Heavy-Flavor Probes of QCD Phase Structure

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1.) Objectives with Heavy Flavor in Medium

Determine modifications of QCD force in medium and its consequences for the many-body system

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

- **Heavy-flavor diffusion: "Brownian motion"**
  - Thermalization: delayed by m_Q/T → memory
  - Scattering rates → widths; quasiparticles? ($m_Q >> T$)
  - Transport coefficients: $\mathcal{D}_s (2\pi T) \sim \eta/s$
  - Space-like interactions (potential-type)

- **Quarkonia kinetics**
  - Same force as in HQ diffusion?
  - **Υ(1S)** vs. Ψ states: Coloumb vs. confining force

Outline

1.) Introduction

2.) Heavy-Quark Interactions in QGP

3.) Heavy-Flavor Transport

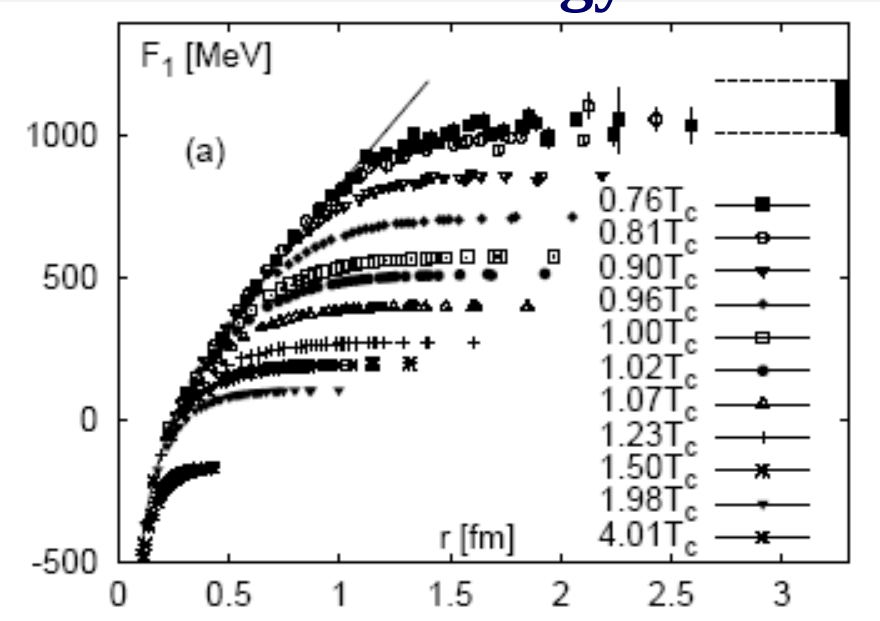
4.) Quarkonia

5.) Conclusions

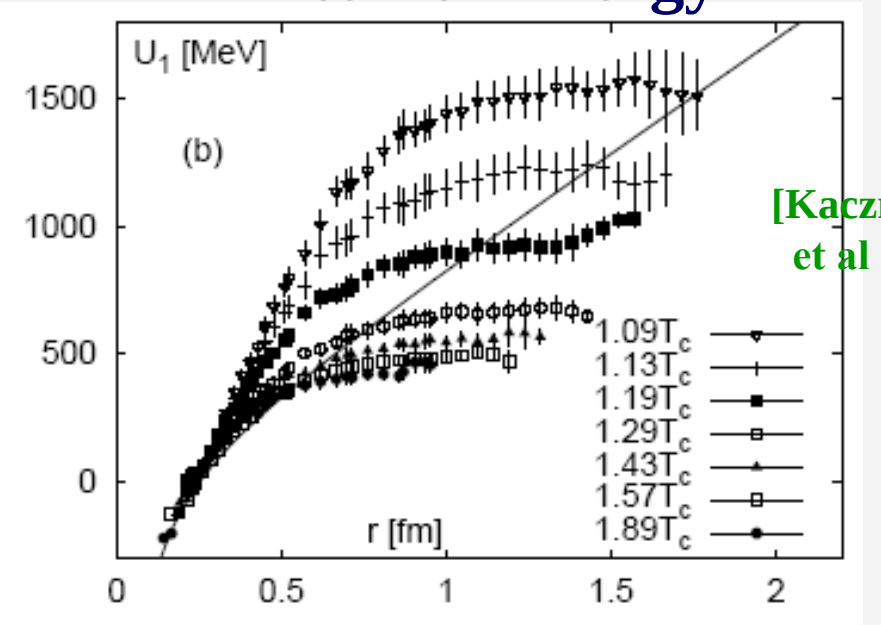
2.1 Heavy-Quark Free and Internal Energies in Lattice QCD

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

Free Energy



Internal Energy



[Kaczmarek et al '05]

- "**weak**" $Q\bar{Q}$ potential
- "**strong**" $Q\bar{Q}$ potential, $U = \langle H_{int} \rangle$

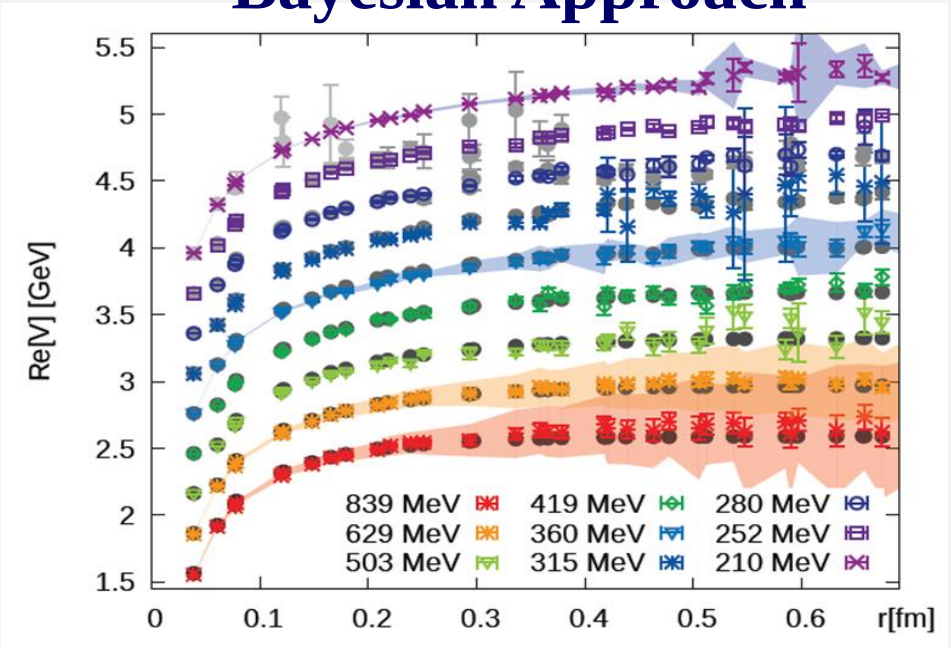
- **F, U, S thermodynamic quantities**
- **Entropy**: many-body effects

2.2 Extraction of Potential 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** $\sigma(\omega, r) = \frac{1}{\pi}\frac{(V+\Sigma)_I(\omega)}{(\omega - (V+\Sigma)_R)^2 + (V+\Sigma)_I^2(\omega)}$

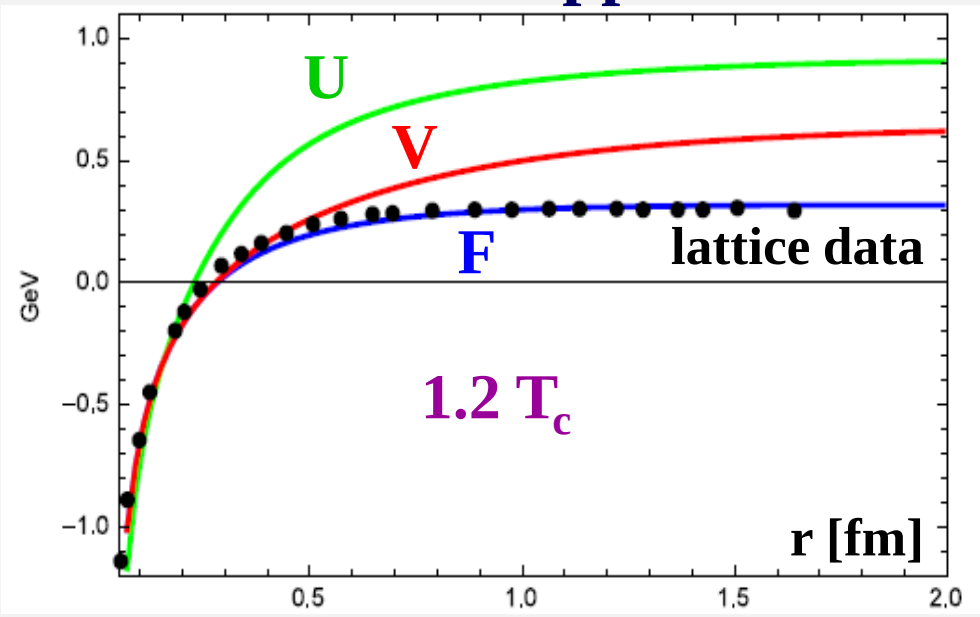
Bayesian Approach



- **Potential close to free energy**

[Burnier et al '14]

T-Matrix Approach



- Account for large imaginary parts
- **Remnant of confining force!**

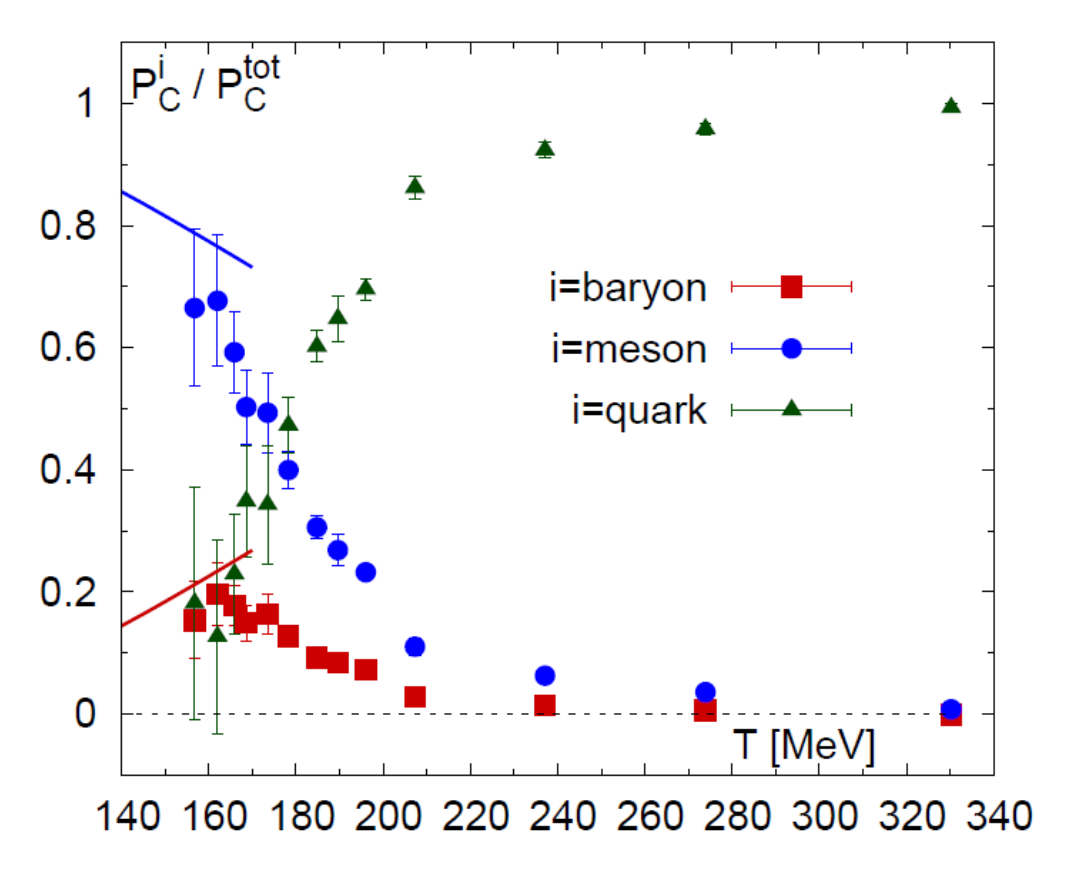
[S.Liu+RR '15]

2.3 Charm Susceptibilities from Lattice QCD

- Extract partial charm pressures from susceptibilities

[Mukherjee,Petreczky +Sharma '15]

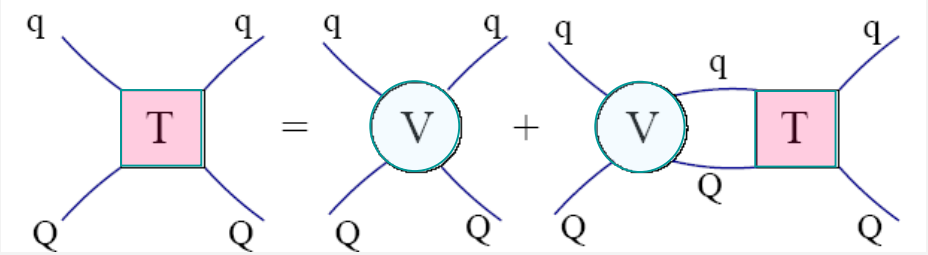
$$p_c(T,\mu_B,\mu_c) = p_M(T)\cosh\left(\frac{\mu_c}{T}\right) + p_B(T)\cosh\left(\frac{\mu_c+\mu_B}{T}\right) + p_Q(T)\cosh\left(\frac{\mu_c+\mu_B/3}{T}\right)$$

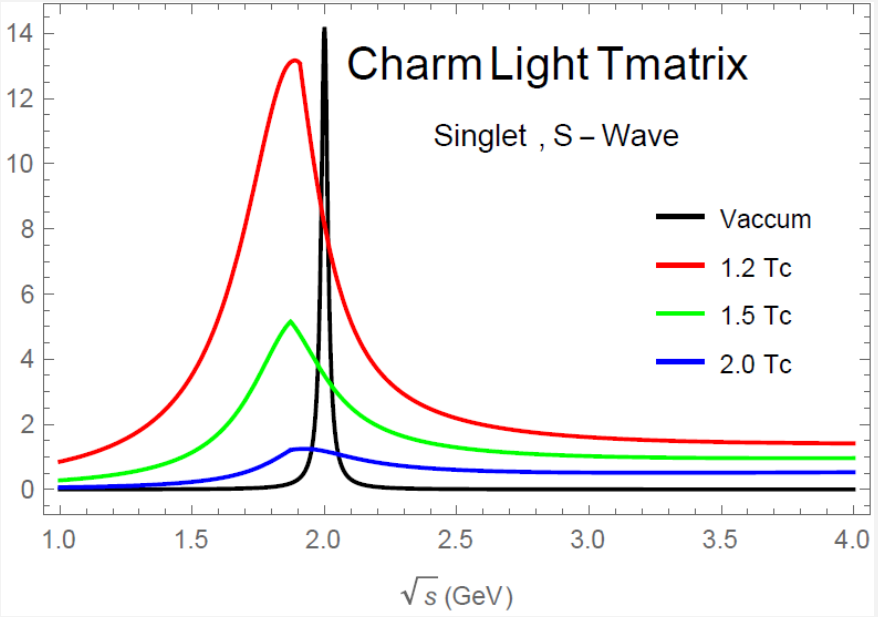


- Hadronic (**D**-meson) correlations contribute until **~1.3 T_c**

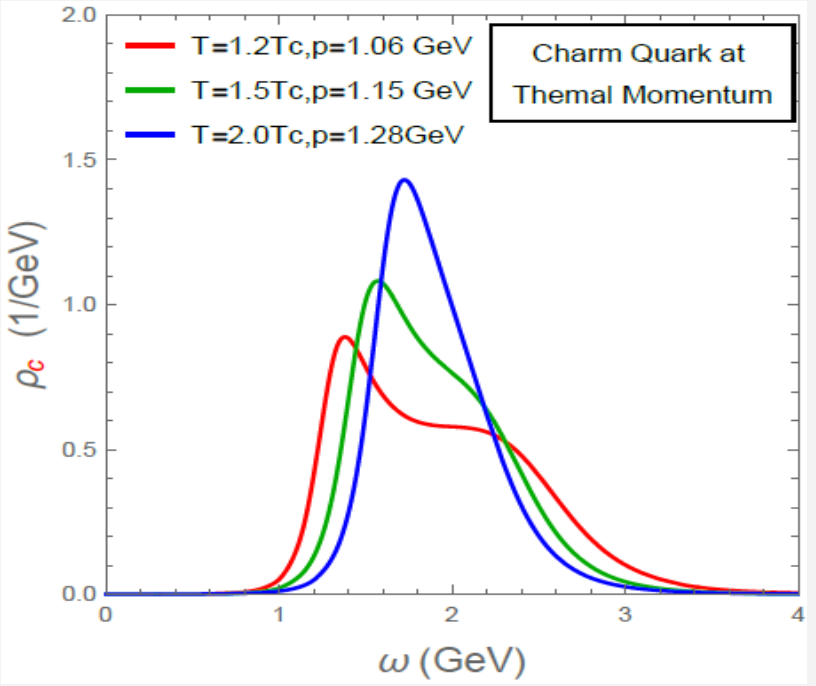
2.4 D-meson + c-Quark Spectral Functions in QGP

T-matrix w/ "lattice potential" V





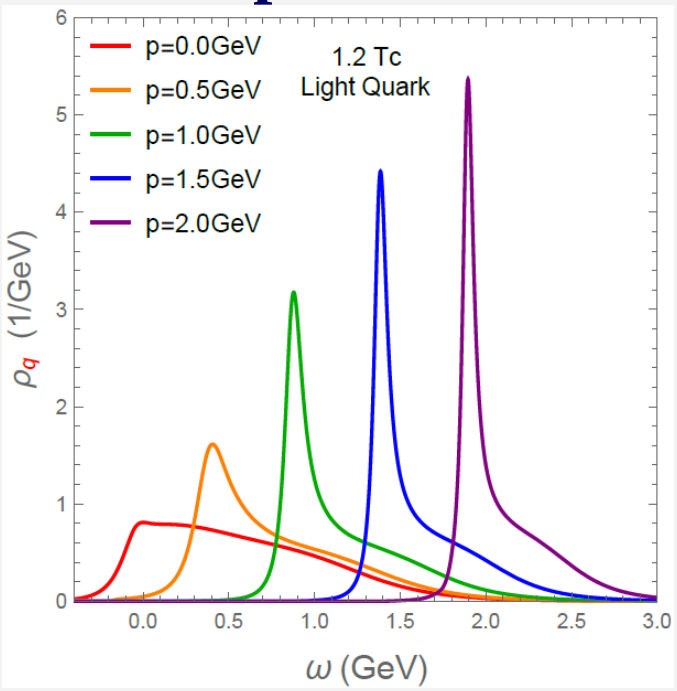
In-Medium c-Quark Selfenergy



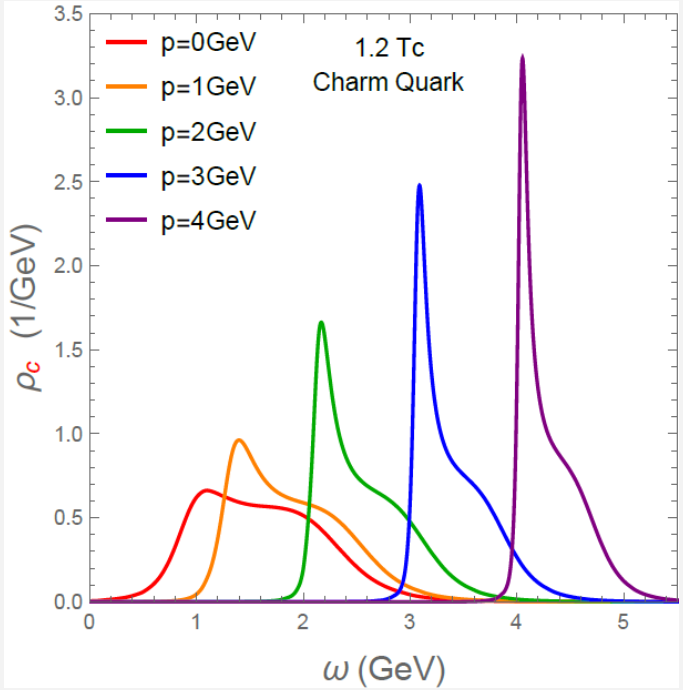
D-meson resonances → **c**-quark quasi-particles

2.5 Quark Spectral Functions in QGP

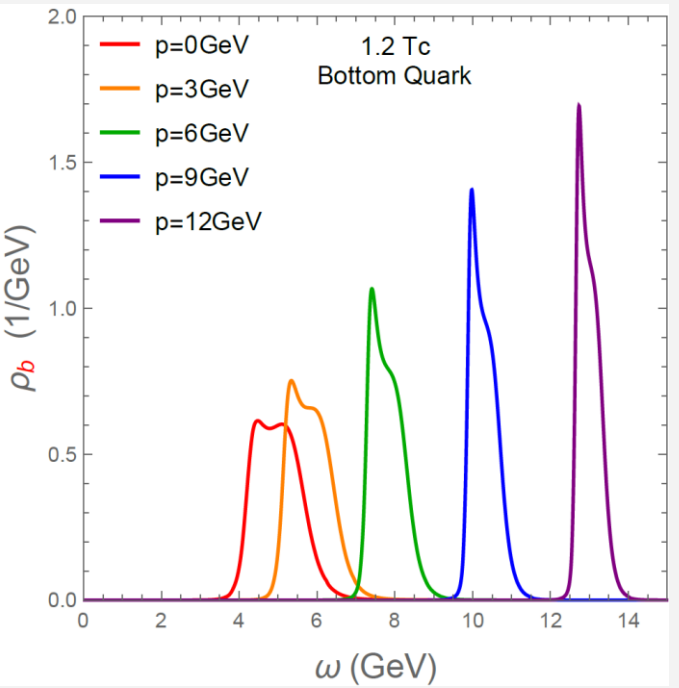
Up/Down



Charm



Bottom



- QGP structure changes with resolution scale:
  - No light-quark quasi-particles at small **p** near $\mathbf{T_c}$
  - Re-emerge with increasing $\mathbf{M_q}$, **p**, **T**

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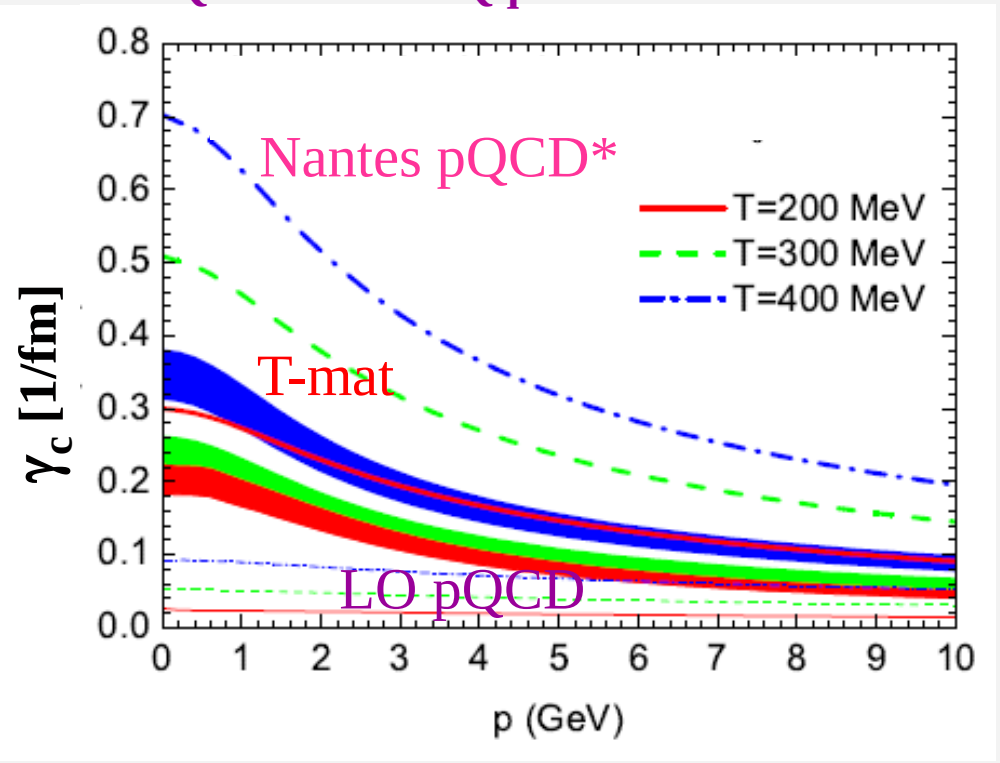
3.1 Charm-Quark Transport

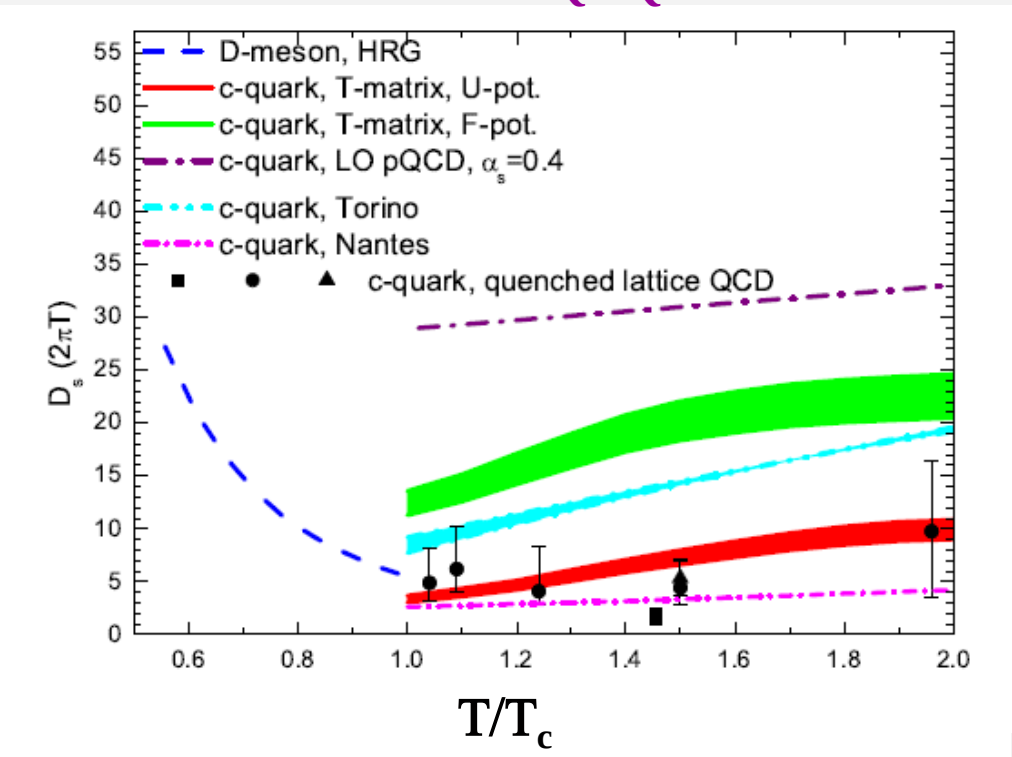
Thermalization Rate

$$\gamma_Q\, p = \int |\mathcal{M}_{Qq}|^2\, (1-\cos\Theta)\, f^q$$



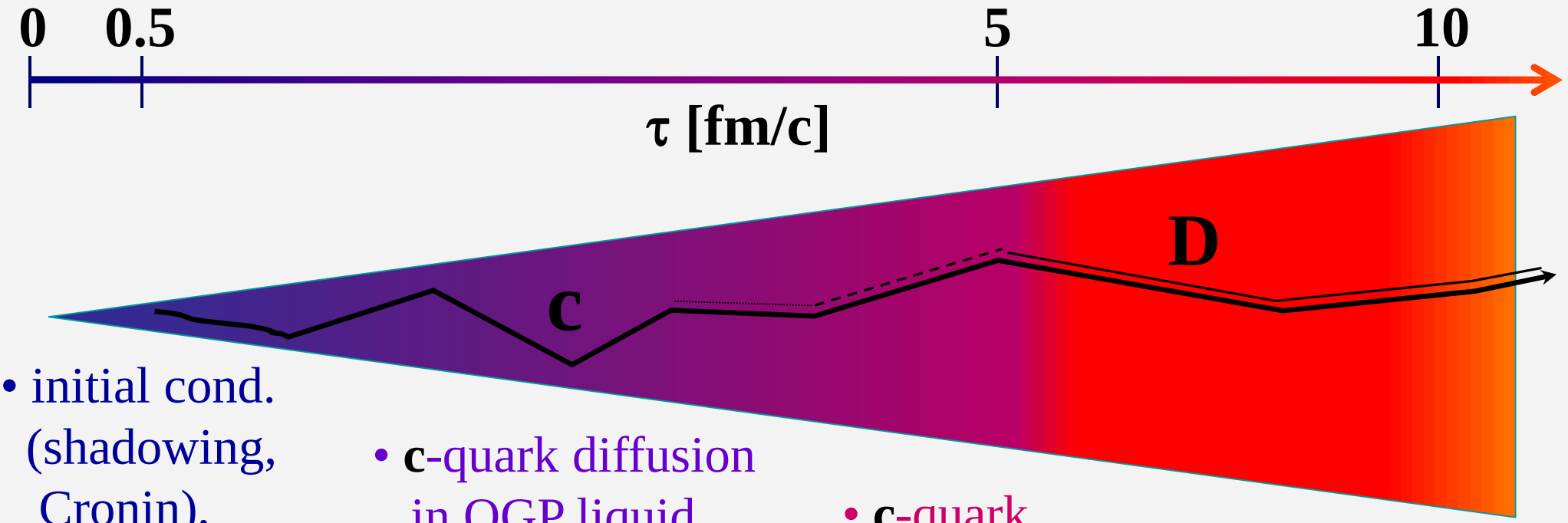
Spatial Diffusion Coefficient

$$\mathcal{D}_s = T / (m_Q\, \gamma_Q(p=0))$$



- **p**- and **T**-dependence reflect core properties of QCD
- suggests minimum of $\mathcal{D}_s(2\pi T) \sim 2\text{-}4$ near T_c
- estimate: $\Gamma_{coll} \sim 3/\mathcal{D}_s \sim 1$ GeV – **no light quasi-particles!**

3.2 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

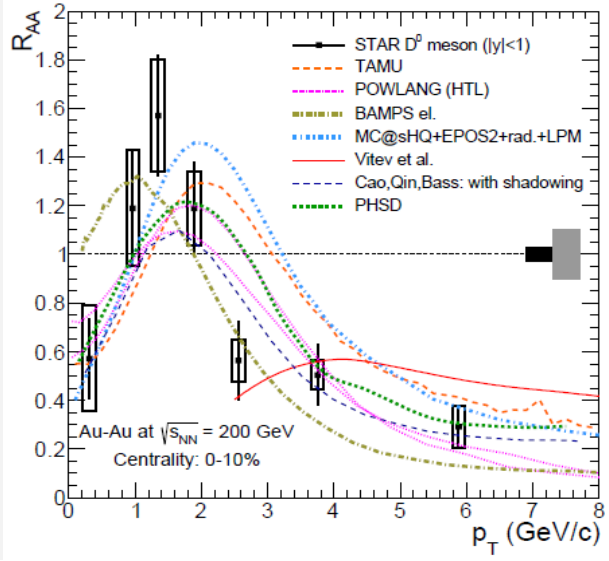
- no "discontinuities" in interaction

$\Rightarrow$ **diffusion toward T_{pc}** and **hadronization** same interaction (**confining**!)

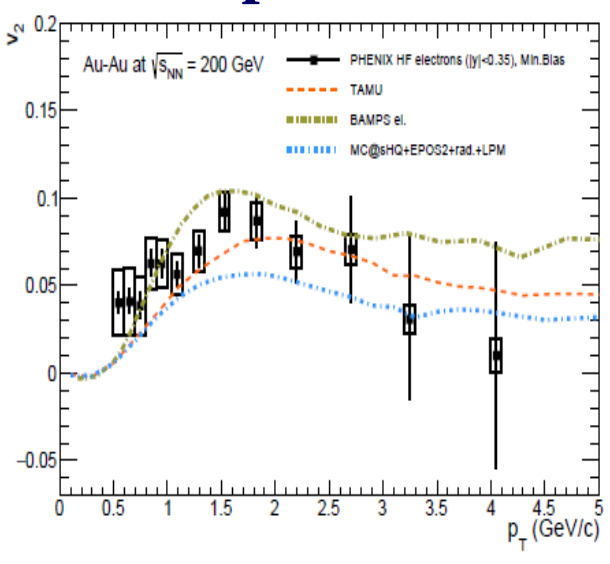
[Moore+Teaney '05, van Hees et al '05, Gossiaux et al '08, Vitev et al '08, Das et al '09, Uphoff et al '10, M.He et al '11, Beraudo et al '11, Cao et al '13, Bratkovskaya et al '14, …]

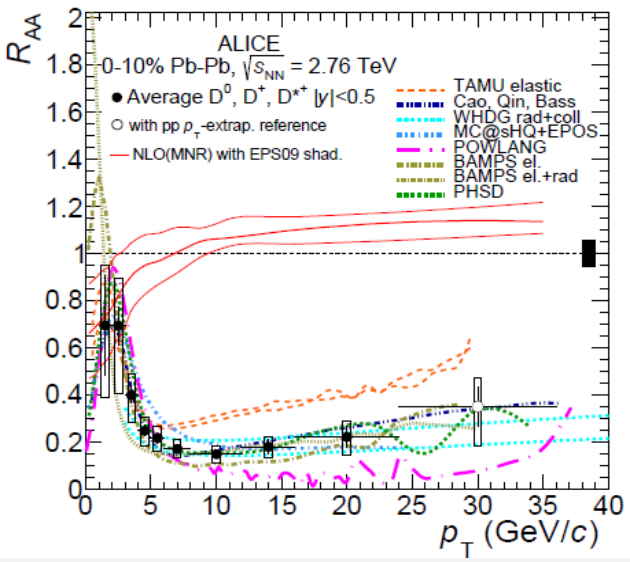
3.3 Heavy-Flavor Transport at RHIC + LHC

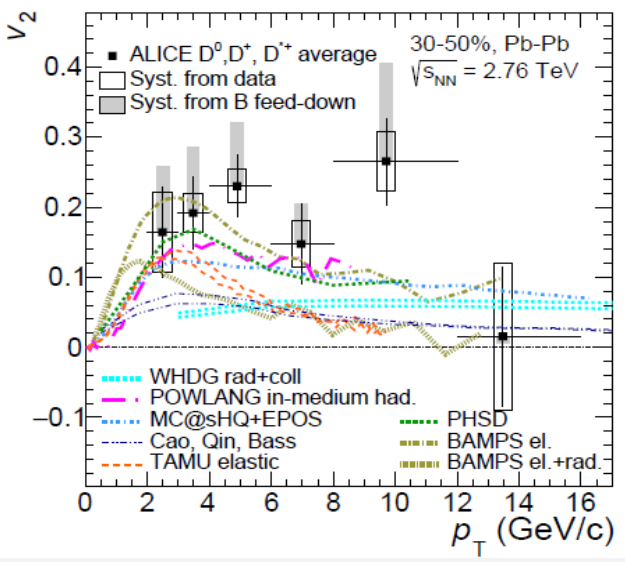
Nucl. Mod. Factor



Elliptic Flow







- radial flow bump in R_{AA}
- coalescence increases v_2 ↔ strong coupling near T_c
- R_{AA}- v_2 correlation favors elastic interactions
- **Transport Coefficient:**
  - **low p_T:** $\mathcal{D}_s(2\pi T) \sim 2\text{-}4$

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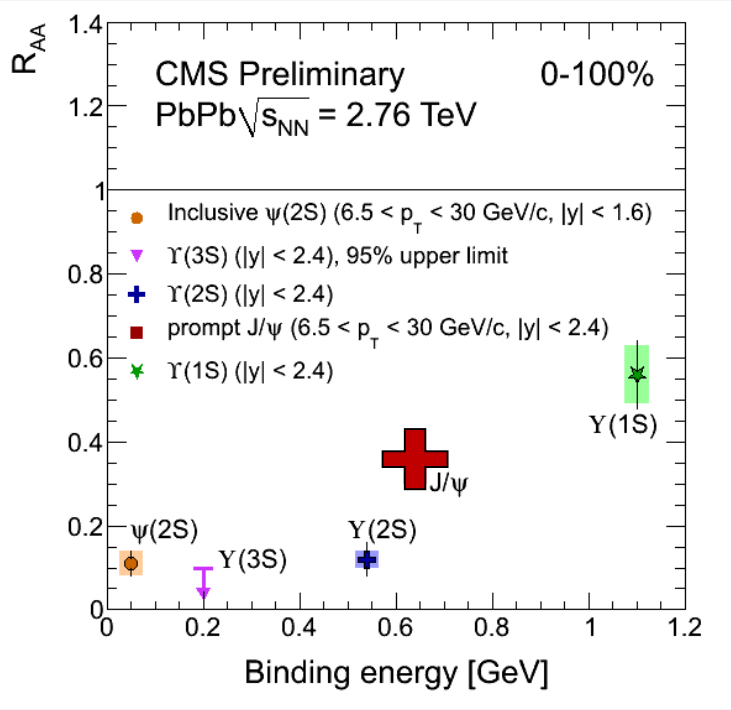
4.1 Summary of Phenomenology

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



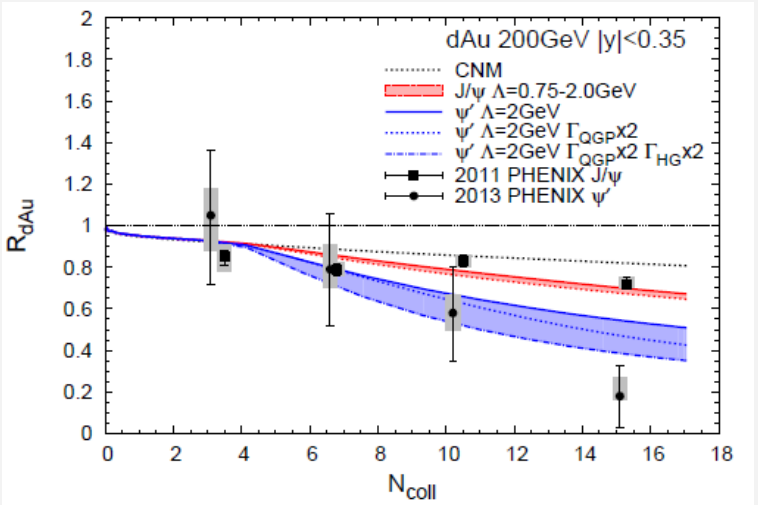
- **Predictive power of transport models**
  - based on description of **SPS+RHIC** data

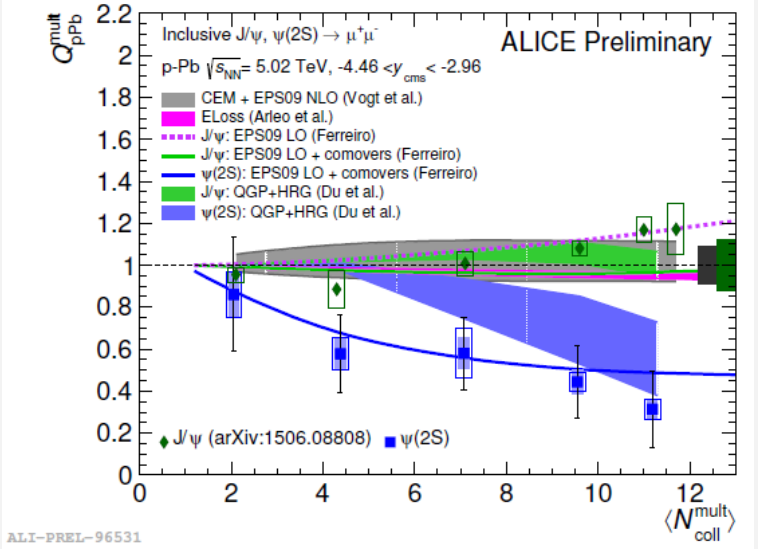
- **Implications**
  - **T_0^{SPS} (~230) < T_{diss}(J/ψ,ϒ') < T_0^{RHIC} (~350) < T_0^{LHC}(~550) ≤ T_{diss}(ϒ)**
  - **confining force screened at RHIC+LHC**
  - diffusing charm quarks recombine at **LHC**

- **Future Developments**
  - couple quarkonium kinetics to HQ diffusion; quantum effects?

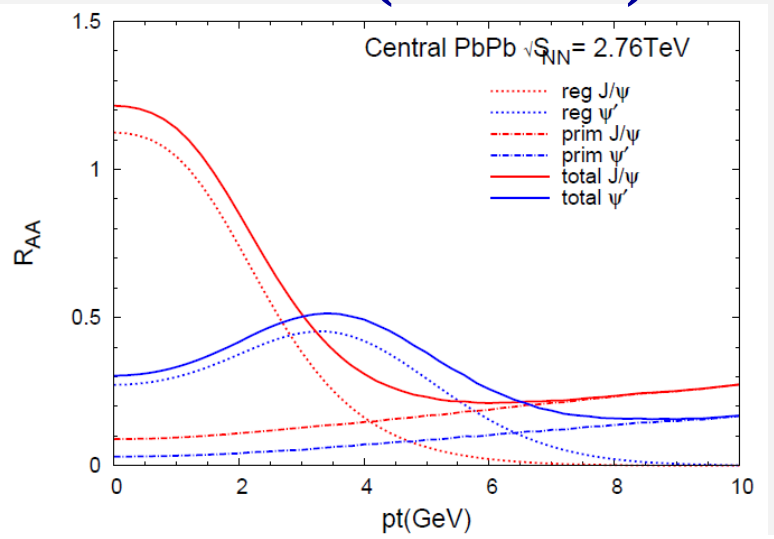
4.2 Charmonia in p/d-A and ψ'/ (J/ψ) Ratio

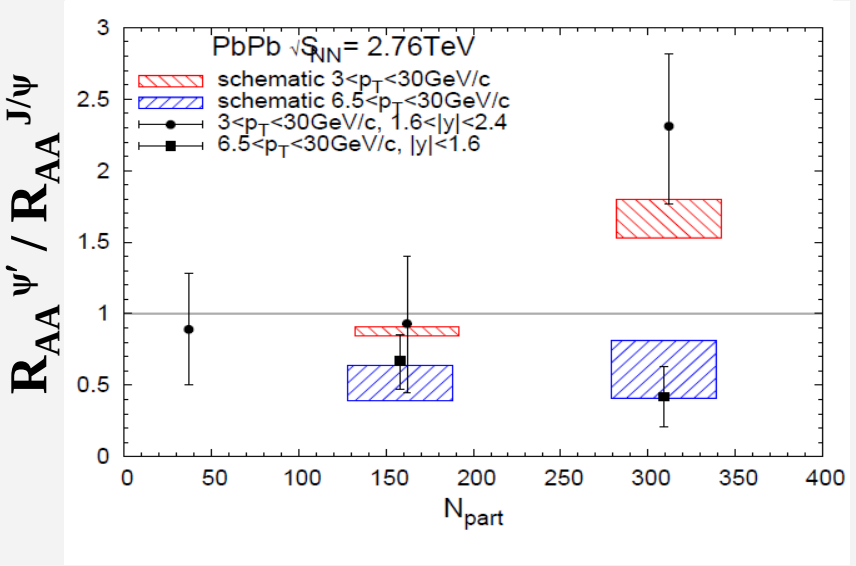
d-Au(0.2TeV) and p-Pb(5TeV)





Pb-Pb(2.76TeV)



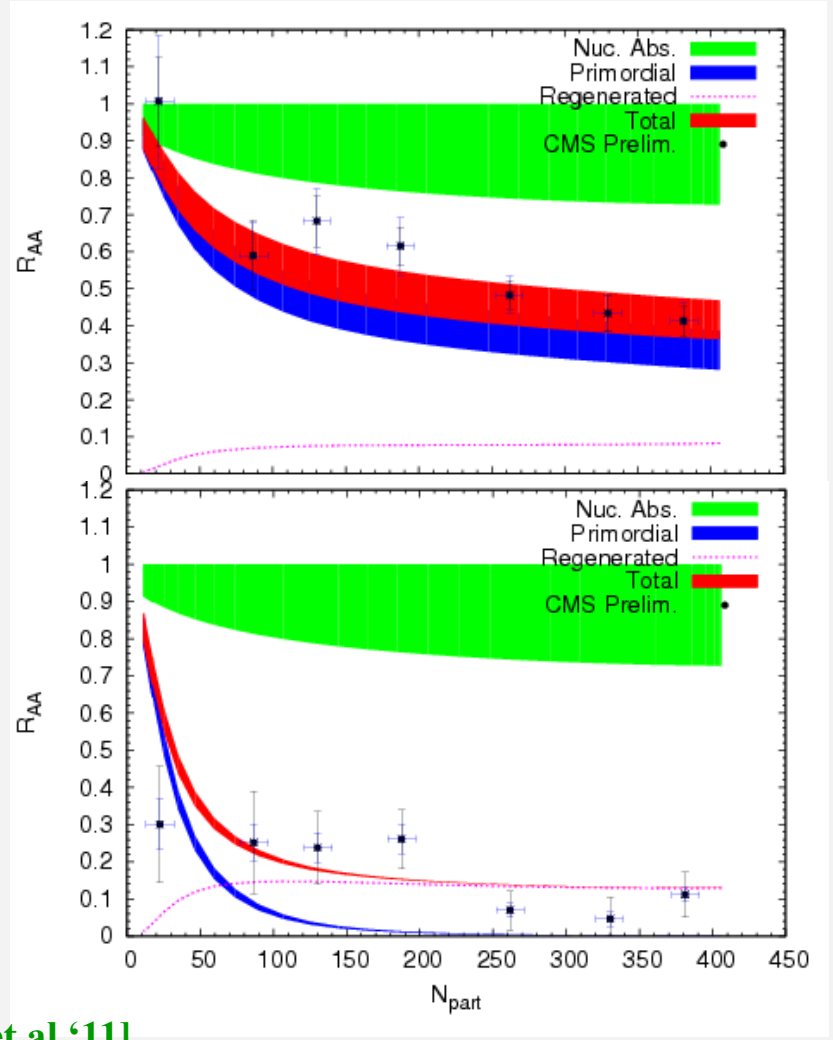


- Hadronic ψ' suppression → regenerated later, with larger flow, than J/ψ

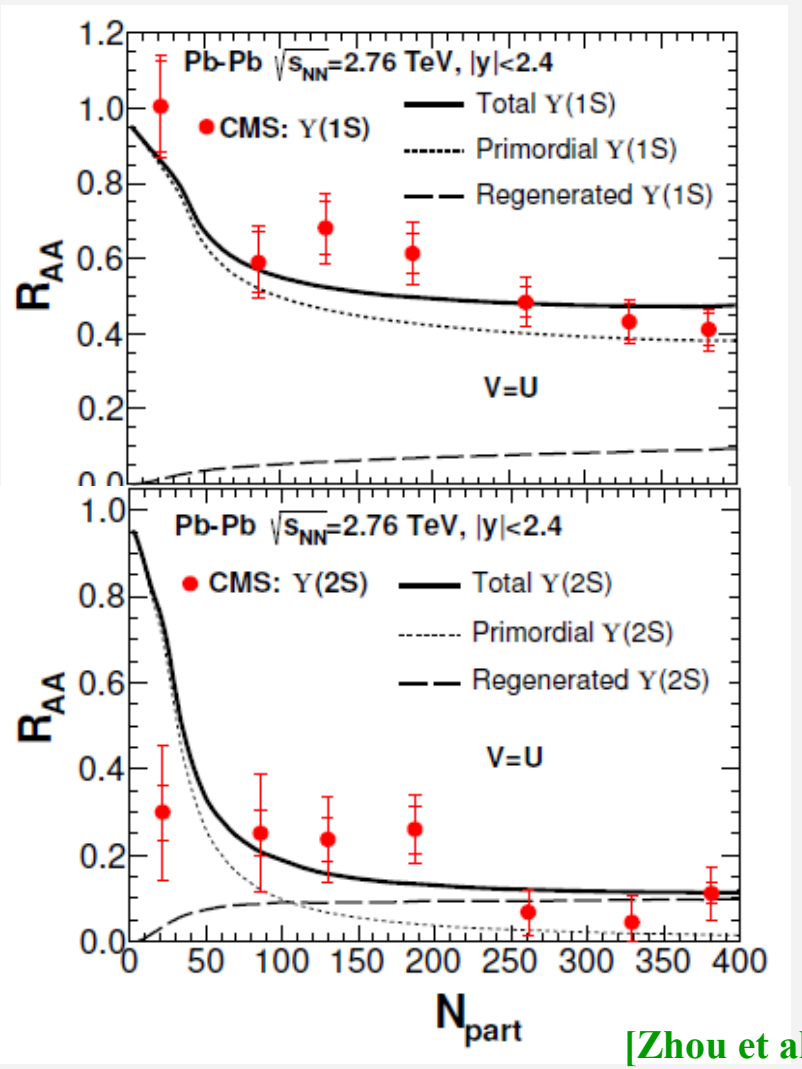
4.3 Υ(1S) and Υ(2S) at LHC

Υ(1S) →

Υ(2S) →



[Emerick et al '11]



[Zhou et al '11,'14]

- sensitive to color-screening + early evolution times
- clear preference for strong binding (**U** potential)
- possible problem in rapidity dependence

5.) Summary

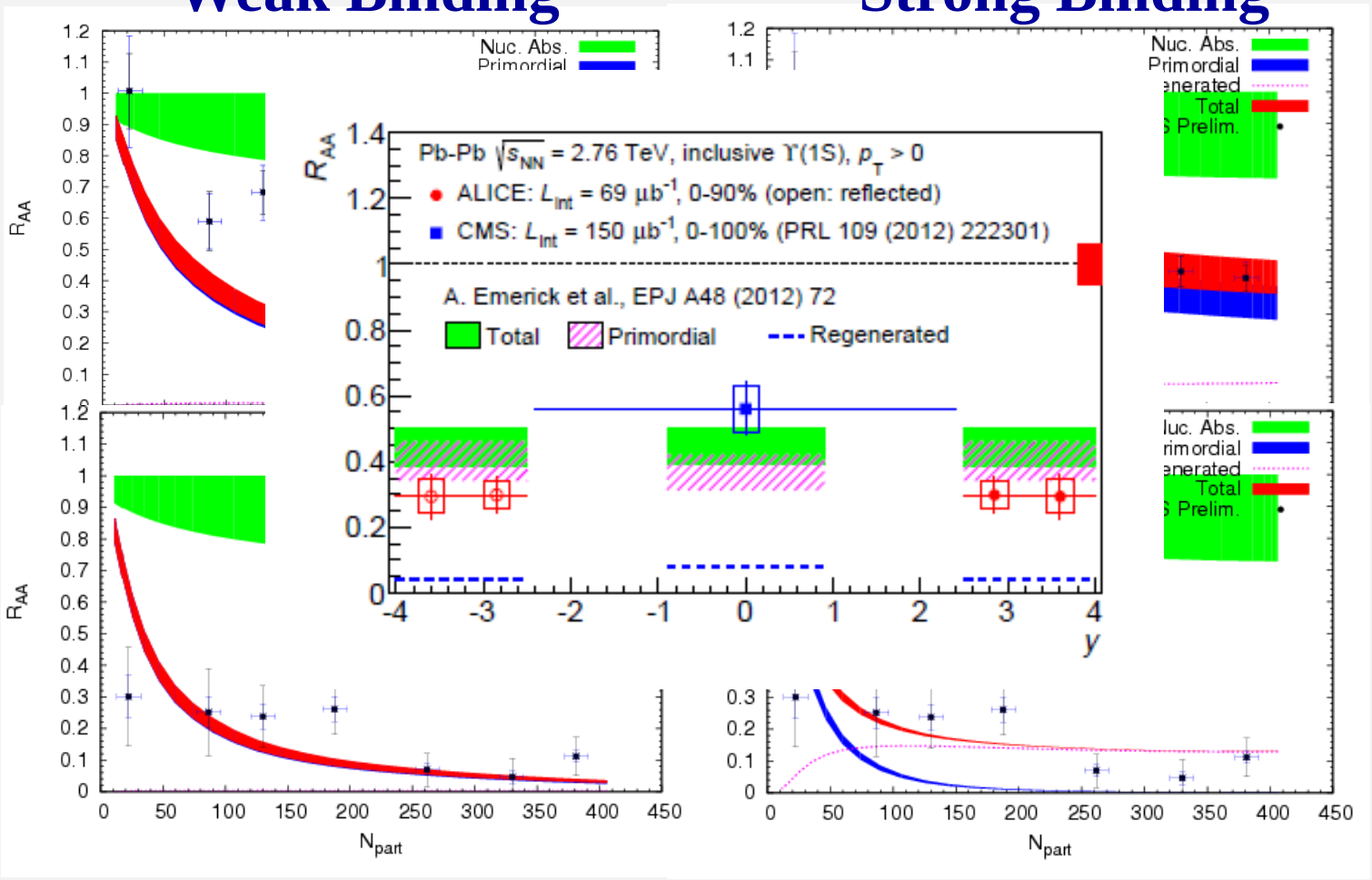
- **Progress in extracting the heavy-quark potential in QGP**
  - **Long-range force → strong coupling, large scattering rates**
  - **No quasi-particles at low p near T_c, re-emerge at higher p, T, M_q**
  - **transition from quark to meson dofs**
- **"Critical" consequences for heavy-flavor diffusion + hadronization**
- **Heavy-flavor phenomenology at RHIC + LHC**
  - **Force properties imprinted on HF R_{AA} and v_2**
  - **Sequential suppression + regeneration of quarkonia**

4.3 Υ(1S) and Υ(2S) at LHC

Weak Binding **Strong Binding**

Υ(1S) →

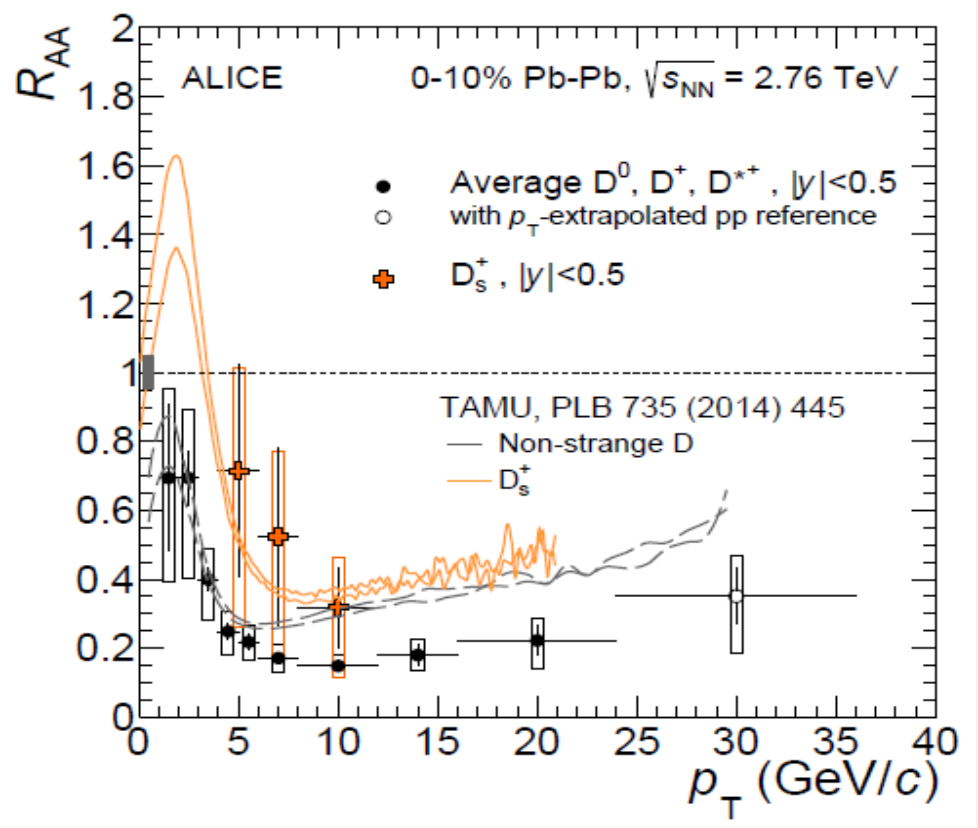
Υ(2S) →

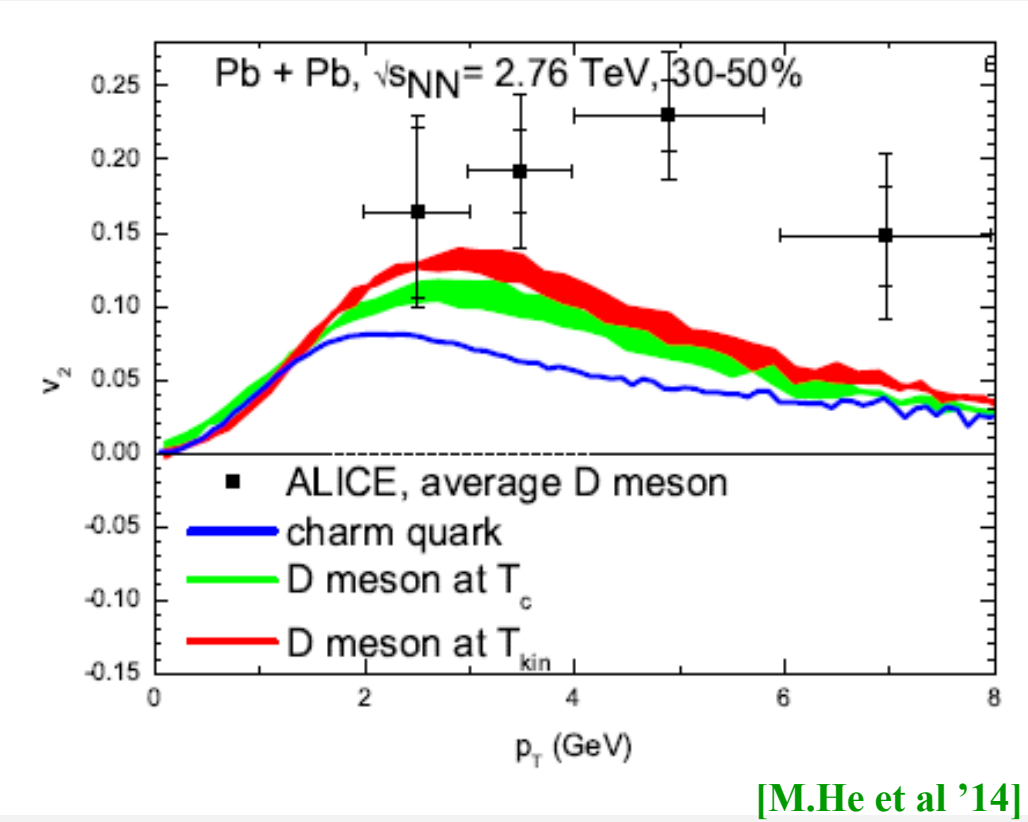


[Grandchamp et al '06, Emerick et al '11]

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

3.6 Charm Transport at LHC: D-Meson Spectra



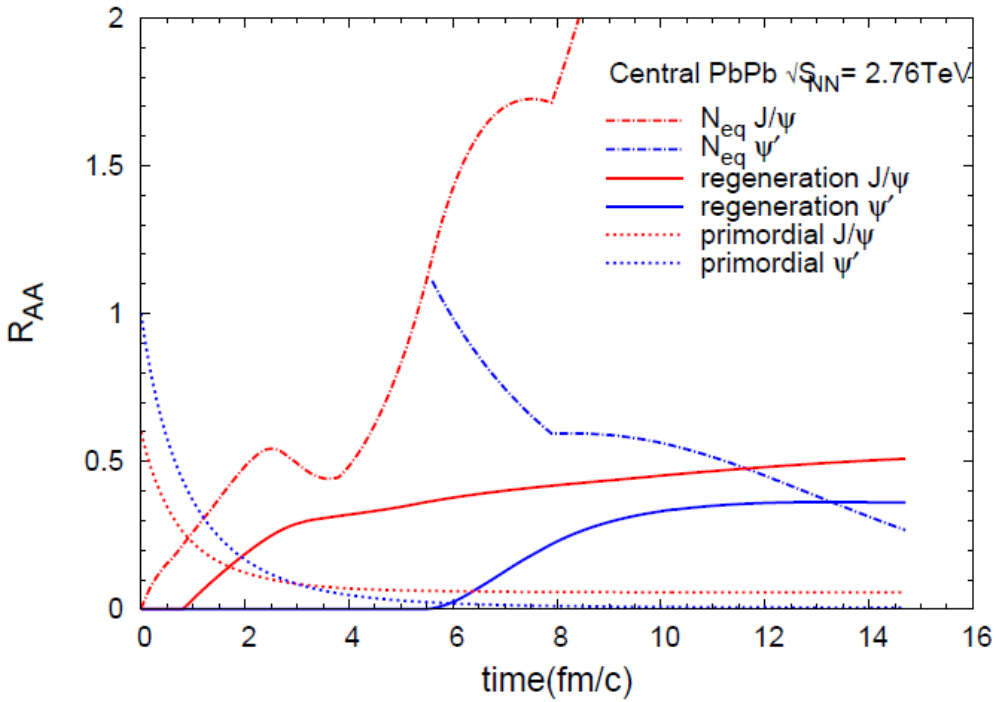


[M.He et al '14]

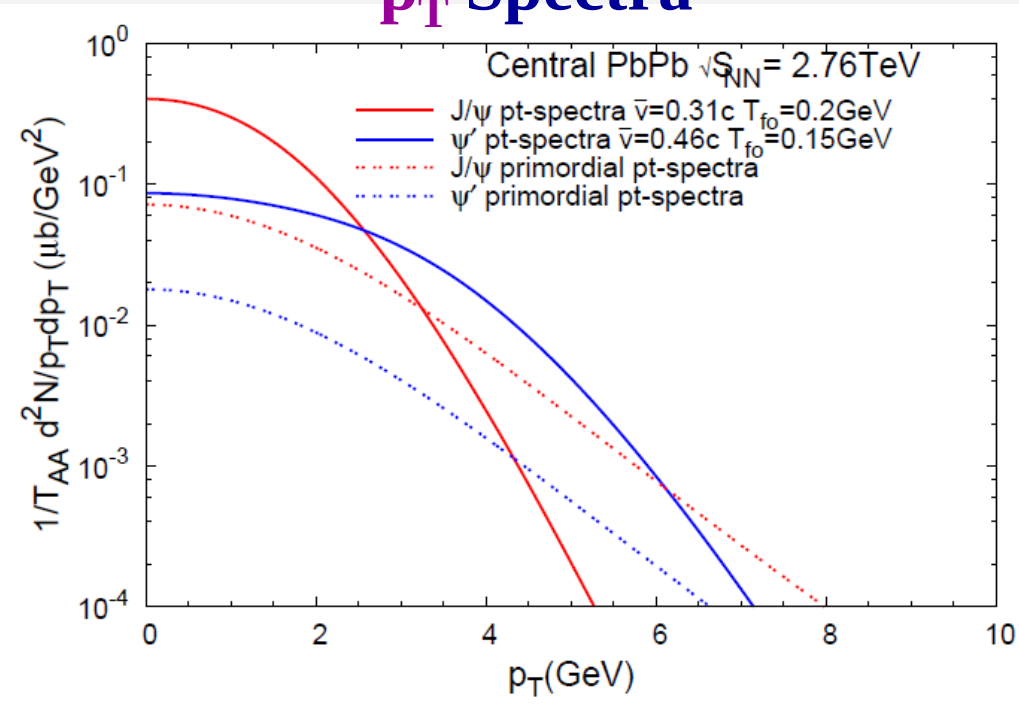
- R_{AA} "bump" from radial flow
- D_s meson (**cs**) enhanced from coalescence with strange quarks
- Coalescence + hadronic diffusion increase v_2
- similar features at **RHIC**

4.3 Sequential Recombination of Charmonia in AA

Time Evolution



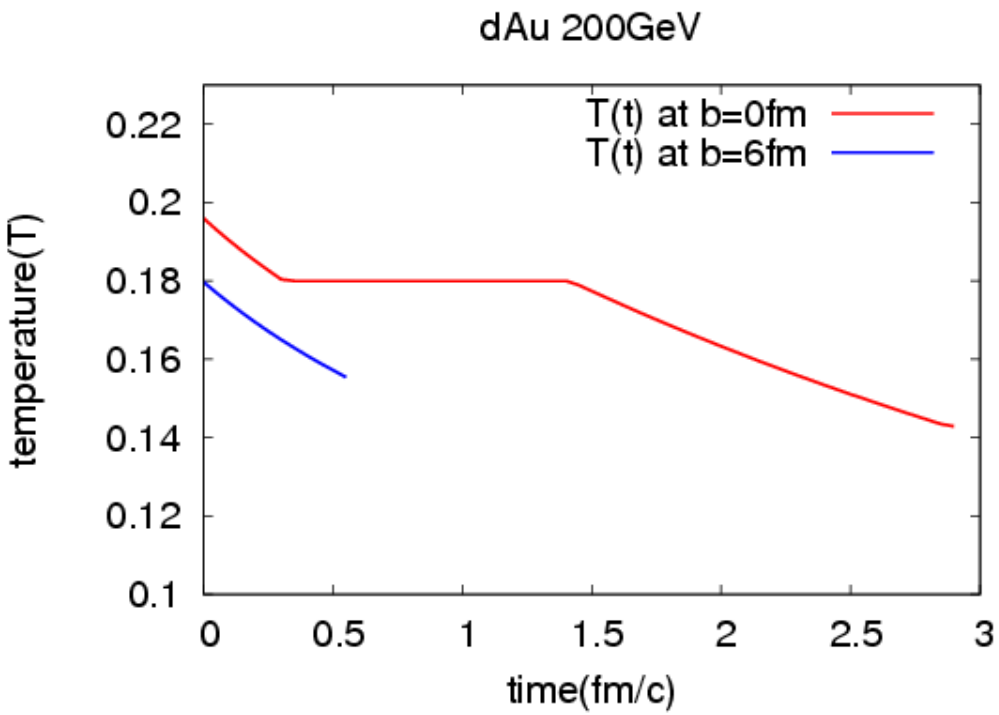
p_T Spectra

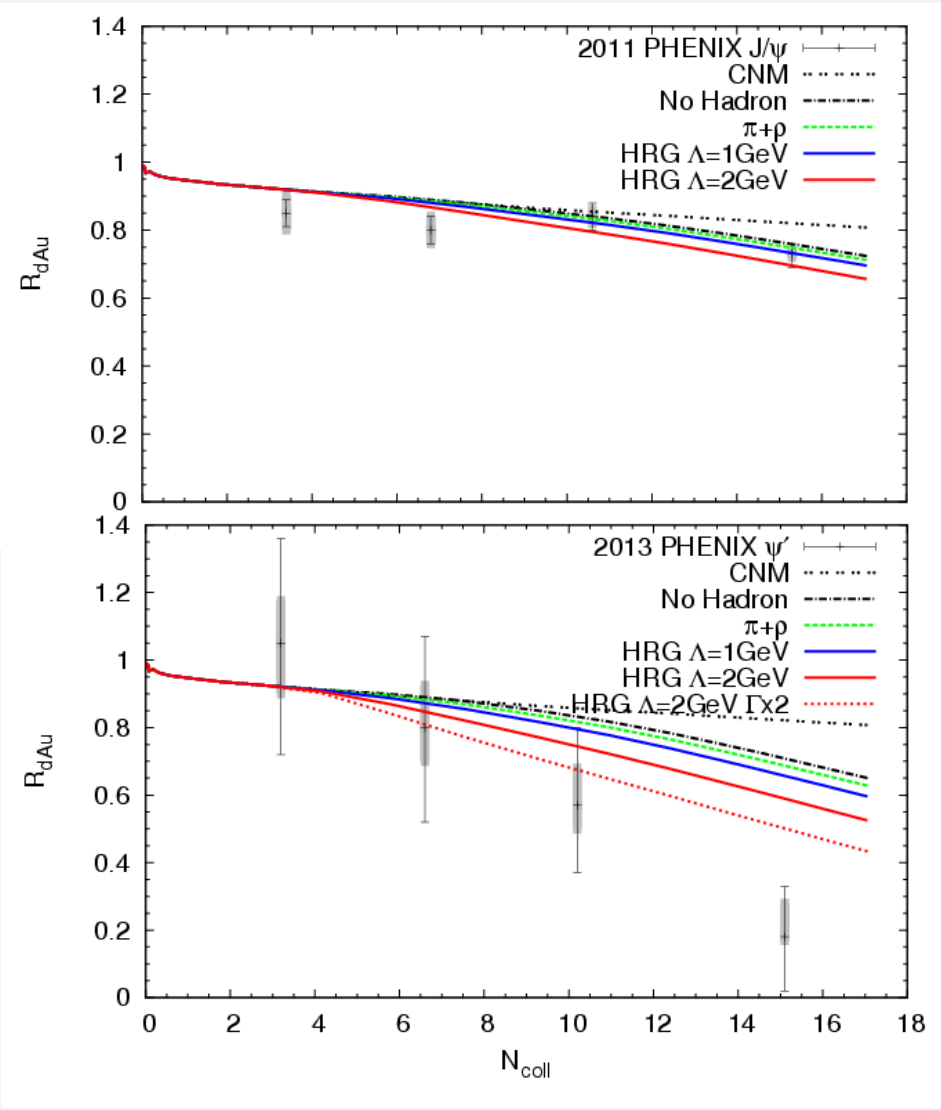


- **smaller binding** → smaller T_{diss} → ψ′ forms later than **J/ψ** !
- **stronger blast wave** for ψ′ formed at later times (**hadronic phase!**)

[X.Du+RR '15]

4.2 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]