Quarkonia at High-Luminosity LHC:

Can we determine the in-medium QCD force?

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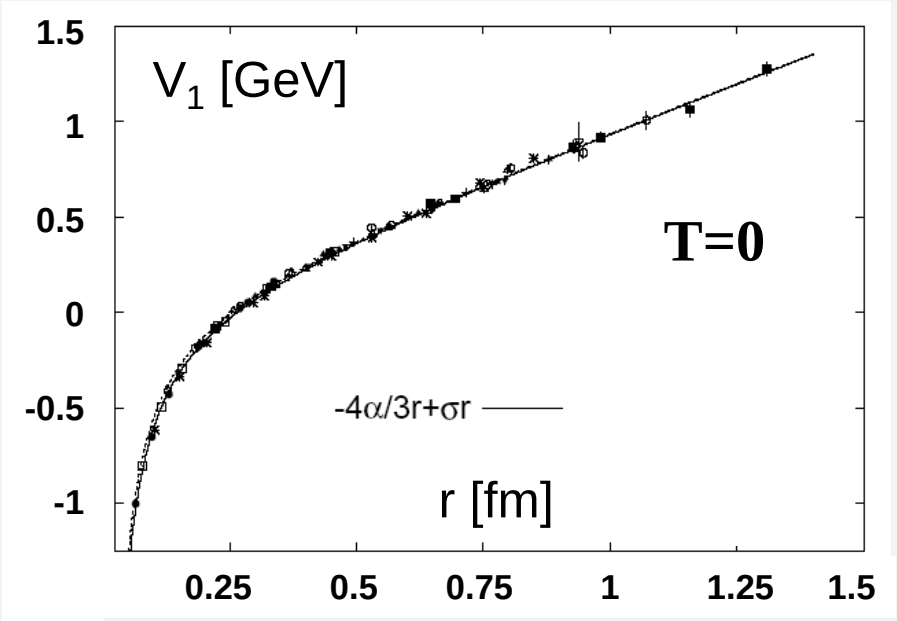
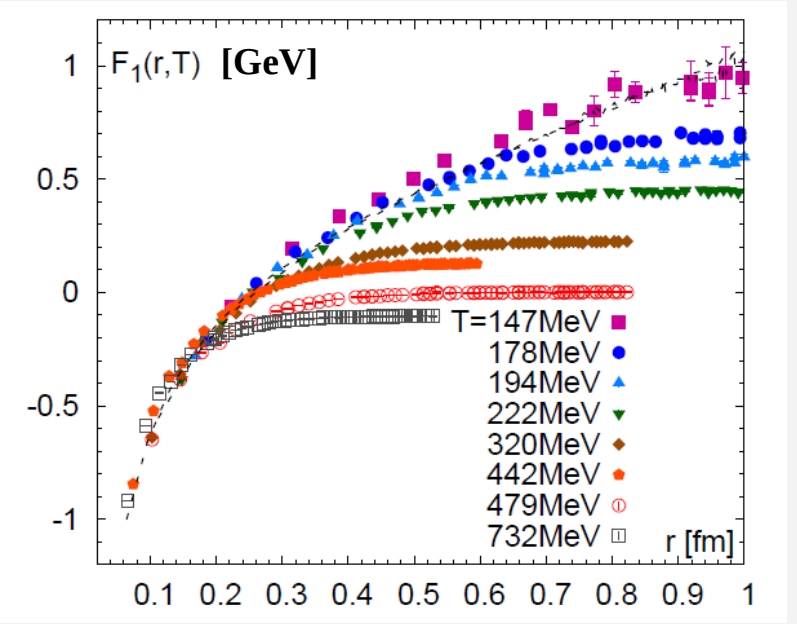
General WG-5 Heavy-Ion Meeting

CERN (Geneva, Switzerland), June 18-20, 2018

1.) Introduction: A "Calibrated" QCD Force





[Bazavov et al '13]

- Vacuum quarkonium spectroscopy well described
- Confinement ↔ **linear part of potential**

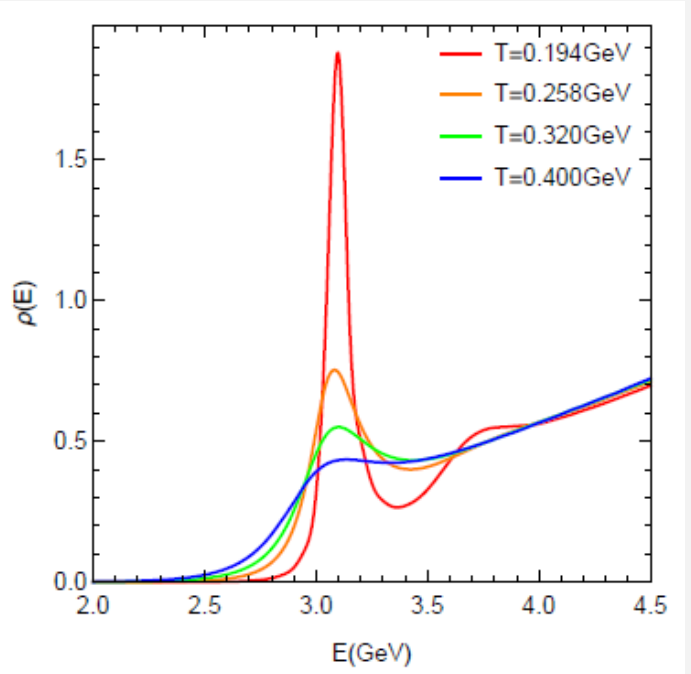
Opportunity: Utilize quarkonia to probe in-medium QCD force

↔ infer consequences for transport coeffs. + spectral functs.

↔ probe QGP properties at varying resolution

1.2 Quarkonia in Medium

- In-medium **spectral functions**:
  - Mass / binding energy $E_B(p,T)$
  - Inelastic reaction rate $\Gamma_{in}(p,T,E_B)$
- Remnant of confining force above T_{pc}
- **Υ(1S): color-Coulomb** (E_B=1.1GeV)
  J/ψ, Υ(2S,3S): confining force (0.6-0.2)
  ψ(2S): barely bound (<0.1)

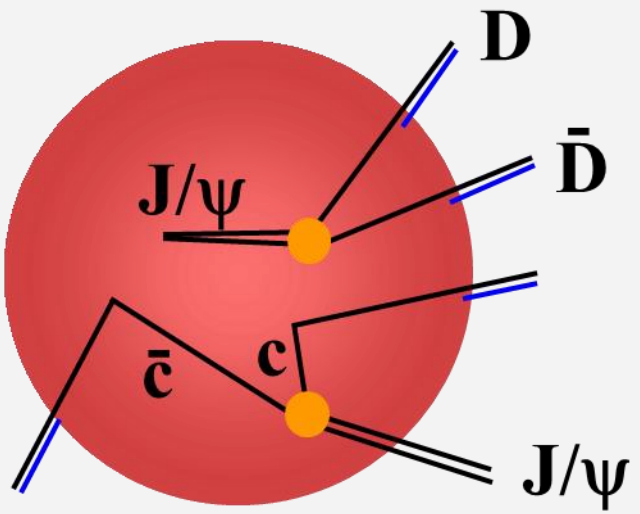


Objective:

Utilize production systematics of the different states to probe the in-medium QCD force
(not a good thermometer …)

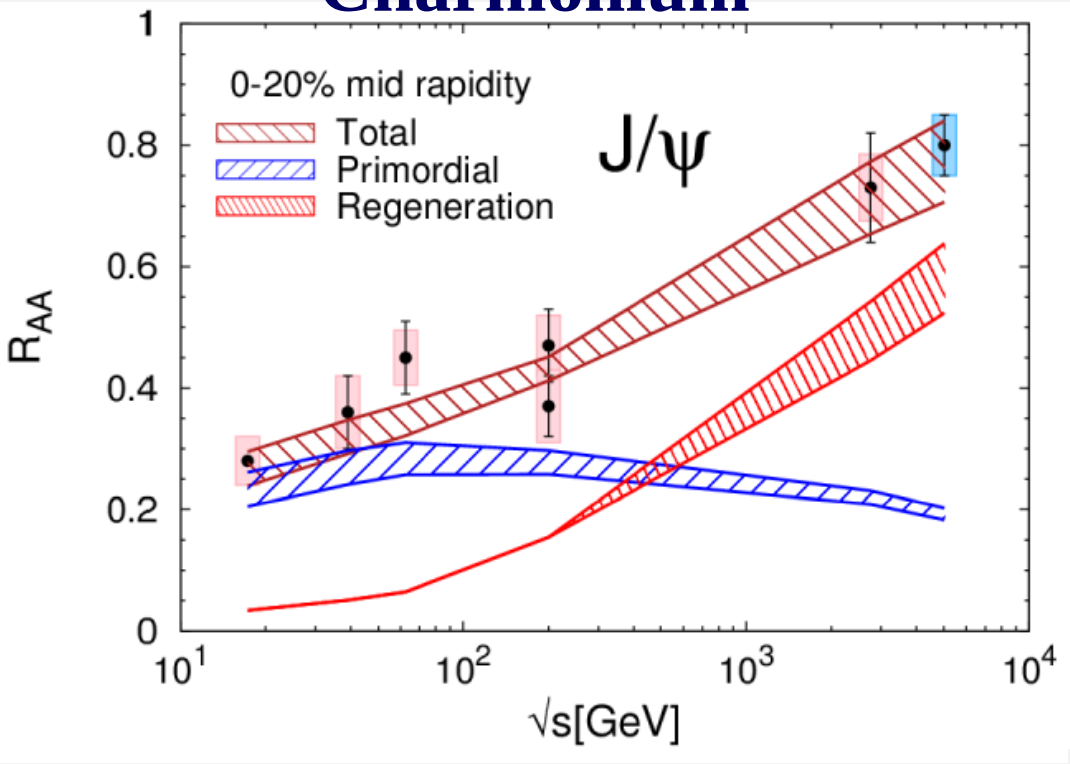
Tool:

Observables sensitive to production "time"

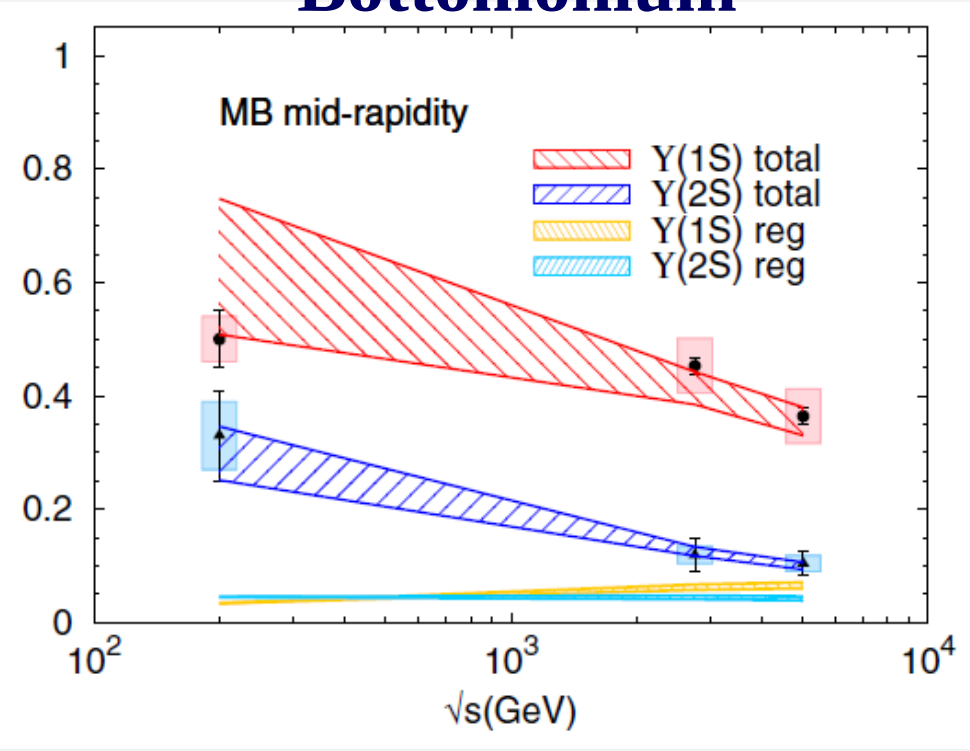


1.3 Excitation Functions in AuAu / PbPb

Charmonium



Bottomonium



- Gradual **increase** of total **J/ψ** R_{AA}
- Regeneration **and** suppression increase
- Regeneration concentrated at low p_T!

- Gradual **suppression**
- Regeneration (N_Υ^{eq}) small
- Qualitative difference from **J/ψ**

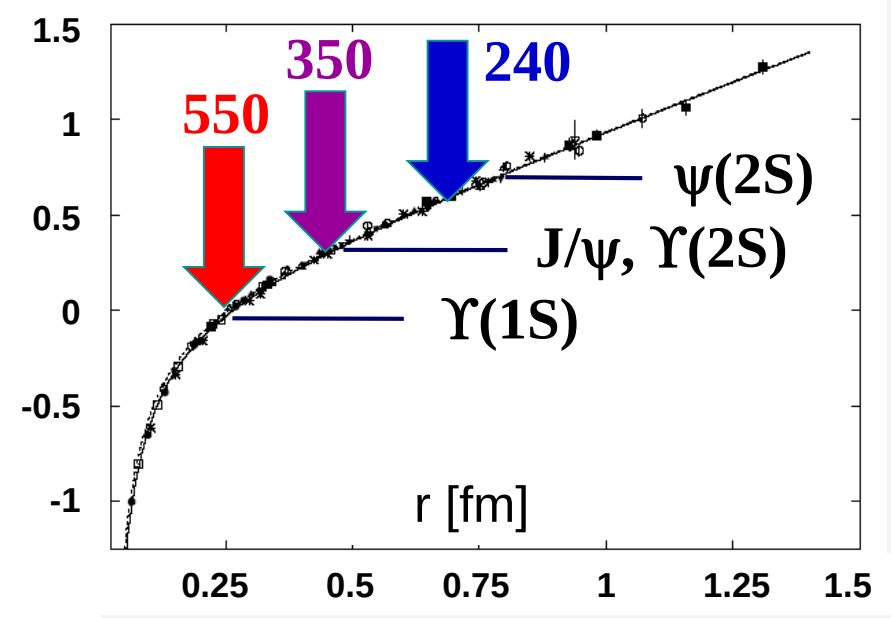
[**data**: **NA50, PHENIX, STAR, ALICE, CMS**]

1.4 Current Quarkonium Phenomenology

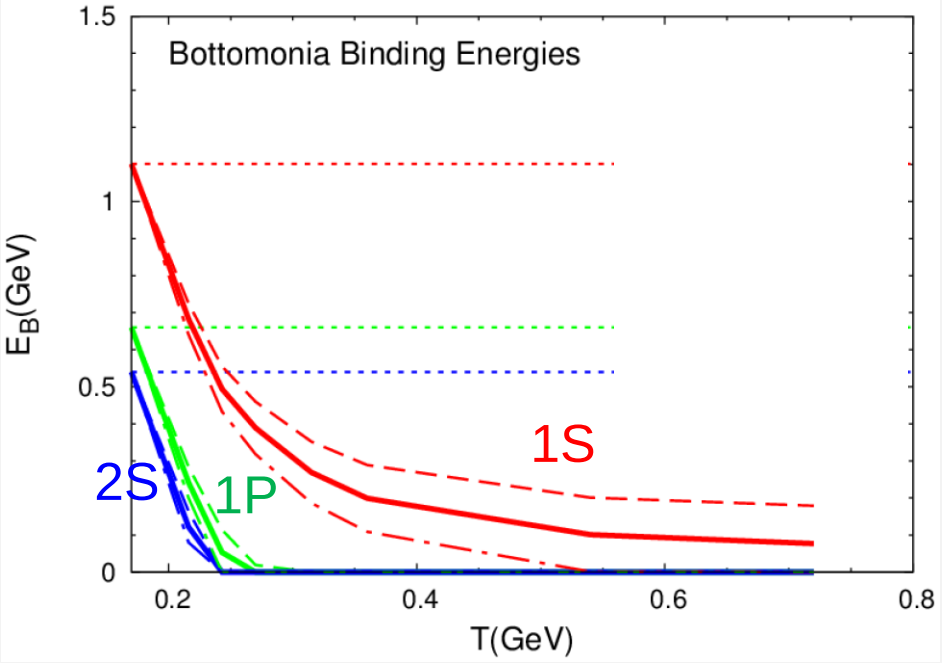
Use temperature estimates from hydro/photons/dileptons to infer:

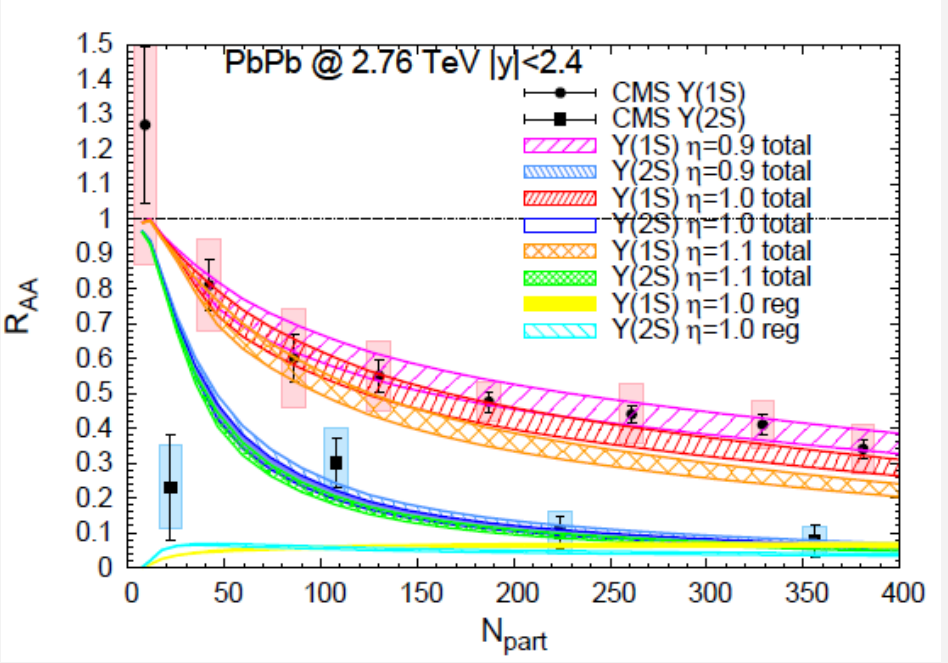
$$T_{melt}(\psi') < T^{SPS}(\sim 240) < T_{melt}(J/\psi, \Upsilon') \leq T^{RHIC}(\sim 350) < T_{melt}(\Upsilon) \leq T^{LHC}(\sim 550)$$

- **Remnants of confining force survive at SPS** [melt ψ', J/ψ intact]
- **Confining force screened at RHIC+LHC** [melt J/ψ + Υ']
- **Color-Coulomb screening at LHC** [Υ(1S) suppression]
- **Thermalizing charm quarks recombine at LHC** [large J/ψ yield]



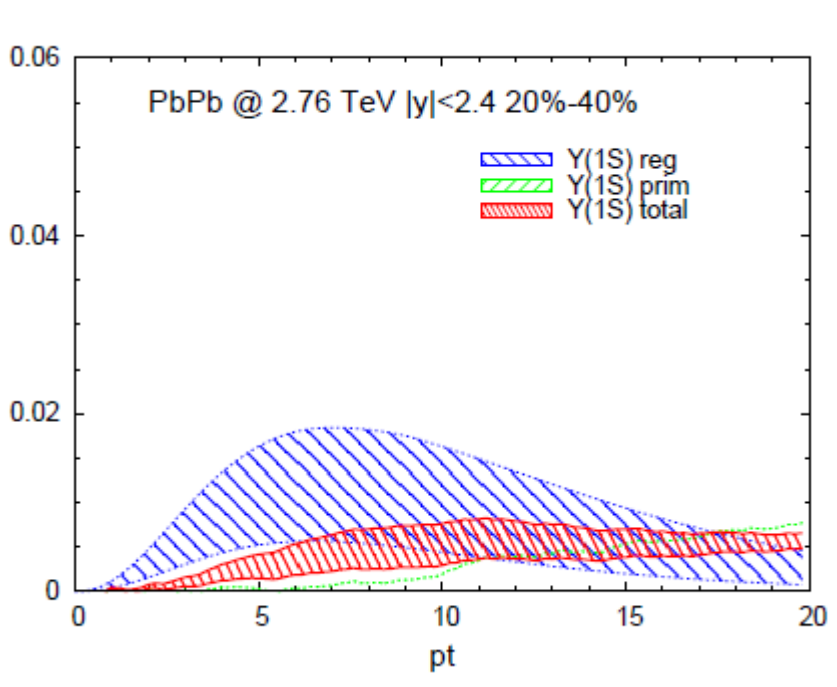
2.1 Sensitivity of R_{AA} to Binding Energies

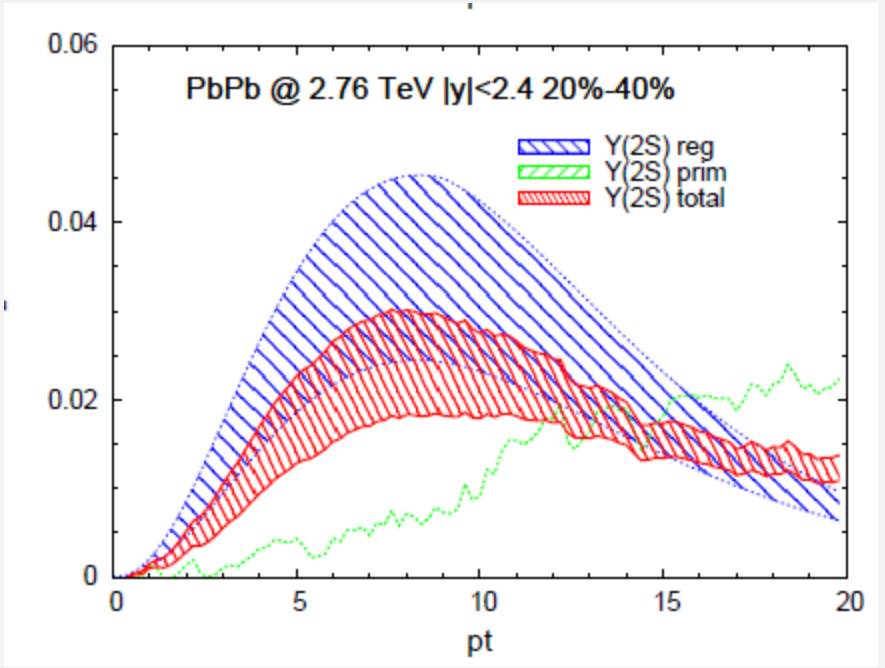




- **ϒ(1S)** suppression can discriminate melting scenarios,
  need good control over auxiliary model components (bulk, CNM,...)
- **ϒ(2S,3S)**: smaller systems, **p+Pb, Ar+Ar**? or …

2.2 ϒ Elliptic Flow

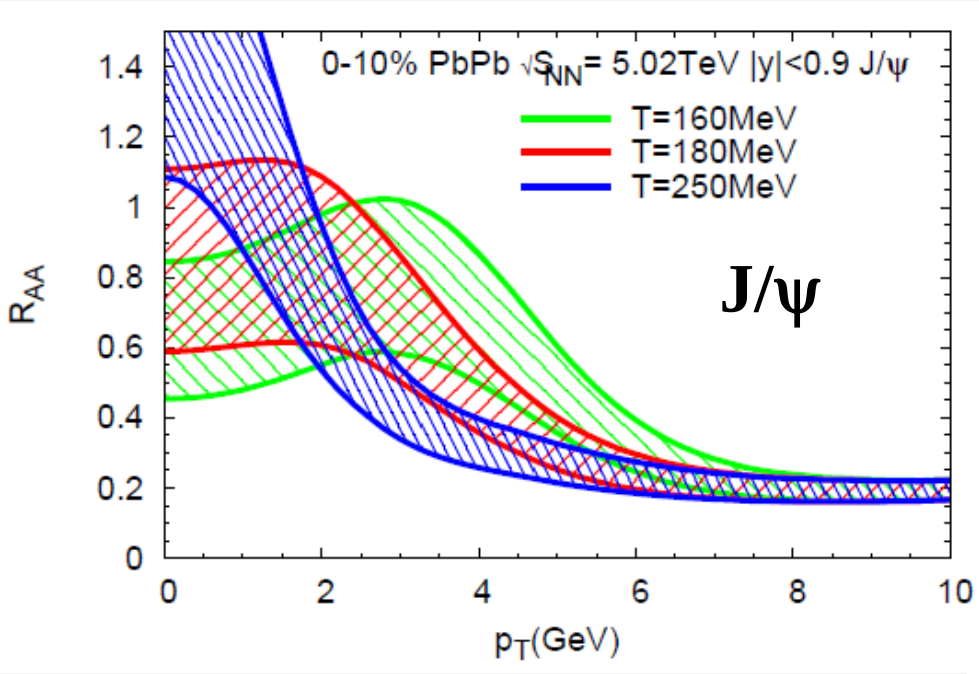


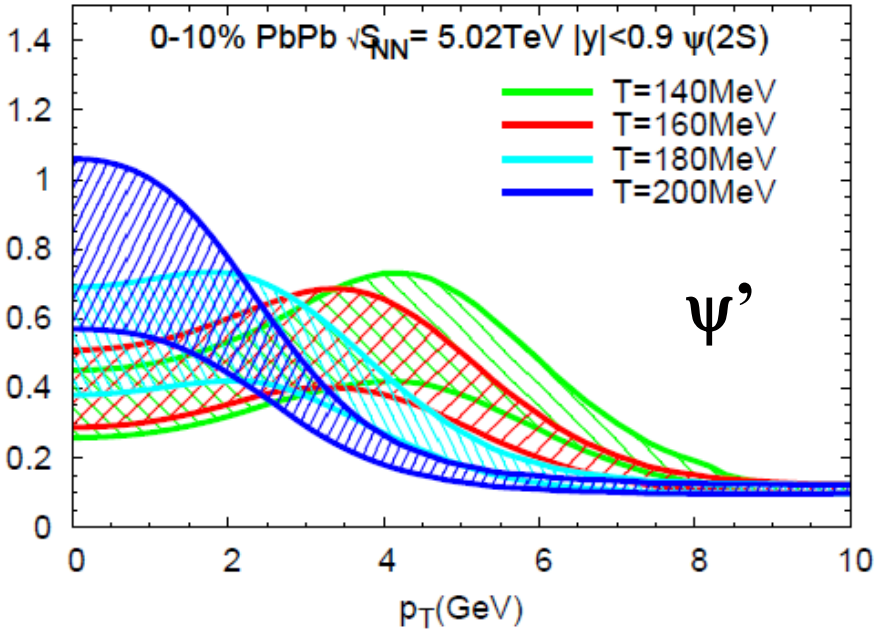


- Directly reflects production/suppression time!

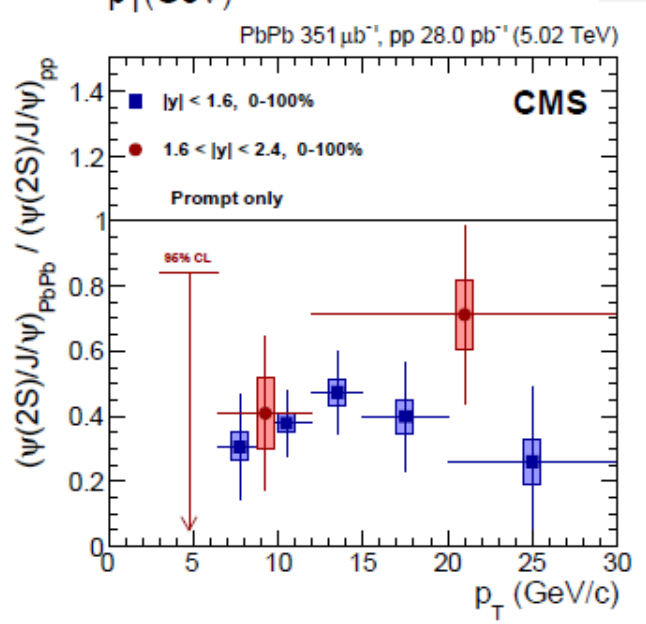
  ϒ(1S): early , ϒ(2S): late(r)

2.3 Charmonia: Production Time + "Flow Bump"





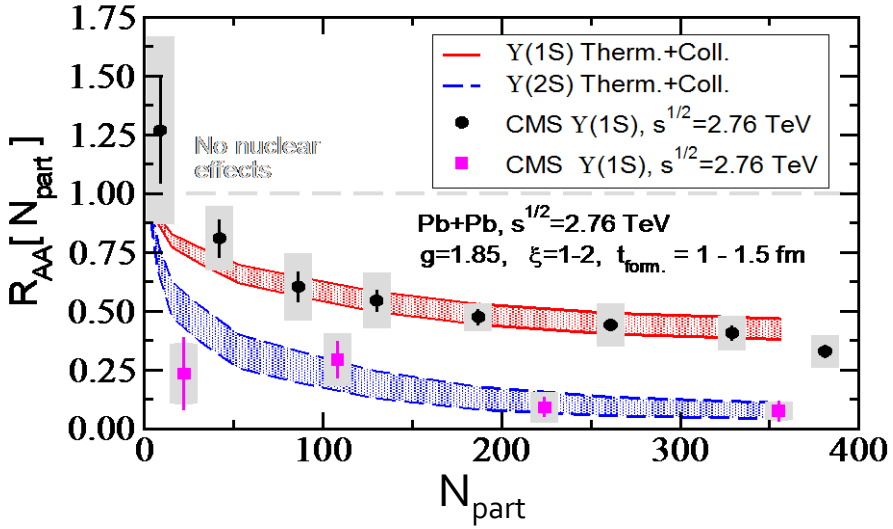
- Need **low-p_T R_{AA}** data to discriminate
- Sequential regeneration?!
- Recall double ratio of **CMS**…
- Similarly for v_2 (**pPb** puzzle?)

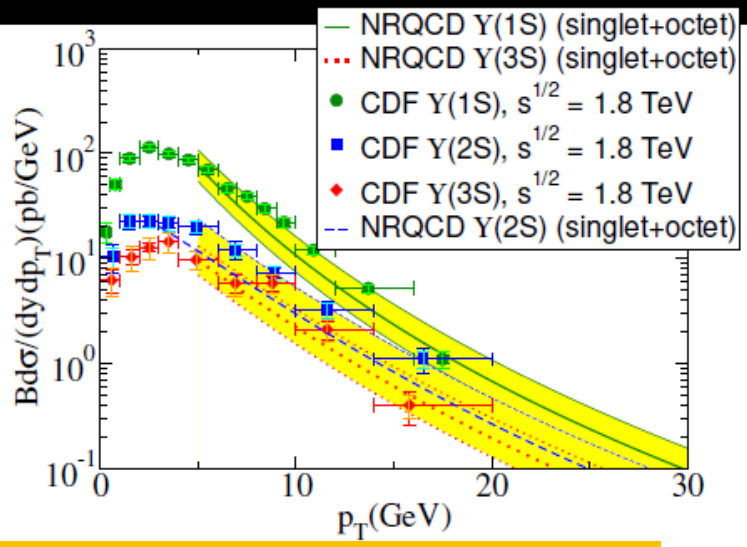


2.4 NRQCD-based quarkonium dissociation theory

S. Aronson, I. Vitev *et al.* (2017)

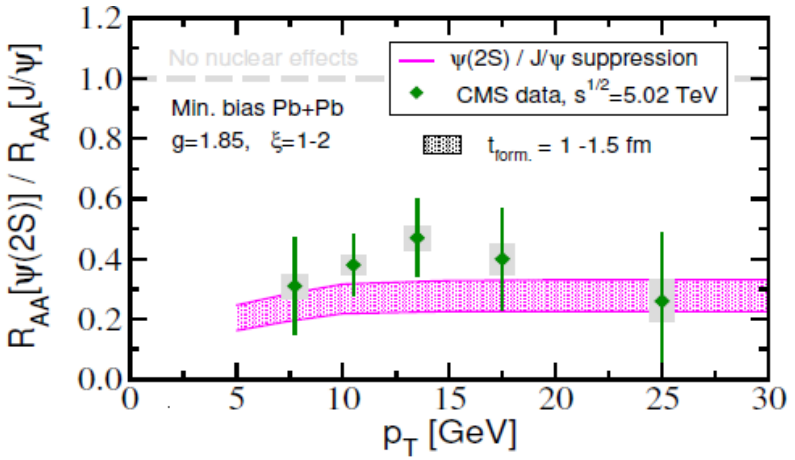
- NRQCD input cross sections
- Importance of p_T-differential feed-down
- Different states modified differently in the QGP





- Handle on thermal and collisional dissociation processes

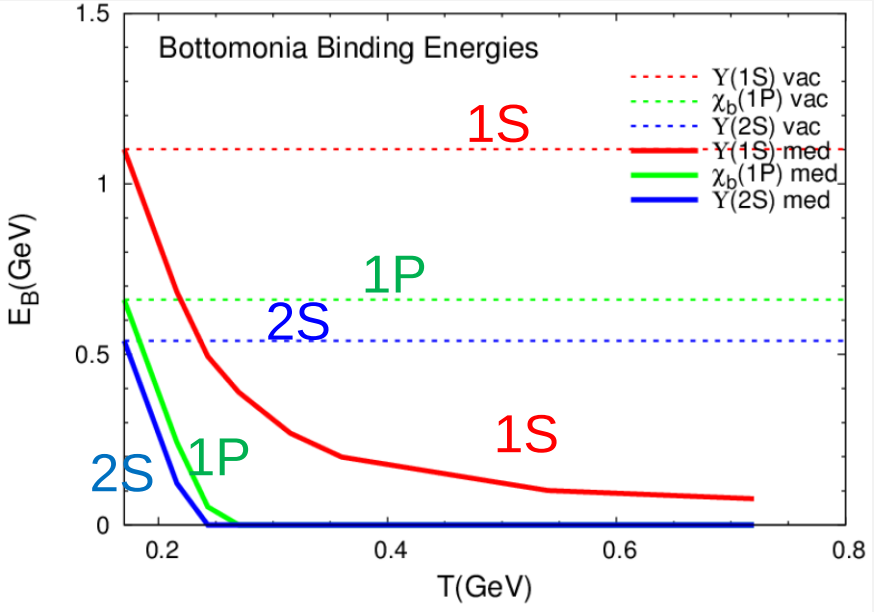
- Simultaneous description of ground and excited J/ψ and Υ states;
- Importance of high-p_T measurements
- Also constrain energy loss mechanisms

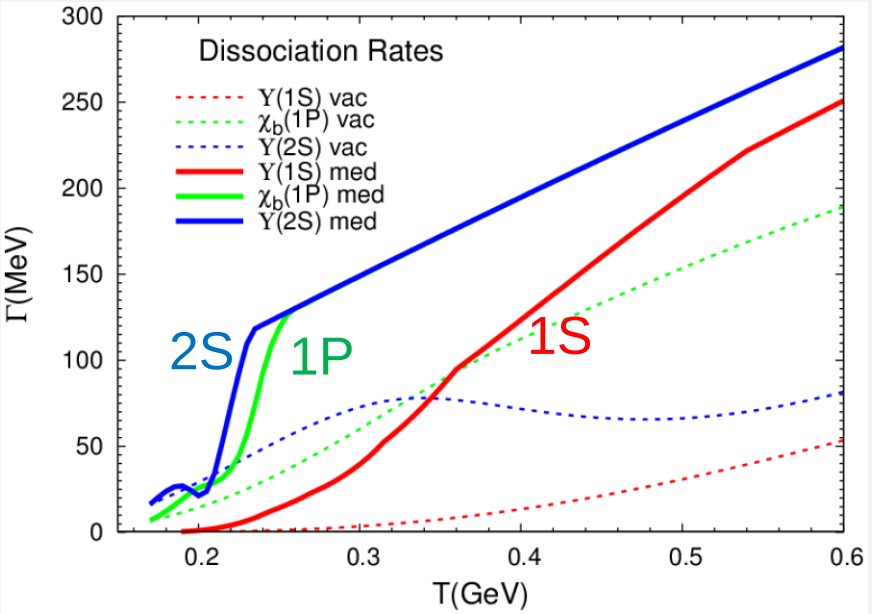


3.) Summary

- Heavy quarkonia: hard production but **soft medium probe**
- Unique opportunity to unravel **in-medium QCD** force via in-medium "spectroscopy" (i.e. production/suppression of different states)
- $\mathbf{p_T}$ spectra + $\mathbf{v_2}$ provide sensitive tests of **temperature profile** of both regeneration (Ψ) and dissociation (Υ)
- Dissociation/regeneration rates closely related to individual **heavy-quark** reaction rates ($\leftrightarrow$ open-HF phenomenology; charm Xsec!)
- Systematic studies of model dependences

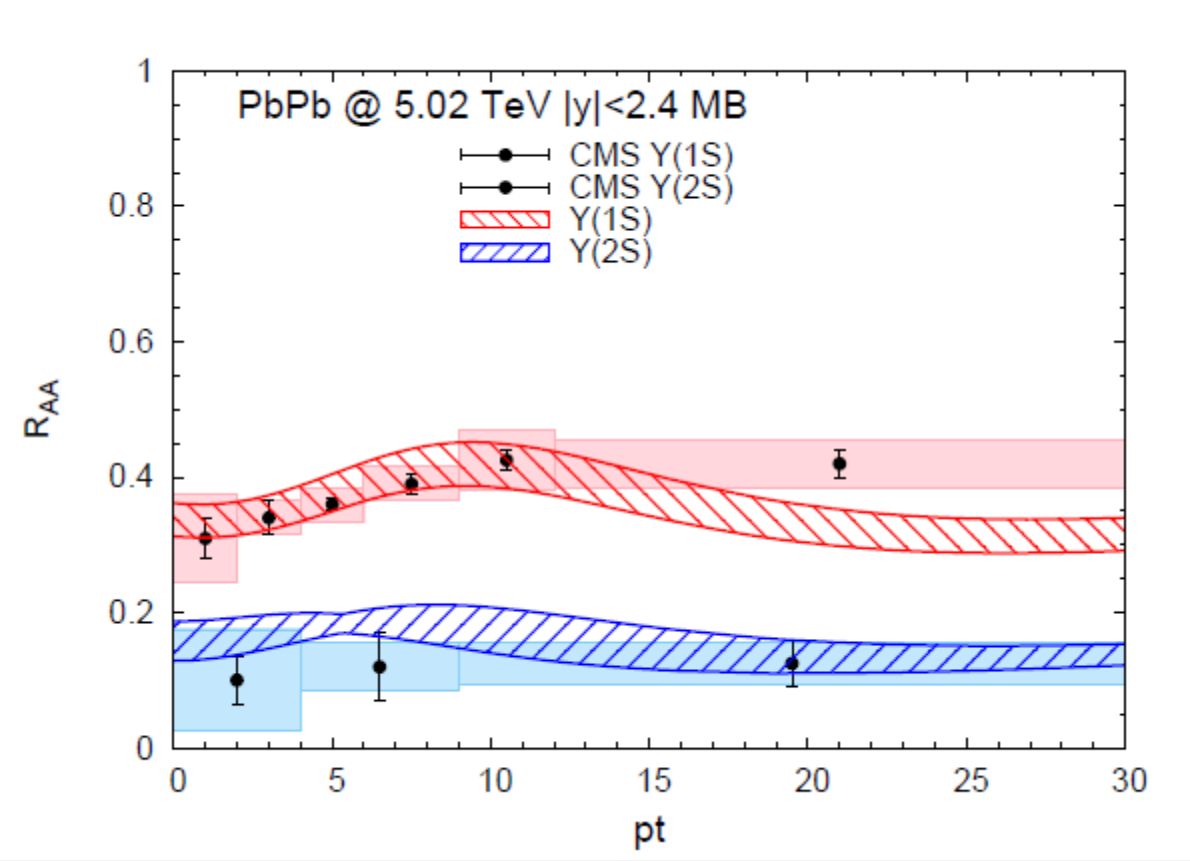
3.1 Binding Energies + Reaction Rates: Υ States





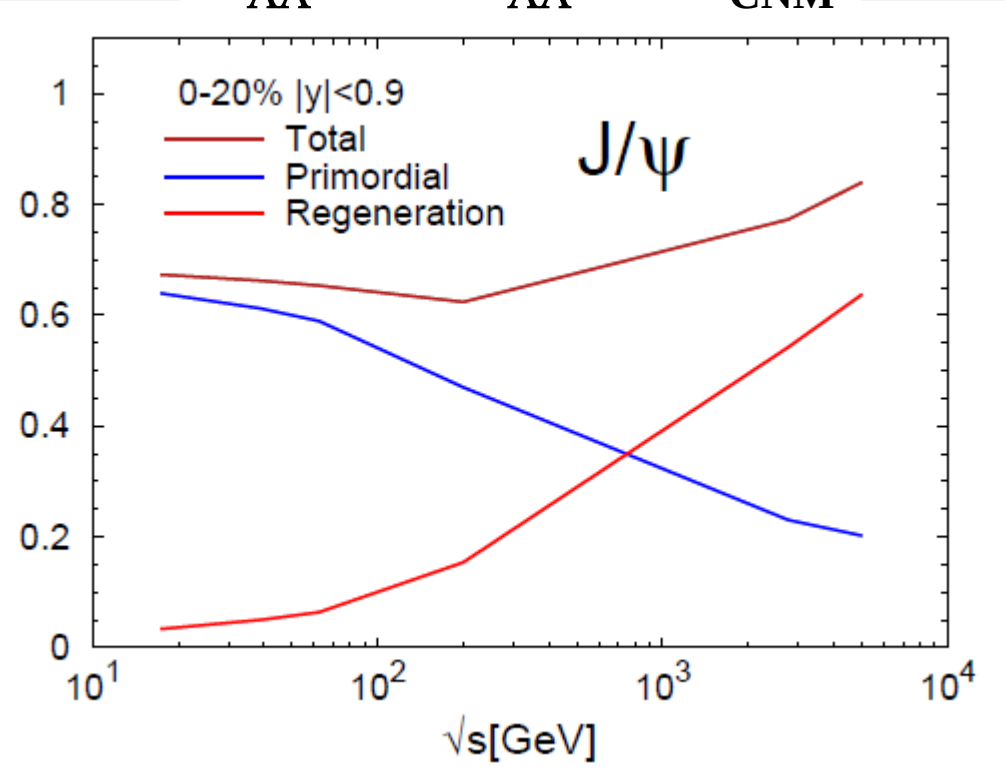
- Reduced binding "accelerates" dissociation ($\Gamma_\Upsilon(E_B=0) = 2\Gamma_b$)
- Localizes dissociation temperatures (centrality dependence!)
- Same rate for regeneration – experimental signatures of production time?

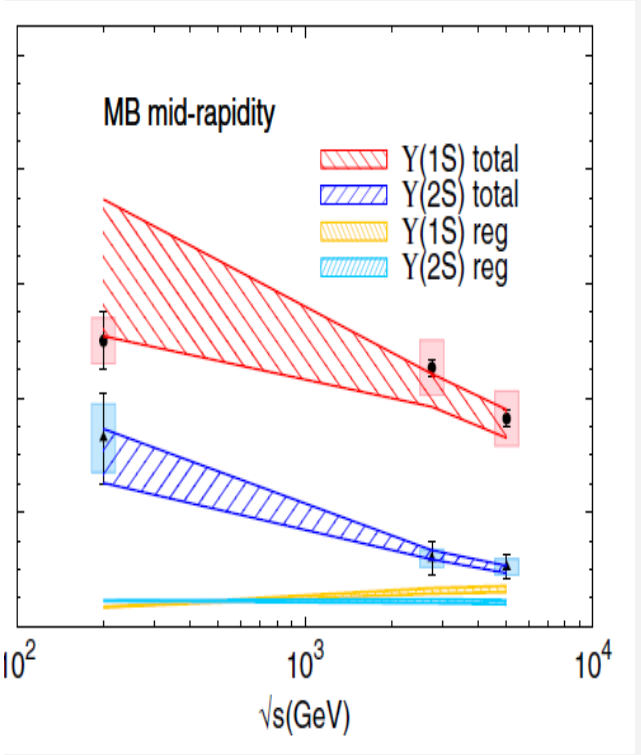
4.5 ϒ p_t Spectra in Pb-Pb(5.02TeV)



4.1 Divide out Cold-Nuclear-Matter Effects

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

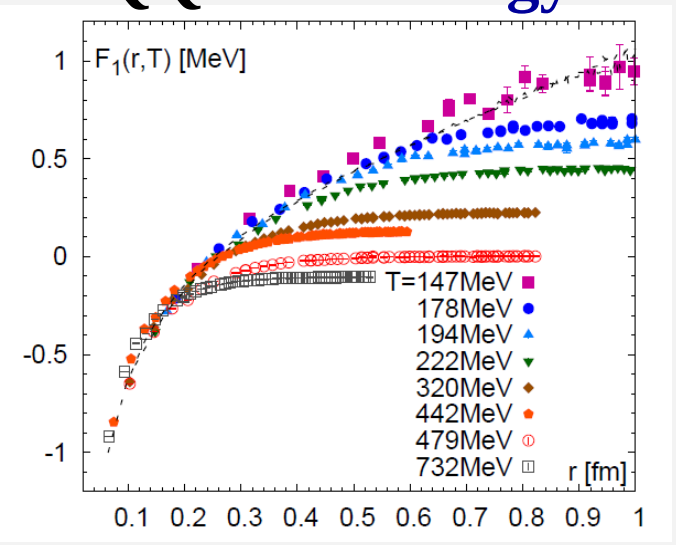




- **J/ψ** suppression at **SPS** mostly from feeddown ($\sigma_{\psi N}$ **~7.5mb**), melts in the **RHIC → LHC** regime (not unlike **ϒ(2S)**)

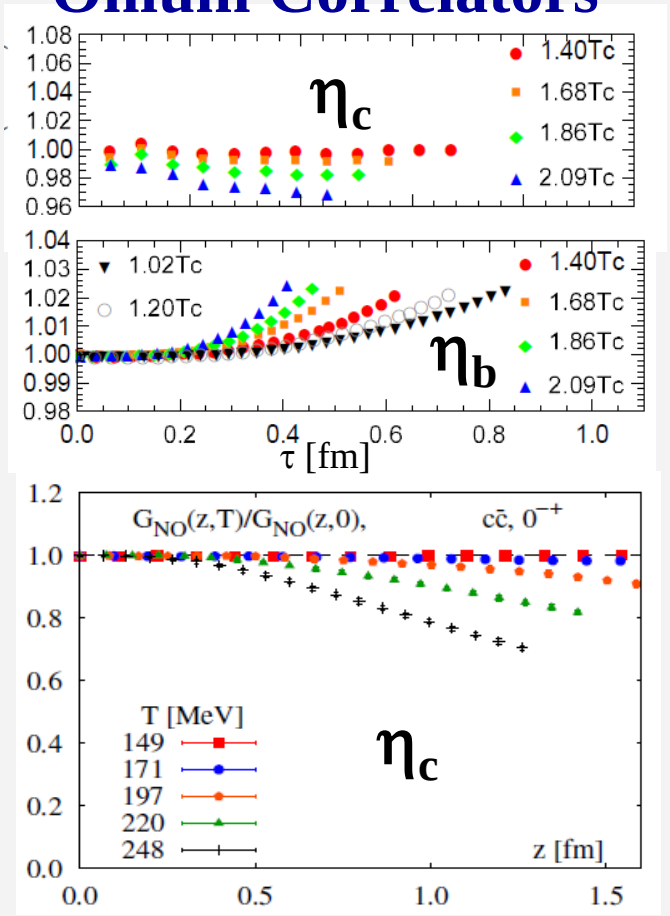
1.2 Heavy Quark/onia on the Lattice

$Q\bar{Q}$ Free Energy



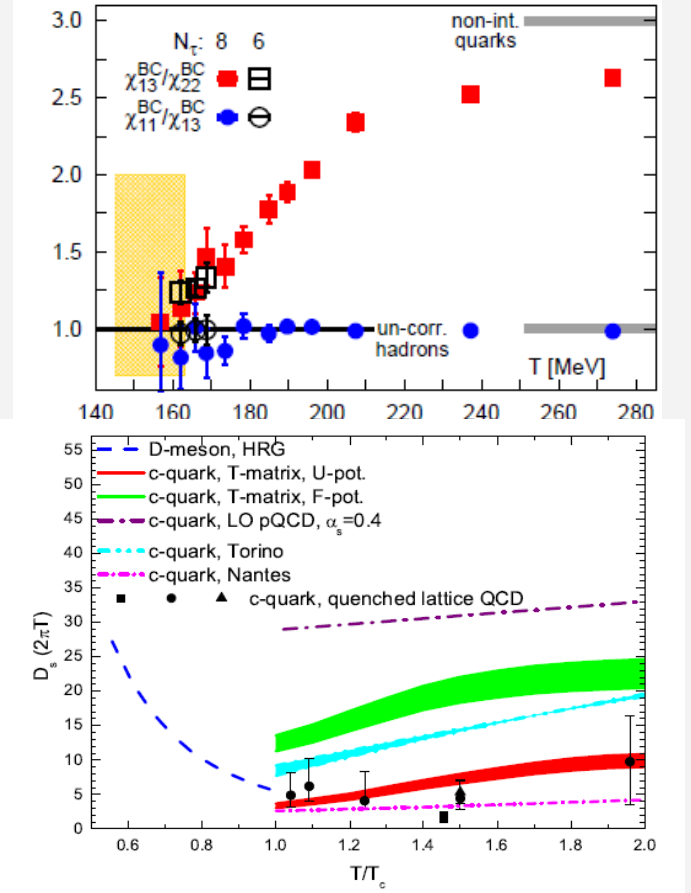
Heavy-quark potential

Onium Correlators



Energy + 3-mom. dep. of Ψ + Υ spectral fcts.

Quark Suscept./Diffusion

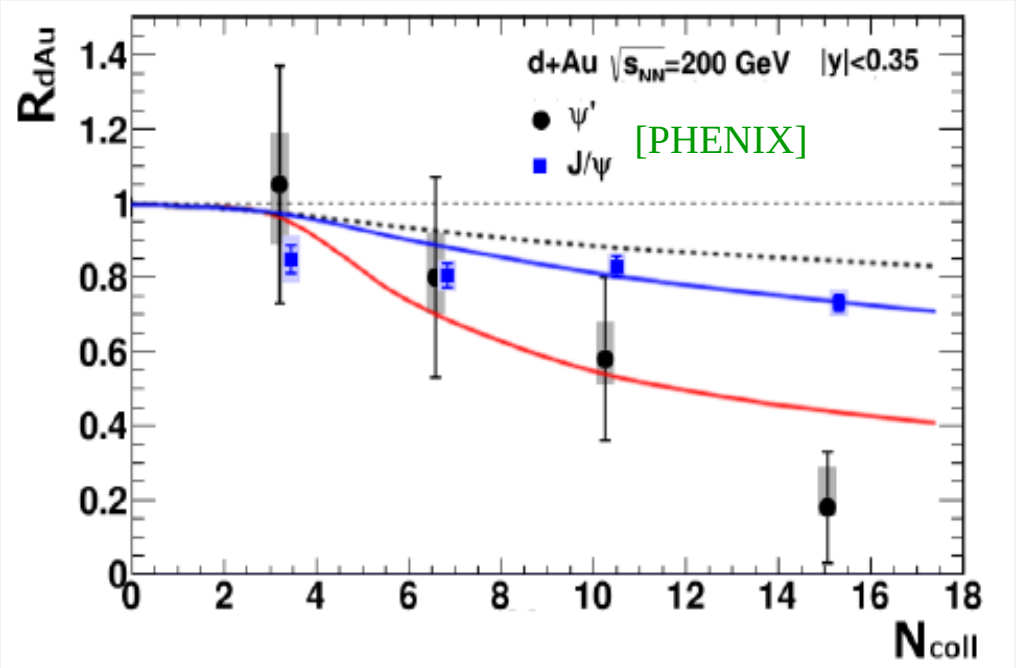


Individual heavy quarks in QGP

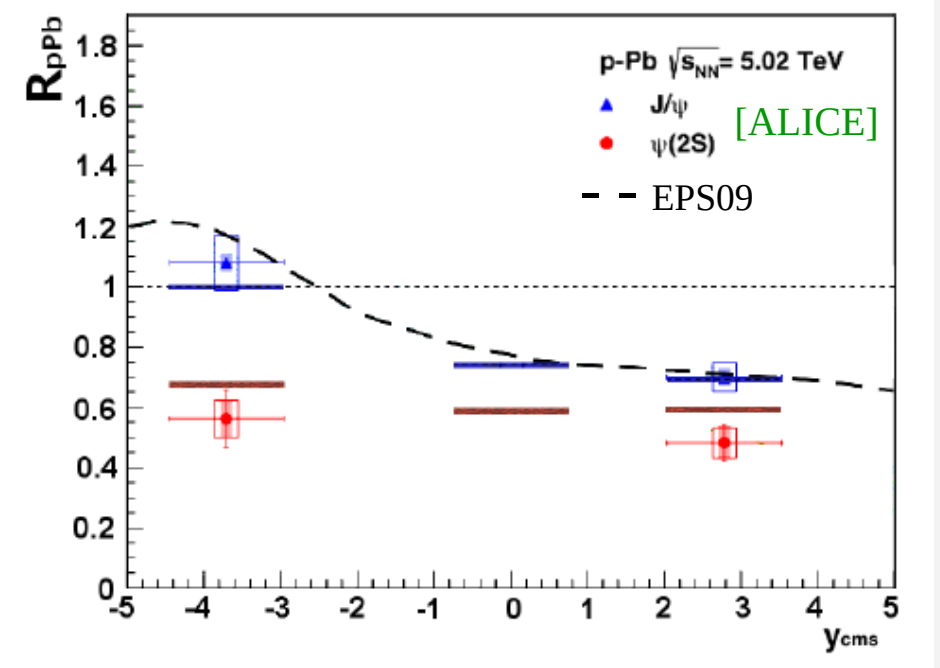
Ample source of information ⇔ **Compelling Case for Experiment!**

3.5 ψ(2S) in p/dA: A Sensitive Medium Probe

d-Au (0.2TeV)



p-Pb (5.02TeV)



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

[Ferreiro '15]

- supports fireball formation with:

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

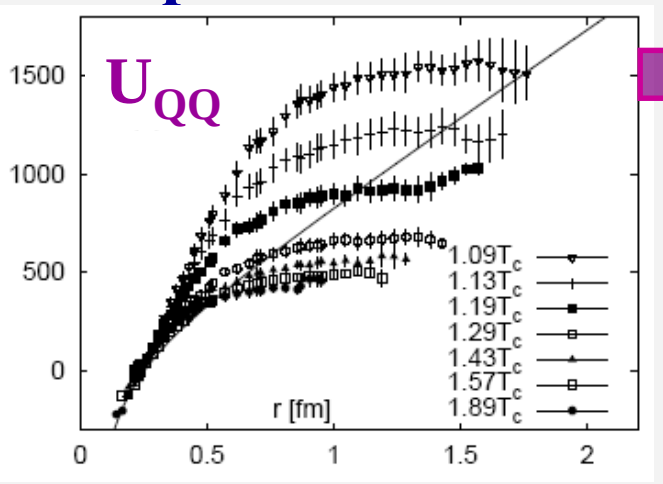
$\tau_{FB}\ \Gamma(J/\psi) << 1 \Rightarrow \Gamma_{avg}(J/\psi) < 20$ MeV

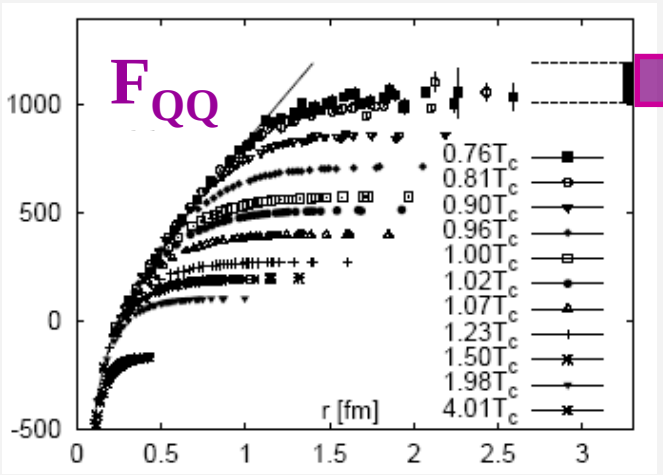
similar to thermal widths at **T≈ 200MeV**

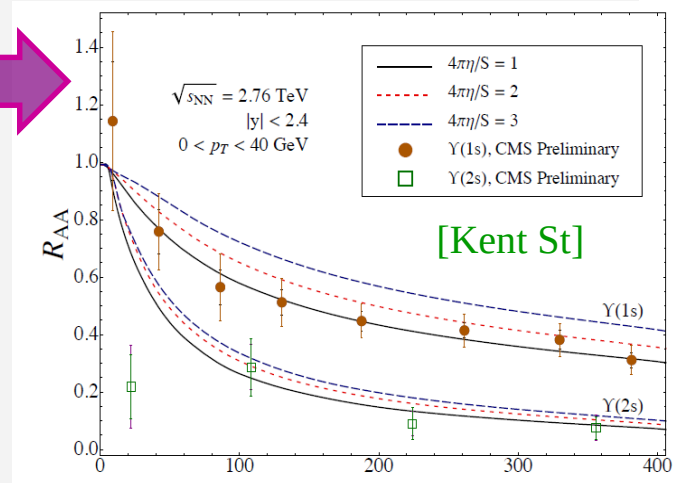
[Du et al '15]

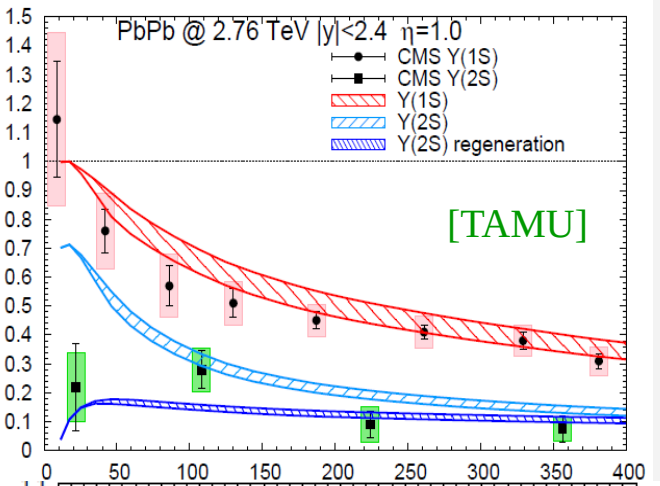
4.2 Heavy-Quark Potential and Υ(1S) Suppression

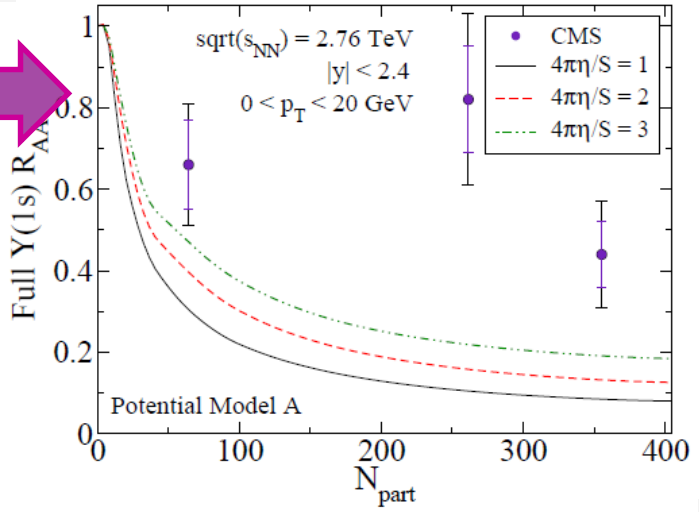
Input "Potential"

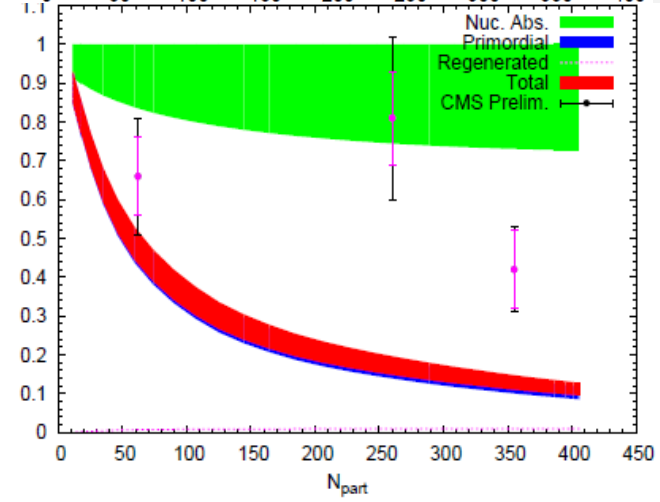






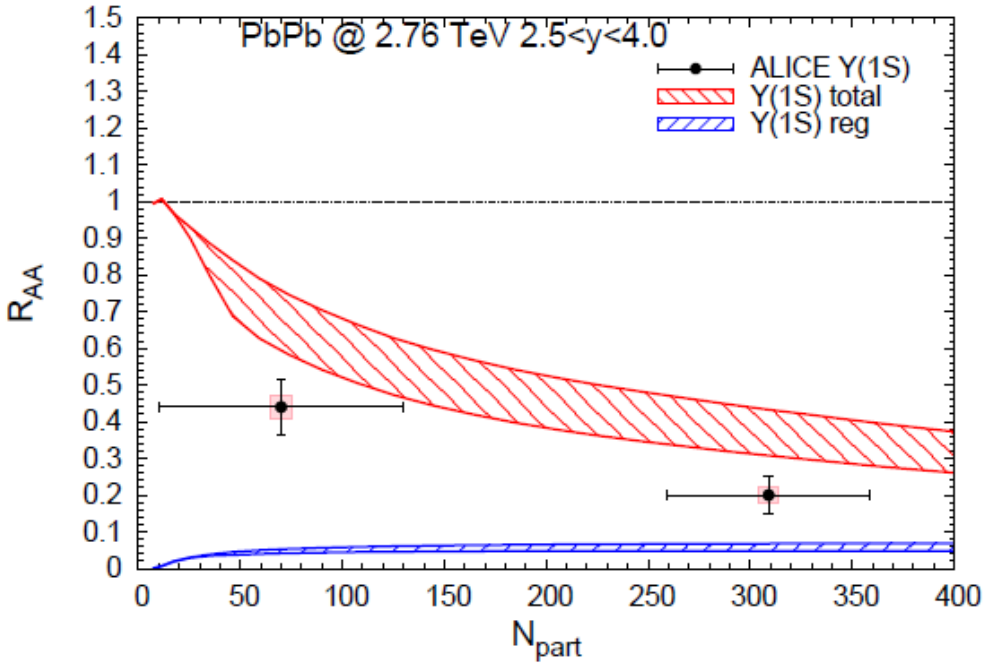


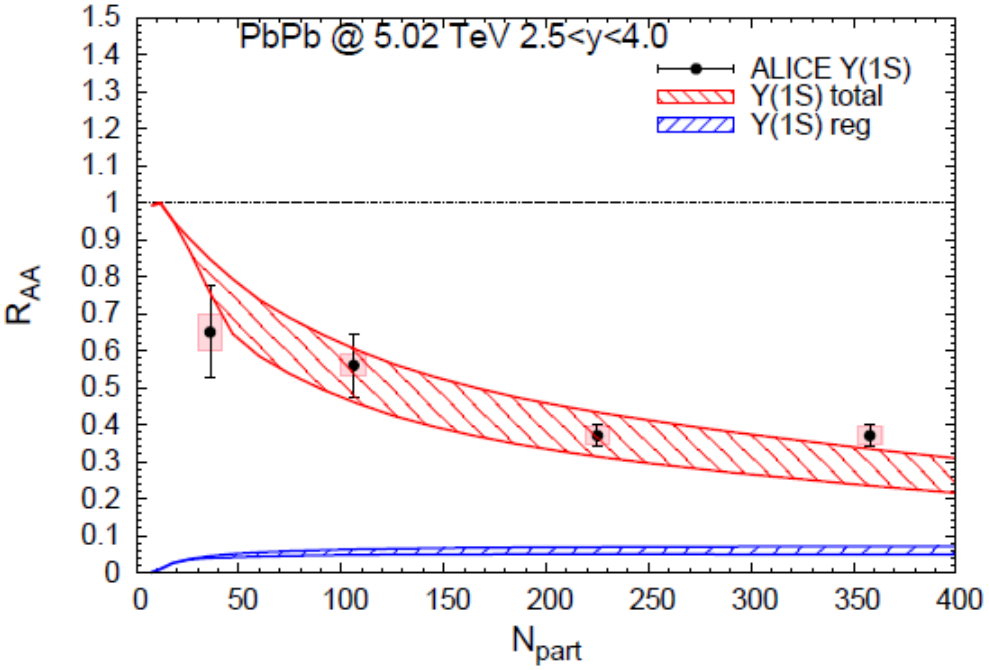




- **Υ(1S)** suppression prefers "strong" (**U**) over "weak" (**F**) in-med. potential
- role of regeneration for **Υ(1S)**, **Υ(2S)** ?

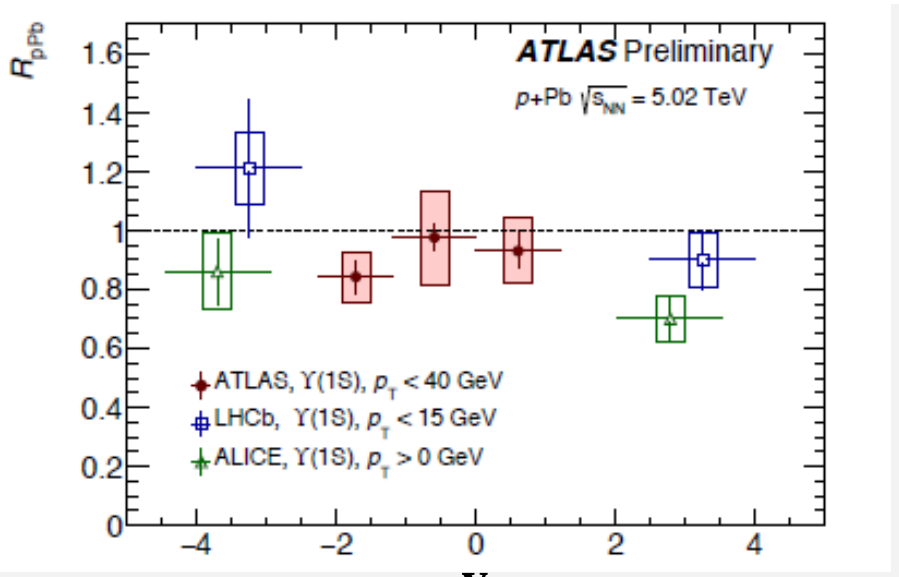
4.2 ϒ(1S): Rapidity Puzzle





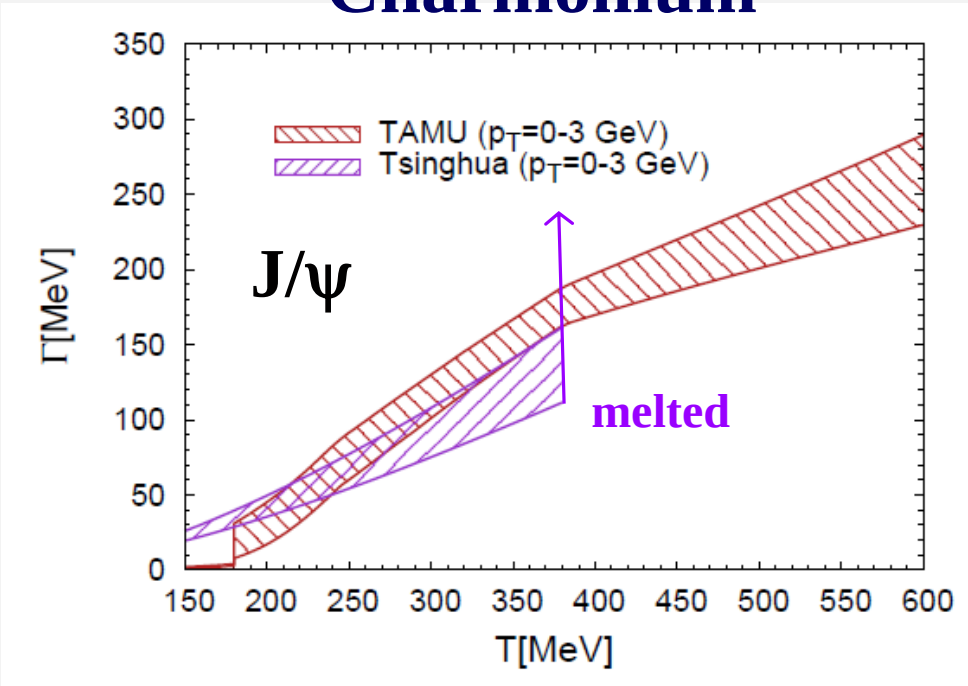
- problem of large(r) suppression in 2.76 TeV **ALICE** data
- beware of cold nuclear matter effects
- Regeneration: $N_{bb} \sim 1$ for central **PbPb**

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



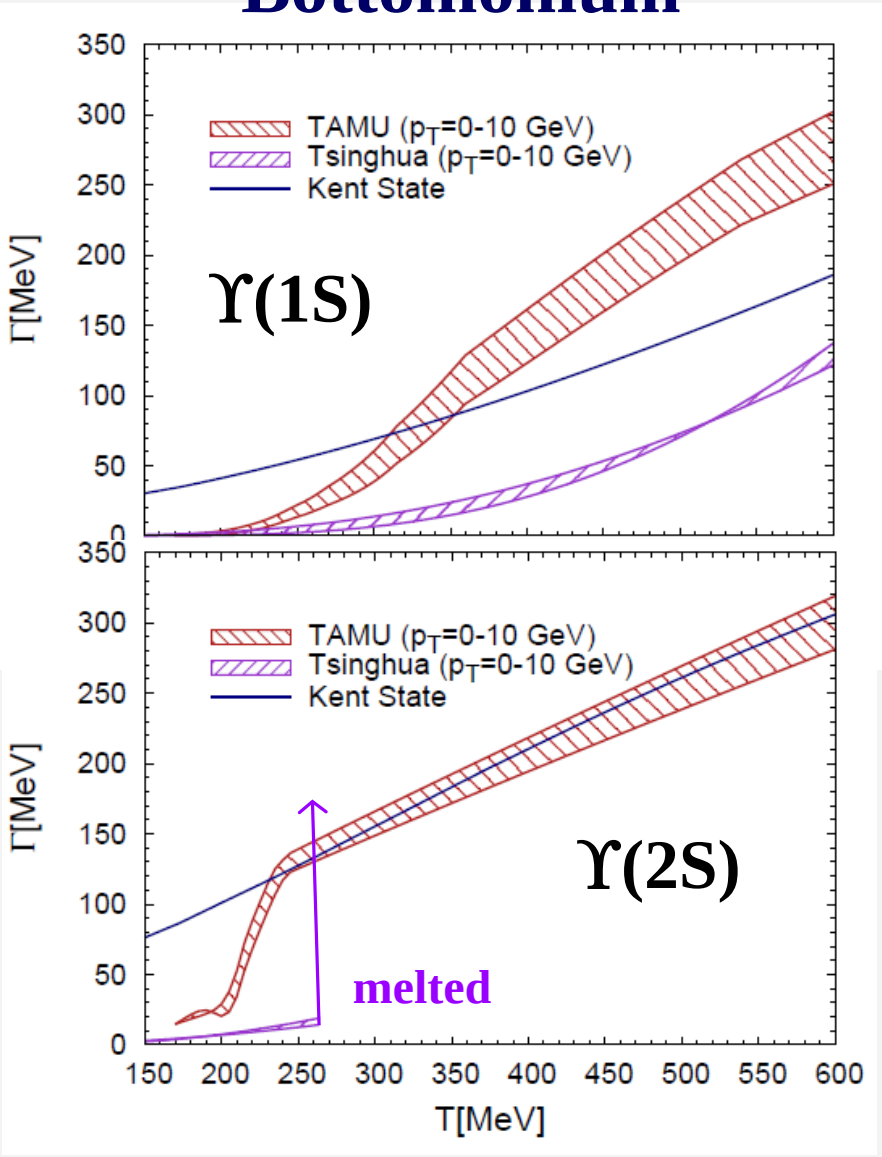
2.2 Quarkonium Width Comparisons

Charmonium



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

Bottomonium



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.

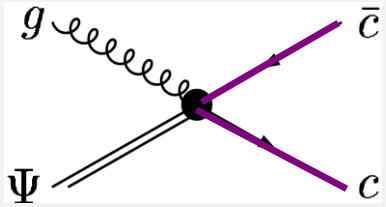
→ **Rate** equation

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

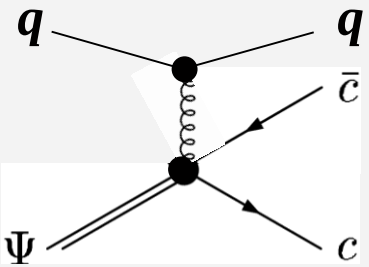
$$\frac{dN_\psi}{d\tau} = -\Gamma_\psi \left[N_\psi - N_\psi^{eq} \right]$$

- **Reaction Rate Γ_ψ**

"Strong" binding $E_B \geq T$



"Weak" binding $E_B < m_D$



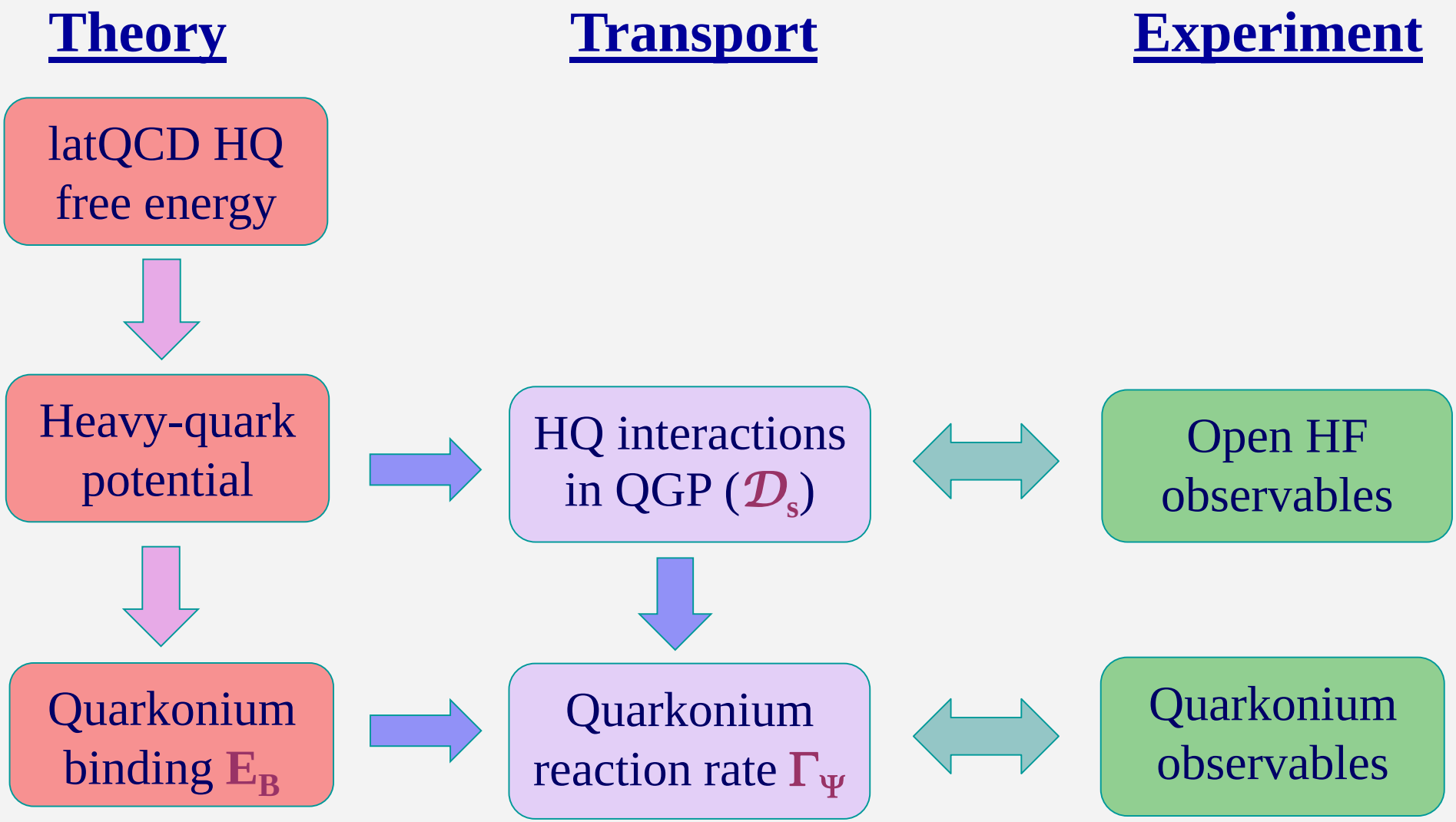
- gluo-dissosciation ("singlet-to-octet")

  [Bhanot+Peskin '85, Brambilla et al '08, Liu et al '13…]

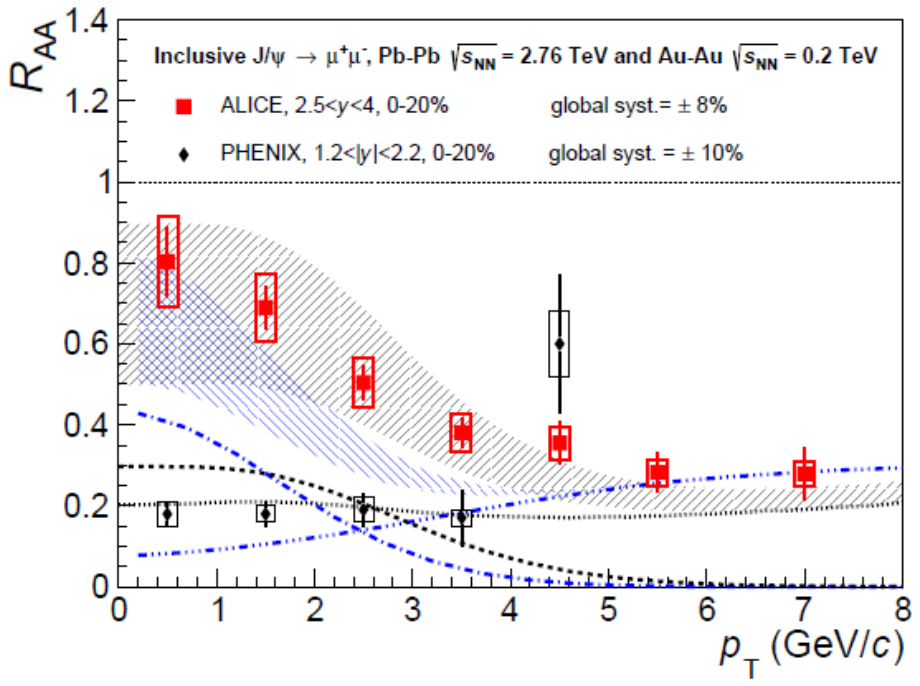
- "quasi-free"/ Landau damping

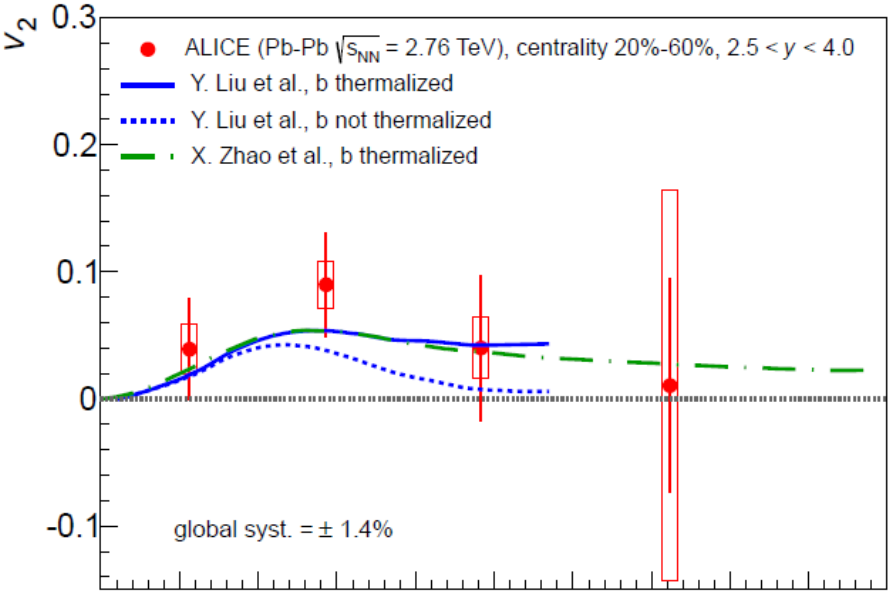
  [Grandchamp+RR '02, Song et al '07, Laine et al '07,…]

1.4 Systematic Approach to Heavy Flavor in Matter

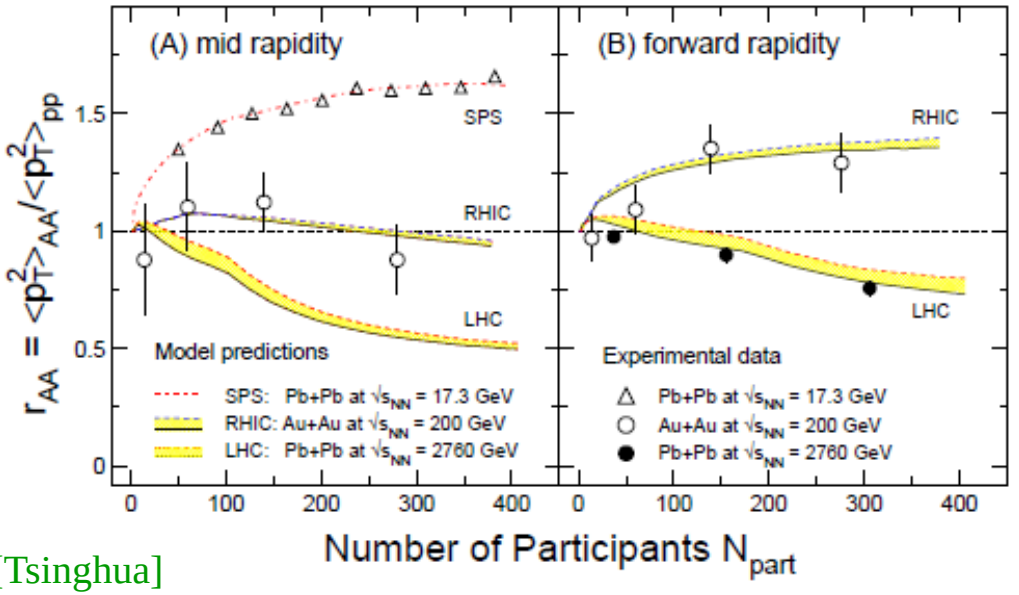


3.3 Properties of Charmonium Excess





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

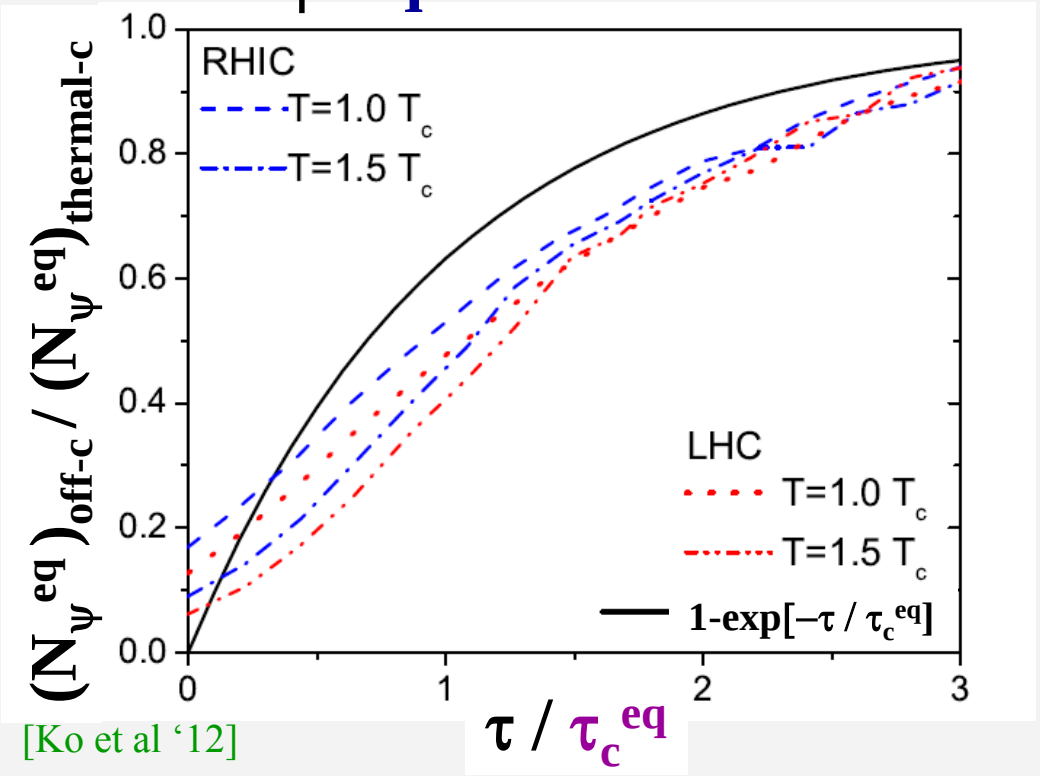


[Tsinghua]

4.1 Charm Thermalization + J/ψ Regeneration

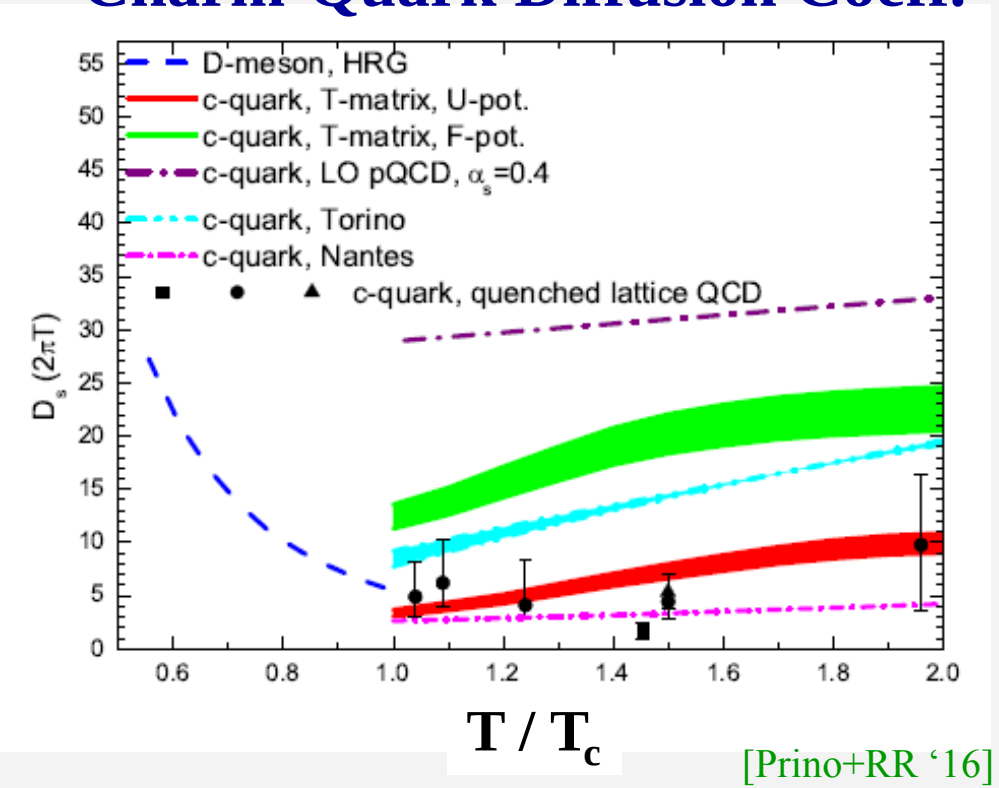
→ Softening of charm-quark spectra facilitates regeneration

J/ψ Equilibrium Fraction



[Ko et al '12]

Charm-Quark Diffusion Coeff.

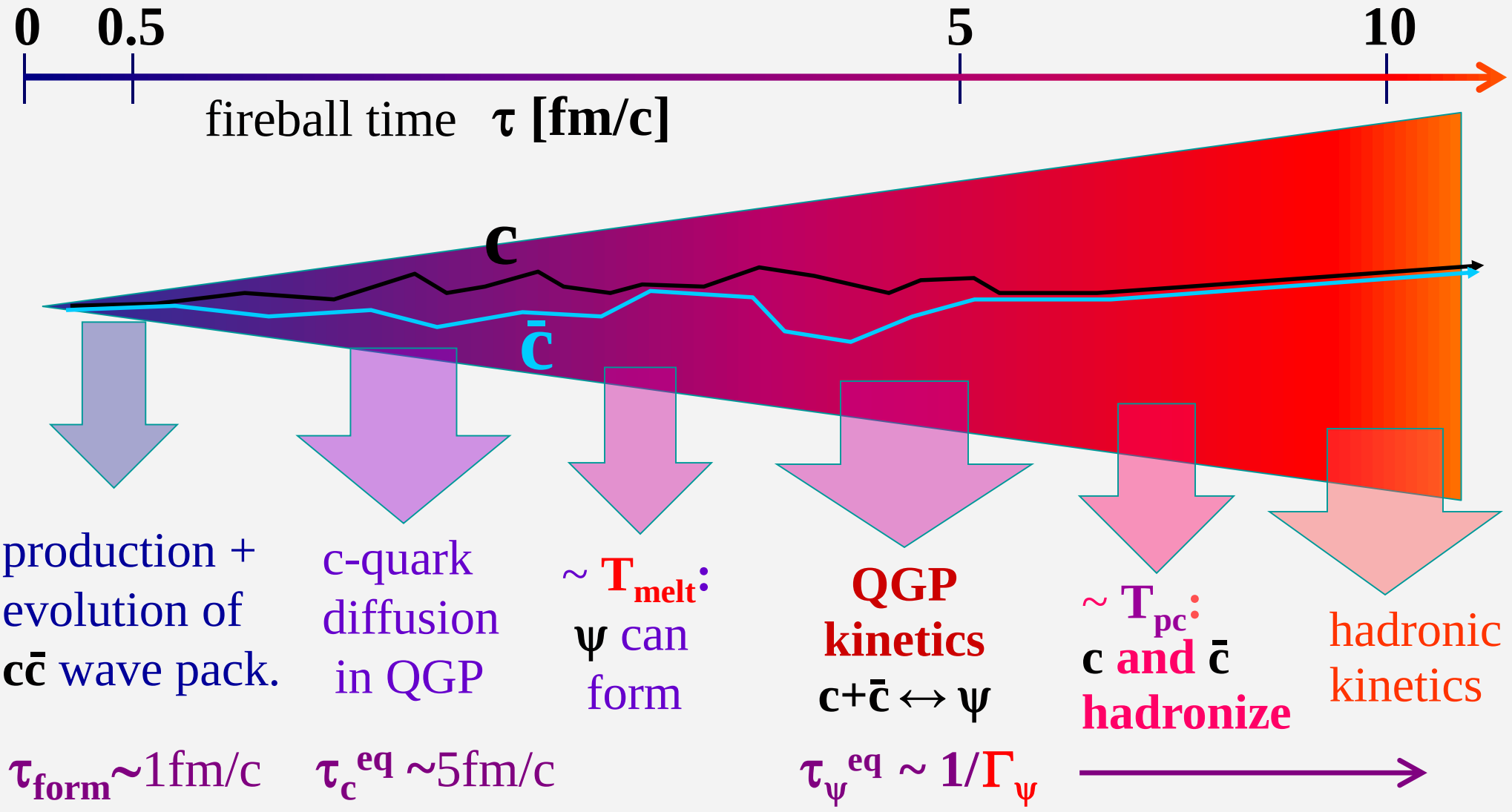


[Prino+RR '16]

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

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

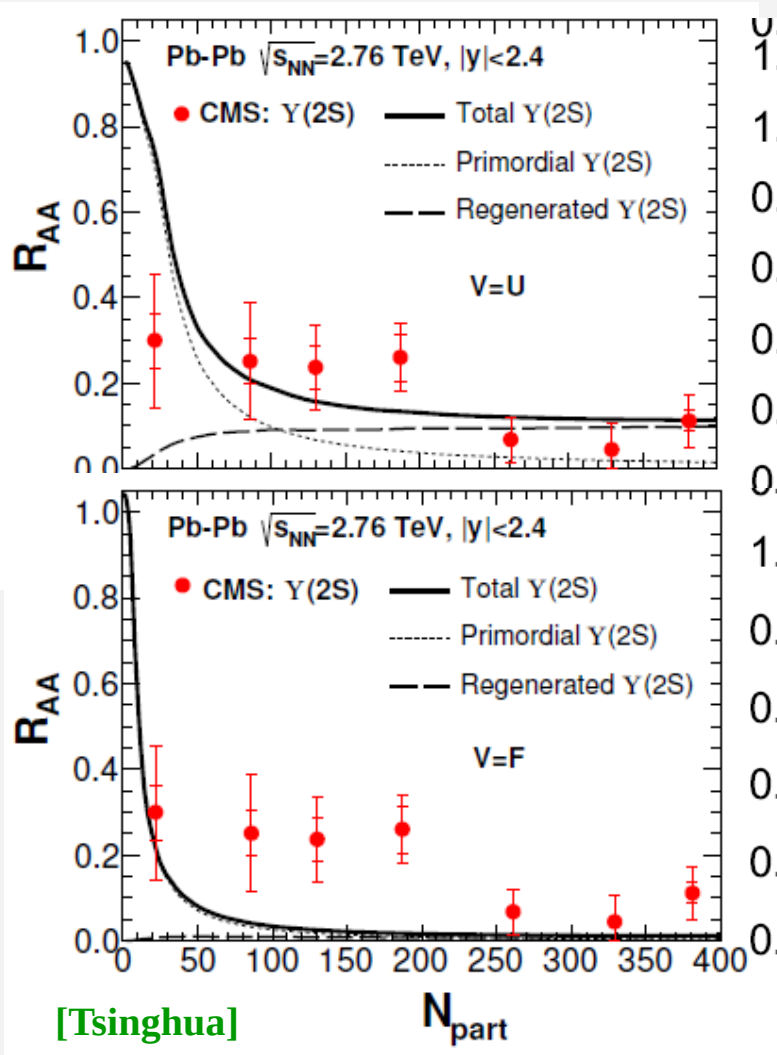
1.3 Quarkonium Transport in URHICs

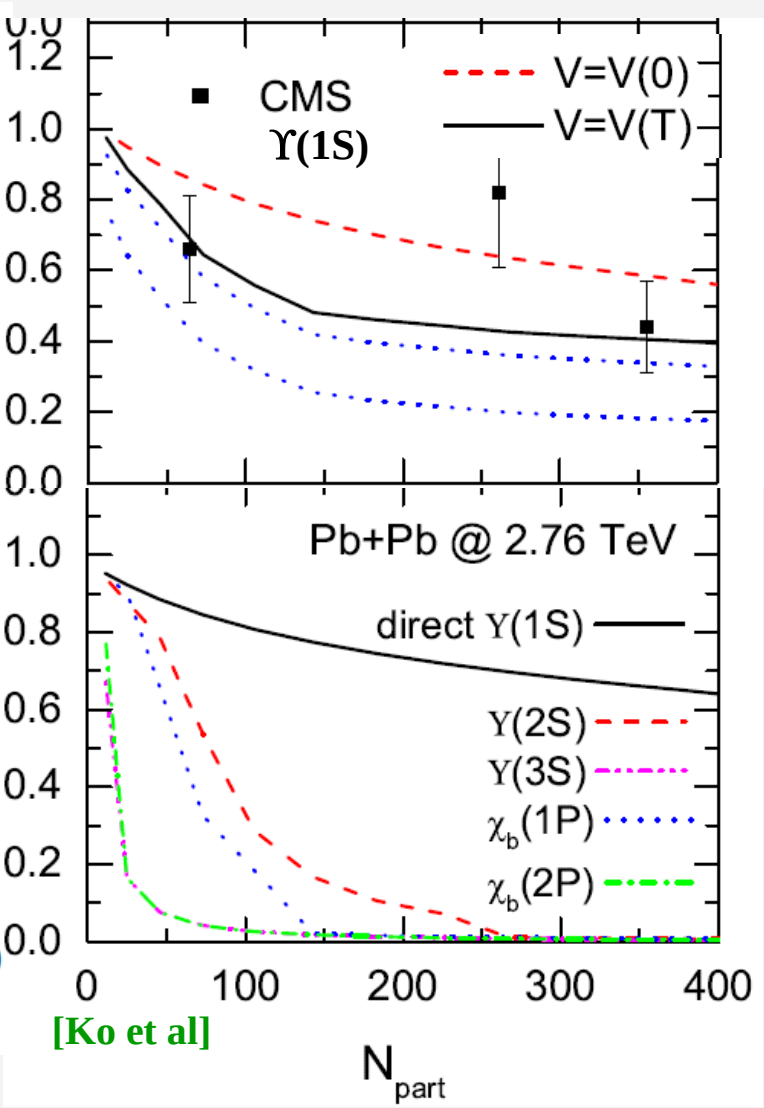


[Satz et al, Capella et al, Spieles et al, PBM et al, Thews et al, Grandchamp et al, Ko et al, Zhuang et al, Zhao et al, Chaudhuri, Gossiaux et al, Young et al, Ferreiro et al, Strickland et al, Brambilla et al, …]

4.2 ϒ(1S) and ϒ(2S) Transport cont'd

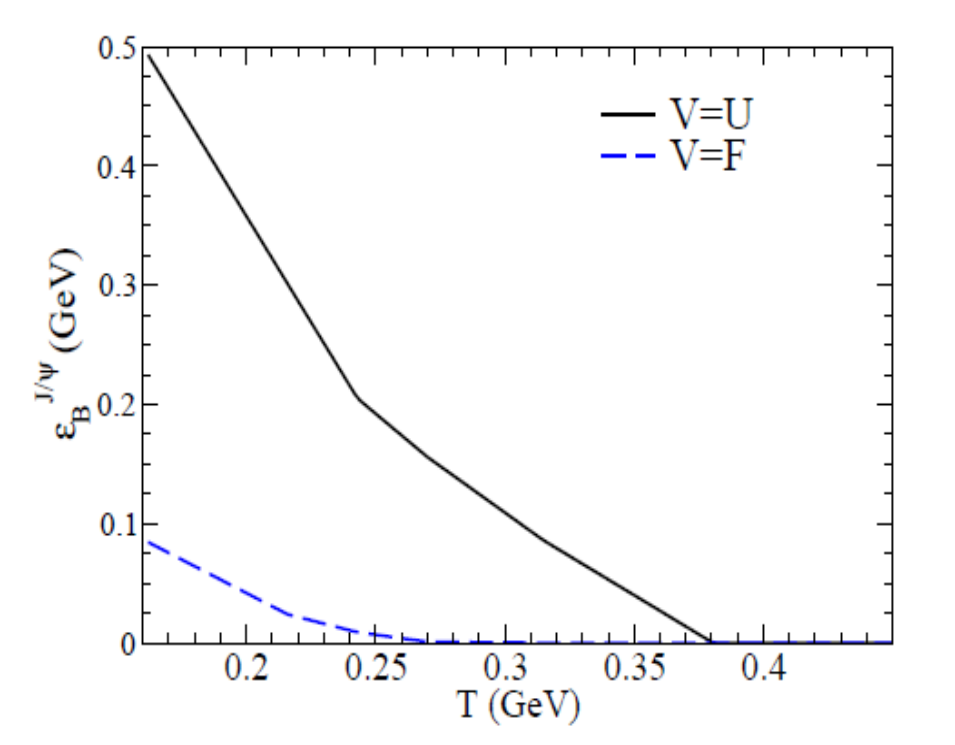
… as implemented in current transport approaches

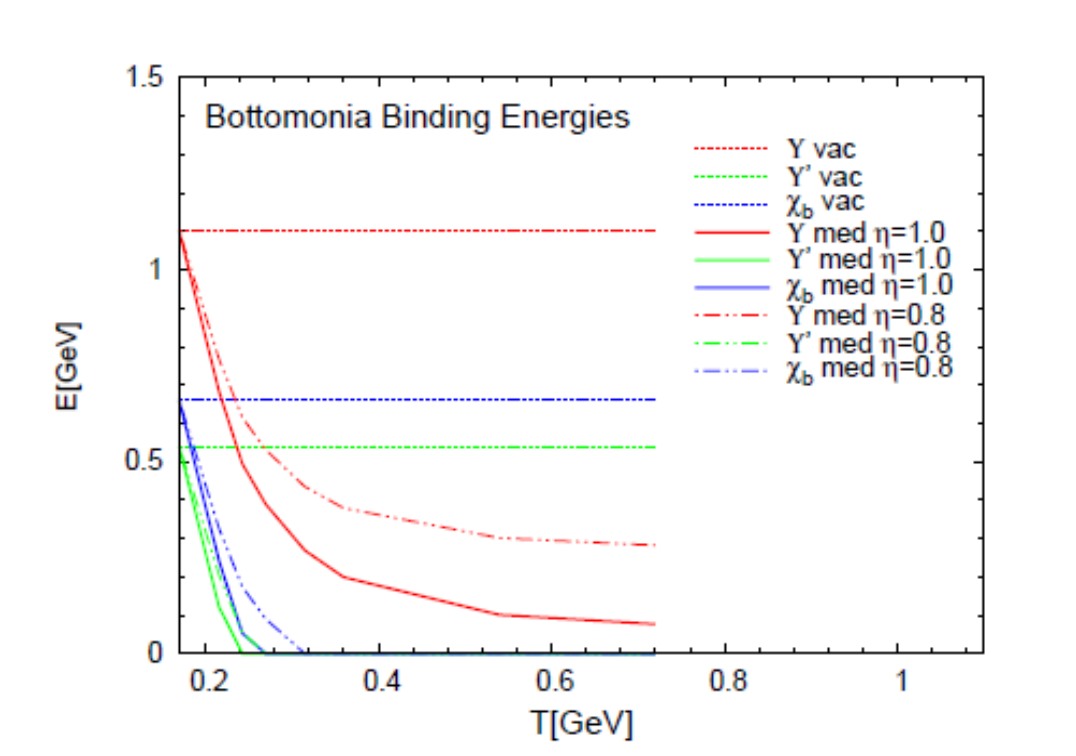




- **ϒ(2S)** more sensitive sensitive to in-medium potential

4.5 In-Medium Quarkonium Binding Energies



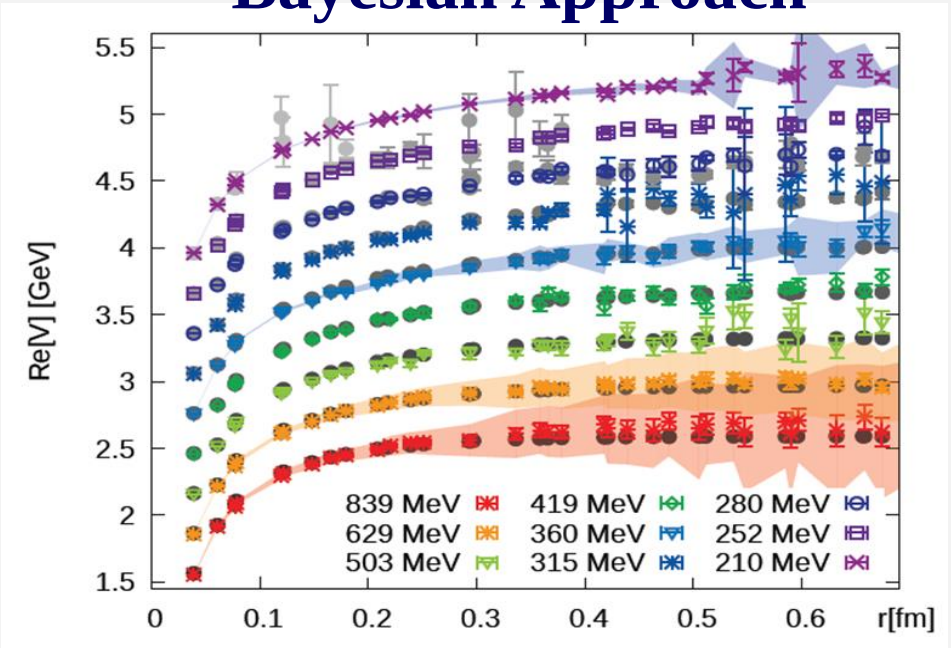


2.1 Potential Extraction from Lattice Data

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

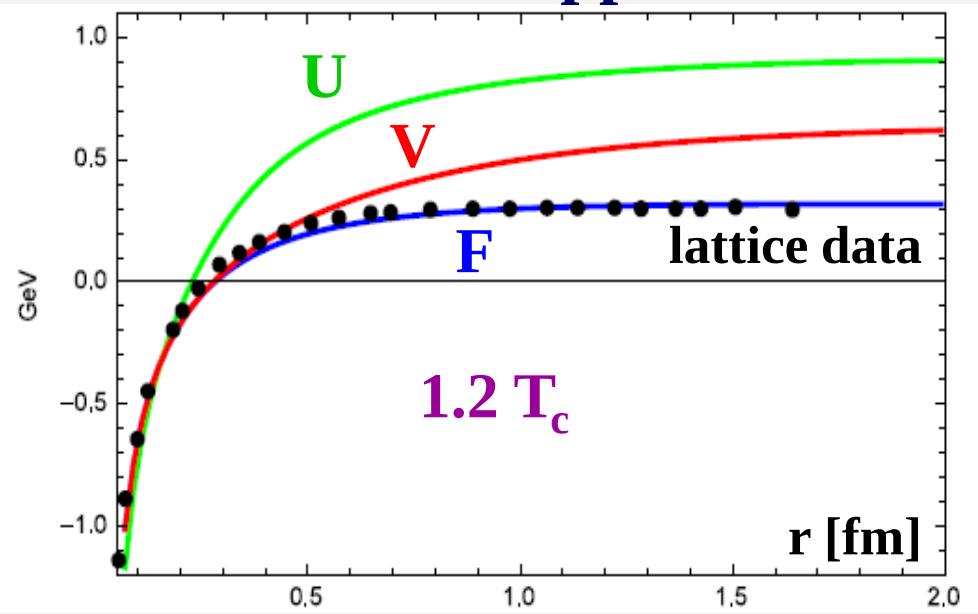
Bayesian Approach



- **Potential close to free energy**

[Burnier et al '14]

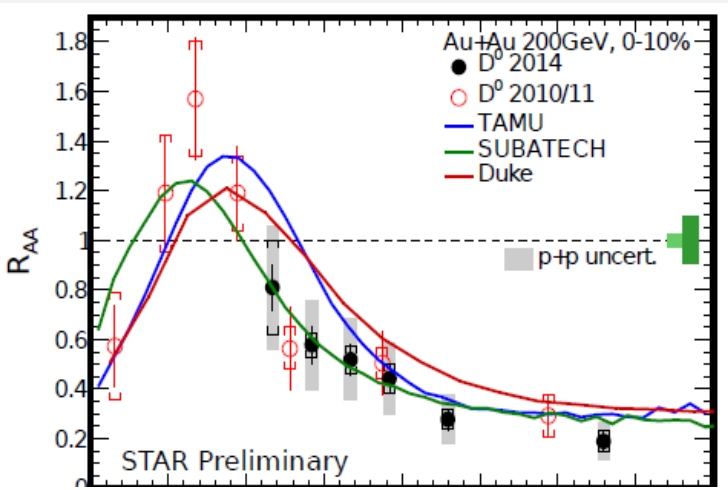
T-Matrix Approach

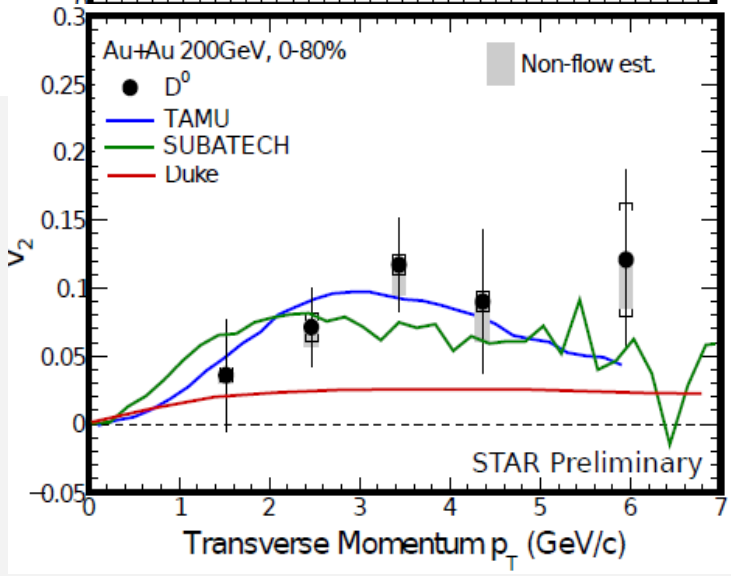


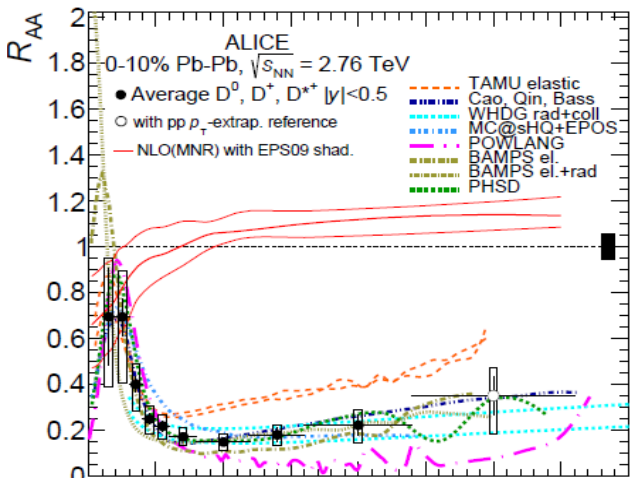
- Account for large imaginary parts
- **Remnant of confining force!**

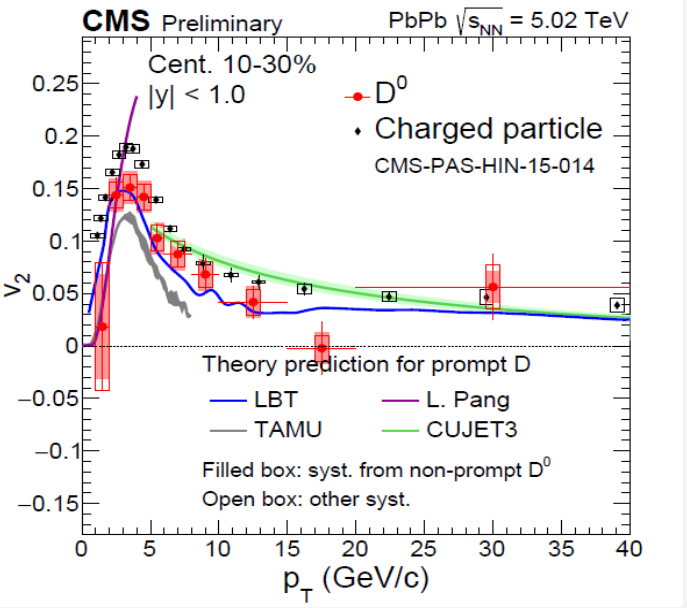
[S.Liu+RR '15]

3.3 Heavy-Flavor Transport at RHIC + LHC









- flow bump in R_{AA} + large v_2 ↔ strong coupling near T_{pc} (**recombination**)
- high-precision v_2: transition from elastic to radiative regime?

Outline

1.) Introduction

2.) Current Status

3.) In-Medium Binding and Dissociation

- Melting vs. Regeneration

4.) Cold-Nuclear-Matter Effects

- Baseline vs. in-Medium Probe

5.) Conclusions