Quark Coalescence and Charm(onium) in QGP

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1.Introduction: The Virtue of HQ's in URHICs

- Common lore: $c\bar{c}$ and $b\bar{b}$ dominantly produced in primary *NN*-collisions

  ⇒ **heavy quarks simultaneously probe:**
  - jet quenching
  - coalescence
  - thermalization
  - ***u***,***d***,***s*** chemistry (e.g. D_s enhancement)

- **In-Medium Modifications:**
  - ***D***-meson masses; ***D=(cq)***: thresholds, χiral Restoration?!
  - Resonances in **QGP**?!

    Quarkonia: dissociation/regeneration above T_c

    D-mesons: enhanced c-quark rescattering

    → link to **lattice QCD**

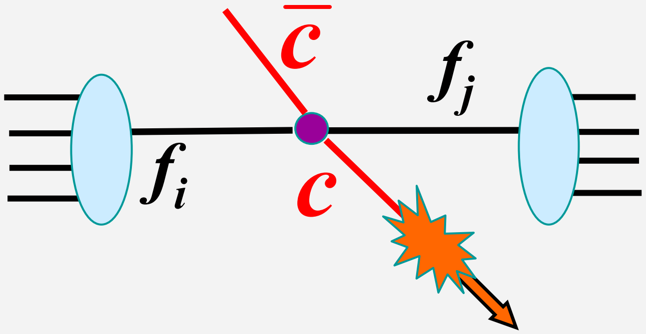
Outline

1. **Introduction**
2. **Open Charm in Hadronic Collisions**
   - **Flavor Asymmetries: Fragmentation vs. Recombination**
3. **c-Quark Interactions in Heavy-Ion Reactions**
   - **Coalescence, Collective Flow**
4. **Charm(onium) in QGP**
   - **4.1 Heavy-Quark Thermalization**
   - **4.2 Inelastic Charmonium Reactions**
   - **4.3 Kinetic Rate Equation**
5. **Phenomenology in URHICs**
   - **5.1 J/ψ Suppression vs. Regeneration**
   - **5.2 Lighter Ions (A≈100)**
6. **Conclusions**

2. Open-Charm in Hadronic Collisions

2.1 Production Systematics of D-Mesons

Baseline:



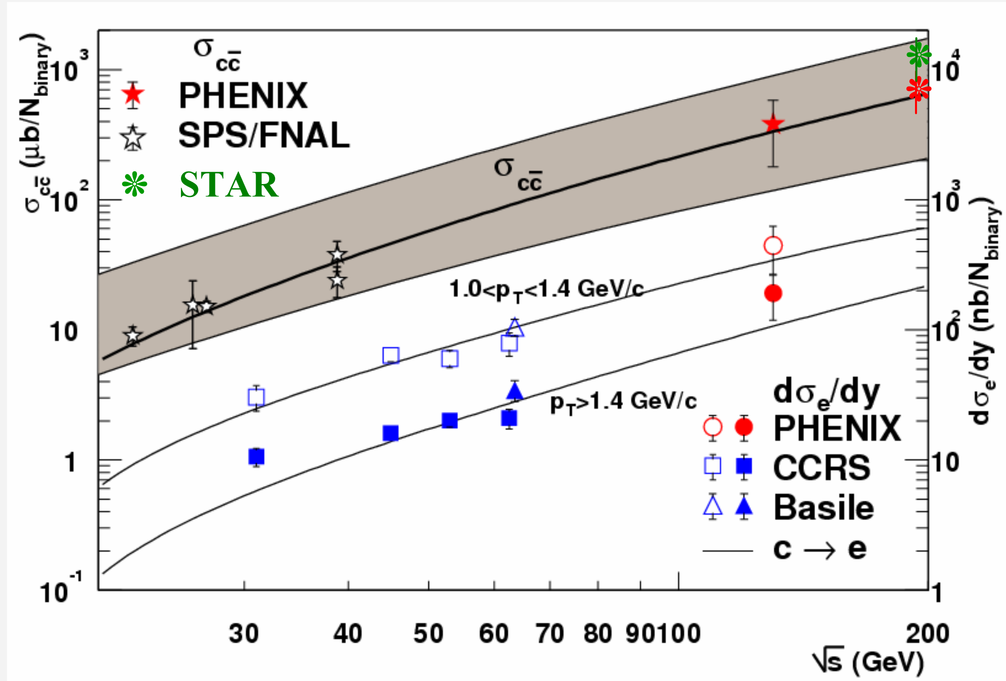
$$\frac{d\sigma_D}{dx_F} = \int f_i(x_1)\, f_j(x_2) \frac{d\sigma_{ij\to c\bar{c}}}{d\hat{t}}\, D_{D/c}(z)$$

Factorization

+

Fragmentation

(isospin symmetry + $D^*/D=3$)

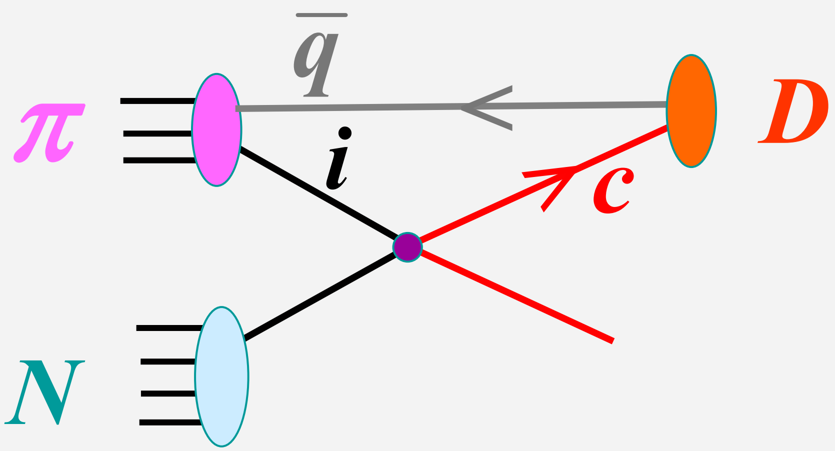


π^-N	D^-/D^+	$D^0/\bar{D}^0$	$D^\pm/D^0$
Frag	1	1	1/3
Exp	1.35±0.05	0.93±0.03	0.415±0.01

marked flavor asymmetries not accounted for !

2.2 Recombination Approach

- historically: forward π^+/π^- , K^+/K^- asymmetries [Das+Hwa '77, …]
- similarly for **c**-quarks: recomb. with q_{val} [Likhoded etal '80s, Hwa '95, Braaten etal '02, …]
- here: recomb. also with sea-quarks; [RR+Shuryak '03]



Input:

- 2-parton distribution fct.:

$$f^{(2)}_{i\bar{q}} = C_2\, f_{\bar{q}}(x_{\bar{q}})\, f_i(x_1)\, (1 - x_{\bar{q}} - x_1)^p$$

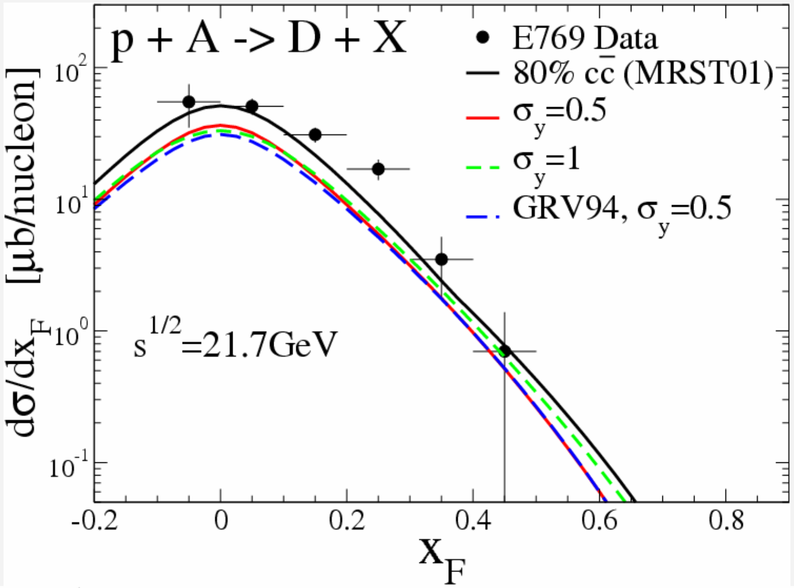
- recombination fct.:

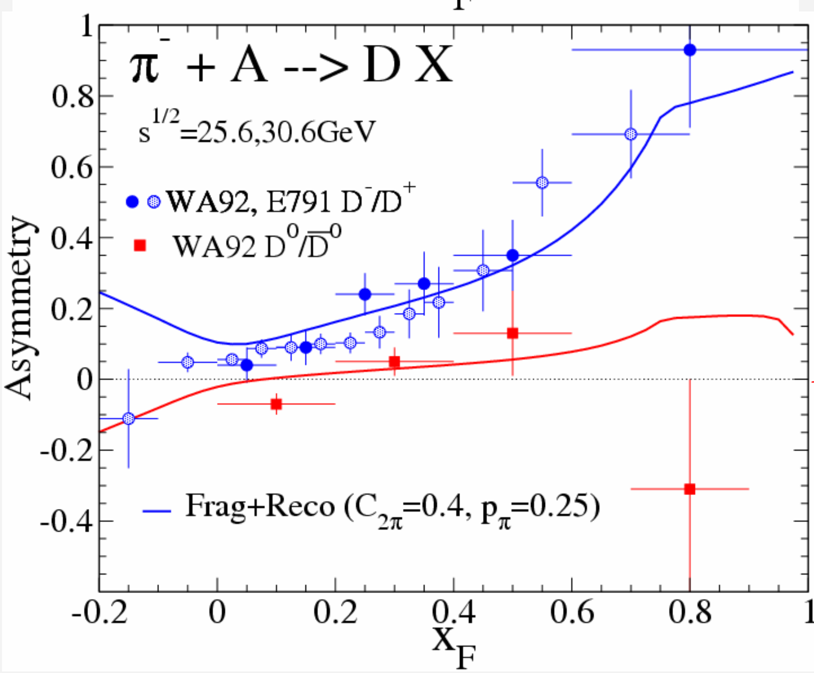
$$R(y_{\bar{q}}, y_c, y) = \exp(\Delta y^2 / 2\sigma_y^2) / \sqrt{2\pi\sigma_y^2}$$

$$x^* \frac{d\sigma^{rec}_{(c\bar{q})}}{dx_F} = \int \frac{dx_{\bar{q}}}{x_{\bar{q}}} \int \frac{dz}{z} \left(\frac{d^2\sigma_{c,\bar{q}}}{dx_{\bar{q}}\, dz} \right) R_{(c\bar{q})}(x_{\bar{q}}, z; x_F)$$

Recombination + Fragmentation Approach

[RR+Shuryak '03]

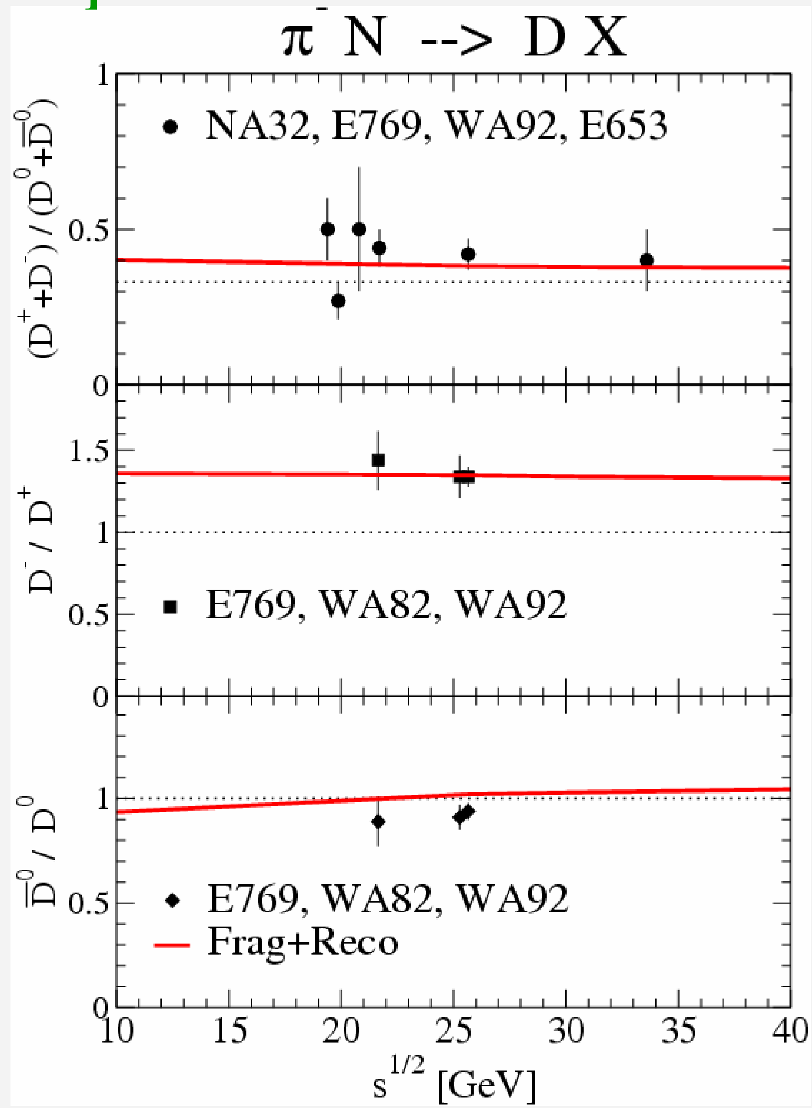




$D^- = \bar{c}d$

$\pi^- = d\bar{u}$

$D^0 = c\bar{u}$



flavor-asym. reproduced ok

3. c-Quark Interactions in HI Collisions

- **high p_t:** pQCD E-loss ↔ modified frag. [Dokshitzer+Kharzeev'01, Djordjevic etal '03, …]
- **intermediate p_t:** (onset of) coalescence [Lin+Molnar '03, Greco,Ko+RR '03,…]

$$E\frac{dN_D}{d^3p} = g_D \int \frac{d\sigma^\mu p_\mu}{(2\pi)^3} \int d^3q\, |\psi_D(\vec{q})|^2 f_{\bar{q}}(\vec{p}_{\bar{q}})\, f_c(\vec{p}_c)$$

f_q : thermal light quarks incl. v_0 , v_2 from fit to π, K

f_c : **c**-quark distribution, e.g.: - **PYTHIA** ↔ no reinteractions
- thermal incl. v_0 , v_2

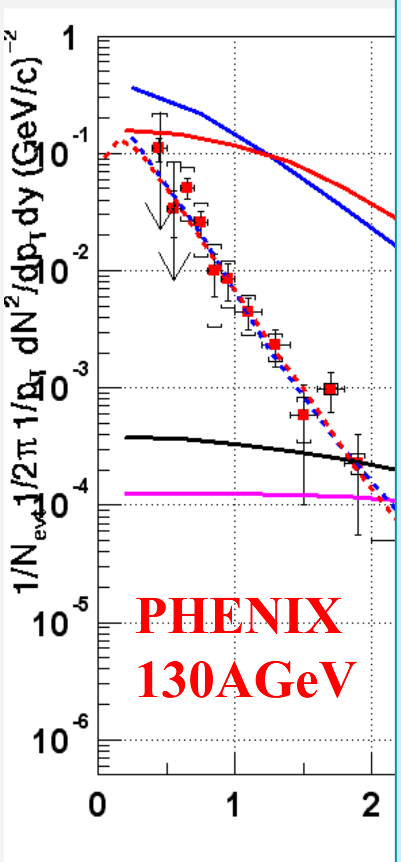
(also: $c+\bar{c} \rightarrow \Psi$)

Limitations: energy conservation (sudden approx.), m_q^*, …

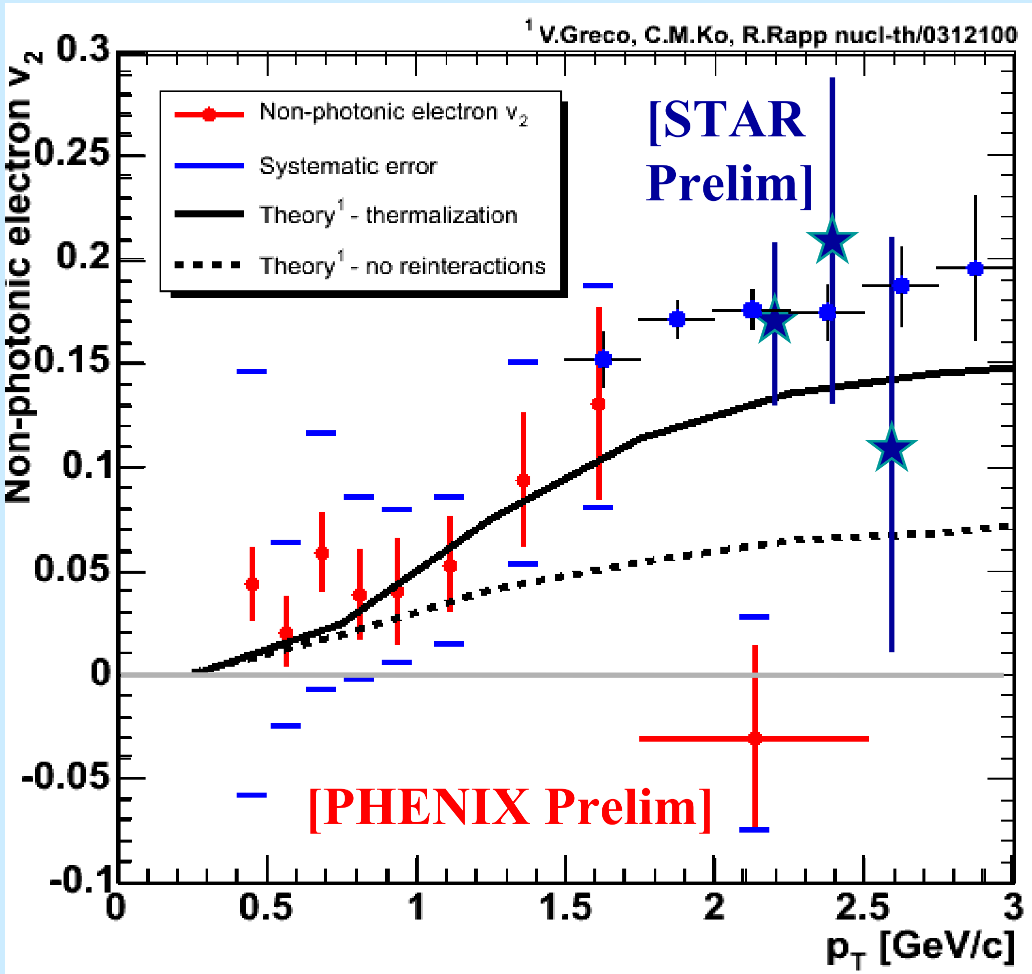
- **low p_t:**
rescattering → thermalization → "statistical coalescence" ?!

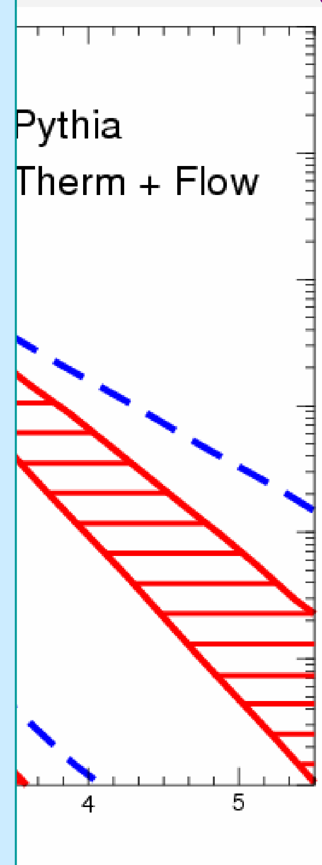
Open-Charm and e$^{\pm}$ p_t-Spectra in Au-Au

PYTHIA vs. … cence at T_c



Elliptic Flow



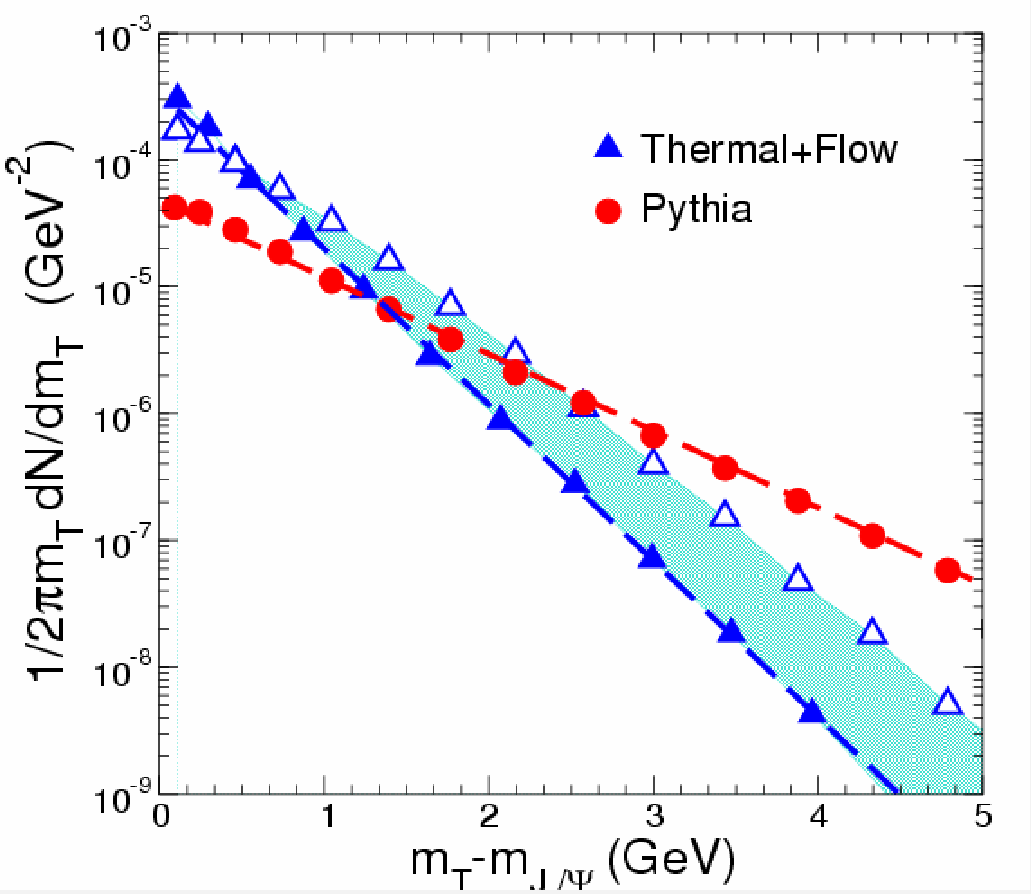


practically i… ive either

[Batsouli,Gyulassy,Kelly+Nagle ’02]

[Greco,Ko+RR ’03]

J/ψ p_t-Spectra: Coalescence at T_c



- total yields different by factor 3
- large sensitivity to radial flow ($\beta_{t,max}$=*0.5-0.65*)

4.) Charm(onium) in the QGP

4.1 Heavy-Quark Thermalization?!

- Naively: 1 scatt. $Q^2 \approx T^2$, $(p_{t,therm})^2 \approx m_c T \Rightarrow N_{scatt} \approx (p_{t,therm}/Q)^2 \approx 5$
- more quantitative: Boltzmann Eq. **[Svetitsky '88]**

$$\frac{\partial}{\partial t} f(p,t) = \left[\frac{\partial f}{\partial t}\right]_{coll} = \int d^3k \; [\, w(p+k,k) f(p+k) - w(p,k) f(p) \,]$$

$$\Rightarrow \boxed{\frac{\partial f}{\partial t} = \gamma \frac{\partial (pf)}{\partial p} + D \frac{\partial^2 f}{\partial p^2}}$$ 1-D Fokker Planck Eq.

$$\gamma p = \int d^3k \; w(k,p)\, k$$ scatt. rate

$$D = \frac{1}{2} \int d^3k \; w(k,p)\, k^2$$ diff. const.

$$\boxed{f(p,t) = \frac{1}{\sqrt{2\pi\sigma}} e^{-[p-p_0(t)]^2/2\sigma^2}} \rightarrow e^{-E_p/T}$$

$$\sigma(t)^2 = \frac{D}{\gamma}(1 - e^{-2\gamma t})$$

- e.g.: **pQCD** Xsections (***gc→gc***), T=500MeV, α_s=0.6(0.3)

$\Rightarrow \gamma = 0.25\ (0.06)\ fm^{-1} \leftrightarrow \tau = 4\text{-}15 fm/c$ **(very) slow!**

Resonant Open-Charm Rescattering

$$c + \bar{q} \rightarrow \text{“}D\text{”} \rightarrow c + \bar{q}$$

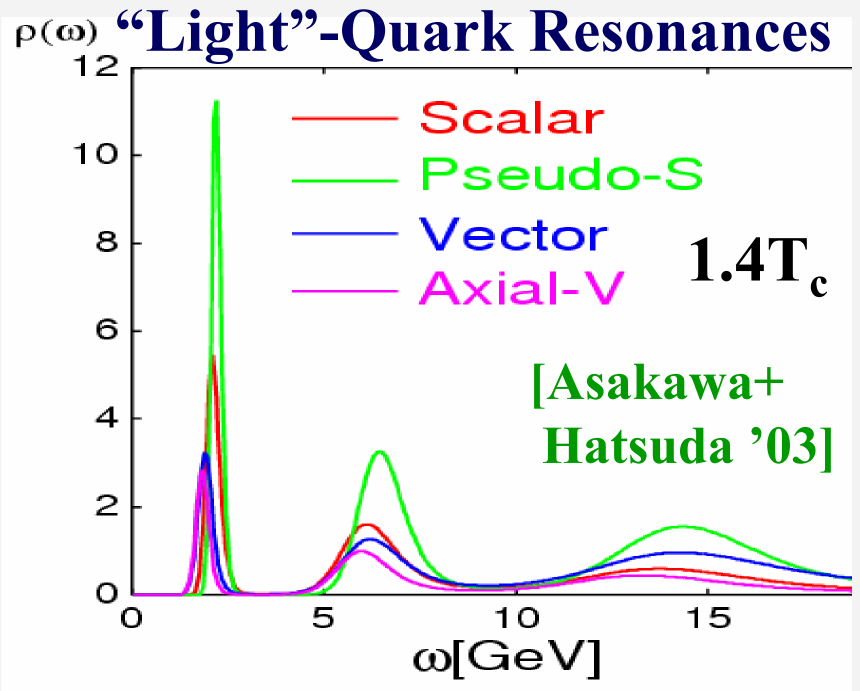
- effective model with pseudo/scalar + axial/vector “***D***-mesons”

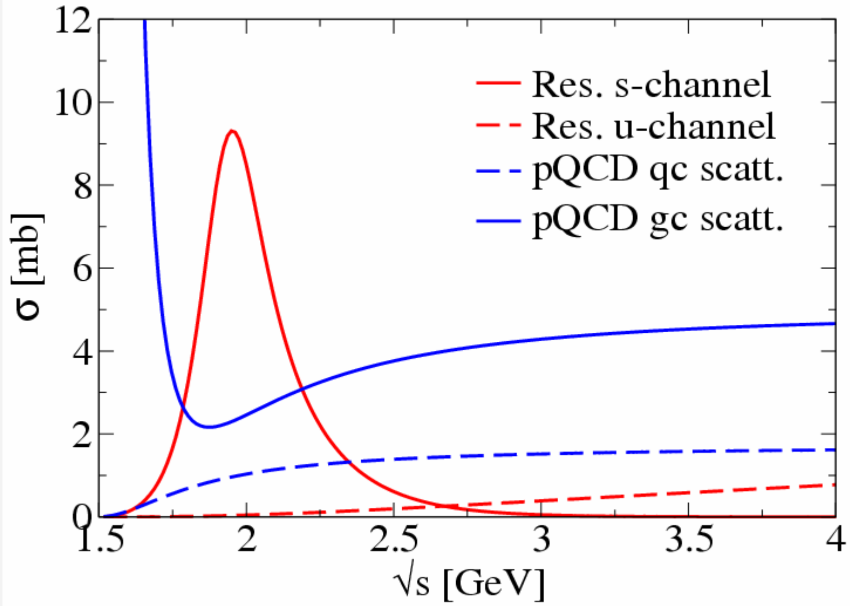
$$\mathcal{L}_{Dcq} = G_D\, \bar{q}\, \frac{(1+\not{v})}{2}\, \Gamma\, \phi_D\, c \;+\; \text{h.c.}$$

$$\Gamma = 1, \gamma_5, \gamma_\mu, \gamma_5\gamma_\mu$$

- chirally symmetric for light quarks
- heavy-quark symmetry
  $\Rightarrow j^\mu$ conserved to *LO(1/m_c)*
- parameters: $m_D^{(0)}, G_D$

[van Hees+RR ’04]

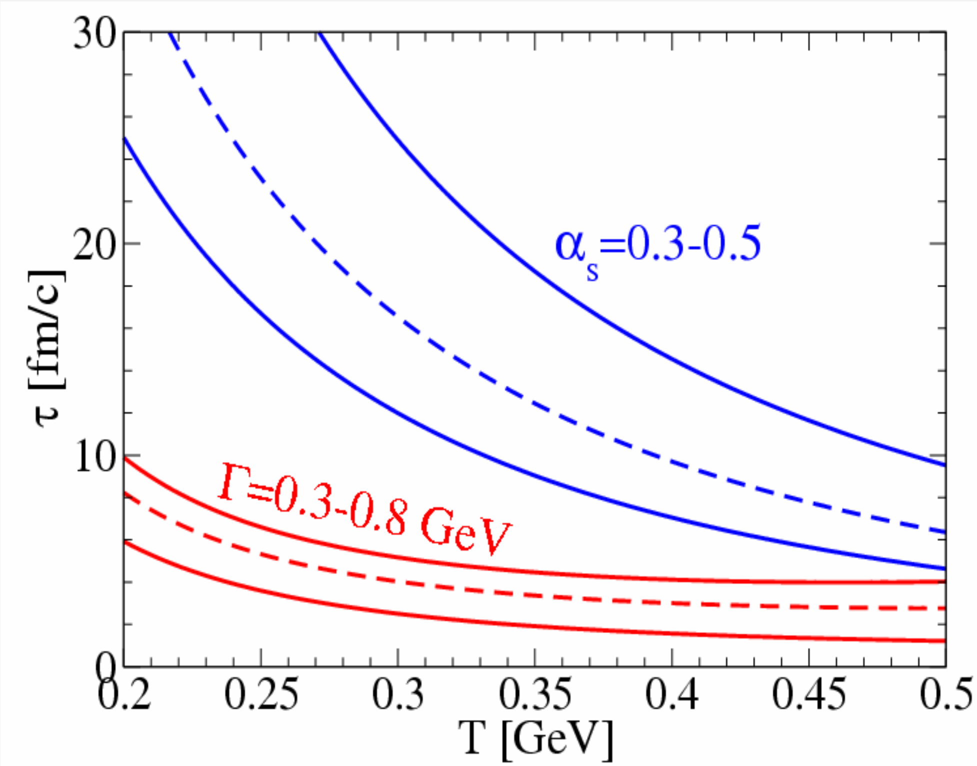




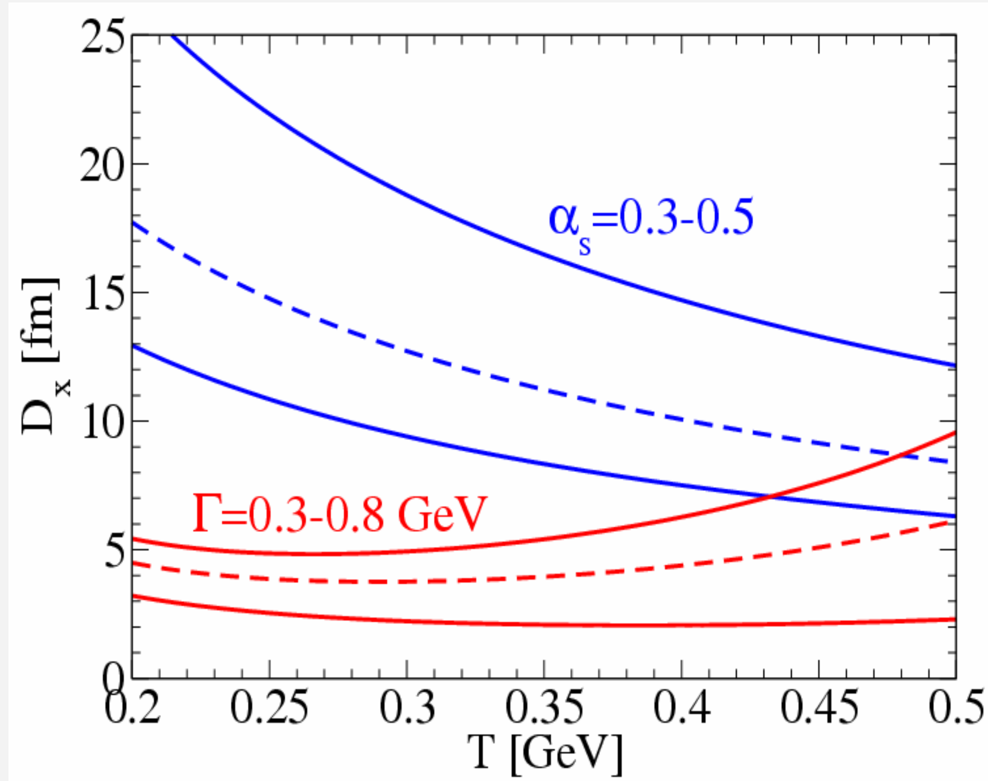
c-Quark Drag and Diffusion Constants in QGP

[van Hees+RR '04]

Thermalization Times



Coordinate Space Diffusion



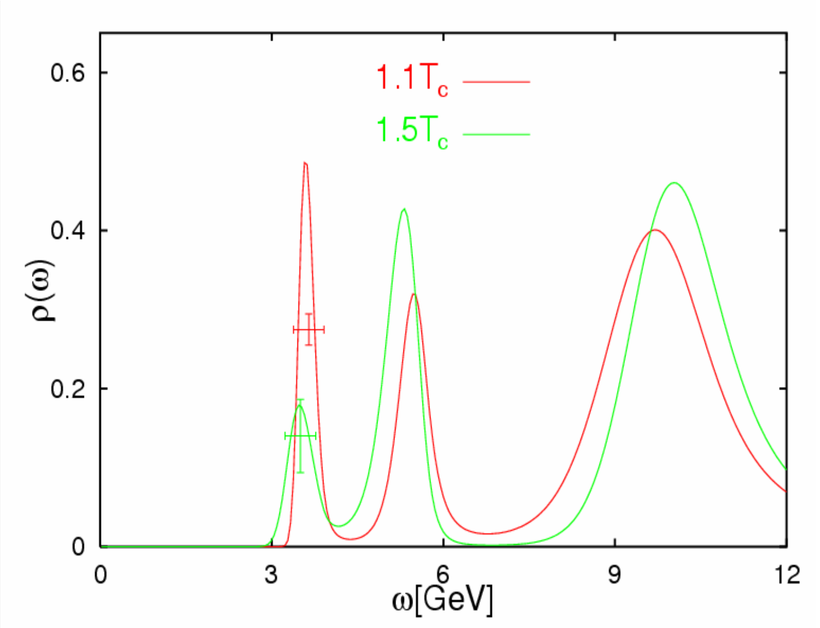
- resonance scatt. isotropic
- secondary open-charm ?!
  [*50%* for $3\times\sigma(gg\rightarrow\bar{c}c)$]

- $\langle x^2\rangle - \langle x\rangle^2 = D_x\, t \approx (4\text{-}5\ fm)^2$
  ~ fireball size at T_c

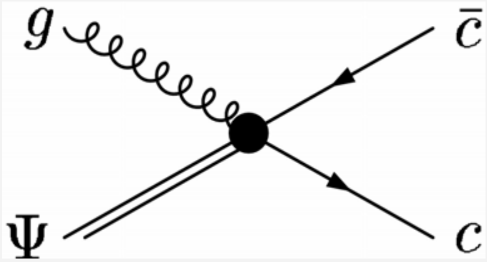
4.2 Charmonium in QGP

- Lattice: η_c, J/ψ survive up to $\sim 2T_c$
- mass $m_\psi \approx const \sim 2m_c^*$
- width:

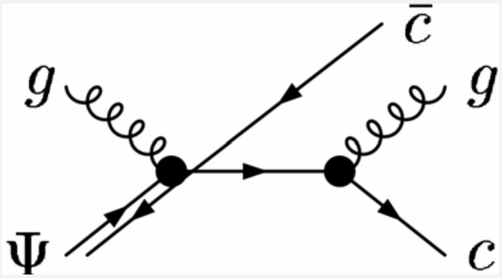
$$\Gamma_\psi = \tau_\psi^{-1} = \int \frac{d^3k}{(2\pi)^3} f^{q,g}(T)\, \sigma^{diss}_{q,g-\psi}\, v_{rel}$$



[Datta etal '03]

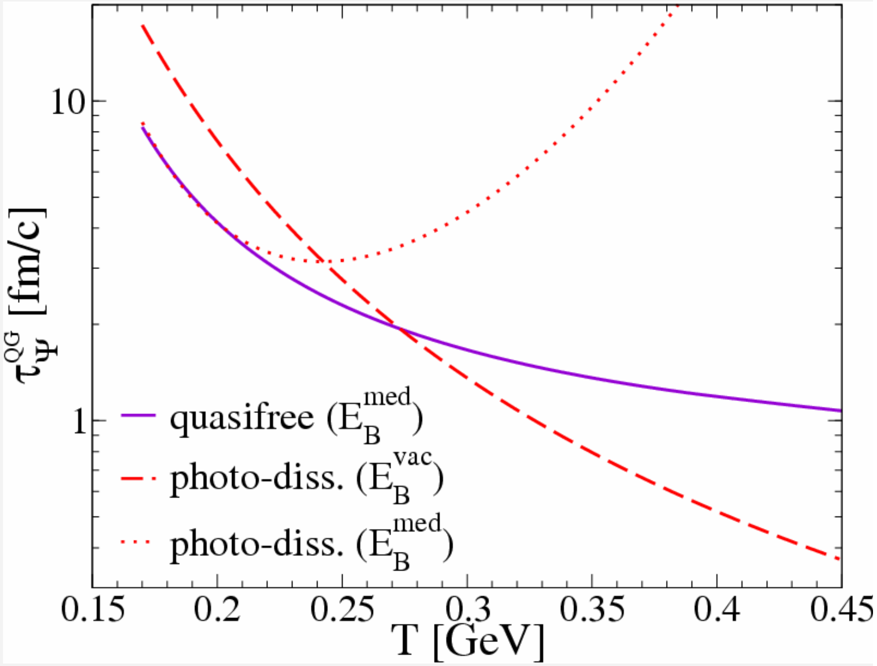


gluo-dissociation, inefficient for $m_\psi \approx 2\, m_c^*$



"quasifree" dissoc.

[Grandchamp+RR '01]



4.3 Time Evolution and Regeneration

- statistical coalescence at T_c: thermal equilib. **[Braun-Munzinger etal '01, Gorenstein etal '02, …]**
- charmonia above T_c

⇒ formation in **QGP**: detailed balance! **[Thews etal '01, Ko etal '02, Grandchamp+RR '02, …]**

$$\mathbf{J/\psi + g \rightleftarrows c + \bar{c} + X}$$

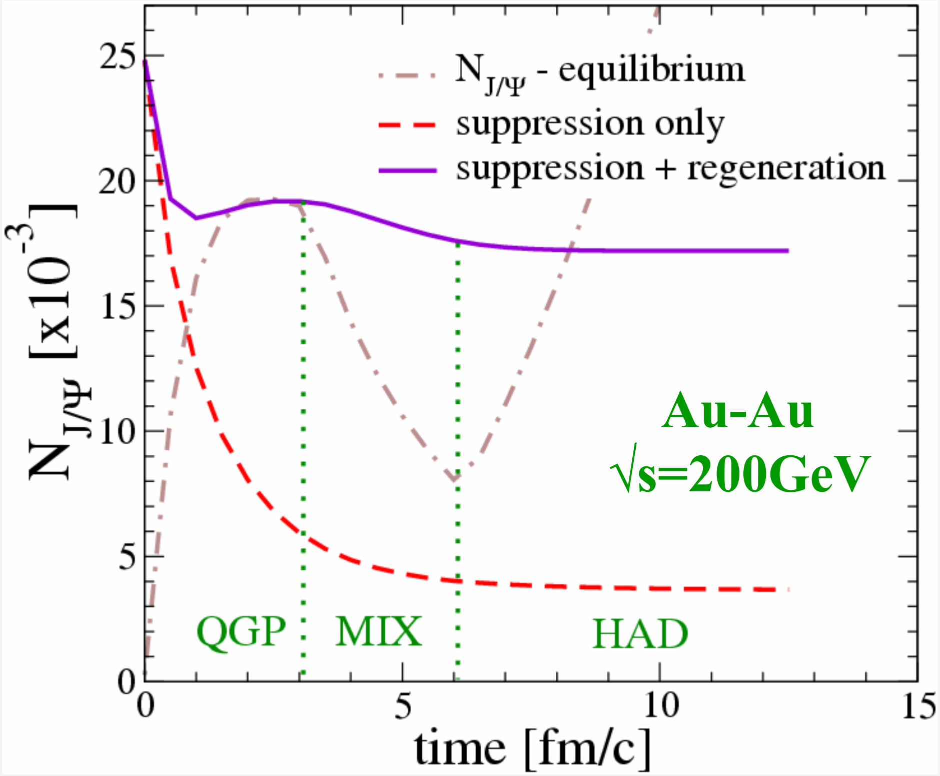
for thermalized *c*-quarks:

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

"jumps" at T_c? sensitive to $N_{c\bar{c}}$, m_c^*

rather direct link to **lattice QCD**!

Equilibration close to T_c ?!

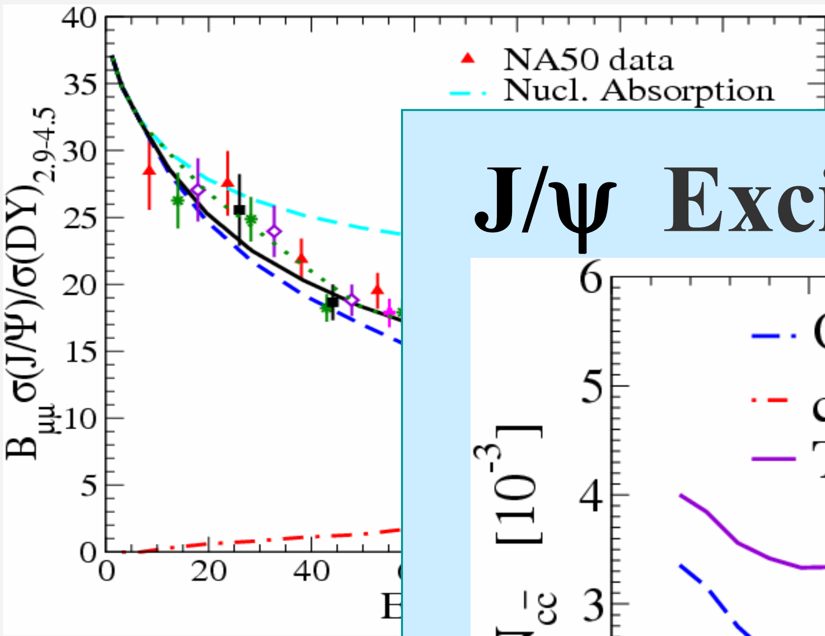


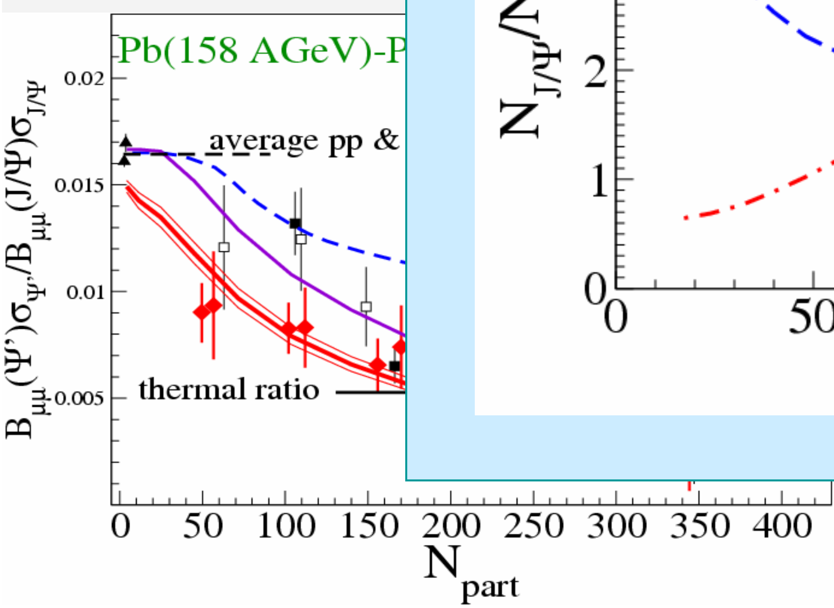
5.) Charmonium in A-A

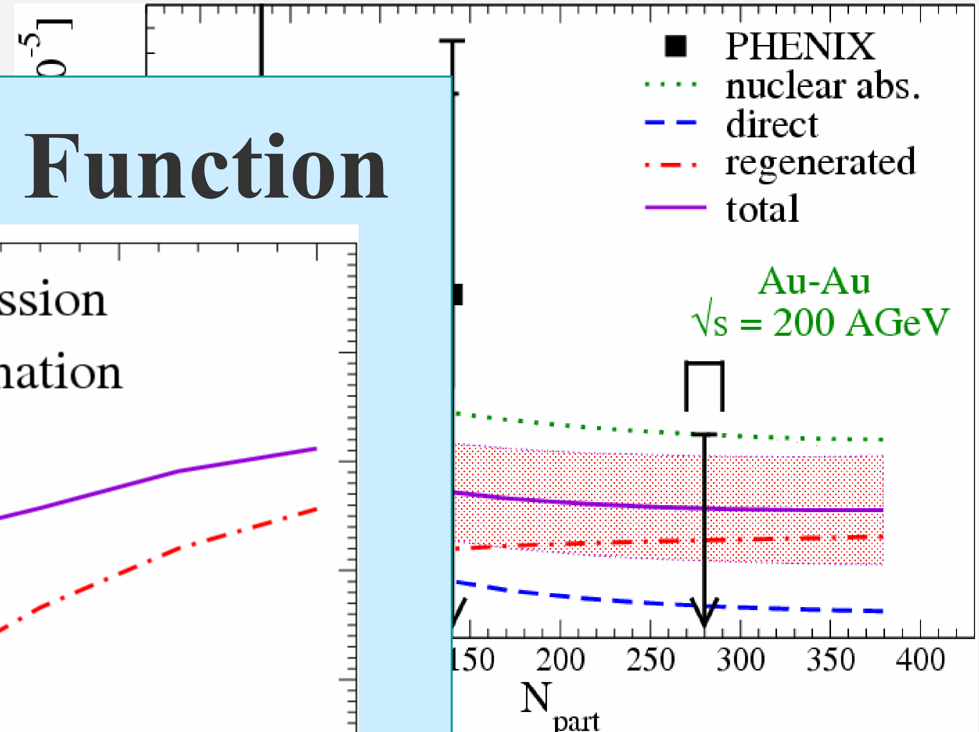
SPS

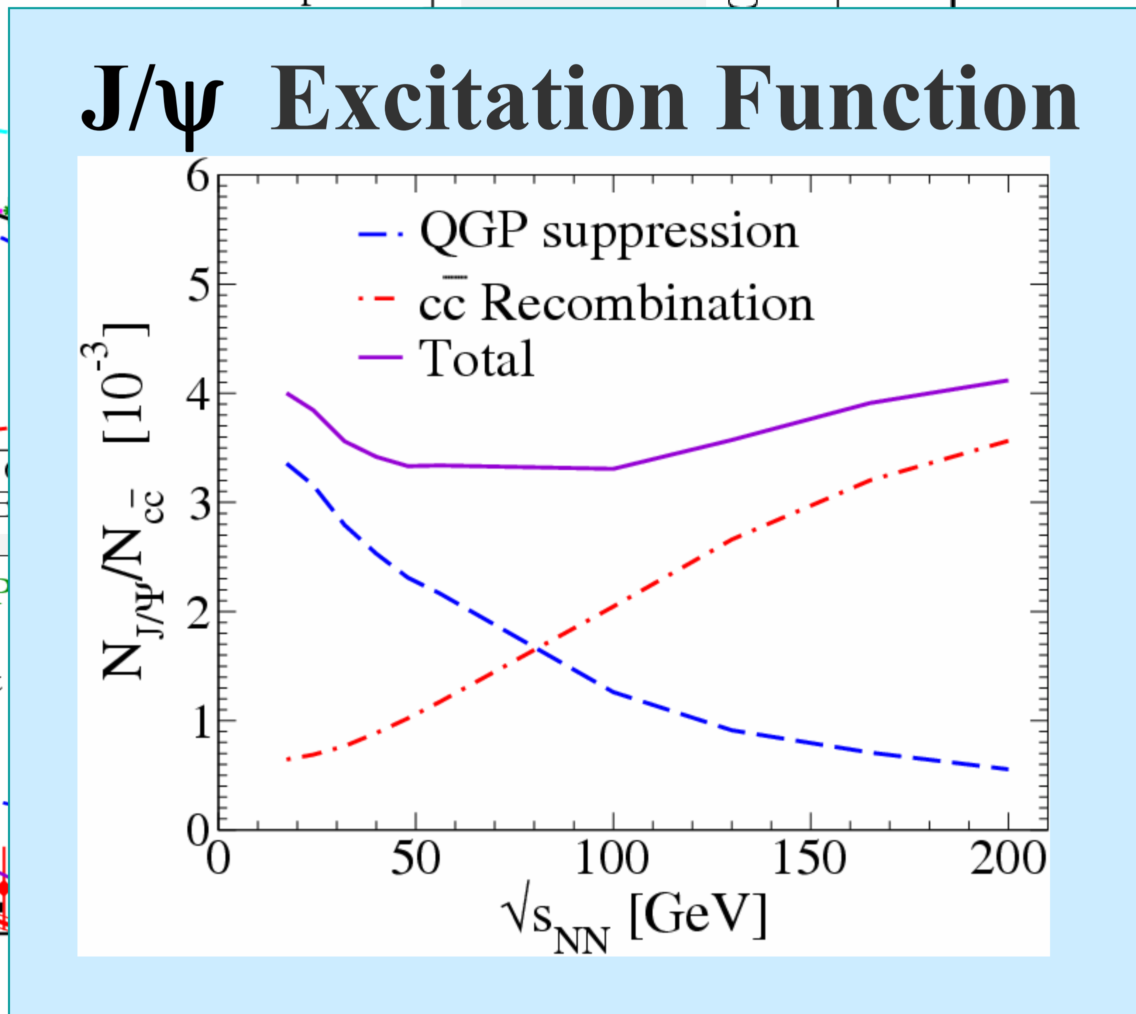
RHIC

[Grandchamp +RR '03]









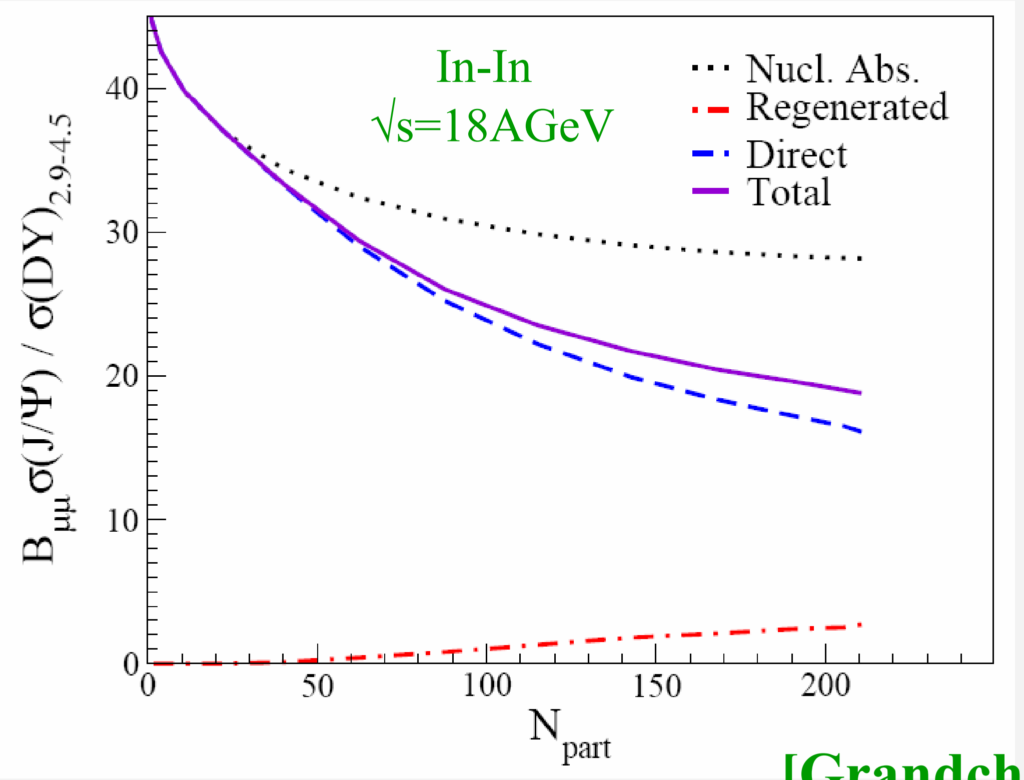
ation dominant

harm degeneracy,

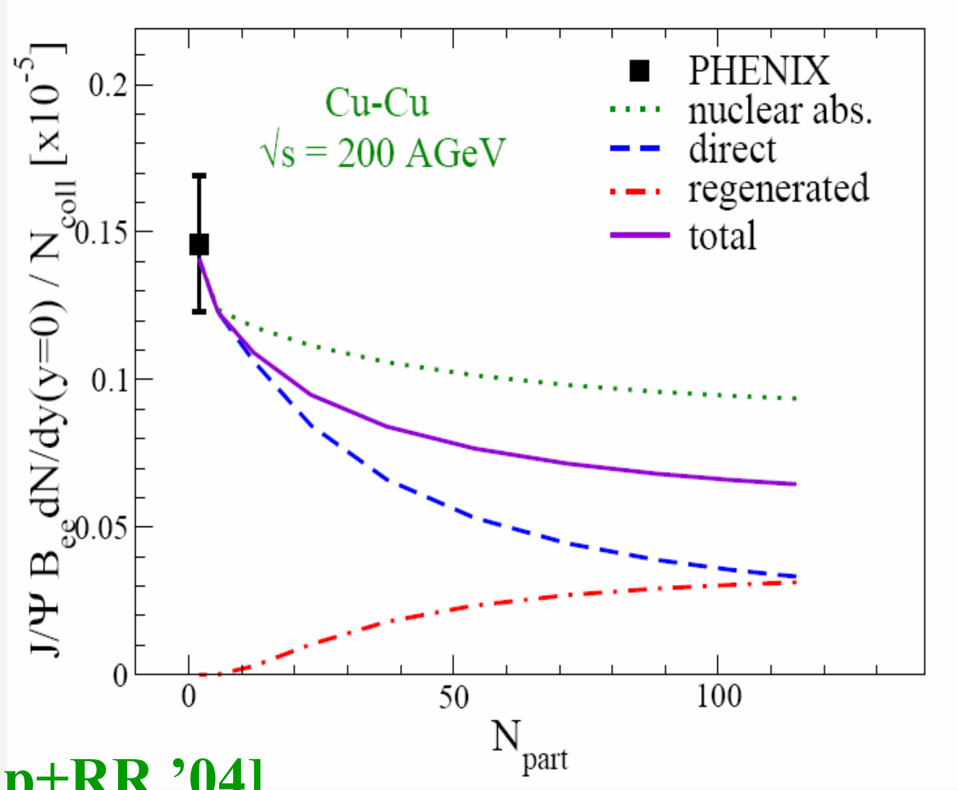
(N_{cc}) … rapidity, $\sqrt{s}$, A

5.2 Lighter Ions

SPS



RHIC



[Grandchamp+RR '04]

- **suppression**
- **onset of regeneration**

6. Conclusions

• **Elementary hadron collisions:**

- **"soft" recomb.: chemistry pre-established by PDF's?**
- **baseline for heavy ions**

• **URHICs:**

Open Charm: E**-loss / coalescence** (p_t)**,**
equilibration (v_2) $\leftrightarrow$ **resonances?!**

Charmonium: - regeneration if $v_2(D)$ **large**
- formation in QGP $\leftrightarrow$ $\Gamma_\psi(T)\,,\, m_c^*(T)$
- (N_{cc}, V, τ_{QGP}) $\leftrightarrow$ $(N_{part}, y, \sqrt{s})$
- deconfinement order parameter?

Bottomonium Suppression at RHIC ?!

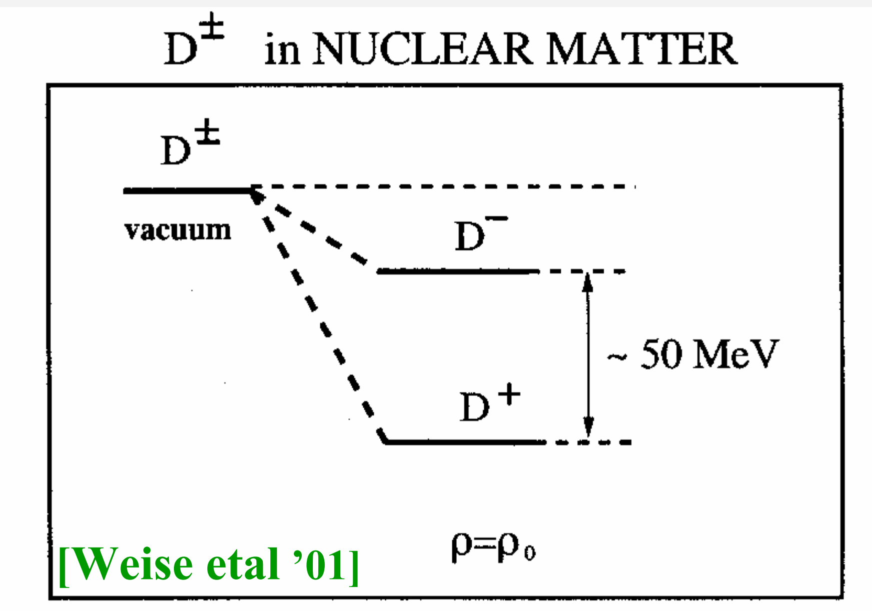
Additional Slides

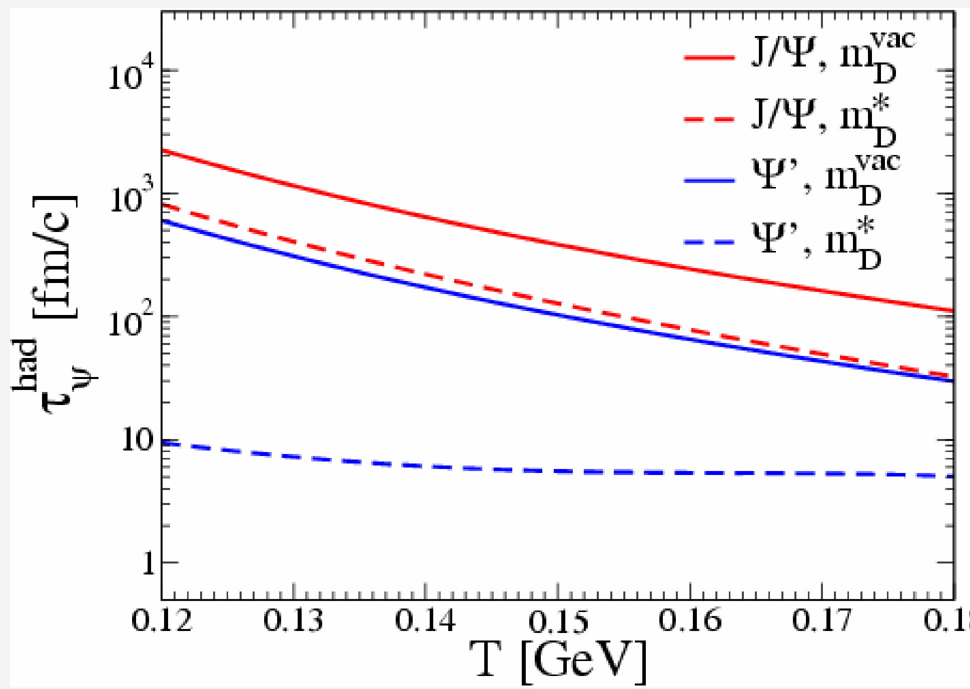
4. Charmed Mesons in Medium

4.1 Hadronic Matter: D-Mesons and ψ'

$m_D(T,\rho_B)$ expected to decrease (Chiral Symmetry Restoration)

$$\Gamma_\psi = \tau_\psi^{-1} = \int \frac{d^3k}{(2\pi)^3} f^{\pi,\rho}\, \sigma^{diss}_{\pi,\rho-\psi}\, v_{rel}$$





[Grandchamp+RR '03]

⇒ reduced threshold for $\pi,\rho + \Psi \rightarrow DD$

- J/ψ robust
- Ψ' fragile: Ψ' → *DD* decays

5.3 Open-Charm Chemistry

	Central A-A (Statistical Model) [Andronic et al. '03]		p-p (Frag. + Recomb.) [RR+Shuryak '03]	
$\sqrt{s}$ [GeV]	17	200	17	200
$D^{\pm} / D^0$	0.456	0.454	0.39	0.4
D^- / D^+	1.6	1.04	1.35	1.24
$\bar{D}^0 / D^0$	1.59	1.05	1.4	1.35
D_s / D	0.253	0.260	0.14	0.23

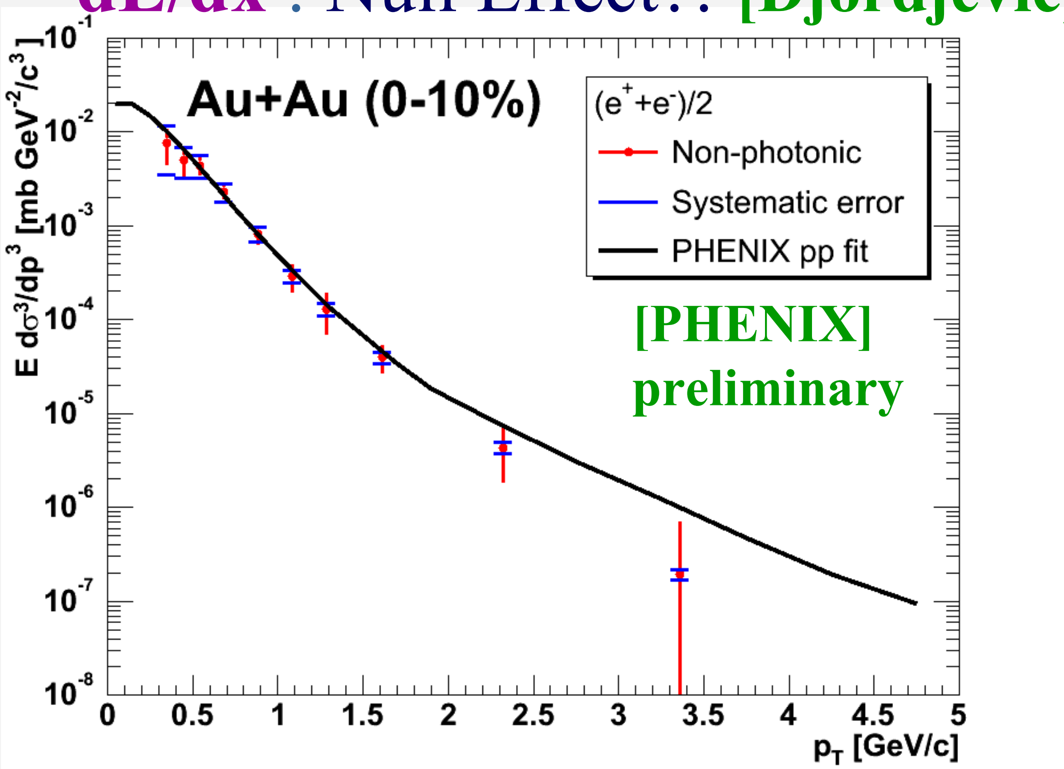
4.3 Charm I: Open Charm (Central A-A)

(i) Yields

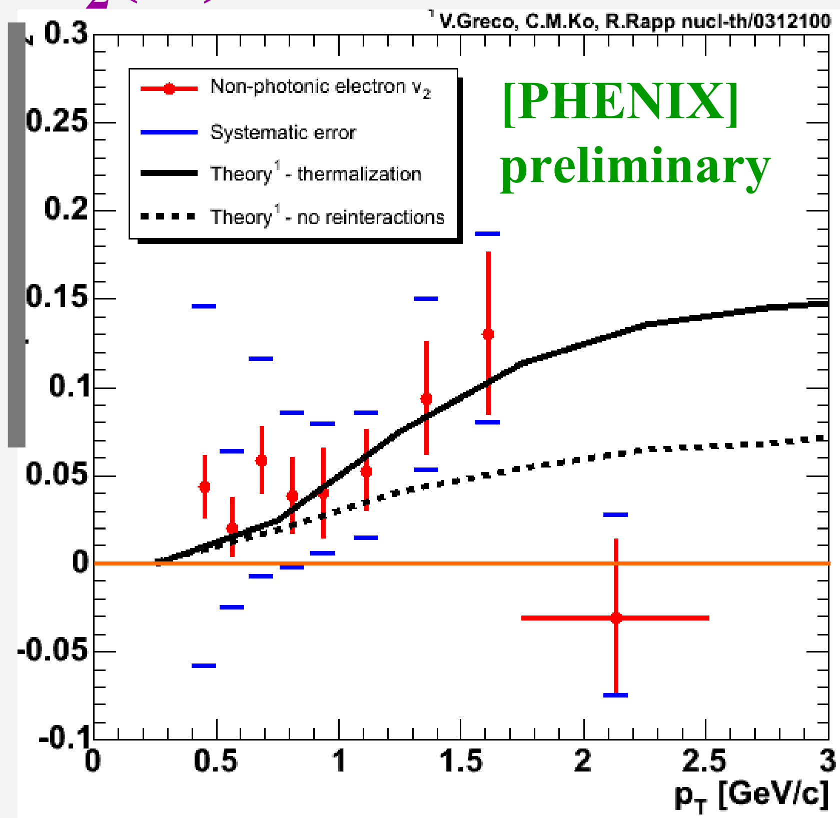
- RHIC: **-30%** for **η=0→2**: **CGC** **[Tuchin]**, Color-Dipole **[Raufeisen]**
- LHC: **CGC**: N_{part} ; nonlin. DGLAP: enhanced! **[Kolhinen]**

(ii) p_T-Spectra

dE/dx : Null Effect?! **[Djordjevic]**

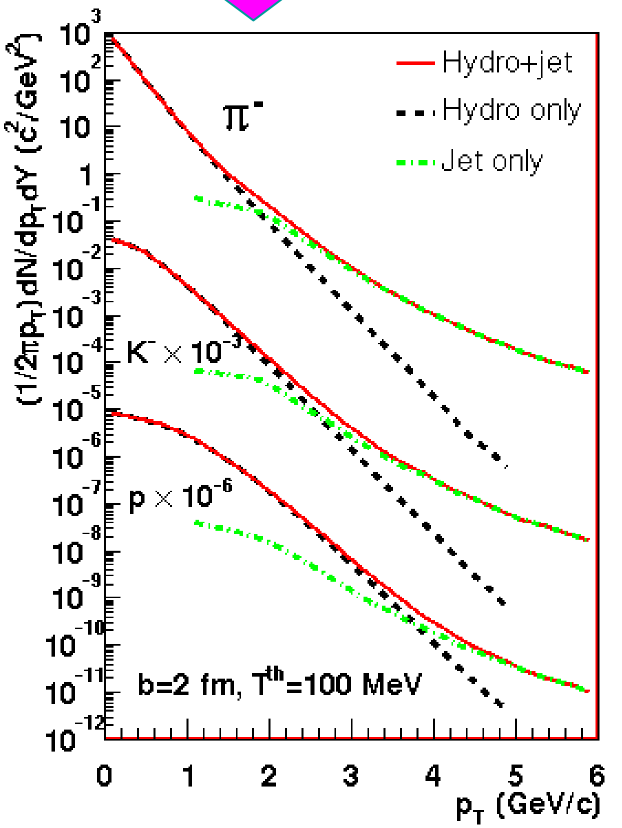


$v_2(e^{\pm})$: Thermalization?!



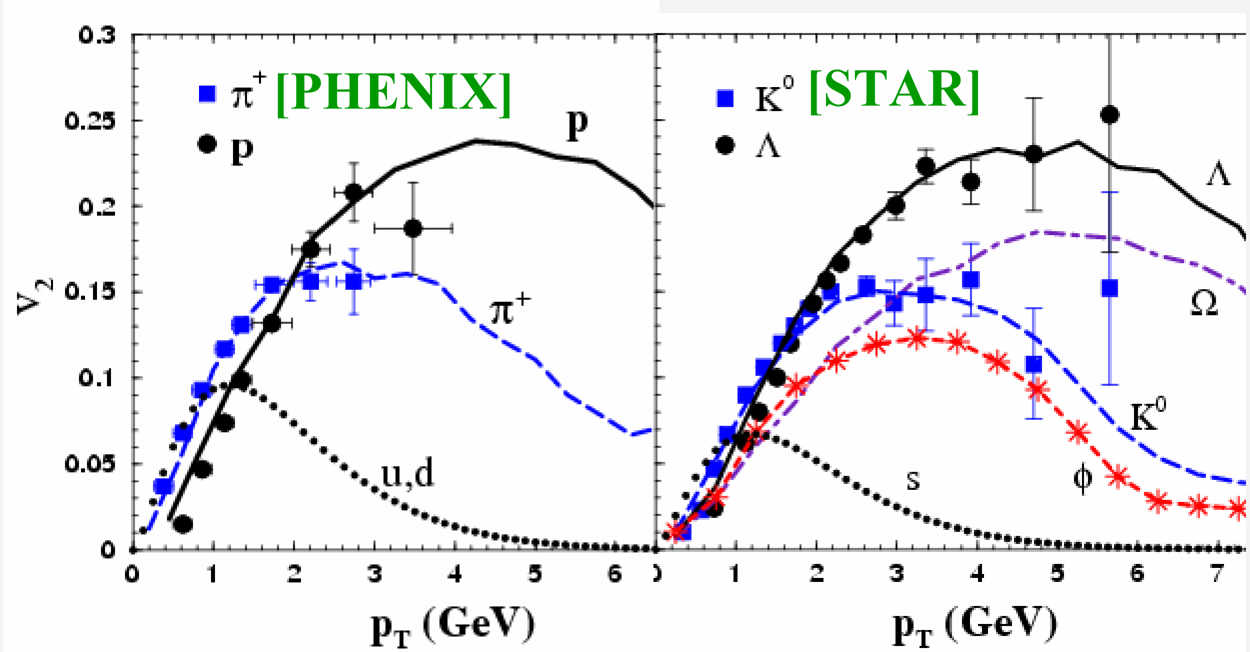
3.4 Hydro vs. Coalescence: The 2-6GeV Regime

[Hirano,Nara]



[Fries,Hwa,Molnar]

$$E\frac{dN_h}{d^3p} = g_h \int \frac{d\sigma^\mu p_\mu}{(2\pi)^3} \int d^3q \, |\psi_h(\vec{q})|^2 \, f_a(\vec{p}_a) \, f_b(\vec{p}_b)$$



[Greco et al.]

v_2: mass-dependent

But: p/π(4GeV)≈0.3

[PHENIX]: 1±0.15

⇒ universal partonic $v_2(p_T/n)$ / n

soft-soft ≈ thermal ($p_T \gg m$)

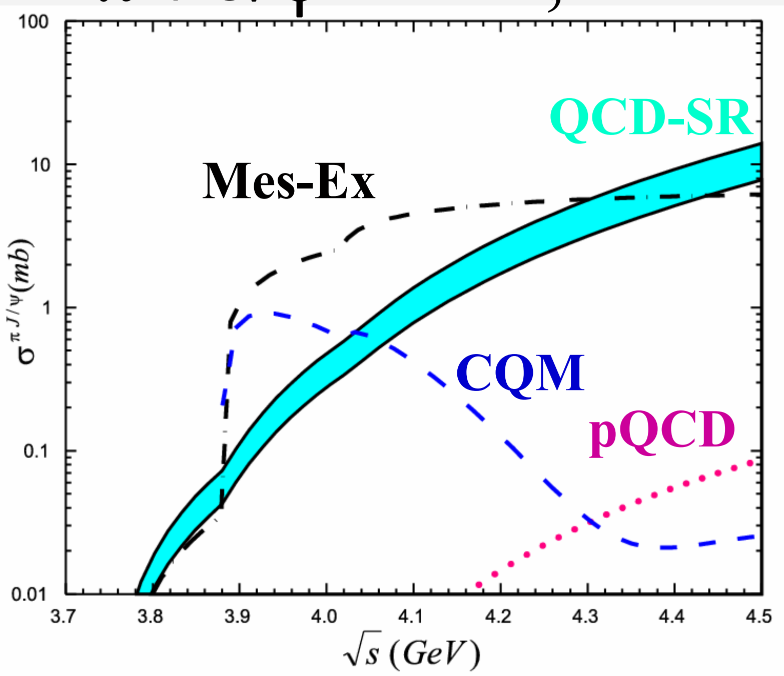
soft-hard: explicit thermal+jet (correlations!)

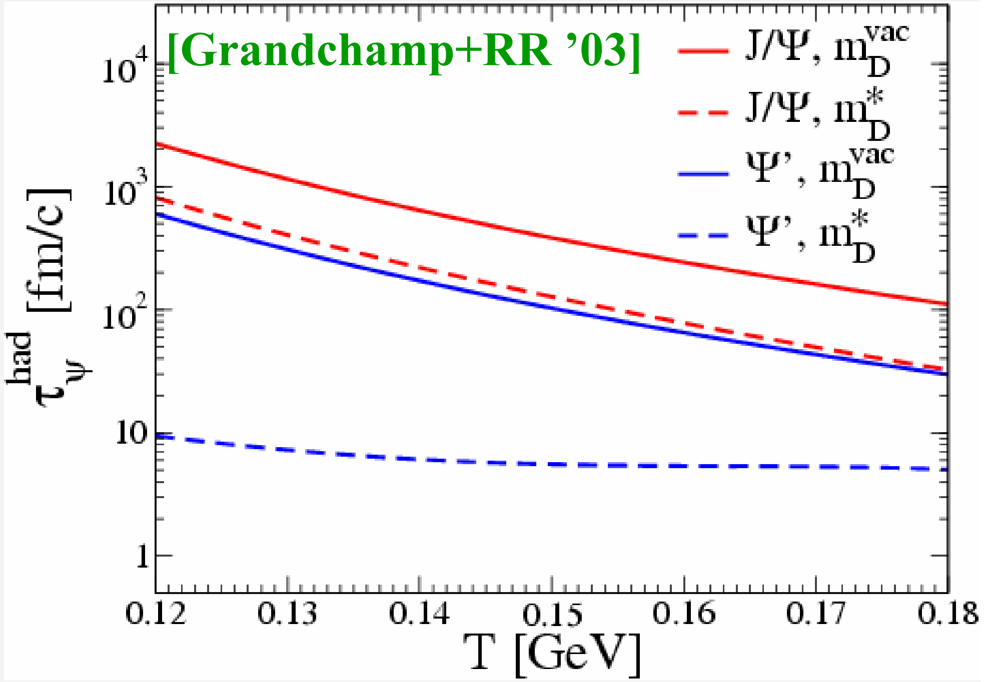
Challenges: p/π=1 + jet correlation , ϕ elliptic flow

2.3 Charm(onium) below T_c

Dissociation rate $\Gamma_\psi = \tau_\psi^{-1} = \int \frac{d^3k}{(2\pi)^3} f^{\pi,\rho}(E_k,T)\, \sigma^{diss}_{\pi,\rho-\psi}(s)\, v_{rel}$

$\pi + J/\psi \rightarrow D\bar{D}, D^*\bar{D}$





Reduced DD threshold: **$\Delta m_D(T_c) \approx$-140MeV** (NJL)

$\Rightarrow$
- **J/ψ** robust
- **Ψ'** fragile: direct **Ψ'**→ **DD** decays