Heavy-Flavor Probes of Quark-Gluon Plasma: Objectives and Opportunities

Ralf Rapp
Cyclotron Institute +
Dept. of Physics & Astronomy
Texas A&M University
College Station, TX
USA

CYCLOTRON INSTITUTE
TEXAS A&M UNIVERSITY

NATIONAL SCIENCE FOUNDATION
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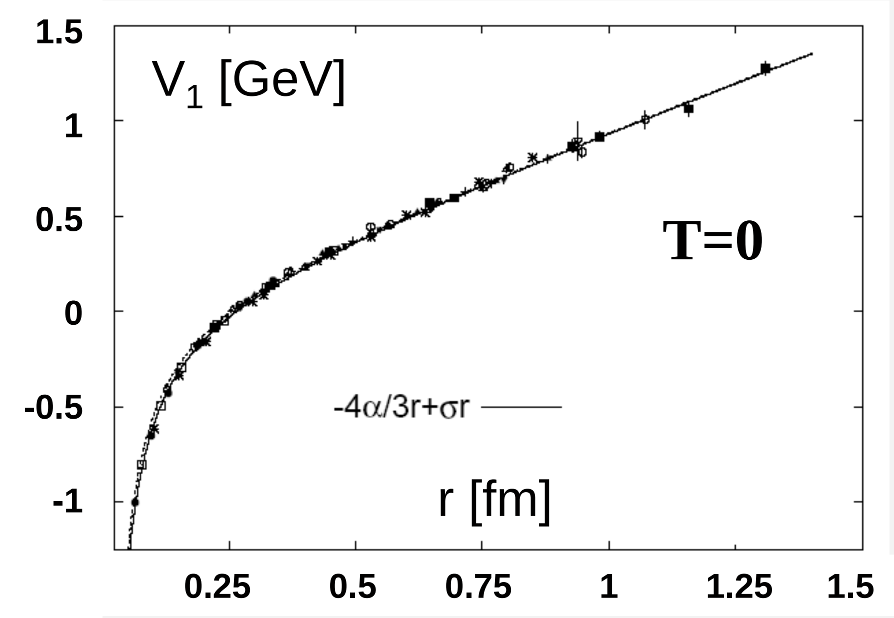
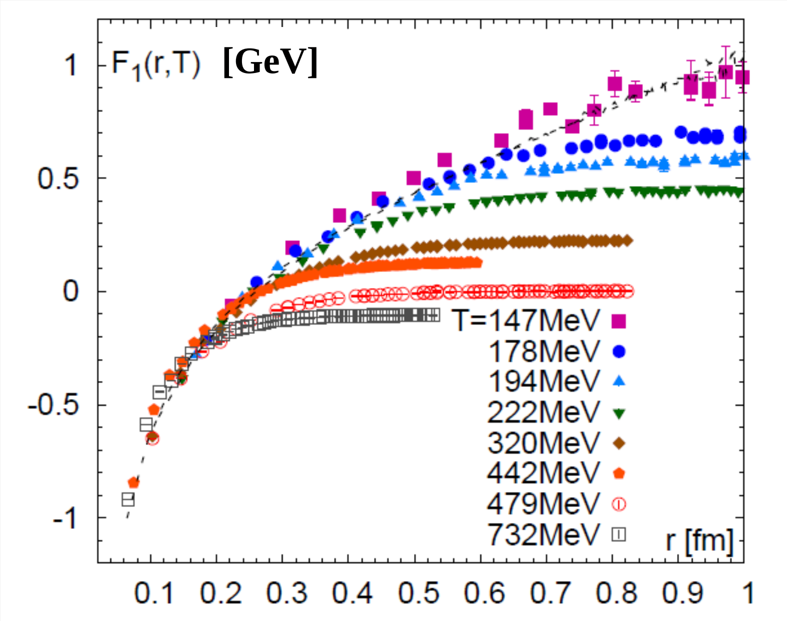
1.) Introduction: A "Calibrated" QCD Force





[Bazavov et al '13]

- Vacuum quarkonium spectroscopy well described
- Approx. works also for heavy-light + light hadrons (not **π**)
- Confinement ↔ **linear part of potential**

Opportunities:

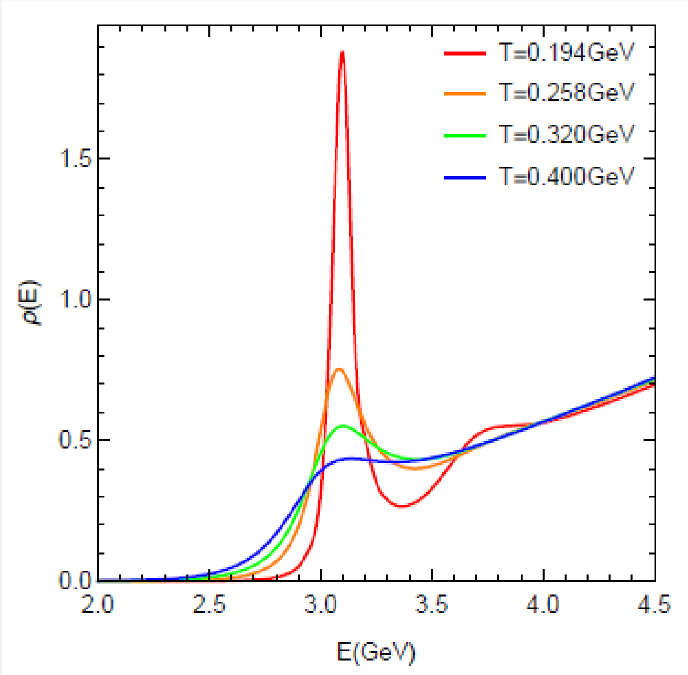
- Quarkonium properties in QGP ↔ "chemical" transport in URHICs

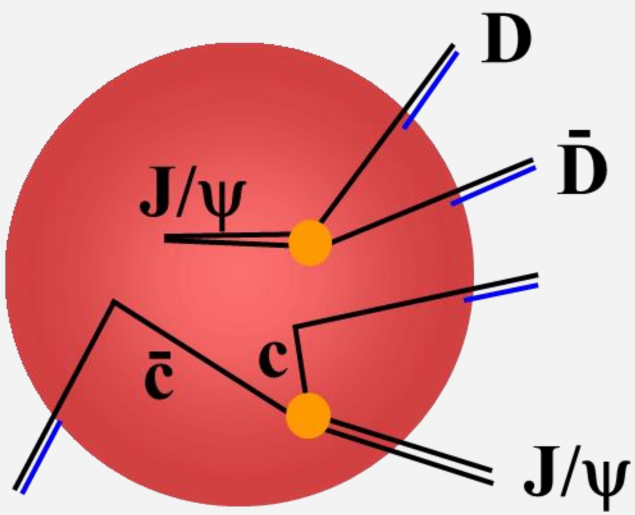
- Heavy-quark interactions in QGP ↔ "kinetic" transport in URHICs

Objective: Implications for QGP structure (spectral functions)?

1.2 Quarkonia in Medium

- In-medium **spectral functions**:
  - Mass / binding energy **$E_B(p,T)$**
  - Inelastic reaction rate **$\Gamma_{in}(p,T,E_B)$** (dissociation **and** regeneration)
- **ϒ(1S)**: **color-Coulomb force**
  J/ψ, ϒ(2S), …: **confining force**
- **How do heavy quarks within quarkonia interact with the medium?**
- **Not a good thermometer…**

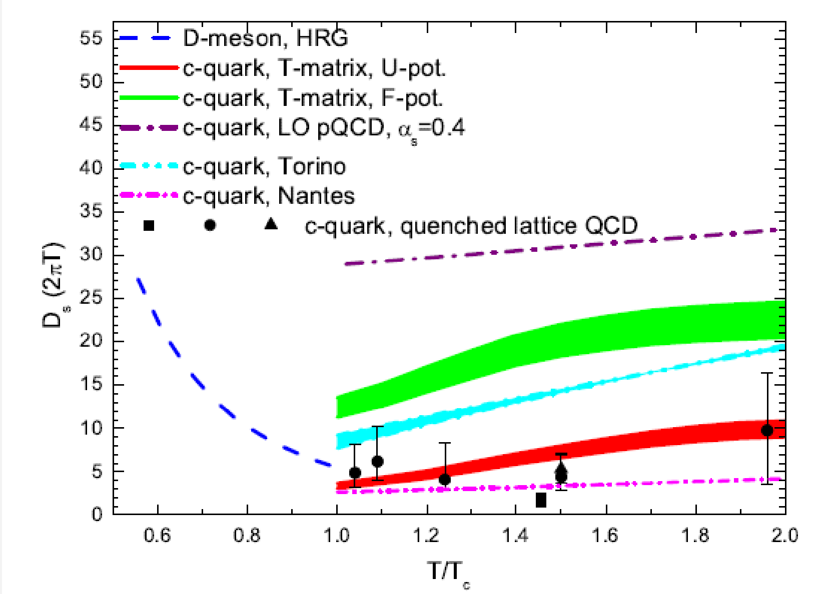




1.3 Heavy Quarks in Medium

- **Diffusion: "Brownian motion"**
- Thermalization **delayed** by **m_Q/T**
  → memory in URHICs
- Direct access to transport coefficient

  $\mathcal{D}_s$ (2πT) (~ **η/s** ~ **σ_{EM}/T** !?)



- Scattering rates
  → widths (quantum effects); quasiparticles? (**m_Q>>T**)
  → simple estimate: **$\mathcal{D}_s$(2πT)=3 ⇒ Γ_Q~1GeV**

  - **Need realistic medium to evaluate HQ interactions**

- Nonperturbative effects
- Probe of hadronization (**D_s, Λ_c**)
- Transition elastic → radiative stretched out to **p ≥ $\mathcal{O}$ (m_Q)**

Outline

1.) Introduction

2.) Quarkonia

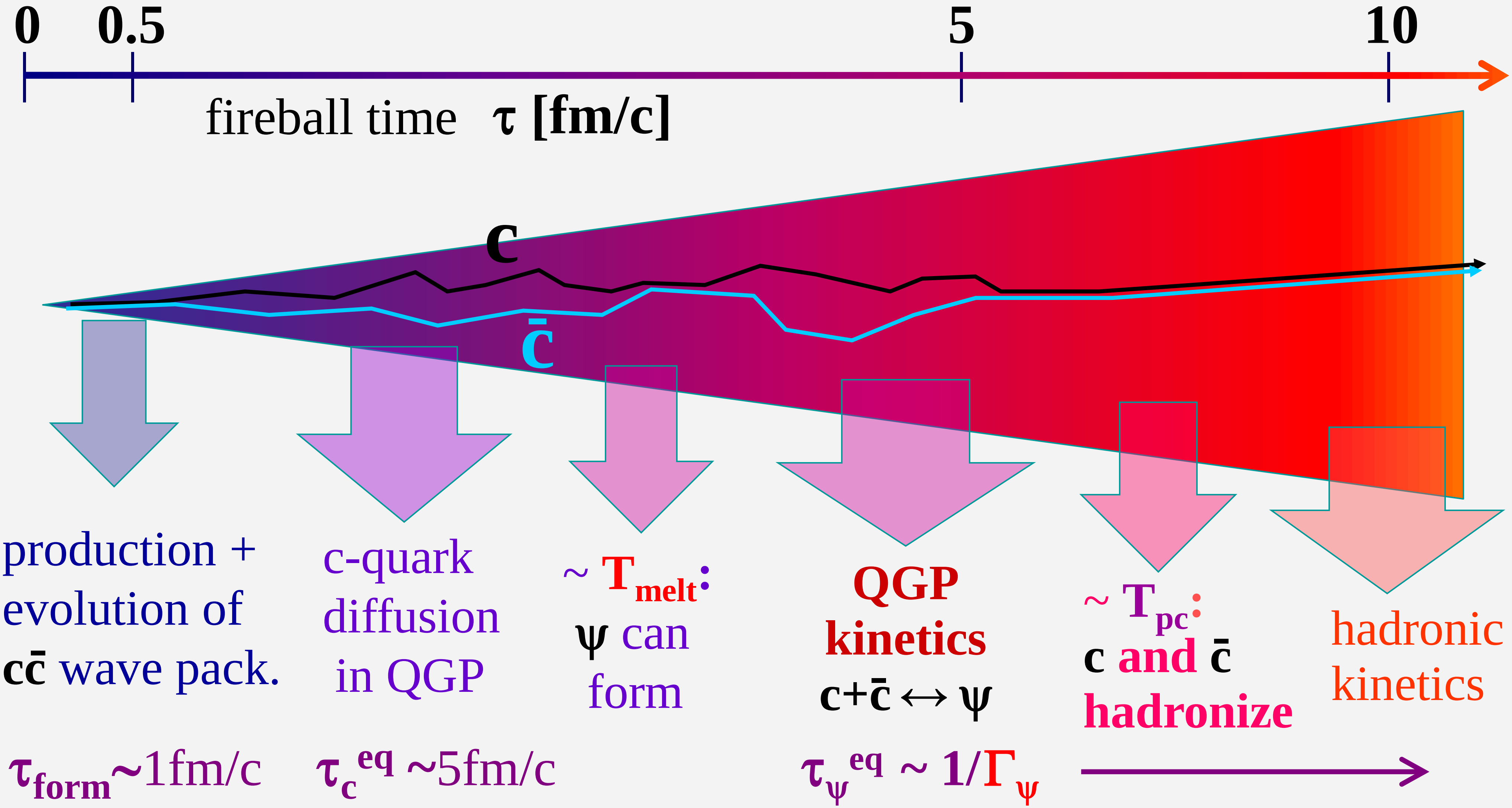
- Transport coefficients
- Phenomenology

3.) Open Heavy Flavor

- HQ interactions in QGP
- Probing the medium

4.) Conclusions

2.1 Quarkonium Transport in URHICs



[Satz et al, Capella et al, Spieles et al, PBM et al, Thews et al, Grandchamp et al, Ko et al, Zhuang et al, Zhao et al, Chaudhuri, Gossiaux et al, Young et al, Ferreiro et al, Strickland et al, Brambilla et al, …]

2.2 Theoretical Tools

- **Statistical Hadronization model:**

  chem. equil. of charm hadrons

$$N_\psi^{eq}(T_{ch}) = V_{FB} d_\psi \gamma_c^2 \int \frac{d^3p}{(2\pi)^3} f^\psi(m_\psi, T_{ch})$$

- **Transport Approaches**

  Boltzmann equat.

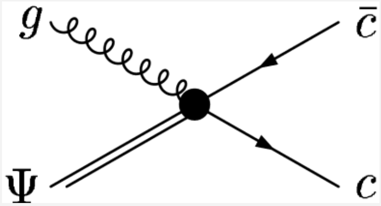
  → **Rate** equation

$$p^\mu \partial_\mu f^\psi = -E_p \, \Gamma_\psi f^\psi + E_p \, \beta$$

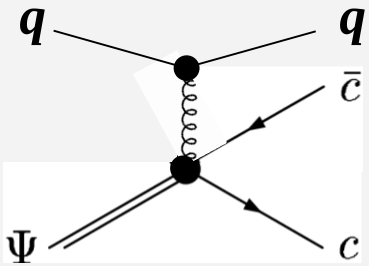
$$\frac{dN_\psi}{d\tau} = -\Gamma_\psi \left[N_\psi - N_\psi^{eq} \right]$$

- **Reaction Rate** Γ_ψ

"Strong" binding $E_B \geq T$



"Weak" binding $E_B < m_D$



- gluo-dissosciation ("singlet-to-octet")

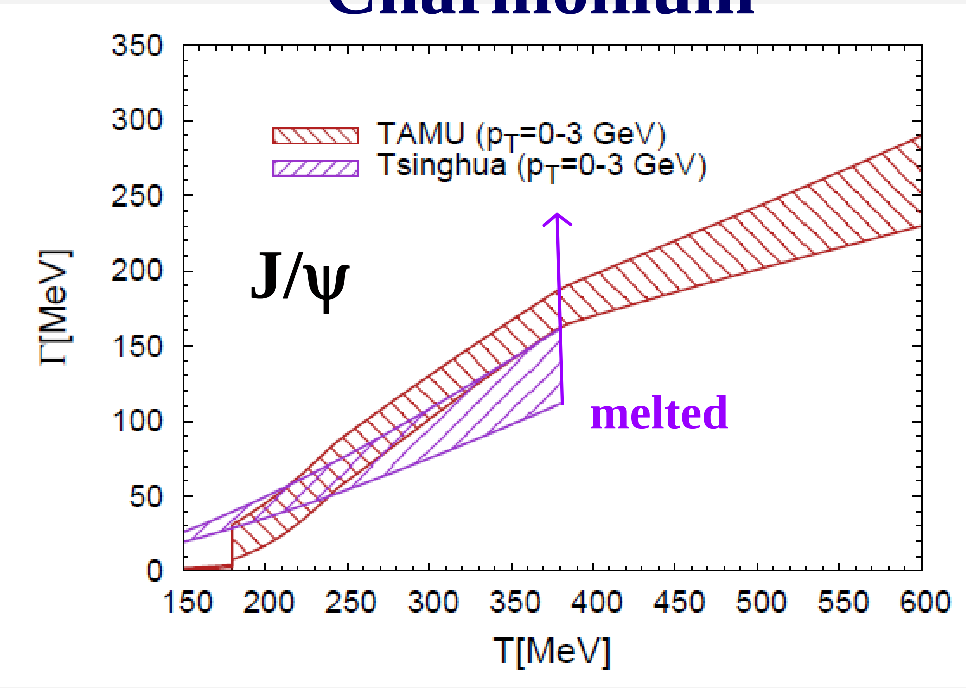
  [Bhanot+Peskin'85, Kharzeev+Satz'94, Brambilla et al'08,…]

- "quasi-free"/ Landau damping

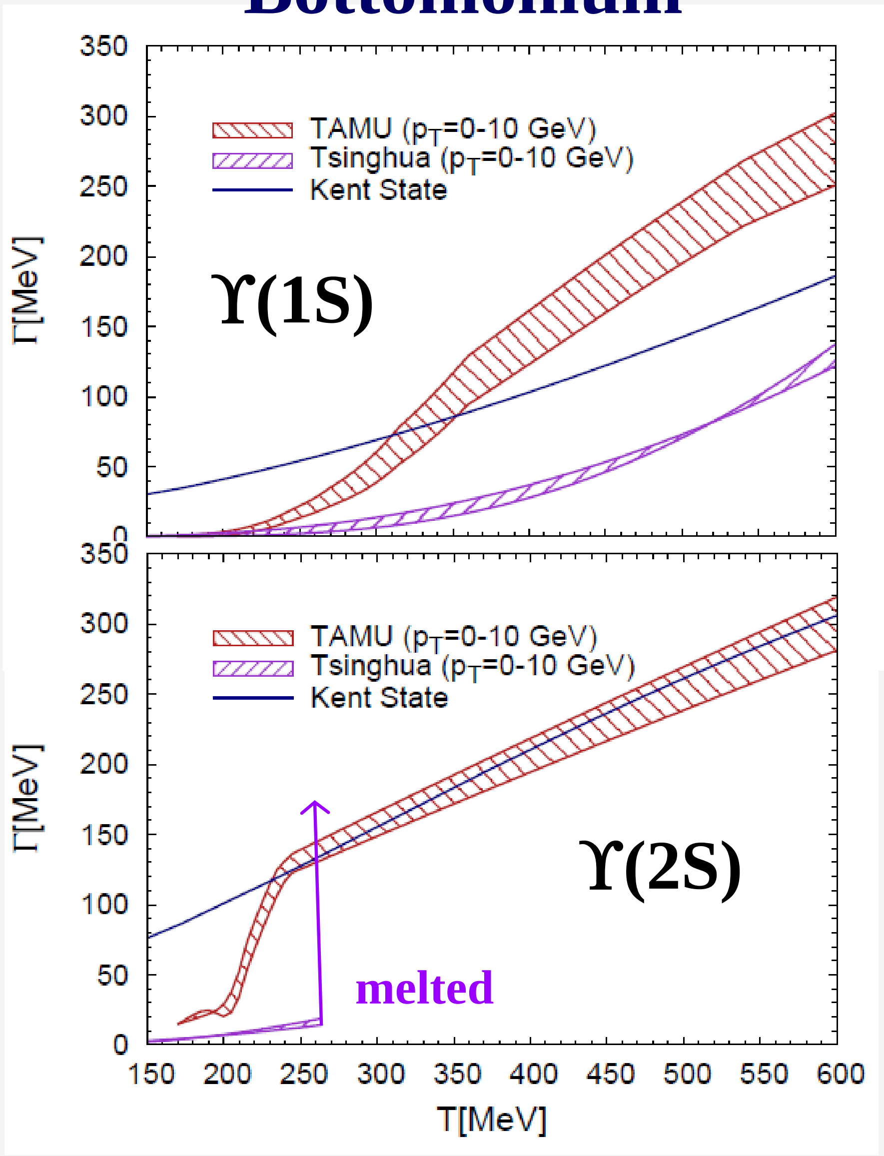
  [Grandchamp+RR'02, Song et al'07, Laine et al'07,…]

2.3 Quarkonium Width Comparisons

Charmonium



Bottomonium

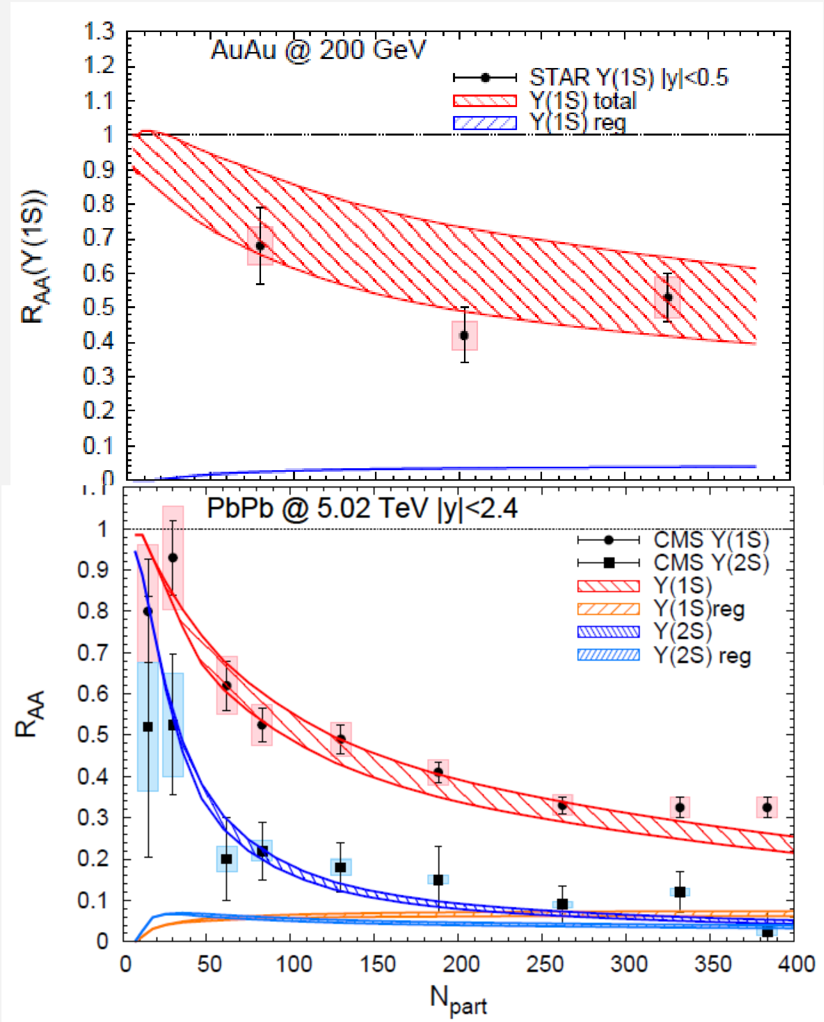


- Fair agreement for **J/ψ**
- Larger spread for **ϒ** states
- Binding energies differ

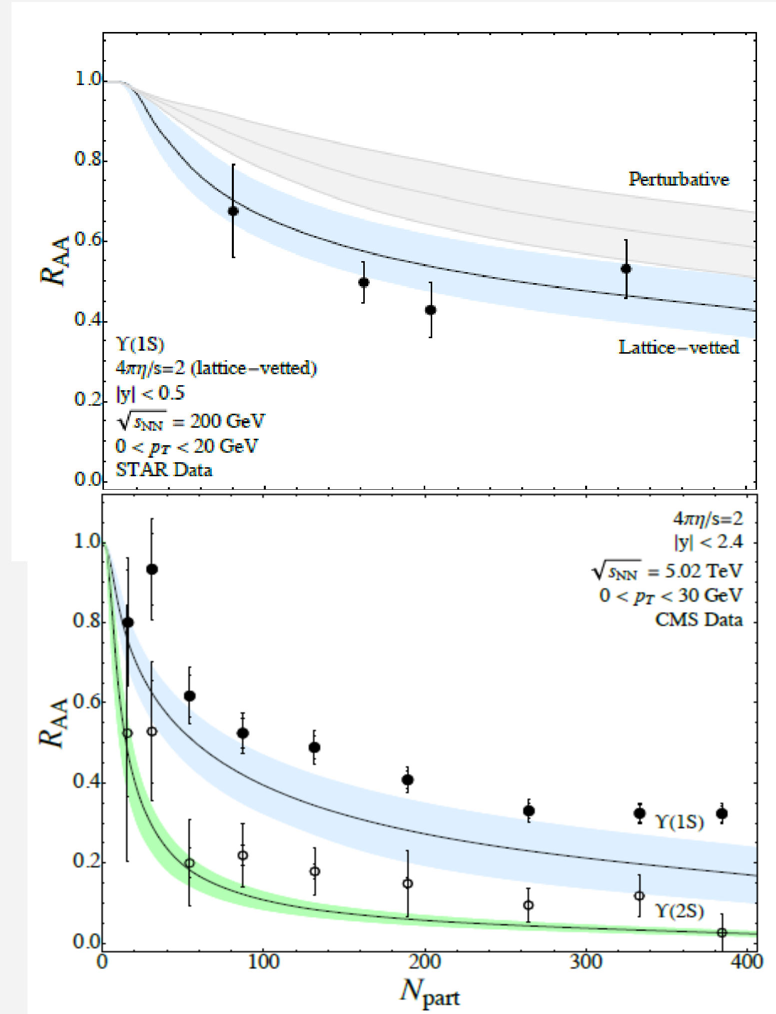
2.4 Heavy-Quark Potential + Regeneration

Lattice-based potentials

[TAMU '11,'17]



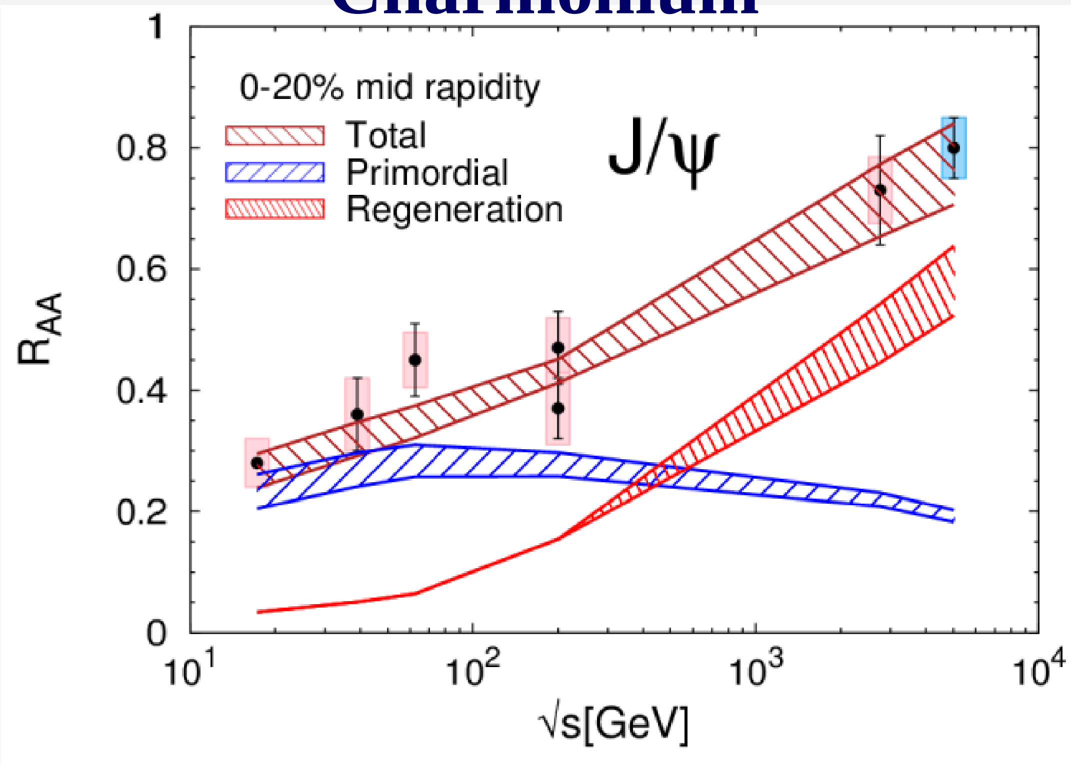
[Kent St '17]



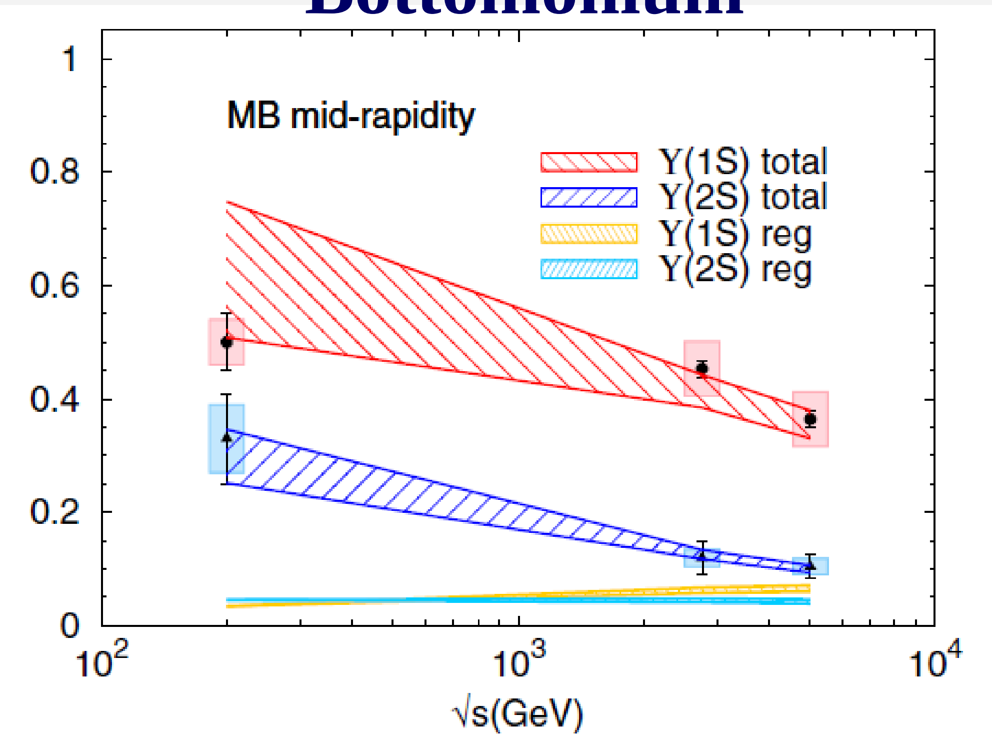
- **ϒ(1S)** suppression at **RHIC** → regeneration at **LHC**
- Regeneration dominant for **ϒ(2S)** in central **PbPb** at **LHC**?

2.5 Excitation Functions in AuAu and PbPb

Charmonium



Bottomonium



- Gradual increase of total **J/ψ** **R_{AA}**
- Regeneration **and** suppression increase
- **Cold-** vs. **Hot-**nuclear-matter effects

[**data**: **NA50, PHENIX, STAR, ALICE, CMS**]

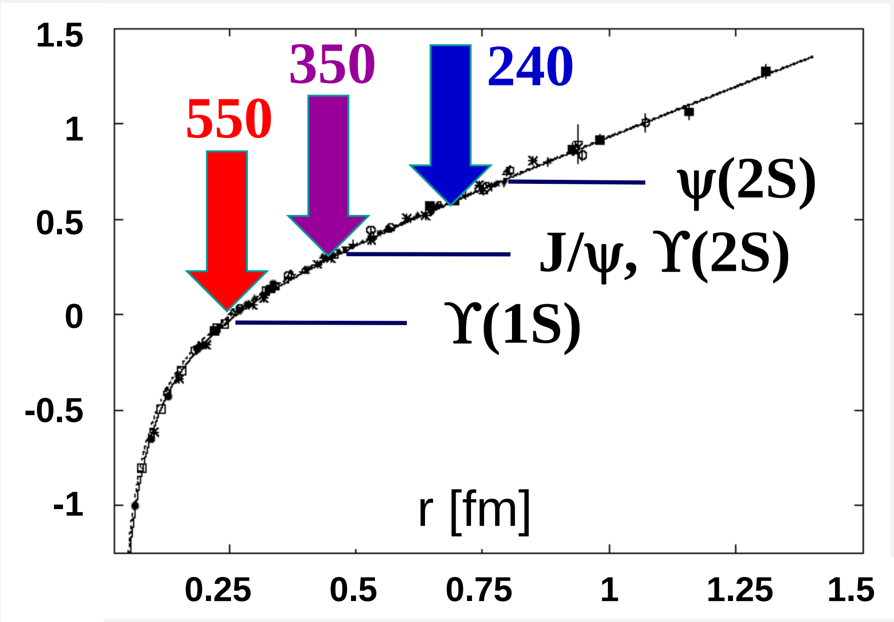
- Gradual suppression
- **ϒ(2S)** melts at **RHIC**, **ϒ(1S)** melts at **LHC**
- Regeneration!?

2.6 Upshot of Quarkonium Phenomenology

Use temperature estimtates from hydro/photons/dileptons to infer:

T_0^{SPS} (~240) < $T_{melt}(J/\psi,\Upsilon')$ ≤ T_0^{RHIC} (~350) < $T_{melt}(\Upsilon)$ ≤ T_0^{LHC} (~550)

- **Remnants of confining force survive at SPS** [hold **J/ψ** together]
- **Confining force screened at RHIC+LHC** [“melts” **J/ψ+ϒ(2S)**]
- **Color-Coulomb screening at LHC** [**ϒ(1S)** suppression]
- **Thermalizing charm quarks recombine at LHC** [large **J/ψ** yield]



Outline

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- HQ interactions in QGP
- Probing the medium

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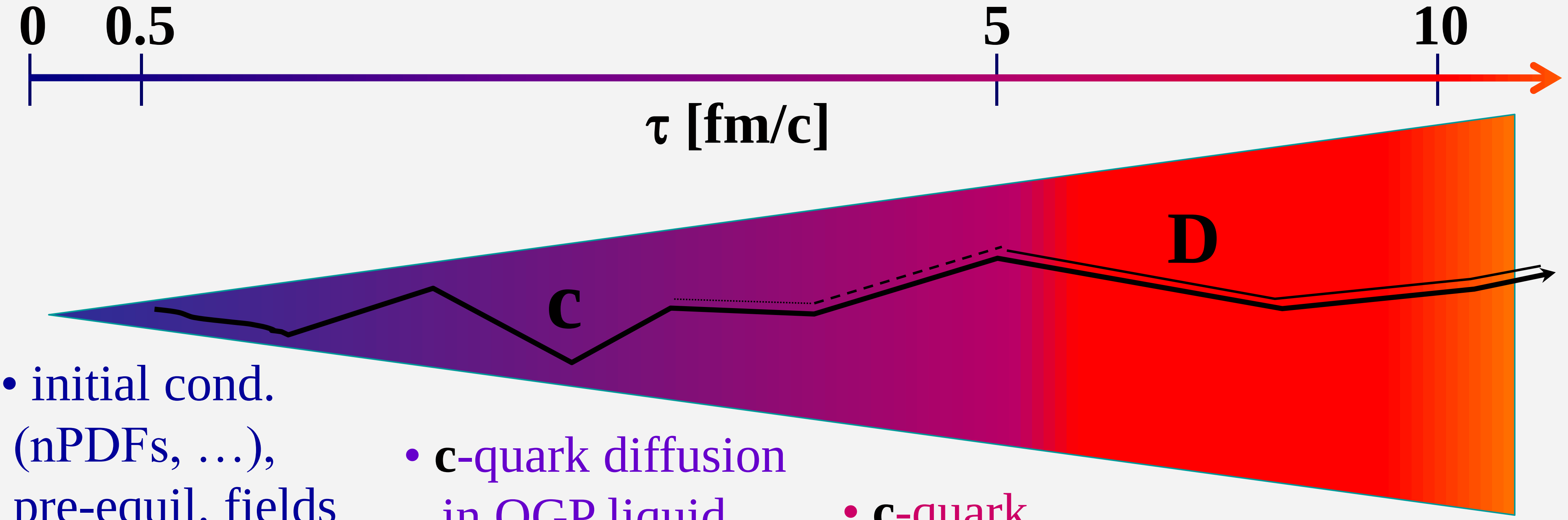
3.1 Heavy-Flavor Transport in URHICs



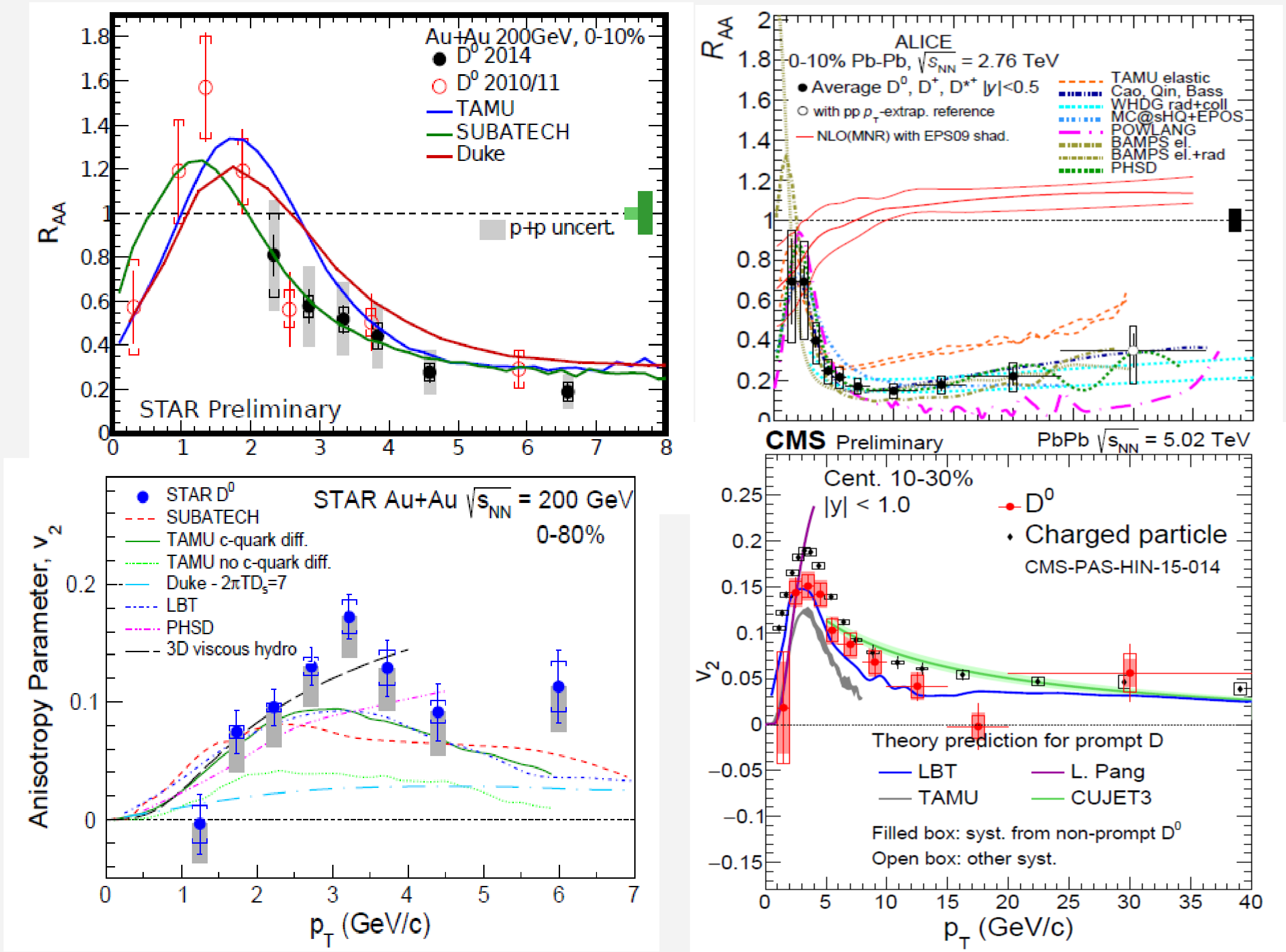
- initial cond. (nPDFs, …), pre-equil. fields
- **c**-quark diffusion in QGP liquid
- **c**-quark hadronization
- **D**-meson diffusion in hadron liquid

- no "discontinuities" in interaction

⇒ **diffusion toward T_{pc}** and **hadronization** same interaction (**confining**!)

[Moore+Teaney '05, van Hees et al '05, Gossiaux et al '08, Vitev et al '08, Das et al '09, Uphoff et al '10, M.He et al '11, Beraudo et al '11, Cao et al '13, Bratkovskaya et al '14, …]

3.2 Heavy-Flavor Phenomemology at RHIC + LHC

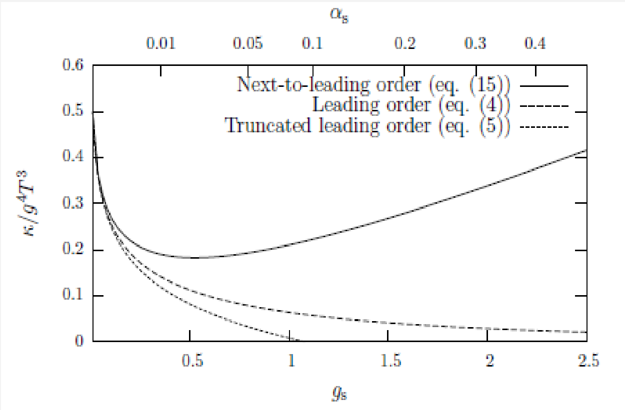


- Flow bump in R_{AA} + large v_2 ↔ strong coupling near T_{pc} (**recombination**)
- Importance of **T**- + **p**-dependence of transport; $\mathcal{D}_s(2\pi T)$ ~ 2-4 near T_{pc}
- High-precision v_2: transition from elastic to radiative regime

3.3 Heavy-Quark Interactions in QGP

Minimal / Desirable Ingredients and Features

- **Microscopic** description of scattering **amplitude**
- Realistic in-medium **interaction kernel** (screening)
- **Nonperturbative** interactions (color-Coulomb / pQCD not enough)
- **Resummation** (strong coupling)
- **Hadronization** approaching T_c from above (bound states)
- Elastic + radiative processes (low / high p_T)
- Realistic **medium partons**: quasiparticles, widths, parton spectral functions, …? Equation of state?
- Quantitatively rooted in **constraints from lattice QCD**

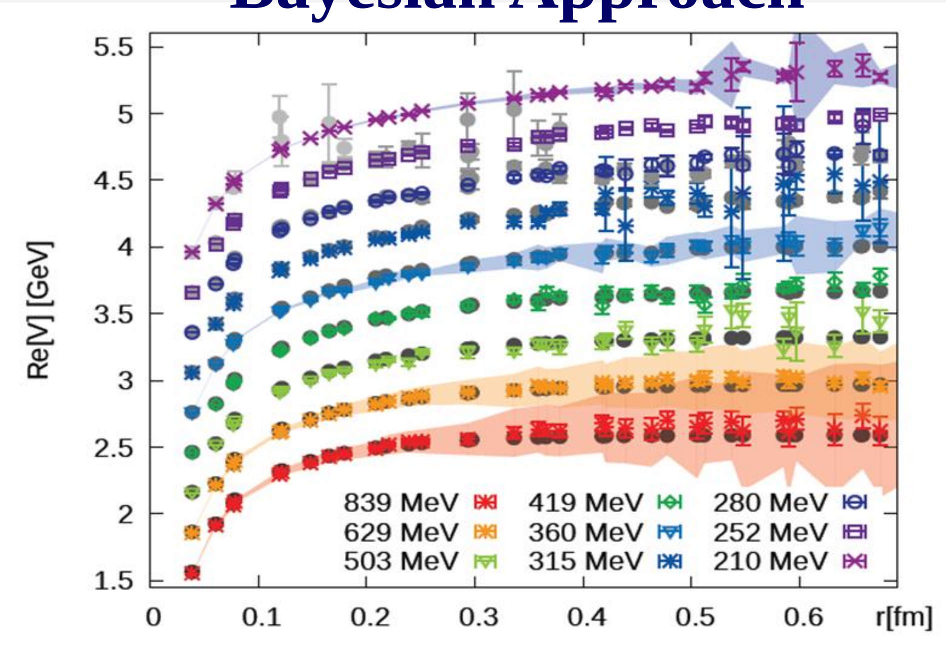


[Caron-Huot+Moore '08]

3.4 Potential Extraction from Lattice Data

- **Free Energy** $F_{Q\bar{Q}}(r_1 - r_2) = -\frac{1}{\beta}\ln\left(G^{>}(-i\beta, r_1 - r_2)\right) = -\frac{1}{\beta}\ln\left(\int_{-\infty}^{\infty} d\omega\sigma(\omega, r_1 - r_2)\, e^{-\beta\omega}\right)$
- **$Q\bar{Q}$ Spectral Function** $\sigma(\omega, r) = \frac{1}{\pi}\frac{(V+\Sigma)_I(\omega)}{(\omega - (V+\Sigma)_R)^2 + (V+\Sigma)_I^2(\omega)}$

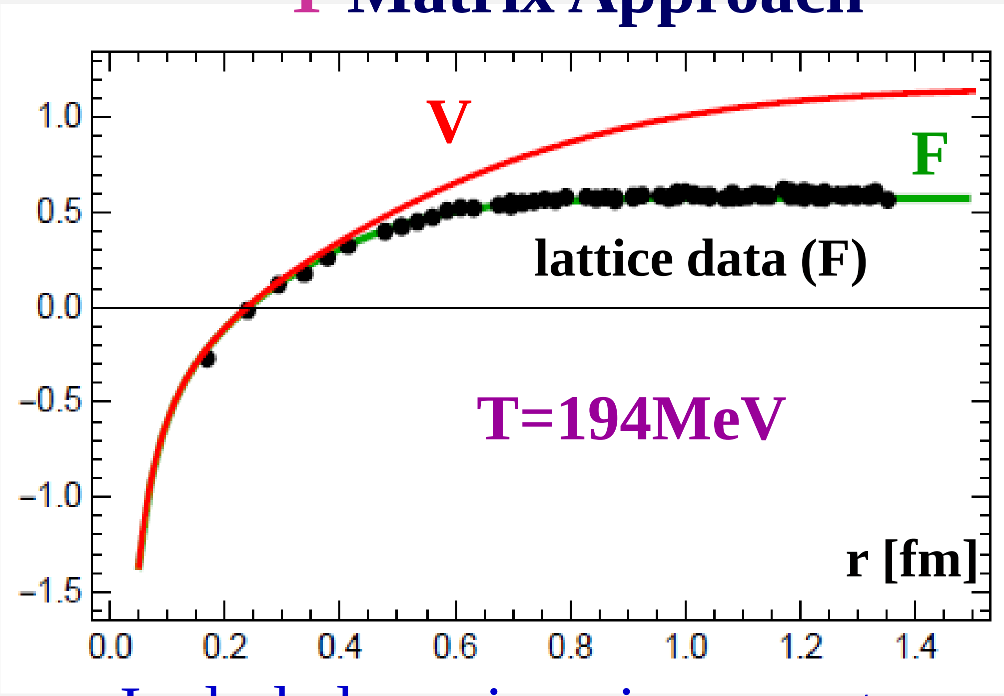
Bayesian Approach



- **Potential close to free energy**

[Burnier et al '14]

T-Matrix Approach

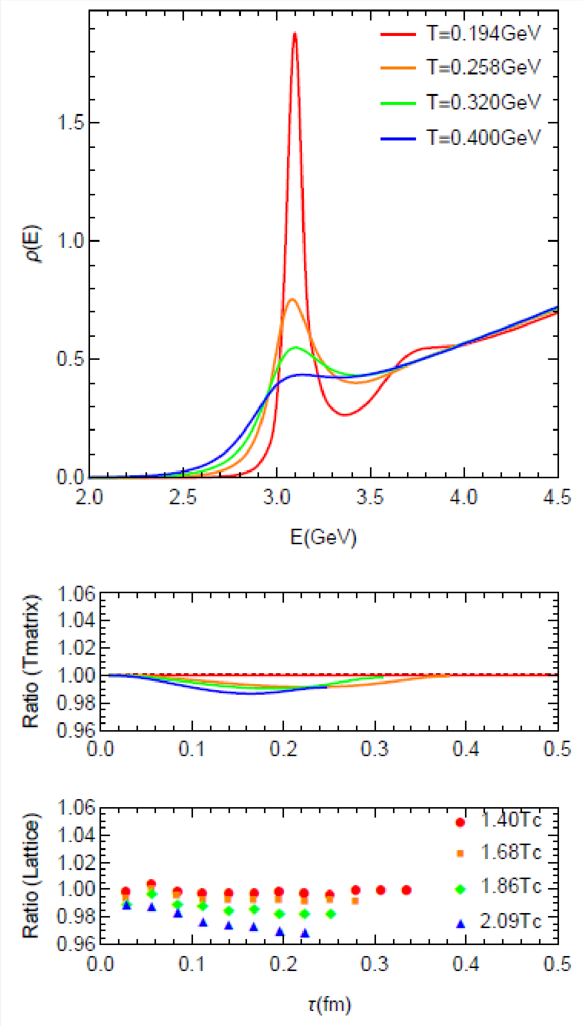


- Include large imaginary parts
- **Remnant of confining force!**

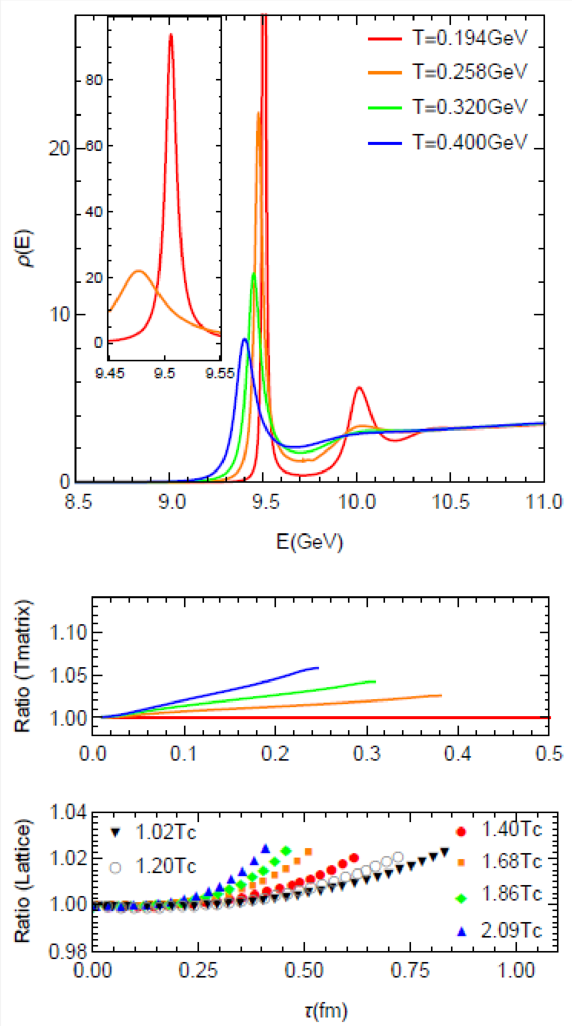
[S.Liu+RR '15]

3.5 Quarkonium Spectral Functions + Correlators

Charmonium



Bottomonium



[S.Liu+RR in prep]

- **J/ψ / Y(1S/2S)** melting (300/500/250MeV) not inconsistent with pheno.

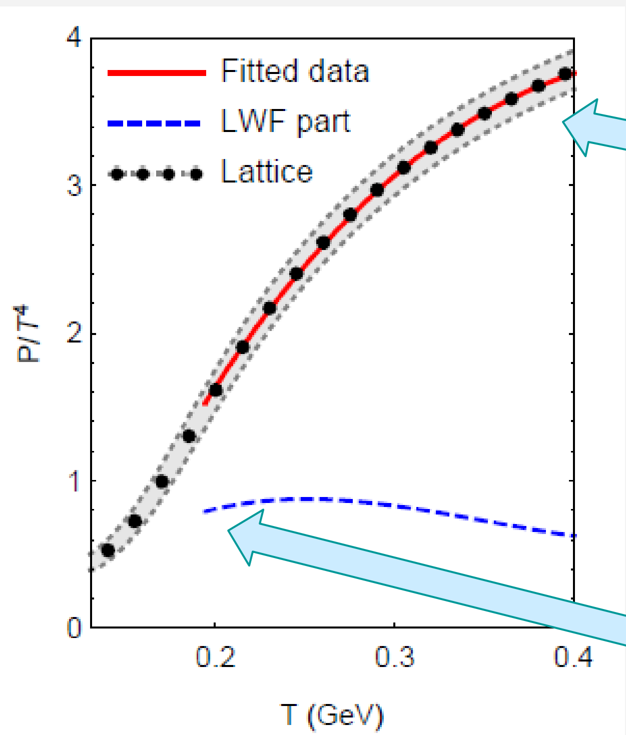
3.6 QGP Equation of State + Spectral Functions

Thermodynamic Potential

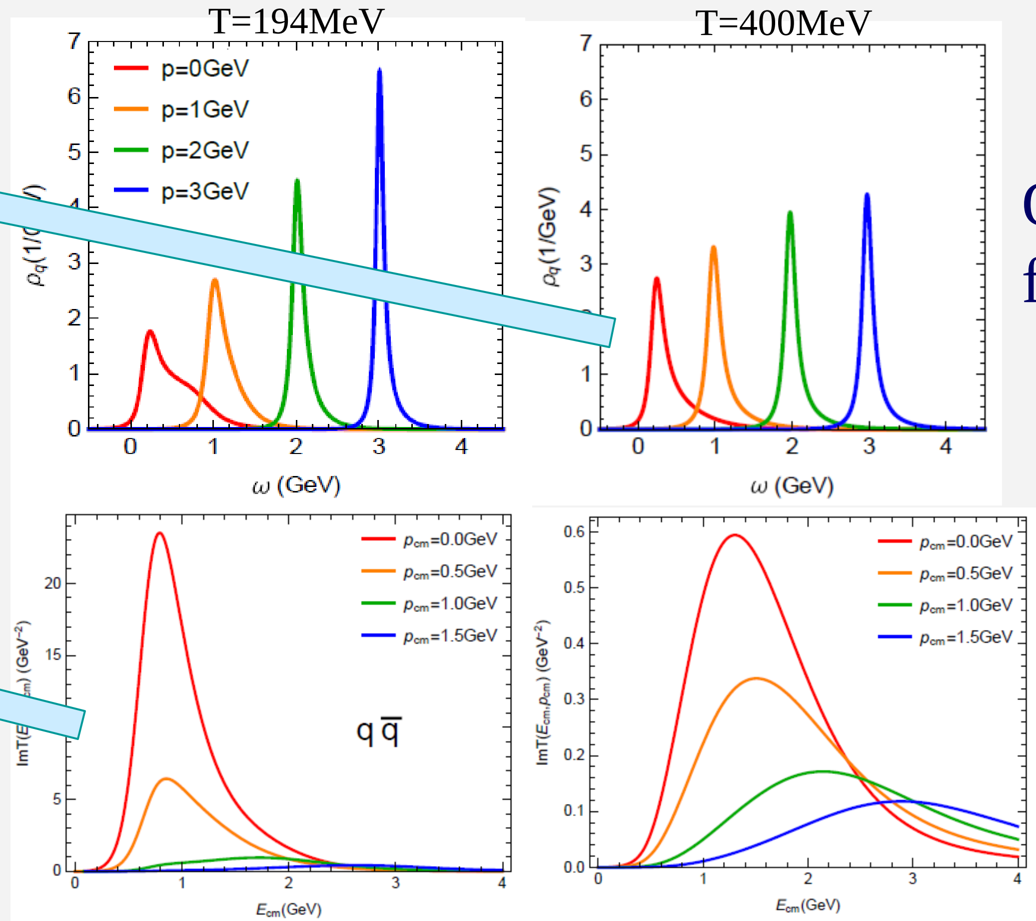
$$\Omega = \mp \frac{-1}{\beta} \sum_n \mathrm{Tr}\{\ln(-G^{-1}) + (G_0^{-1} - G^{-1})G\} \pm \Phi$$

Selfconsistent SFs

$$G = G_0 + G_0 \Sigma G \qquad \Sigma = GT \qquad T = V + VGGT$$



[S.Liu+RR '16]



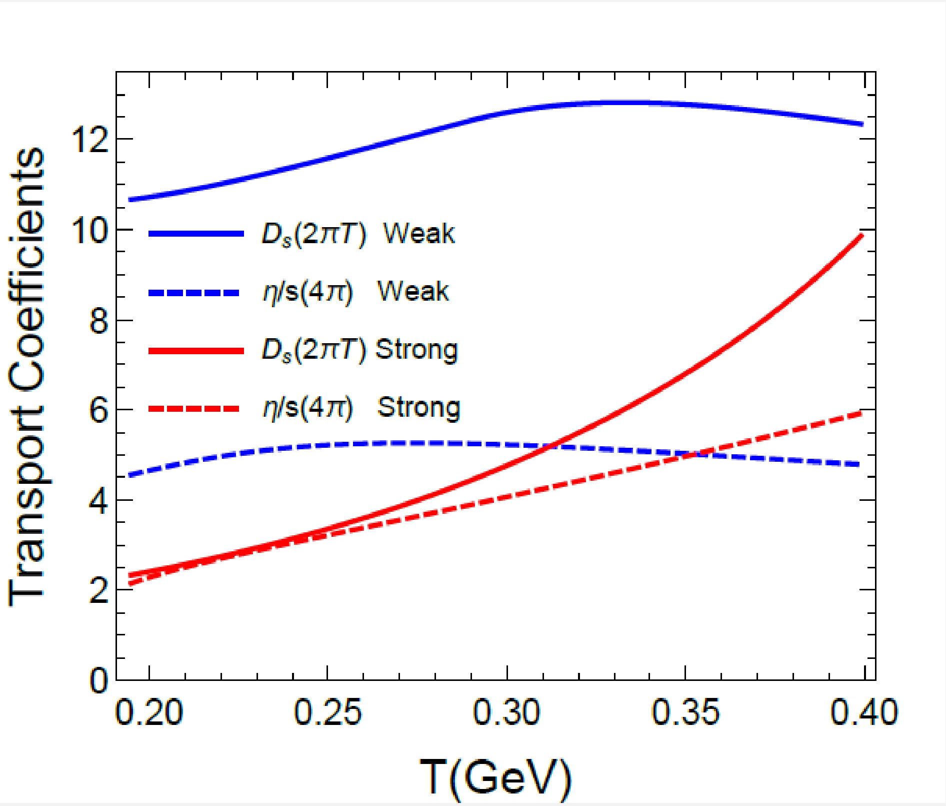
Quark spectral functions

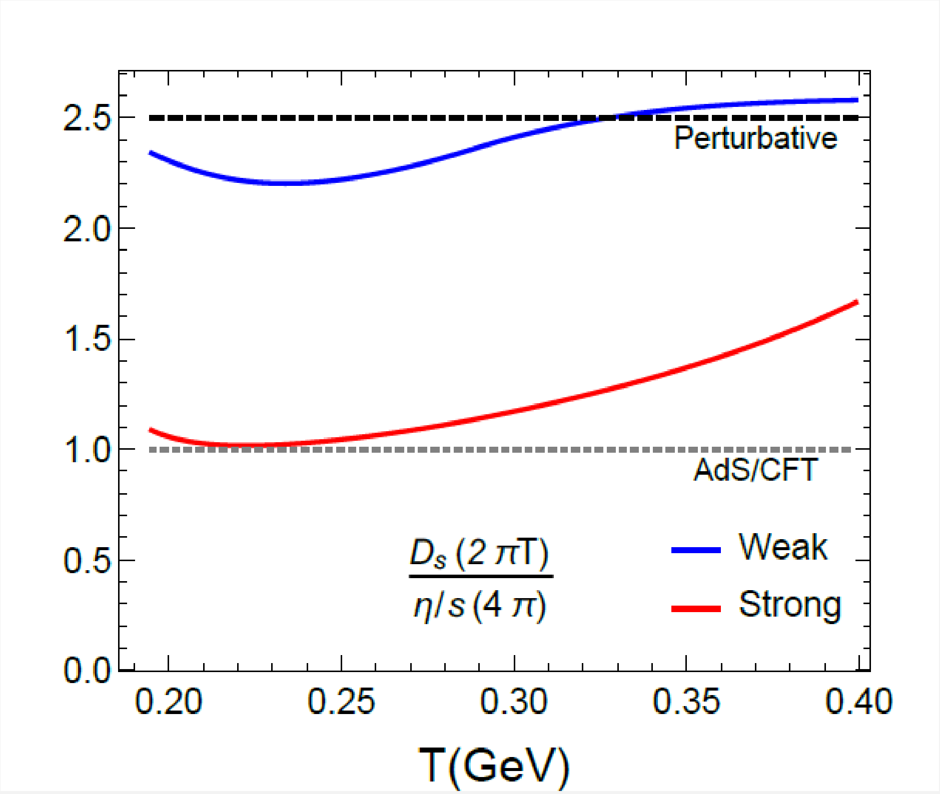
"Meson" **T**-matrix

- **Near T_c light partons melt + broad hadronic resonances emerge**

3.7 Transport Coefficients

Viscosity and Heavy-Quark Diffusion

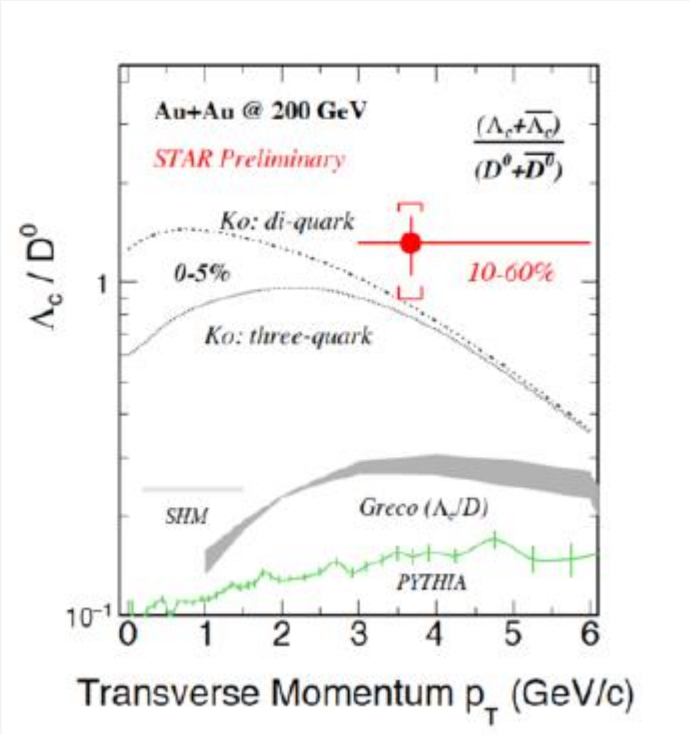




- Strongly coupled: **$(2\pi T)\,D_s \sim (4\pi)\,\eta/s$**
- Perturbative: **$(2\pi T)\,D_s \sim 5/2\,(4\pi)\,\eta/s$**
- Transition as **T** increases

3.8 Versatility of Equilibrium Benchmarks

- Quarkonium equilibrium abundance in "chemical" transport
- Heavy-quark equilibration controls quarkonium regeneration
- Heavy-quark transport to satisfy detailed balance (2↔2, 2↔3)
- Quark coalescence (energy conservation):
  equilibrated quarks → equilibrated hadrons (!)



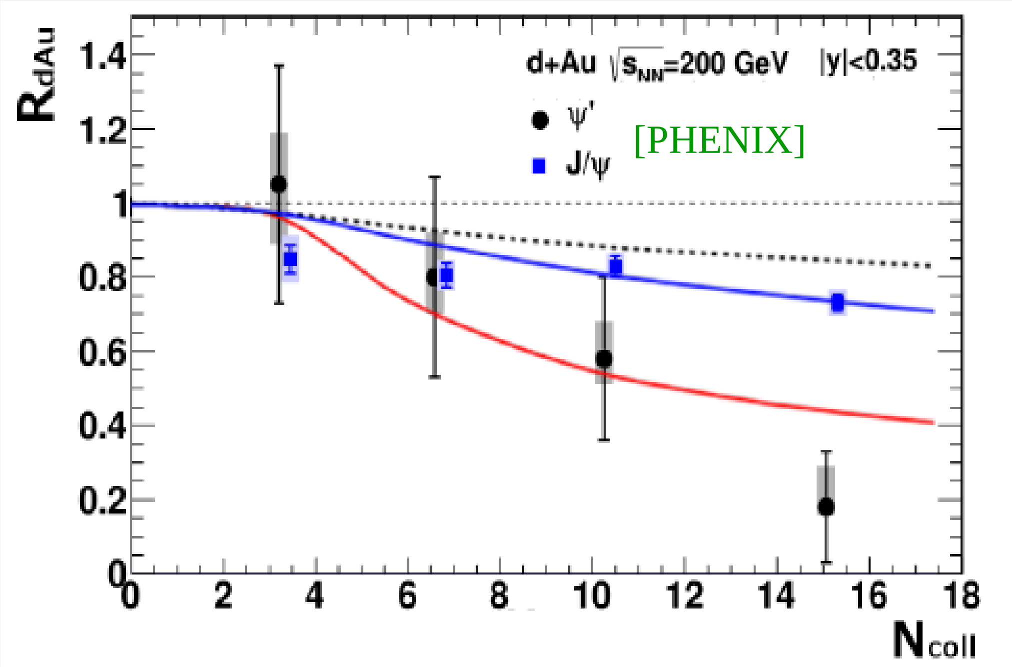
- Constraints from lattice QCD

4.) Summary

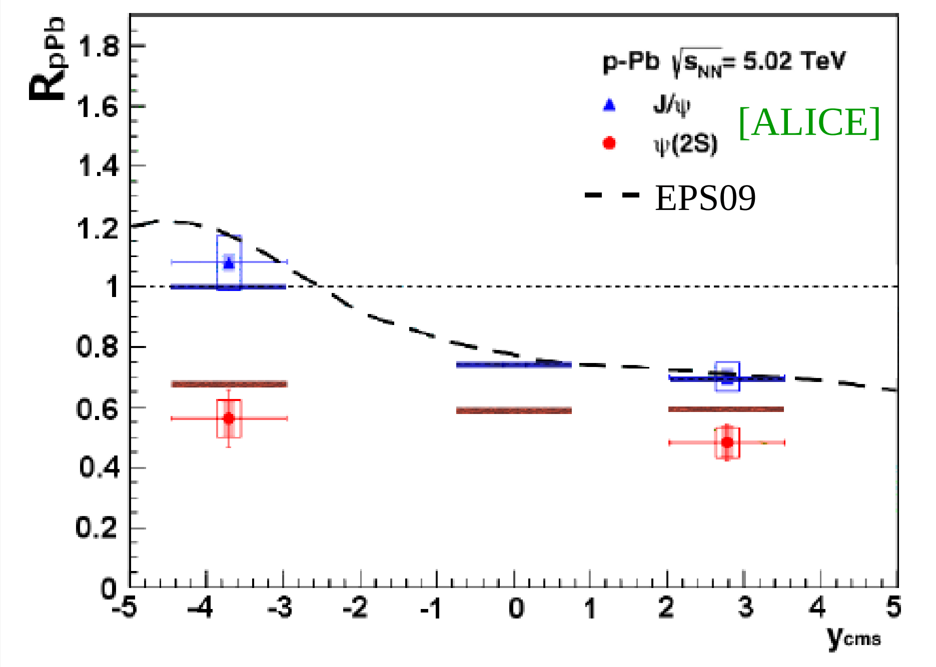
- Transport analyses of quarkonia in URHICs suggest interplay of dissociation+formation processes of diffusing **Q**'s with "strong" potential
- Consensus starts to emerge on transport coefficients + (re-)generation
- Open heavy flavor a more direct probe of in-medium force strength
- Reached the point where the description of the strongly coupled medium needs to be made consistent to realize premise of **Q**'s as QGP probe
- Importance of equilibrium limit / lQCD as benchmarks

3.5 ψ(2S) in dAu and pPb

d-Au (0.2TeV)



p-Pb (5.02TeV)



- noticeable **ψ′** and little **J/ψ** suppression, consistent with "comovers"

[Ferreiro '15]

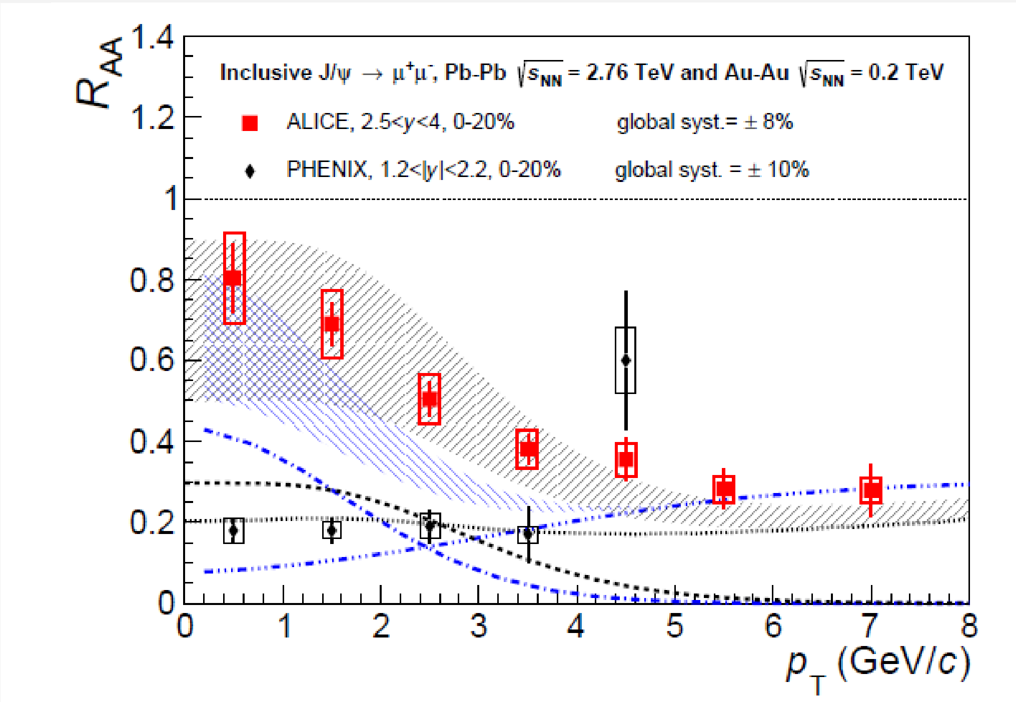
- supports fireball formation with:

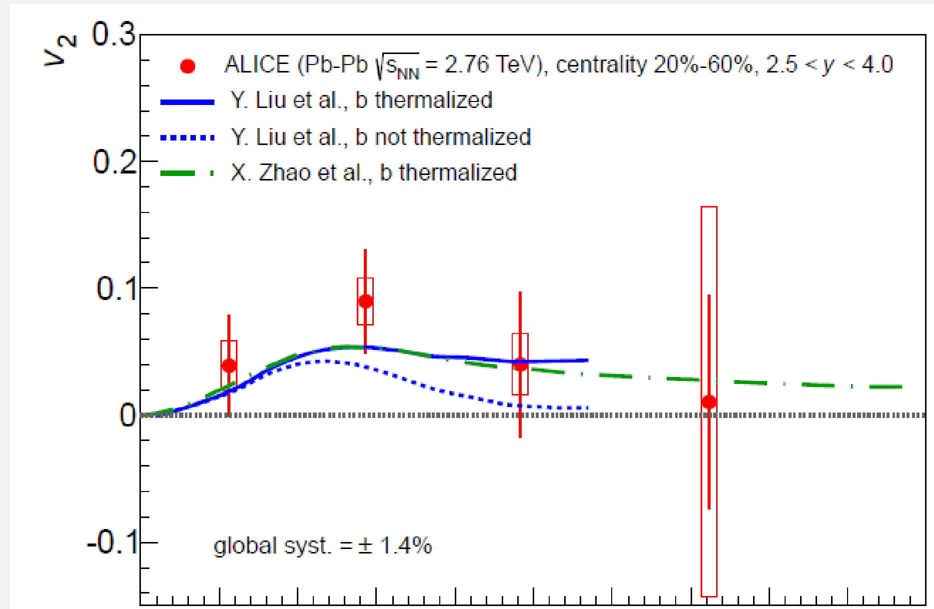
$\tau_{FB}\ \Gamma(\psi') \sim 1 \Rightarrow \Gamma_{avg}(\psi') \sim$ 50-100 MeV similar to thermal

$\tau_{FB}\ \Gamma(J/\psi) << 1 \Rightarrow \Gamma_{avg}(J/\psi) <$ 20 MeV widths at T≈ 200MeV

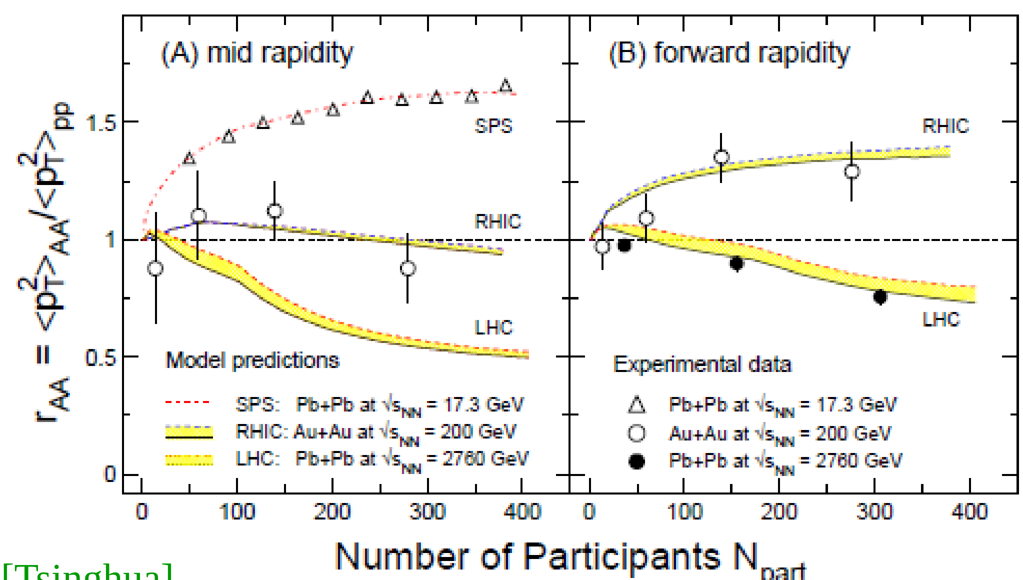
[Du et al '15]

3.3 Properties of Charmonium Excess





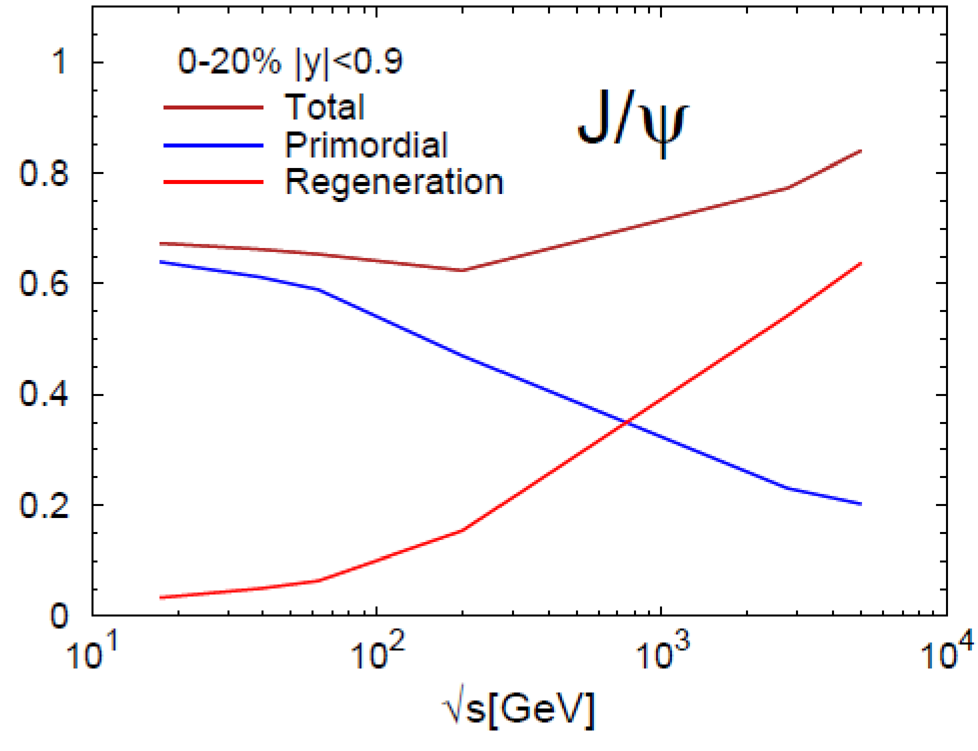
- excess concentrated at low p_T
- systematic softening of J/ψ p_T-spectra with increasing √s → nature of source changes

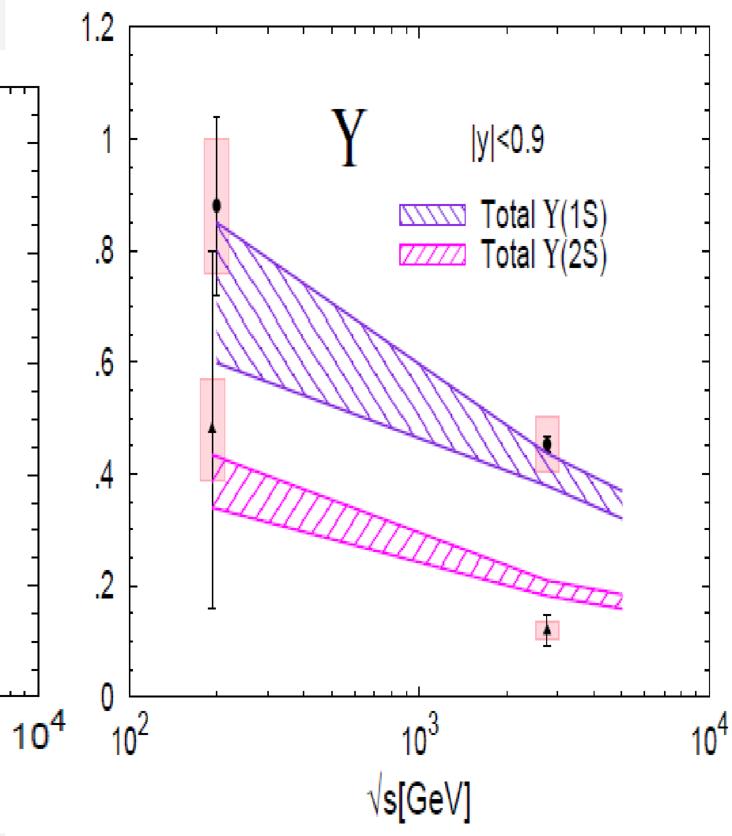


[Tsinghua]

3.2 Attempt to Divide out Cold-Nucl.-Matter Effects

$$R_{AA}^{hot} \equiv R_{AA}^{tot} / S_{CNM}$$



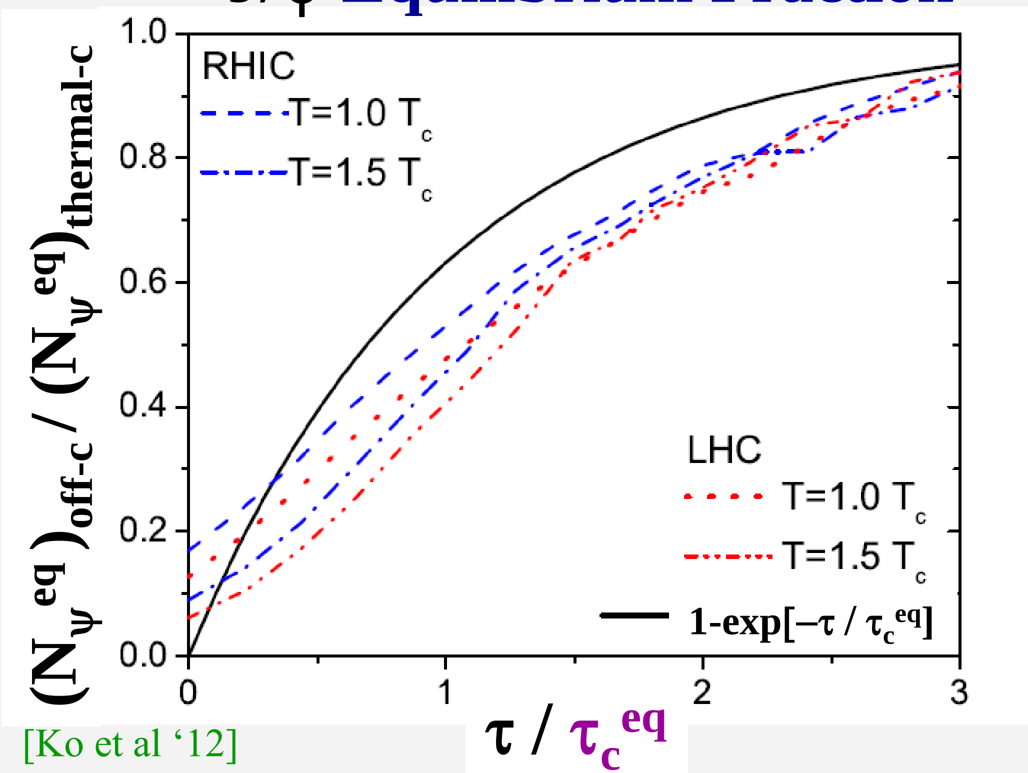


- **J/ψ** suppressed at **SPS** mostly from feeddown (**$\sigma_{\psi N}$ ~7.5mb**), melts in the **RHIC** → **LHC** regime (not unlike **Υ(2S)**)

4.1 Charm Thermalization + J/ψ Regeneration

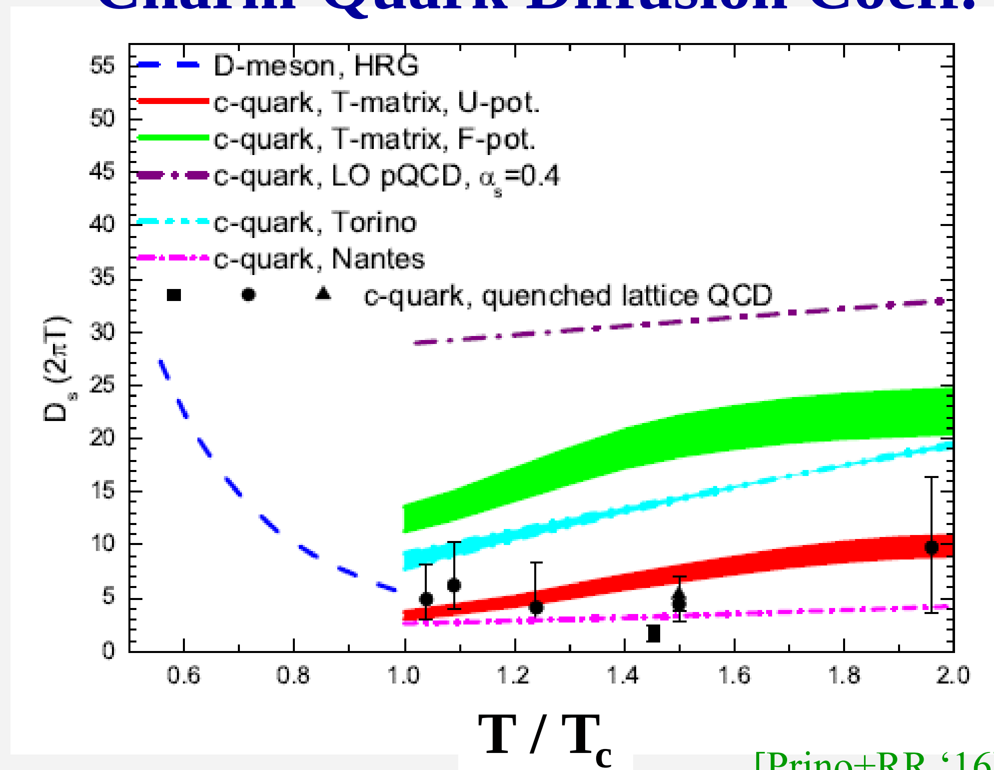
→ Softening of charm-quark spectra facilitates regeneration

J/ψ Equilibrium Fraction



[Ko et al '12]

Charm-Quark Diffusion Coeff.

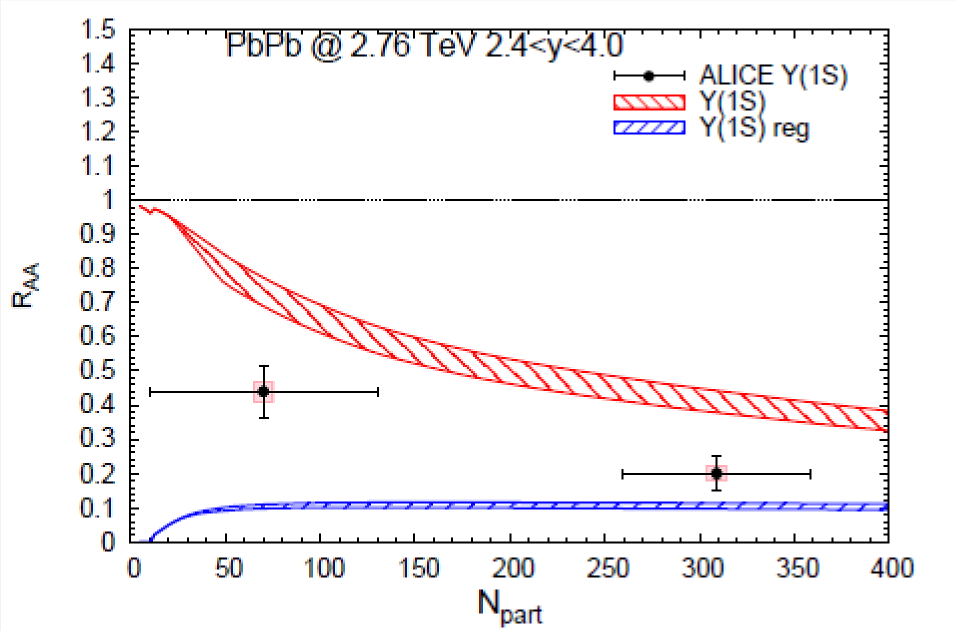


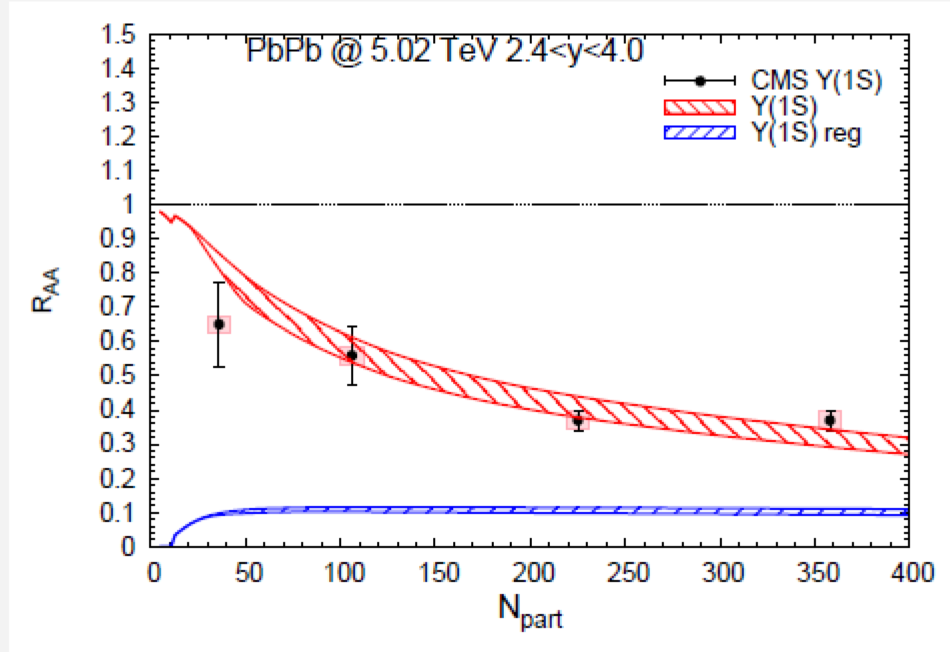
[Prino+RR '16]

- Charmonium phenomenology favors $\tau_c^{eq} \leq 5$ fm/c ("**strong**" coupling)

$$D_s = \tau_c^{eq}\, T/m_Q \leq (4\text{-}8)/(2\pi T)$$

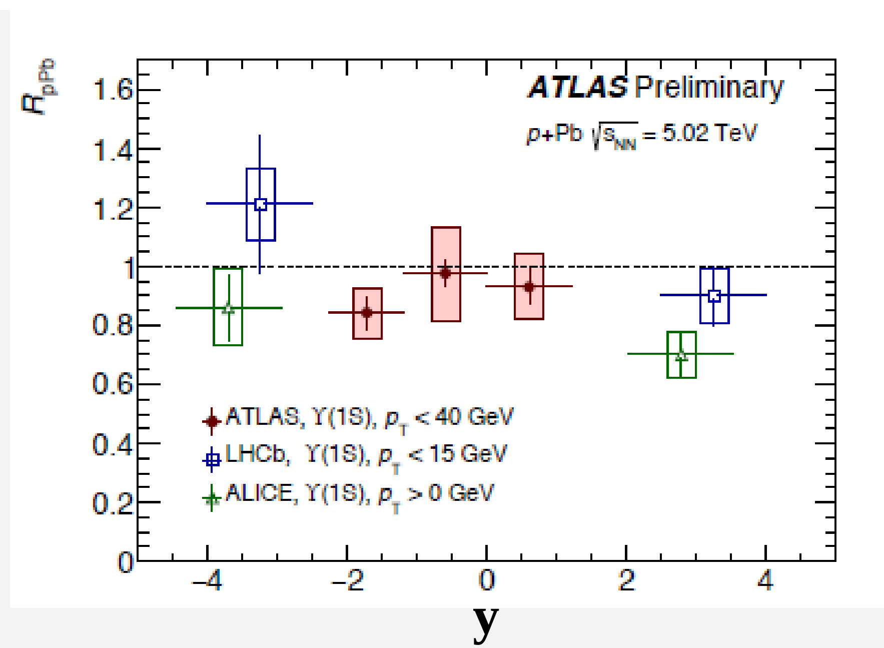
4.3 ϒ(1S): Rapidity Puzzle





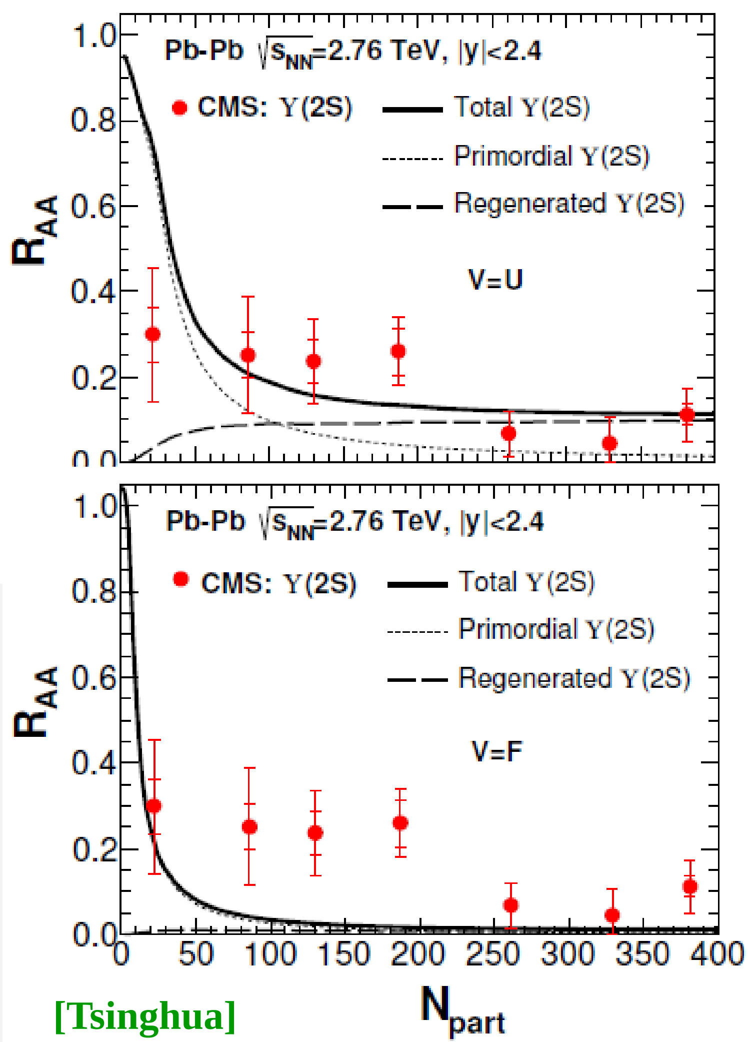
- problem of large(r) suppression in 2.76 TeV **ALICE** data
- beware of cold nuclear matter effects
- Regeneration: $\mathbf{N_{bb} \sim 1}$ for central PbPb

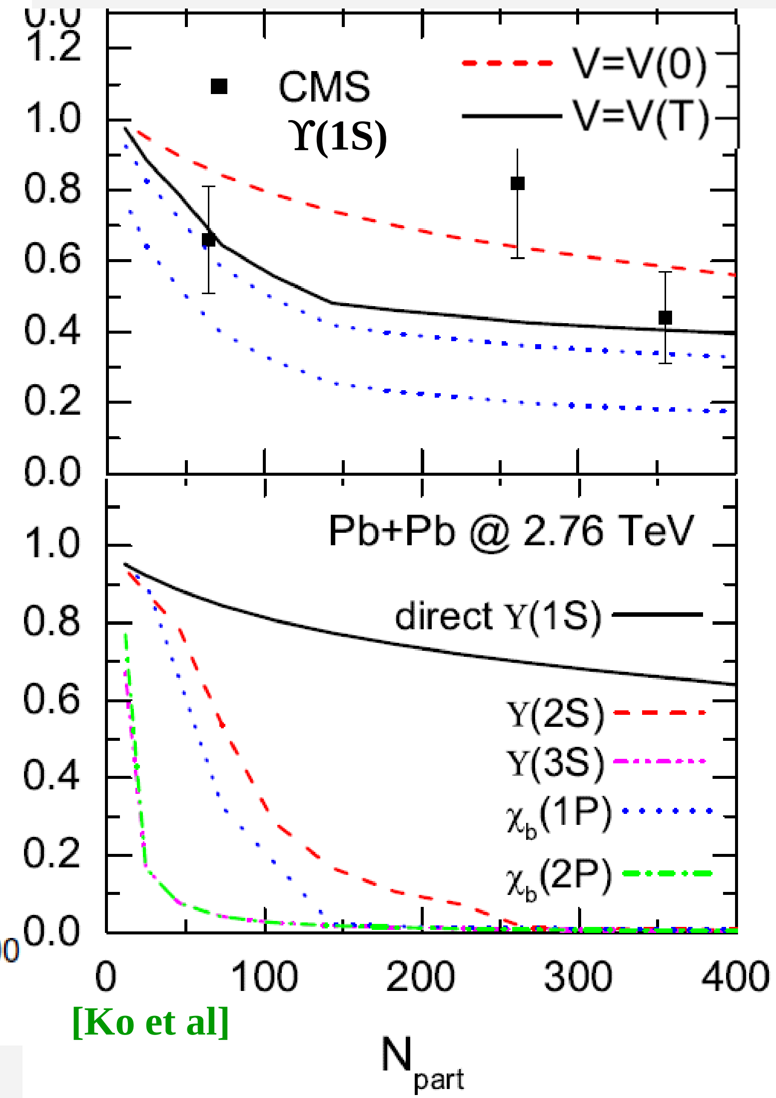
  $\Rightarrow$ canonical limit $\mathbf{N_{Y} \sim (N_{bb})^1}$



4.2 ϒ(1S) and ϒ(2S) Transport cont'd

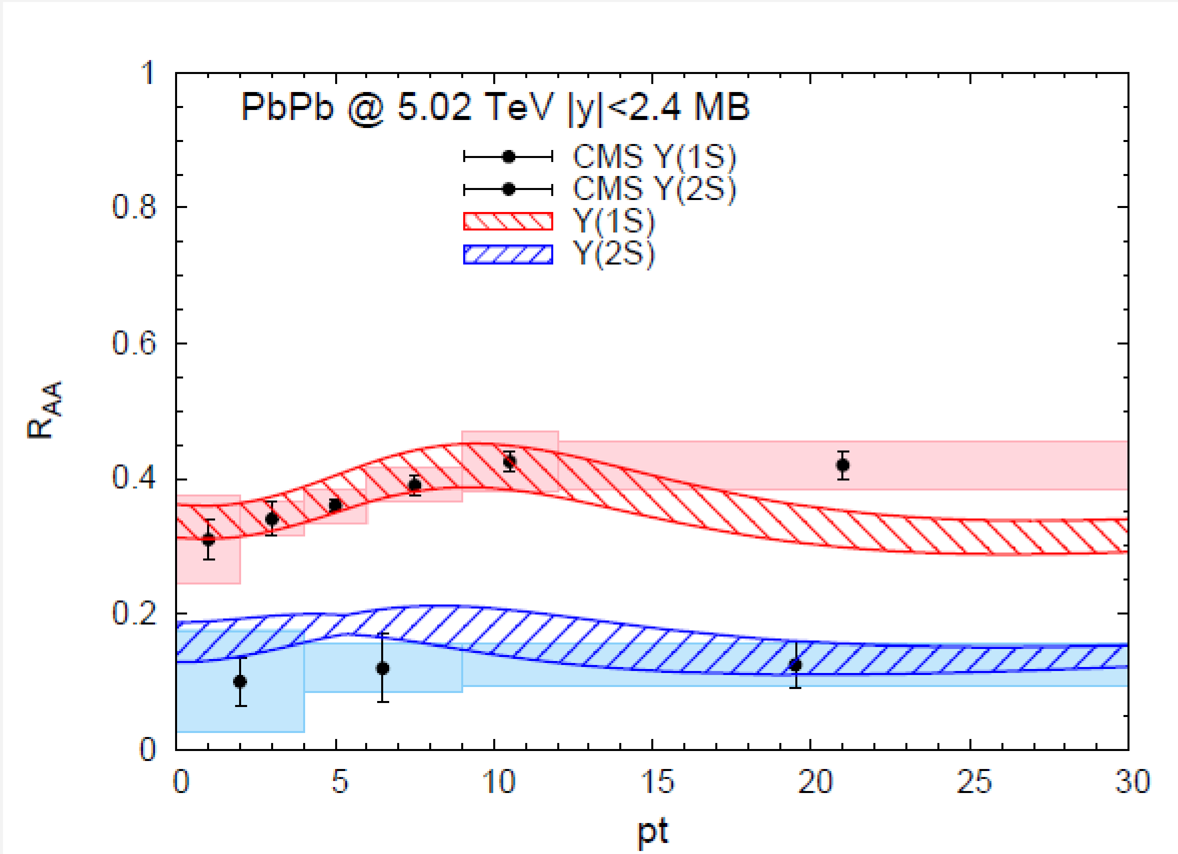
… as implemented in current transport approaches



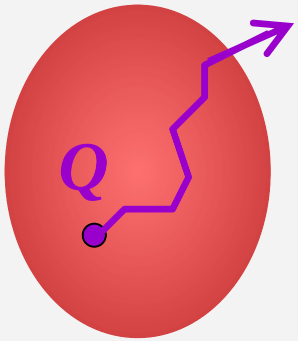


- ϒ(2S) more sensitive sensitive to in-medium potential

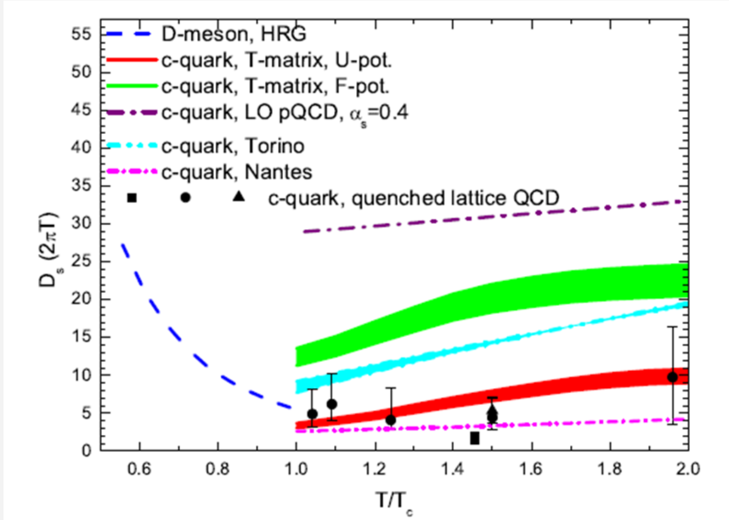
4.5 ϒ p_t Spectra in Pb-Pb(5.02TeV)



1.3 Heavy Quarks in Medium

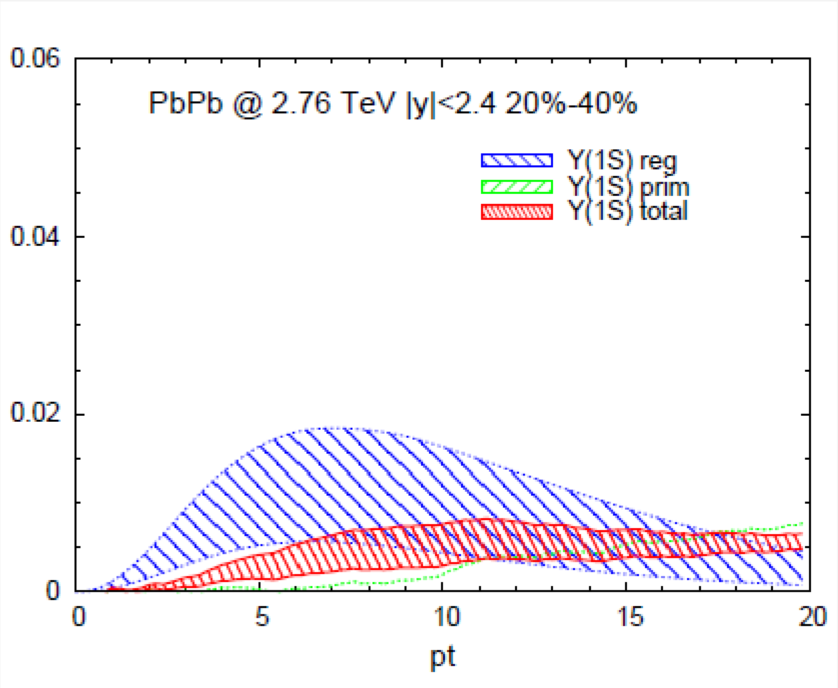


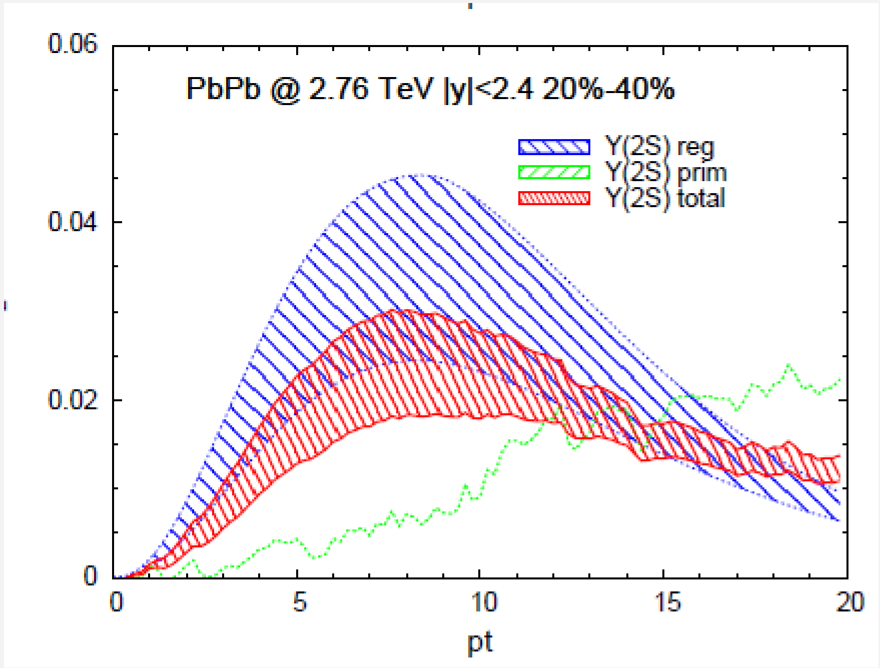
- **Diffusion: "Brownian motion"**
- Thermalization delayed by $\mathbf{m_Q/T}$
  → memory in URHICs
- Direct access to transport coefficient $\mathcal{D}_s$ **(2πT)** **(~ η/s ~ σ_{EM}/T)**
- Elastic scattering rates (radiation suppressed, $\mathbf{q_0^2 << q^2}$)
  → widths; quasiparticles? ($\mathbf{m_Q >> T}$)
- Probe of hadronization
- Non-perturbative effects until **~ $2T_{pc}$**
- Potential-type interactions ($\mathbf{q_0 \sim q^2/m_Q << q}$)
  → same as for heavy quarkonia!?
- Ample connections to lattice QCD



[He et al '12]

4.4 ϒ Regeneration and Elliptic Flow





- Sizeable effect only for **ϒ(2S)**

4.5 In-Medium Quarkonium Binding Energies