Heavy Flavor in Medium

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

Internat. Workshop XLIV on Gross Properties of Nuclei+Nucl. Excitations

"QCD Matter: Dense and Hot"

Hirschegg (Austria), Jan 17 - 23, 2016

A few Personal Remarks…

- First meeting (1992): thermodynamics?!
- Diploma thesis: pion gas with ππ T-matrix
- PhD Thesis: "σ" channel in Nuclear Matter
- 1995 Lyon Plaza, Jochen: "Let's work on the ρ-meson" - A vision for the physics of low-mass dileptons…
- Tremendous opportunities, e.g.:

  - After-lunch talk at IKP-TH Jülich (→ Stony Brook)

  - 3 stays at Urbana-Champaign

Thanks for the great ride, Jochen!

1.) Objectives with Heavy Flavor in Medium

Determine modifications of QCD force in medium

+ infer consequences for the many-body system

- **exploit** $m_Q >> \Lambda_{QCD}$, T_c , $T_{RHIC,LHC}$

- **Heavy-flavor diffusion: "Brownian markers of QGP"**
  - Scattering rates: widths, quasiparticles? ($m_Q>>T$)
  - Thermalization: delayed by m_Q/T → memory
  - Transport coefficient $\mathcal{D}_s\,(2\pi T) \sim \eta/s$

- **Quarkonia kinetics**
  - Screening of confining ($\geq T_c$?) + Coulomb ($\geq 2T_c$?) force
  - Υ states: sequential melting?
  - Ψ states: (sequential?) regeneration

Outline

1.) Introduction

2.) Heavy-Quark Interactions in QGP

3.) Open Heavy-Flavor Transport

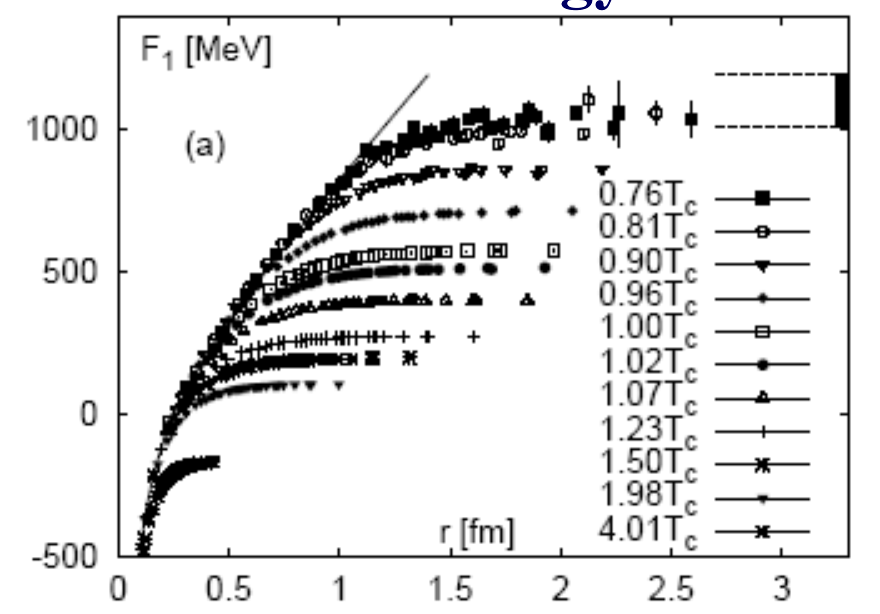
4.) Quarkonia: ψ' Puzzle(s)

5.) Conclusions

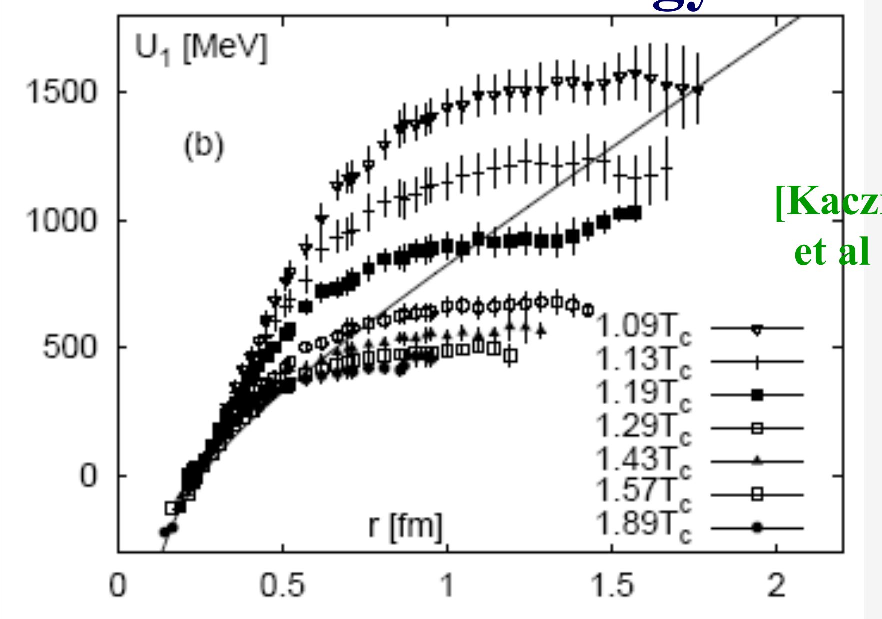
2.1 Heavy-Quark Free and Internal Energies in Lattice QCD

$$F_1(r,T) = U_1(r,T) - T\,S_1(r,T)$$

Free Energy



Internal Energy



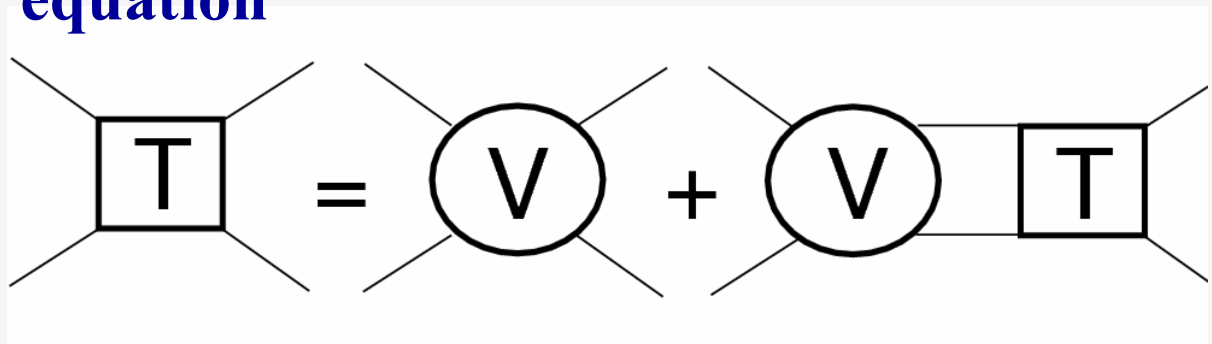
[Kaczmarek et al '05]

- "**weak**" $Q\bar{Q}$ potential
- "**strong**" $Q\bar{Q}$ potential, $U = \langle H_{int} \rangle$
- **F, U, S thermodynamic quantities**
- **Entropy**: many-body effects

2.2 Thermodynamic T-Matrix in QGP

- **Lippmann-Schwinger equation**

In-Medium
Q-Q̄ T-Matrix:

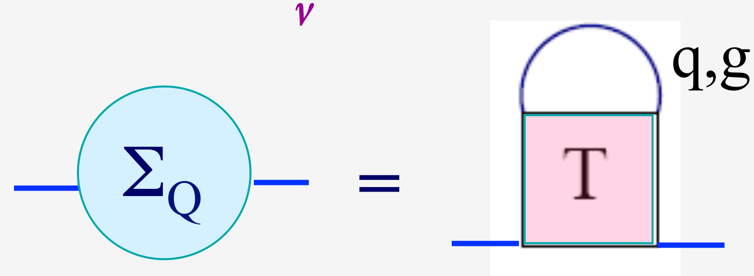


$$T_\alpha(E;q,q') = V_\alpha(q,q') + \int k^2 dk\ V_\alpha(q,k)\ G^0_{Q\bar{Q}}(E,k)\ T_\alpha(E;k,q')$$

- thermal 2-particle propagator: $G^0_{Q\bar{Q}}(E,k;T) = T\sum_\nu D_Q(z_\nu,\vec{k})D_{\bar{Q}}(E-z_\nu,-\vec{k})$

- selfenergy:

$$\Sigma_Q(\omega,k) = \sum_{p=q,g}\int T_{Qp}(\omega+\omega_p)\ f^p(\omega_p)$$



- **In-medium potential V?**

[Cabrera+RR ’06,
Riek+RR ‘10]

2.3 Free Energy from T-Matrix

- **Free Energy** $F_{Q\bar{Q}}(r_1 - r_2) = -\frac{1}{\beta} \ln\left(G^{>}(-i\beta, r_1 - r_2)\right) = -\frac{1}{\beta} \ln\left(\int_{-\infty}^{\infty} d\omega \sigma(\omega, r_1 - r_2) e^{-\beta\omega}\right)$

[Beraudo et al '08]

- Euclidean **T-matrix** in static limit

$$\tilde{T}(z_t|r) = V(z_t, r) + V(z_t, r)\tilde{G}_0^{(2)}(z_t - \nu^a, \nu^a)\tilde{T}(z_t|r) = \frac{V(z_t, r)}{1 - V(z_t, r)\tilde{G}_0^{(2)}(z_t)}$$

- **Spectral Function** $\sigma(\omega, r) = \frac{1}{\pi} \frac{(V + \Sigma)_I(\omega)}{(\omega - (V + \Sigma)_R)^2 + (V + \Sigma)_I^2(\omega)}$

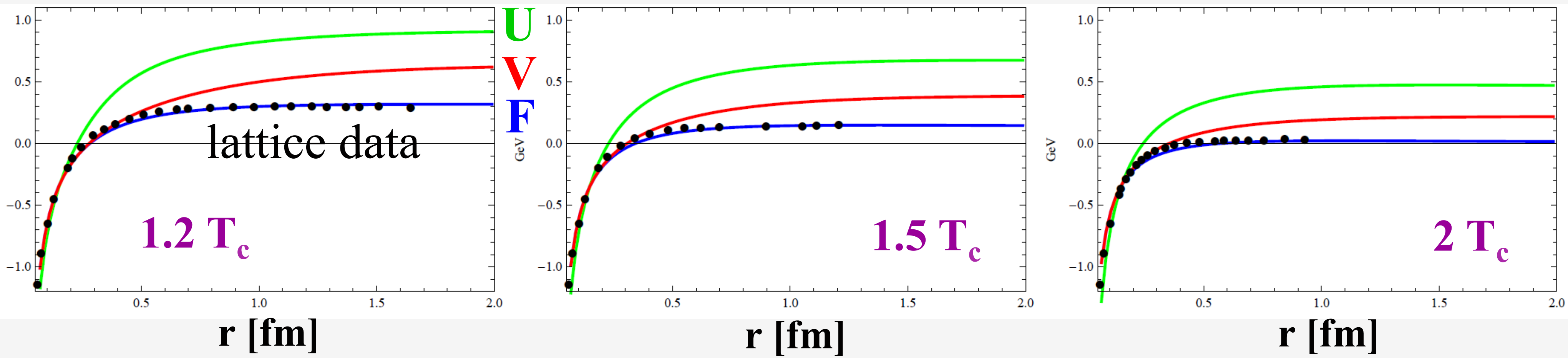
[S.Liu+RR '15]

- **Weak coupling**: $V_{QQ} \rightarrow F_{QQ}$
- **Key ingredients**:
  - imaginary parts + their ω dependence
  - heavy-quark selfenergies (from previous **T-matrix** calculations)

2.3.2 Free + Internal Energy from T-Matrix

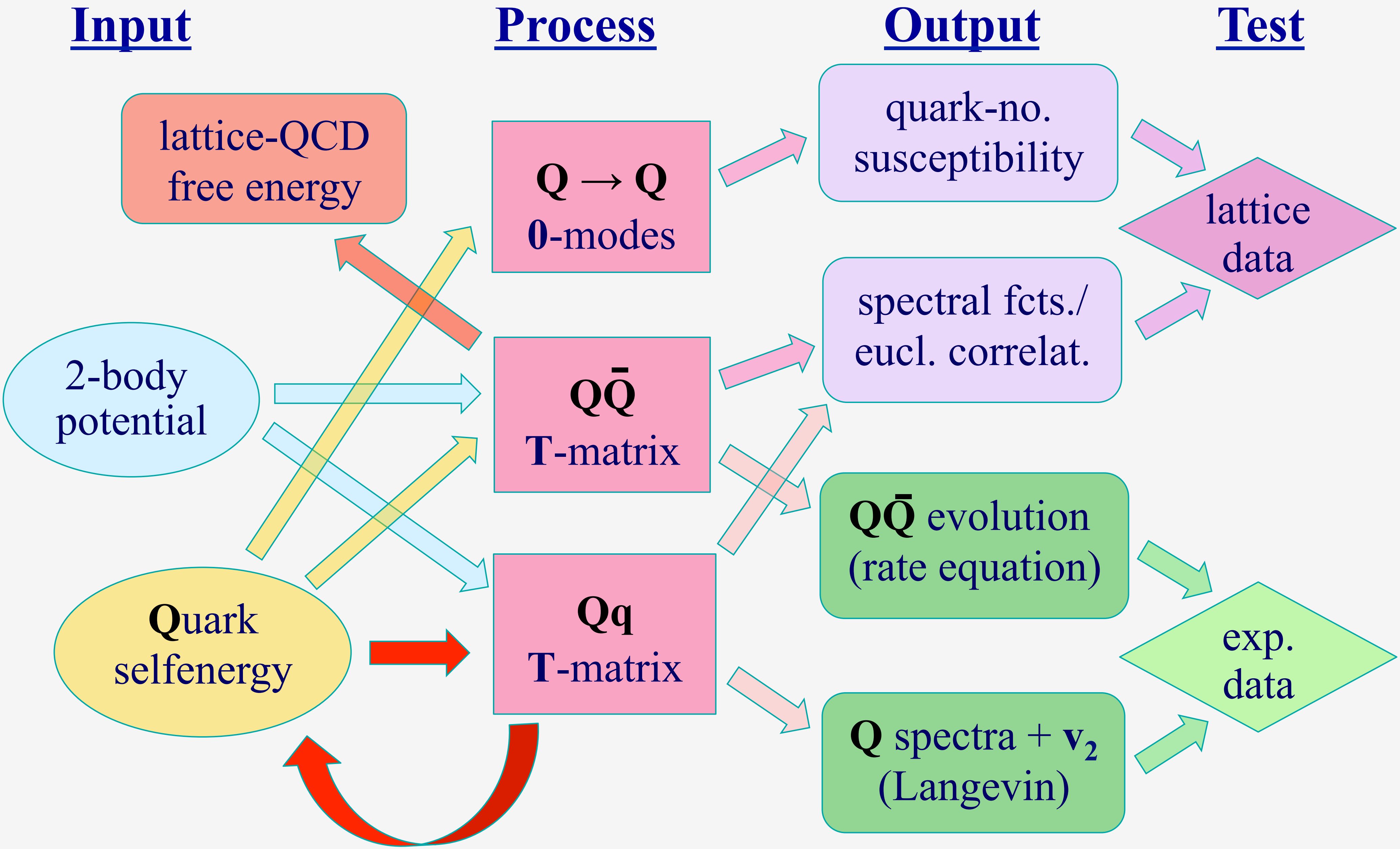
- potential ansatz: $$V_R(E,r) = -\frac{4}{3}\alpha_s \frac{e^{-m_D r}}{r} - \sigma \frac{e^{-m_s r}}{m_s} - \frac{4}{3}\alpha_s m_D + \sigma \frac{1}{m_s}$$

[Megias et al ’07]



- **remnant of long-range “confining” force in QGP**
- smaller in-medium quark mass relative to internal energy

2.4 Brueckner Theory of Heavy Flavor in QGP



Outline

1.) Introduction

2.) Heavy-Quark Interactions in QGP

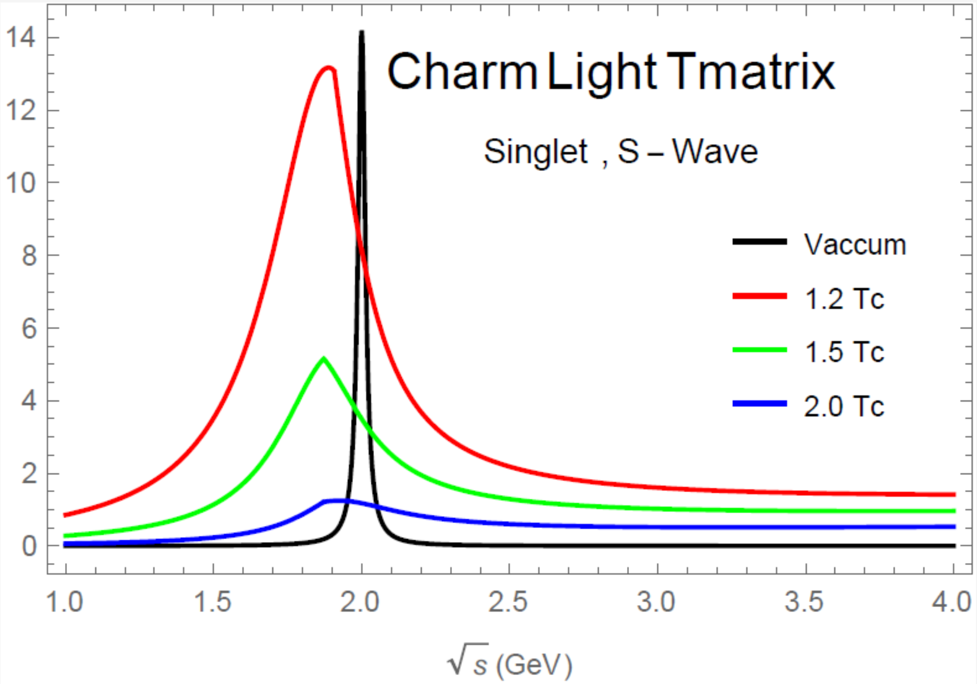
3.) Open Heavy-Flavor Transport

4.) Quarkonia: ψ' Puzzle(s)

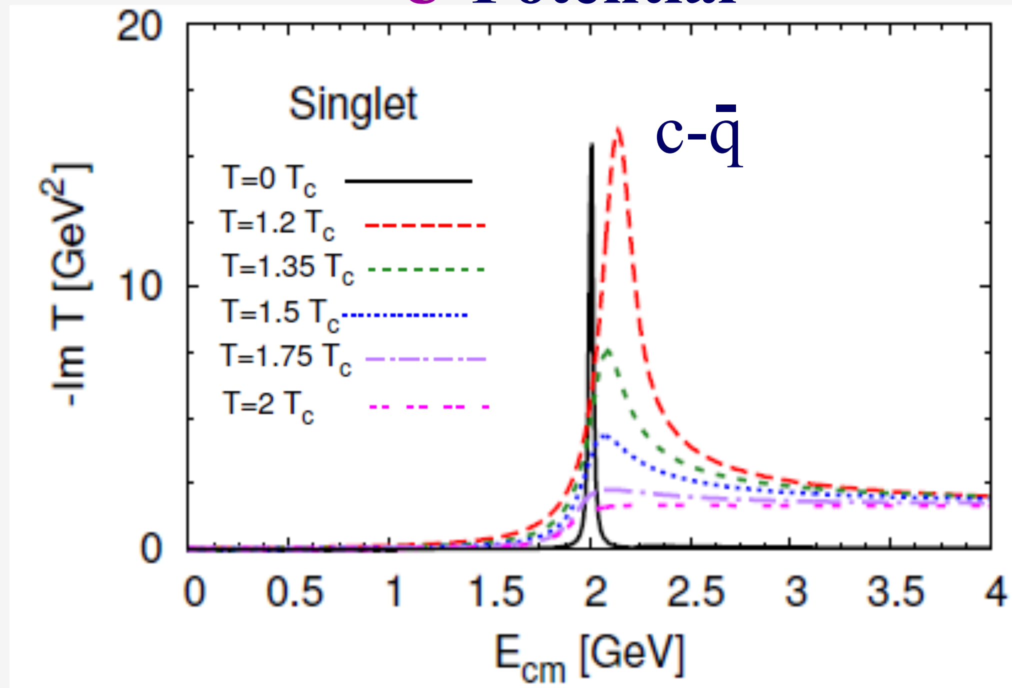
5.) Conclusions

3.1 Heavy-Light Scattering Amplitudes

New Potential V



U-Potential

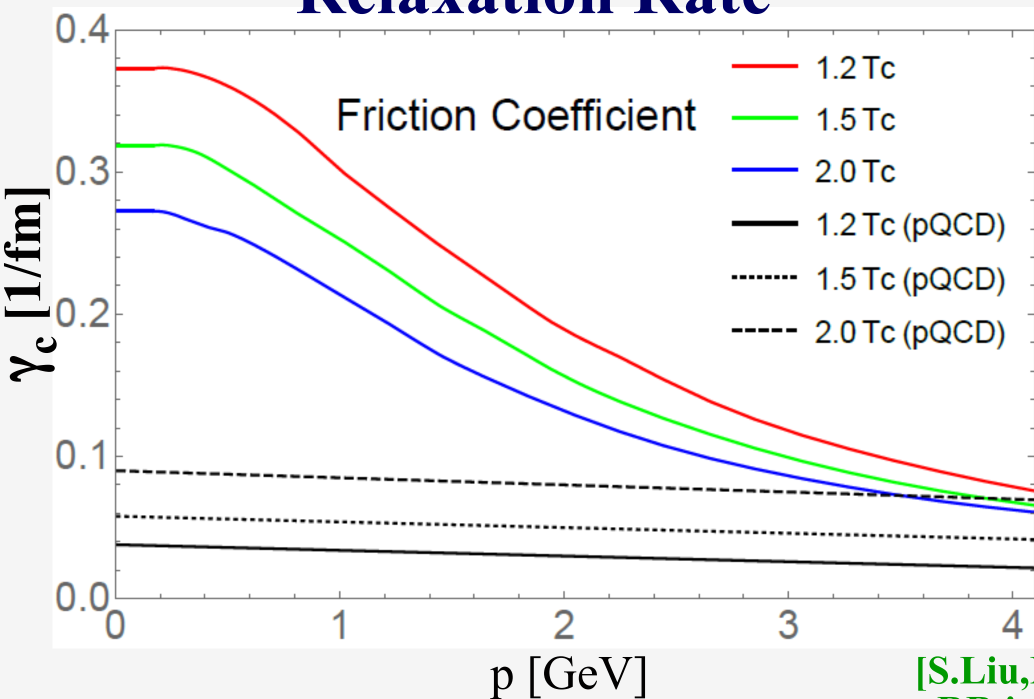


- "confining" force induces "Feshbach resonances" in **Qq** **T**-matrix
- strength comparable to internal-energy (**U**) potential

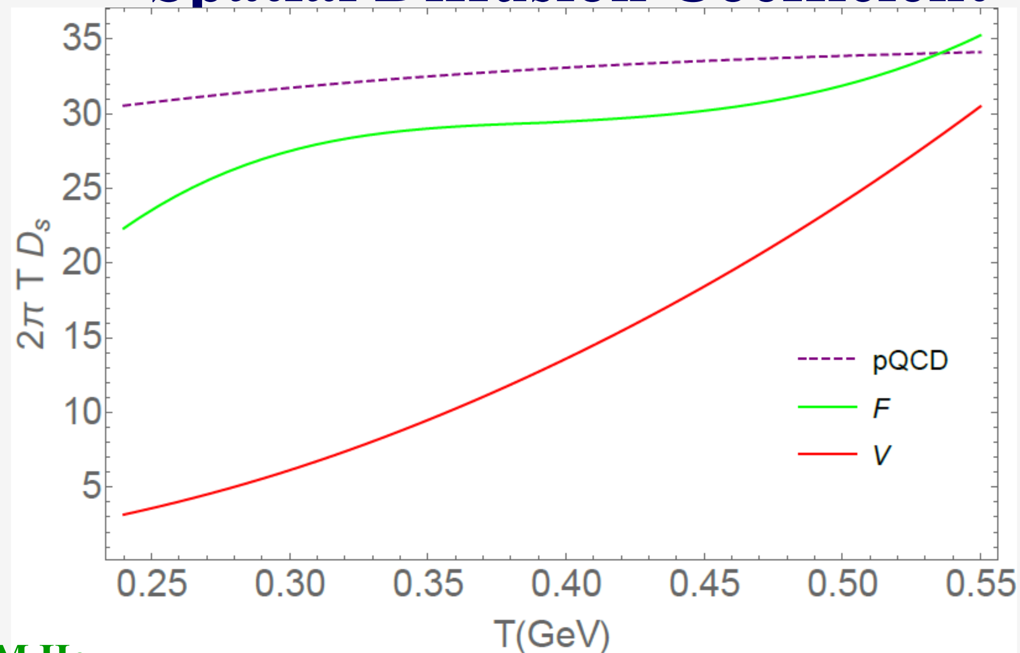
3.2 Charm-Quark Relaxation Rates

- heavy-light **T**-matrix → HQ transport: $\gamma_Q\, p = \int |T_{Qq}|^2\ (1-\cos\theta)\ f^{q,g}$

Relaxation Rate



Spatial Diffusion Coefficient

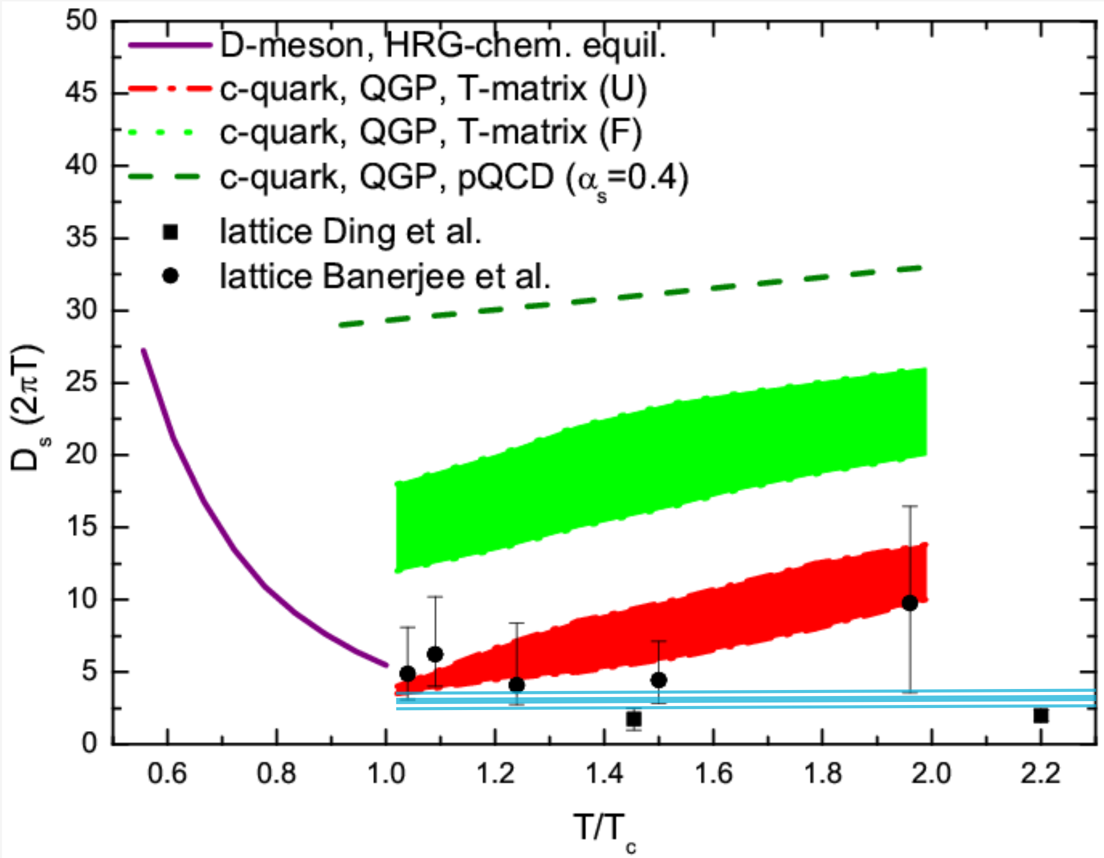


[S.Liu,M.He +RR in prep]

- $\tau_c \approx$ **3 fm/c** close to T_c at low **p**
- 3-mom. + temperature dependence reflect **core properties** of QCD!

3.3 Summary of Charm Diffusion in Matter

$\mathcal{D}_s = T/m\gamma_Q$: **Hadronic Matter** vs. **QGP** vs. **Lattice QCD**

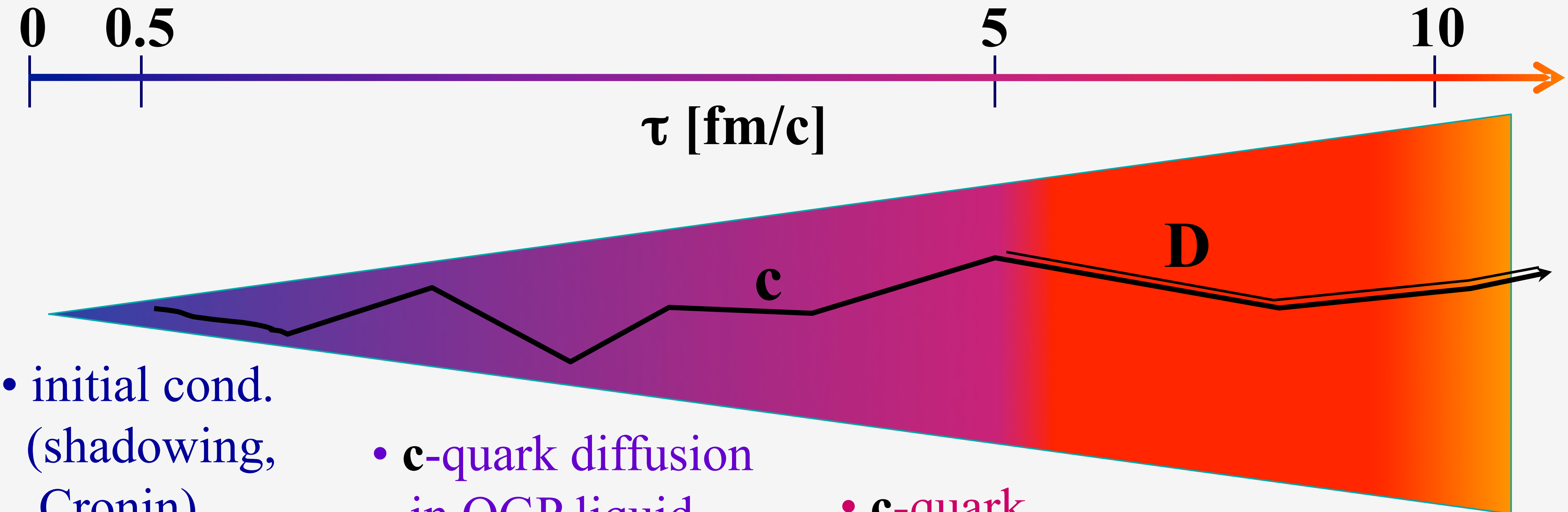


[He et al '11,
Riek+RR '10,
Ding et al '11,
Gavai et al '11]

AdS/QCD [Gubser '07]

- shallow minimum near T_c
- Quark-Hadron continuity?

3.4 Heavy-Flavor Transport in URHICs



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

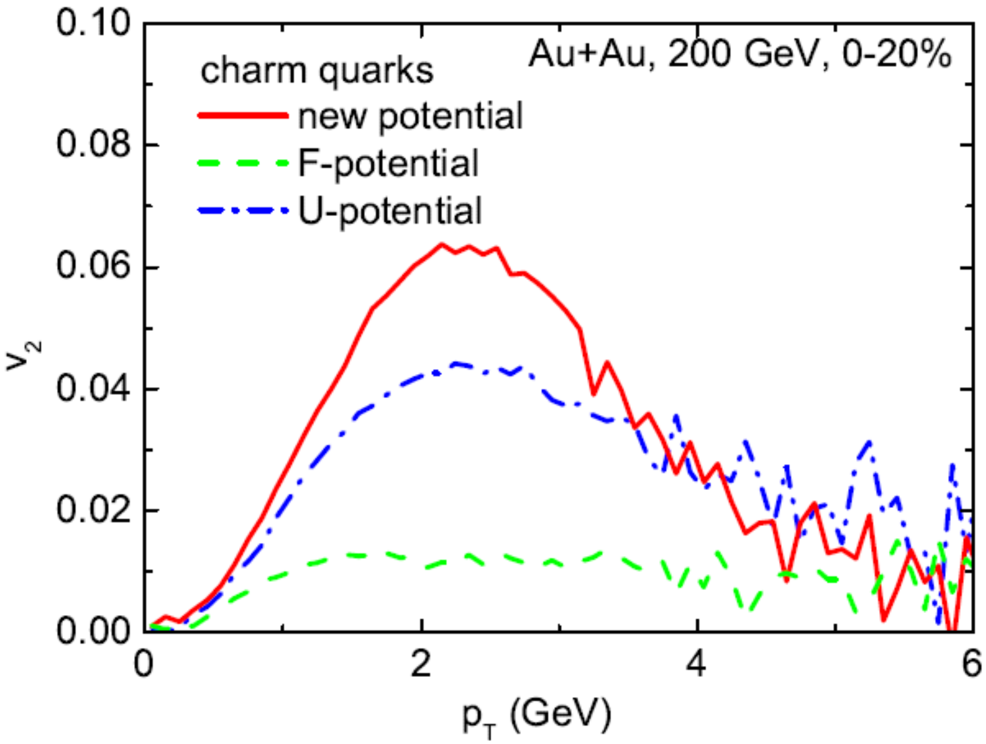
- no "discontinuities" in interaction

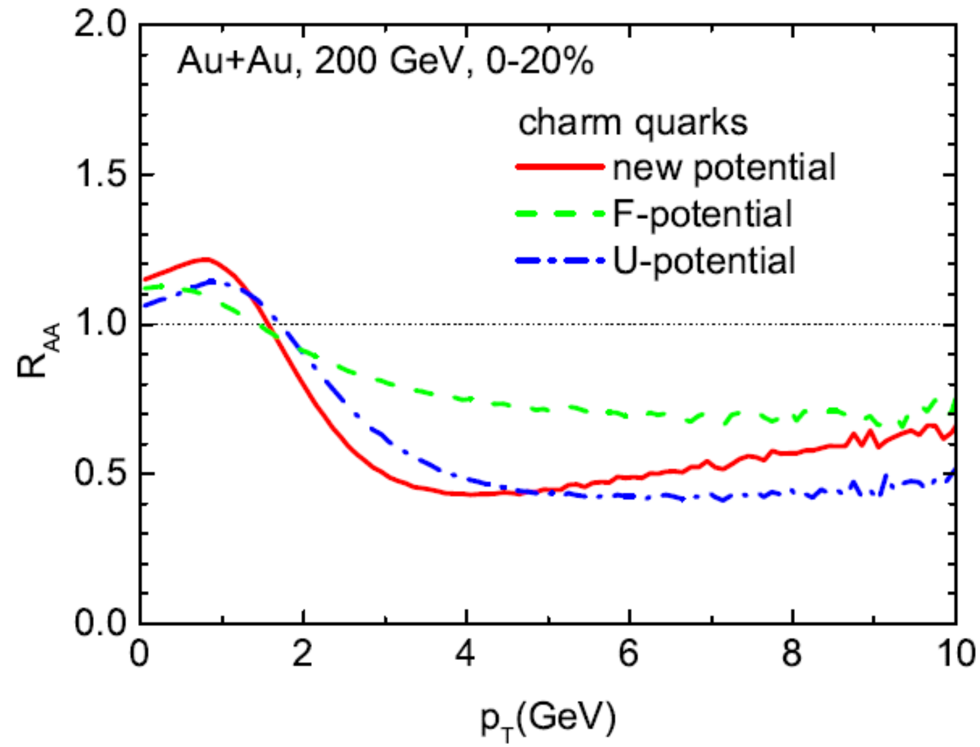
⇒ **diffusion toward** T_{pc} and **hadronization** same interaction (**confining**!)

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

3.5 Charm v_2 as Gauge of Transport Coefficient

- **Implement transport coefficients into Hydro/Langevin simulations**



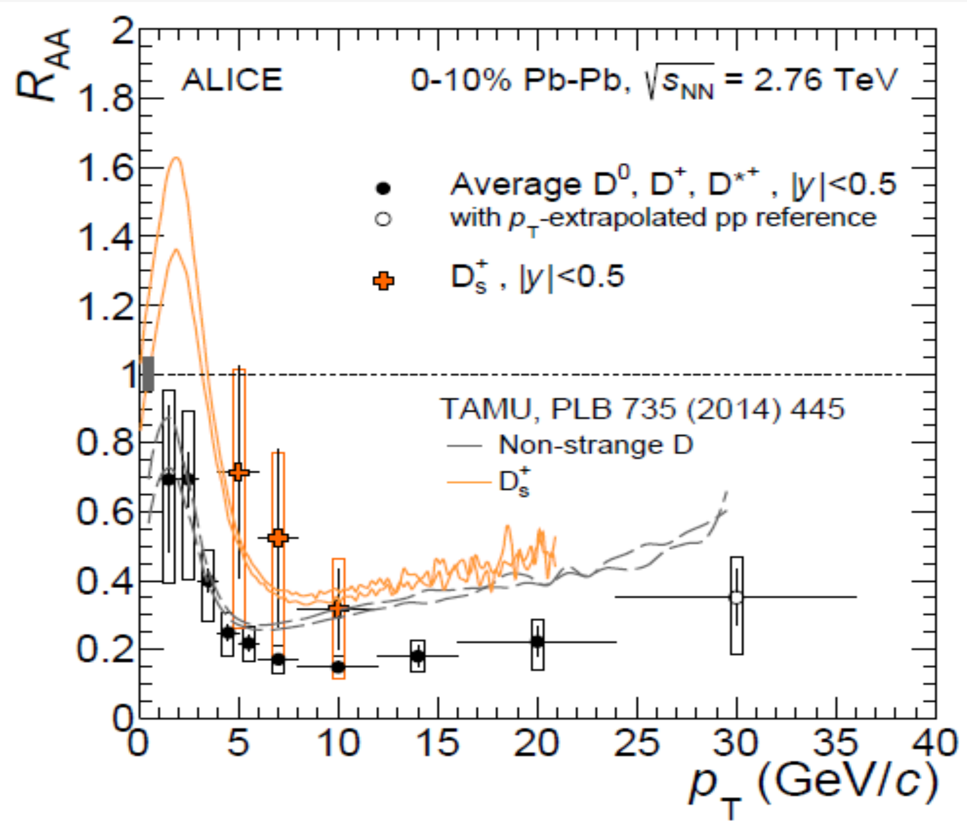


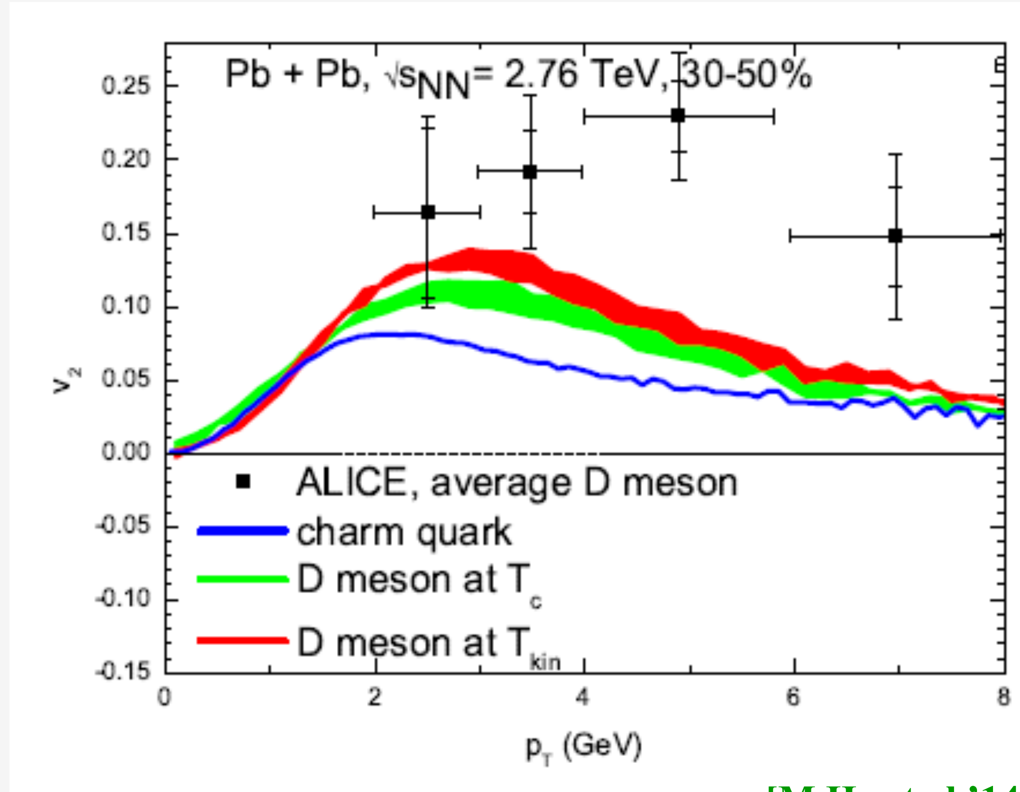
[S.Liu,M.He+RR in prep]

- Free-energy "potential" much too weak
- **New potential gives largest effect**

⇒ $v_2^c(p_t \approx 2\text{GeV})$ probes $\mathcal{D}_s$ via intermediate-range force

3.6 Charm Transport at LHC: D-Meson Spectra





[M.He et al '14]

- R_{AA} "bump" from radial flow
- **D_s** meson (**cs**) enhanced from coalescence with strange quarks
- Coalescence + hadronic diffusion increase v_2
- similar features at **RHIC**

Outline

1.) Introduction

2.) Heavy-Quark Interactions in QGP

3.) Open Heavy-Flavor Transport

4.) Quarkonia: ψ' Puzzle(s)

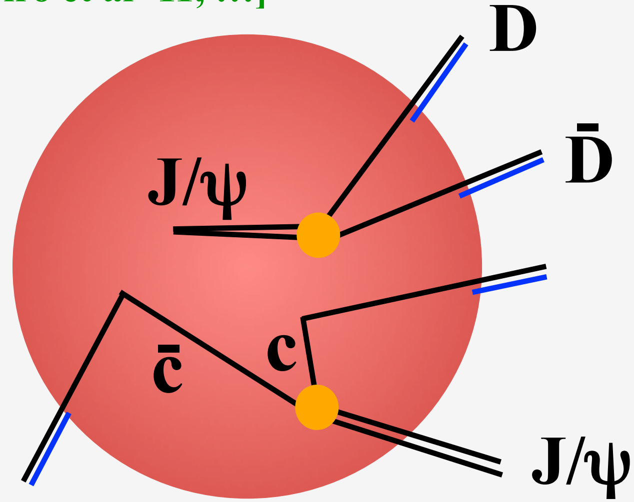
5.) Conclusions

4.) Quarkonium Transport in Heavy-Ion Collisions

[PBM+Stachel '00,Thews et al '01, Grandchamp+RR '01, Gorenstein et al '02, Ko et al '02, Andronic et al '03, Zhuang et al '05, Ferreiro et al '11, …]

- **Inelastic reactions:**

  detailed balance: $J/\psi + g \rightleftarrows c + \bar{c} + X$



- **Rate equation:**

$$\frac{dN_\psi}{d\tau} = -\Gamma_\psi \,(N_\psi - N_\psi^{eq})$$

- **Theoretical input: transport coefficients**
  - chemical relaxation rate Γ_ψ
  - equililbrium limit $N_\psi^{eq}(\varepsilon_\psi^B, m_c^* , \tau_c^{eq})$

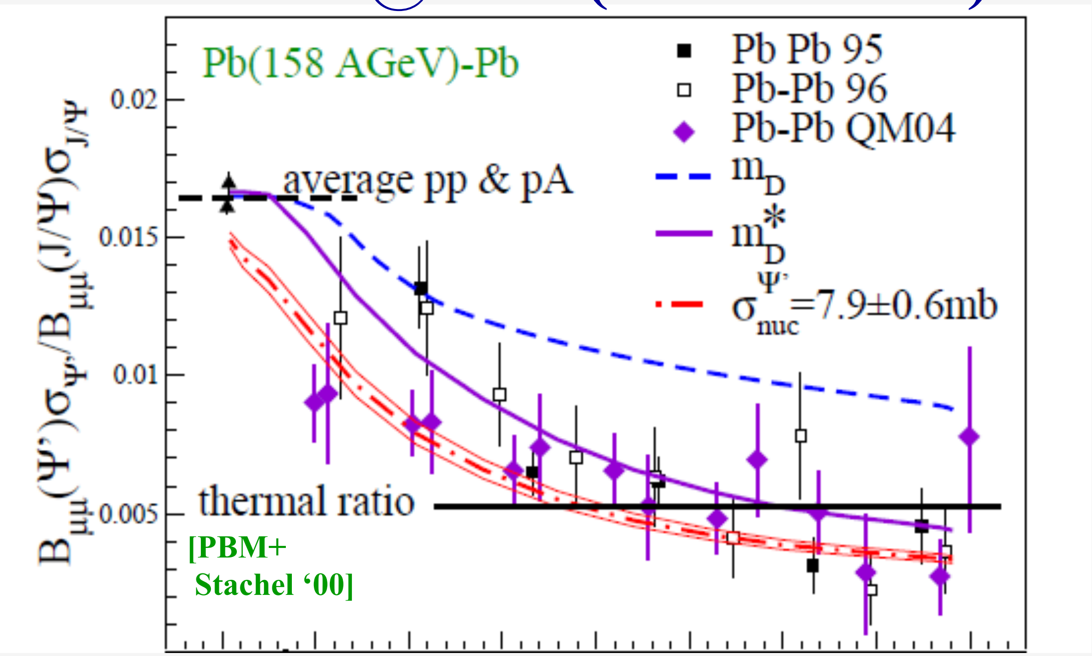
- **Phenomenological input:**
  - $J/\psi, \chi_c, \psi'$ +c,b initial distributions [pp, pA]
  - space-time medium evolution [AA: hydro,...]

Observables

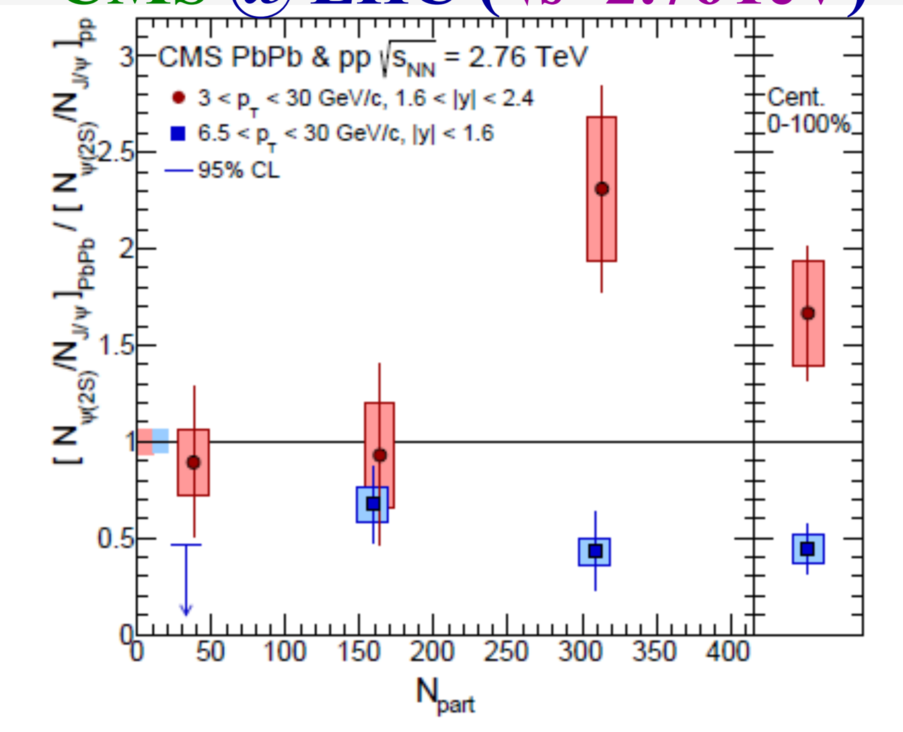
4.2 Excited Charmonium: ψ′(3686)

- easily dissociated in hadronic matter: π, ρ, ... + ψ′ →DD, ψ′ → $D_{med}D_{med}$

NA50 @ SPS (√s=17.3GeV)



CMS @ LHC (√s=2.76TeV)



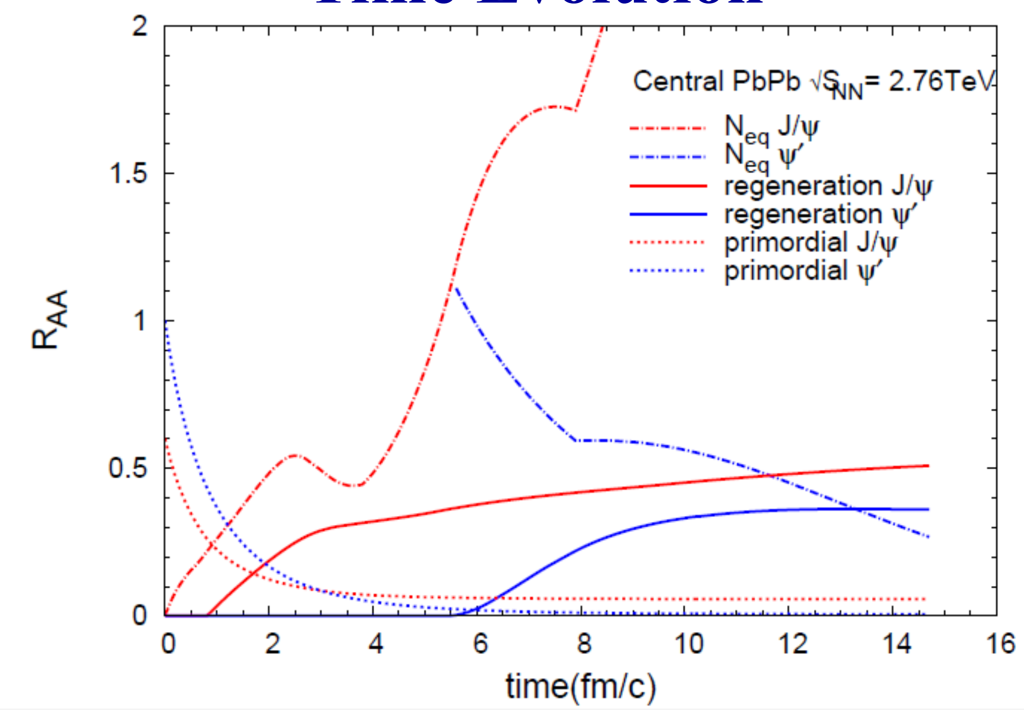
- **hadronic** ψ′ dissociation at **SPS** important in transport models

[Sorge et al '97, Grandchamp et al '02 ....]

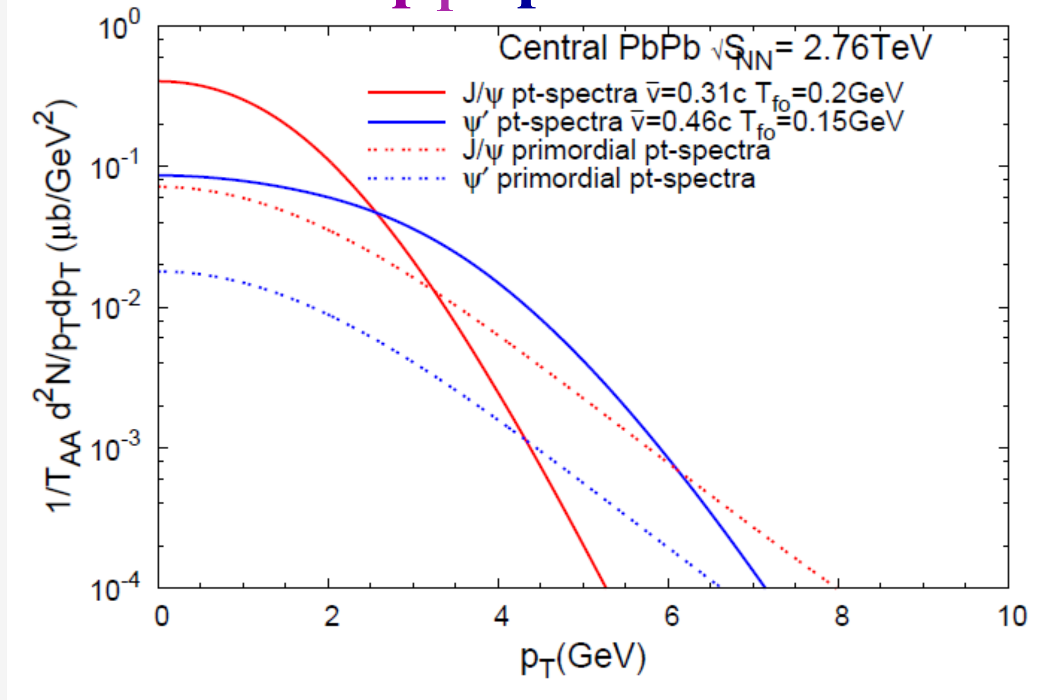
- ψ′ enhanced relative to **J/ψ ?!**

4.3 Sequential Recombination of Charmonia in AA

Time Evolution



p_T Spectra

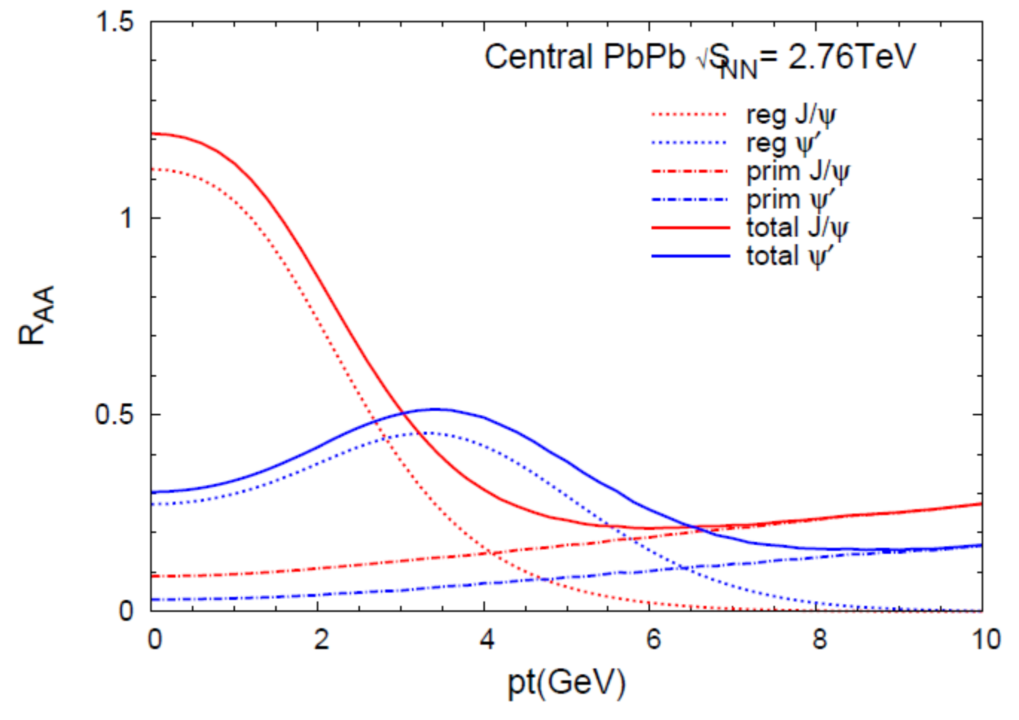


- **smaller binding** → smaller **T_{diss}** → ψ′ forms later than **J/ψ** !
- **stronger blast wave** for ψ′ formed at later times (**hadronic phase!**)

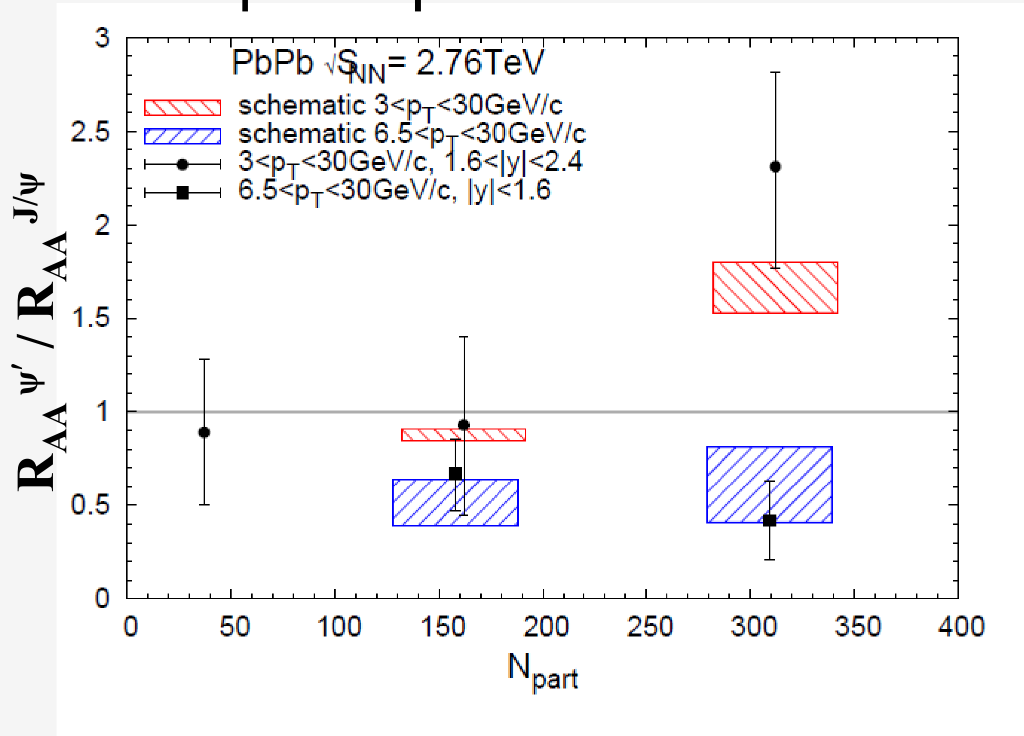
[X.Du+RR '15]

4.3.2 Sequential Recombination vs. Dissociation

Nuclear Modification Factor



ψ′ / J/ψ Double Ratio



- ψ′ blast wave fills p_t = 3-6 GeV region, primordial for p_t > 6 GeV
- may help explain **CMS double-ratio puzzle …**

[X.Du+RR '15]

5.) Summary

- **Heavy-quark potential in QGP from lattice-F using T-matrix**
  - **Large imaginary parts**
  - **Remnants of confining force generate strong coupling**
- **T-Matrix approach to bridge lattice and phenomenology**
- **"Critical" consequences for heavy-flavor diffusion**
- **Continuity(?) + minimum of transport coefficient through T_{pc}**
- **No principal difference between diffusion forces + hadronization**
- **Sequential recombination of charmonia?**

2.6.2 Charmonia in QGP from T-Matrix

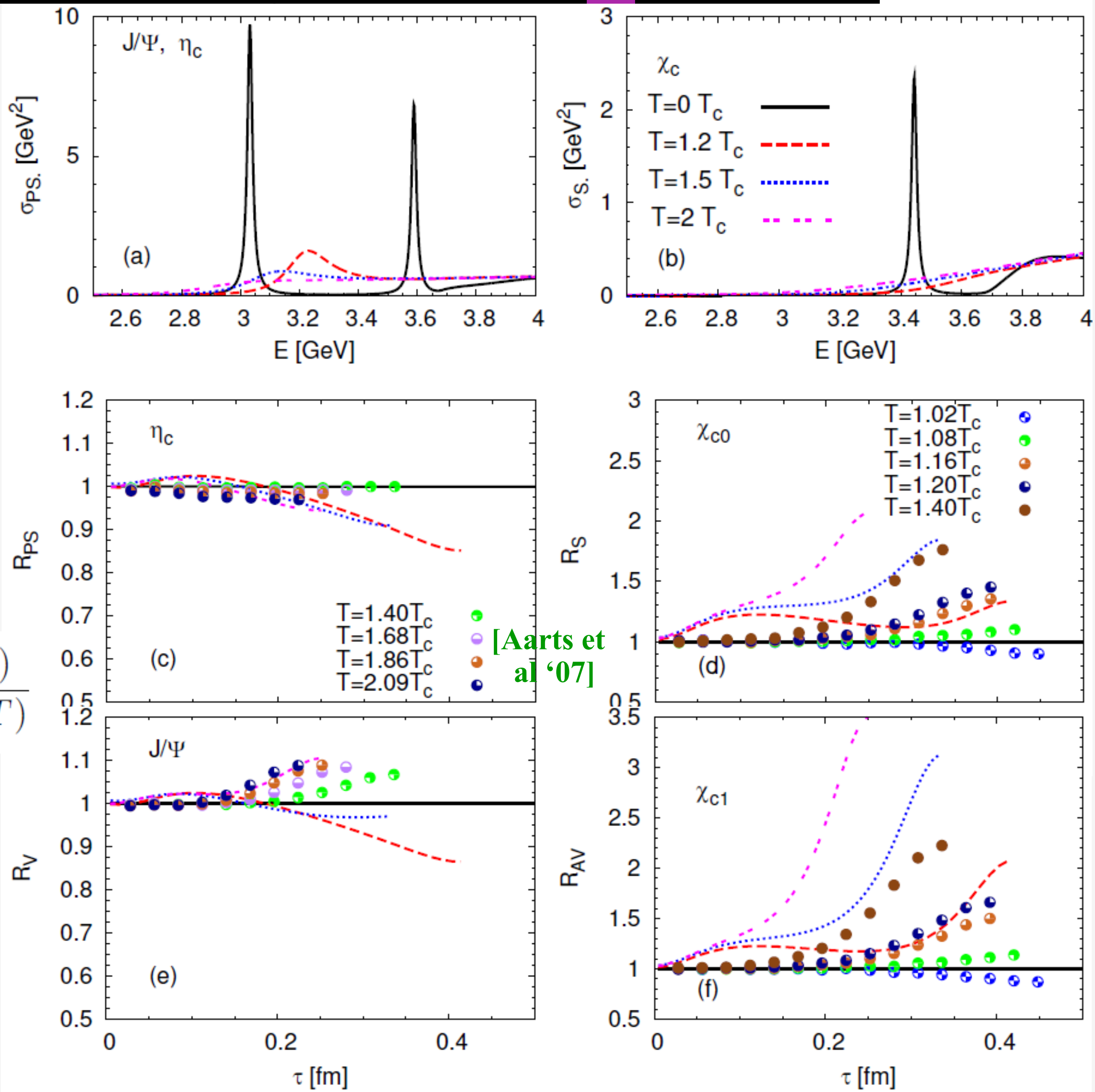
- **U**-potential, selfconsist. **c**-quark width

- **Spectral Functions**
  - J/ψ melting at **~1.5T$_c$**
  - χ_c melting at **~T$_c$**
  - **Γ_c ~ 200MeV**

- **Correlator Ratios**

$$R_\alpha(\tau;T) = \frac{\int dE\, \sigma_\alpha(E,T)\, \mathcal{K}(\tau,E,T)}{\int dE\, \sigma_\alpha(E,T_{\rm rec})\, \mathcal{K}(\tau,E,T)}$$

  - rough agreement with lattice-QCD

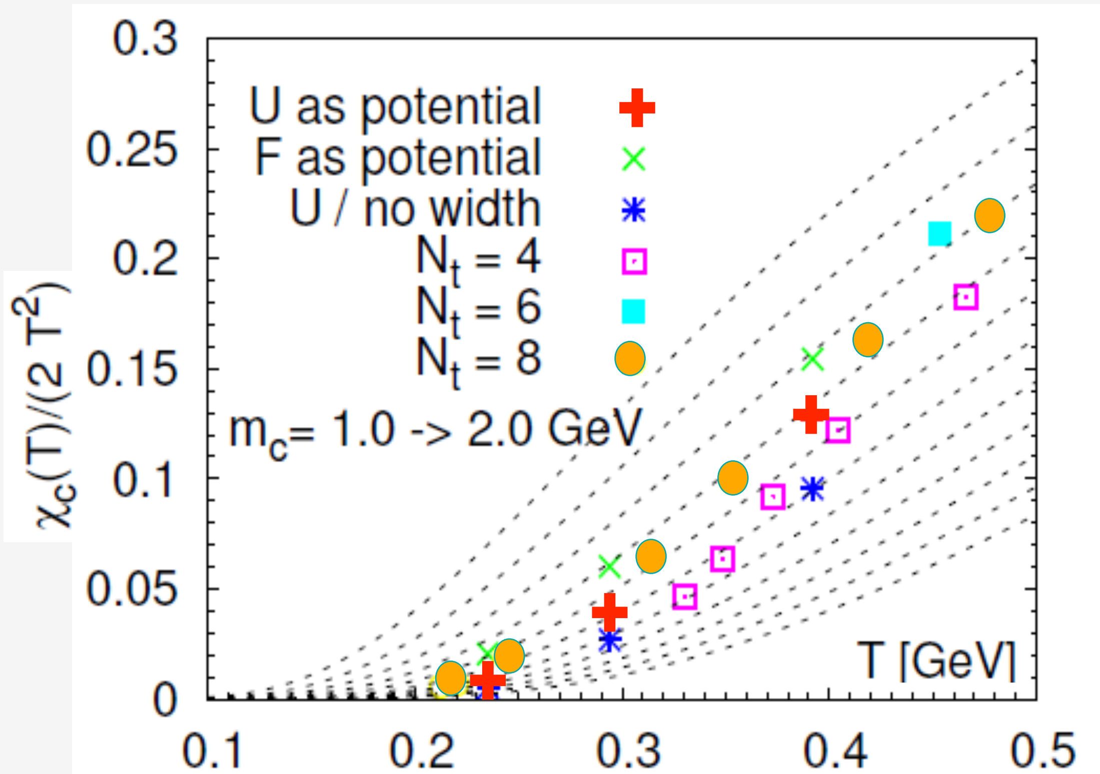


[Mocsy+ Petreczky '05+'08, Wong '06, Cabrera+RR '06, Beraudo et al '06, Satz et al '08, Lee et al '09, Riek+RR '10, …]

2.6.3 Charm-Quark Susceptibility in QGP

$$\chi_c(T) = \frac{1}{T}\int_0^\infty \frac{dE}{2\pi}\frac{2}{1-\exp(-E/T)}\rho_{00}(E,\mathbf{0}) \rightarrow -2N_c\int\frac{d^3\mathbf{k}}{(2\pi)^3}2\frac{\partial f^c(\omega_c(\mathbf{k}))}{\partial\omega_c(\mathbf{k})} \rightarrow \frac{2N_c}{6}T^2$$

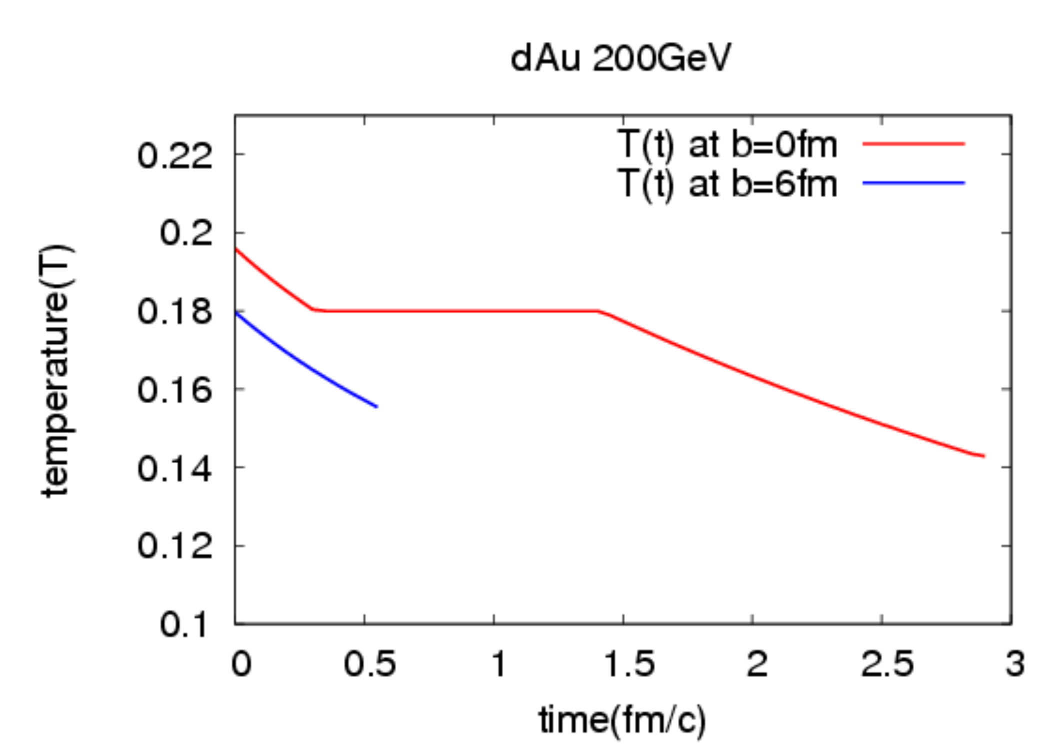
$\Gamma \rightarrow 0$ $\qquad$ $m \ll T$

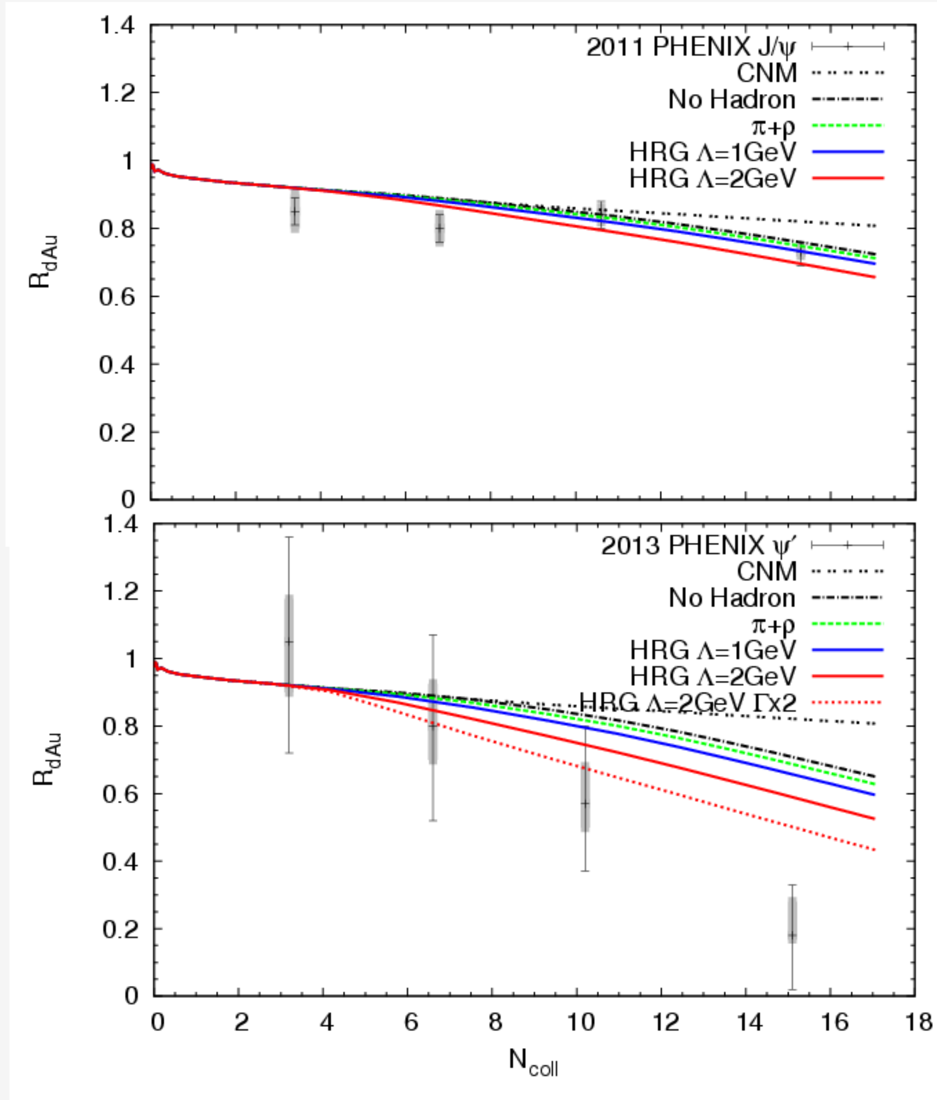


[Riek+RR '10]

- sensitive to in-medium charm-quark mass
- finite-width effects can compensate in-medium mass increase

4.2 Charmonia in d+Au Fireball





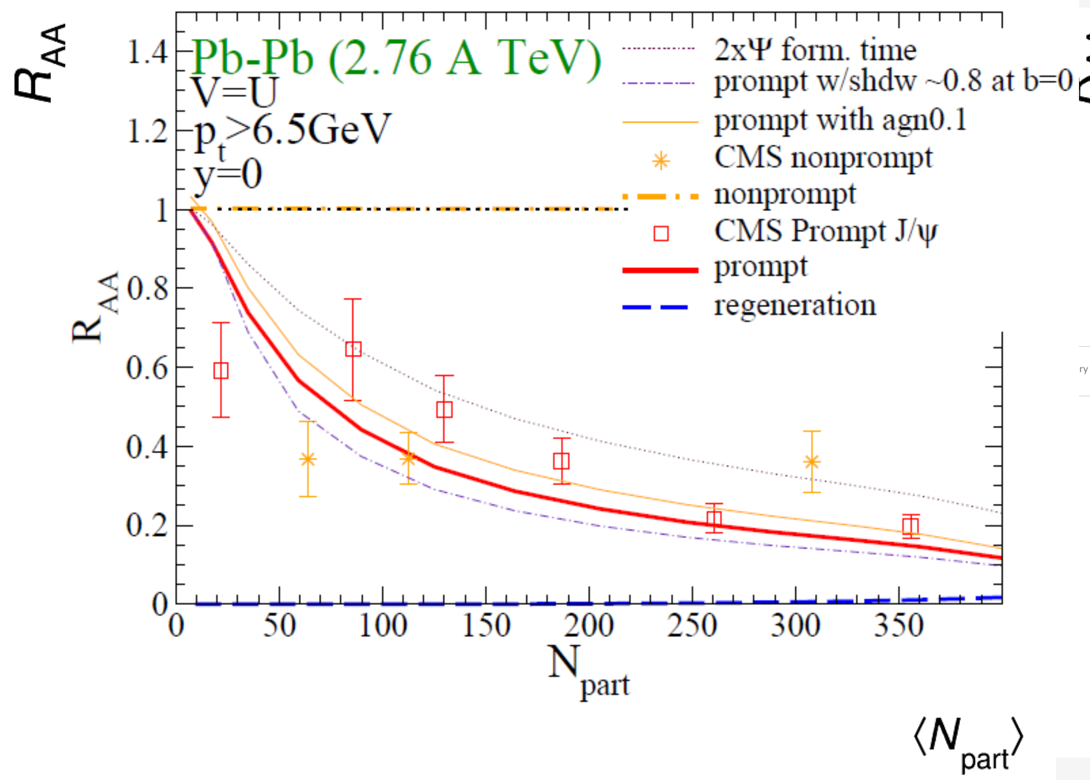
- construct fireball + evolve rate equat.
  → ψ′ suppression from hot medium
- similar in spirit to comover approach [Ferreiro '14]
- formation time effects?!

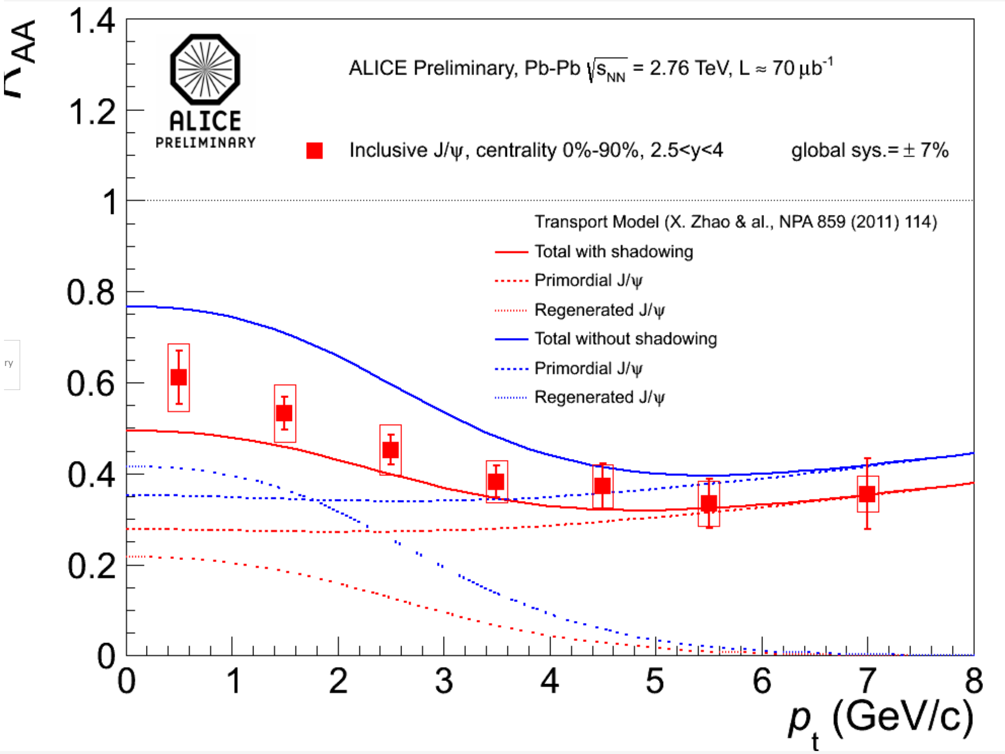
[X.Du+RR, in prep]

[Y.Liu, Ko et al '14]

3.5 J/ψ Predictions at LHC

[Zhao+RR '11]





- regeneration becomes dominant
- uncertainties in σ_{cc}+shadowing

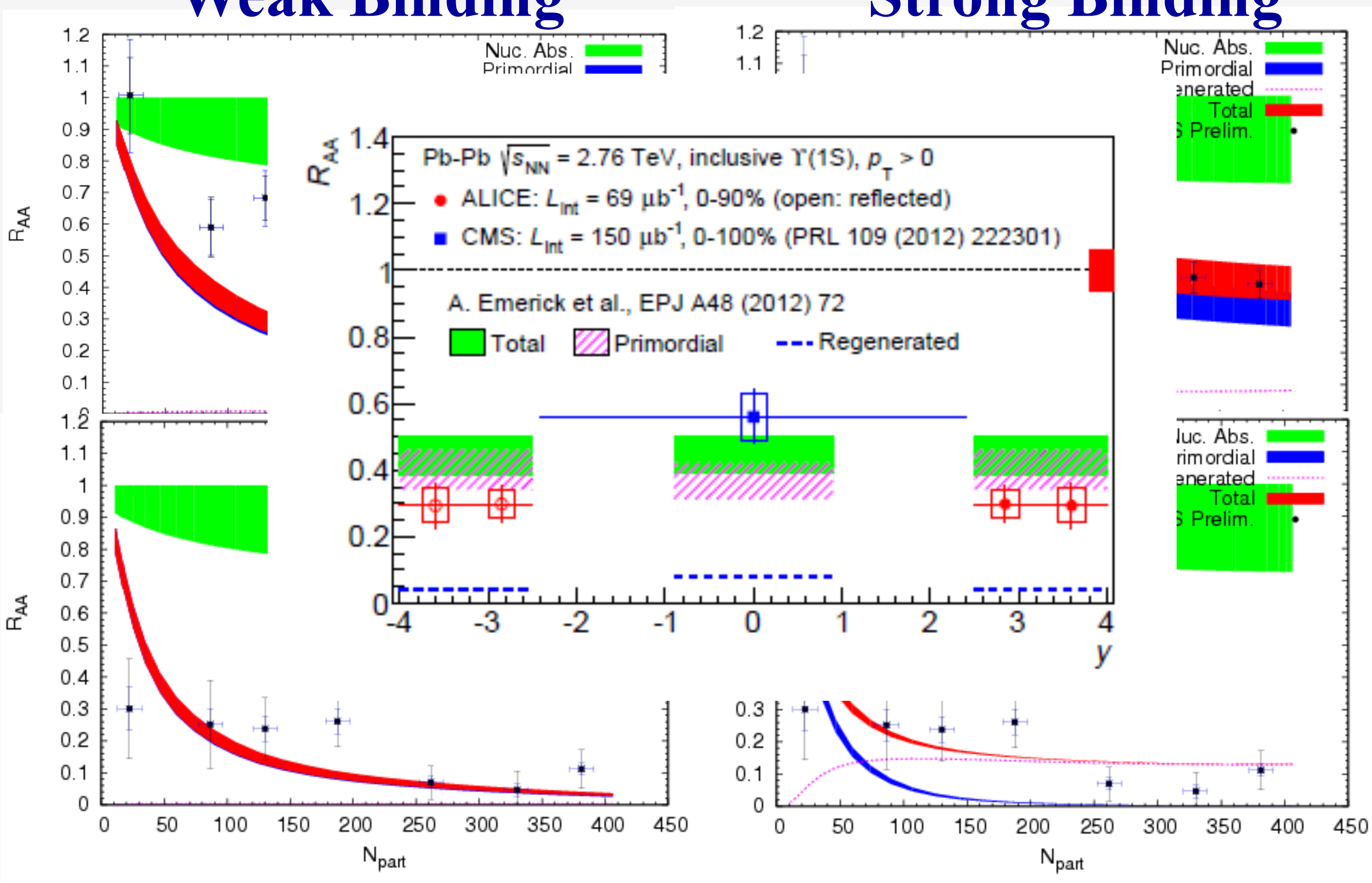
- low p_T maximum confirms regeneration
- too much high-p_T suppression?

3.6 Υ(1S) and Υ(2S) at LHC

Weak Binding **Strong Binding**

Υ(1S) →

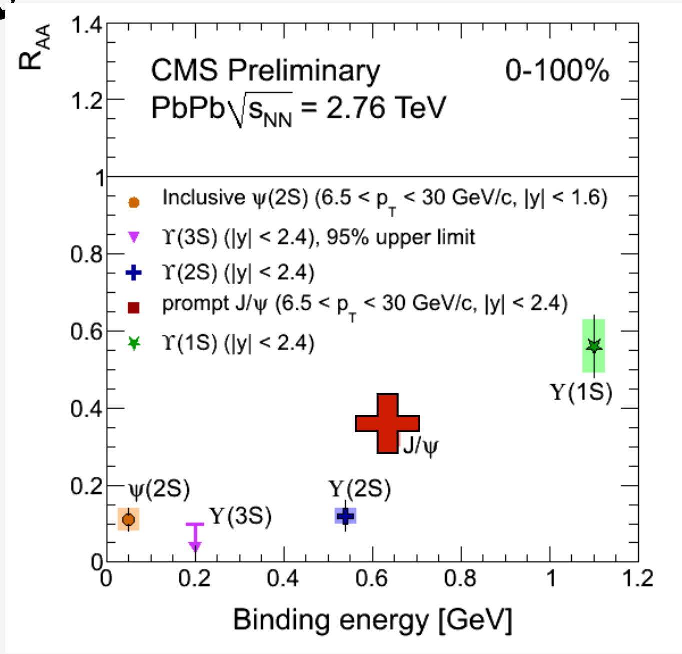
Υ(2S) →



[Grandchamp et al '06, Emerick et al '11]

- sensitive to color-screening + early evolution times
- clear preference for strong binding (**U** potential)
- similar results by [Strickland '12]
- possible problem in rapidity dependence

3.7 Summary of Phenomenology

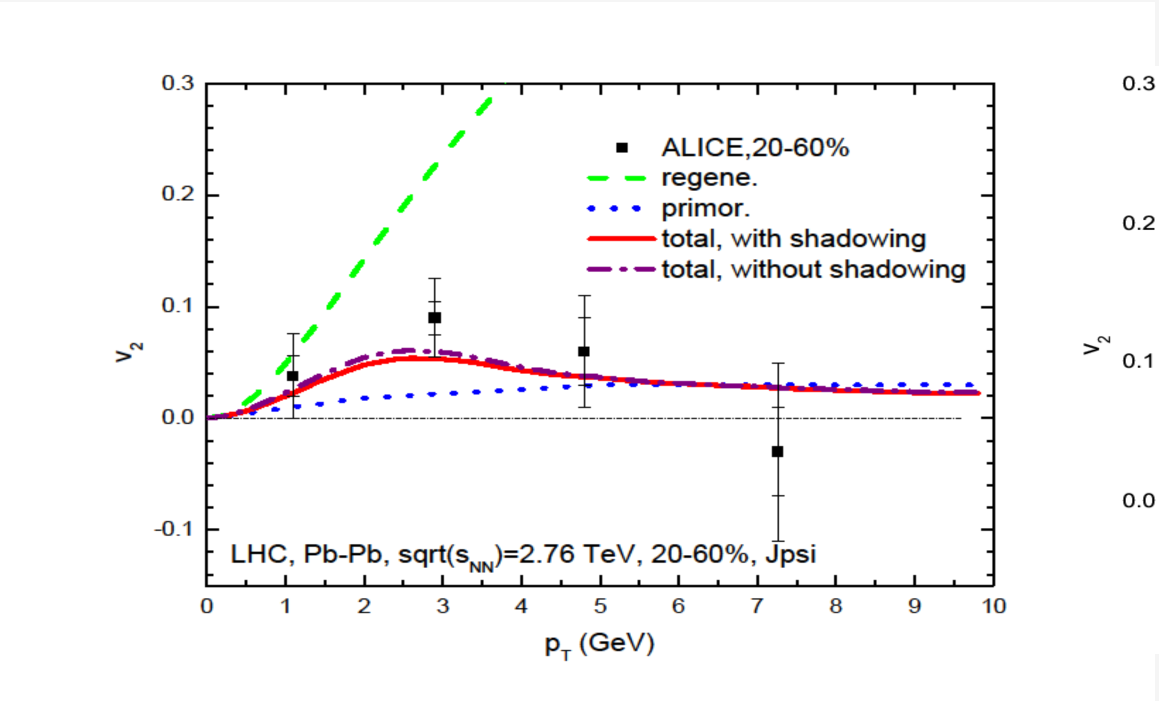


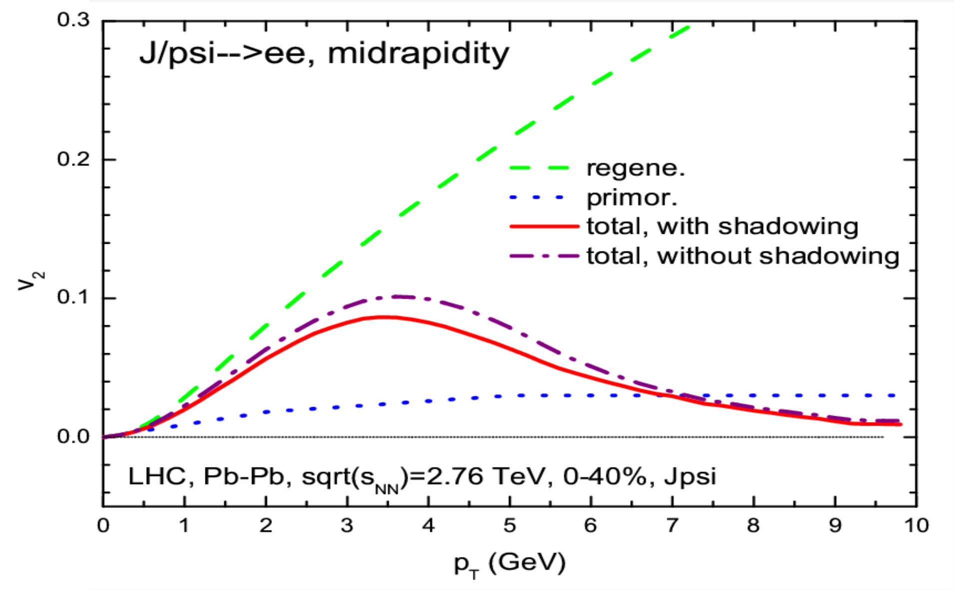
- **Quarkonium discoveries in URHICs:**
  - increase of **J/ψ** R_{AA} **SPS, RHIC → LHC**
  - low-p_T enhancement
  - sizable v_2
  - increasing suppression of Υ' ($\varepsilon_B^{\Upsilon'} \sim \varepsilon_B^{J/\psi}$)

- **Fair predictive power of theoretical modeling**
  - based on description of SPS+RHIC with 2 main parameters

- **Implications**
  - T_0^{SPS} (~230) < T_{diss}(J/ψ,Υ') < T_0^{RHIC} (~350) < T_0^{LHC}(~550) ≤ T_{diss}(Υ)
  - **confining force screened at RHIC+LHC**
  - marked recombination of diffusing charm quarks at **LHC**

3.2.2 J/ψ at LHC: v_2

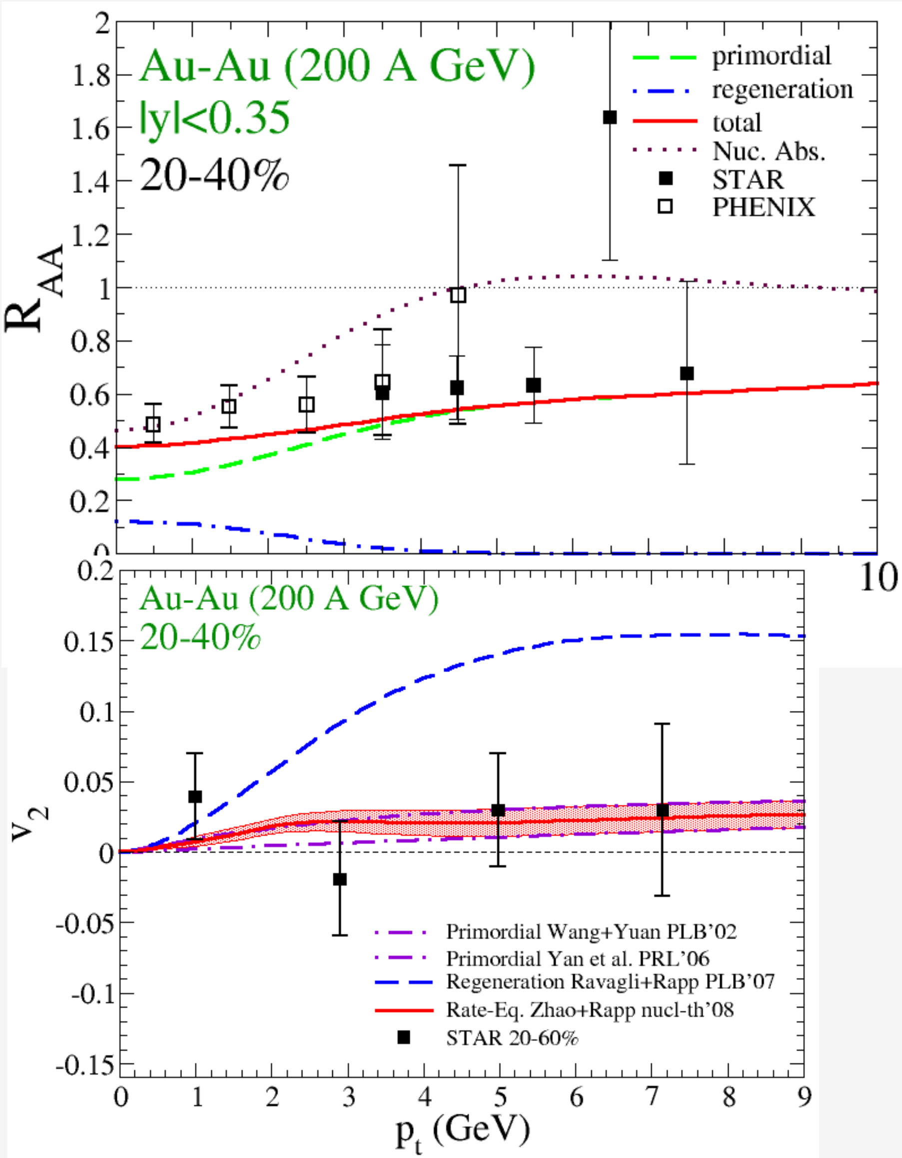




[He et al '12]

- further increase at mid-y

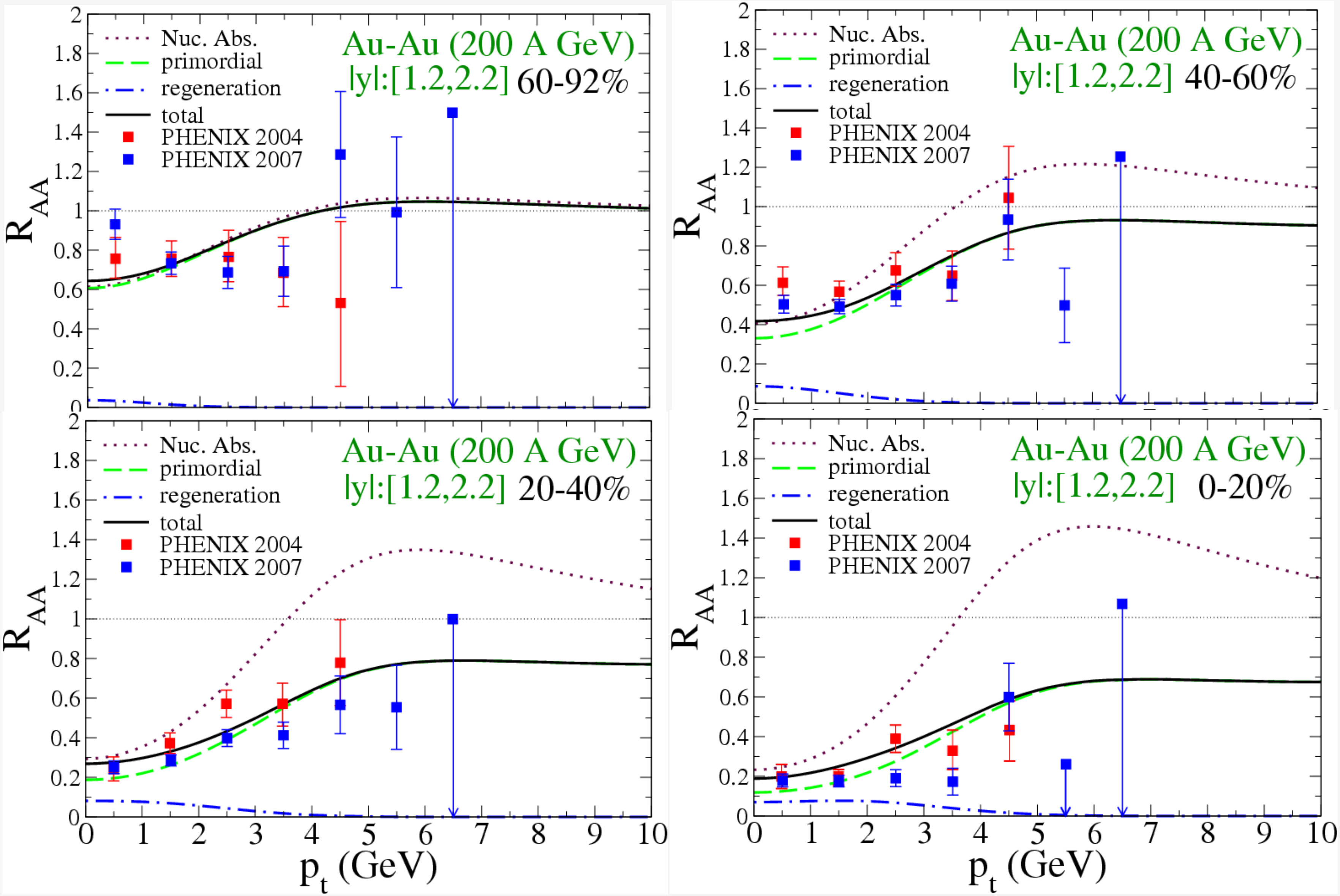
3.1.2 J/ψ p_T Spectra + Elliptic Flow at RHIC



(strong binding)

- shallow minimum at low p_T
- high p_T: formation time, **b** feeddown, Cronin
- small v_2 **limits** regeneration, but does **not exclude** it

4.3 J/ψ at Forward Rapidity at RHIC



[Zhao+ RR '10]