Quarkonia at High-Luminosity LHC:

Can we determine the in-medium QCD force?

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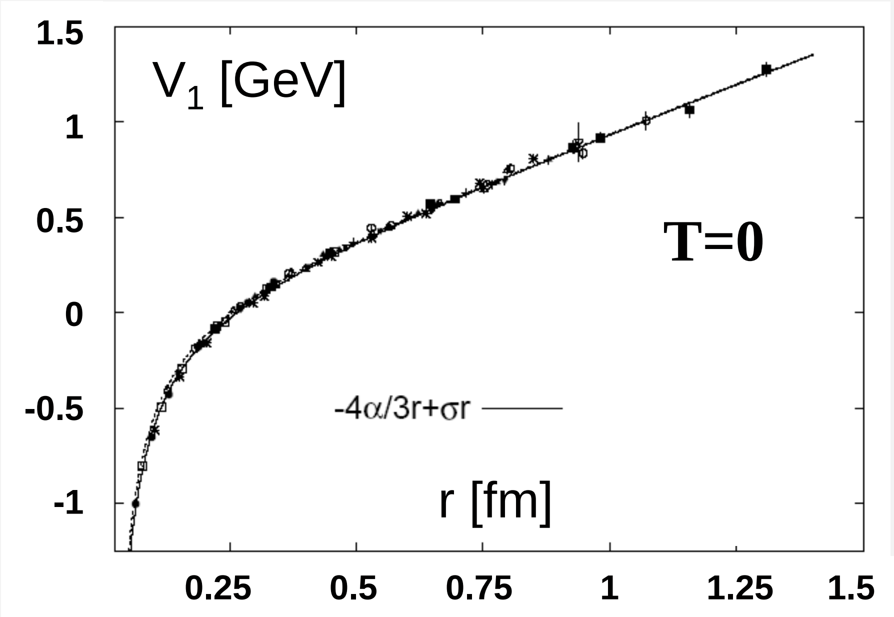
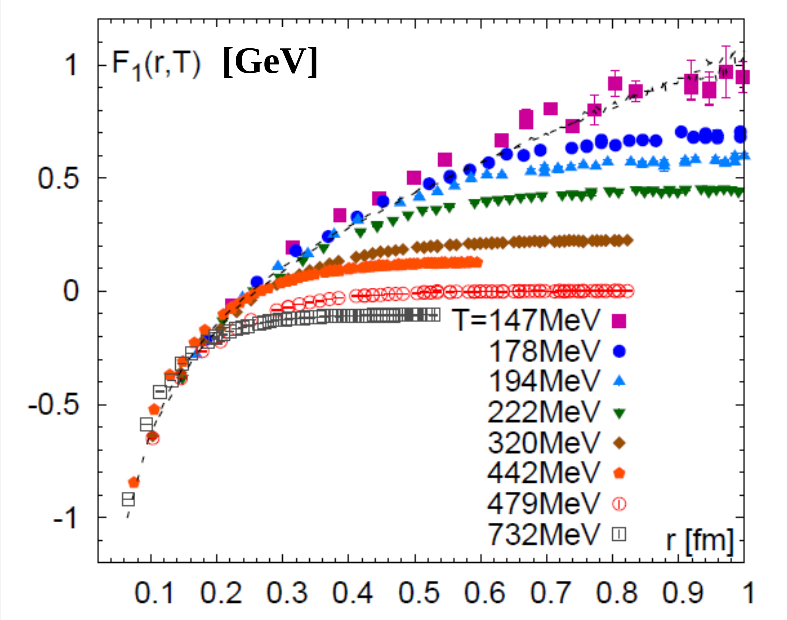
General WG-5 Heavy-Ion Meeting

CERN (Geneva, Switzerland), Mar 06, 2018

[remote presentation from CS]

1.) Introduction: A "Calibrated" QCD Force





[Bazavov et al '13]

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

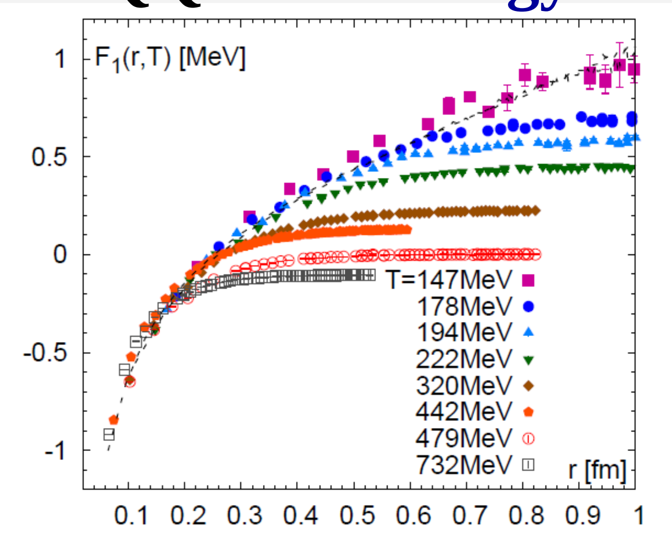
Opportunity: Utilize quarkonia to probe in-medium QCD force

↔ infer consequences for transport coeffs. + spectral functs.

↔ probe QGP properties at varying resolution

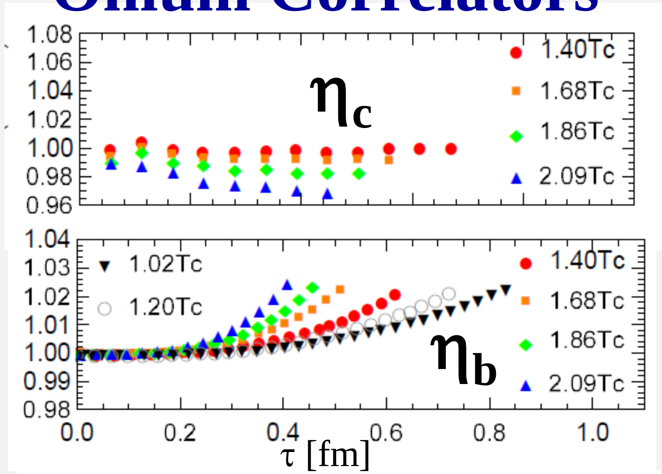
1.2 Heavy Quark/onia on the Lattice

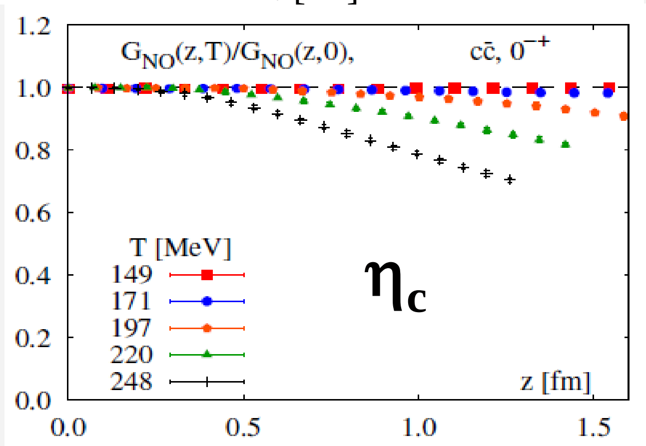
$Q\bar{Q}$ Free Energy



Heavy-quark potential

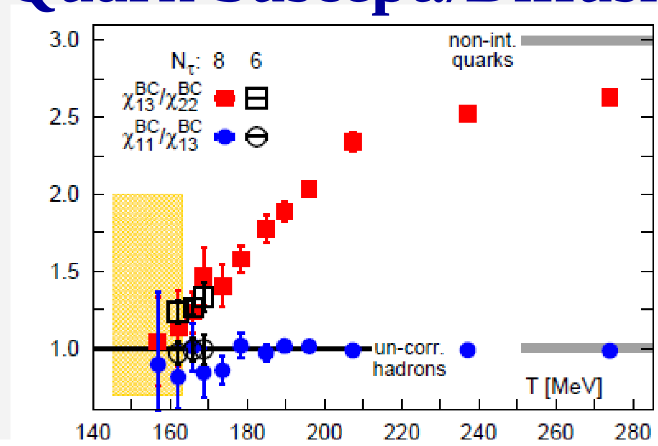
Onium Correlators

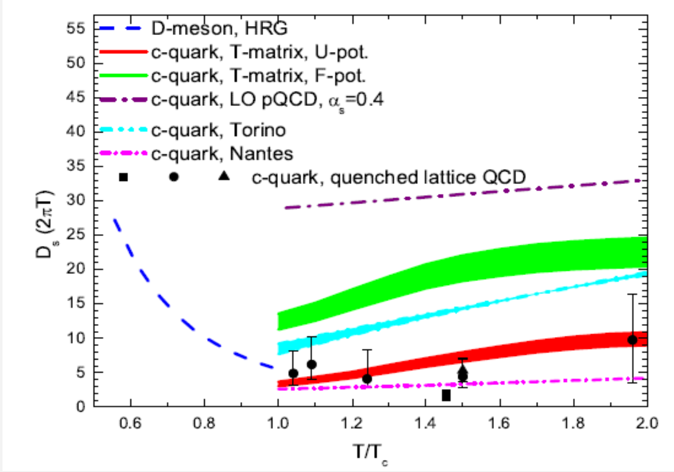




Energy + 3-mom. dep. of Ψ + Υ spectral fcts.

Quark Suscept./Diffusion



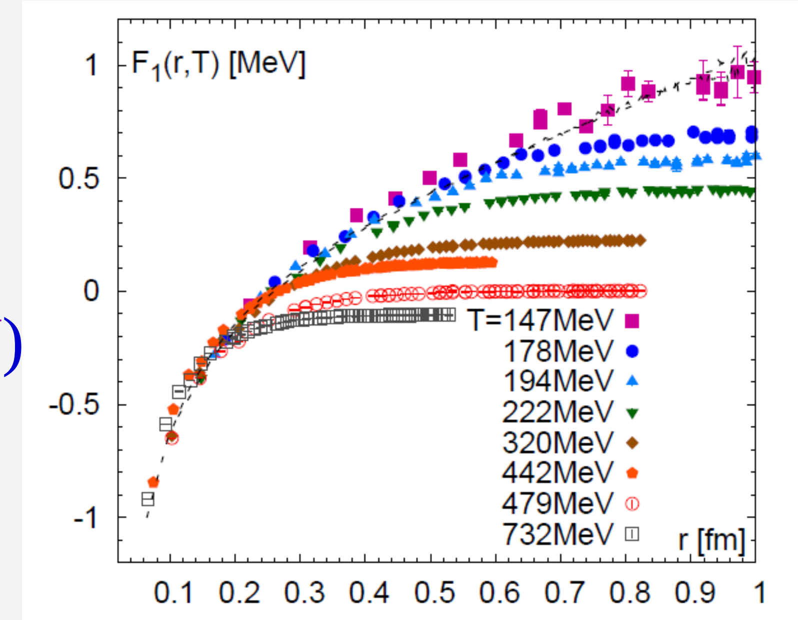


Individual heavy quarks in QGP

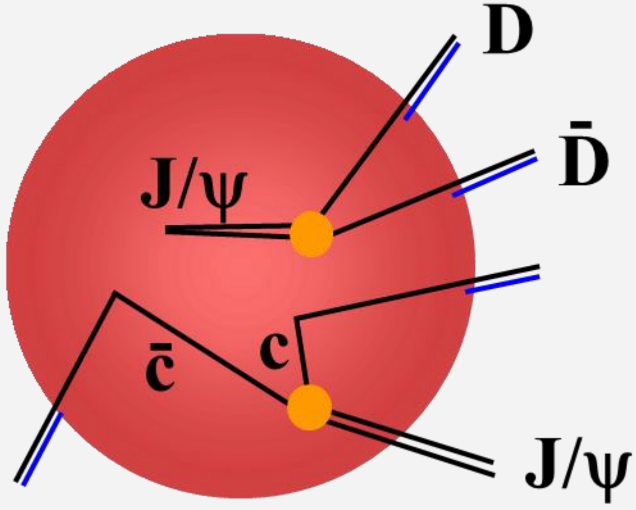
Ample source of information ⇔ Compelling Case for Experiment!

1.3 Quarkonia in Medium

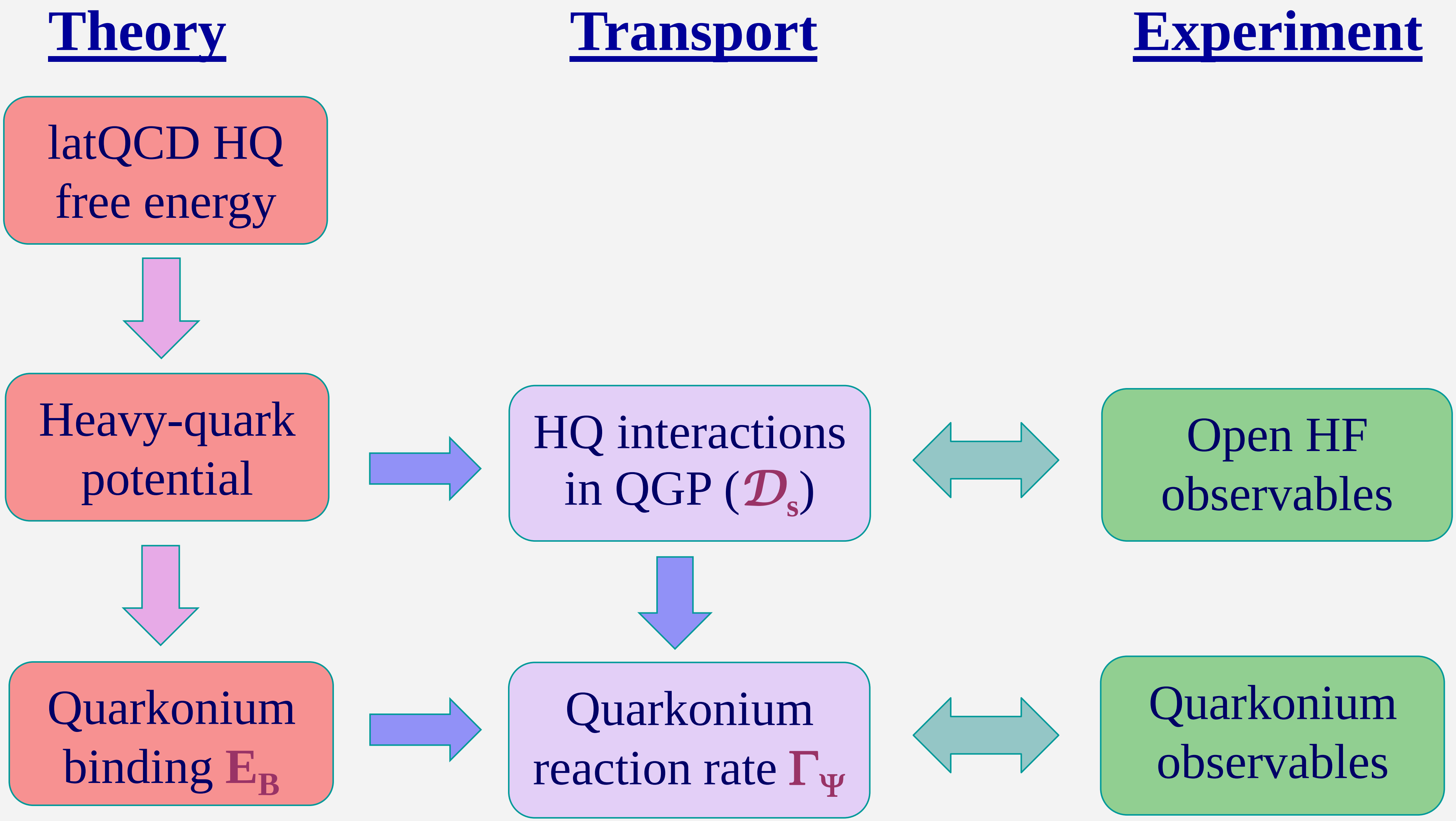
- Lattice-QCD suggests gradual progression of color screening
- Remnant confining force above T_{pc}
- **Υ(1S)**: **color-Coulomb** (E_B=1.1GeV)
  J/ψ, Υ(2S,3S): **confining force** (0.6-0.2)
  ψ(2S): **barely bound** (<0.1)
- **Do not** use as a thermometer …



- Screening lowers **binding energies** $E_B(T)$
  ⇒ opens phase space for dissociation
- **Dissociation rate** $\Gamma_\psi(p;T)$ is key **transport parameter** for phenomenology



1.4 Systematic Approach to Heavy Flavor in Matter



Outline

1.) Introduction

2.) Current Status

3.) In-Medium Binding and Dissociation

- Melting vs. Regeneration

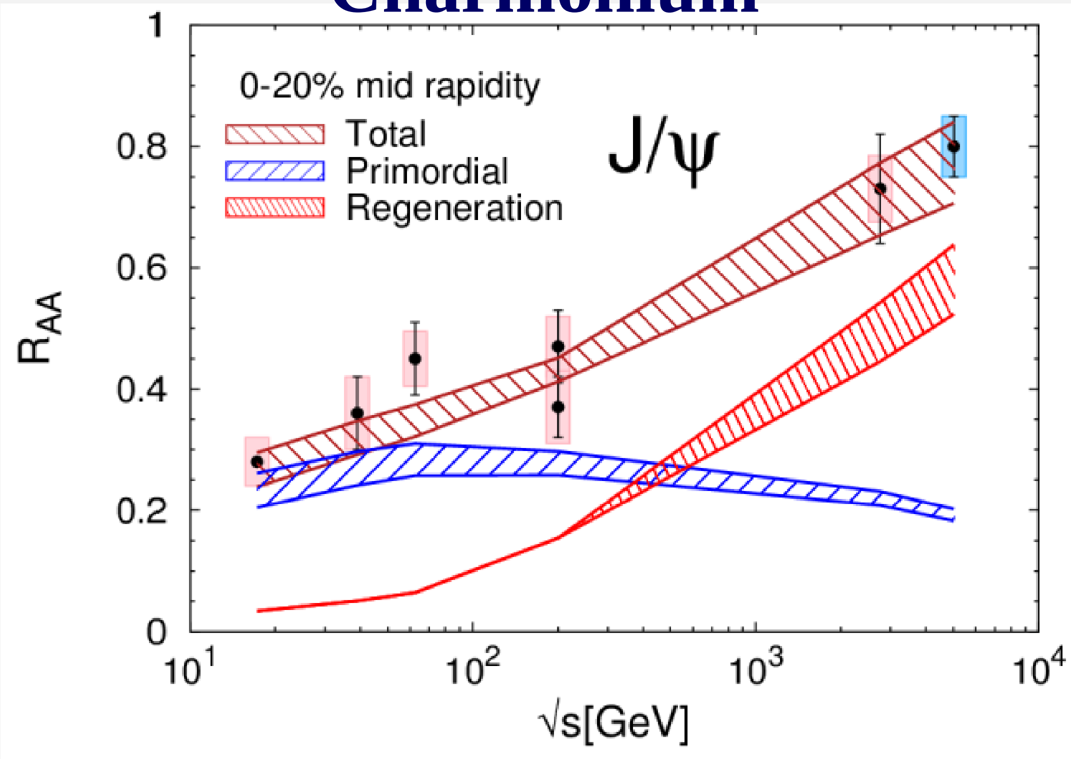
4.) Cold-Nuclear-Matter Effects

- Baseline vs. in-Medium Probe

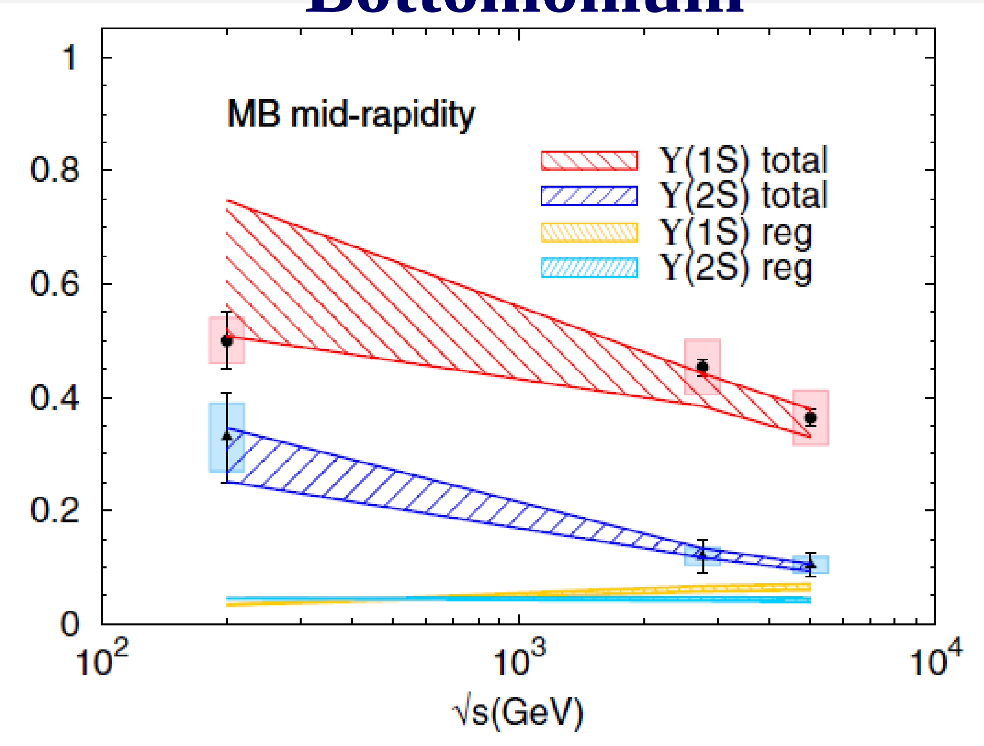
5.) Conclusions

2.1 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**

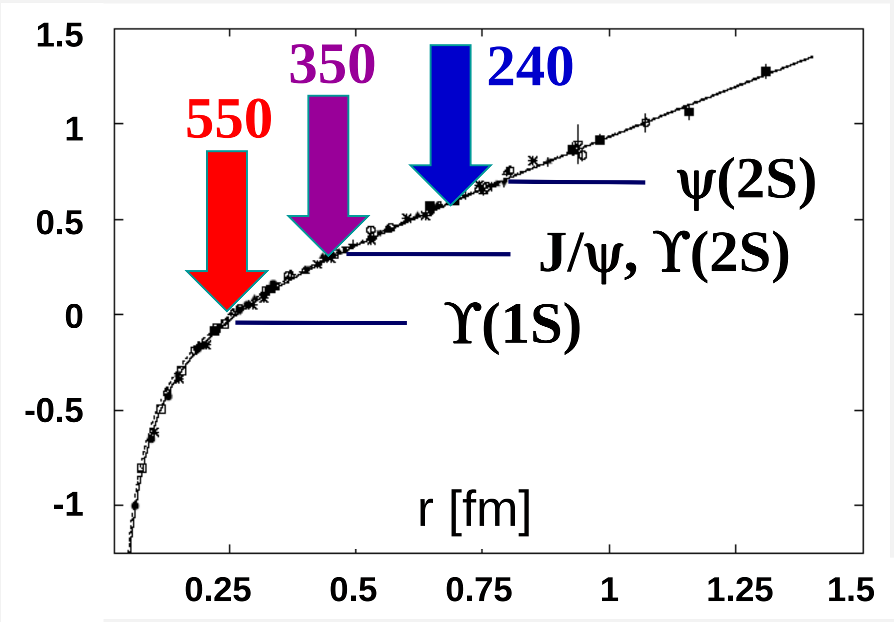
[**data**: **NA50, PHENIX, STAR, ALICE, CMS**]

2.2 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]



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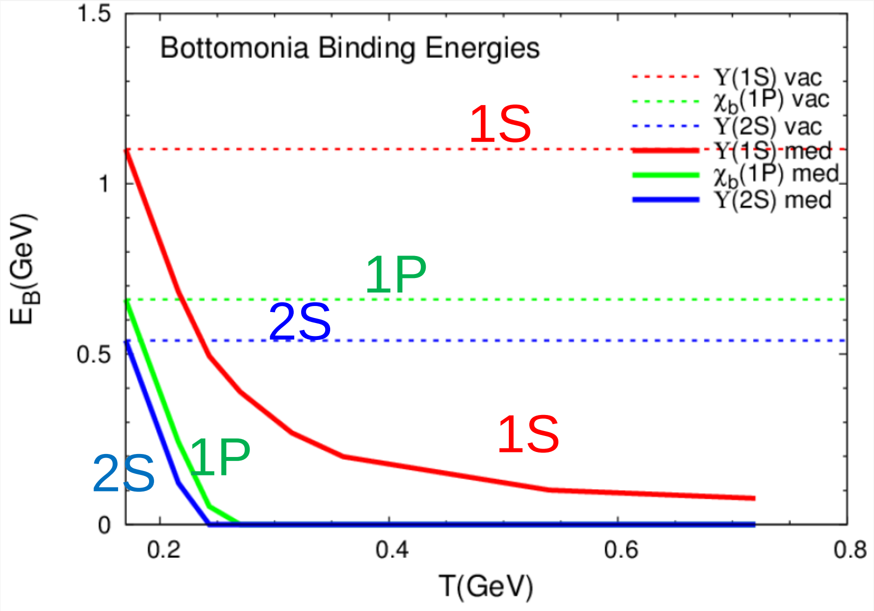
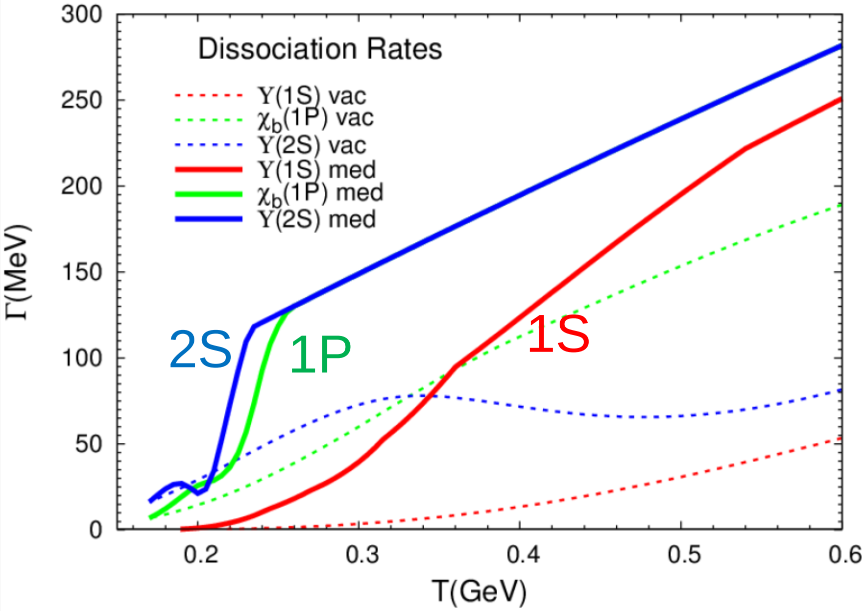
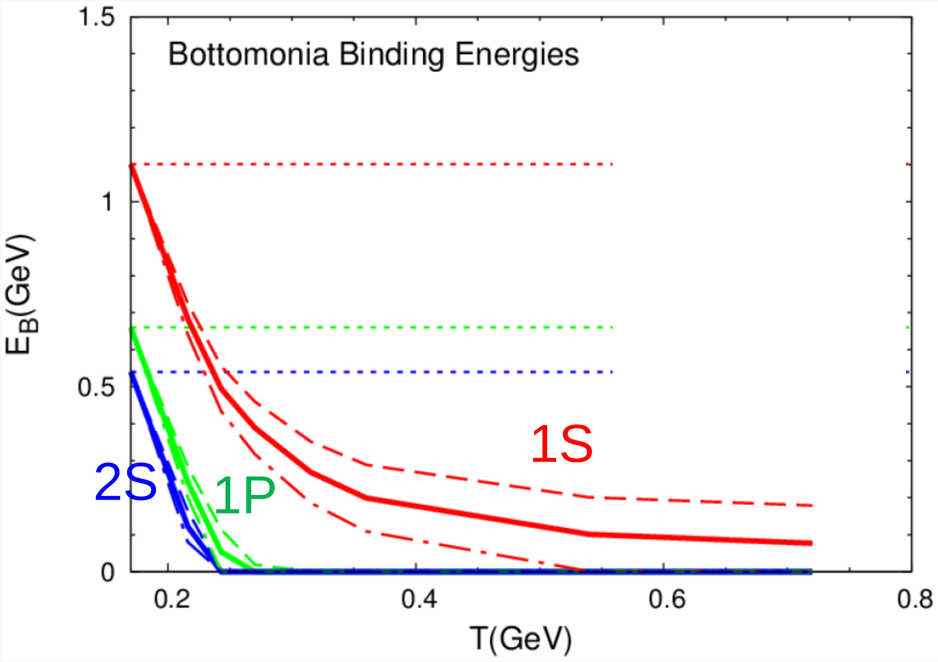
3.1 Binding Energies + Reaction Rates: Υ States

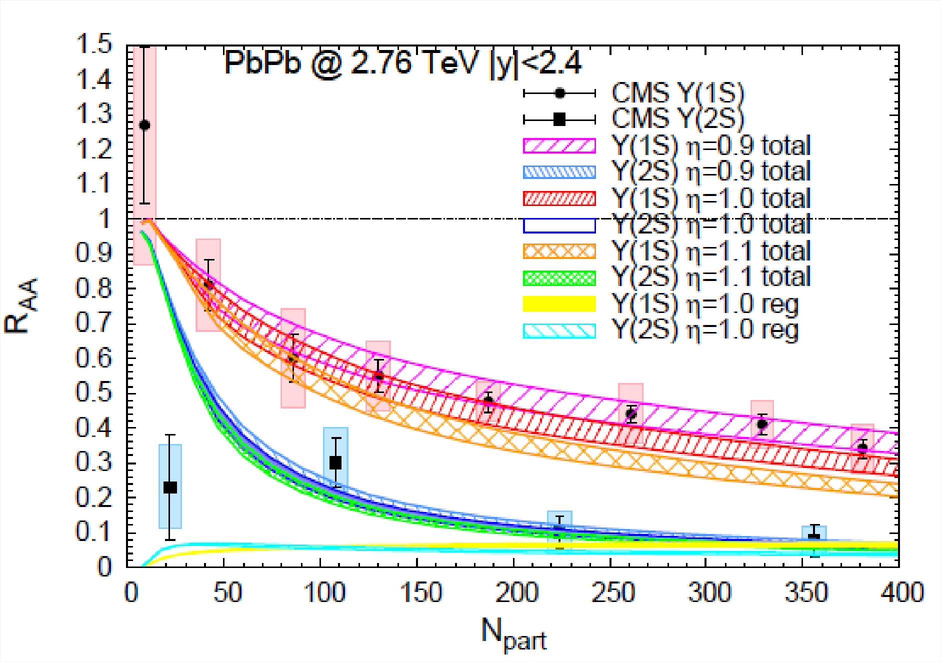




- Reduced binding “accelerates” dissociation ($\Gamma_{\Upsilon}(E_B=0) = 2\Gamma_b$)
- Localizes dissociation temperatures (centrality dependence!)
- Same rate for regeneration – experimental signatures of production time?

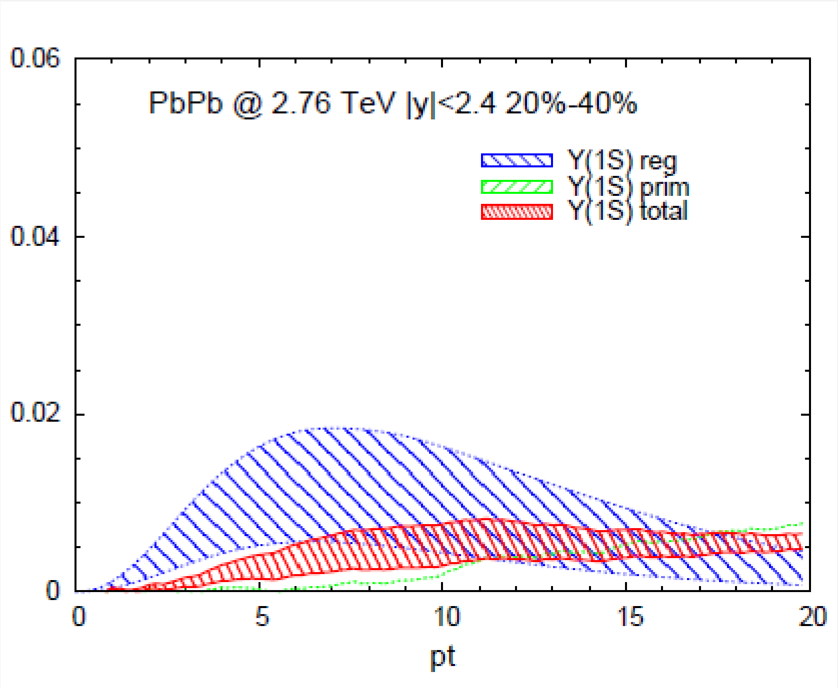
3.2 Sensitivity of R_{AA} to Binding Energies

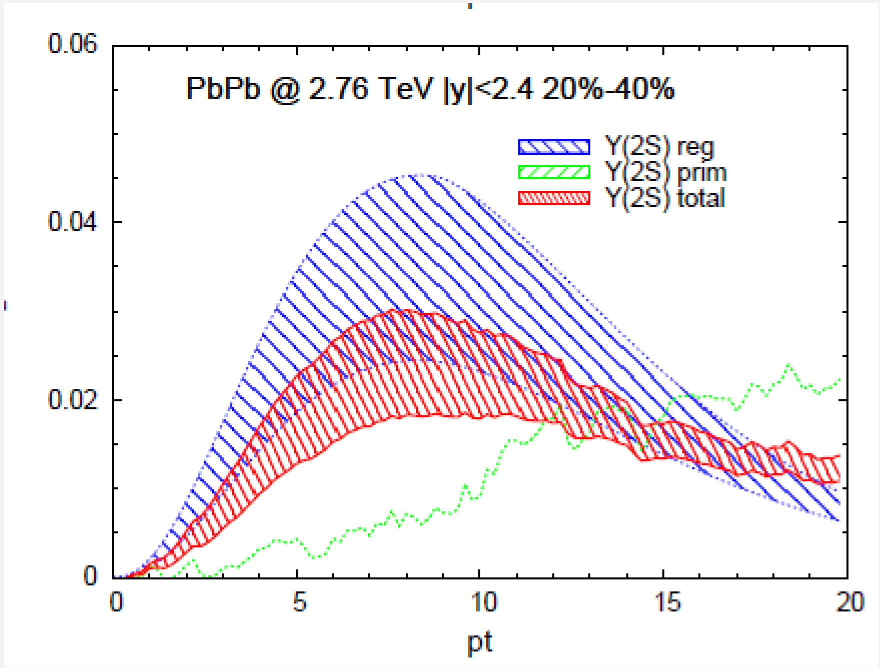




- **Υ(1S)** suppression can discriminate (gradual) melting scenarios, need good control over auxiliary model components (bulk, CNM,...)
- **Υ(2S,3S)**: need lower energies (**RHIC**), smaller systems (**pPb**!), or…

3.3 ϒ Elliptic Flow

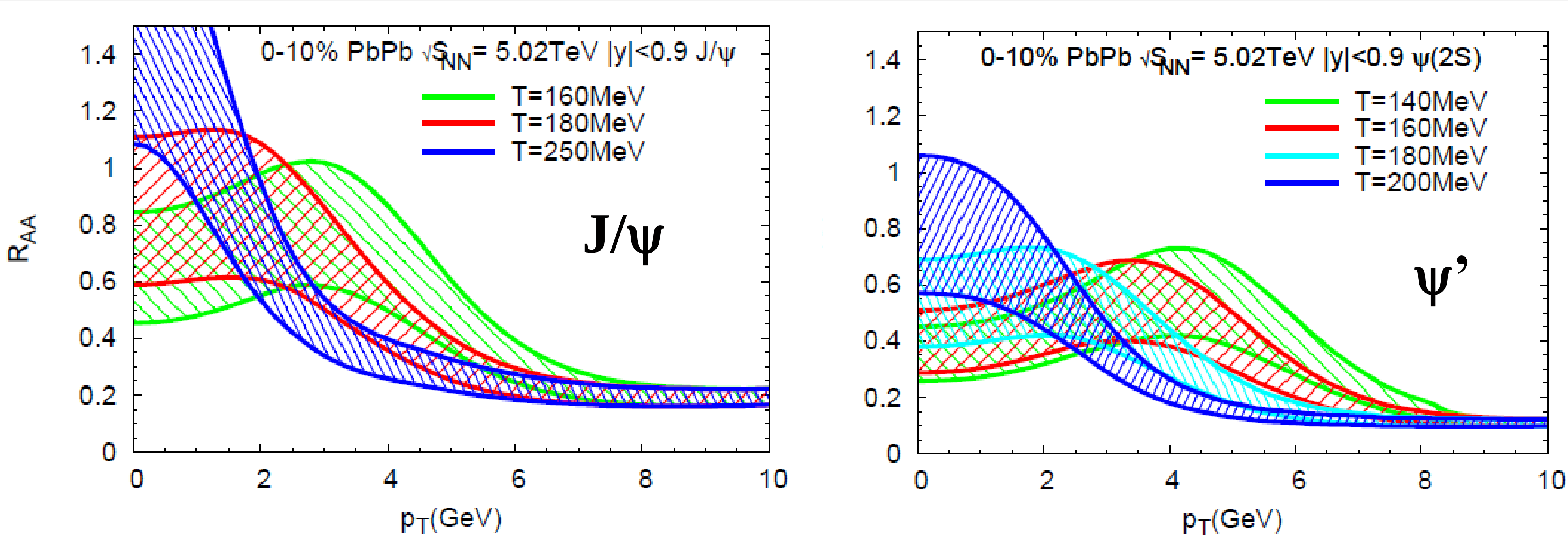




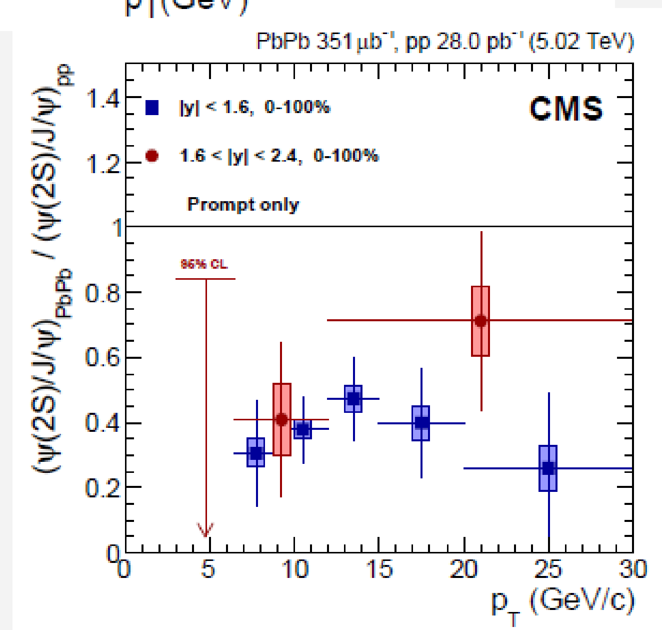
- Directly reflects production/suppression time!

  ϒ(1S): early , ϒ(2S): late(r)

3.4 Charmonia: Production Time + "Flow Bump"



- Need **low-p_T R_{AA}** data to discriminate
- Sequential regeneration?!
- Recall double ratio of **CMS**…



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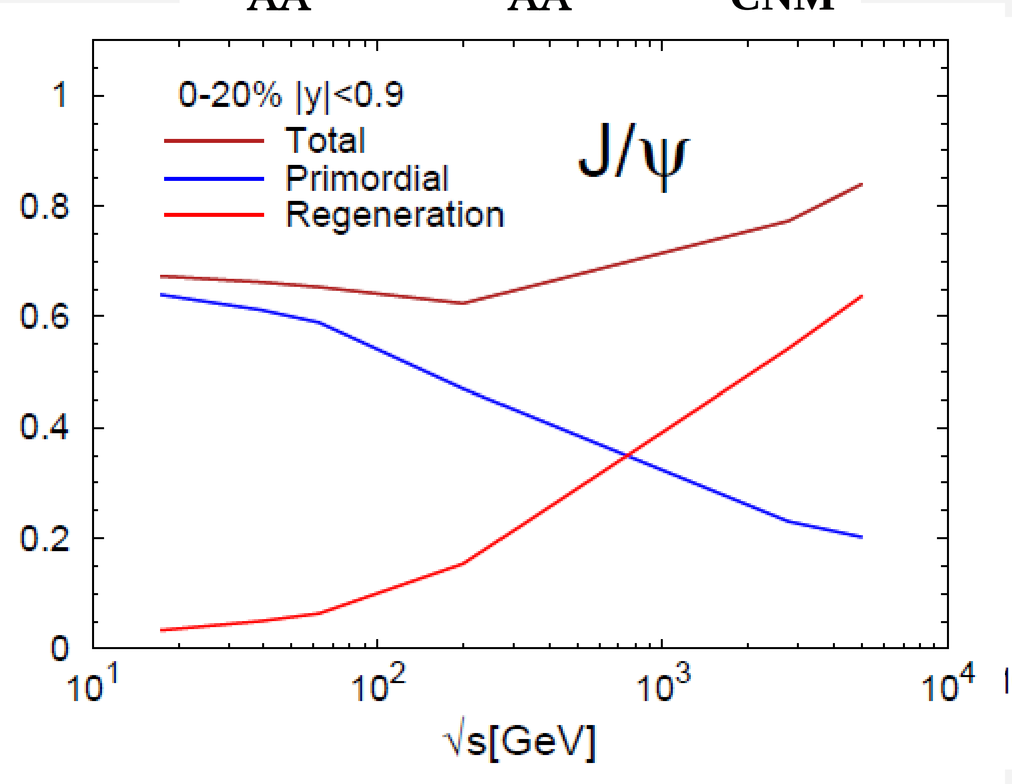
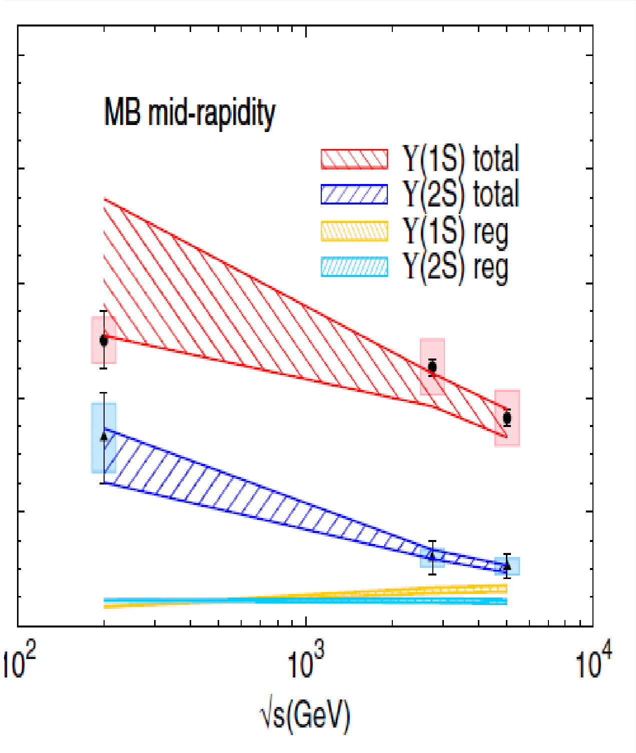
4.1 Divide out Cold-Nuclear-Matter Effects

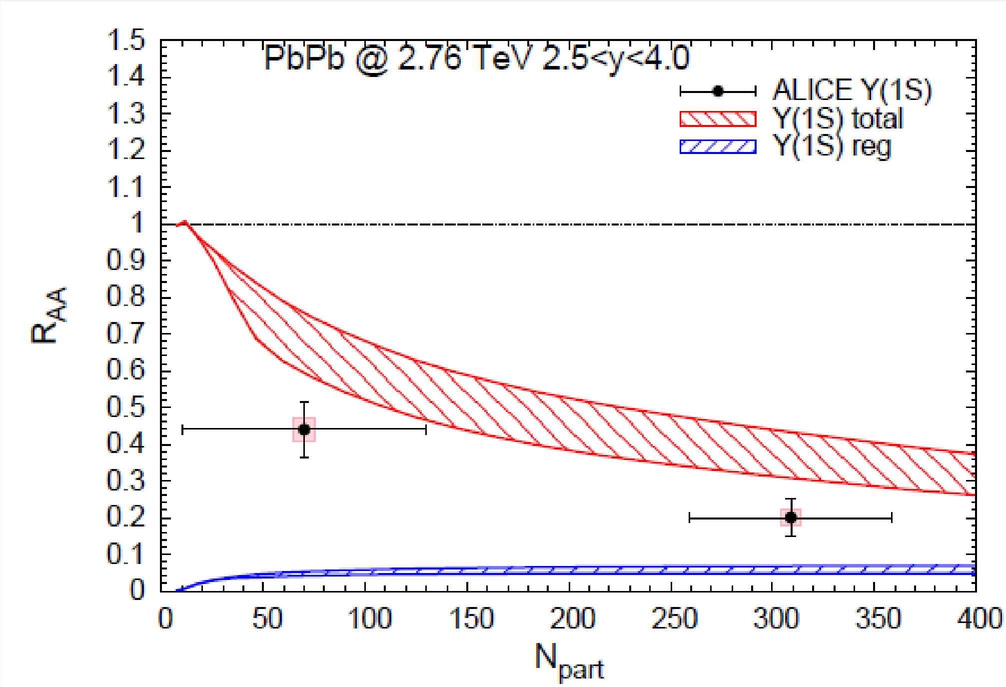
$$R_{AA}^{hot} \equiv R_{AA}^{tot} / S_{CNM}$$

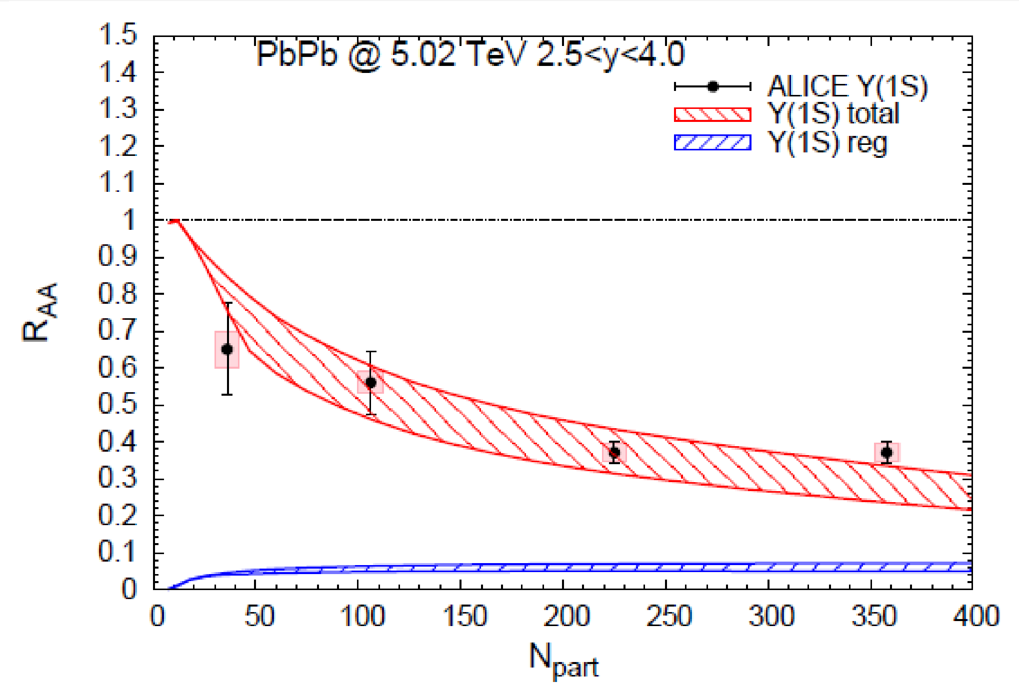




- **J/ψ** suppression at **SPS** mostly from feeddown (**$\sigma_{\psi N}$ ~7.5mb**), melts in the **RHIC → LHC** regime (not unlike **Υ(2S)**)

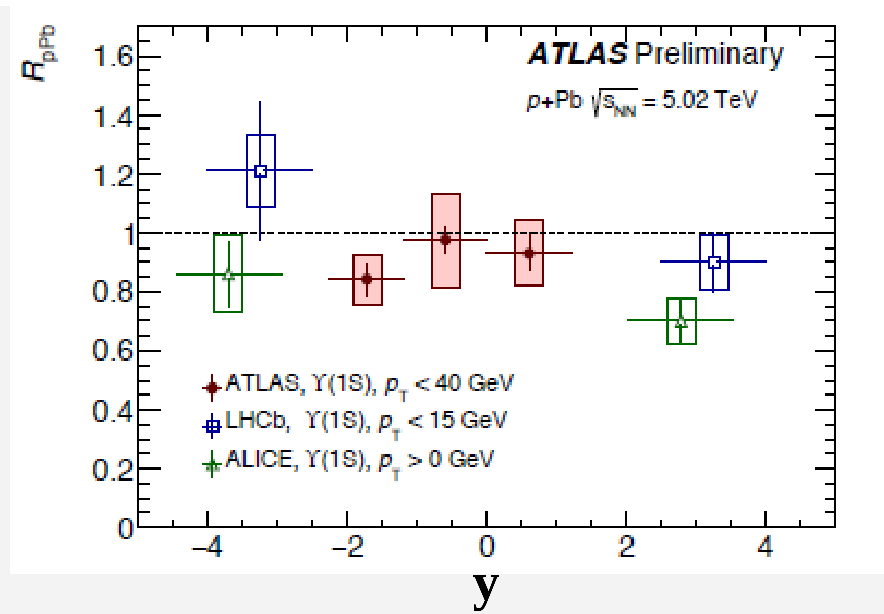
4.2 ϒ(1S): Rapidity Puzzle





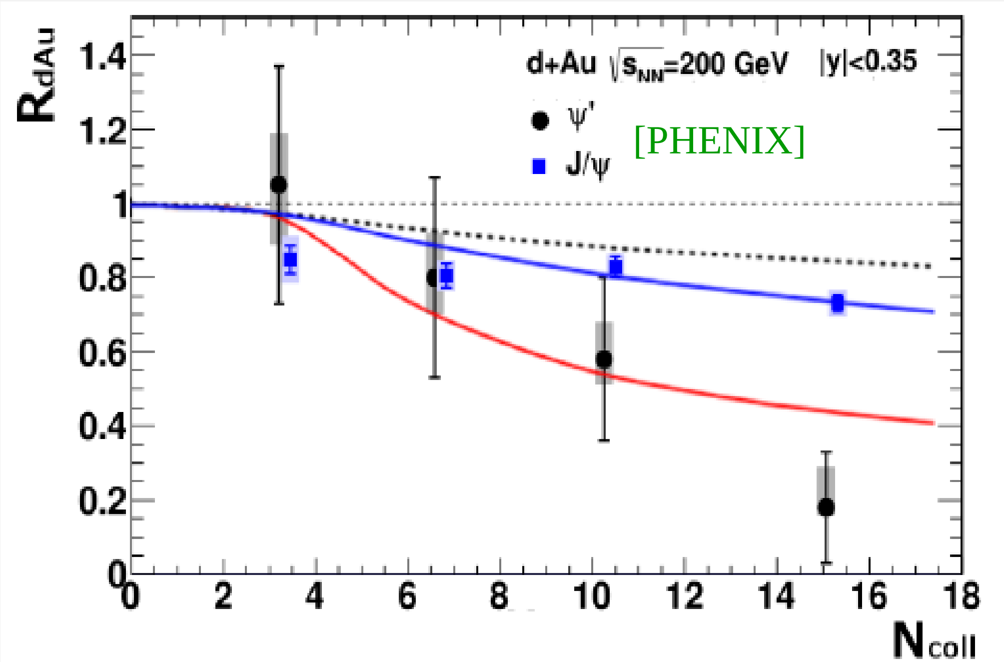
- problem of large(r) suppression in 2.76 TeV **ALICE** data
- beware of cold nuclear matter effects
- Regeneration: $\mathbf{N_{bb} \sim 1}$ for central **PbPb**

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

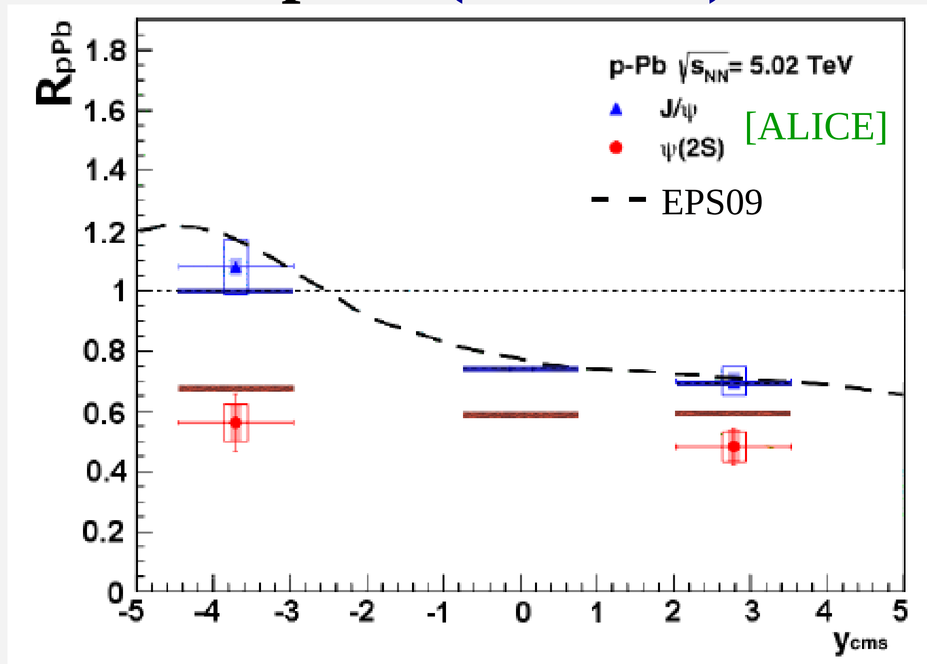


3.5 ψ(2S) in p/dA: A Sensitive Medium Probe

d-Au (0.2TeV)



p-Pb (5.02TeV)



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

[Ferreiro '15]

- supports fireball formation with:

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

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

similar to thermal widths at $T \approx$ 200MeV

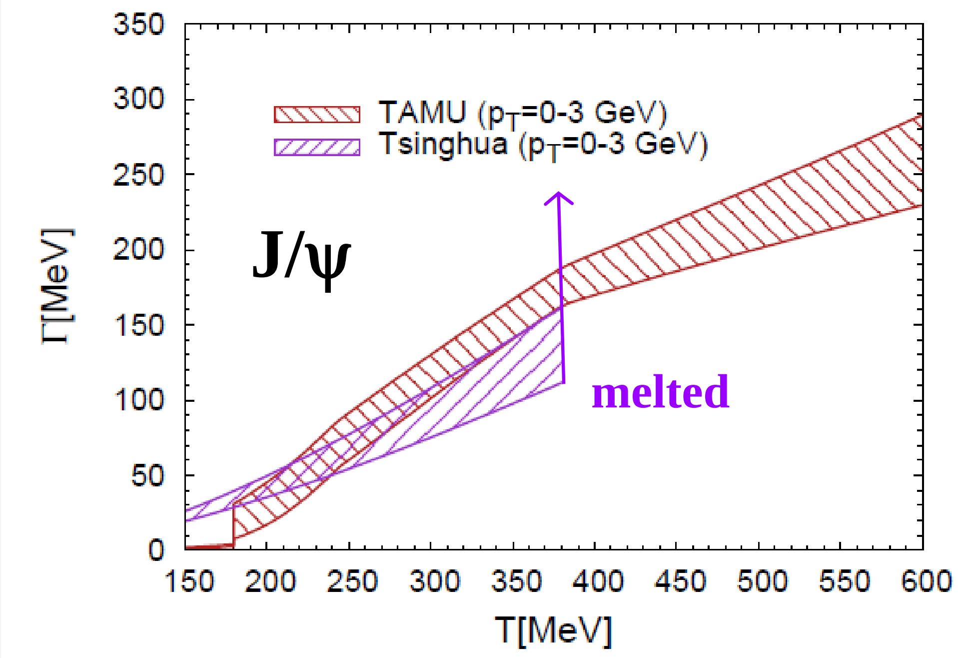
[Du et al '15]

5.) Summary

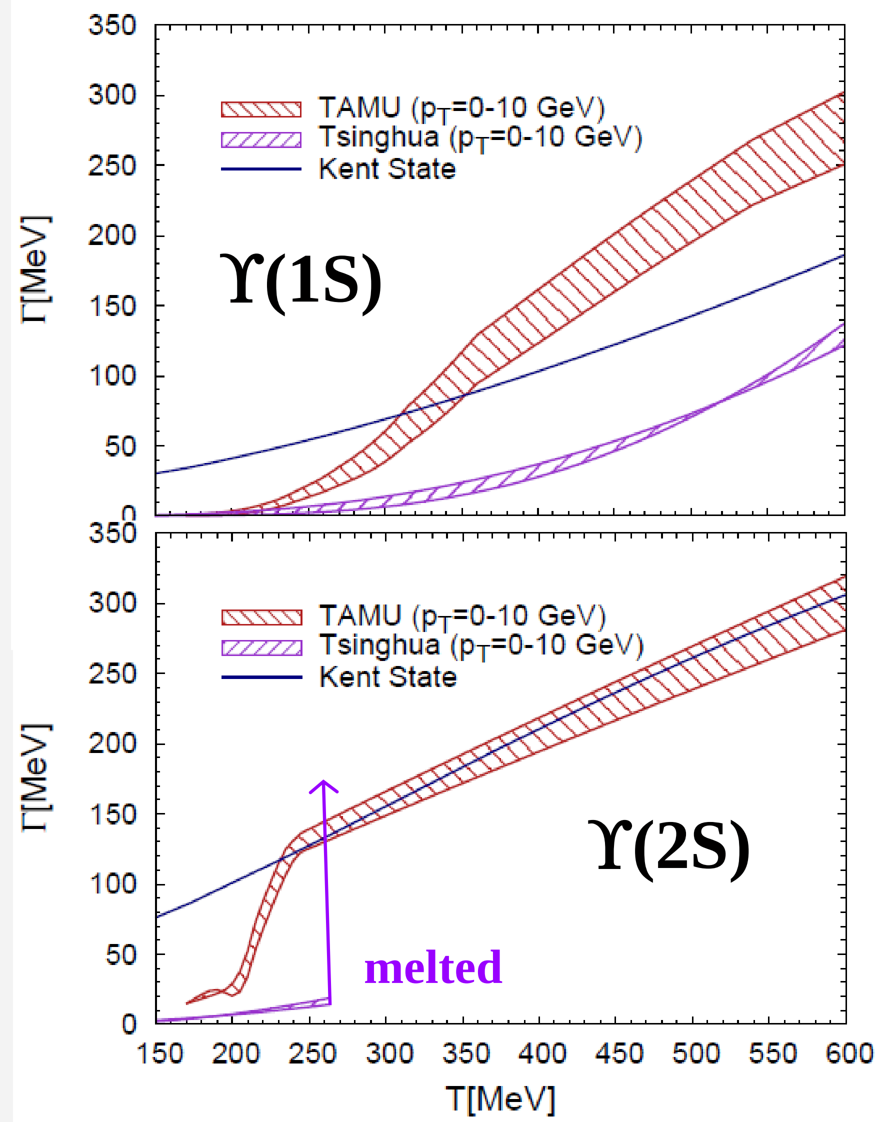
- Heavy quarkonia: hard production but **soft medium probe**
- Unique opportunity to unravel in-medium QCD force via thorough rooting in **lattice QCD**
- Both regeneration (**Ψ**) and dissociation (**ϒ**) provide tell-tale signatures of in-medium screening
- Heavy-quark reaction rates rooted in open-HF phenomenology
- Key roles also in **pA**: CNM effects (**J/ψ**, **ϒ(1S)**) + sensitive probes of putative medium (**ψ(2S)**, **ϒ(3S)**)

2.2 Quarkonium Width Comparisons

Charmonium



Bottomonium



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

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.

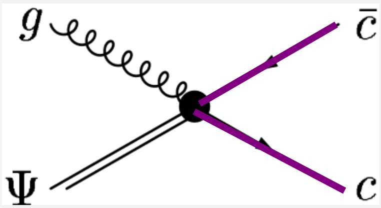
→ **Rate** equation

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

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

- **Reaction Rate** Γ_ψ

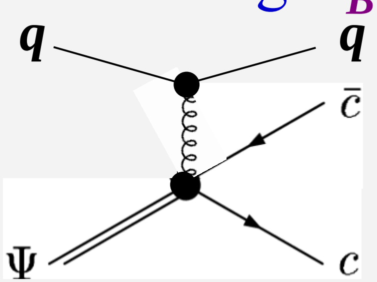
"Strong" binding $E_B \geq T$



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

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

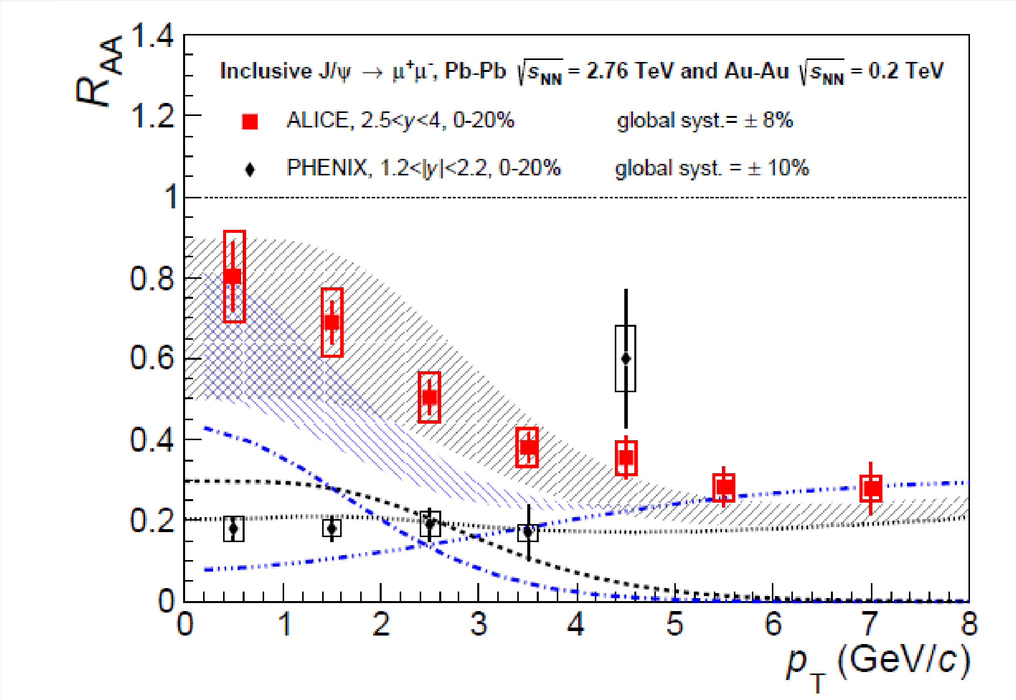
"Weak" binding $E_B < m_D$

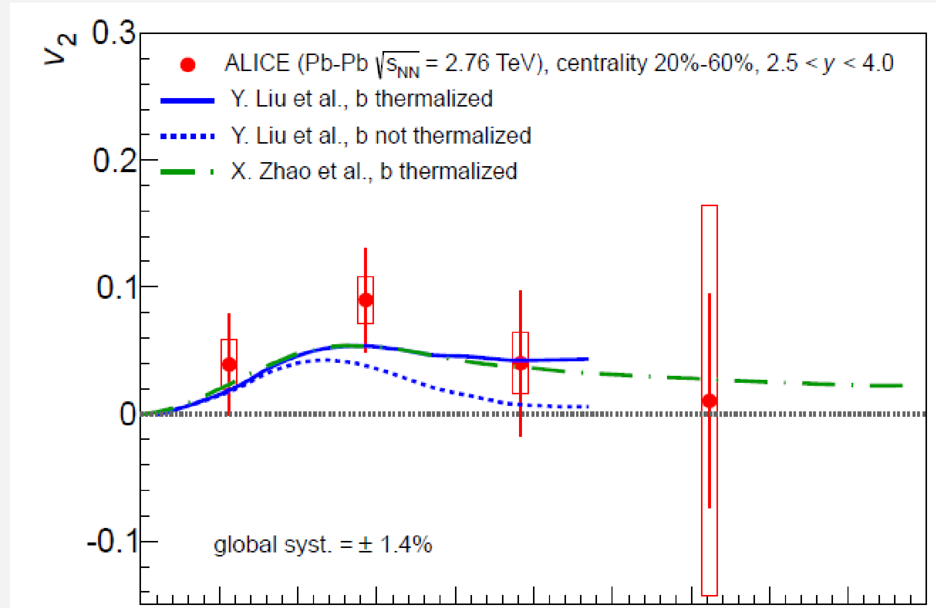


• "quasi-free"/ Landau damping

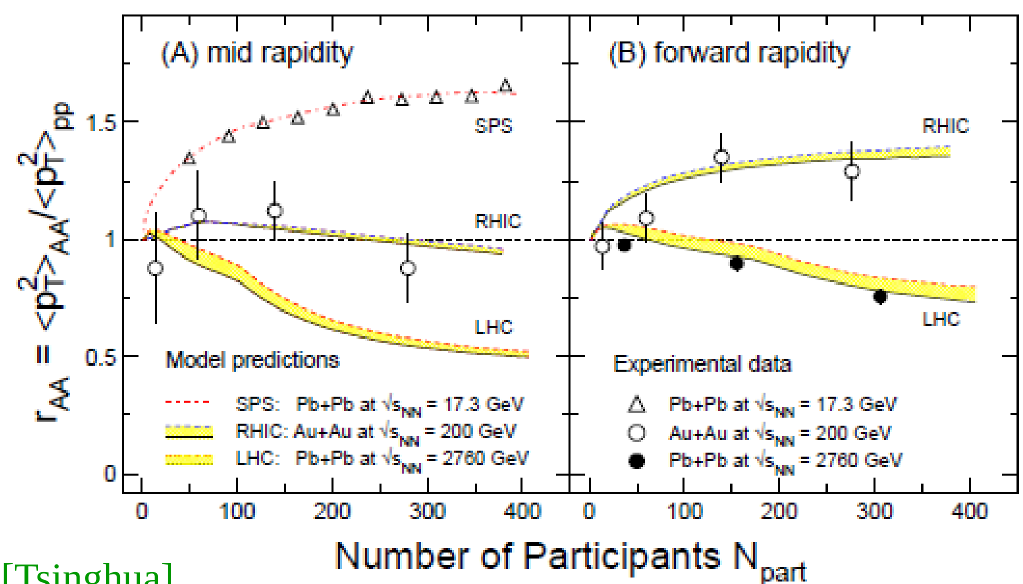
[Grandchamp+RR '02, Song et al '07, Laine et al '07,…]

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

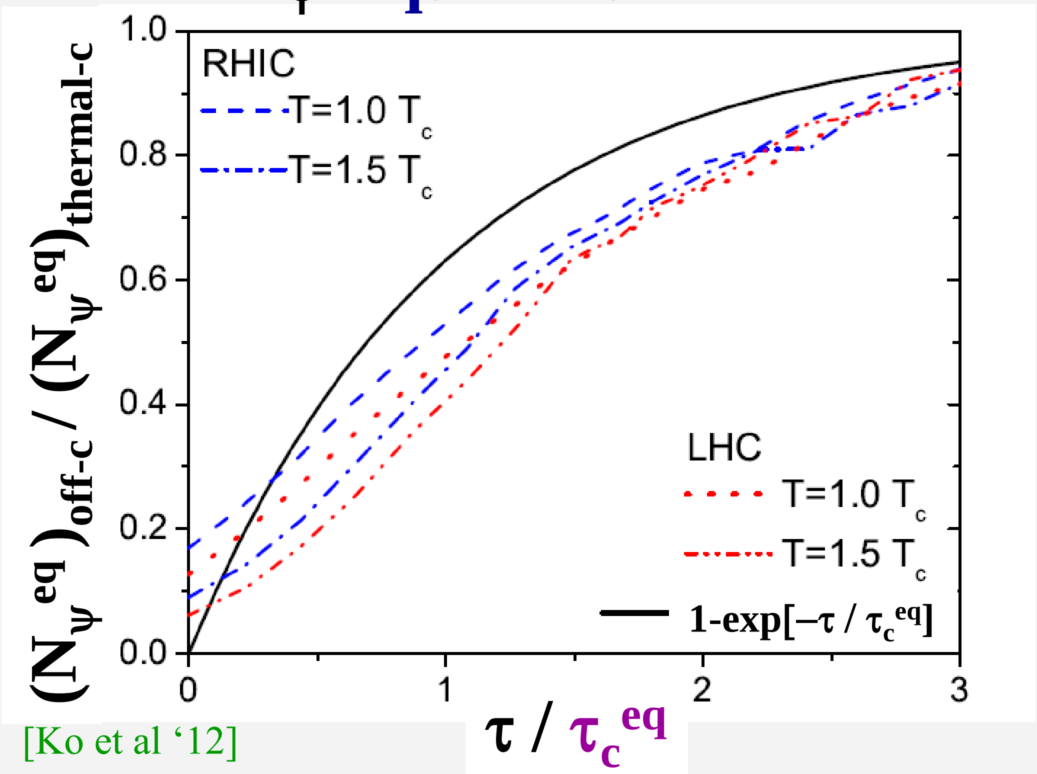


[Tsinghua]

4.1 Charm Thermalization + J/ψ Regeneration

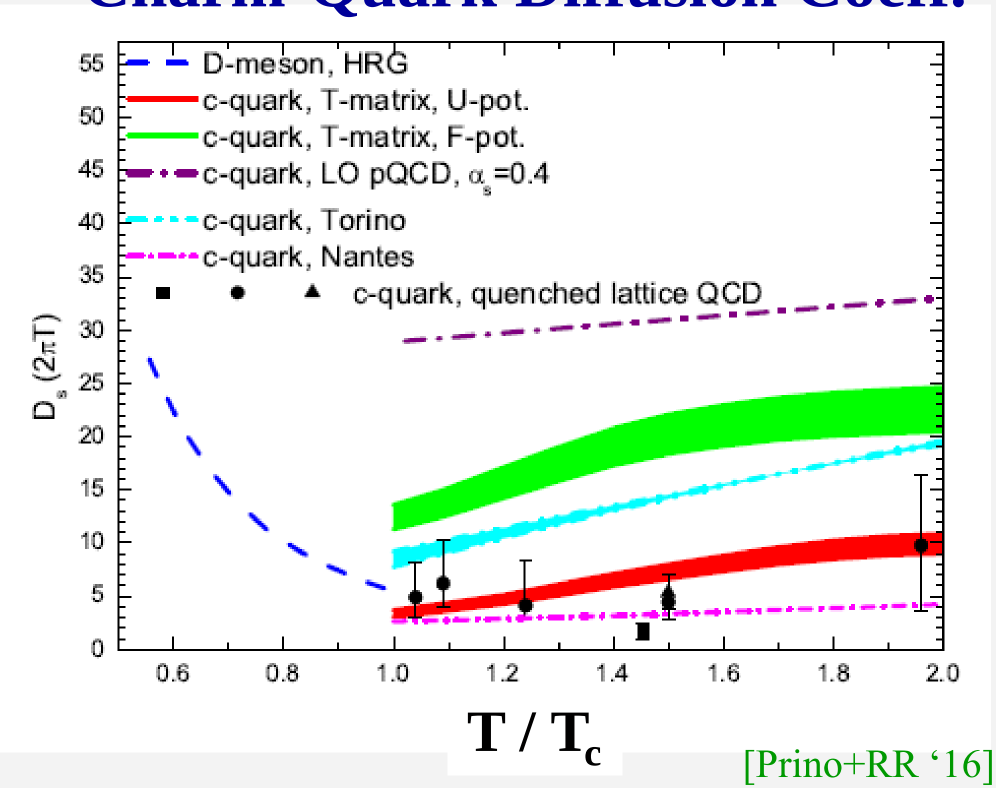
→ Softening of charm-quark spectra facilitates regeneration

J/ψ Equilibrium Fraction



[Ko et al '12]

Charm-Quark Diffusion Coeff.



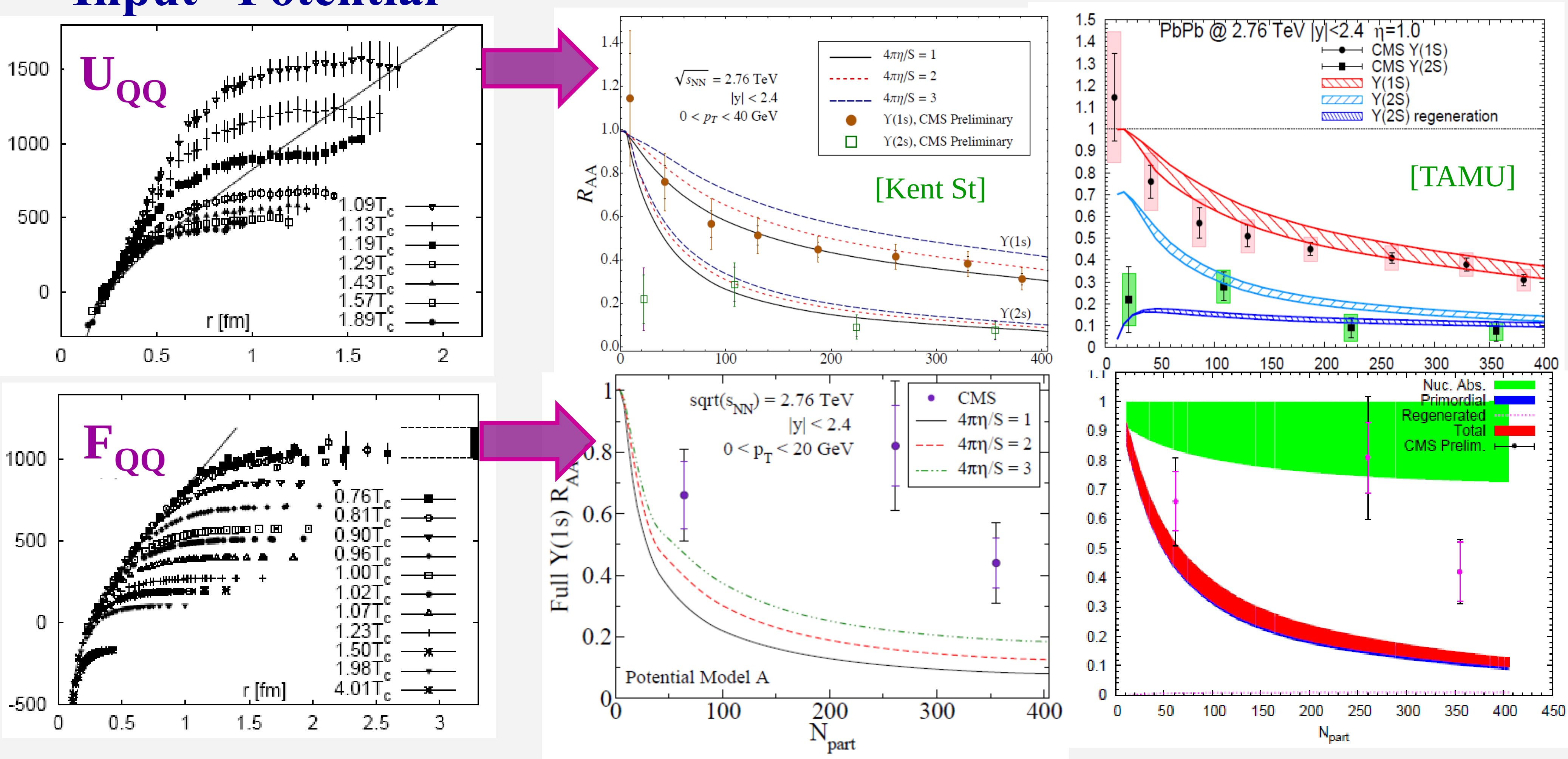
[Prino+RR '16]

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

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

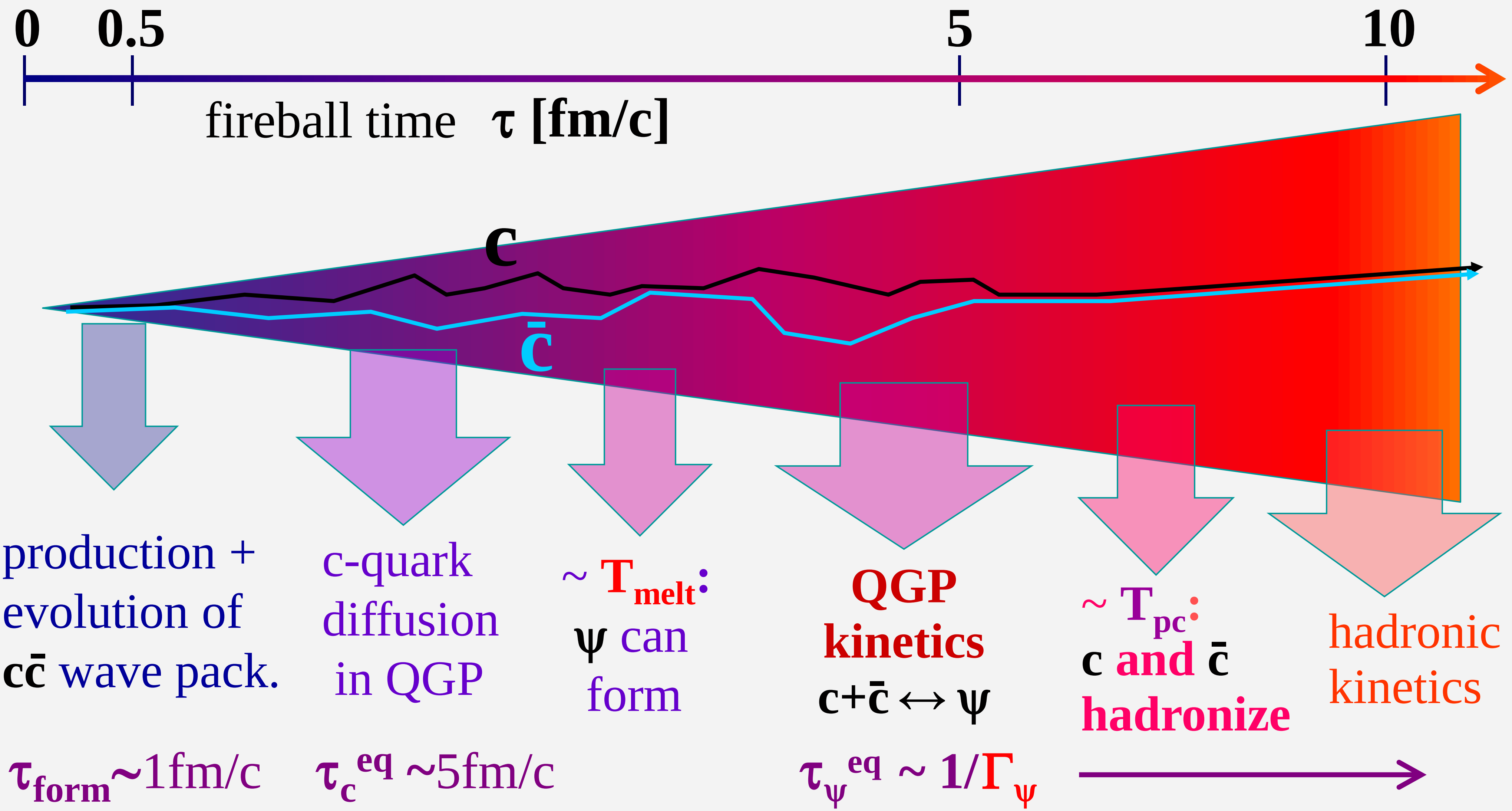
4.2 Heavy-Quark Potential and ϒ(1S) Suppression

Input "Potential"



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

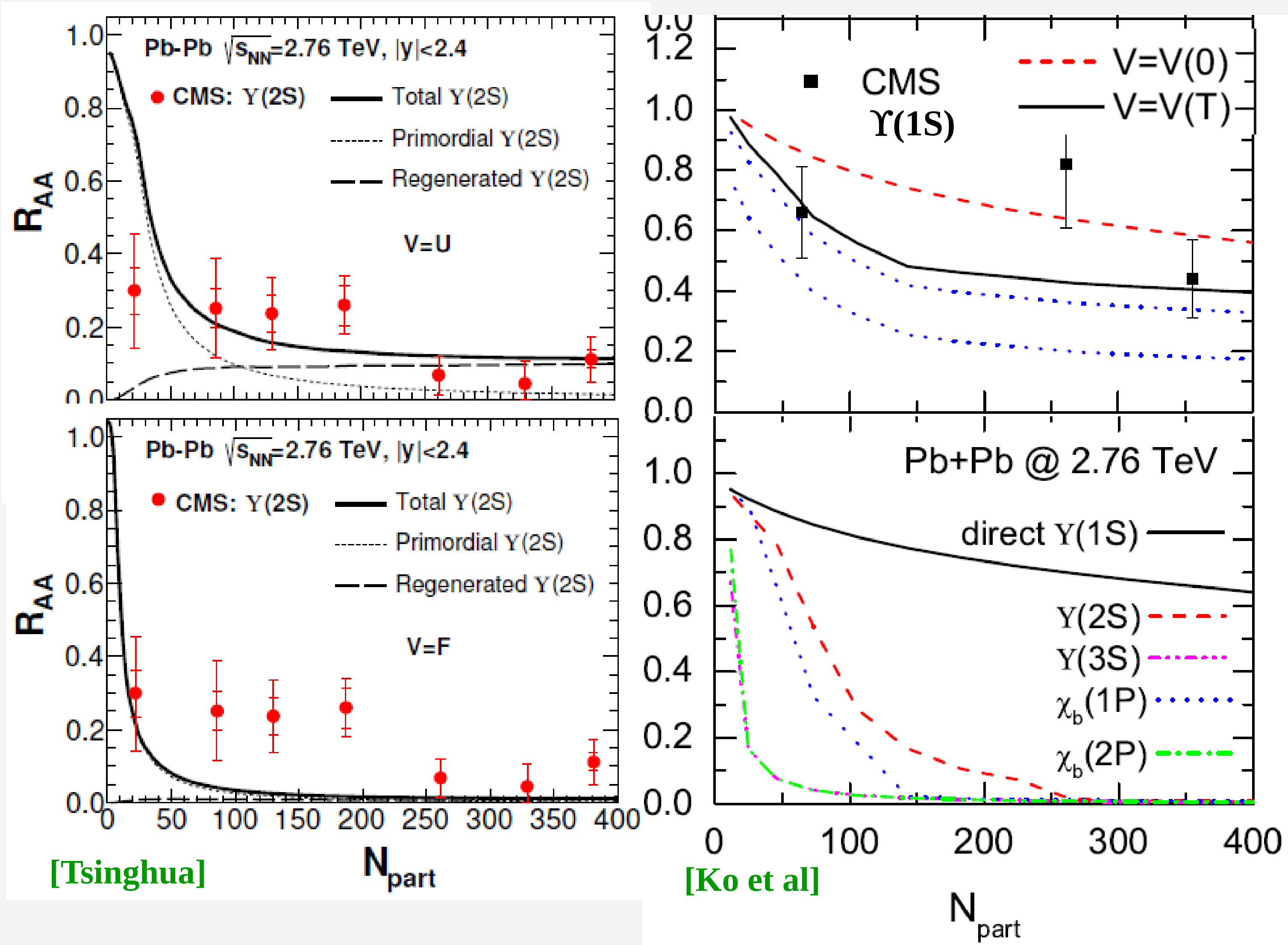
1.3 Quarkonium Transport in URHICs



[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, …]

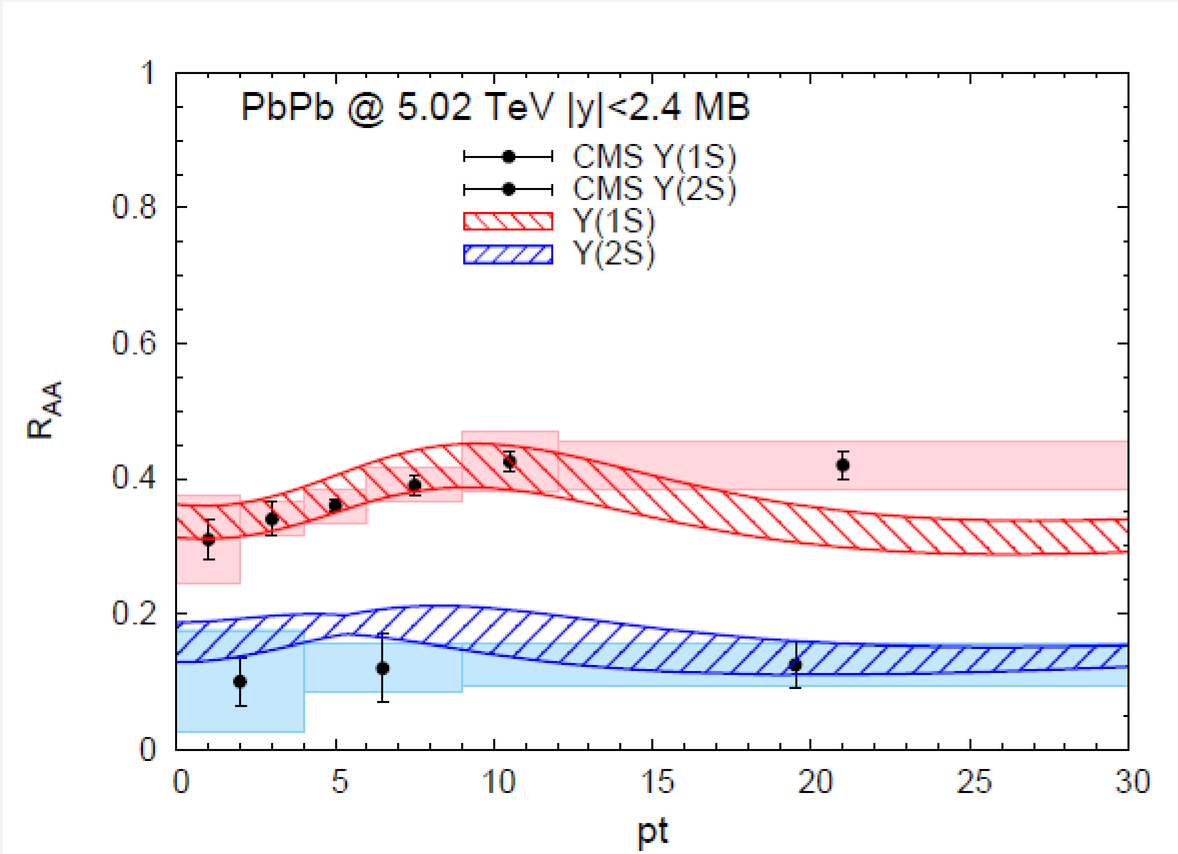
4.2 ϒ(1S) and ϒ(2S) Transport cont'd

… as implemented in current transport approaches

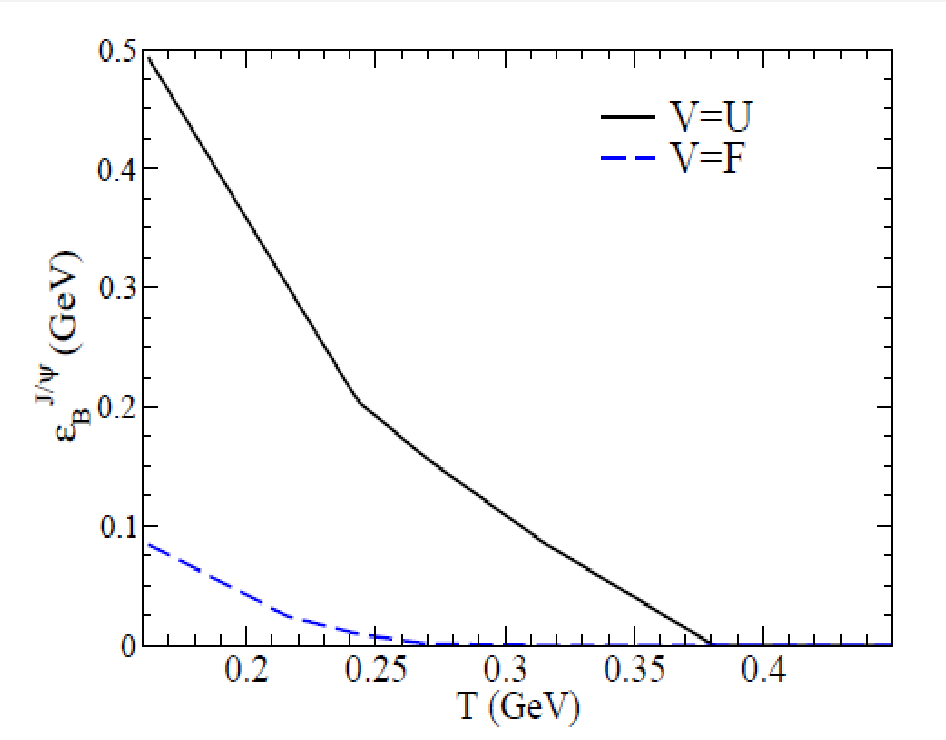


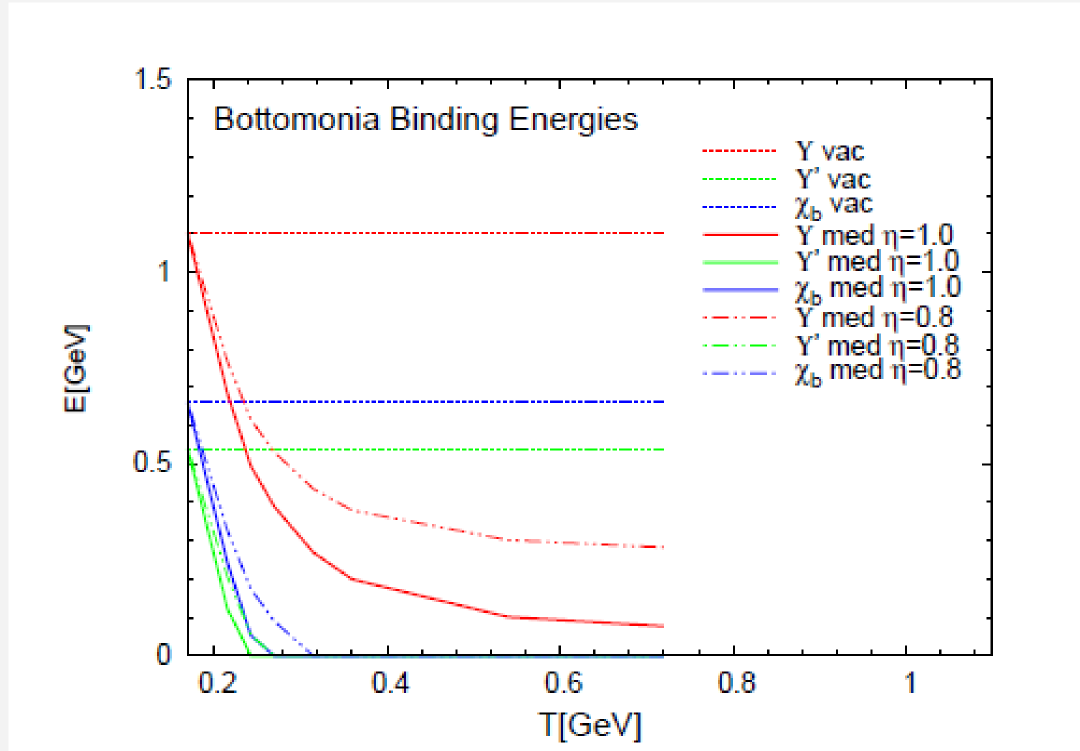
- ϒ(2S) more sensitive sensitive to in-medium potential

4.5 ϒ p_t Spectra in Pb-Pb(5.02TeV)



4.5 In-Medium Quarkonium Binding Energies

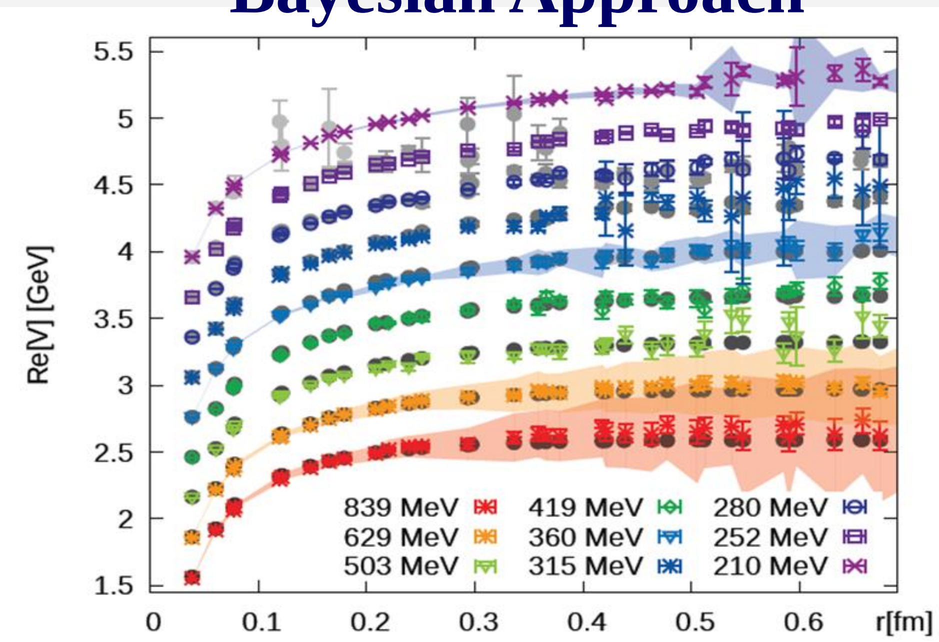




2.1 Potential Extraction from Lattice Data

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

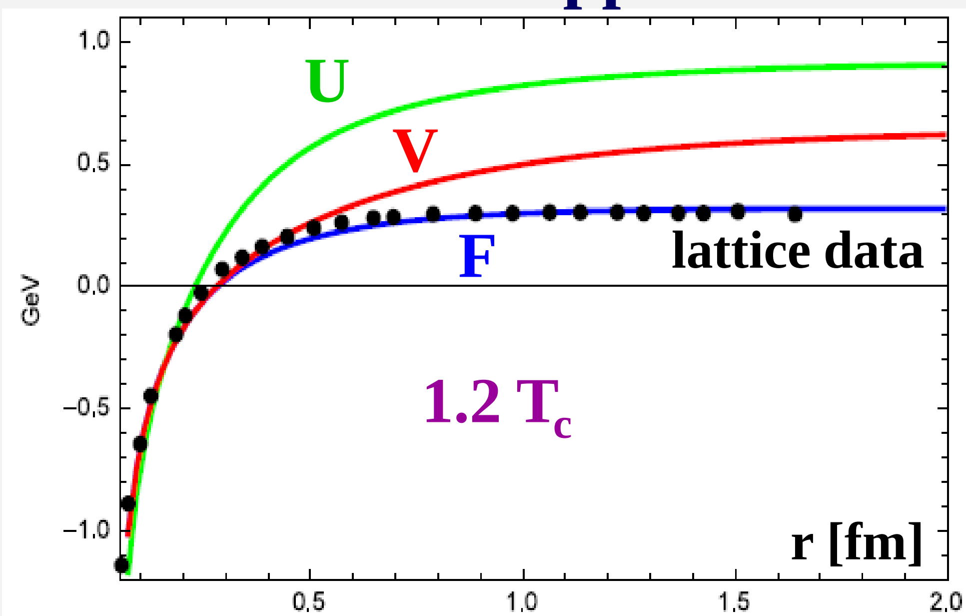
Bayesian Approach



- **Potential close to free energy**

[Burnier et al '14]

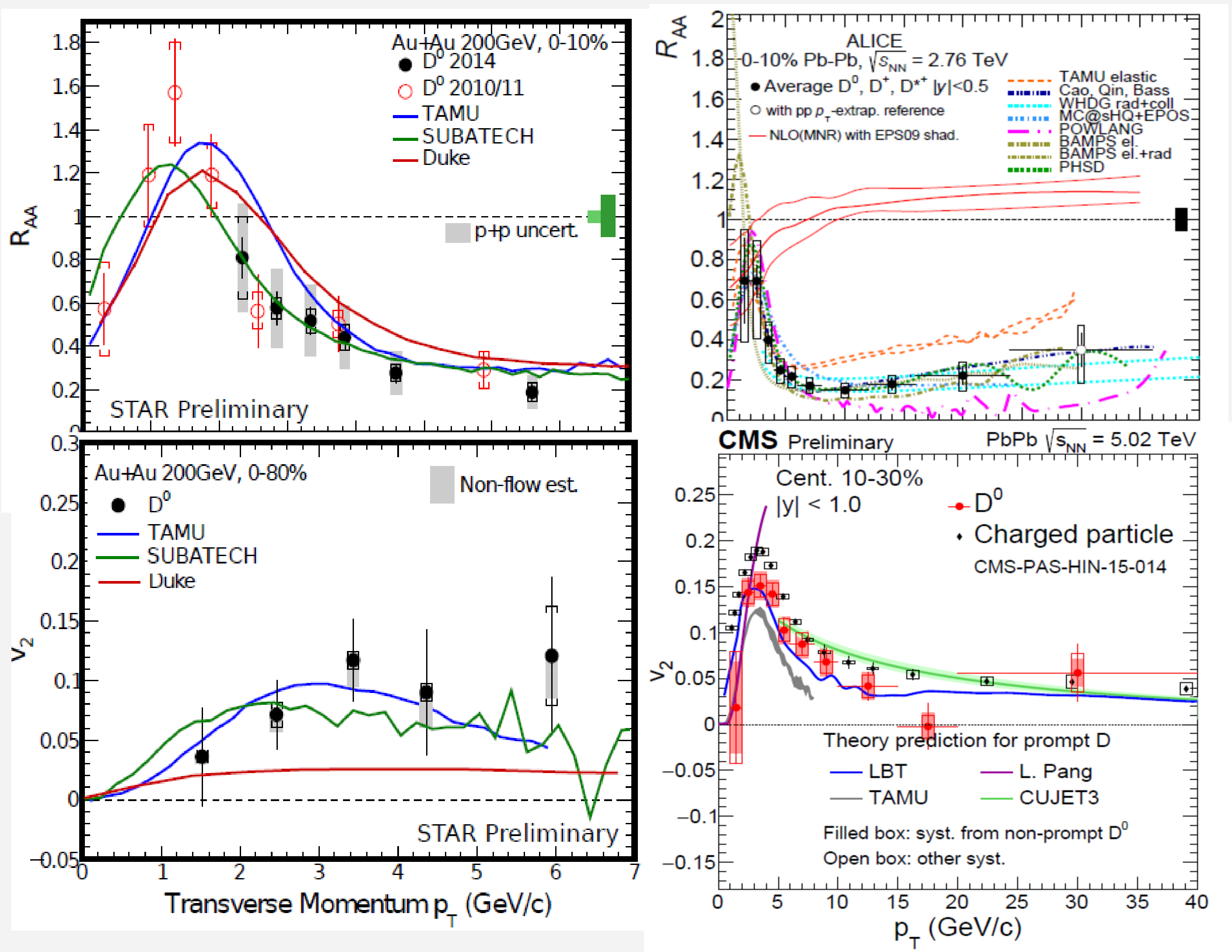
T-Matrix Approach



- 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?