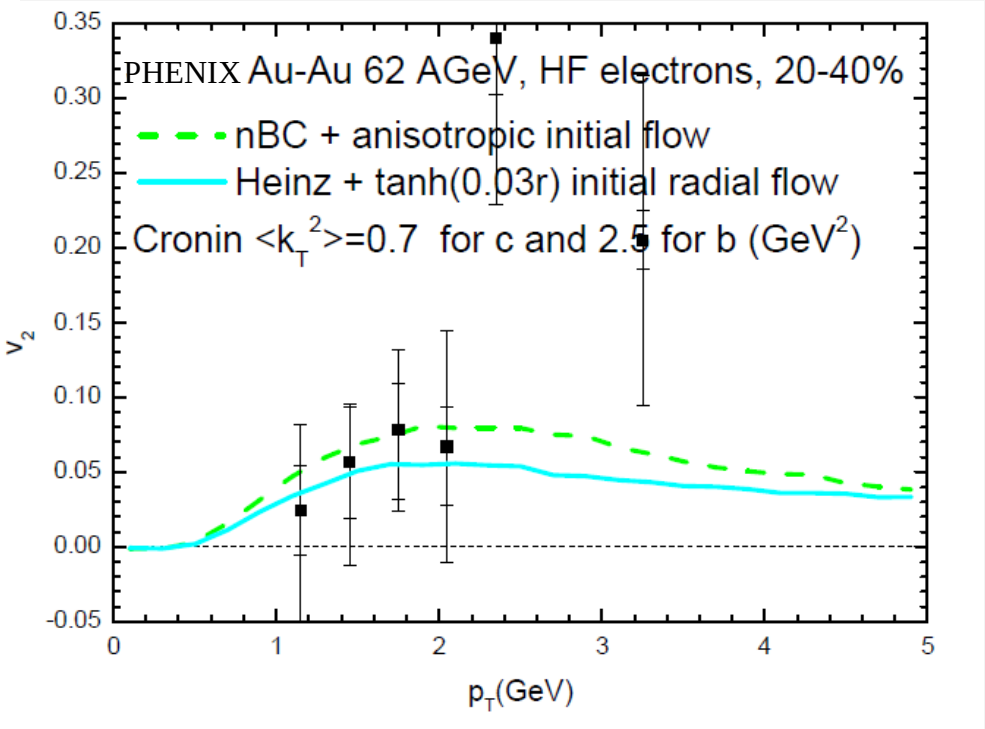




- No fully consistent description
- Perturbative approaches too weakly coupled for $\mathbf{v_2}$

5.3 Heavy-Flavor Electrons at √s=62GeV





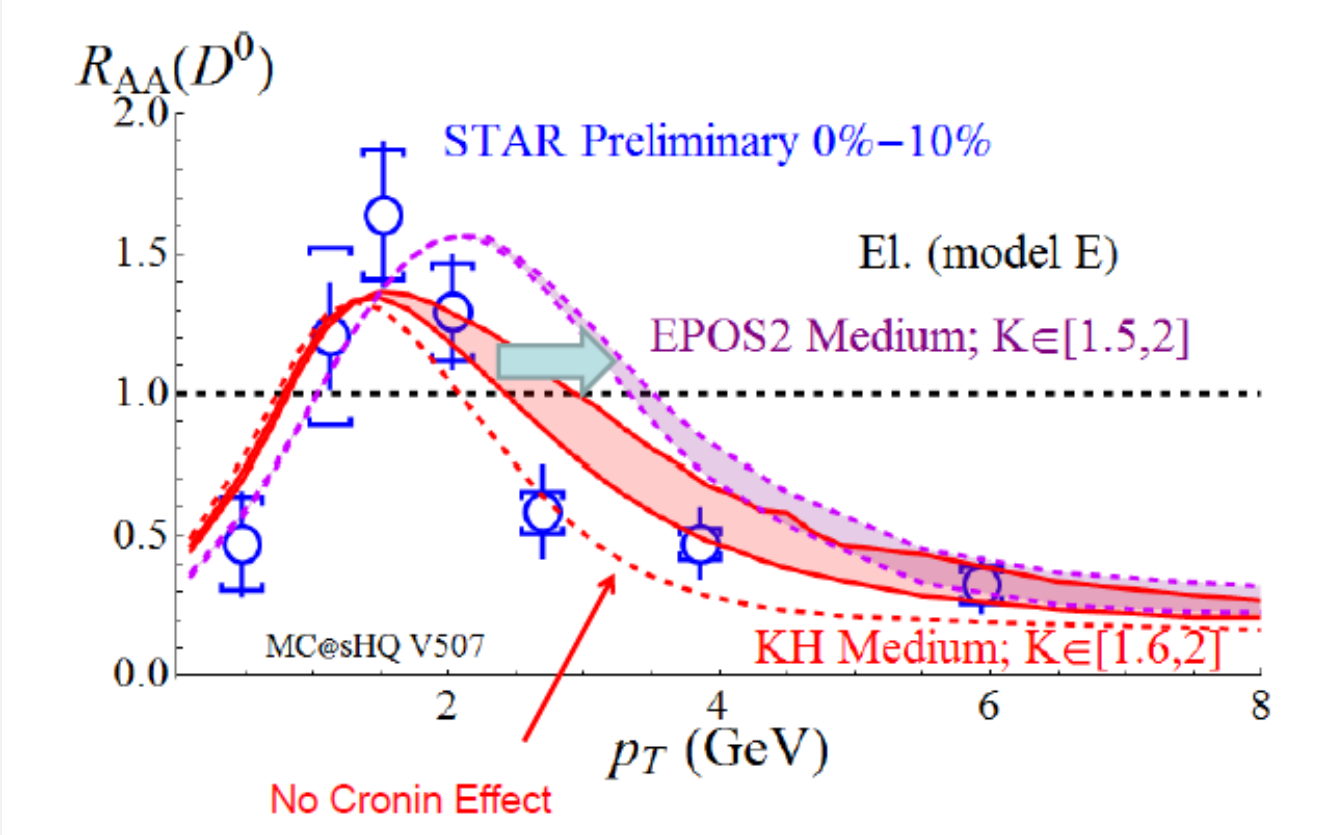
[He et al '14]

- Importance of **pp** baseline, Cronin (**pA**) and flow (**AA**)
- see also [Cao et al '14]

6.) Conclusions

- **Nonperturbative interactions govern heavy-flavor diffusion**
- **Diffusion coefficient D_s $(2\pi T) \sim 3\text{-}5$ (momentum dependent…)**
- **Same interaction for QGP diffusion + hadronization (resonance correlations near T_c)**
- **Hadronic diffusion significant**
- **Role of radiative interactions?**
- **BES results of high interest**

5.1.2 Impact of Bulk-Medium Evolution on D-mesons at RHIC



[Gossiaux et al '14]

- Significant shift of flow bump with "harder" medium

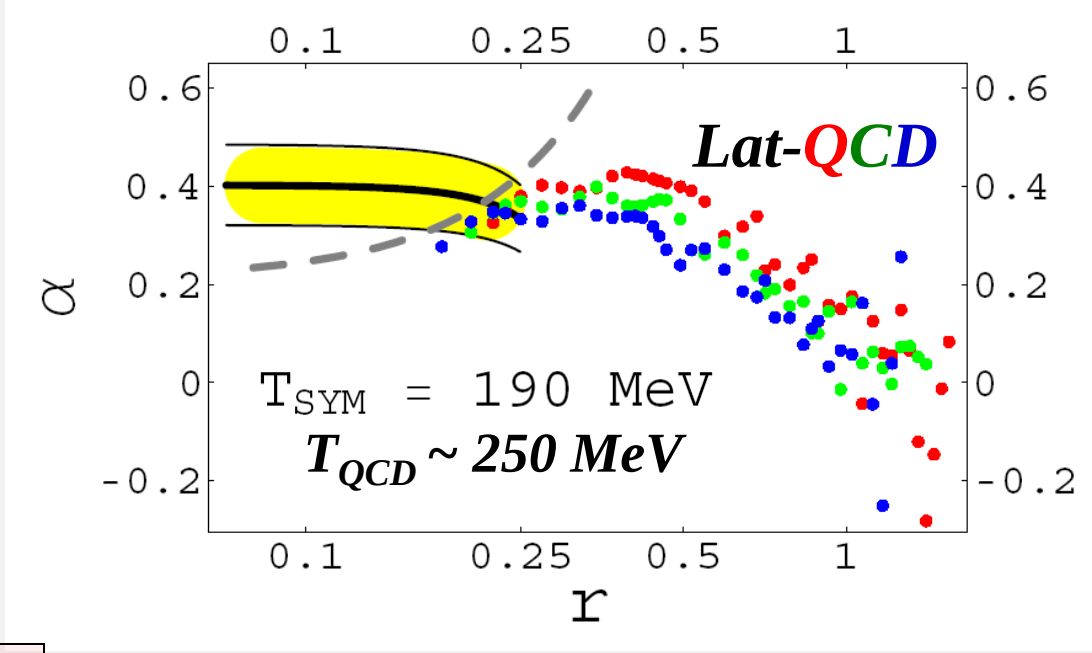
2.3 AdS/CFT-QCD Correspondence

$$\frac{dp}{dt} = -\gamma\, p \qquad \gamma_{ADS/CFT} \approx \frac{\pi\sqrt{\lambda}}{2m_c} T_{SYM}^2$$

3-momentum independent

[Herzog et al, Gubser '06]

- match energy density (d.o.f = **120** vs. **~40**) and coupling constant (heavy-quark potential) to QCD

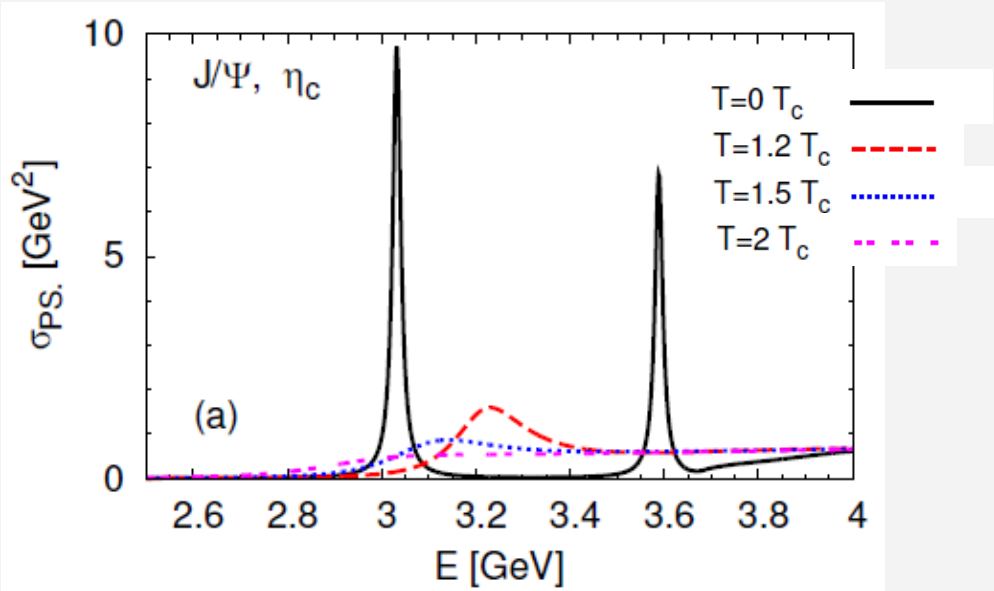


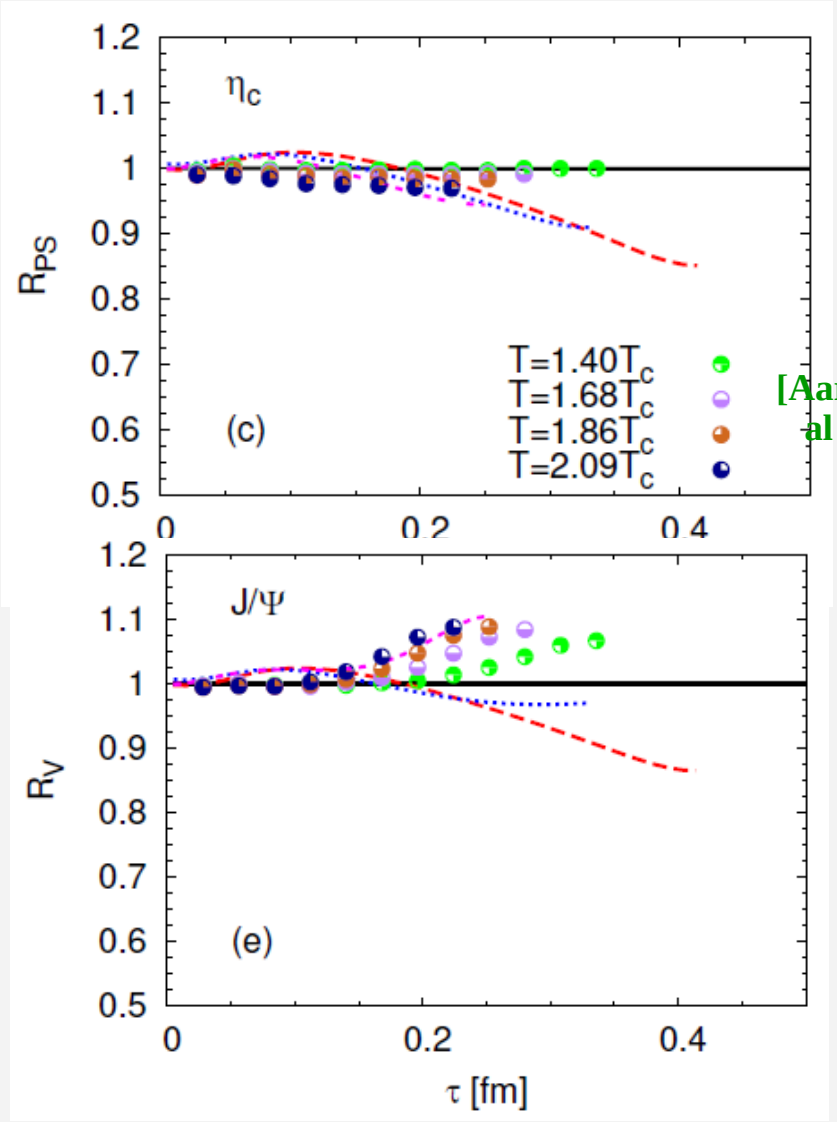
$$\Rightarrow \quad \gamma_{ADS/QCD} \approx (2.1 \pm 0.5)\frac{T^2}{m_c}$$

≈ (4-2 fm/c)$^{-1}$ at T=180-250 MeV

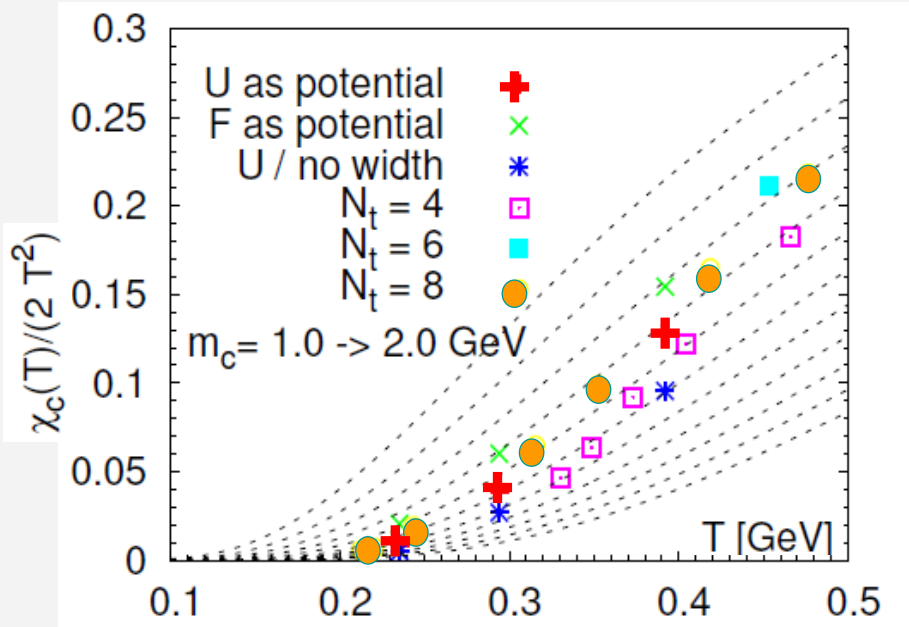
[Gubser '07]

3.3 Quarkonium Spectral Functions + Correlators





[Aarts et al '07]



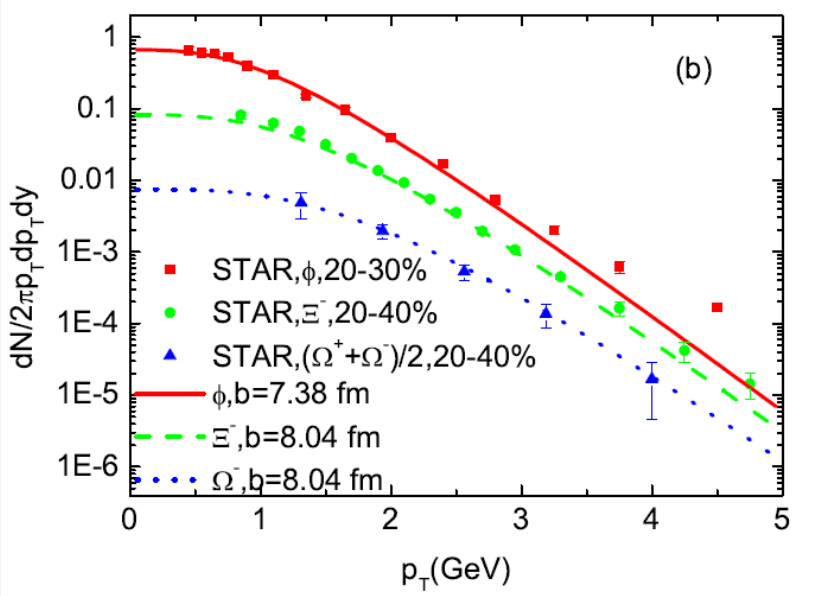
[Satz et al '01+'08, Mocsy+Petreczky '05+'08, Wong '06, Cabrera,Riek+RR '06+'10, Beraudo et al '06, Lee et al '09, …]

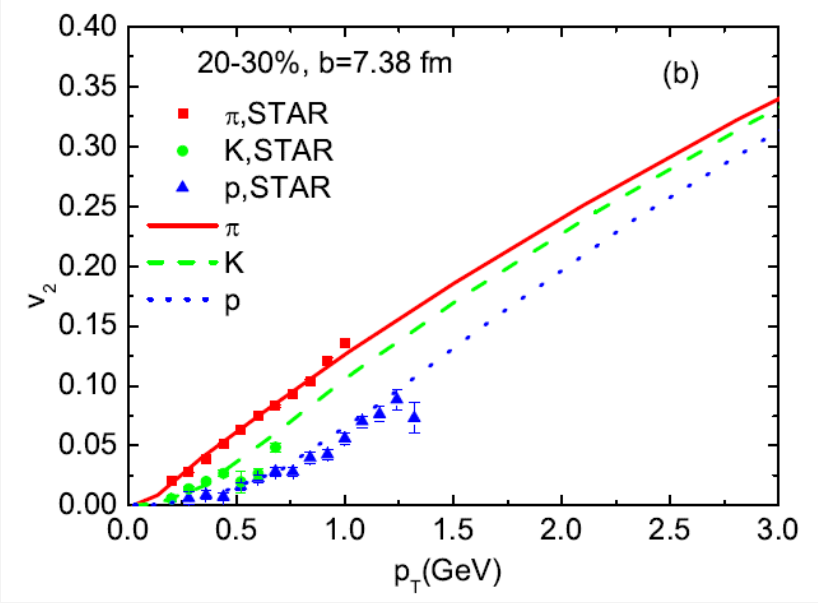
4.1 Quantitative Bulk-Medium Evolution

- initial conditions (compact, initial flow?)
- EoS: lattice (QGP, T_c~170MeV) + chemically frozen hadronic phase
- spectra + elliptic flow: multistrange at T_{ch} ~ 160MeV

  π, K, p, Λ, … at T_{fo} ~ 110MeV

[He et al '11]





- v_2 saturates at T_{ch}, good light-/strange-hadron phenomenology