# Recent Developments for Quarkonia in Medium


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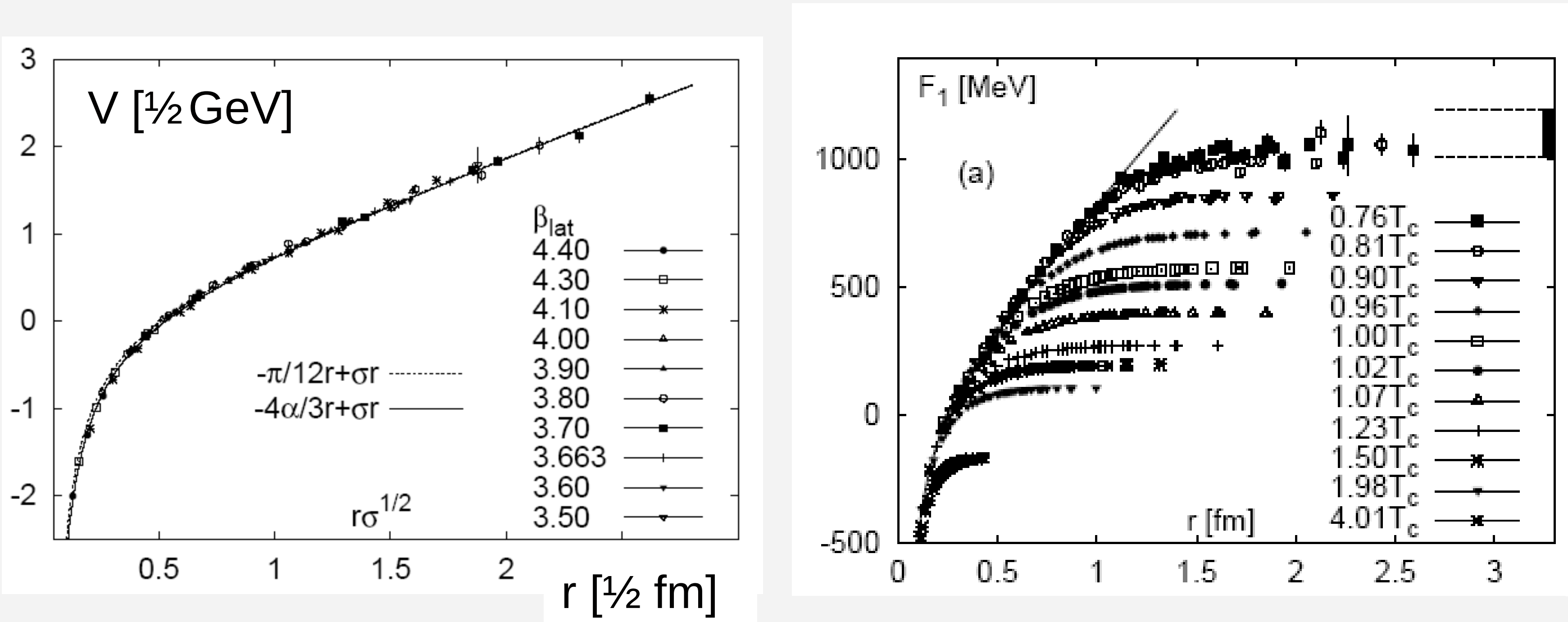
INT (Seattle, WA), 29.09. - 02.10.14

# 1.) Introduction: A "Calibrated" QCD Force




[Kaczmarek et al '03]

- Vacuum charm-/bottomonium spectroscopy well described
- Confinement?! Operational criterion: **linear part of potential**
- most sensitive to **J/ψ** + **ϒ'** (**$E_B^{Coul}$(J/ψ) ~ 0.05 GeV** vs. **0.6 GeV** exp.)
- **nonperturbative** treatment
- potential approach in medium?

# Outline

1.) Introduction

2.) T-Matrix for Heavy Flavor in QGP

3.) Quarkonium Transport at RHIC + LHC

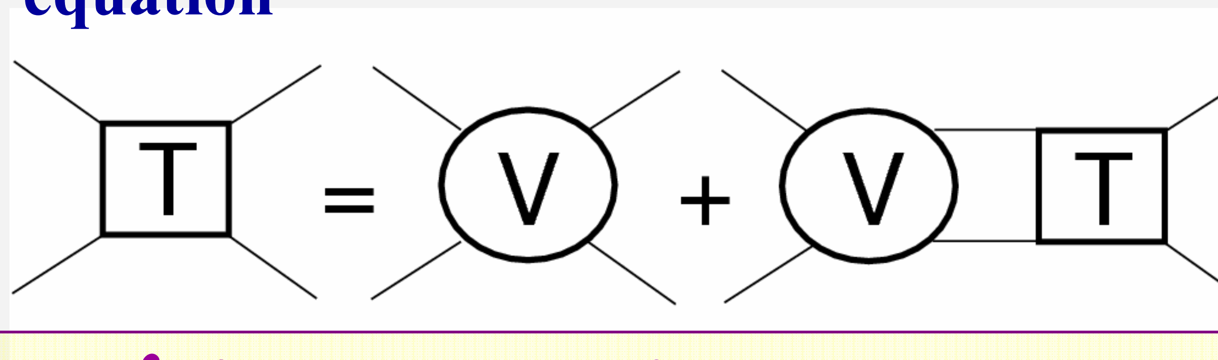
4.) Heavy-Quark Potential in Medium

5.) Conclusions

# 2.) Thermodynamic T-Matrix for Quarkonia in QGP

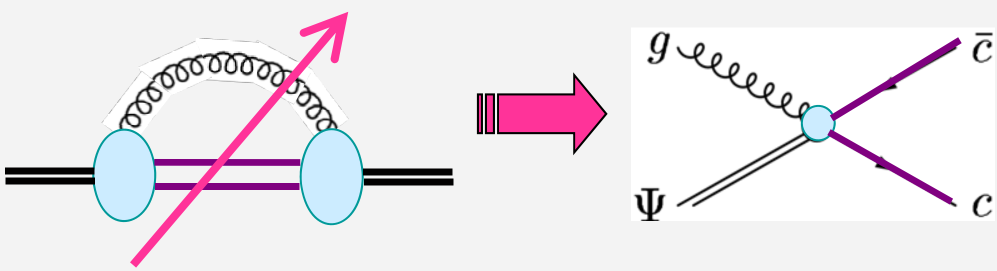
- **Lippmann-Schwinger equation**

**In-Medium**
**Q-Q̄ T-Matrix:**

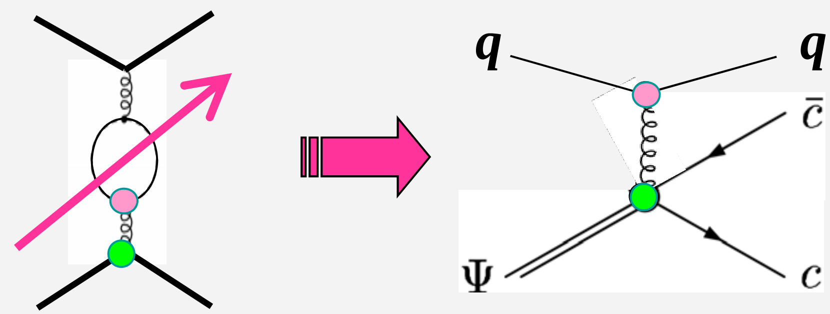



$$T_\alpha(E;q,q')=V_\alpha(q,q')+\int k^2dk\; V_\alpha(q,k)\; G^0_{Q\bar{Q}}(E,k)\; T_\alpha(E;k,q')$$

- potential $V_\alpha$ real
- imaginary parts: unitarization (cuts in in-med. **QQ̄** propagator $G_{QQ}$)

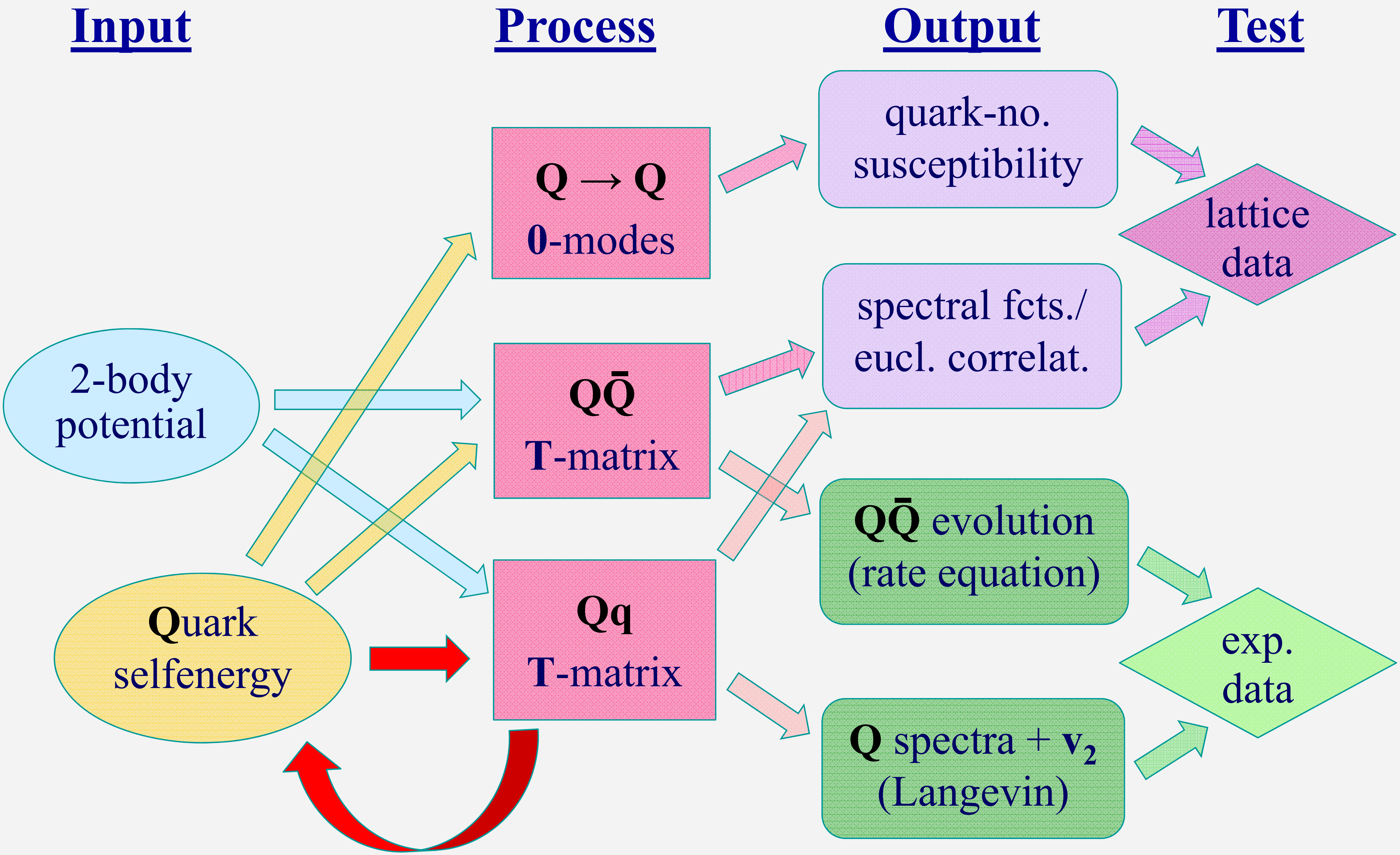



- gluo-dissosciation (coupled channel)
  [Bhanot+Peskin ‘85]




- Landau damping (HQ selfenergy)

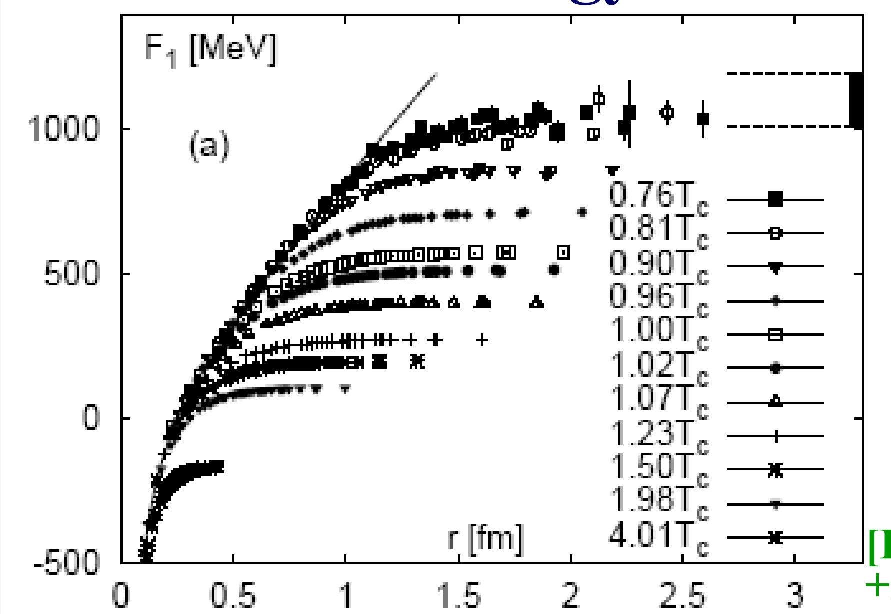
# 2.2 Brueckner Theory of Heavy Quarks in QGP



# 2.3 Free vs. Internal Energy in Lattice QCD

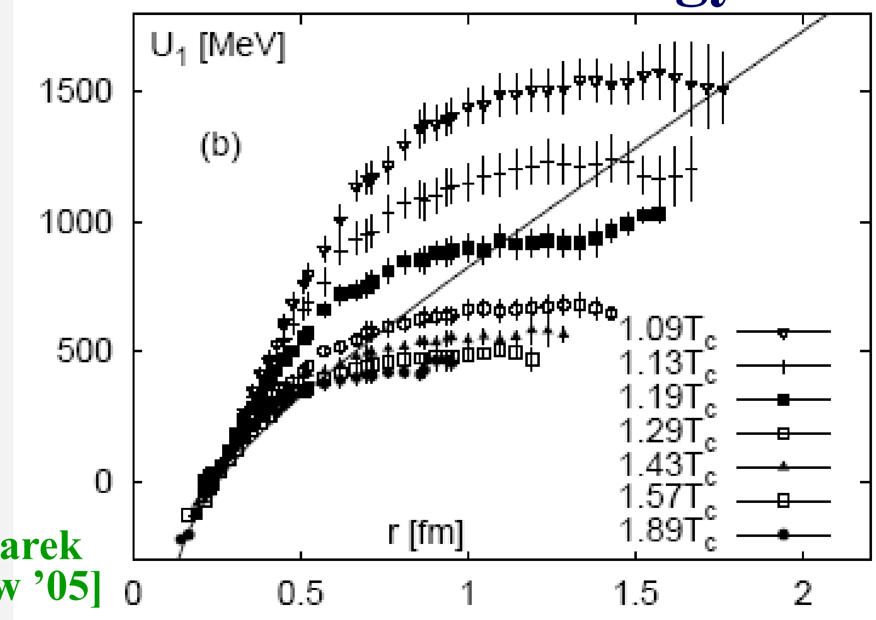
$$F_1(r,T) = U_1(r,T) - T\,S_1(r,T)$$

**Free Energy**




[Kaczmarek +Zantow '05]

**Internal Energy**




- weak **$Q\bar{Q}$** potential
- small $m_Q^* \sim m_Q + F_1(\infty,T)/2$

- strong **$Q\bar{Q}$** potential, $U = \langle H_{int} \rangle$
- large $m_Q^* \sim m_Q + U_1(\infty,T)/2$

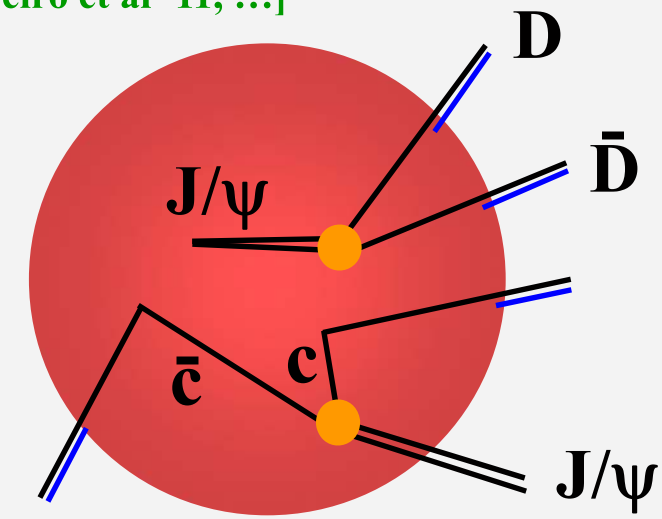
- **F, U, S thermodynamic quantities**
- Entropy: many-body effects

# 3.) 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 $\Gamma_\psi$
  - 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**

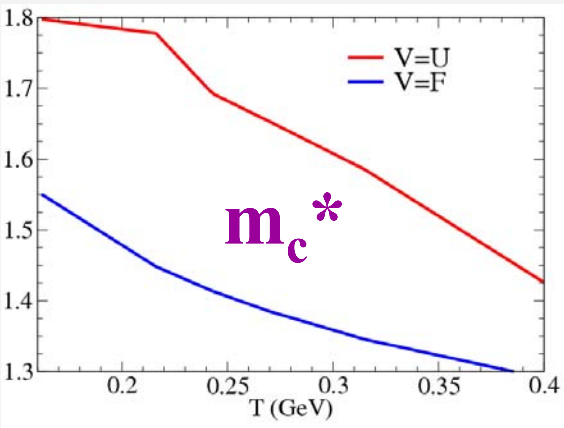
# 3.1 Thermal Charmonium Properties

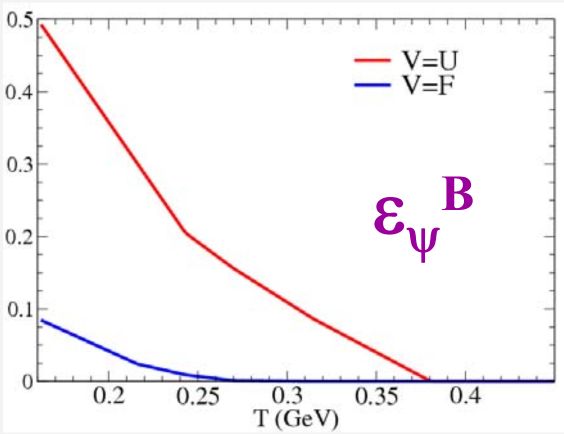
## (a) Equilibrium Ψ number:

$$N_\psi^{eq} = V_{FB}\, 3\, \gamma_c^2 \int \frac{d^3q}{(2\pi)^3}\, f^\psi(m_\psi, T)$$

- $\gamma_c$ from fixed $c\bar{c}$ number: $N_{c\bar{c}} = \frac{1}{2} V_{FB}\, \gamma_c\, n_c(m_c^*, T)\, I_1 / I_0 + \sum_\psi N_\psi^{eq}$
- interplay of $m_c$* and $m_\psi = 2m_c^* - \varepsilon_\psi^B$
- constrain spectral shape by lattice-QCD correlators

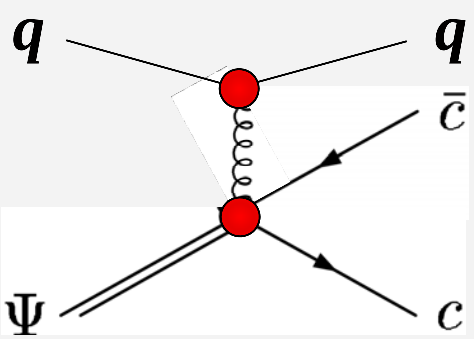
$$R_\alpha(\tau;T) = \frac{\int dE\, \sigma_\alpha(E,T)\, \mathcal{K}(\tau,E,T)}{\int dE\, \sigma_\alpha(E,T_{\rm rec})\, \mathcal{K}(\tau,E,T)}$$

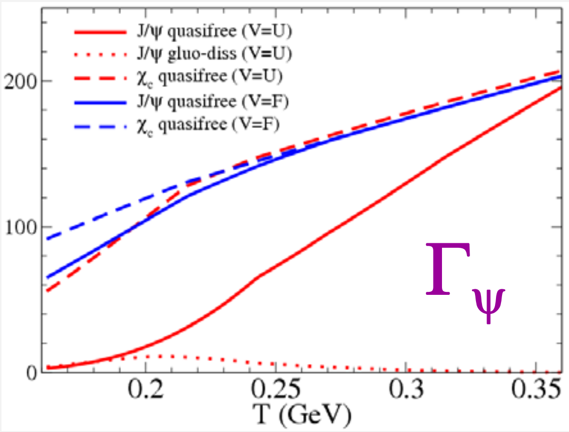



## (b) Inelastic Ψ Width

- controlled by $\alpha_s$ (parameter)

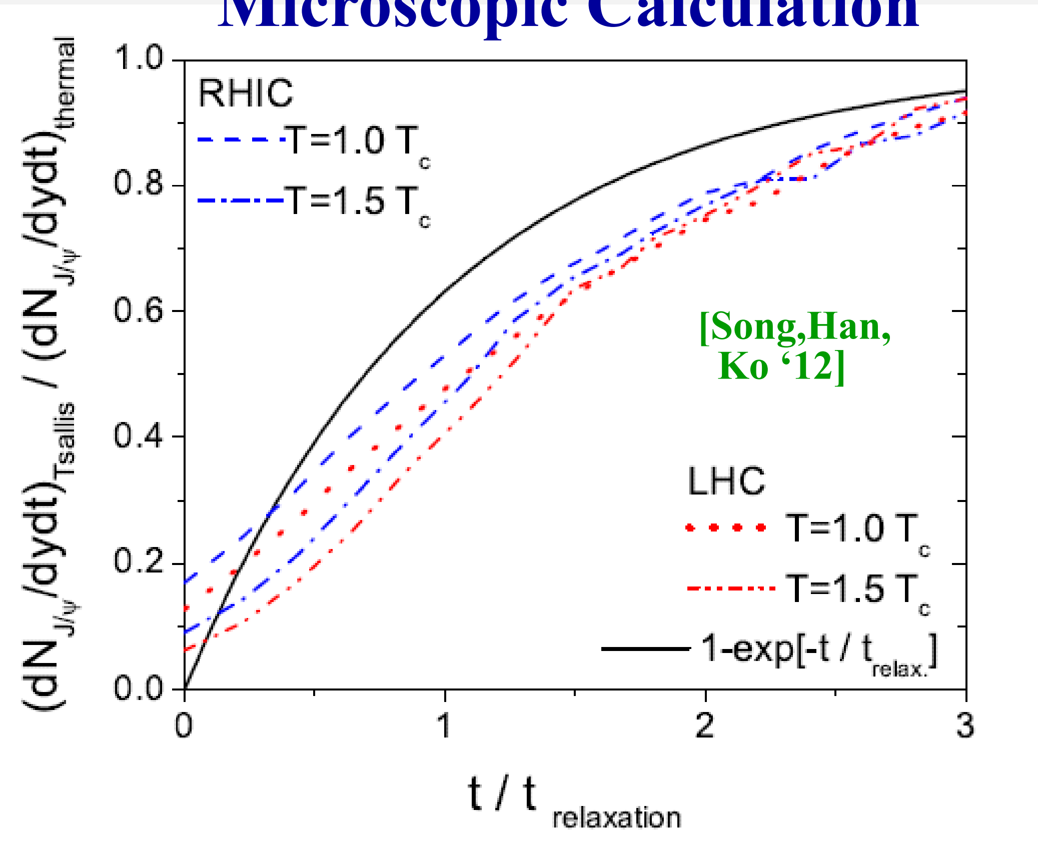


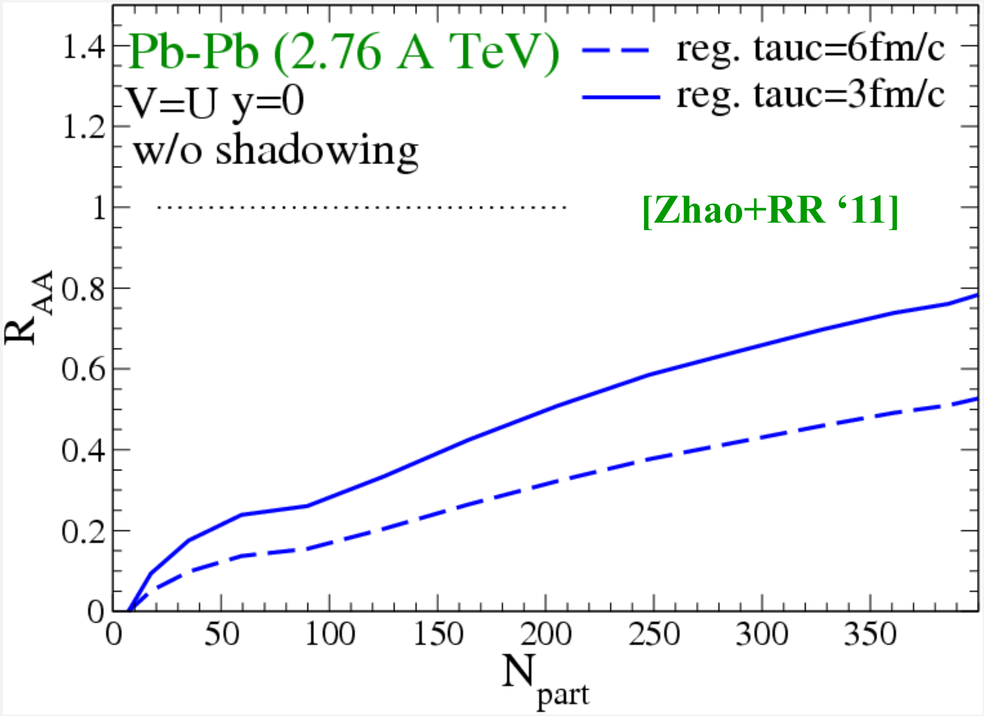
# 3.2 Incomplete c-Quark Thermalization

- Relaxation time ansatz: $N_\psi^{eq}(\tau) \sim N_\psi^{therm}(\tau) \cdot [1-\exp(-\tau/\tau_c^{eq})]$

**Microscopic Calculation**



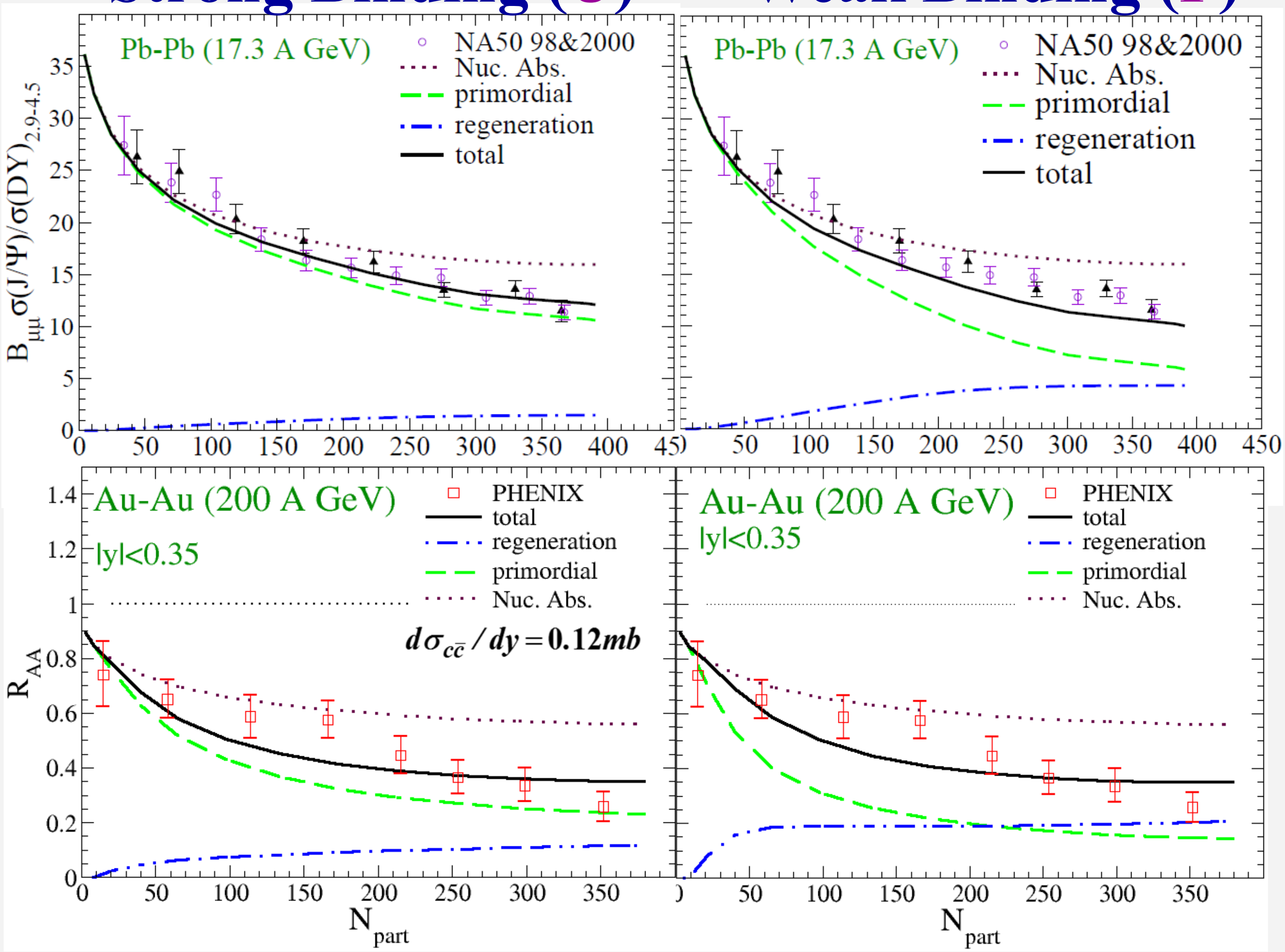

**Impact on Regeneration**




- regeneration sensitive to charm-quark spectra

# 3.3 Inclusive J/ψ at SPS + RHIC

**Strong Binding (U)** **Weak Binding (F)**



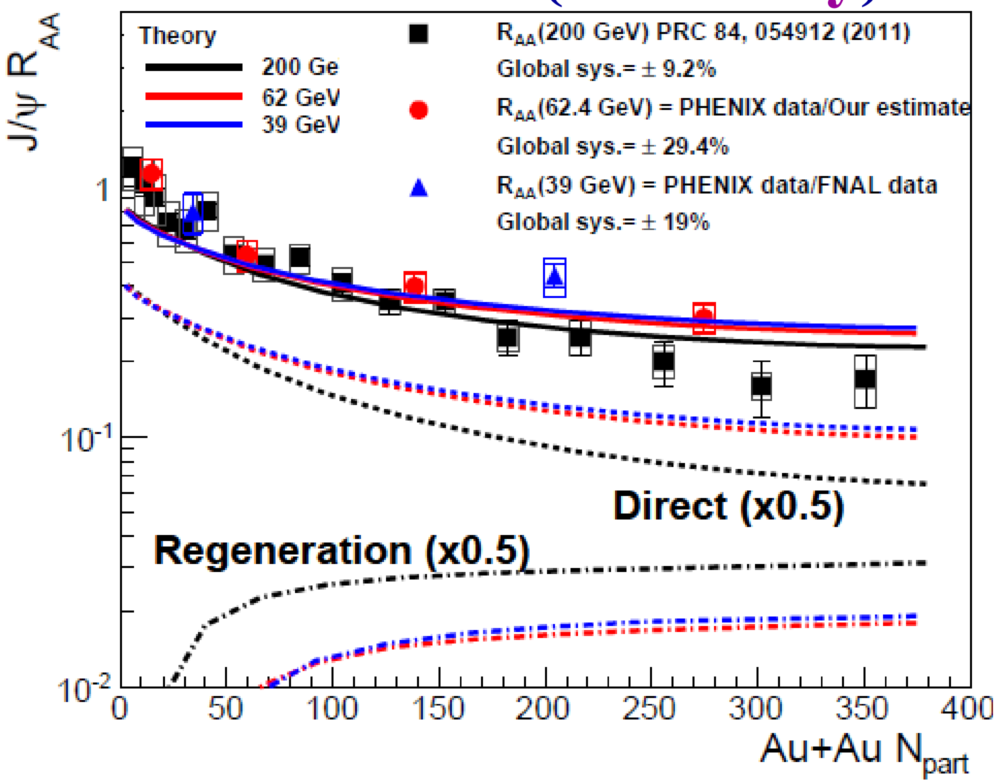

[Zhao+RR '10]

- **Fix two main parameters:**

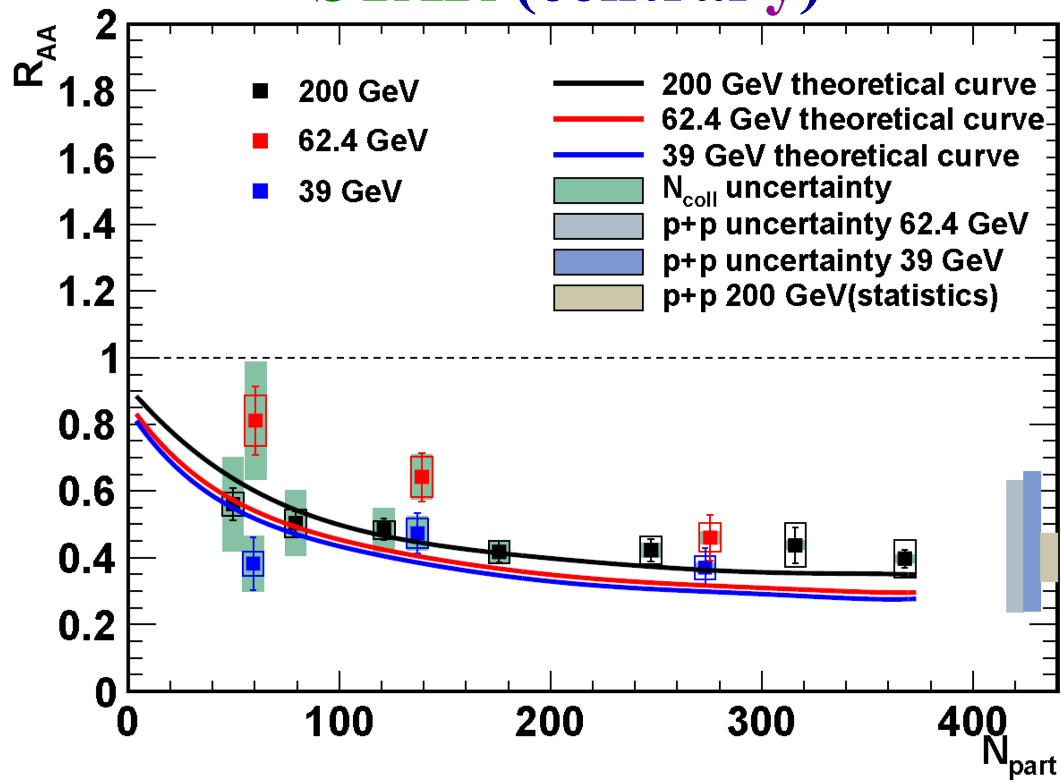
  $\alpha_s$~0.3, charm relax. $\tau_c^{eq}$ = 4(2) fm/c for U(F) vs. ~5(10) from T-matrix

# 3.4 J/ψ Excitation Function: BES at RHIC

**PHENIX (forward y)**



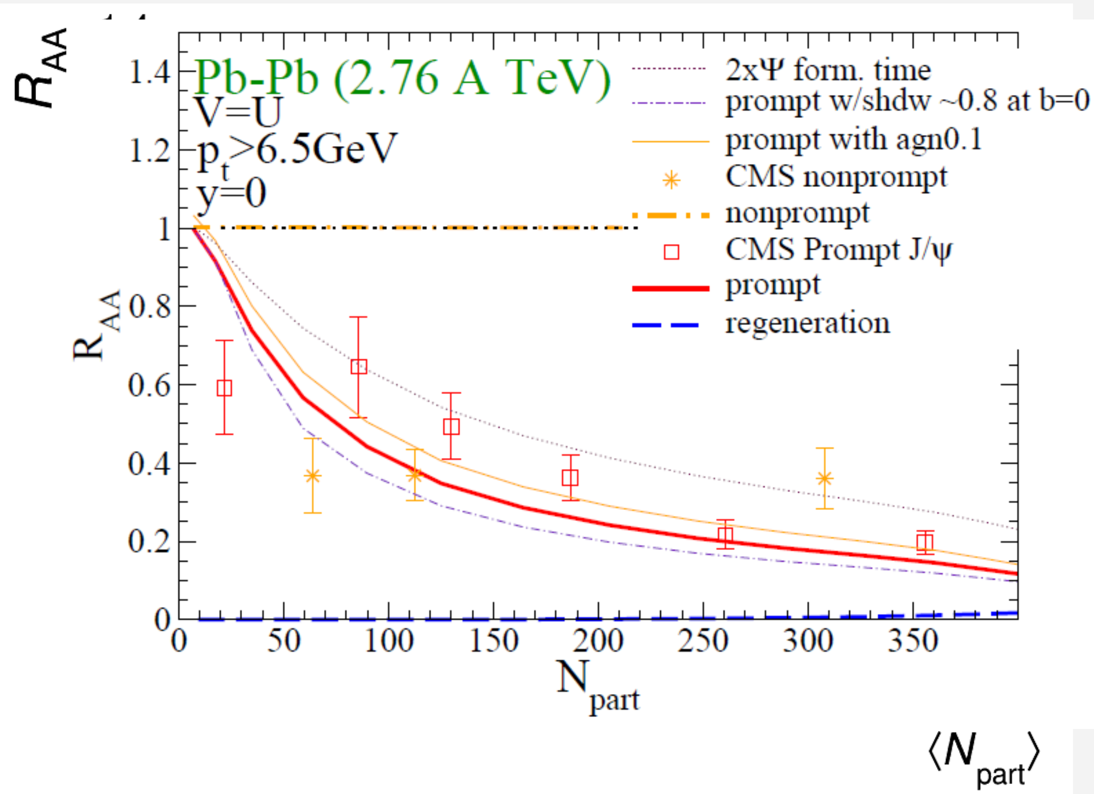

**STAR (central y)**

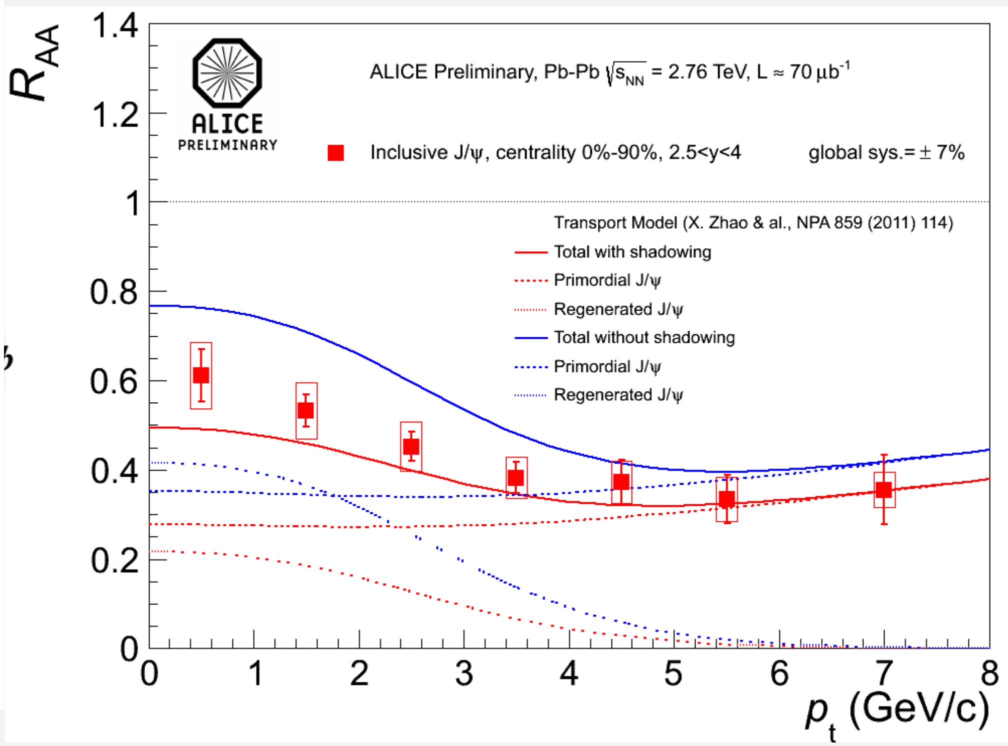



- suppression pattern varies little (expected from transport) [Grandchamp +RR '02]
- quantitative **pp** + **pA** baseline critical to extract systematics

# 3.5 J/ψ Predictions at LHC

[Zhao+RR '11]




- regeneration becomes dominant
- uncertainties in $\sigma_{cc}$+shadowing

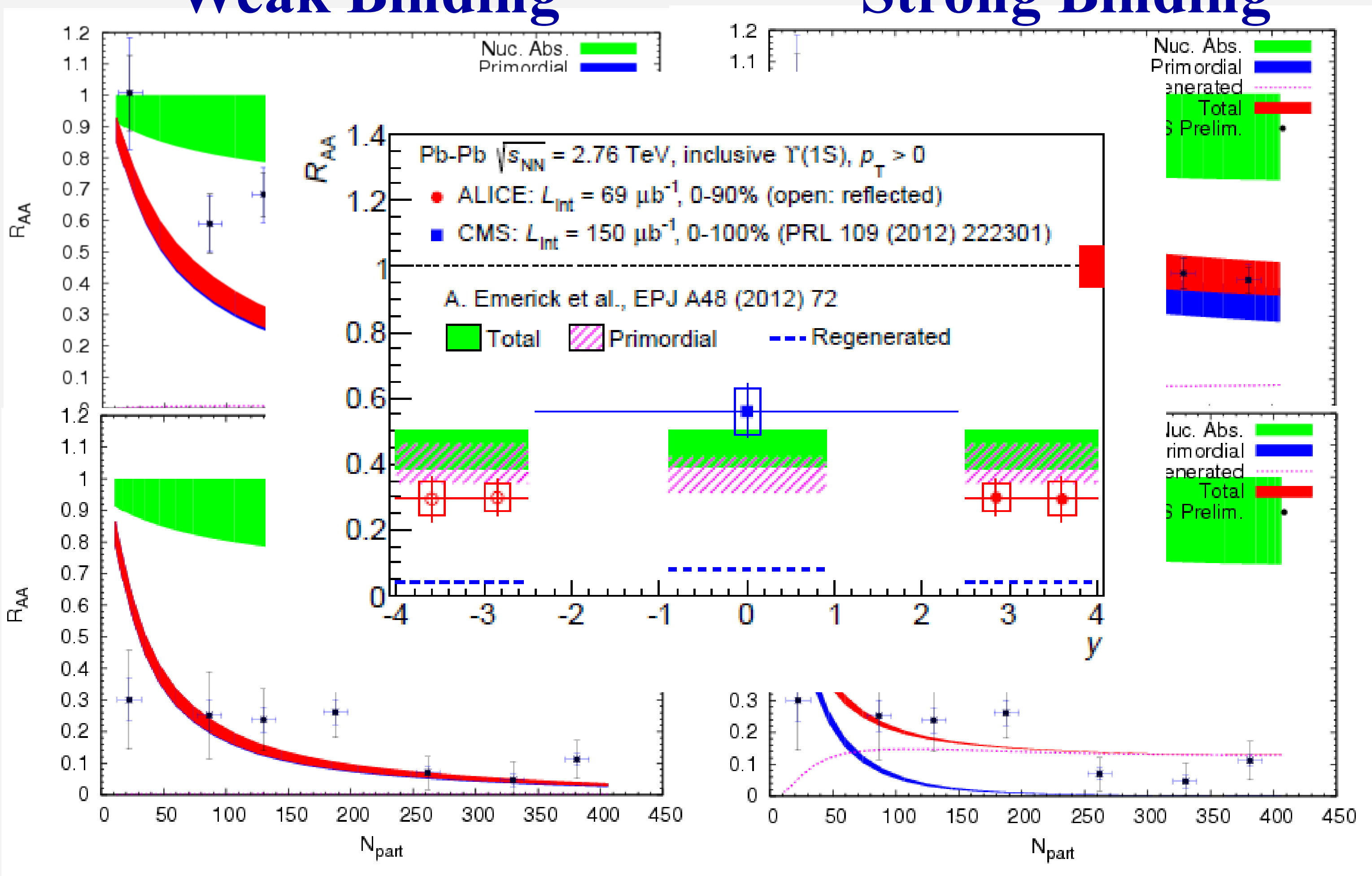
- low $p_T$ maximum confirms regeneration
- too much high-$p_T$ suppression?

# 3.6 ϒ(1S) and ϒ(2S) at LHC

**Weak Binding** **Strong Binding**

ϒ(1S) →

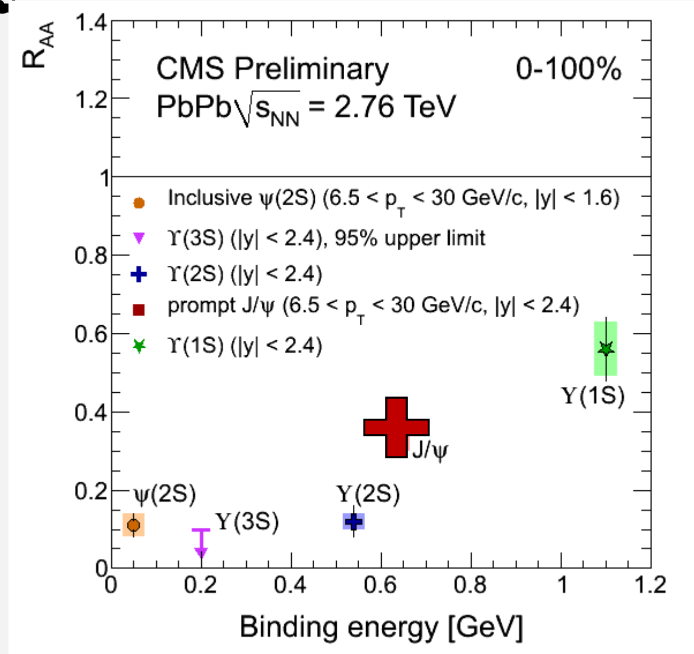
ϒ(2S) →




[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** $\mathbf{R_{AA}}$ **SPS, RHIC → LHC**
  - low-$\mathbf{p_T}$ enhancement
  - sizable $\mathbf{v_2}$
  - increasing suppression of ϒ' $(\varepsilon_B^{\Upsilon'} \sim \varepsilon_B^{J/\psi})$

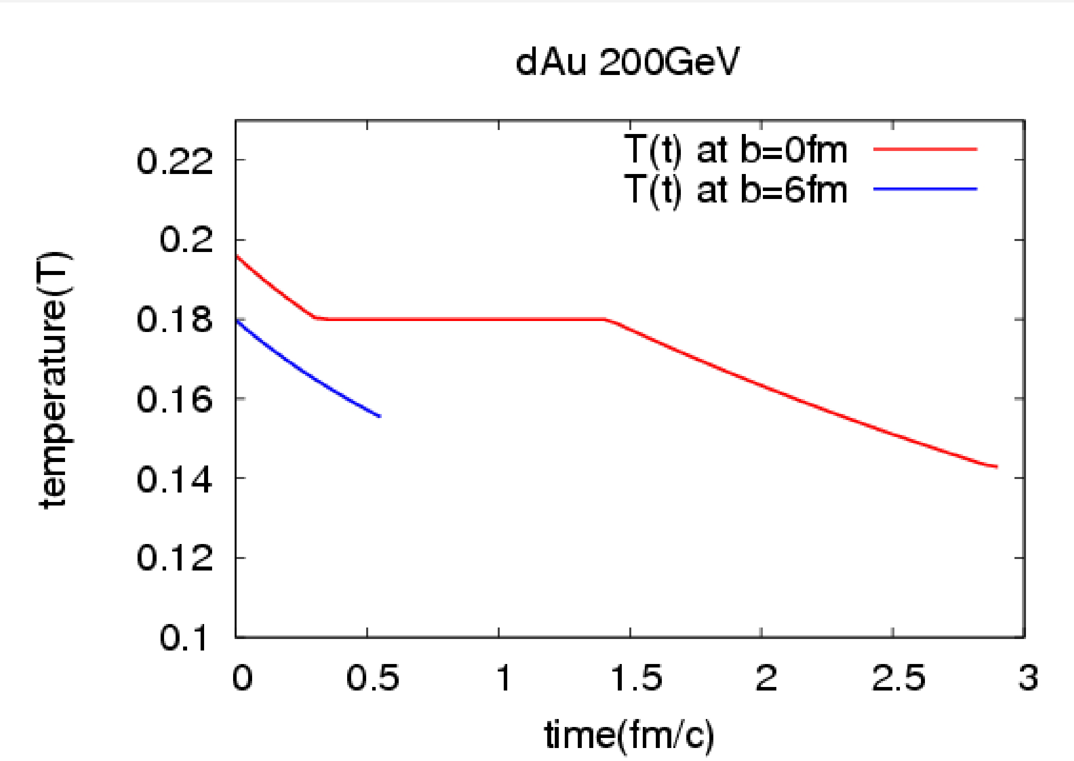
- **Fair predictive power of theoretical modeling**
  - based on description of SPS+RHIC with 2 main parameters

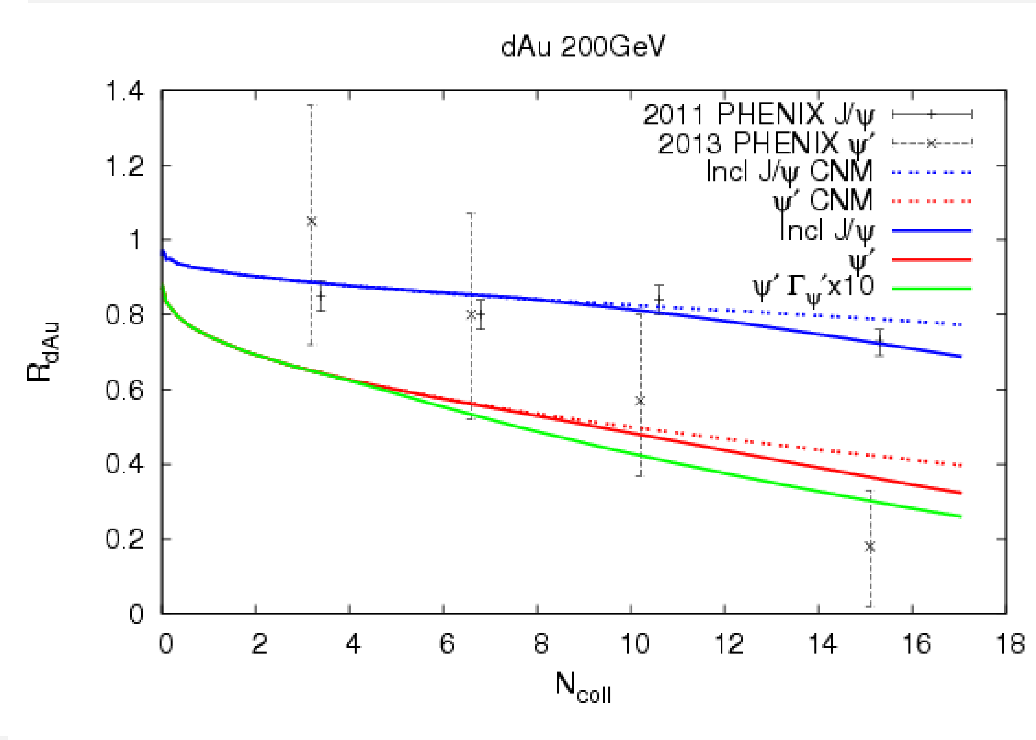
- **Implications**
  - $T_0^{SPS}$ (~230) < $T_{diss}$(J/ψ,ϒ') < $T_0^{RHIC}$ (~350) < $T_0^{LHC}$(~550) ≤ $T_{diss}$(ϒ)
  - **confining force screened at RHIC+LHC**
  - marked recombination of diffusing charm quarks at **LHC**

# 3.8 Future Improvements of Approach

- Check expanding fireball with hydrodynamic evolution
- Microscopic calculation of gain term with time-evolving heavy-quark spectra
- Nonperturbative calculation of dissociation rate
- Better determination of HQ potential (thus far: **V=F** vs. **U**)
- Scrutinize cold nuclear matter and formation time effects

# 3.9 Back to Charmonium: dAu

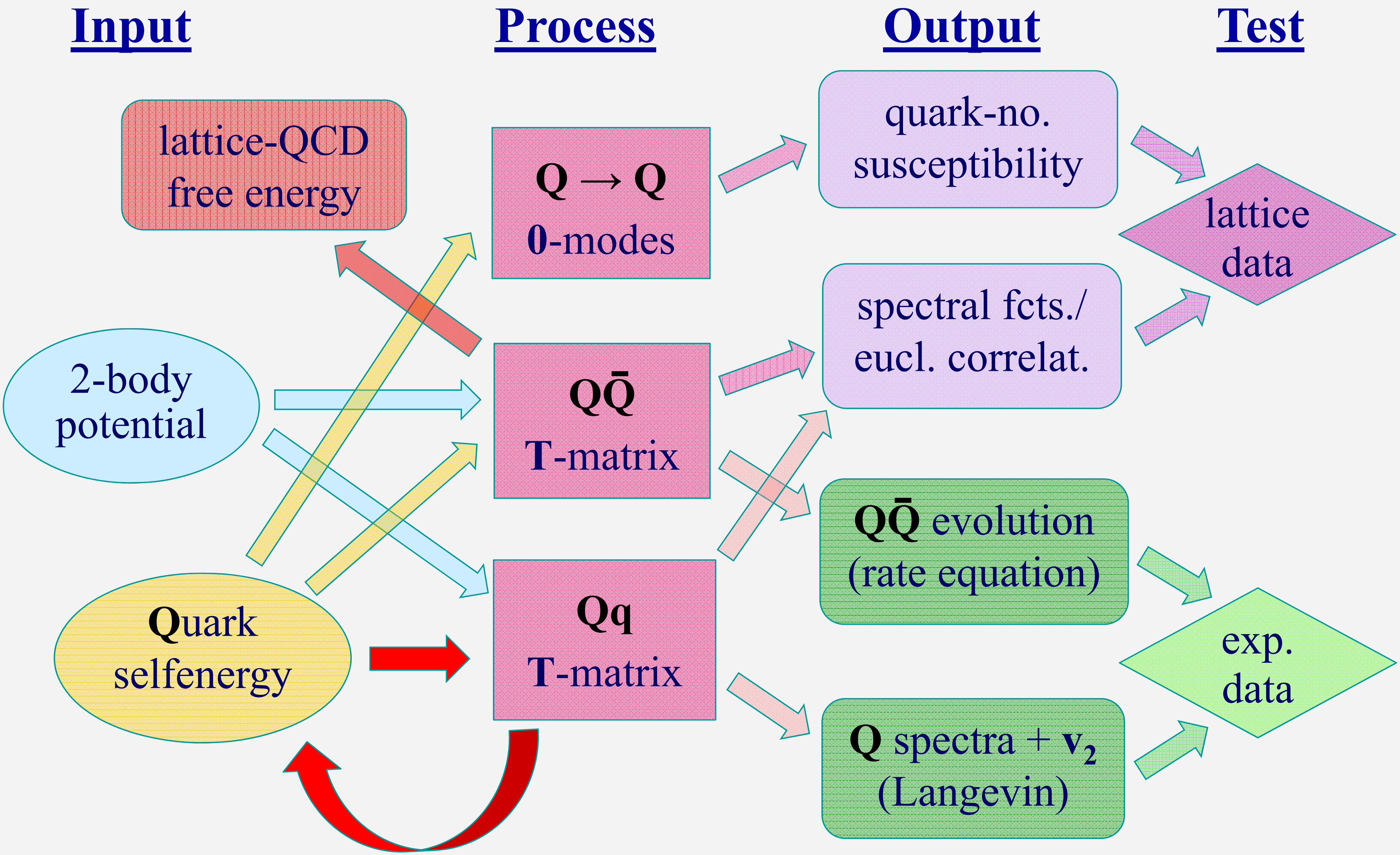



- "Standard" procedure produces significant fireball
- Some extra suppression from hot medium

[X.Du+RR in progress]

# 4.) Back to T-Matrix



# 4.1 Calculate Free Energy in Potential Approach

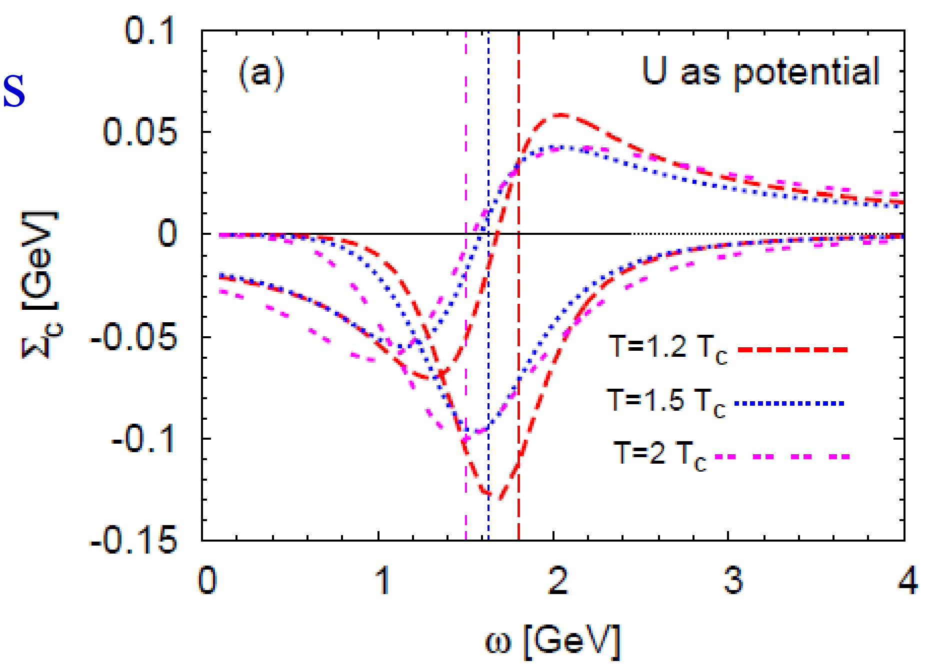
$$\exp(-\beta F_{Q\bar{Q}}) = \frac{1}{Z}\sum_n \left\langle n \left| e^{-\beta H}(e^{\beta H}\chi(r_2)e^{-\beta H})(e^{\beta H}\psi(r_1)e^{-\beta H})\psi^\dagger(r_1)\chi^\dagger(r_2)\right| n\right\rangle$$
$$\equiv G^>(-i\beta, r_1, r_2|r_1', r_2')|_{r_1'=r_1, r_2'=r_2}$$

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

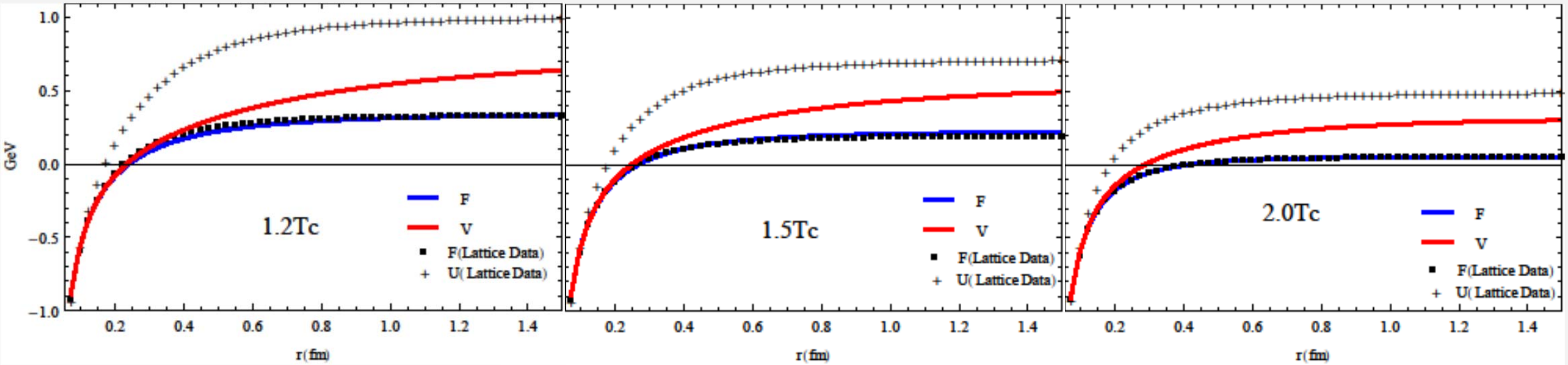
$$\sigma(\omega, r) = \frac{1}{\pi}\frac{(V+\Sigma)_I(\omega)}{(\omega-(V+\Sigma)_R)^2 + (V+\Sigma)_I^2(\omega)}$$

[S.Liu+RR in progress]

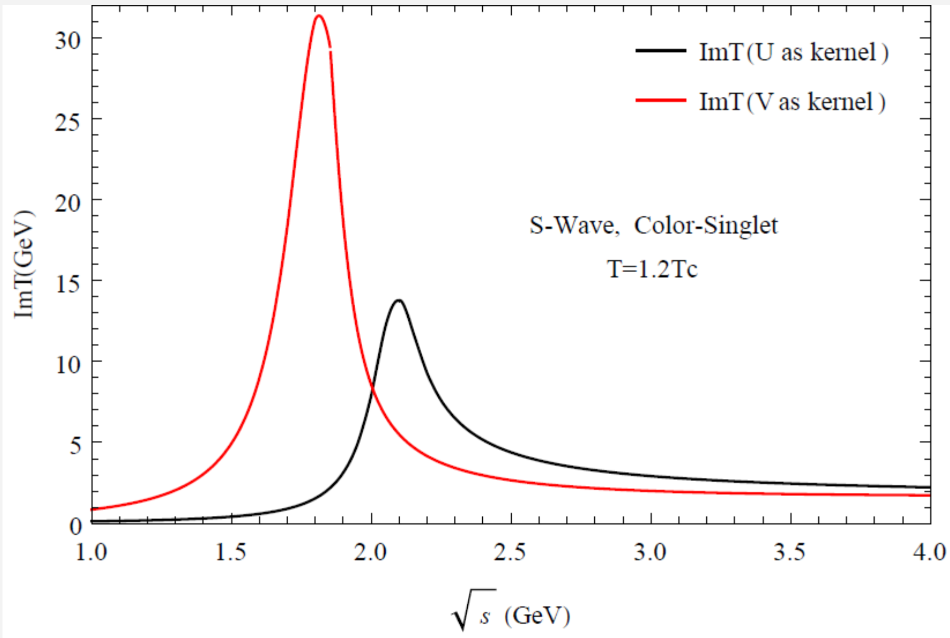
- first step: utilize heavy-quark selfenergies from previous microscopic calculations



# 4.2 Free Energy, Potential + T-Matrix




- long-range confining force induces substantial enhancement in near-threshold **Qq** T-matrix



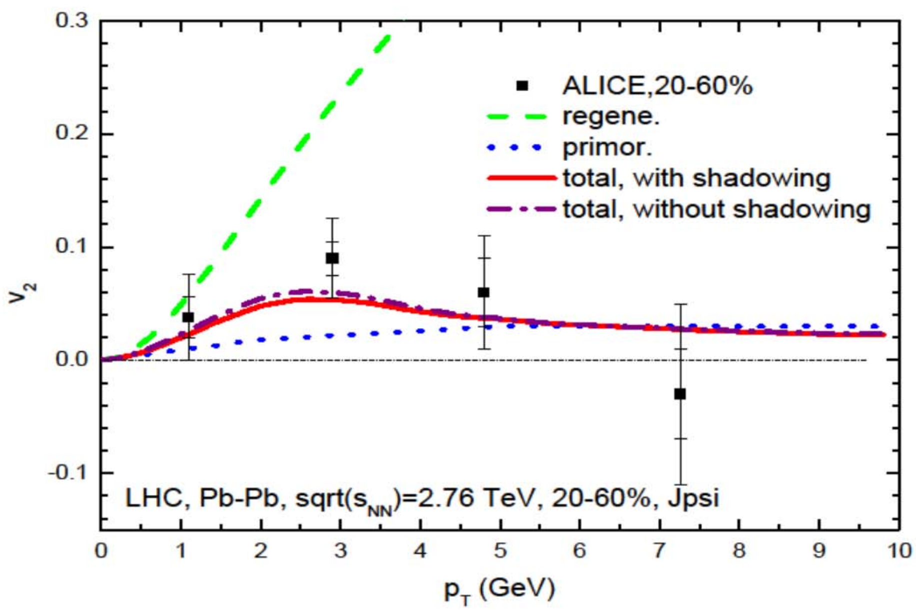
# 5.) Conclusions

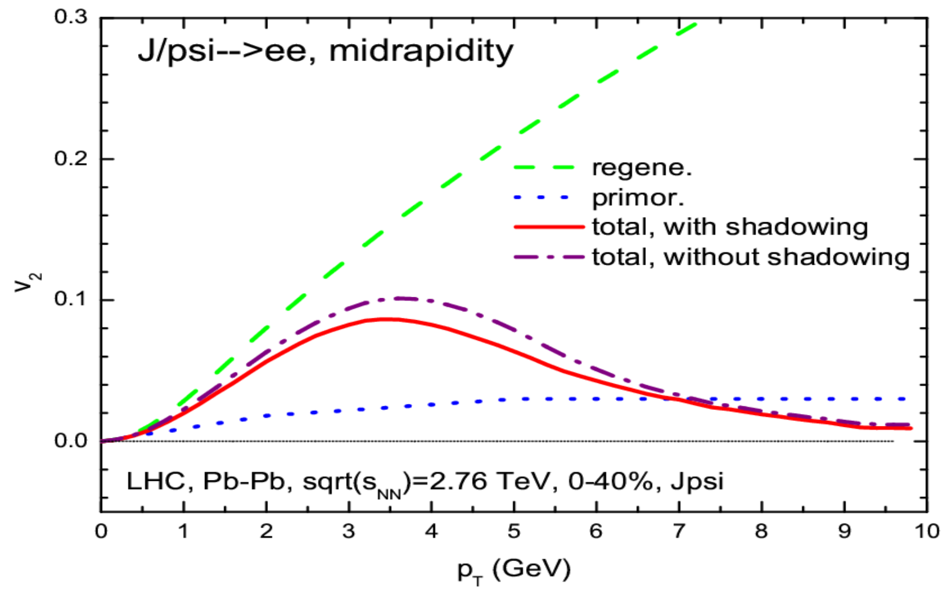
- **Quarkonium transport approach, gauged at SPS + RHIC, yields fair predictive power at LHC**

**⇒ formation of deconfined medium with interplay of suppression + recombination of diffusing charm/bottom quarks**

- **Further refinements in progress**
  - **medium effects in p/dA small**
  - **improved determination of in-medium potential**

# 3.2.2 J/ψ at LHC: $v_2$

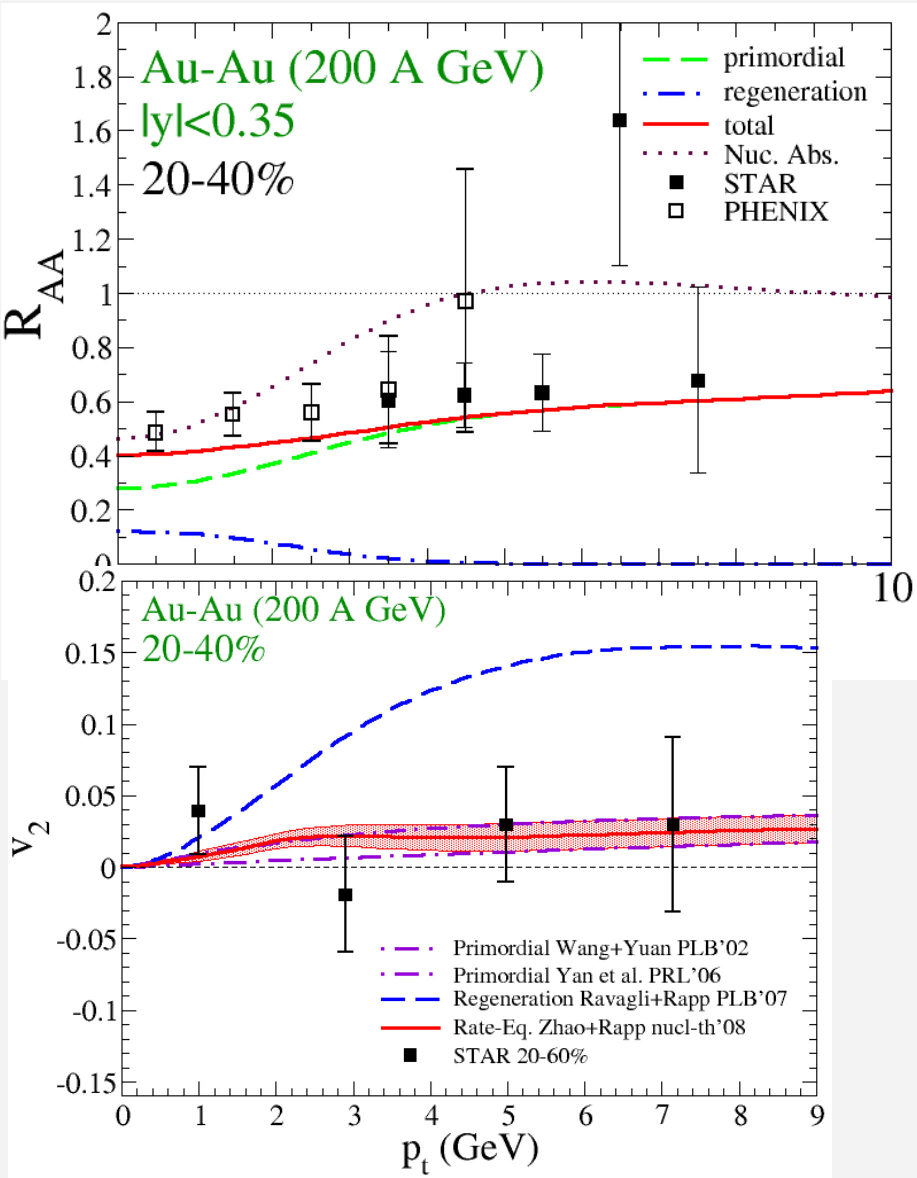



[He et al ’12]

• further increase at mid-y

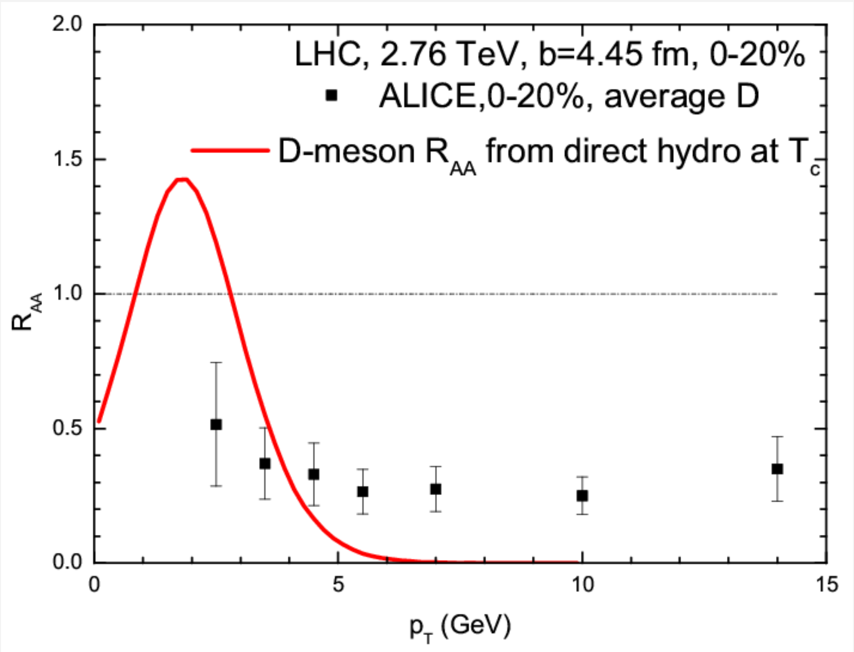
# 3.1.2 J/$\psi$ $p_T$ Spectra + Elliptic Flow at RHIC

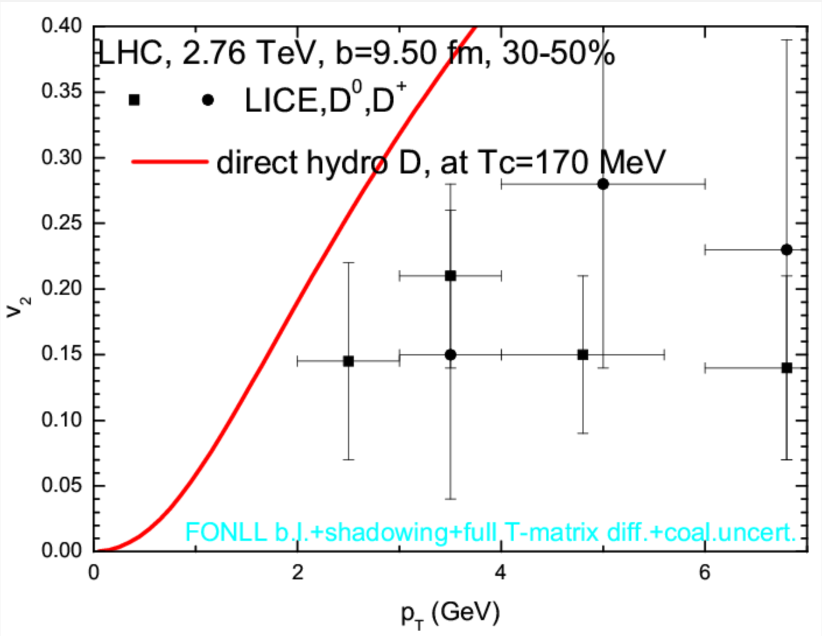



**(strong binding)**

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

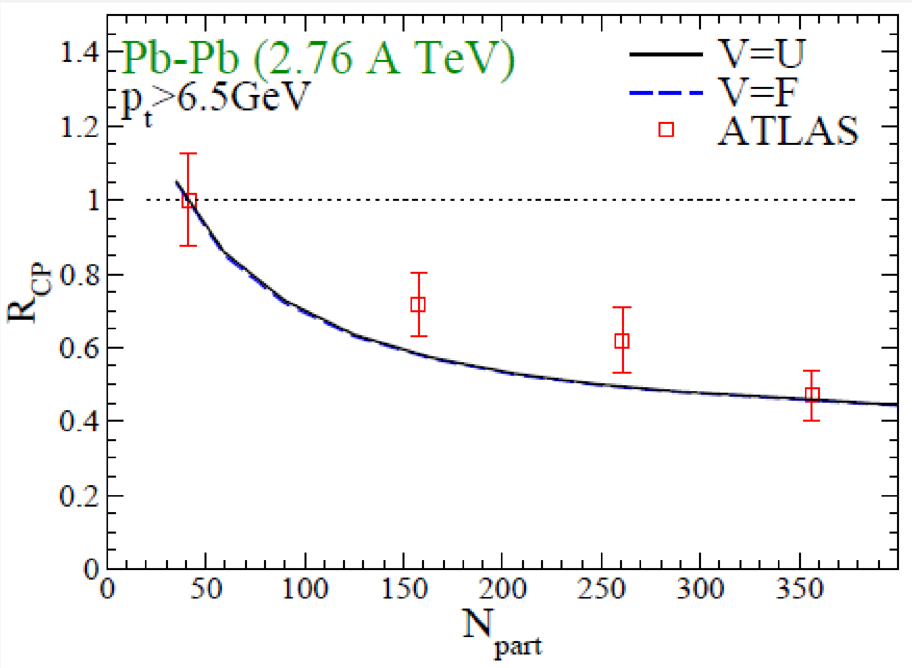
# 3.2.2 D-Meson Thermalization at LHC

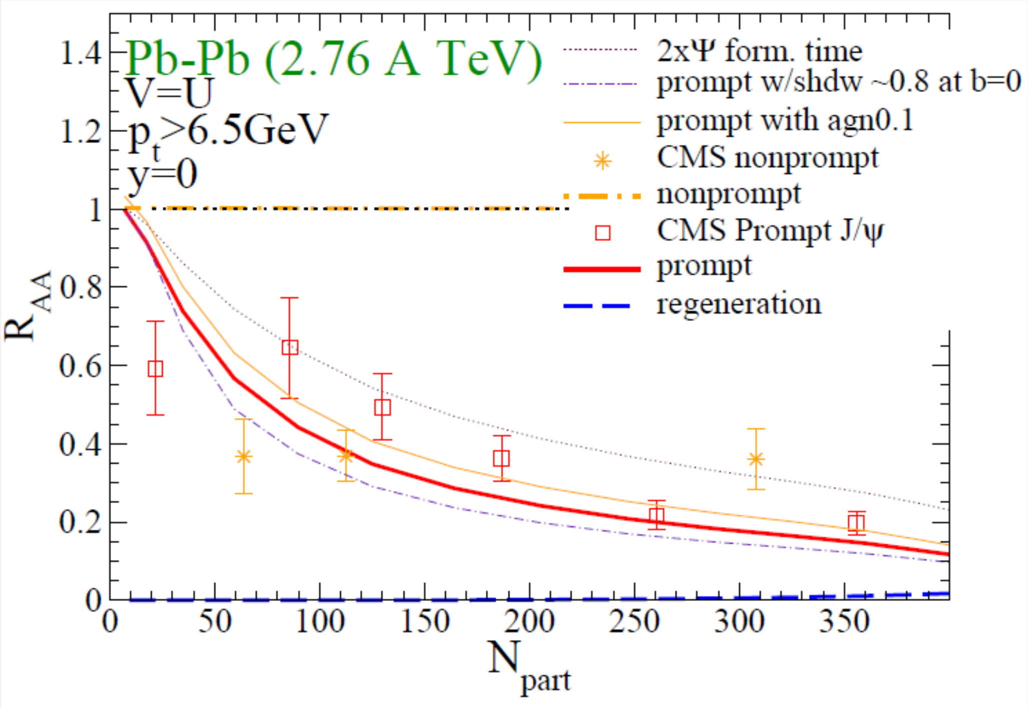



- to be determined…

# 3.3.3 J/ψ at LHC III: High-$p_t$ – ATLAS+CMS



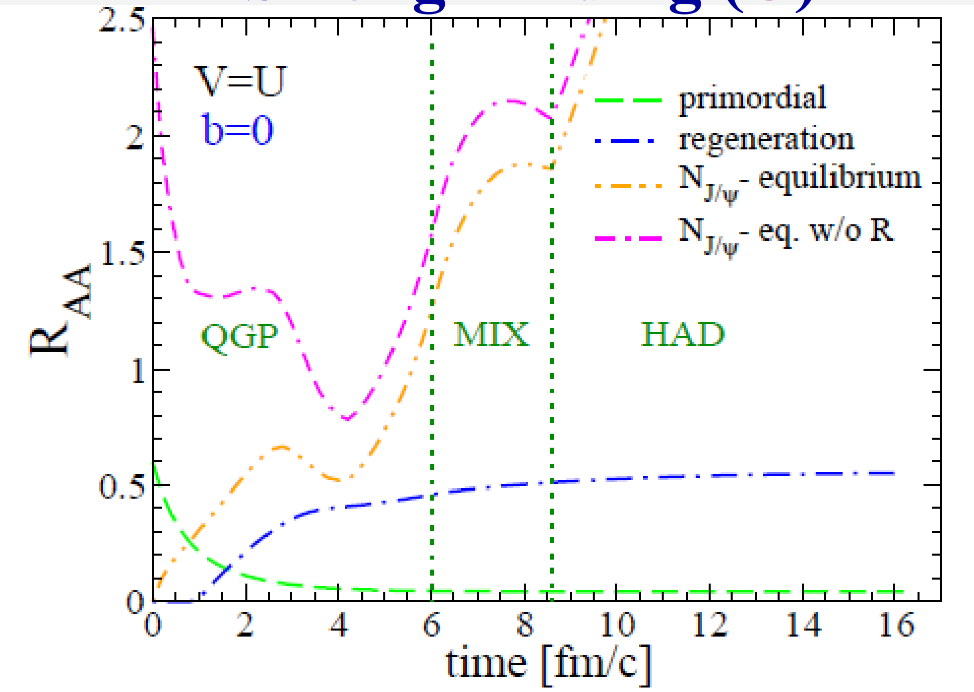




[Zhao+RR '11]

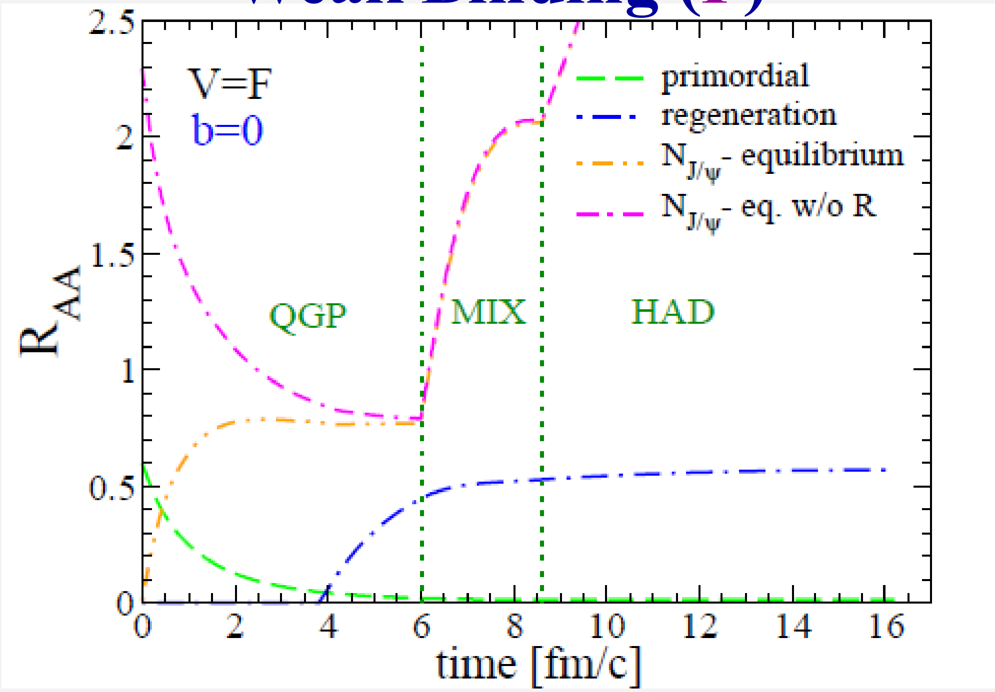
- underestimate for peripheral
  (spherical fireball reduces surface effects …)

# 3.3.4 Time Evolution of J/ψ at LHC

**Strong Binding (U)**




**Weak Binding (F)**




- finite "cooking-time" window, determined by inelastic width

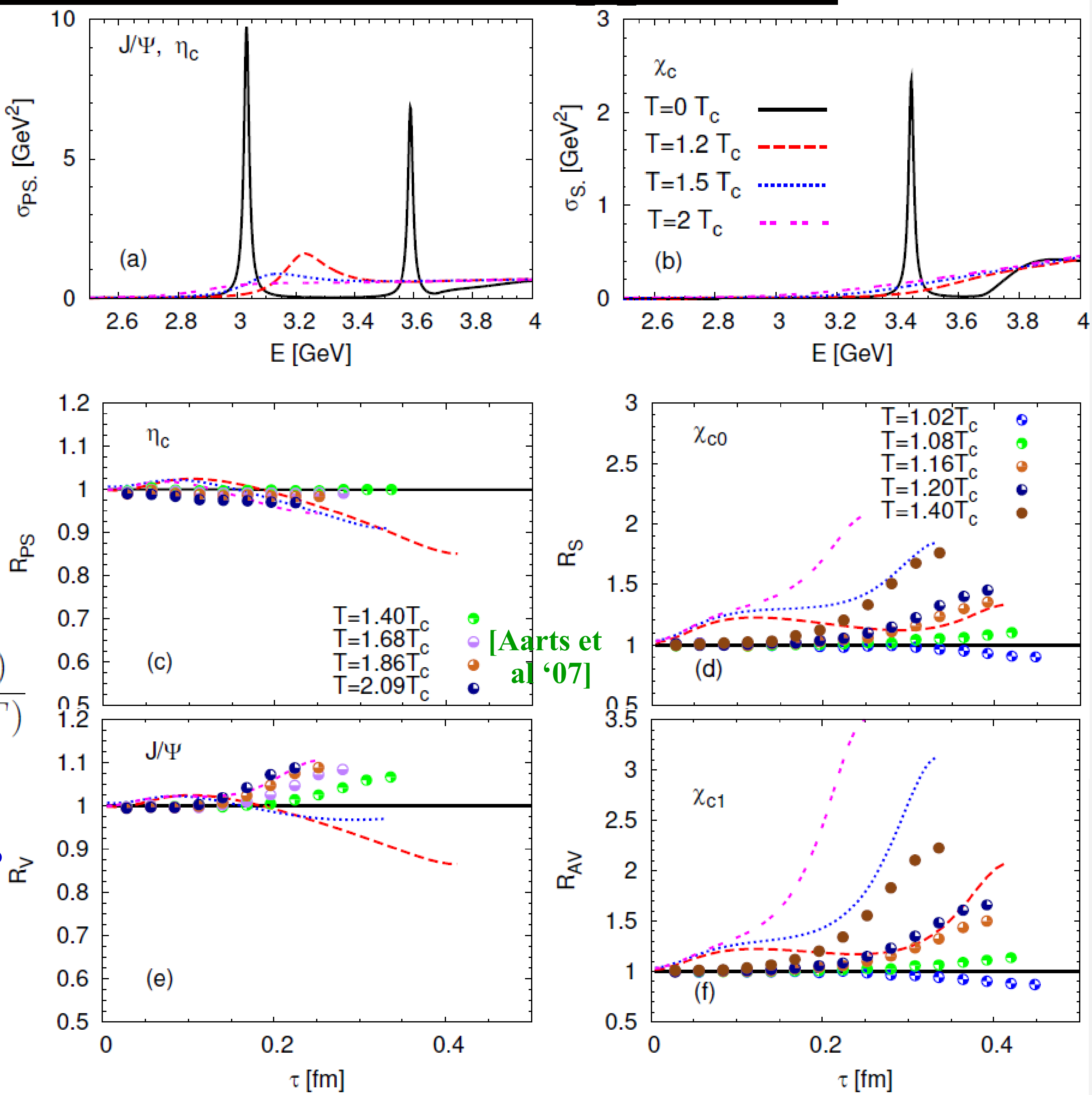
[Zhao+RR '11]

# 3.2 Charmonia in QGP: T-Matrix Approach

- **U**-potential, selfconsist. **c**-quark width
- **Spectral Functions**
  - J/ψ melting at **~1.5T$_c$**
  - $\chi_c$ melting at **~T$_c$**
  - **$\Gamma_c$ ~ 100MeV**
- **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 lQCD within uncertainties

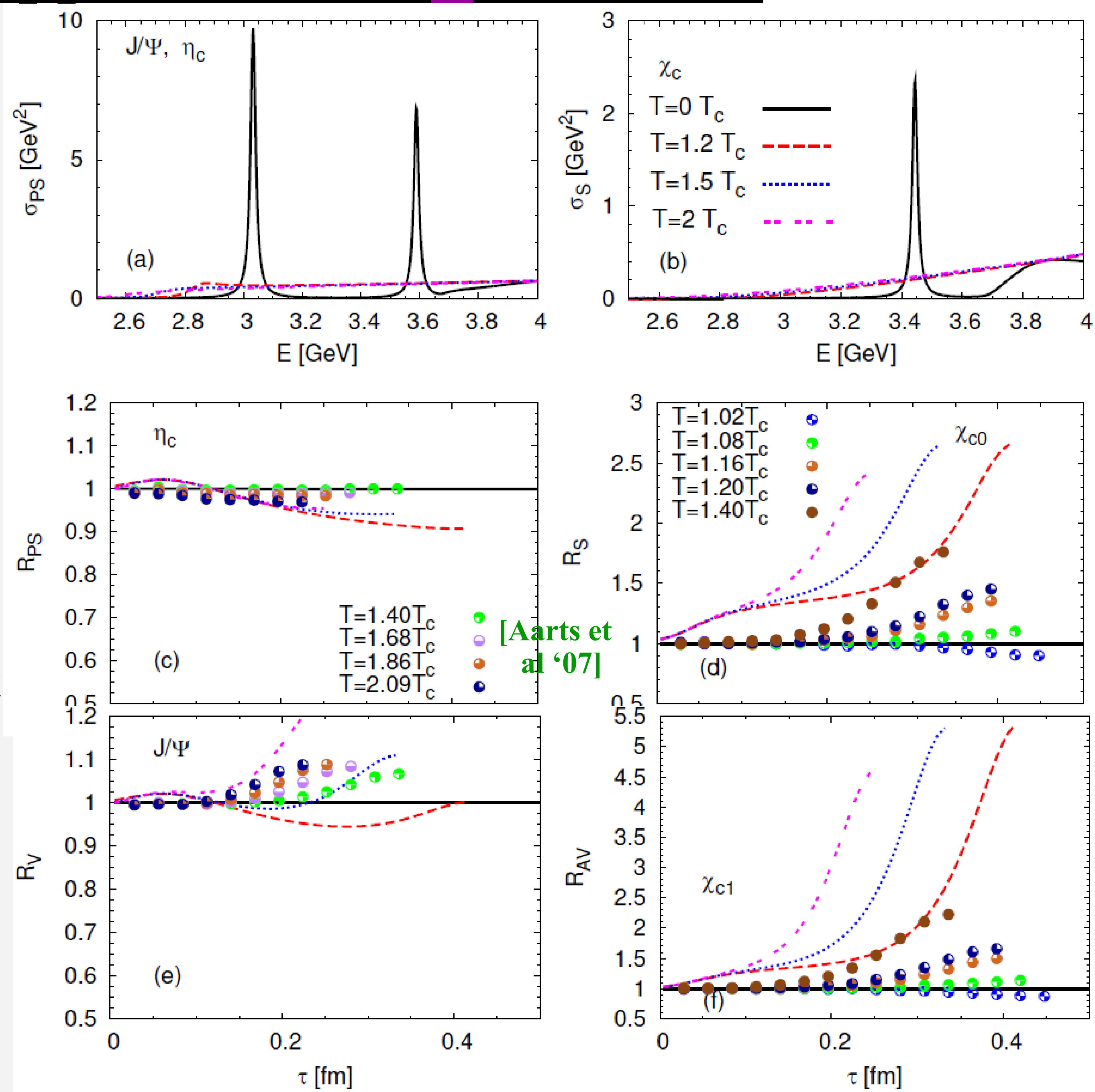



**[Mocsy+ Petreczky '05+'08, Wong '06, Cabrera+RR '06, Beraudo et al '06, Satz et al '08, Lee et al '09, Riek+RR '10, …]**

# 3.2.2 T-Matrix Approach with F-Potential

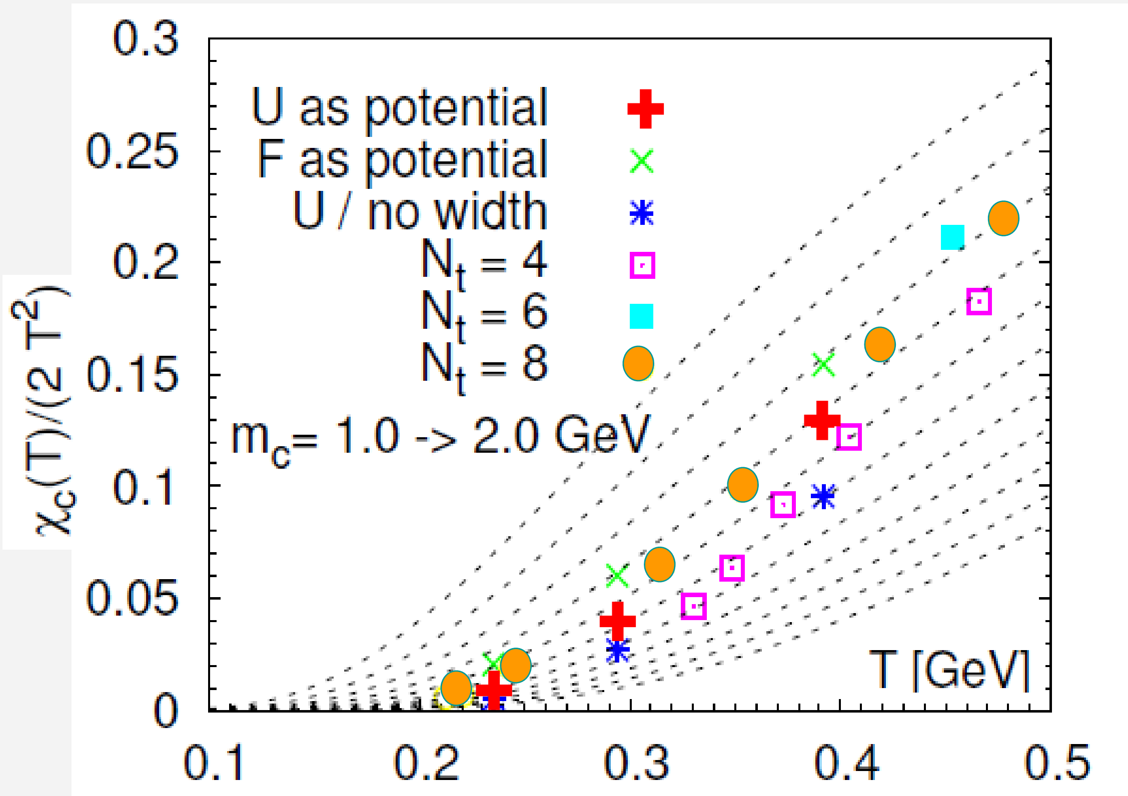
- selfcons. **c**-quark width
- **Spectral Functions**
  - J/ψ melting at ~1.1$T_c$
  - $\chi_c$ melting at ≤ $T_c$
  - $\Gamma_c \sim$ 50MeV
- **Correlator Ratios**
  - slightly worse agreement with lQCD

[Riek+RR '10]



# 3.3 Charm-Quark Susceptibility in QGP

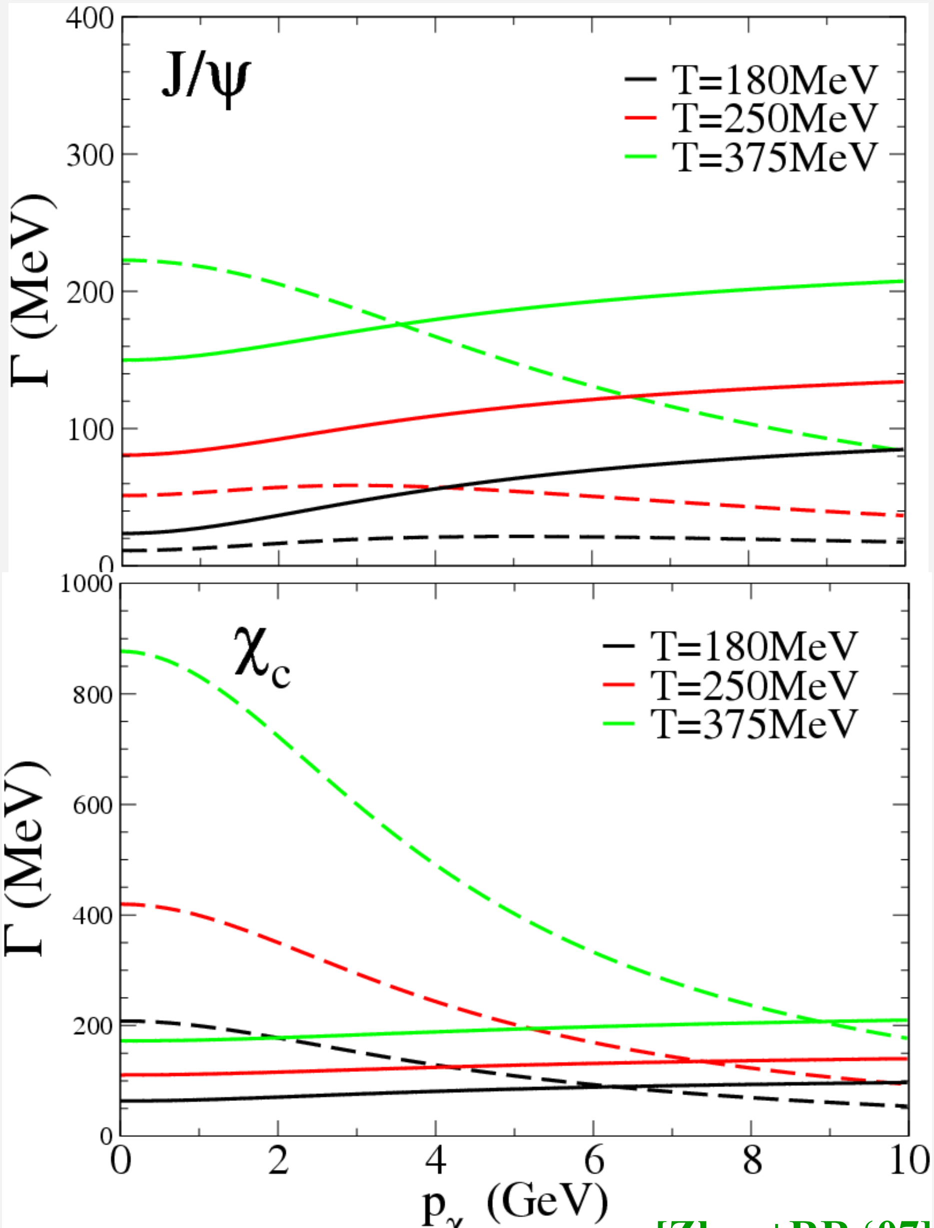
$$\chi_c(T) = \frac{1}{T}\int_0^\infty \frac{dE}{2\pi}\frac{2}{1-\exp(-E/T)}\rho_{00}(E,\mathbf{0}) \xrightarrow{\Gamma\to 0} -2N_c\int\frac{d^3\mathbf{k}}{(2\pi)^3}2\frac{\partial f^c(\omega_c(\mathbf{k}))}{\partial\omega_c(\mathbf{k})} \xrightarrow{m \ll T} \frac{2N_c}{6}T^2$$




[Riek+RR '10]

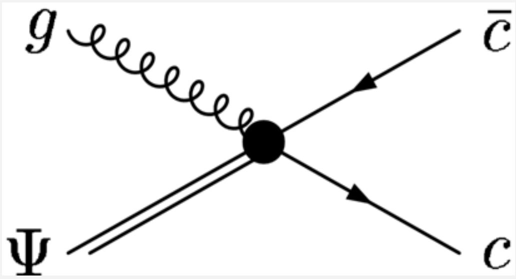
- sensitive to in-medium charm-quark mass
- finite-width effects can compensate in-medium mass increase

# 3.1.3 Momentum Dependence of Inelastic Width

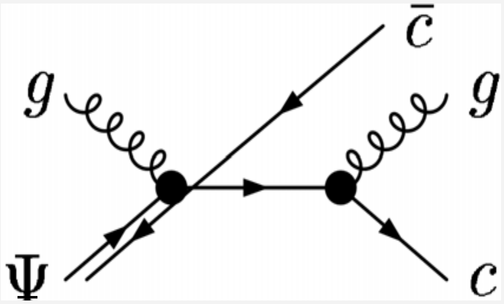



[Zhao+RR '07]

- dashed lines: gluo-dissociation



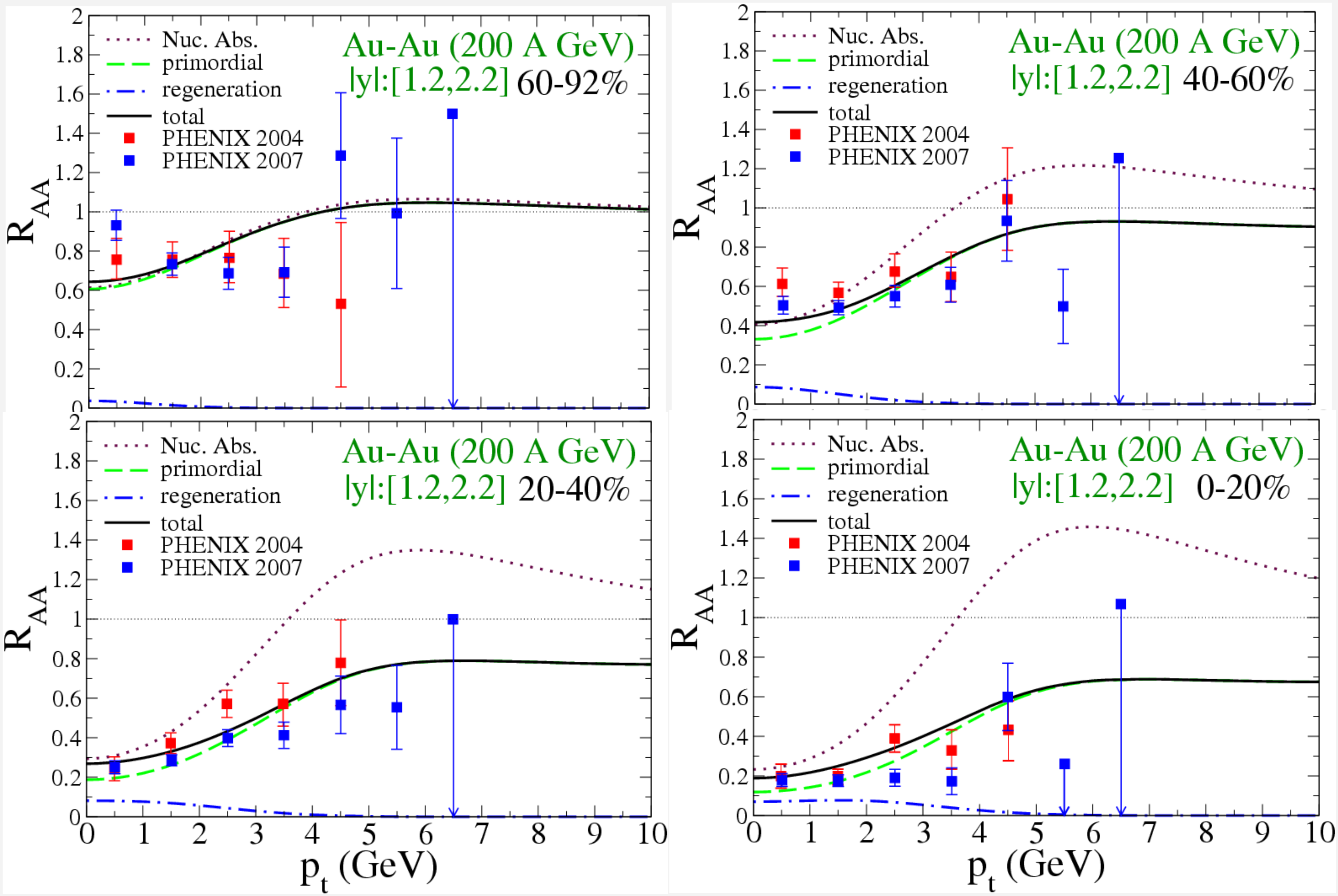

- solid lines: quasifree dissociation




- similar to full NLO calculation

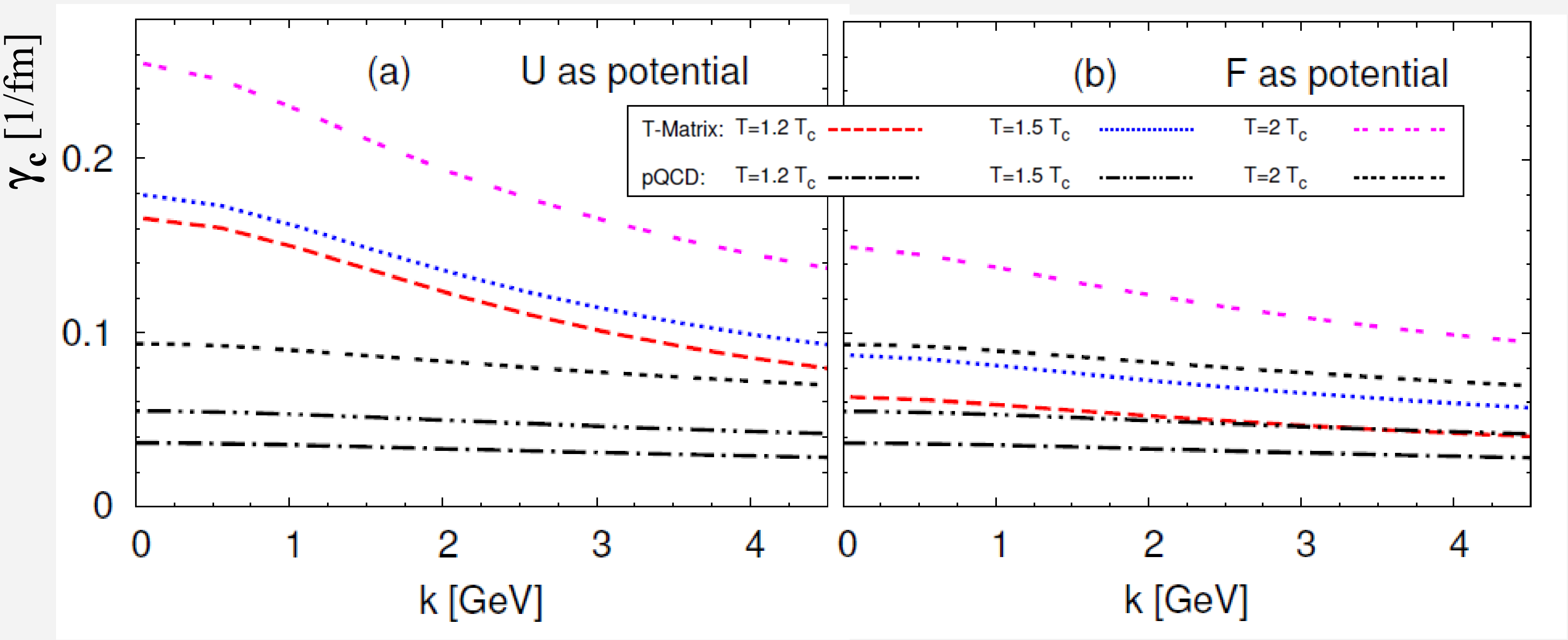
[Park et al '07]

# 4.3 J/ψ at Forward Rapidity at RHIC




[Zhao+ RR '10]

# 4.2.Thermalization Rate from T-Matrix



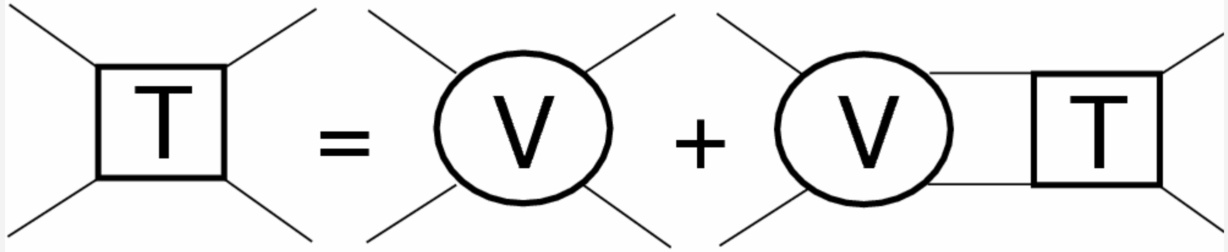

- thermalization **4** (**2**) times faster using **U** (**F**) as potential than pert. QCD
- momentum dependence essential (nonpert. effect ≠ **K**-factor!)

**[Riek+RR ‘10]**

# 3.) Thermodynamic T-Matrix in QGP

• **Lippmann-Schwinger equation**

**In-Medium**
**Q-$\bar{Q}$ T-Matrix:**




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

• potential $V_\alpha$ real
• imaginary parts: unitarization (cuts in in-med. **Q$\bar{Q}$** propagator **$G_{QQ}$**)
• simultaneous treatment of:
  - bound + scattering states
  - quarkonia (**QQ**) + heavy-quark diffusion (**Qq,g**)

**[Wong, Mannarelli+RR,Mocsy+Petreczky,Beraudo et al., Song et al.,Riek+RR,…]**