Heavy Flavor in Medium

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

CYCLOTRON INSTITUTE
TEXAS A&M UNIVERSITY

Alexander von Humboldt
Stiftung/Foundation

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McGill University, Montreal (QC, Canada), 16.-18.06.12

Review Articles

RR and H. van Hees,
Heavy-Quark Diffusion as a Probe of the Quark-Gluon Plasma,
Nova Publishers; arXiv:0803.0901[hep-ph]

RR, D. Blaschke and P. Crochet,
Charmonia and Bottomonia in Heavy-Ion Collisions,
Prog. Part. Nucl. Phys. 65 (2010) 209; arXiv:0907.2470[hep-ph]

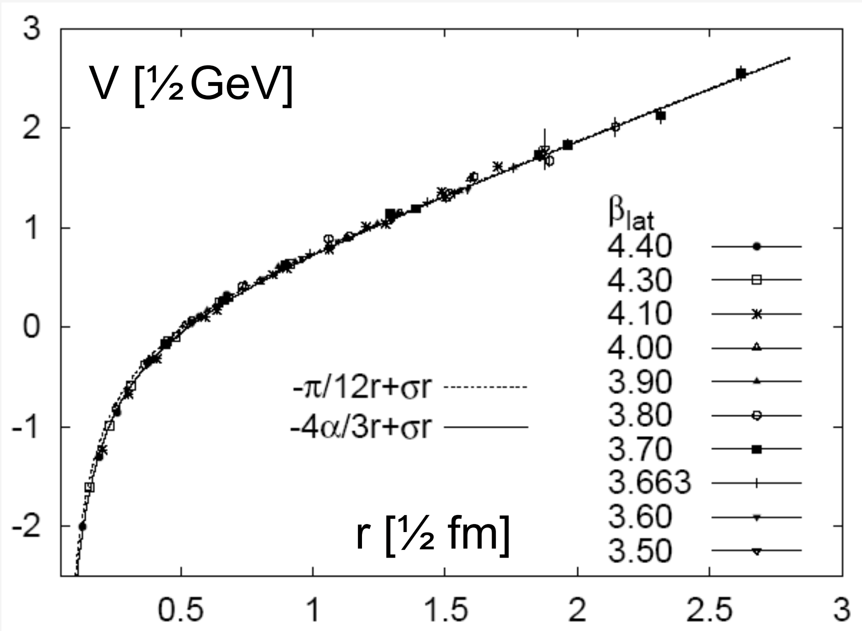
RR and H. van Hees,
Heavy Quarks in the Quark-Gluon Plasma,
in Quark-Gluon Plasma 4 (R. Hwa and X.N. Wang, eds.), World Scientific (2010); arXiv:0903.2096[hep-ph]

1.) Introduction: Why Heavy Quarks in URHICs?

"**Large**" scale $m_Q \gg \Lambda_{QCD}, T$ ($Q = c, b$):

- pair production essentially restricted to primordial NN collisions
  → well defined initial condition, flavor conserved
- thermal relaxation time increased by $\sim m_Q/T \sim 5\text{-}20$
  → incomplete thermalization, "memory" of re-interaction history
- simplifications in theoretical treatment
  → Brownian motion (elastic scattering)
  → access to soft interactions in QGP / hadronization (coalescence)
  → transport properties + contact to lattice QCD
  → potential-type interactions

1.2 Intro II: A "Calibrated" QCD Force



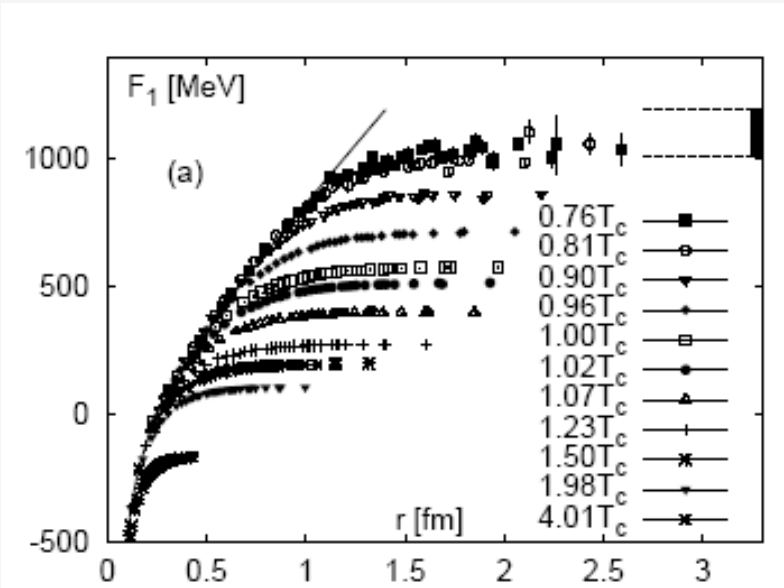
$$V_{Q\bar{Q}}(r) = -\frac{4}{3}\frac{\alpha_s}{r} + \sigma r$$

- **$\sigma \sim$ 1GeV/fm** nonperturbative (gluonic condensate)
- **$V(r_0)=0$ => $r_0 \sim$ ¼ fm ~ $(0.8\text{GeV})^{-1}$**

- Charm- + Bottomonium spectroscopy well described (effective potential theory, **$1/m_Q$** expansion)
- confining term crucial: **$E_B^{Coul}(J/\psi) \sim$ 0.05 GeV** vs. **0.6 GeV expt.**
- **Medium modifications ↔ QCD phase structure (de-/confinement)**

[Matsui+Satz '86]

1.3 Intro III: Heavy-Quark Interactions in Medium



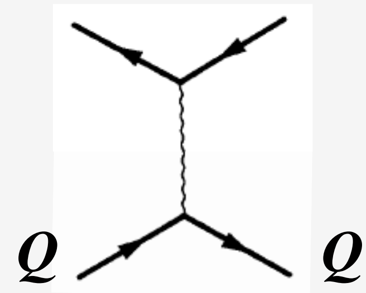
- **strong medium effects, nonpert.:**

  F(r) > 0 for $T \leq 2T_c$

- **momentum transfer**

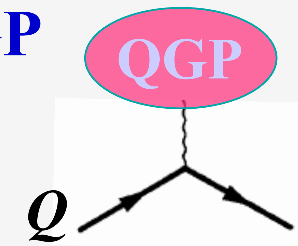
  $$q^2 = q_0^2 - \vec{q}^{\,2} \approx -\vec{q}^{\,2}$$

  $$q_0 \sim \vec{q}^{\,2} / 2m_Q << |\vec{q}\,|$$



- **single heavy quark in QGP**

  $$p_{th}^2 \sim 2m_Q T >> T^2$$



- **soft Q-Q̄ and Q-medium interactions static + elastic**

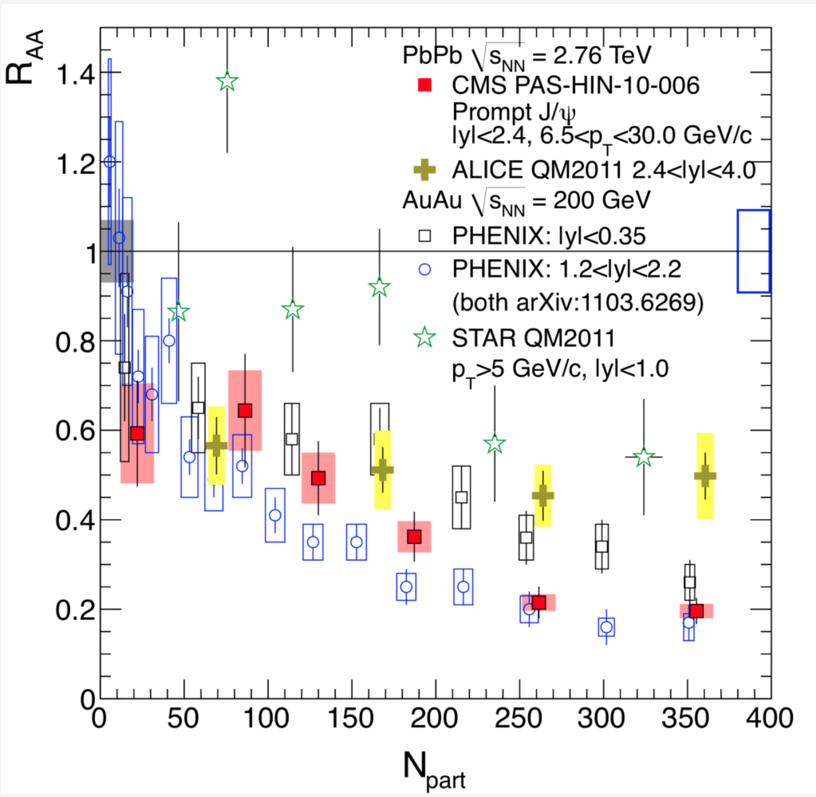
  ⇒ common description of quarkonia + heavy-quark transport

  requires bound + scattering states, resummations

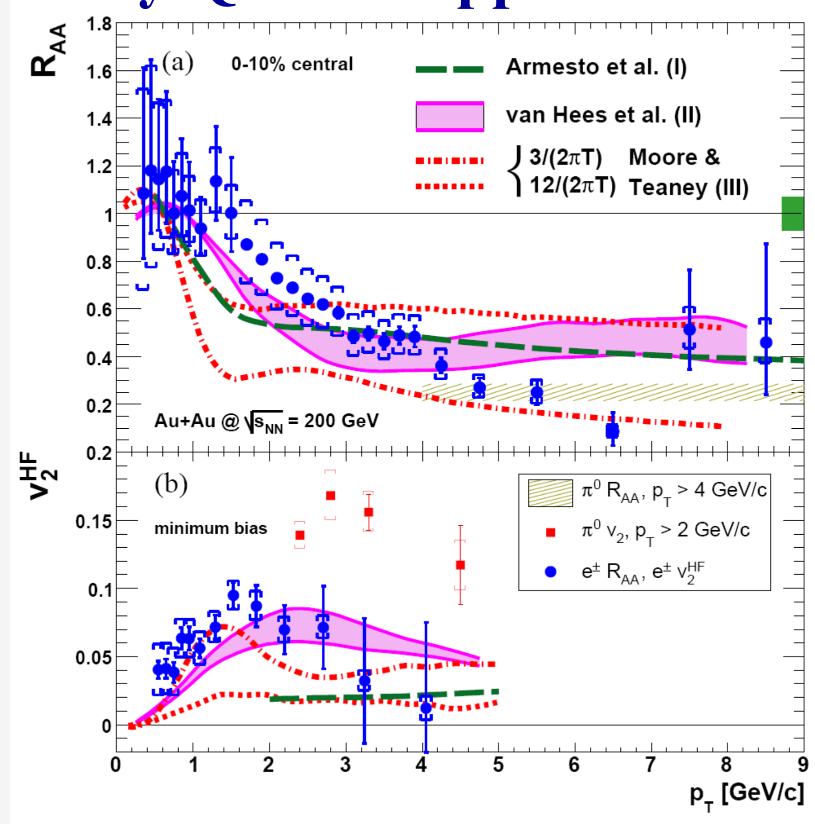
  ⇒ thermodynamic T-matrix approach (e.m. plasmas, nucl. matter)

1.4 Intro IV: Heavy-Quark Observables in URHICs

J/ψ Suppression



Heavy-Quark Suppression+Flow



• **Same force operative for quarkonia + heavy-quark transport?!**

Outline

1.) **Introduction**

2.) **One- and Two-Body Correlations**
- Potential Models
- T-Matrix Approach

3.) **Charmonia in the QGP**
- Spectral Functions
- Tests with Lattice QCD

4.) **Heavy-Flavor Transport**
- Diffusion Approach
- Microscopic Interactions

5.) **Heavy Ions I: Open Heavy Flavor**

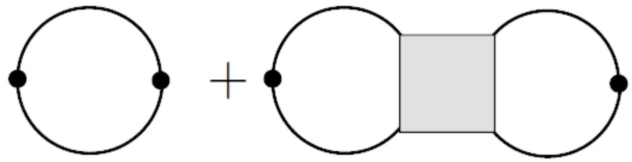
6.) **Heavy Ions II: Quarkonia**

7.) **Conclusions**

2.1 Quarkonium Correlators + Spectral Functions

- **Euclidean Correlation Function**

$$G_\alpha(\tau,\vec{r}) = \langle\langle j_\alpha(\tau,\vec{r}) j_\alpha^\dagger(0,\vec{0})\rangle\rangle$$

$=$ 

$$= G^0 + G^0 T G^0$$

- **Spectral Function**

$$\rho_\alpha(\omega,p) = -2\ \mathrm{Im} G_\alpha^R(\omega,p)$$

- **Relation:**

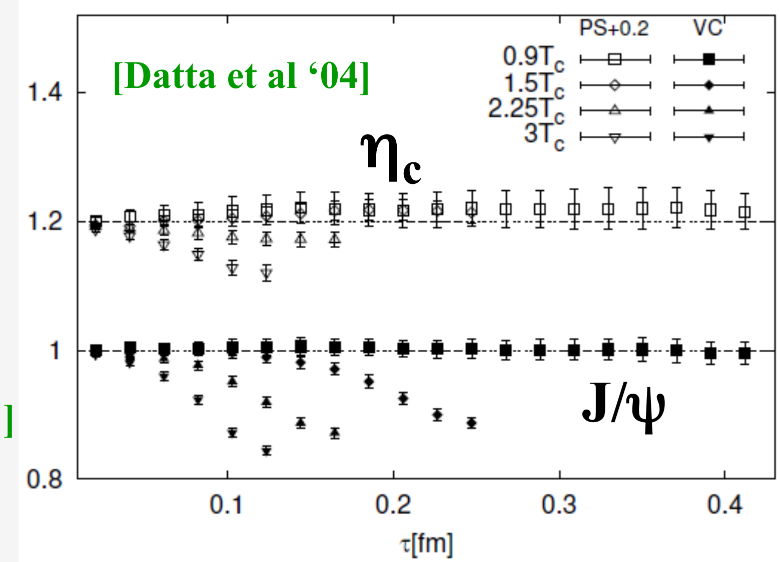
$$G_\alpha(\tau,p;T) = \int_0^\infty \frac{d\omega}{2\pi}\ \rho_\alpha(\omega,p;T)\ \frac{\cosh[(\omega(\tau-1/2T)]}{\sinh[\omega/2T]}$$

- **Correlator Ratio:**

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

- **computable in lattice-QCD with good precision** [Asakawa et al '03, Iida et al '06, Aarts et al '07, Jakovac et al '07, …]

- **Interpretation?!**



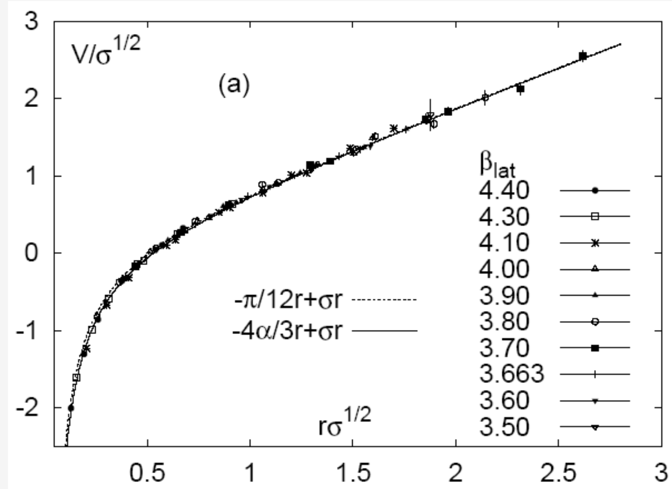
2.2 Potential Models for Spectral Functions

- well established in vacuum (EFT, lattice)
- Schrödinger equation in medium

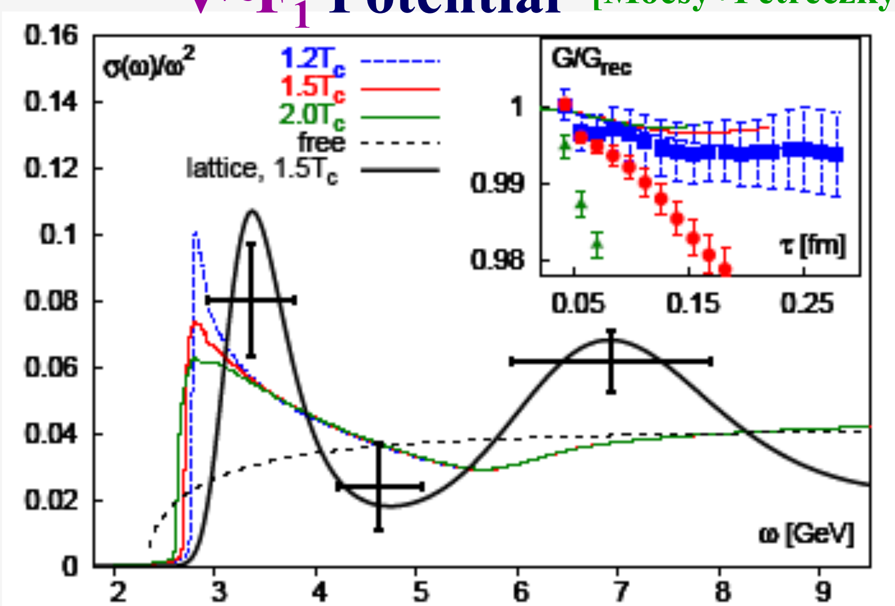
$$\left[\frac{\hat{p}^2}{\overline{m}_Q^0} + 2\,\overline{m}_Q^0 + \hat{V}_{Q\bar{Q}}\right]\Psi = E_\alpha \Psi$$

[Satz et al '01, Mocsy+ Petreczky '05, Alberico et al '06, Wong '07, Laine '07, …]

- correlators: quark rescattering in continuum
- **2-body potential V at finite temperature?**



V~F_1 Potential [Mocsy+Petreczky '05,'08]

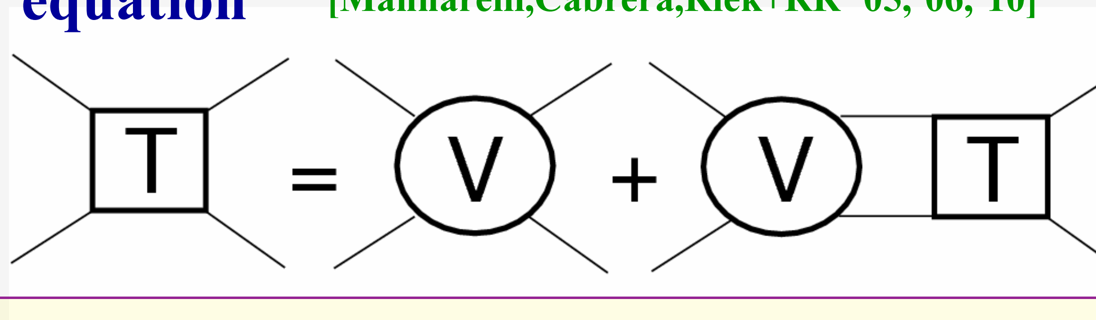


- good agreement with lQCD correlat.
- **J/ψ** melting at **~1.2 T_c**
- continuum with **K**-factor

2.3 Two-Body Scattering Equation

- **Lippmann-Schwinger equation** [Mannarelli,Cabrera,Riek+RR '05,'06,'10]

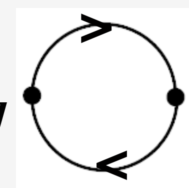
In-Medium
Q-Q̄ T-Matrix:



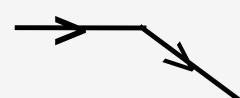
$$T_\alpha(E;q,q') = V_\alpha(q,q') + \int k^2 dk\ V_\alpha(q,k)\ G^0_{Q\bar{Q}}(E,k)\ T_\alpha(E;k,q')$$

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

$$\mathrm{Im}G^0_{Q\bar{Q}}(E) = -\int\frac{d\omega}{2\pi}\Big(\rho_Q(\omega)\rho_{\bar{Q}}(E-\omega)[1-f^Q(\omega)-f^{\bar{Q}}(E-\omega)]$$
$$+\rho_Q(\omega)\rho_Q(E+\omega)[f^Q(\omega)-f^Q(E+\omega)]\Big)$$



Q-Q̄
propagation



Q → Q
scattering
zero mode!

- Vector channel ($\mathbf{j_0}$: density) → **HQ number susceptibility**

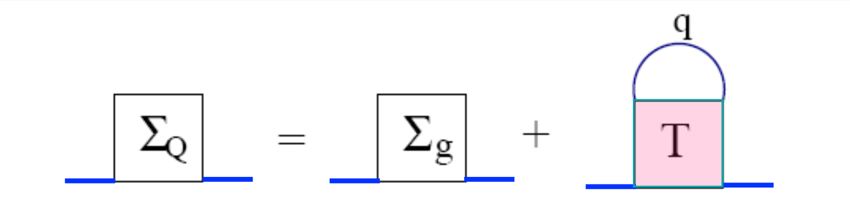
$$\chi_c(T) = -\frac{\partial^2\Omega}{\partial\mu_c^2} = \frac{1}{T}\int\frac{dE}{2\pi}\frac{2}{1-\exp(-E/T)}\rho_V^{00}(E)$$

determined by zero mode!

2.4 Single Heavy-Quark Spectral Fct. + Selfenergy

- **Spectral Function (propagator)**

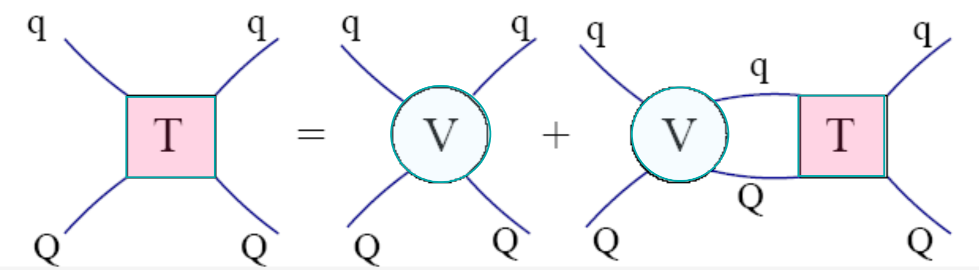
$$\rho_Q = -2\,\mathrm{Im}D_Q = -2\,\mathrm{Im}\frac{1}{\omega-\omega_Q(k)-\Sigma_Q(\omega,k)}$$



- **Gluon-Induced HQ Selfenergy:**
  - condensate-induced: nonperturbative, low **T**, positive
  - thermal Debye cloud: perturbative, large **T**, negative

- **Quark-Induced HQ Selfenergy**

$$\Sigma_Q(\omega,k) = \int T_{Qq}(\omega+\omega_p)\, f^q(\omega_p)$$



- **Selfconsistency problem!**

2.5 Heavy-Quark Free Energy in Lattice QCD

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

- **Potential?!**

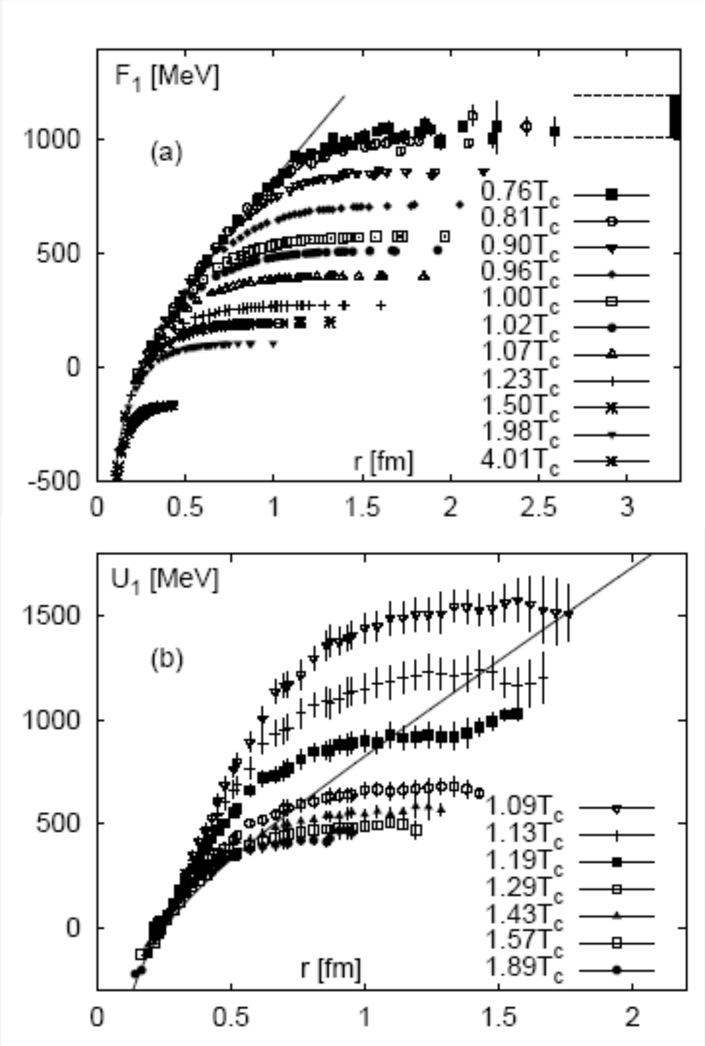
  (a) Free energy $\mathbf{F_1}$
  => weak $\bar{Q}Q$ potential,
  small **Q** "selfenergy" $\mathbf{F_1(r{=}\infty,T)/2}$

  (b) Internal Energy $\mathbf{U_1}$ $\quad$ ($\mathbf{U = \langle H_{int} \rangle}$)
  => strong $\bar{Q}Q$ potential,
  large **Q** "selfenergy" $\mathbf{U_1(r{=}\infty,T)/2}$

→ compensation in $\mathbf{E_\Psi = 2m_Q^* - E_B}$

- **F, U, S thermodynamic quantities**
  (0-point functions), potential: 4-point fct.

- Entropy: many-body effects



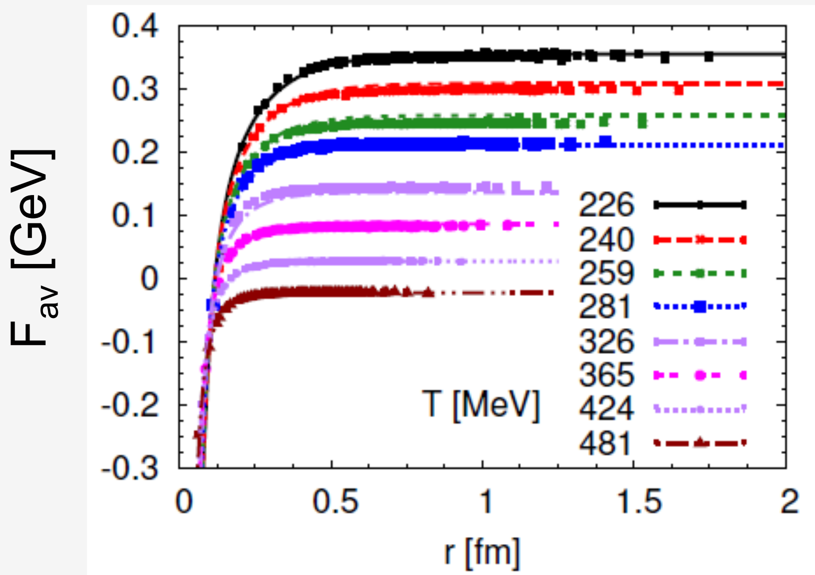
[Kaczmarek+Zantow '05]

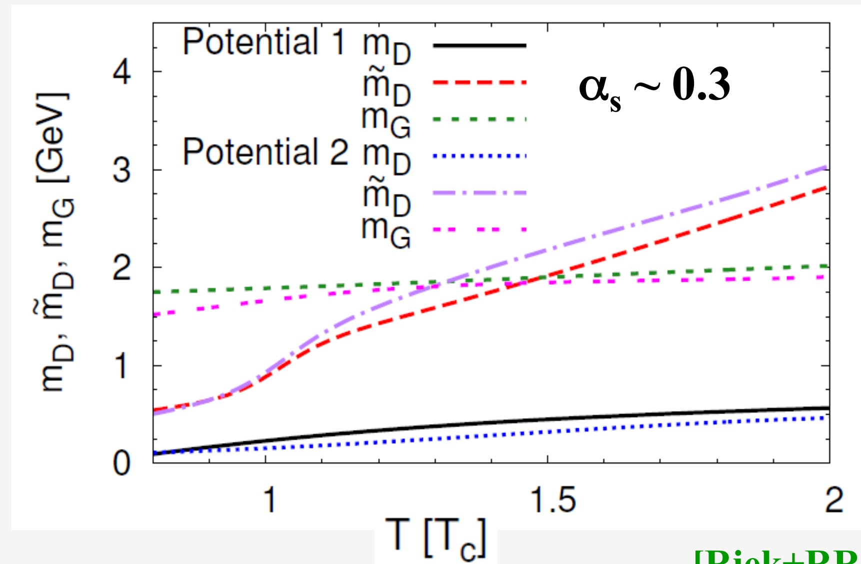
2.6 Field Theoretic Approach to Free Energy in QGP

- effective propagators: Coulomb + string
- fit 4 parameters to lattice-QCD data

$$D_{00}(k) = \frac{\alpha_s^2}{k^2+m_D^2} + \frac{m_G^2}{(k^2+\tilde{m}_D^2)^2}$$

[Megias et al ‘07]



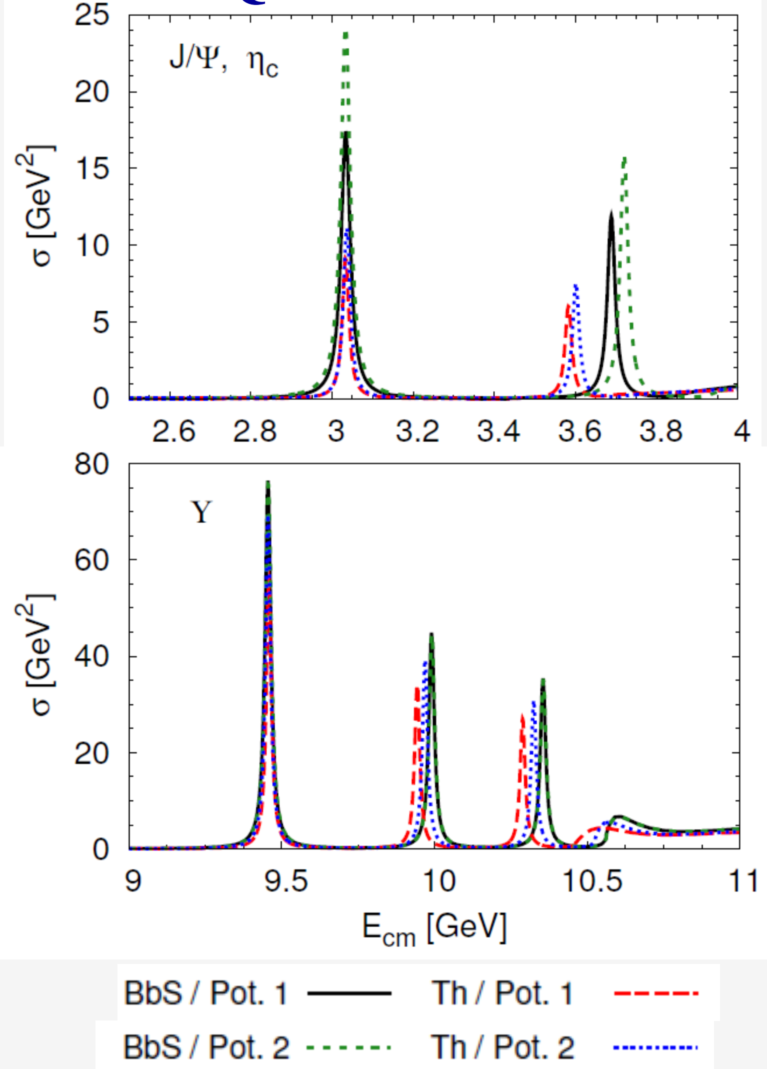


[Riek+RR ‘10]

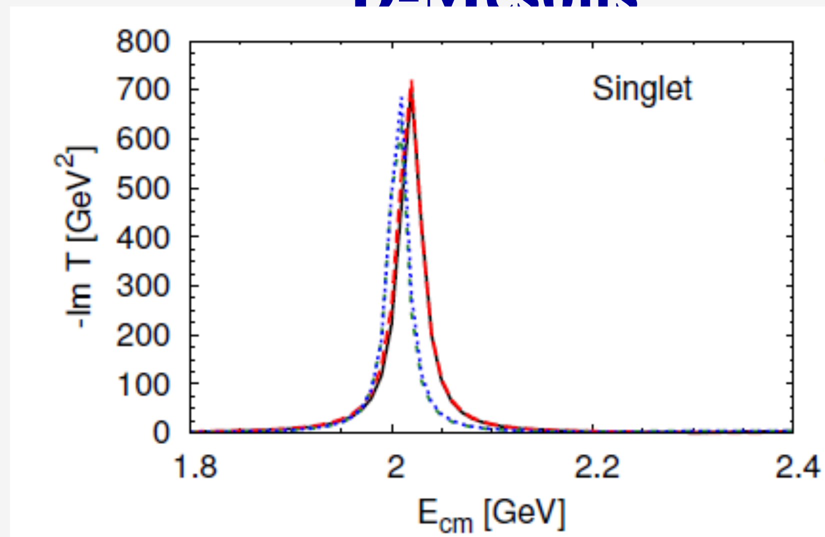
- **Corrections to static potential**
  - **Relativistic:** magnetic “Breit” correction: [Brown et al ‘52, ‘05]
    $V_{Q1Q2}(r) \rightarrow V_{Q1Q2}(r)\ (1 - v_1 \cdot v_2)$ (↔ Poincaré-invariance, pQCD)
  - **Retardation:** **4-D → 3-D** reduction of Bethe-Salpeter eq. (off-shell)

2.7.1 Constraints I: Vacuum Spectroscopy

Quarkonia



D-Mesons



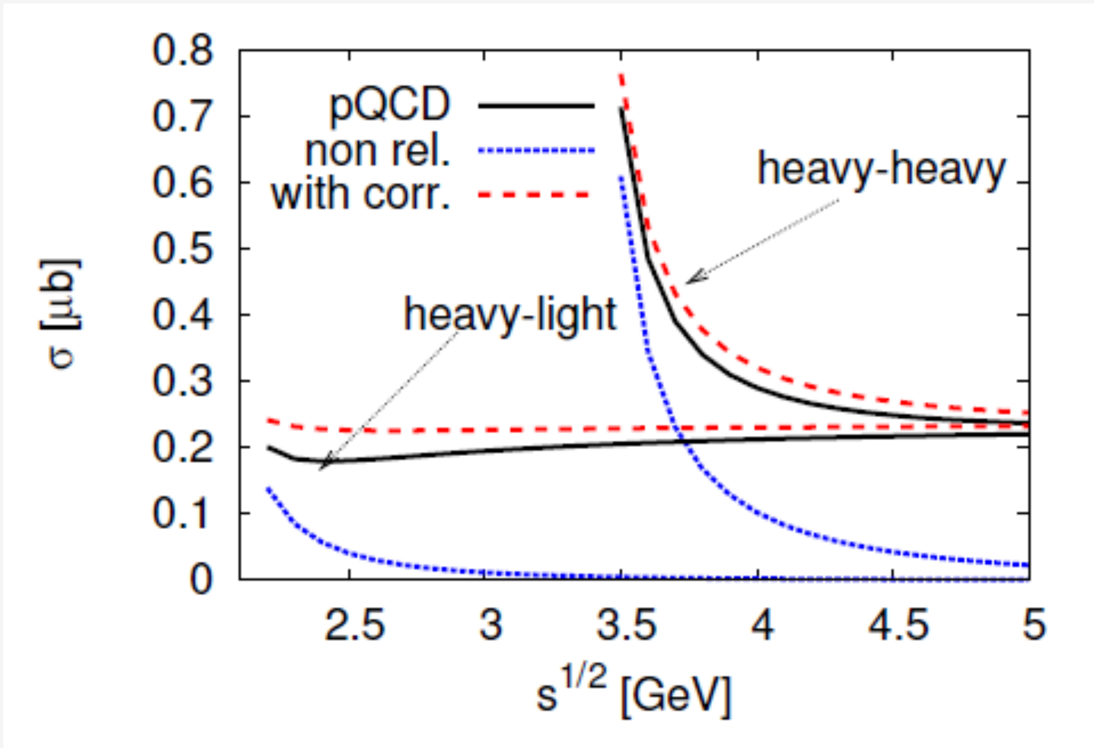
- no hyperfine splitting
- (bare) masses adjusted to ground state
- **~ ±50 MeV** accuracy

		BbS-scheme	Th-scheme
Potential 1	m_c^0	1.355 GeV	1.264 GeV
	m_b^0	4.712 GeV	4.662 GeV
Potential 2	m_c^0	1.402 GeV	1.293 GeV
	m_b^0	4.718 GeV	4.668 GeV

$m_q = 0.4$ GeV, $m_s = 0.55$ GeV

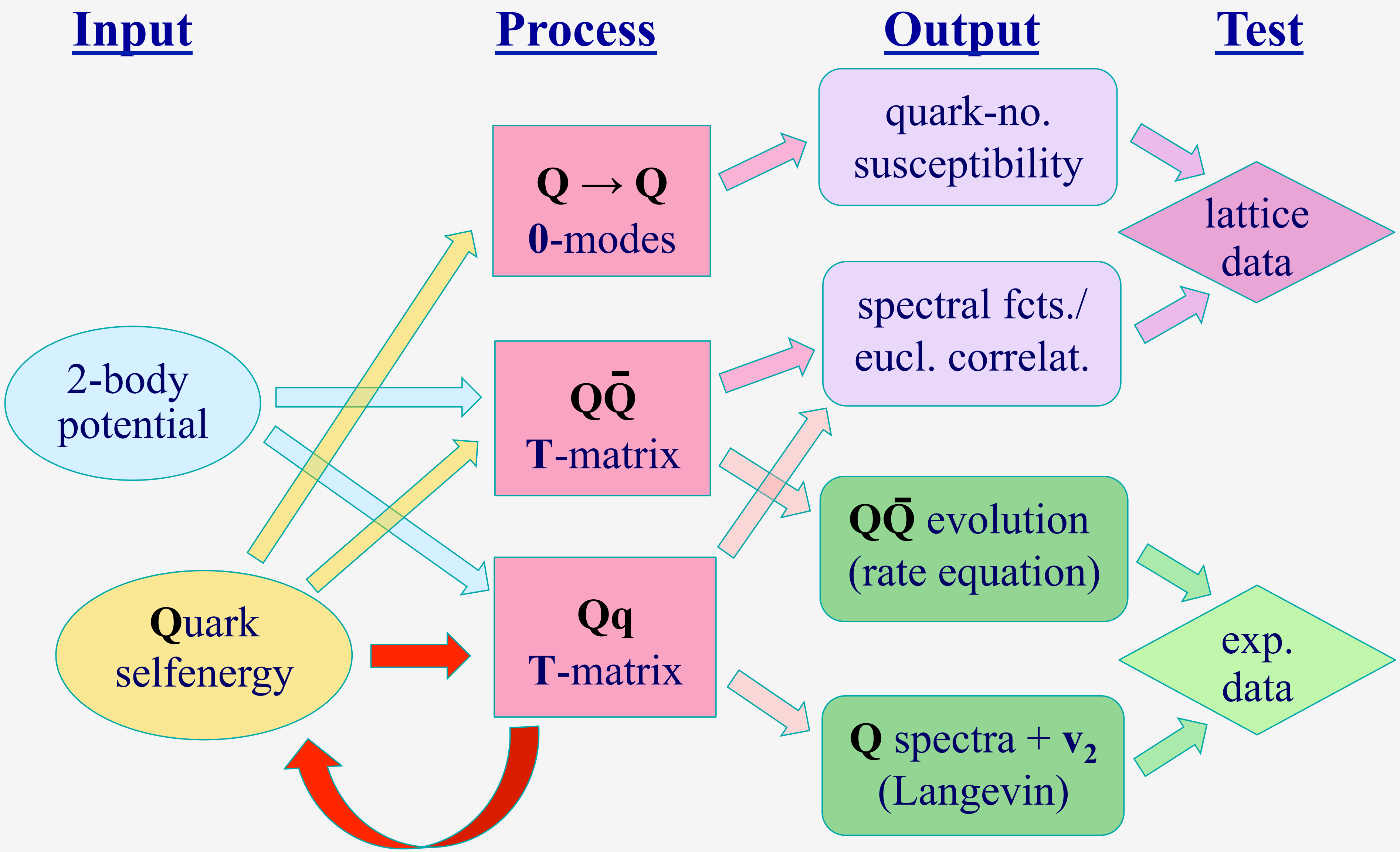
2.7.2 Constraints II: High-Energy Scattering

Born Approximation compared to Perturbative QCD



- Breit correction essential

2.8 Brueckner Theory of Heavy Quarks in QGP



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1.) **Introduction**

2.) **One- and Two-Body Correlations**
- Potential Models
- T-Matrix Approach

3.) **Charmonia in the QGP**
- Spectral Functions
- Tests with Lattice QCD: Eucl. Correlators, Susceptibility

4.) **Heavy-Flavor Transport**
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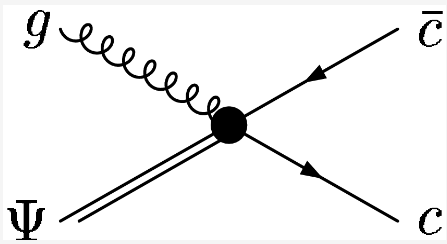
7.) **Conclusions**

3.1 Charmonium Widths in QGP

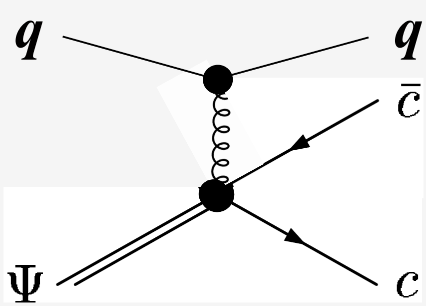
$$\Gamma_\psi = \sum_{p=q,\bar{q},g} \int \frac{d^3k}{(2\pi)^3} f^p(\omega_k;T)\, \sigma^{diss}_{p\psi}(s)$$

→ sensitive to binding energy (i.e., **color screening**)

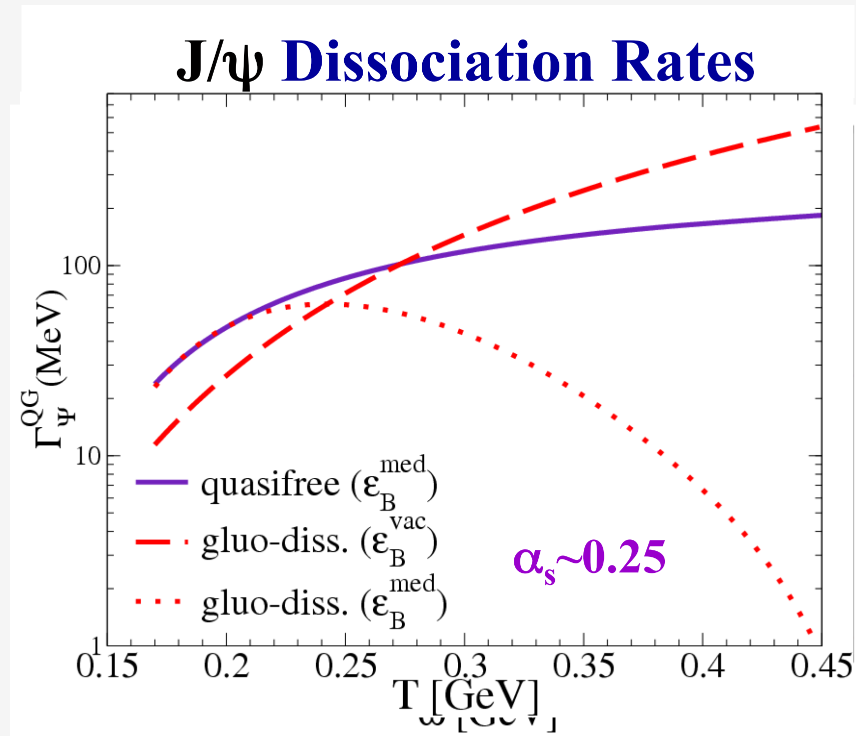
- **$E_B \geq T$: gluo-dissociation** **[Bhanot+Peskin '79]**



- **$E_B < T$: quasi-free dissociation**



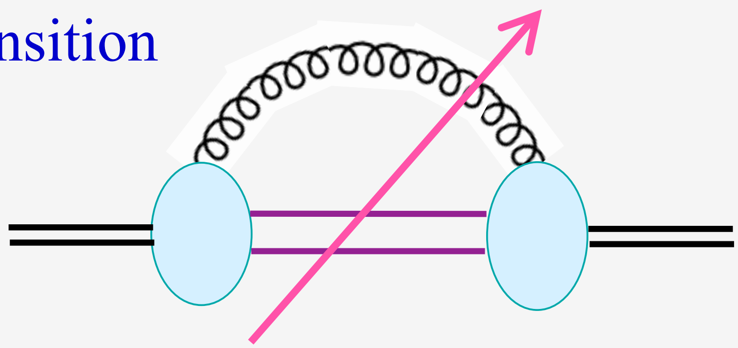
[Grandchamp+RR '01]

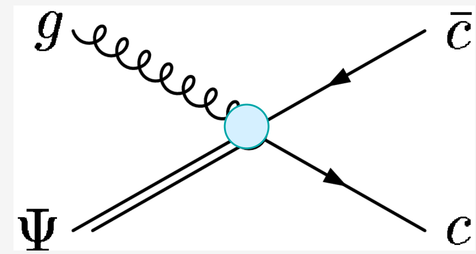


- **J/ψ lifetime ~ 1-4 fm/c**

3.1.2 Relation of Quarkonium Widths to EFT

- Singlet-octet transition

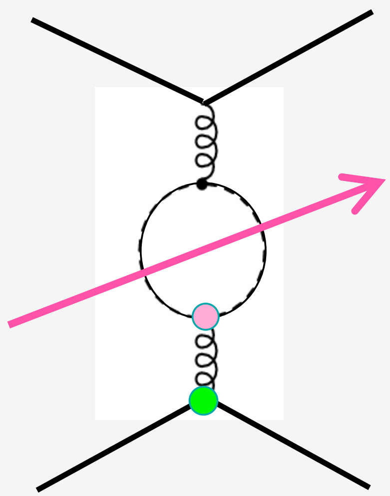


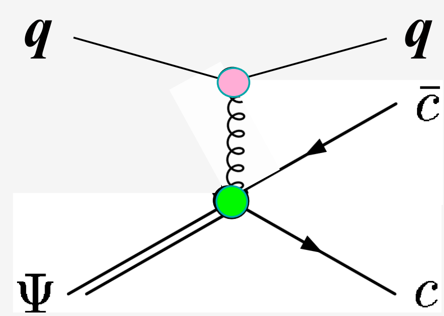


gluo-dissosciation

[Bhanot+Peskin '85]

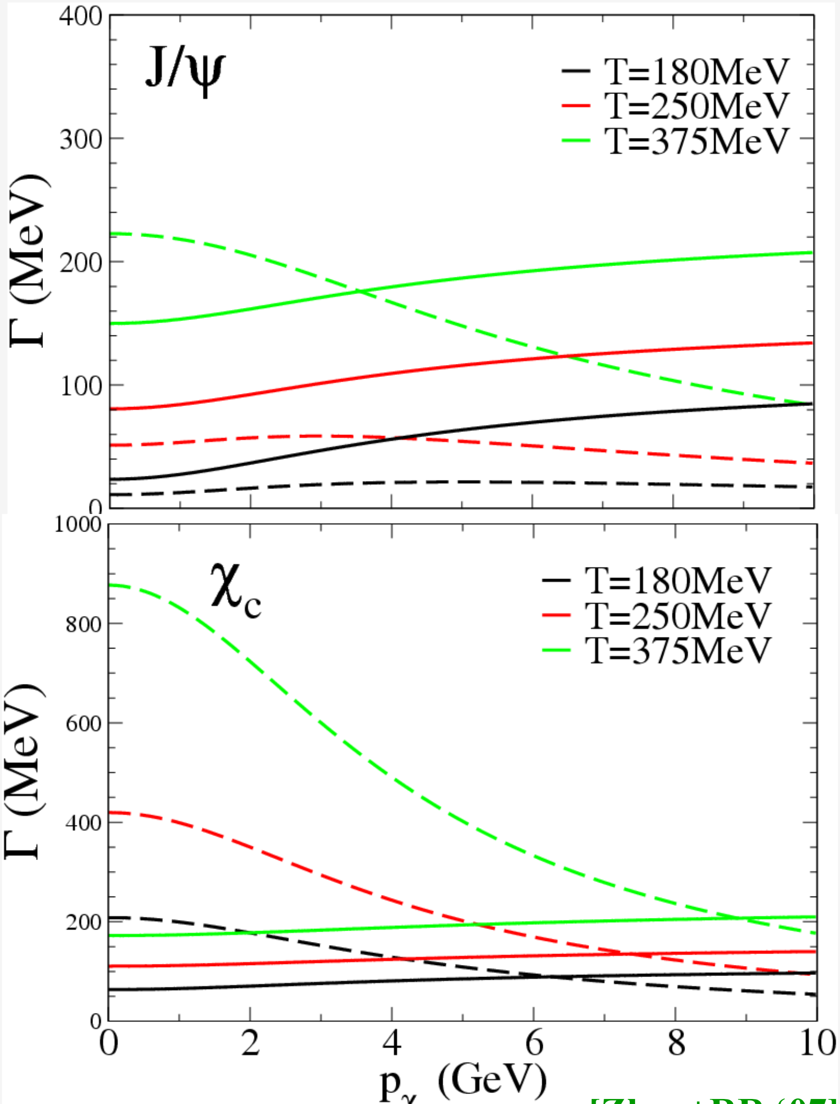
- Landau damping





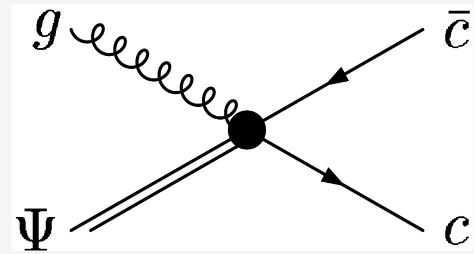
"quasi-free" dissosciation

3.1.3 Momentum Dependence of Inelastic Width

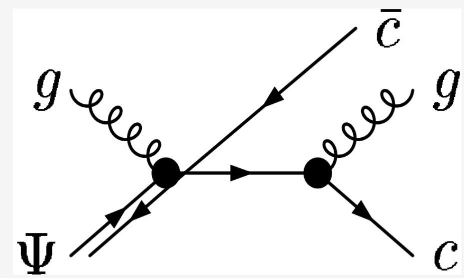


[Zhao+RR '07]

- dashed lines: gluo-dissociation



- solid lines: quasifree dissociation



- similar to full NLO calculation

[Park et al '07]

3.2 Charmonia in QGP: T-Matrix Approach

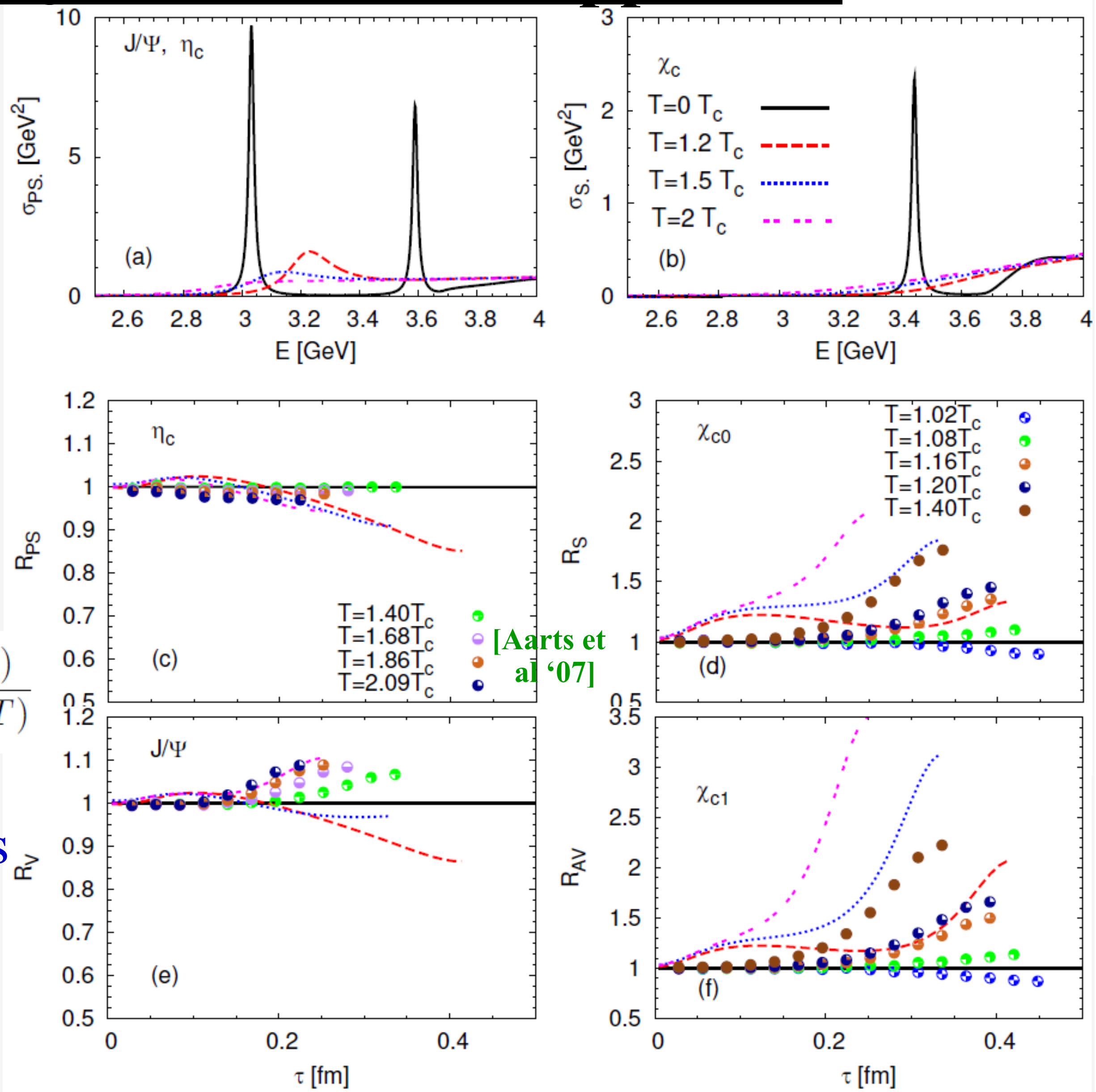
- U-potential, selfconsist. **c**-quark width

- **Spectral Functions**
  - **J/ψ** melting at **~1.5T_c**
  - **χ_c** melting at **~T_c**
  - **Γ_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

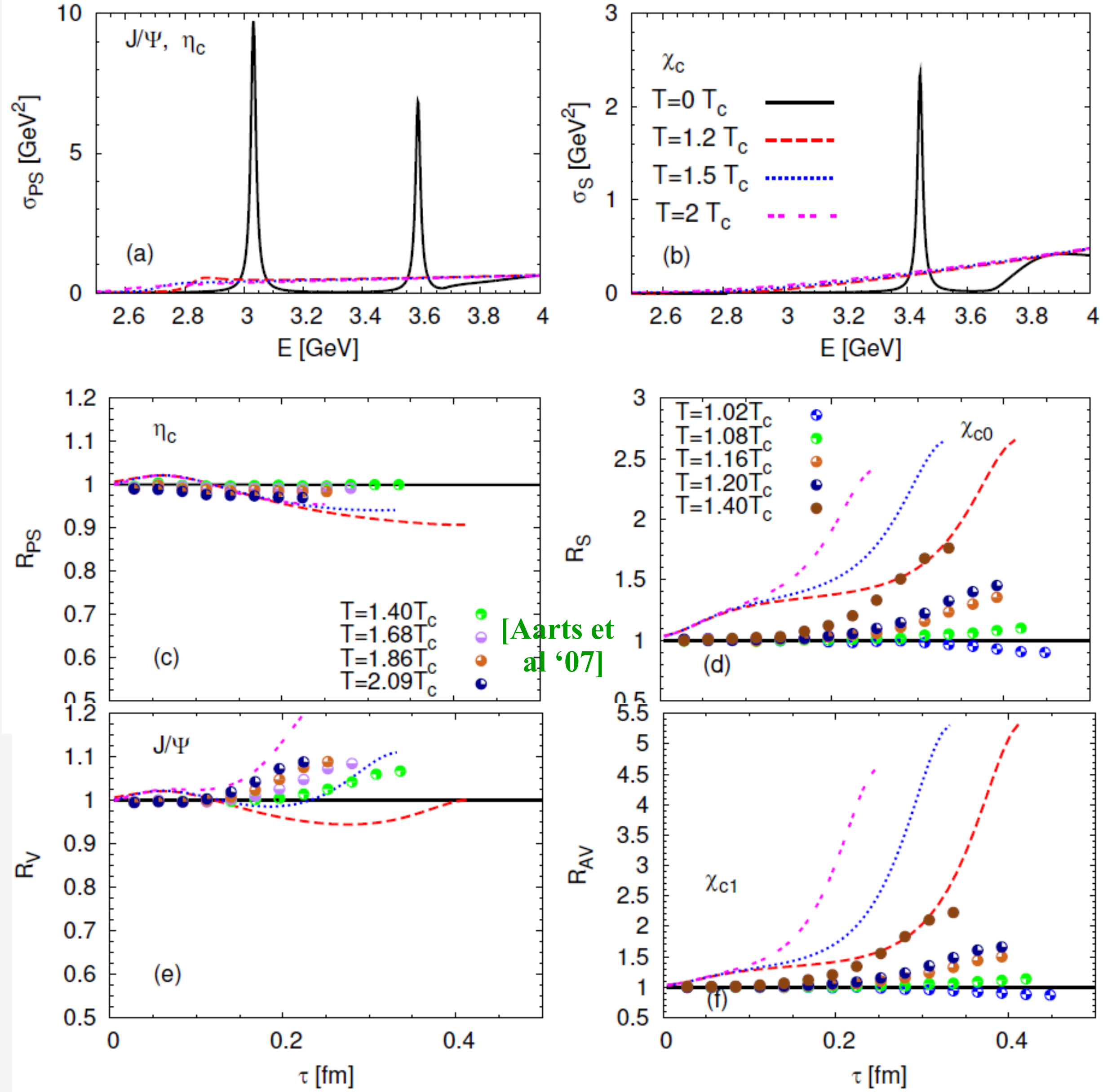


[Mocsy+ Petreczky '05+'08, Wong '06, Cabrera+RR '06, Beraudo et al '06, Satz et al '08, Lee et al '09, Riek+RR '10, …]

3.2.2 T-matrix Approach with F-Potential

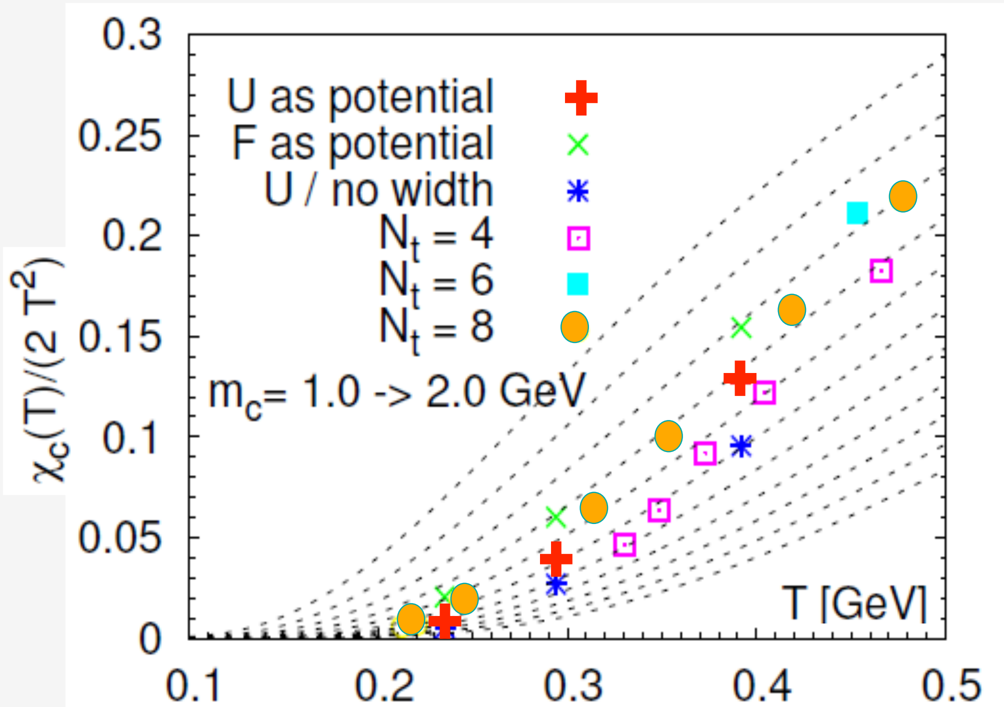
- selfcons. **c**-quark width
- **Spectral Functions**
  - J/ψ melting at **$\sim 1.1 T_c$**
  - χ_c melting at $\leq T_c$
  - **$\Gamma_c \sim 50$MeV**
- **Correlator Ratios**
  - slightly worse agreement with lQCD

[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

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- Diffusion Approach
- Microscopic Interactions (pQCD, AdS/CFT, T-mat)

5.) **Heavy Ions I: Open Heavy Flavor**

6.) **Heavy Ions II: Quarkonia**

7.) **Conclusions**

4.1 Heavy-Quark Diffusion in Matter

- **Boltzmann equation for HQ phase-space distribution *f_Q***

$$\left[\frac{\partial}{\partial t} + \frac{\boldsymbol{p}}{\omega_{\boldsymbol{p}}}\frac{\partial}{\partial \boldsymbol{x}} + \boldsymbol{F}\frac{\partial}{\partial \boldsymbol{p}}\right] f_Q(t,\boldsymbol{x},\boldsymbol{p}) = C[f_Q]$$

- neglect external field, homogenous medium

$$\frac{\partial}{\partial t} f_Q(t,\boldsymbol{p}) = \int \mathrm{d}^3\boldsymbol{k}[w(\boldsymbol{p}+\boldsymbol{k},\boldsymbol{k}) f_Q(\boldsymbol{p}+\boldsymbol{k}) - w(\boldsymbol{p},\boldsymbol{k}) f_Q(\boldsymbol{p})]$$

- transition rate encodes microscopic interaction (scattering amplitude)

$$w(\boldsymbol{p},\boldsymbol{k}) = \gamma_{q,g}\int \frac{\mathrm{d}^3\boldsymbol{q}}{(2\pi)^3} f_{q,g}(\boldsymbol{q}) v_{\mathrm{rel}} \frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}(\boldsymbol{p},\boldsymbol{q}\to\boldsymbol{p}-\boldsymbol{k},\boldsymbol{q}+\boldsymbol{k})$$

- expand transition rate in momentum transfer **$k \sim T \ll p \sim \sqrt{2 m_Q T}$**

$$w(\boldsymbol{p}+\boldsymbol{k},\boldsymbol{k}) f_Q(\boldsymbol{p}+\boldsymbol{k},\boldsymbol{k}) \simeq w(\boldsymbol{p},\boldsymbol{k}) f_Q(\boldsymbol{p}) + \boldsymbol{k}\frac{\partial}{\partial \boldsymbol{p}}[w(\boldsymbol{p},\boldsymbol{k}) f_Q(\boldsymbol{p})] + \frac{1}{2} k_i k_j \frac{\partial^2}{\partial p_i \partial p_j}[w(\boldsymbol{p},\boldsymbol{k}) f_Q(\boldsymbol{p})]$$

$$\Rightarrow \quad \frac{\partial}{\partial t} f_Q(t,\boldsymbol{p}) = \frac{\partial}{\partial p_i}\left\{ A_i(\boldsymbol{p}) f_Q(t,\boldsymbol{p}) + \frac{\partial}{\partial p_j}[B_{ij}(\boldsymbol{p}) f_Q(t,\boldsymbol{p})] \right\}$$

- transport coefficient(s)

$$A_i(\boldsymbol{p}) = \int \mathrm{d}^3\boldsymbol{k}\, w(\boldsymbol{p},\boldsymbol{k}) k_i = A(\boldsymbol{p}) p_i$$ thermalization rate

$$B_{ij}(\boldsymbol{p}) = \frac{1}{2}\int \mathrm{d}^3\boldsymbol{k}\, w(\boldsymbol{p},\boldsymbol{k}) k_i k_j = B_0(\boldsymbol{p}) P_{ij}^{\parallel}(\boldsymbol{p}) + B_1(\boldsymbol{p}) P_{ij}^{\perp}(\boldsymbol{p})$$ diffusion coeff.

$$\gamma \equiv A(\boldsymbol{p}) = \text{const}$$

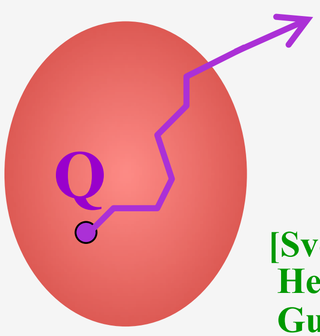
$$D \equiv B_0(\boldsymbol{p}) = B_1(\boldsymbol{p}) = \text{const}$$

$$\frac{\partial f}{\partial t} = \gamma \frac{\partial (pf)}{\partial p} + D \frac{\partial^2 f}{\partial p^2}$$

Fokker Planck Equation

- Brownian Motion, long-time solution:

$$f_Q(t,\boldsymbol{p}) = \left(\frac{2\pi D}{\gamma}\right)^{3/2} \exp\left(-\frac{\gamma \boldsymbol{p}^2}{2D}\right)$$

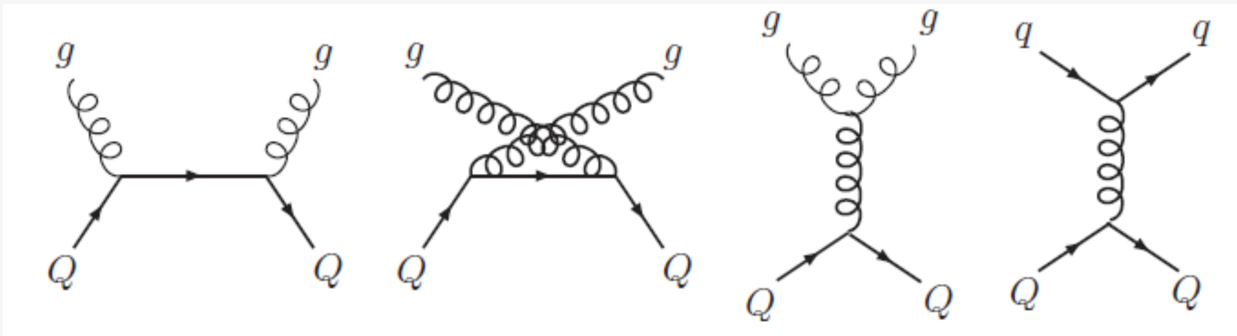


- Einstein relation $D = m_Q \gamma T$

[Svetitsky '87, Mustafa et al '98, Hees+RR '04, Teaney+Moore '04, Gubser '07, Peshier '09, Gossiaux et al '08, Alam et al '09, …]

4.2 Elastic Heavy-Quark Scattering in the QGP

4.2.1 Leading-Order Perturbative QCD



• gluon exchange regularized by Debye mass:

$$G(t) = \frac{1}{t} \rightarrow \frac{1}{t - \mu_D} \ , \quad \mu_D = gT$$

[Svetitsky '88, Mustafa et al '98, Molnar et al '04, Zhang et al '04, Hees+RR '04, Teaney+Moore'04]

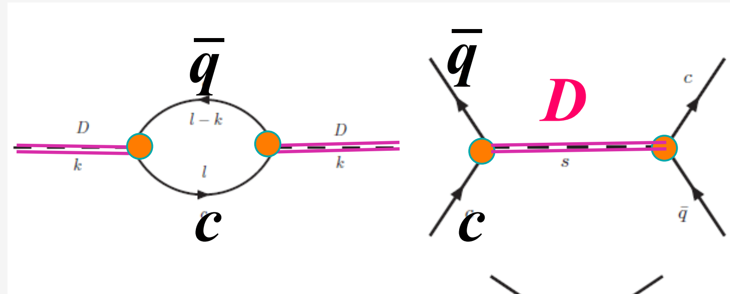
• dominated by forward scattering

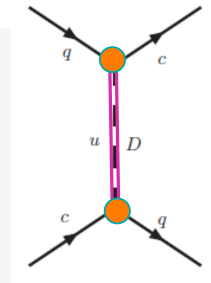
• thermalization time $\gamma^{-1} = \tau_{therm} \geq 20$ **fm/c long** ($T \leq 300$MeV, α_s=0.4)

4.2.2 Effective Resonance Model

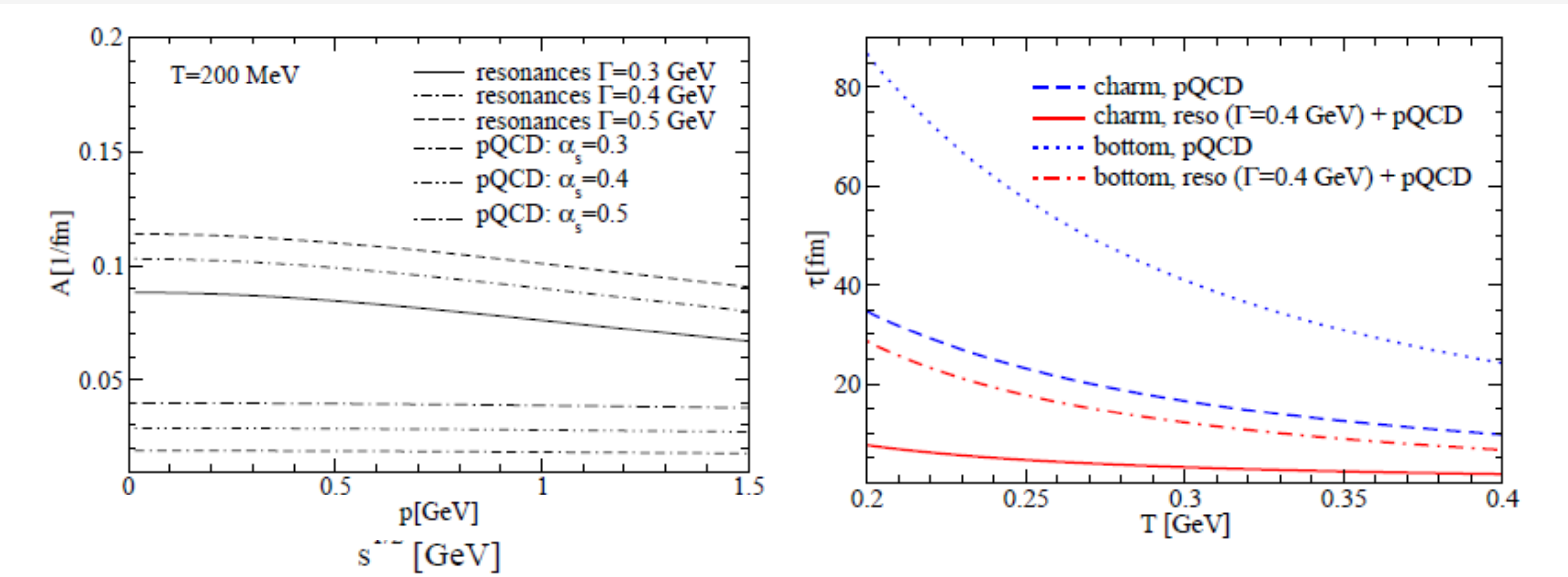
- Postulate **D**-meson **resonances** in "sQGP" close to **T$_c$** **[van Hees+RR '04]**

$$
\begin{aligned}
\mathscr{L}_{Dcq} = & \mathscr{L}^0_D + \mathscr{L}^0_{c,q} - \mathrm{i} G_S \left(\bar{q} \Phi^*_0 \frac{1+\not{v}}{2} c - \bar{q} \gamma^5 \Phi \frac{1+\not{v}}{2} c + h.c. \right) \\
& - G_V \left(\bar{q} \gamma^\mu \Phi^*_\mu \frac{1+\not{v}}{2} c - \bar{q} \gamma^5 \gamma^\mu \Phi_{1\mu} \frac{1+\not{v}}{2} c + h.c. \right) ,
\end{aligned}
$$





- parameters: m_D , G_D

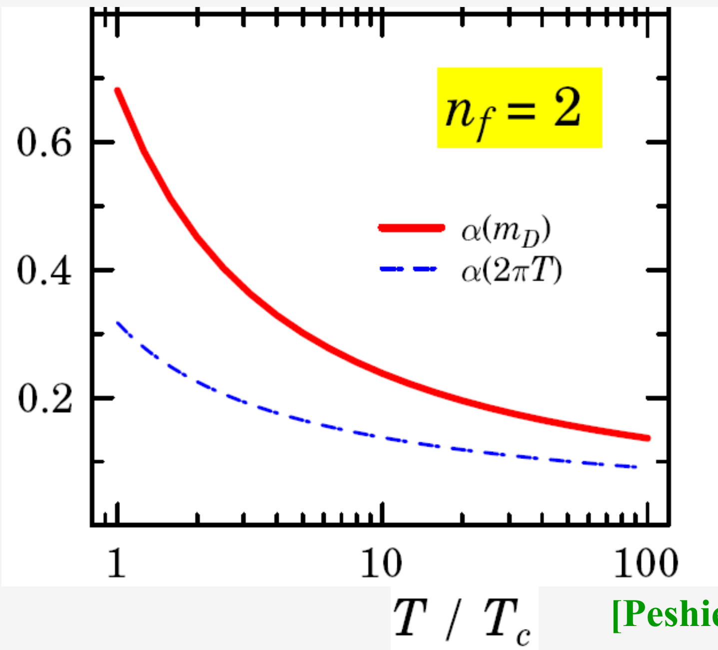


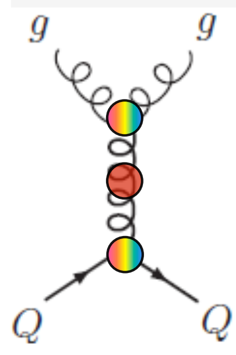
- 3-4 times faster thermalization than LO-pQCD (τ_{therm} ~ **5 fm/c** ~ τ_{QGP})
- falling 3-momentum dependence

4.2.3 Perturbative QCD with Running Coupling

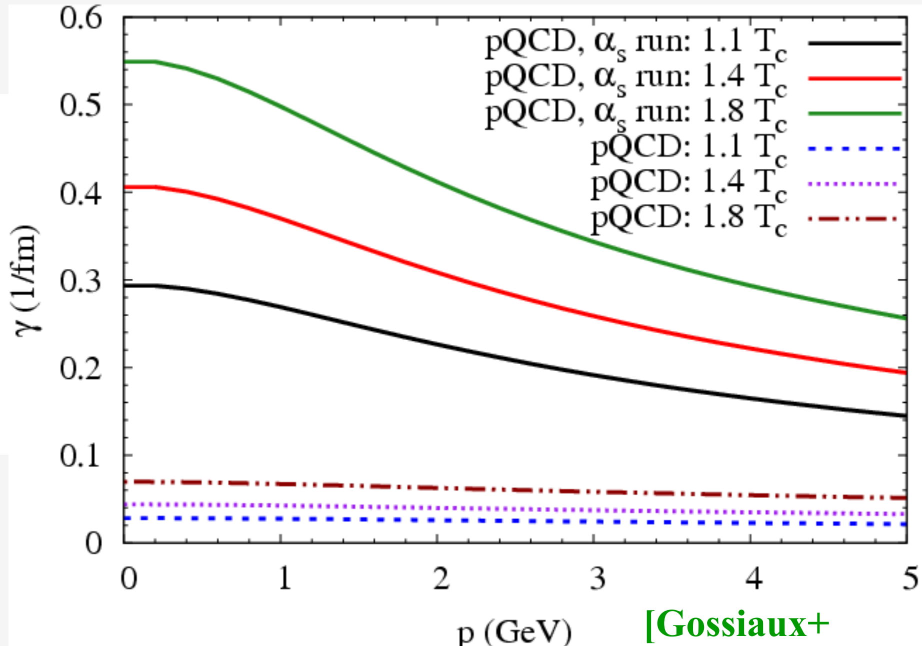
- QCD coupling run to **μ_D ~ gT** rather than **$2\pi T$**
- reduced Debye mass $\tilde{\mu}^2 = \frac{1}{5}\mu_D^2$

$$G(t) = \frac{\alpha}{t} \rightarrow \frac{\alpha_{\text{eff}}(t)}{t - \tilde{\mu}^2}$$





[Peshier '07]



[Gossiaux+ Aichelin '08]

- factor **~10** increase in heavy-quark drag coefficient
- perturbative regime? Need to resum large diagrams…
- full NLO calculation gives similar effect **[Caron-Huot+Moore '08]**

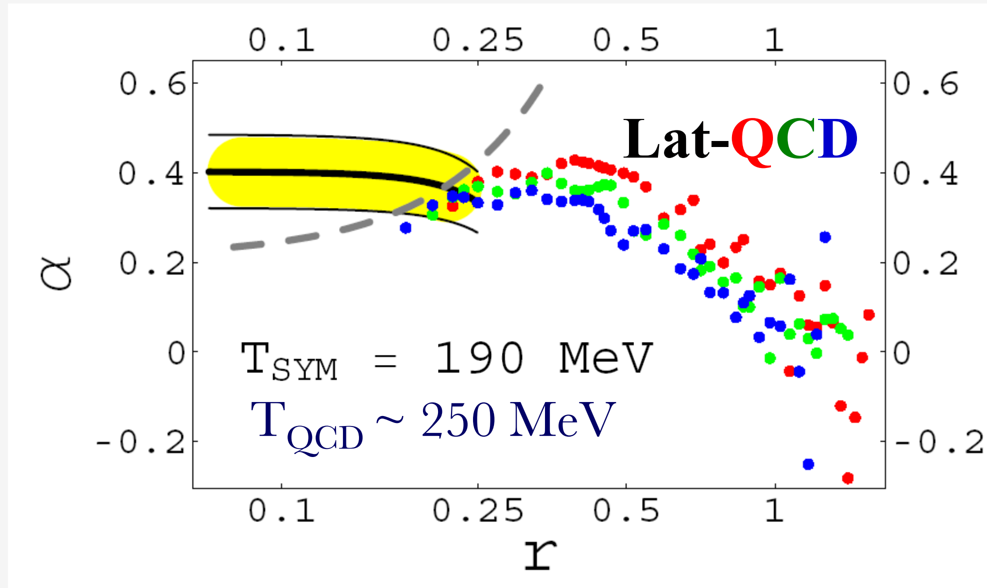
4.2.4 AdS/CFT-QCD Correspondence

$$\frac{dp}{dt} = -\gamma\, p \qquad \gamma_{AdS/CFT} = \frac{\pi\sqrt{\lambda}}{2m_c}\, T_{SYM}^2$$

3-momentum **in**dependent

[Herzog et al, Gubser '06]

- match energy density (d.o.f = 120 vs. ~40) and coupling constant (heavy-quark potential) to QCD

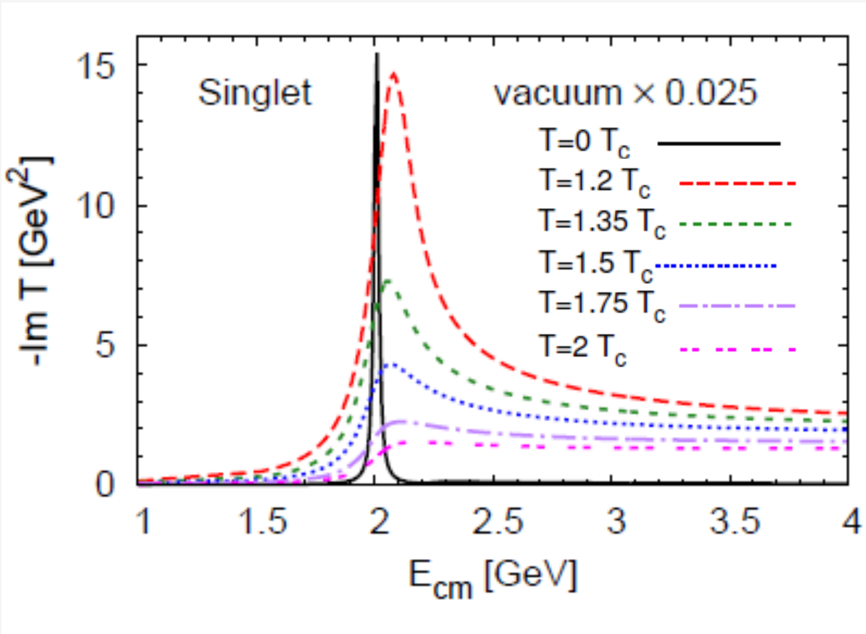


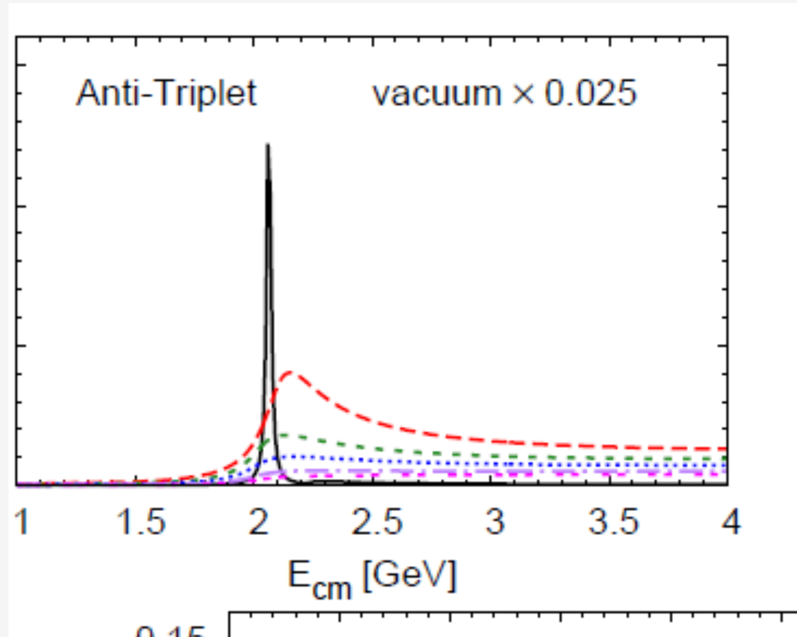
$$\Rightarrow \quad \gamma_{AdS/CFT} = (2.1 \pm 0.5)\,\frac{T^2}{m_c}$$

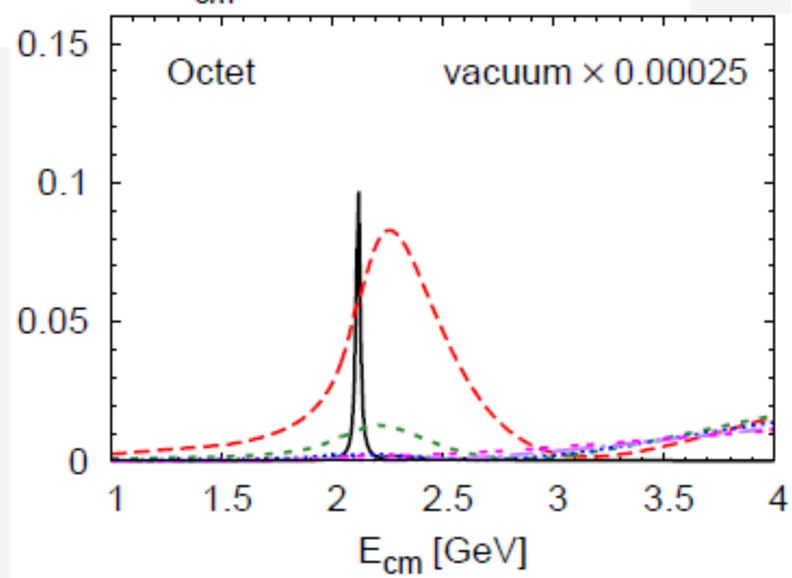
≈ (4-2 fm/c)$^{-1}$ at T=180-250 MeV

[Gubser '07]

4.2.5 Thermodynamic T-Matrix



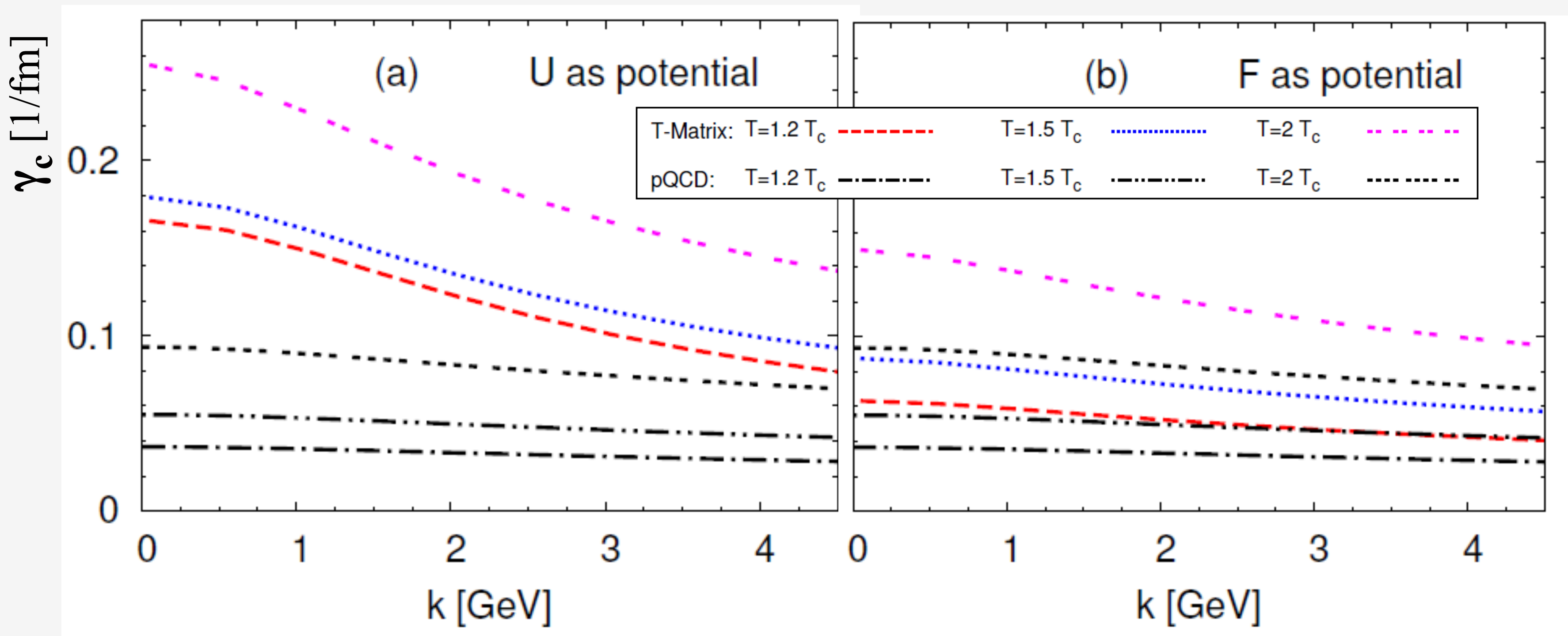




- meson/diquark resonances for $T < 1.5 T_c$
- resummation suppresses repulsive channels (alternating sign in Born series of **T**-matrix)

[Riek+RR ‘10]

4.2.5.2 Thermalization Rate from T-Matrix

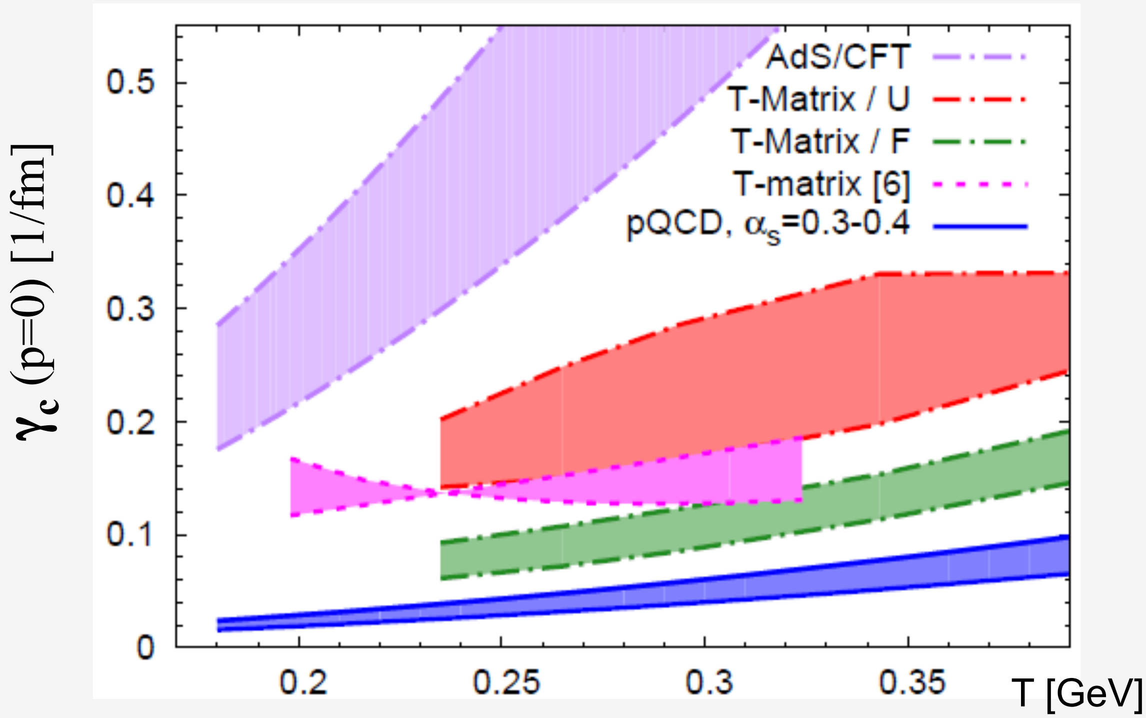


- thermalization **4** (**2**) times faster using **U** (**F**) as potential than pert. QCD
- momentum dependence essential (nonpert. effect ≠ **K**-factor!)

[Riek+RR '10]

4.3 Summary: Charm-Quark Transport in QGP

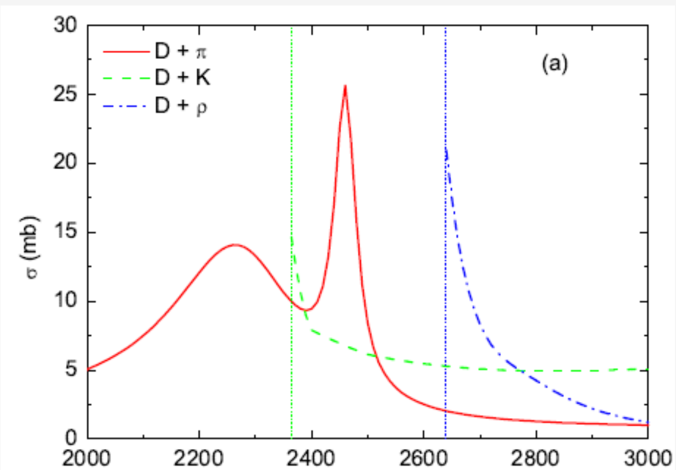
Thermalization Rate

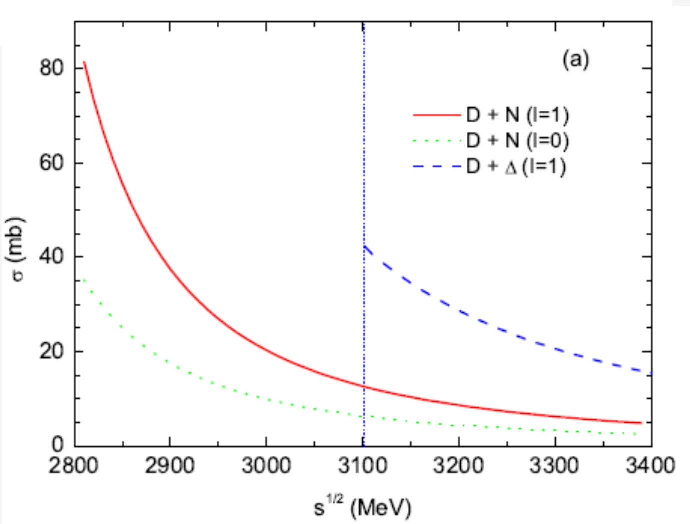


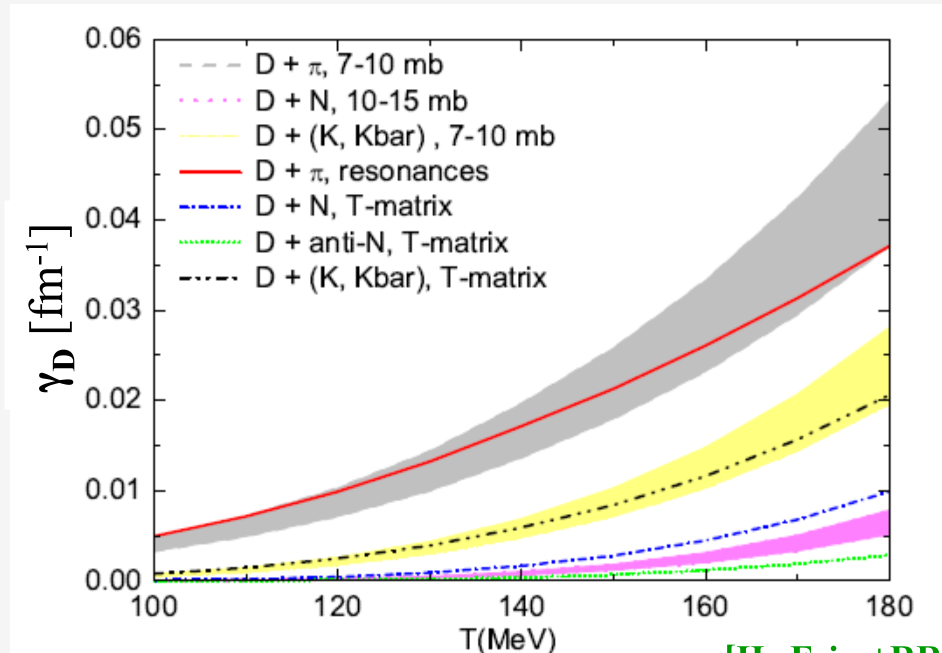
- AdS/CFT ~ Coulomb, marked **T**-dependence, **p**-independent
- **T**-matrix thermalization **4** (**2**) times faster for **U** (**F**) than pert. QCD
- running coupling (not shown) similar to AdS/CFT

4.4 Thermal Relaxation of Charm in Hadron Matter

- employ **D-hadron** scattering amplitudes from effective Lagrangians



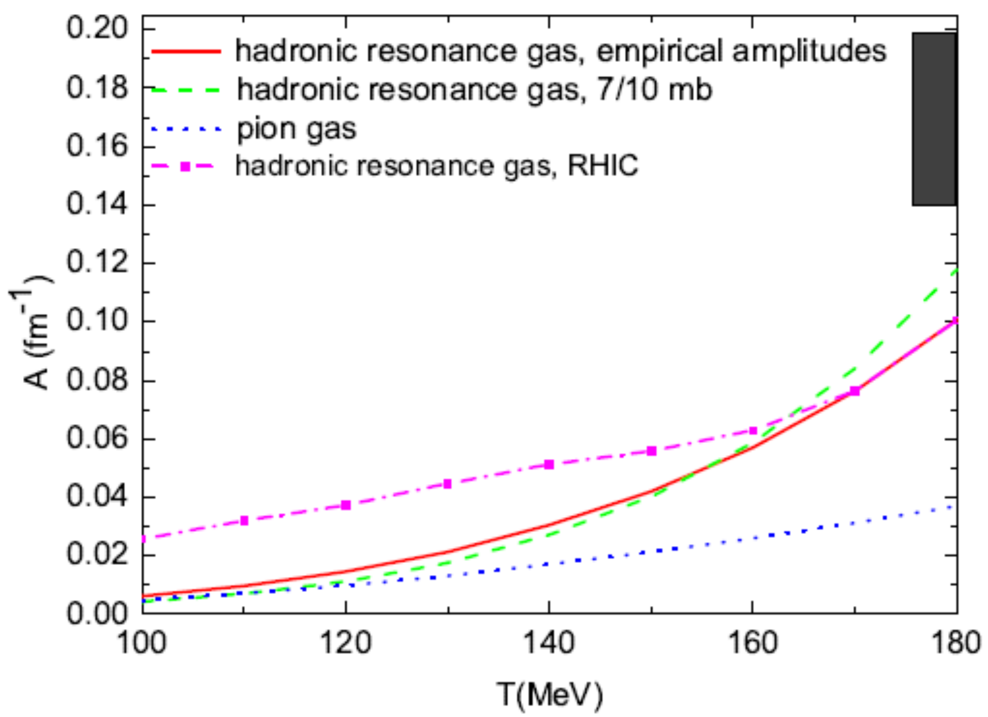




[He,Fries+RR '11]

- pion gas:
  - consistent with unitarized HQET [Cabrera et al '11]
  - factor 10 smaller than Heavy-Meson χPT [Laine '11]
- substantial contributions from resonance gas

4.4.2 D-Meson Relaxation Rate in Hadron Matter

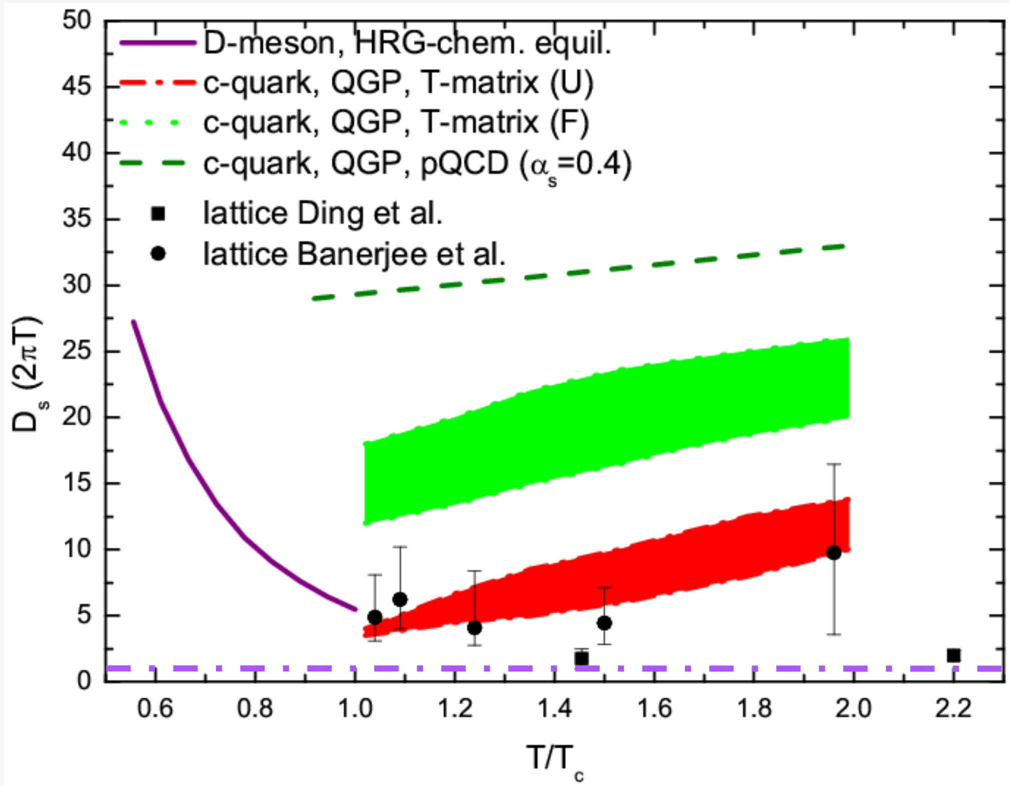


Hadrons	$L_{I,2J}$	γ_D [fm^{-1}]
π	$S_{1/2,0},\ P_{1/2,2},\ D_{1/2,4},\ S_{3/2,0}$	0.0371
$K+\eta$	$S_{0,0},\ S_{1,0}$	0.0236
$\rho+\omega+K^*$	$S_{1/2,2},\ S_{0,2},\ S_{1,2}$	0.0129
$N+\bar{N}$	$S_{0,1},\ S_{1,1}$	0.0128
$\Delta+\bar{\Delta}$	$S_{1,3}$	0.0144

- thermal relaxation time in hadron resonance-gas as low as **$\tau_D \approx$ 10fm/c**
- chemical off-equilibrium below **T_{ch}** significant
- expect **~20%** effect from hadronic phase at RHIC/LHC

4.5 Summary of Charm Diffusion in Matter

Hadronic Matter vs. QGP vs. Lattice QCD (quenched)



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

AdS/CFT

- Shallow minimun around T_c ?!
- Quark-Hadron Continuity?!
- 20% reduction by non-perturbative HQ-gluon scattering

Outline

1.) **Introduction**

2.) **One- and Two-Body Correlations**

- Potential Models, T-Matrix Approach

3.) **Charmonia in the QGP**

- Spectral Functions, Eucl. Correlators, Suscpetibility

4.) **Heavy-Flavor Transport**

- Diffusion Approach
- Microscopic Interactions

5.) **Heavy Ions I: Open Heavy Flavor**

- Bulk Evolution, Hadronization
- Langevin Simulations, Observables

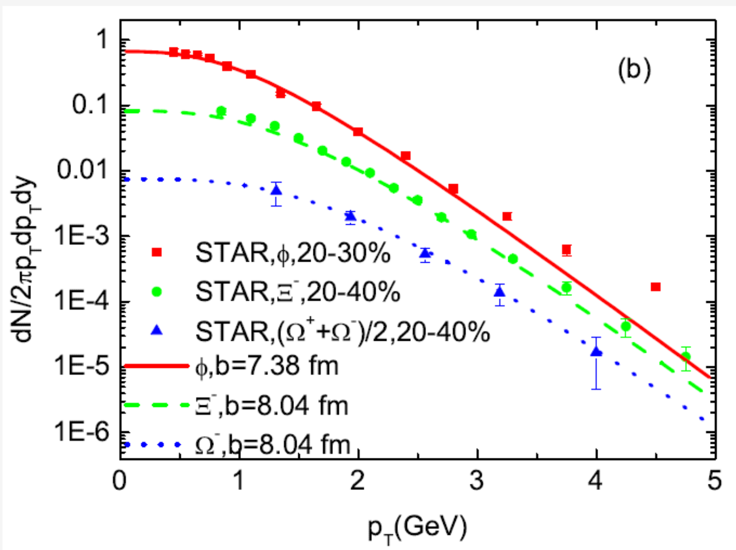
6.) **Heavy Ions II: Quarkonia**

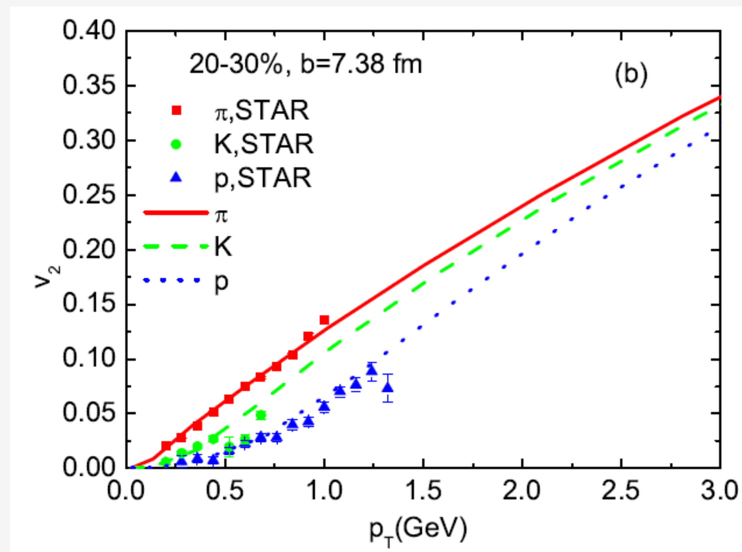
7.) **Conclusions**

4.) Heavy-Quark Phenomenology with Heavy Ions

4.1 Bulk-Medium Evolution

- updated ideal 2+1D hydrodynamics (based on AZHYDRO [Kolb+Heinz ’03])
  - lattice EoS, initial flow, compact initial conditions, partial chemical equilibrium in hadronic phase [He et al ’11]
  - multistrange / bulk freezeout at $T_{ch} \sim 160$MeV / $T_{fo} \sim 110$MeV





- v_2 saturates at T_{ch}, good light-/strange-hadron phenomenology

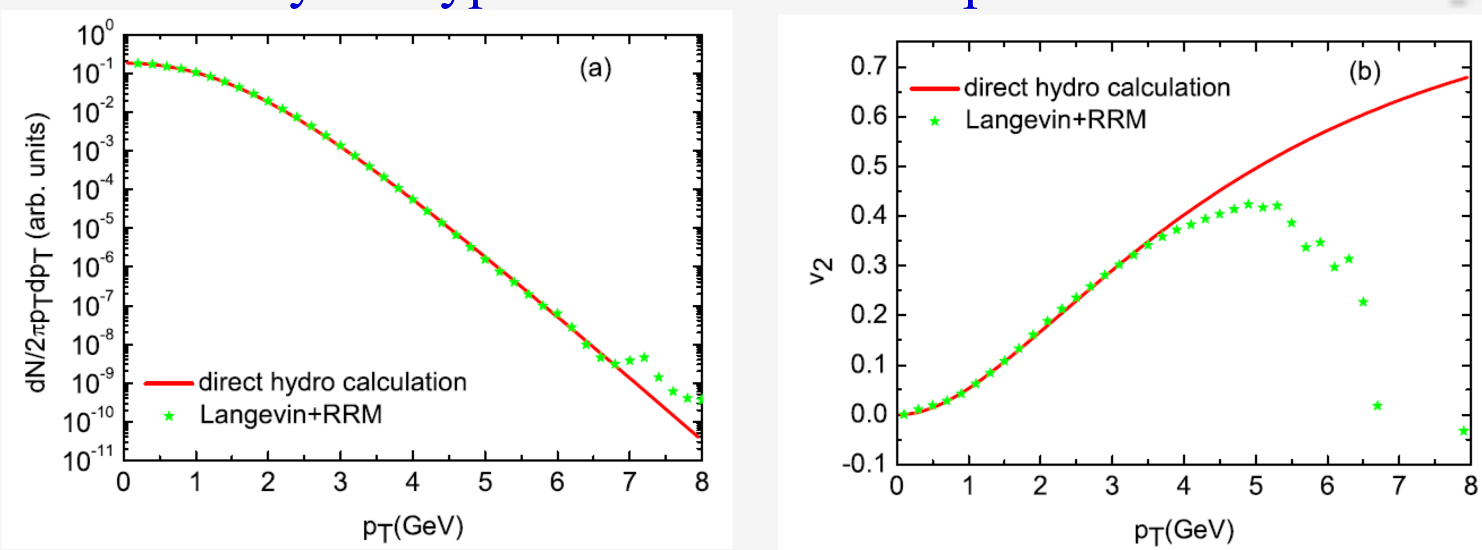
4.2 Hadronization of Charm Quarks

- **Fragmentation**: **c → D + X**, incompatible with thermalization
- **Coalescence**: **c + q → D** → **Resonance Recombination Model**

$$\frac{dN_M}{d^3p} \sim \int \frac{d^3p_1 d^3p_2}{(2\pi)^6} \int d^3x \; f_q(\vec{x},\vec{p}_1) \; f_{\bar{q}}(\vec{x},\vec{p}_2) \; \sigma(s) \; v_{\rm rel}(\vec{p}_1,\vec{p}_2) \; \delta^{(3)}(\vec{p}-\vec{p}_1-\vec{p}_2)$$

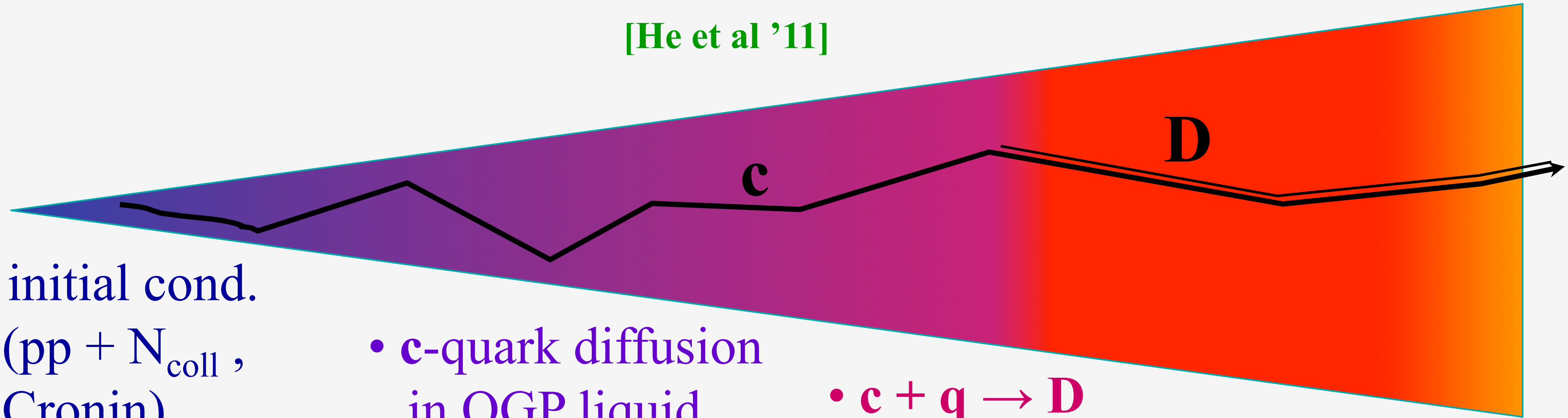
[Ravagli +RR '07]

- 4-mom. conservation, correct thermal equilibrium limit
- implement on hydro hypersurface with full space-mom. correl.



- **Conceptual Consistency:**
  same interaction (T-matrix) underlying diffusion + hadronization!

4.3 Dynamical Scheme for Heavy Quarks in URHICs



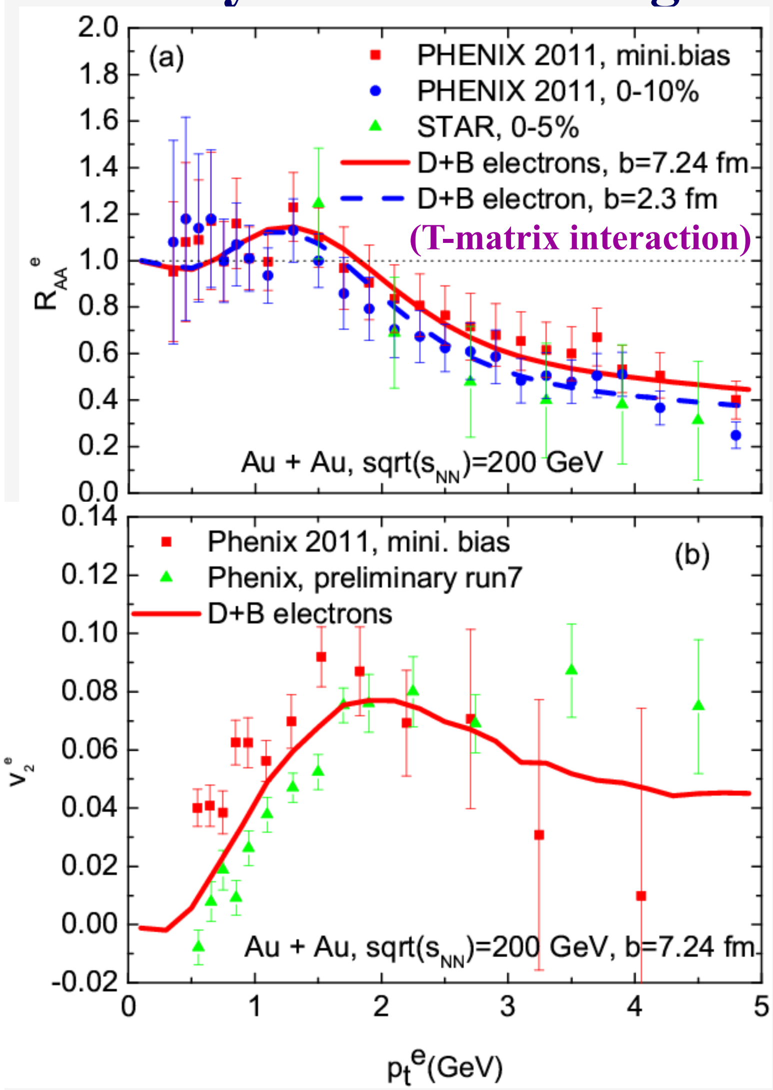
- initial cond. (pp + N_{coll} , Cronin)
- **c**-quark diffusion in QGP liquid (**T**-matrix)
- **c + q → D** resonance recombination
- **D**-meson diffusion in hadron liquid

- **Conceptual Consistency**
  - **diffusion ↔ hadronization:**
    strong coupling (non-pert.) → resonance correlations → recombination
    weak coupling (perturb.) → fragmentation
  - **diffusion ↔ bulk medium:**
    strong coupling → hydrodynamics , weak coupling → transport

4.4.1 Heavy-Flavor Transport I: e$^{\pm}$ Spectra at RHIC

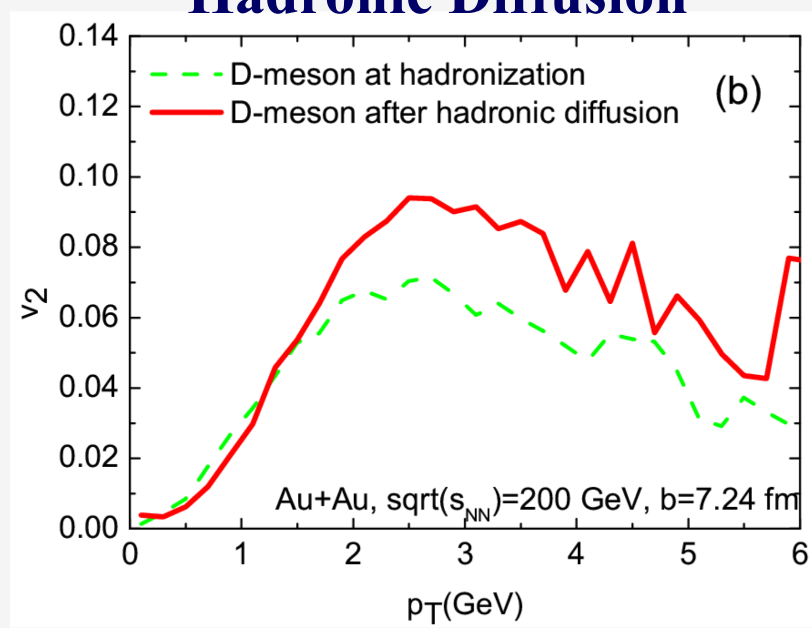
e$^{\pm}$ Decays from c/b Langevin in Hydro

[Teaney+Moore ’04, Mustafa ’05, Hees et al ’05, Gossiaux et al ’09, Akamatsu et al ‘09, Alam et al ’10, Beraudo et al ’10, …]



- hadronic resonances at ~T_c ↔ quark coalescence
- connects 3 “pillars” of RHIC: hydro + strong coupl. + coalescence

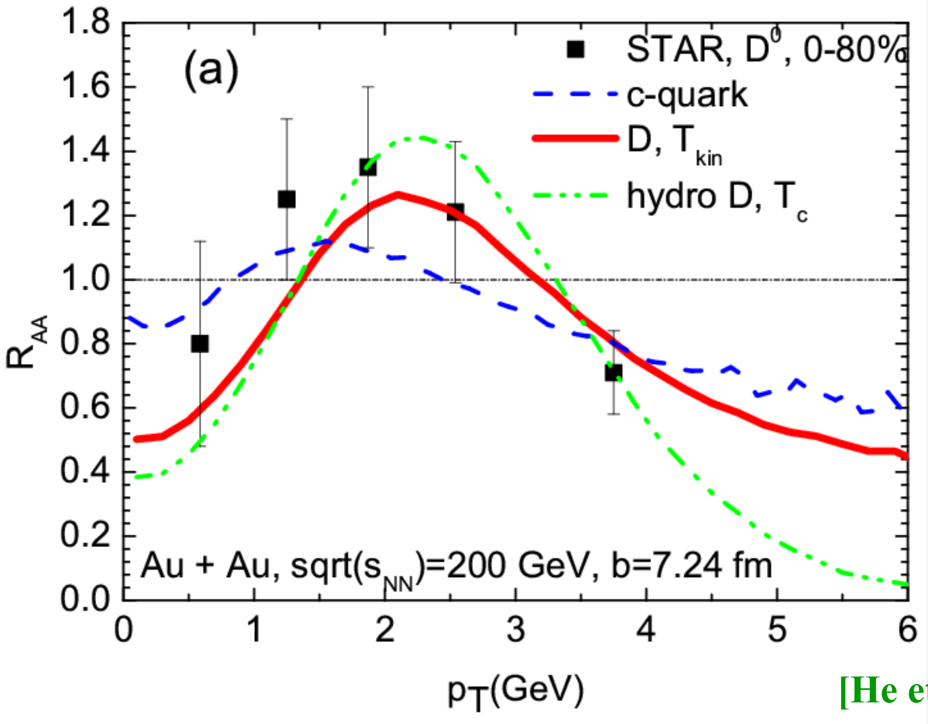
Hadronic Diffusion



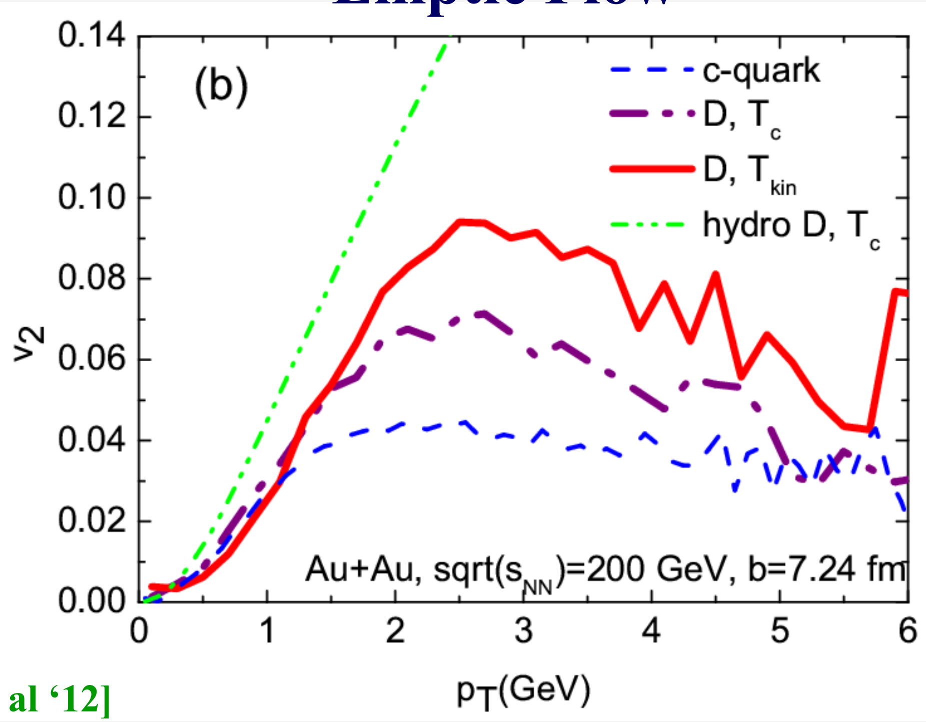
[He et al ‘11]

4.4.2 HF Transport II: D-Meson at RHIC

Nuclear Modification Factor



Elliptic Flow

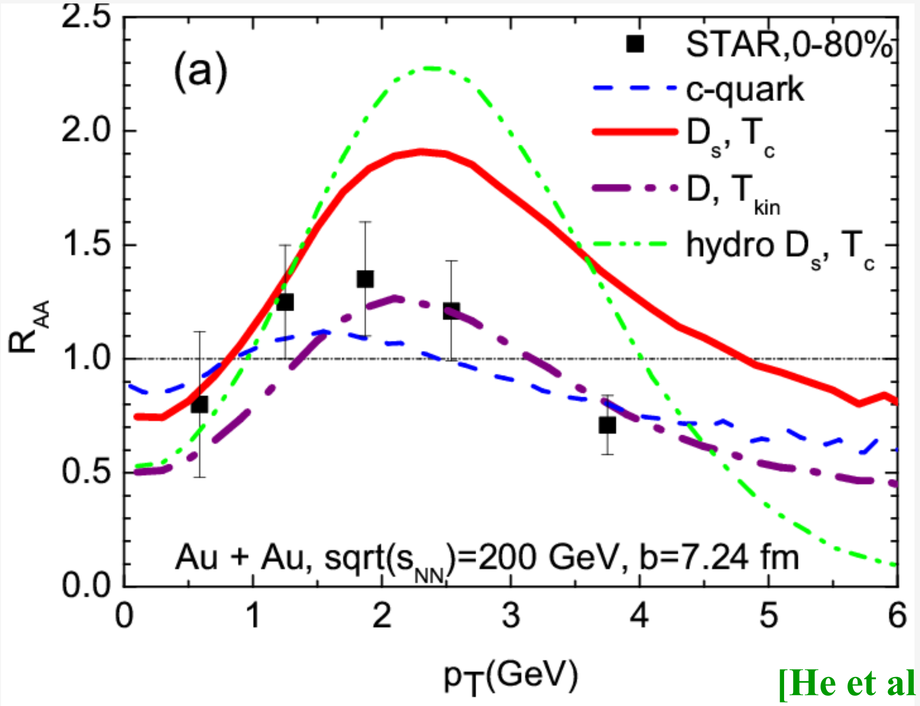


[He et al '12]

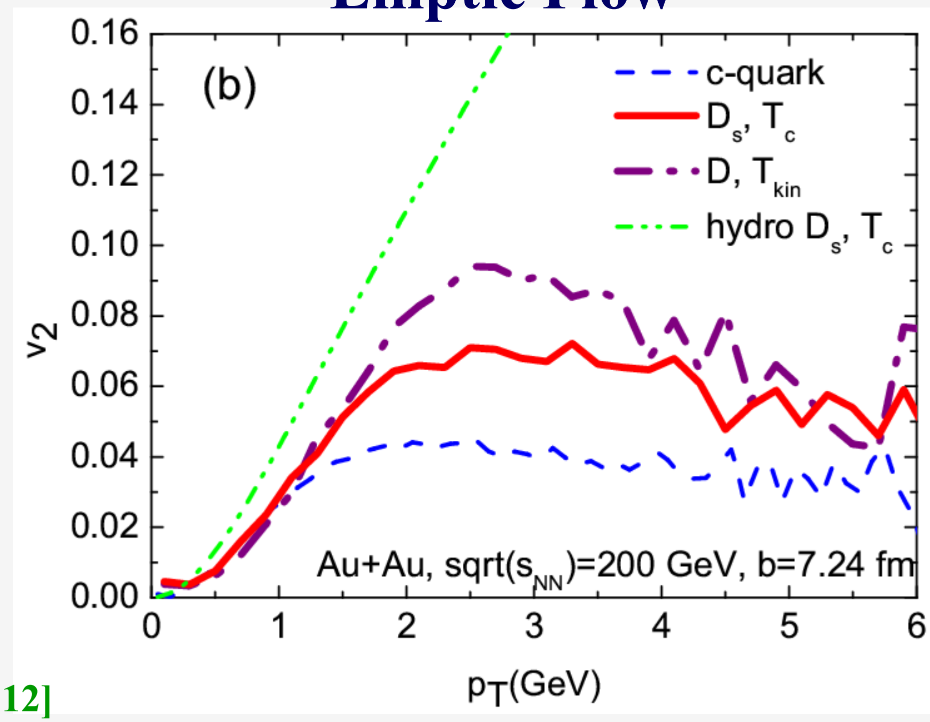
- **D-meson flow-bump?!**
- **hadronization (resonance recomb.) acts as extra interaction**
- **v_2 imparted from hadronic phase significant (20-30%)**

4.4.3 HF Transport III: D$_s$-Meson

Nuclear Modification Factor



Elliptic Flow



[He et al '12]

- Predicts meson-R_{AA} > 1 !
- requires QGP diffusion, coalescence + strangeness enhancement
- quantitative measure of hadronic phase: D vs D$_s$

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6.) **Heavy Ions II: Quarkonia**

- Rate Equation + Medium Effects
- Charmonium + Bottomonium Observables

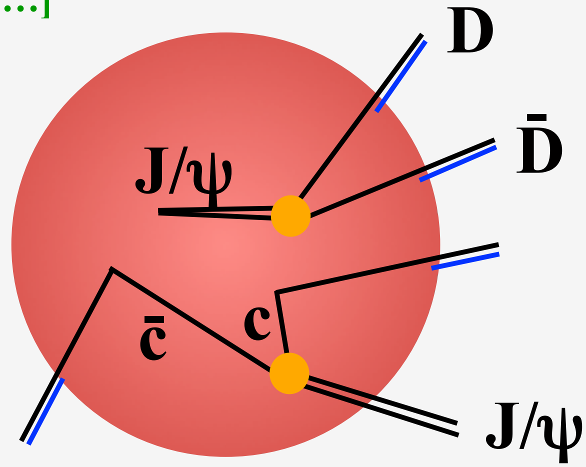
7.) **Conclusions**

5.1 Transport Approach to Quarkonium Evolution

- **Regeneration in QGP + HG:**

[PBM et al ’01, Gorenstein et al ’02,Thews et al ’01, Grandchamp+RR ’01, Ko et al ’02, Cassing et al ’03, Zhuang et al ’05, …]

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



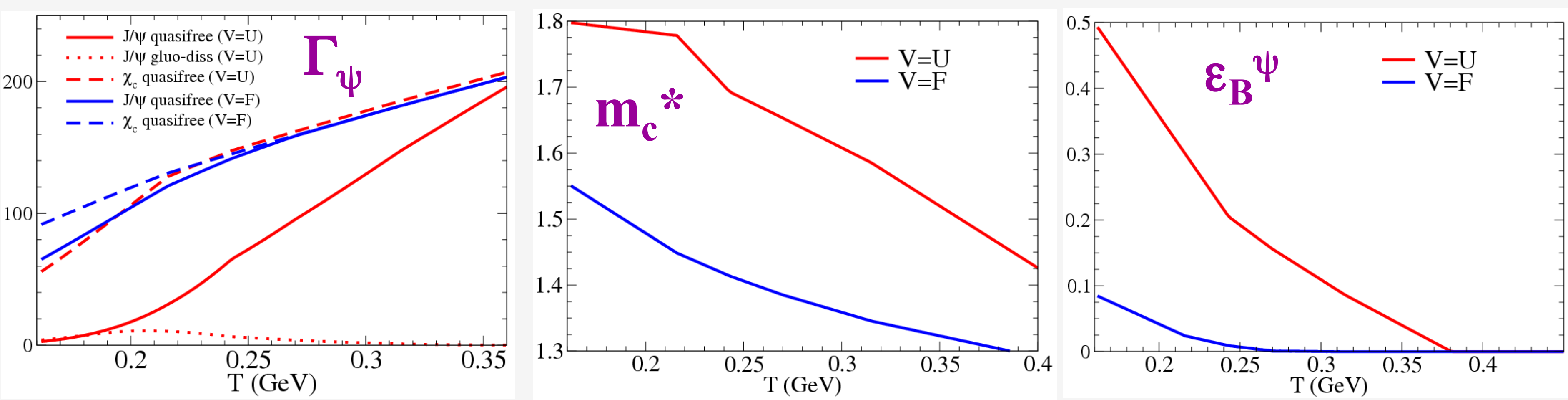
- **Rate Equation:**

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

reaction rate (ψ -width)

equilibrium limit $(dN_c/dp_T, m_\psi, m_c^*)$

- **Input from Thermodynamic T-Matrix (weak/strong binding)**



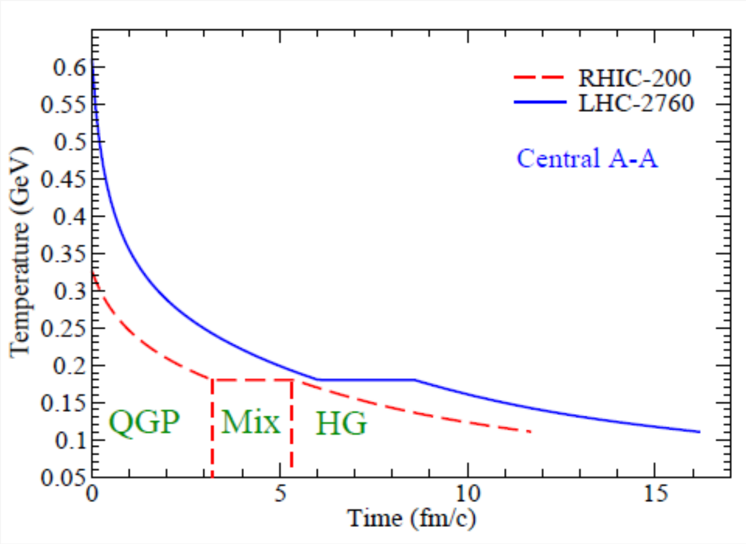
5.2 Inputs and Parameters

- **Input**

  - J/ψ (χ_c, ψ'), c-$\bar{c}$ production cross sections, **b** feeddown [**p-p** data]

  - "Cold Nuclear Matter": shadowing, nuclear absorption, p_t broadening [**p/d-A** data, shad. est.]

  - Thermal fireball evolution: thermalization time (↔ initial T_0), expansion rate, lifetime, T_c , freezeout … [**A-A** hadron data, hydrodynamics]

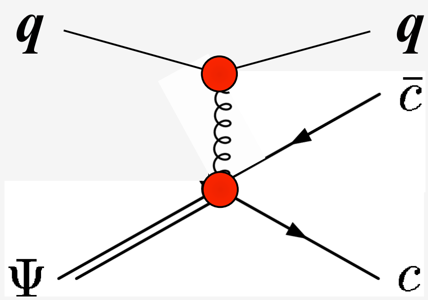


- **Parameters**

  - strong coupling α_s controls Γ_{diss}

  - schematic **c**-quark off-equilibrium:

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

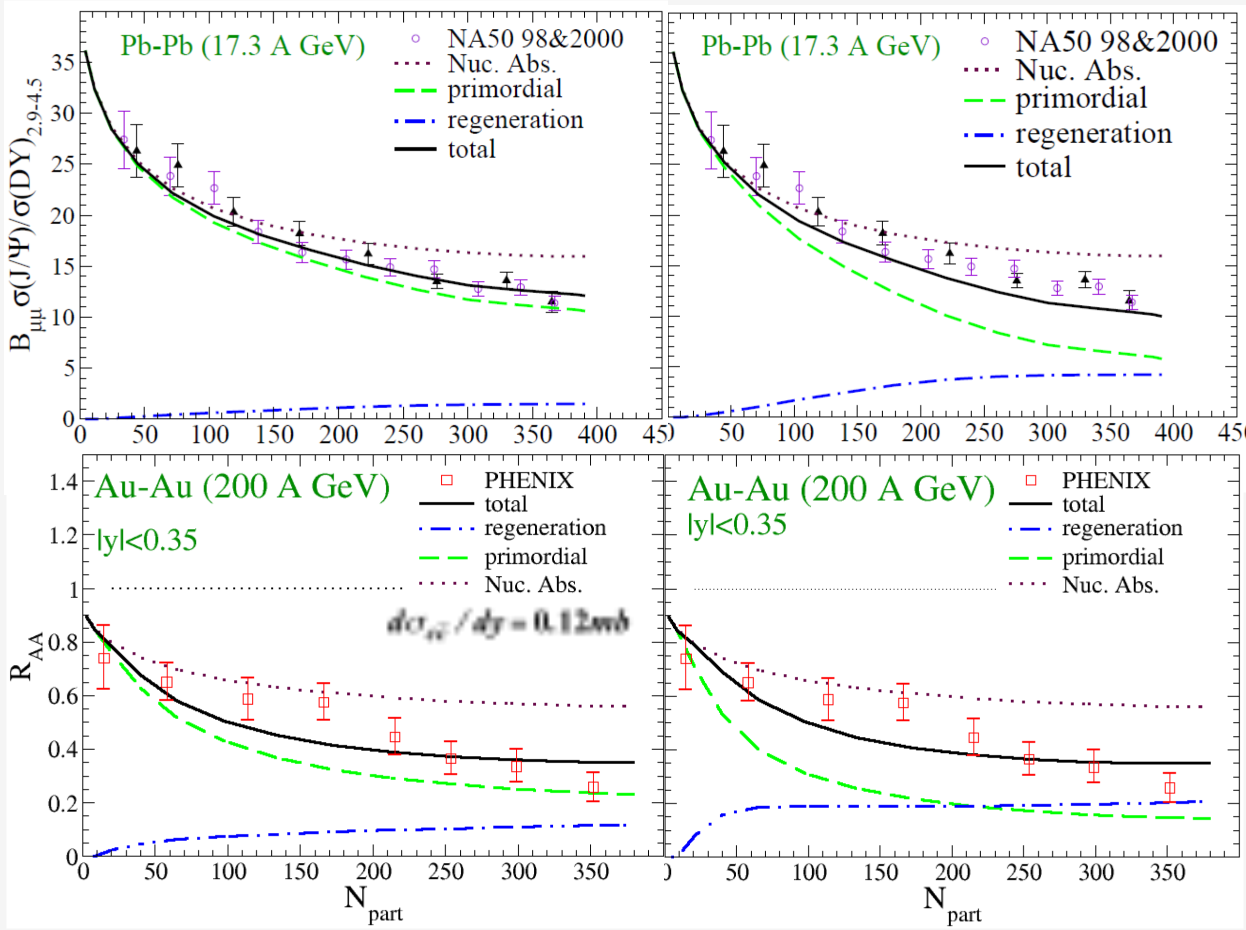


5.3 Inclusive J/ψ in Thermal Media at SPS + RHIC

U-Potential **F-Potential**

- thermal rate equation through **QGP / T_c / HG** for **J/ψ , χ_c , ψ'**

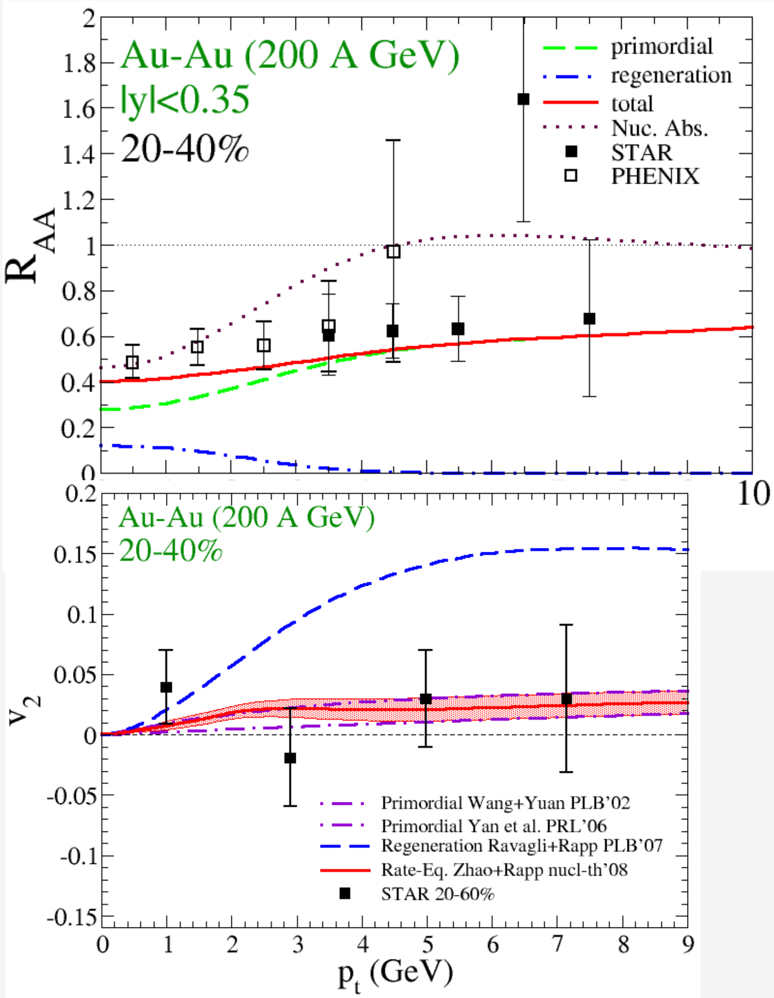
$$\frac{dN_\psi}{d\tau} = -\Gamma_\psi \left(N_\psi - N_\psi^{eq} \right)$$



- 2 parameters (α_s~0.3, charm relax. τ_c^{eq} = 6(3) fm/c)
- different composition in two scenarios

[Zhao+RR '10]

5.3.2 J/ψ p_T Spectra + Elliptic Flow at RHIC

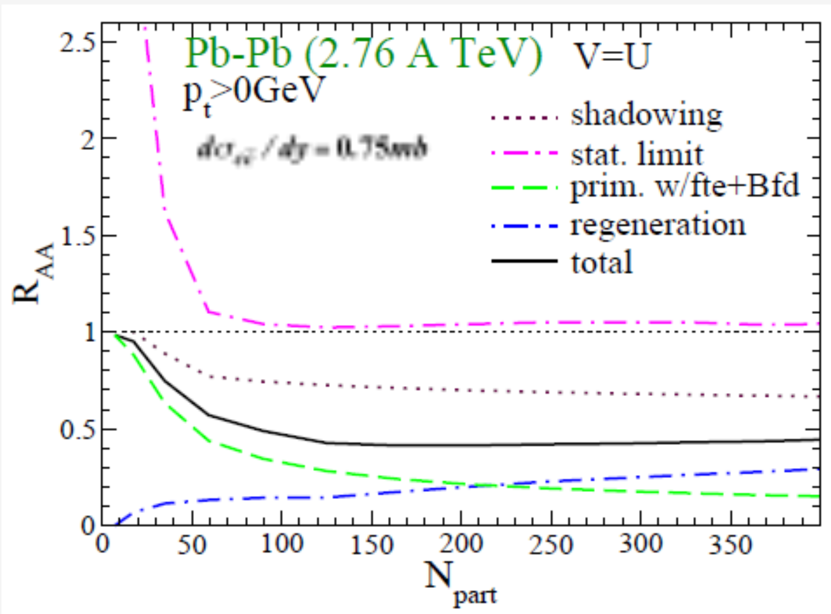


(Strong Binding)

• small v_2 **limits** regeneration, but does **not exclude** it **[Zhao+RR '08]**

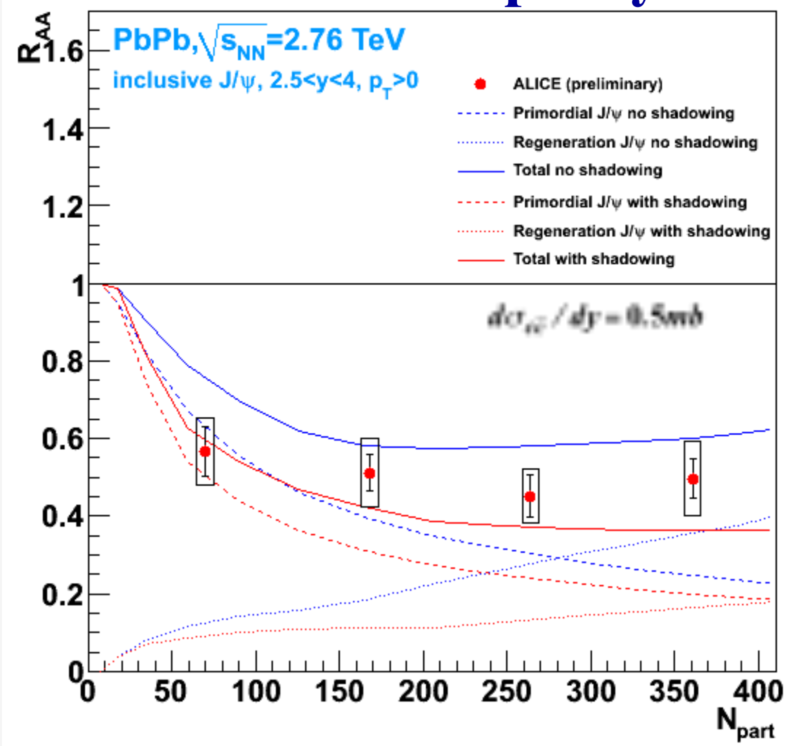
5.4 J/ψ Predictions for LHC

Mid-Rapidity



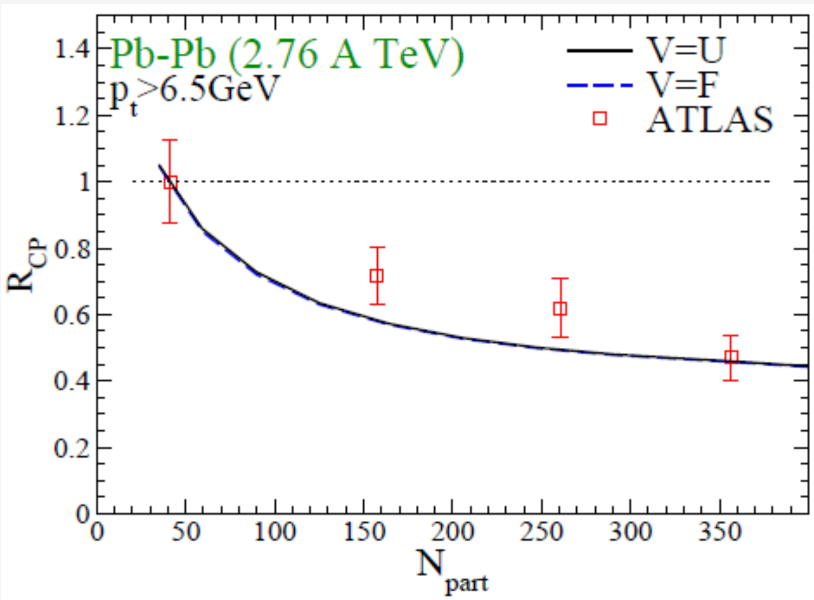
[Zhao+RR '11]

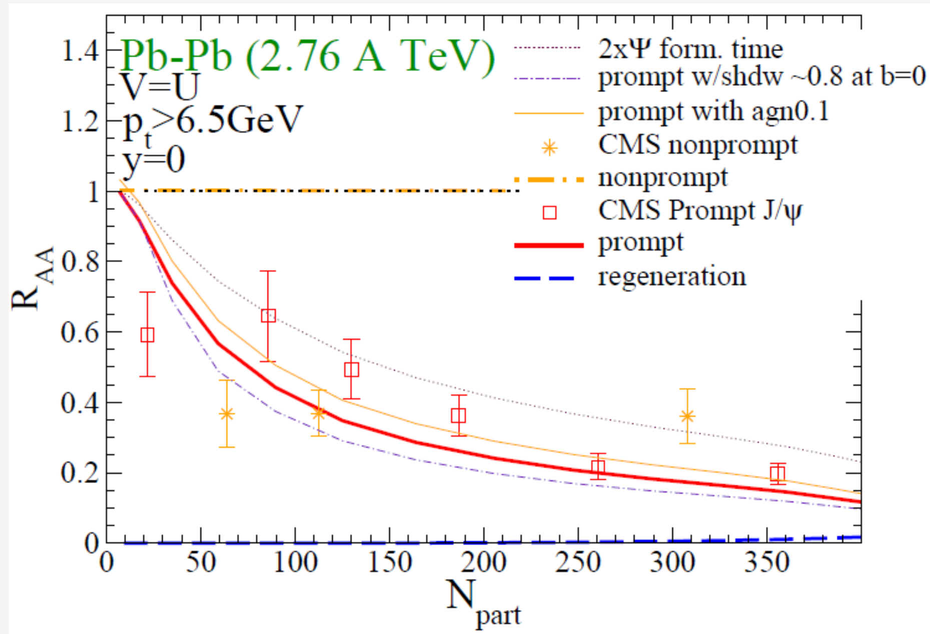
Forward Rapidity



- regeneration component increases, still **net suppression**
- confirmed within main uncertainty of input (shadowing) …

5.4.2 J/ψ Predictions at LHC High-p_t – ATLAS+CMS





[Zhao+RR '11]

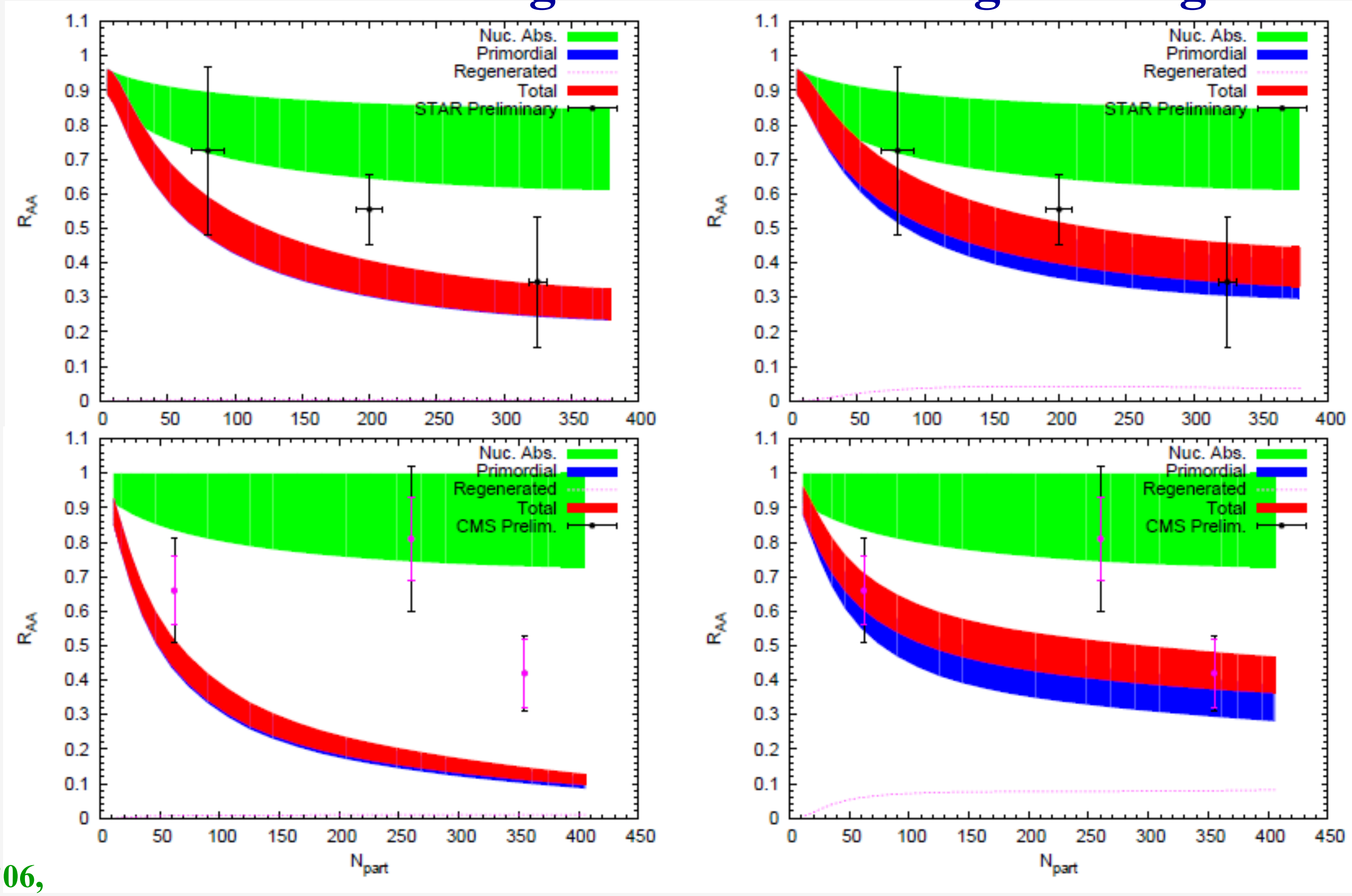
- underestimate for peripheral (expected from **RHIC**)
  (spherical fireball reduces surface effects …)

5.5 ϒ at RHIC and LHC

Weak Binding **Strong Binding**

RHIC →

LHC →



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

• sensitive to color-screening + early evolution times

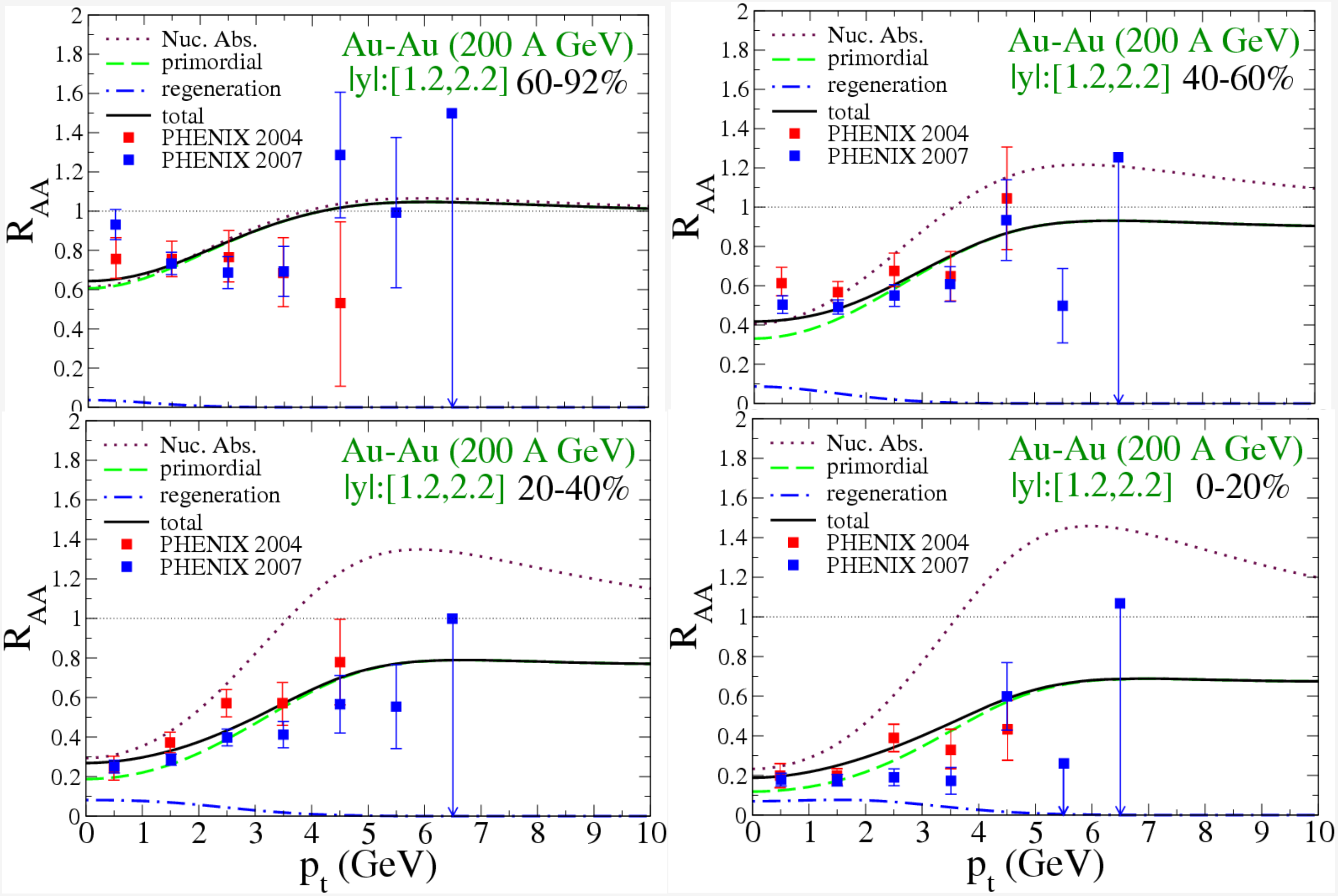
6.) Conclusions

- **Low-momentum HQ interactions elastic + nonperturbative**
  → quarkonia + HQ transport ↔ thermodynamic T-matrix
- **Versatile constraints + observables**
  - heavy-quark diffusion + susceptibilities
  - quarkonia dissolution + euclidean correlator ratios

heavy-ion data **lattice "data"**

- **Open problems:**
  - input potential (neither U nor F?), correlations near T_c
  - radiative scattering (high p_t), finite μ_q …
- **Heavy-Quark Phenomenology:**
  - consistency diffusion-hadronization; hadronic phase
  - predict remarkable D_s enhancement

4.3 J/ψ at Forward Rapidity at RHIC

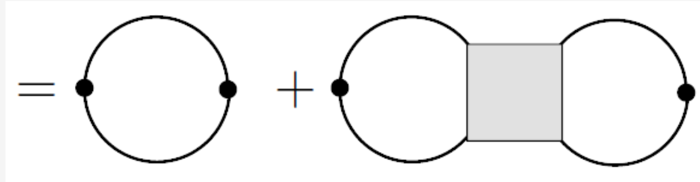


[Zhao+ RR '10]

2.1 Quarkonium Correlators + Spectral Functions

- **Euclidean Correlation Function**

$$G_\alpha(\tau,\vec{r}) = \langle\langle j_\alpha(\tau,\vec{r}) j_\alpha^\dagger(0,\vec{0})\rangle\rangle$$



$$= G^0 + G^0 T G^0$$

- **Spectral Function**

$$\rho_\alpha(\omega,p) = -2\ \mathrm{Im}G_\alpha^R(\omega,p)$$

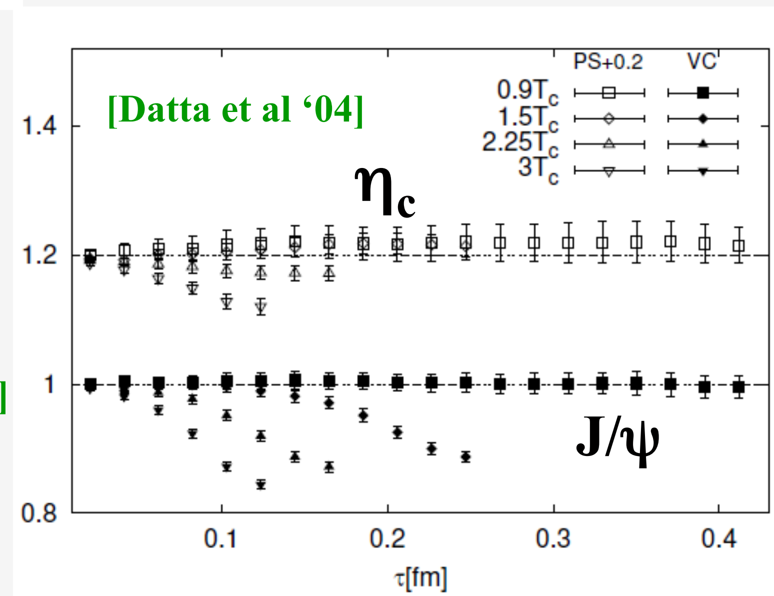
- **Relation:**

$$G_\alpha(\tau,p;T) = \int_0^\infty \frac{d\omega}{2\pi}\ \rho_\alpha(\omega,p;T)\ \frac{\cosh[(\omega(\tau-1/2T))]}{\sinh[\omega/2T]}$$

- **Correlator Ratio:**

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

→ **Lattice QCD!** [Asakawa et al '03, Iida et al '06, Aarts et al '07, Jakovac et al '07]



Interpretation?!