Charmonium + Open-Charm in Heavy-Ion Collisions

Ralf Rapp (NORDITA), HIC03, Montreal 27.06.03

1.) Introduction

2.) Open-Charm Production + Reinteractions

3.) Charmonium in QCD Matter

- Lattice QCD + Spectral Functions
- Rate Equations
- Equilibrium Numbers + Reaction Rates in QGP + HG

4.) Model Comparisons to Data

- SPS : J/Ψ and Ψ'
- RHIC : J/Ψ

5.) Conclusions

with: L. Grandchamp (Stony Brook)

1.) Introduction: Charmonium (Re-) Interactions in the Heavy-Ion Environment

Elementary hadron-hadron reactions:

$$\sigma(pN \to J/\Psi\, X) \approx 1\%\ \sigma(pN \to c\bar{c}\, X)$$

(Central) Heavy-ion collisions

- "primordial" J/Ψ-number "**suppressed**" due to reinteractions:
  - nuclear absorption
  - Quark-Gluon Plasma: Debye-screening and/or parton-induced dissociation
  - Hadron Gas
- Reinteractions also imply (approach to) thermalization

→ J/Ψ's can be **recreated**: $X_1 + J/\Psi \rightleftarrows X_2 + c + \bar{c}$ $(+ D + \bar{D}, \dots)$

Questions:

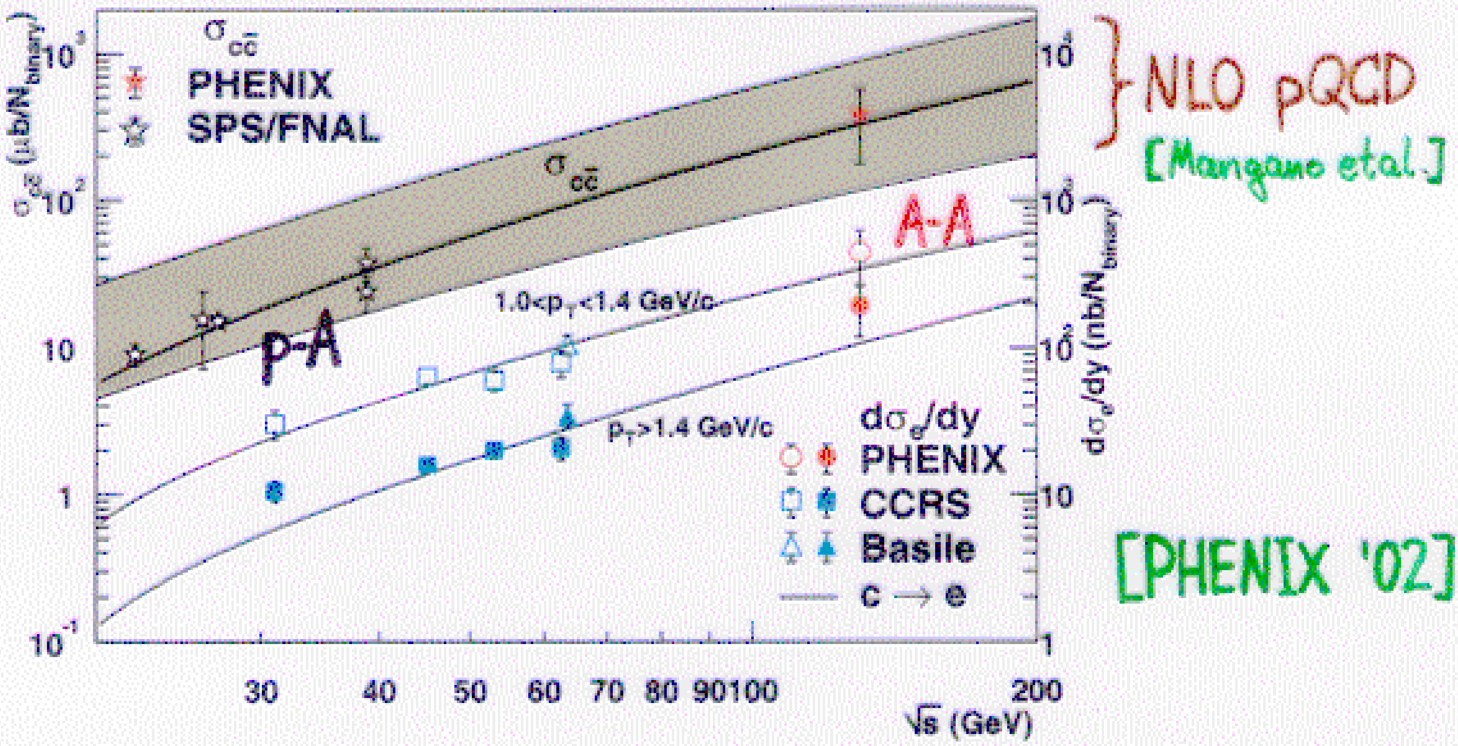
- inelastic charmonium Xsections, equilibration times
- in-medium properties of charmonia + open-charm states
- primordial vs. equilibrium abundances

} significance of T_c?

- production + equilibration of open charm (elast. Xsections) ...

2.) Open-Charm Production + Reinteractions

$c\bar{c}$ Cross Section in Nuclear Collisions



[PHENIX '02]

Theory: pQCD ⊗ PDF $\quad \sigma_{pp\to c\bar{c}} = K \int \sum_{i,j} \frac{d\sigma_{ij\to c\bar{c}}}{d\hat{t}} f_i^p f_j^p$

large uncertainty in magnitude ($K \simeq 5$), $\sqrt{s}$-dependence o.k.

p-A, A-A: $N_{c\bar{c}} \simeq N_{coll} N_{c\bar{c}}^{(pp)}$ (?!)

Charm-Quark Rescattering in A-A

$c, \bar{c}$ might thermalize rapidly:

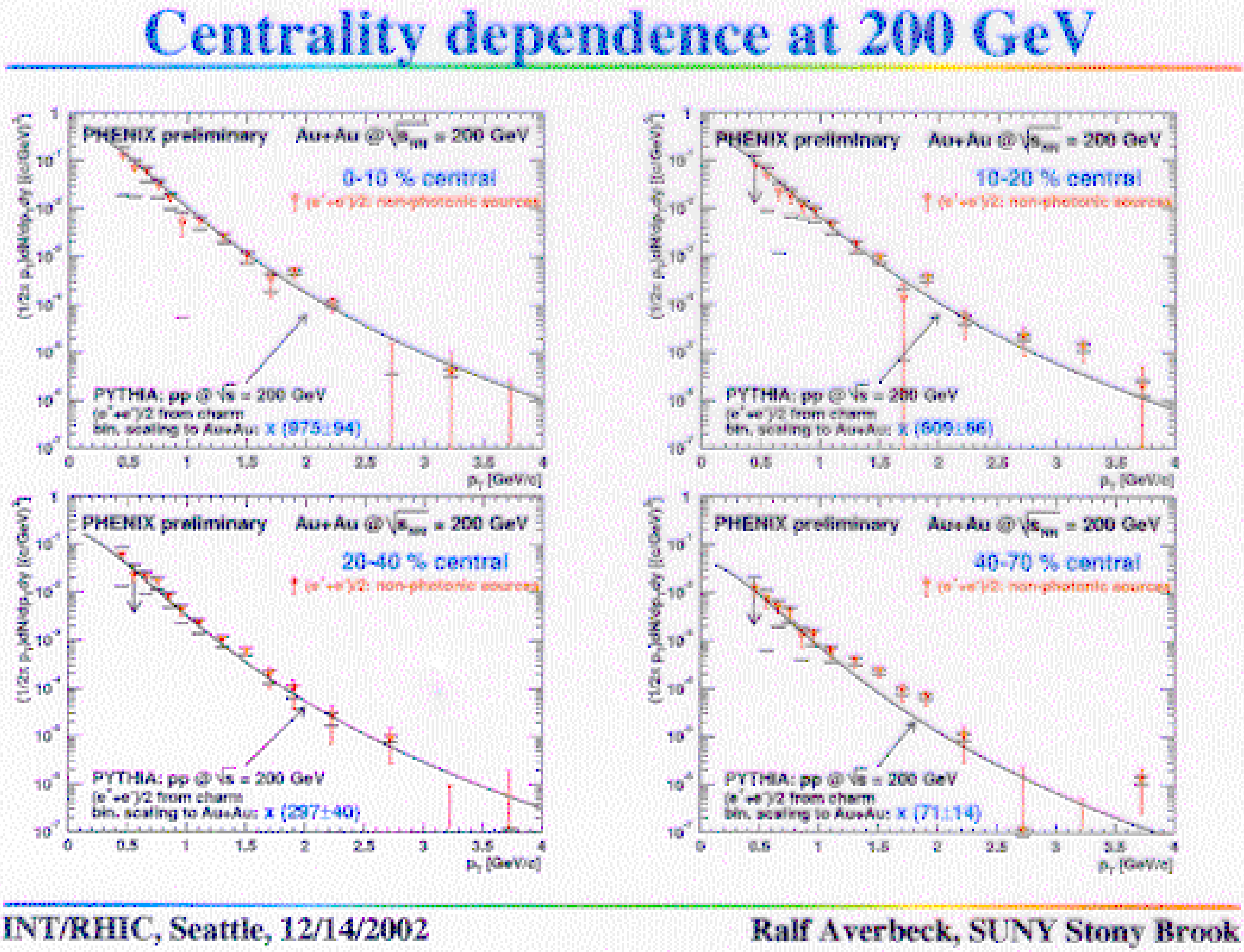
QGP: $\langle \vec{p}_c \rangle_{thermal}$ after $\sim 1 fm/c$ [Svetitsky '88] ($\alpha_s = \frac{1}{3}$: $\sim 3 \frac{fm}{c}$)

Hadron Gas: $\tau_D^{therm} \simeq \frac{1}{\langle \sigma_{Dh}^{el} v \rangle n_h} \simeq \frac{1}{5mb\ 2\rho_0} \simeq 6 fm/c \lesssim \tau_{FB}$

⇒ D-meson p_t-spectra

Single - $e^{\pm}$ Excess at RHIC

(w.r.t. hadron-decay sources)



rescattering (thermalization) of c-/$\bar{c}$-quarks ?

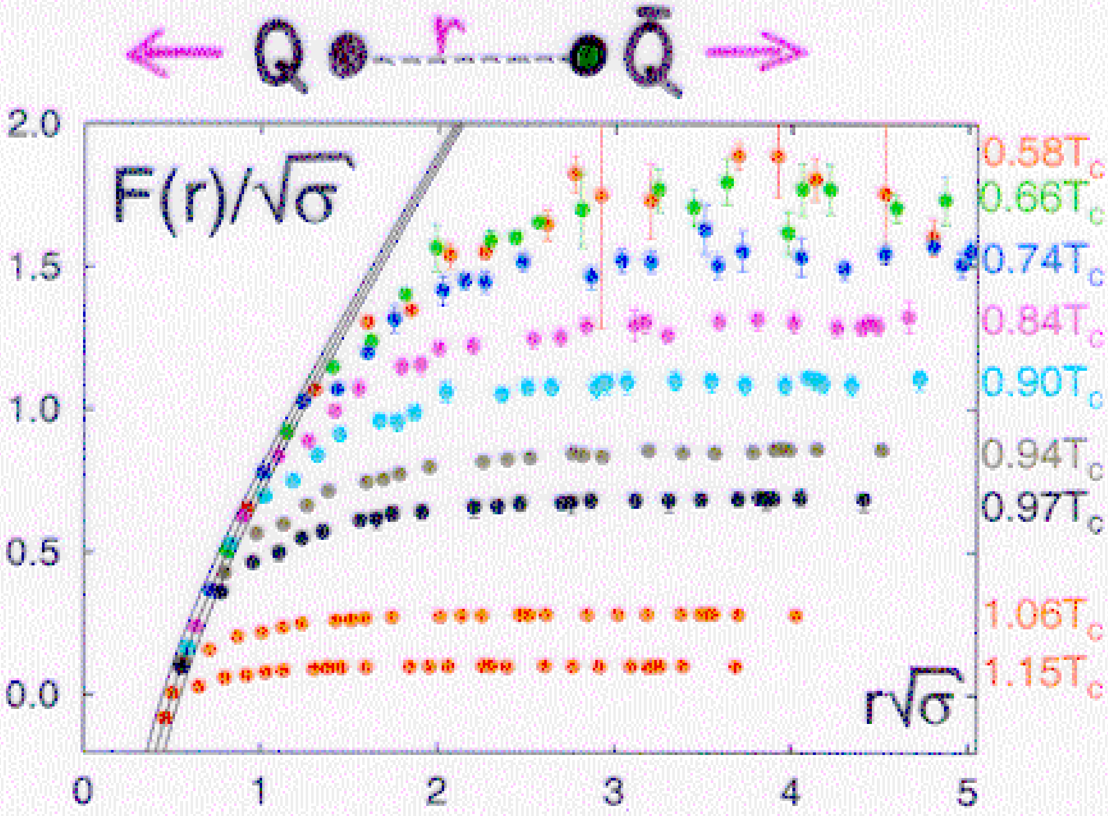
→ expect suppression at "high"-$p_\perp$

but : collective flow of charm quarks ?

⇒ conspire to "null"-effect [Batsouli et al. '02]

3.) Charmonium in QCD Matter

Lattice QCD : Q-$\bar{Q}$ Free Energy ($N_f = 2+1$)



$F_{Q\bar{Q}}(r,T) = V_{\bar{Q}Q} - T\,S_{\bar{Q}Q}$

[Karsch et al. '01]

- open-charm threshold ($\bar{D}D/\bar{c}c$) continuously decreases across T_c

  $\Delta m_D^*(T_c) \simeq 0.3\,\mathrm{GeV} \leftrightarrow m_c^*(T_c) \simeq 1.5\,\mathrm{GeV}$

  [Chiral Restoration!]

- charmonium bound-states subsequently "dissolve"

  Ψ', χ_c : $T_{diss} < T_c$, J/Ψ: $T_{diss} \simeq 1.1\,T_c$

  [Digal et al. '01]

Do "dissolved" bound states disappear from spectrum?

not necessarily ... → spectral functions !

Finite-T Charmonium Spectral Functions from (Quenched) Lattice QCD

$A_\psi(\omega) \propto \text{Im}\, D_\psi(\omega)$: encodes medium effects on $V_{c\bar{c}}$ + intermediate states!

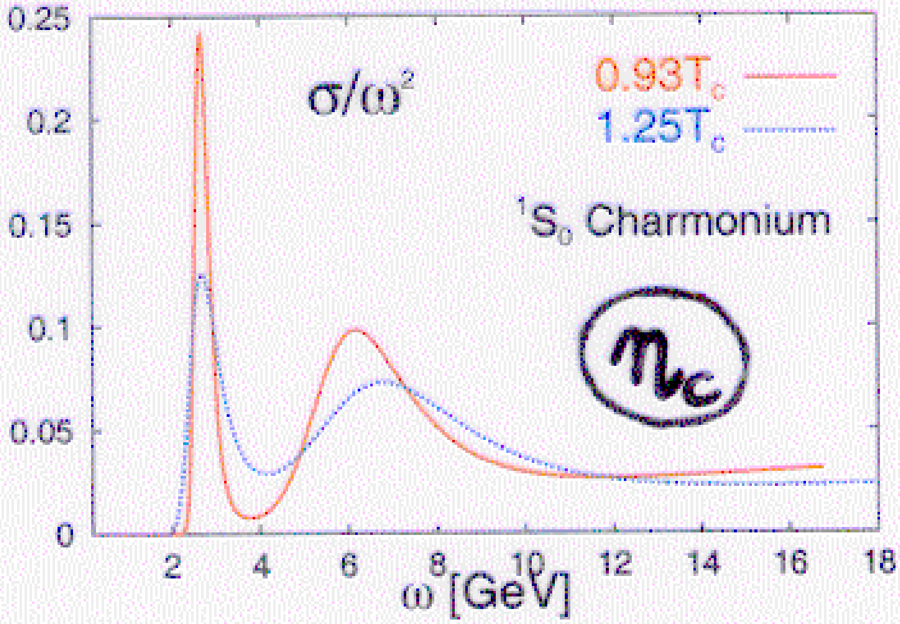
$D_\psi \hat{=}$ J/ψ 

[Bielefeld group '02]

clear signal above T_c

$m_\psi(T) \simeq$ const

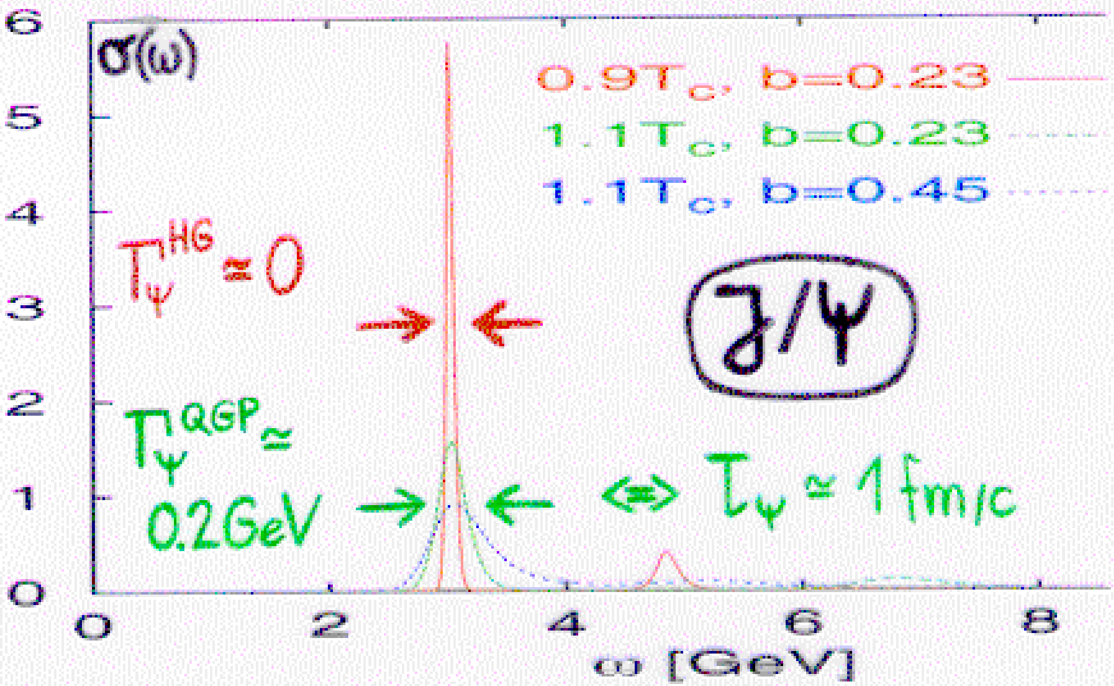
Γ_ψ increased (?!)



[Umeda et al. '02]

$m_\psi(T) \simeq$ const

systematic study of Γ_ψ



⟹ η_c, J/Ψ survive as resonances in QGP up to ~$1.5T_c$

(χ_c, Ψ' probably "melted")

J/Ψ Regeneration in QGP ?!

Time Evolution → Rate Equation:

$$\frac{d}{d\tau} n_\Psi = - n_\Psi L(\tau) + G(\tau) = - n_\Psi \left[\frac{1}{\tau_\Psi} + \frac{1}{V_{FB}} \frac{dV_{FB}}{d\tau} \right] + n_\Psi^{eq} \frac{1}{\tau_\Psi}$$

$$= - \frac{1}{\tau_\Psi(T)} \left[n_\Psi(\tau) - n_\Psi^{eq}(T) \right] \qquad \text{(static)}$$

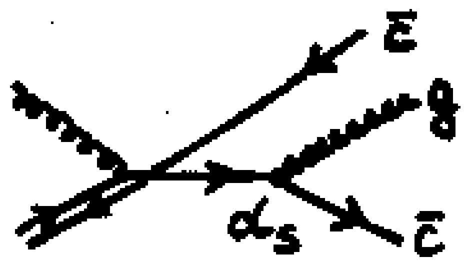
Contributions to $\tau_\Psi^{-1} = \int f^p(T)\, \sigma_{p\Psi}^{inel}$

[Shuryak '78]

- gluon- ("photo"-) dissociation
  efficient/applicable if $E_B \simeq E_B^{vac} \simeq 640\,MeV$

[Bhanot + Peskin '79]
[Thews et al. '01]

- "quasifree" destruction
  efficient for loosely bound charmonium (Debye-screened)



[Grandchamp + R.R. '04]

- constituent quark models: "π" J/Ψ ↔ "D" "D̄"
  ≙ coupling to in-med. (broad) resonances

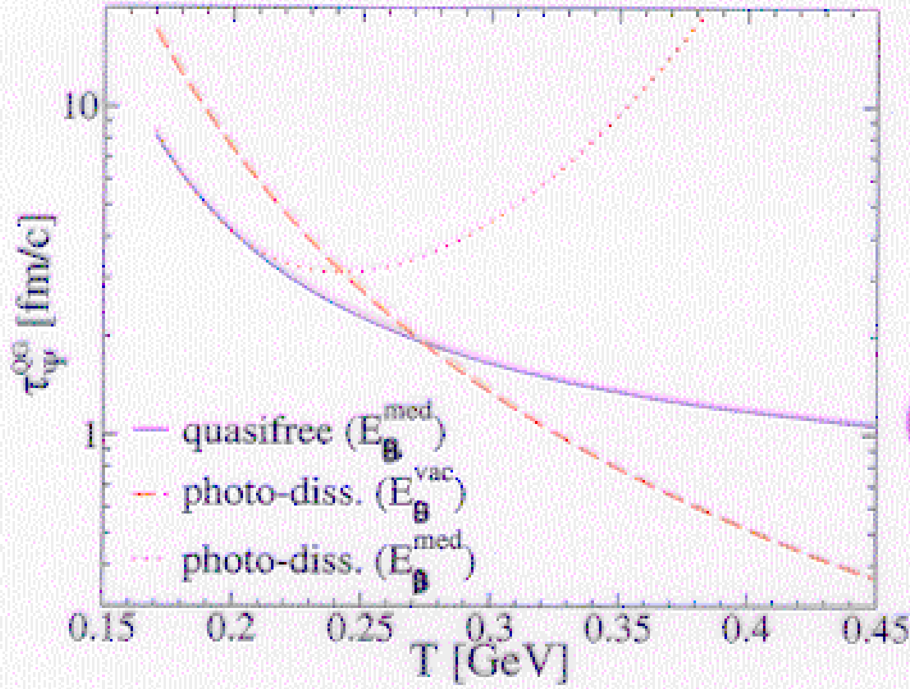
[Hansson, Lee + Zahed '88
Blaschke et al. '12, ...]

Gain term can be neglected if

(i) $\tau_\Psi \gg \tau_{FB}$ **and** (ii) $N_\Psi^0 \gg N_\Psi^{eq}$

[SPS: yes
RHIC: maybe (not)]

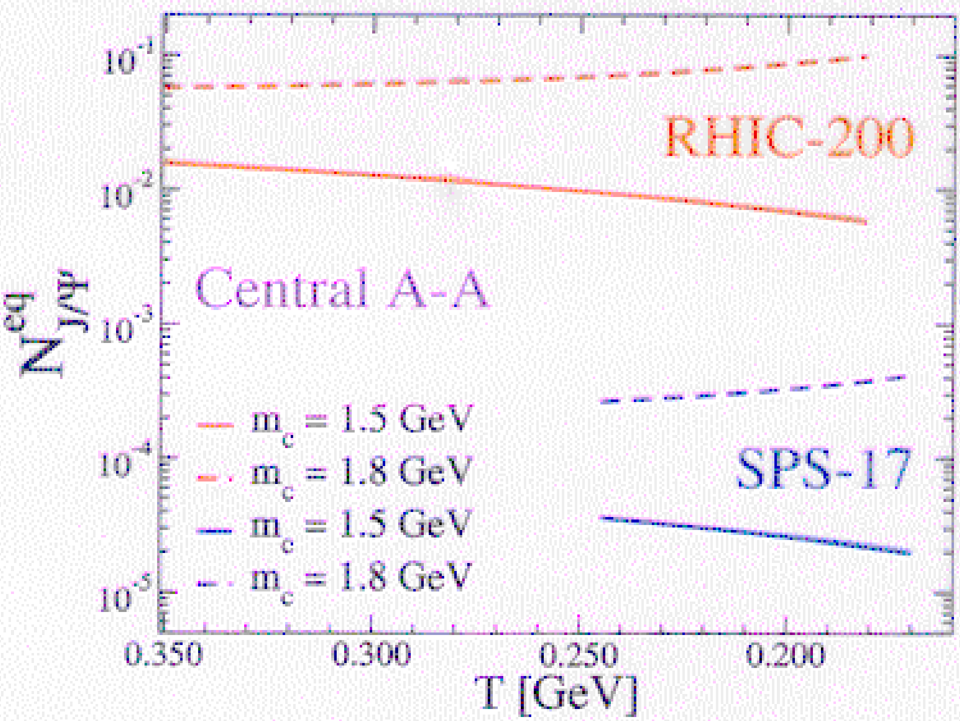
J/Ψ Lifetimes in QGP



(α_s=0.25)

Thermal-Equil. J/Ψ-Number in QGP

[using $N_{c\bar{c}}^{hard}$, m_Ψ=3.1GeV
$N_\Psi^{eq} = \gamma_c(T)^2 n_\Psi^{therm}(T)$]



← $N_{J/\Psi}^{hard}$ (RHIC)

← $N_{J/\Psi}^{hard}$ (SPS)

→ equilibrium abundance (well) below hard prod. ($N_\Psi^{hard} \simeq 1\% N_{c\bar{c}}$)

→ eq.-abund. rather sensitive to (in-medium) m_c

Charmonium at Hadronization + in Hadron Gas

(i) Hadronization

[Braun-Munzinger + Stachel '00
Gorenstein et al. '01, ...]

Statistical Recombination ("Coalescence") of c and $\bar{c}$:

$$N_\psi(T_H) = \gamma_c(N_{c\bar{c}}, m_D, T_H) \;\; n_\psi(m_\psi, T_H) \;\; V_{FB}(T_H)$$

- γ_c: fugacity to match open charm: $N_{c\bar{c}} \stackrel{!}{=} \gamma_c V_{FB} \sum_{i=D,D^*,\Lambda_c,\ldots} n_i(m_i, T_H)$
- n_ψ: thermal density
- V_{FB}: from light hadrochemistry

$\Leftrightarrow$ equilibrium limit of rate equation at T_H !

Corrections:

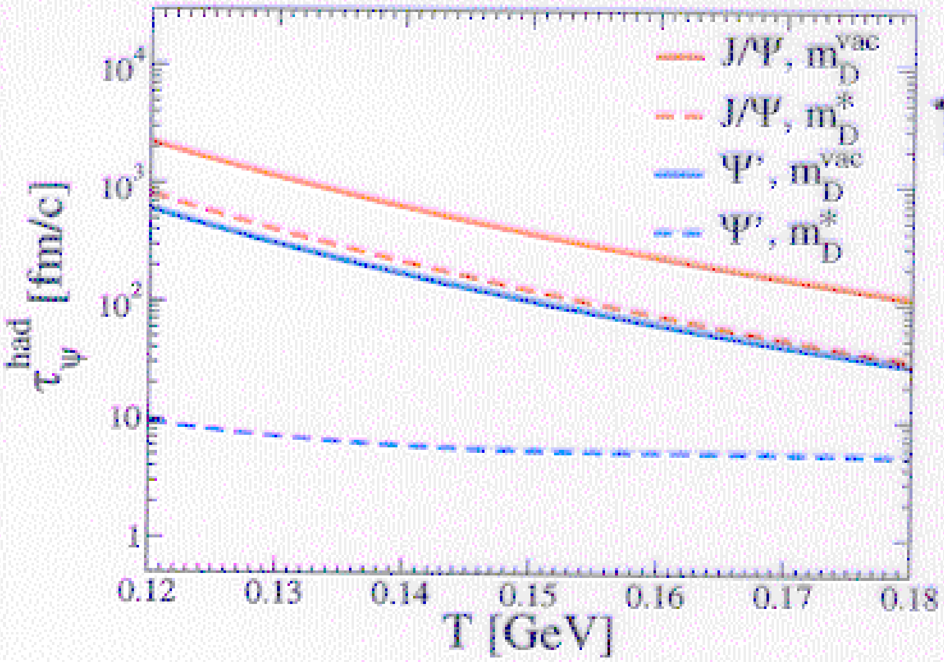
- thermalization of charm quarks: $\tau_0 < \tau_{c,\bar{c}}^{therm} \stackrel{!}{<} \tau_{FB}$
- $c\bar{c}$ "correlation" volume $V_{corr} < V_{FB}$

- J/ψ formation rate $\Gamma_\psi^{form} \gtrsim (\tau_{had})^{-1}$
- evolution below T_H → hadronic rates

(ii) Charmonium Properties in Hadronic Matter

- **Dissociation Cross Sections + Rates**

[Matinyan + Müller '98, Haglin + Gale '01, Lin + Ko '00, Wong et al. '00, Duraes et al. '03 ...]



$\pi, \rho + J/\psi \to D^*\bar{D}, D\bar{D}, \ldots$

$\langle \sigma_{\psi\pi,\rho} v_{rel} \rangle \simeq \frac{1}{2}$ mb

$\sigma_{\chi,\psi'} \propto \sigma_\psi \, (R_{\chi,\psi'}/R_\psi)^2$

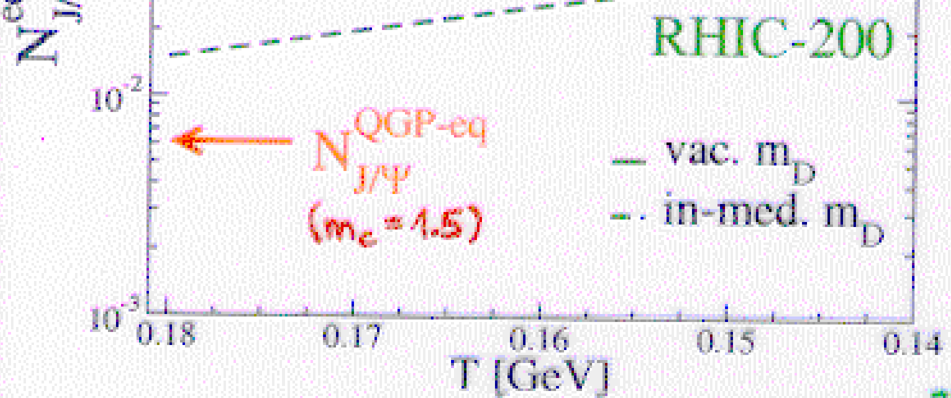
$\tau_\psi \simeq \frac{1}{\langle \sigma_{\psi h} v \rangle \, n_h}$

in-medium effects: reduced D-meson masses m_D^*

→ accelerate rates

→ open new channels: $\chi_c, \psi' \to D\bar{D}, \ldots$

- **J/Ψ Equilibrium Abundances** ($N_{c\bar{c}} \stackrel{!}{=}$ const)



- reduced by in-medium effects
- increase with decreasing temperature (γ_c!)

⇒ J/Ψ Regeneration in Hadron Gas ?!

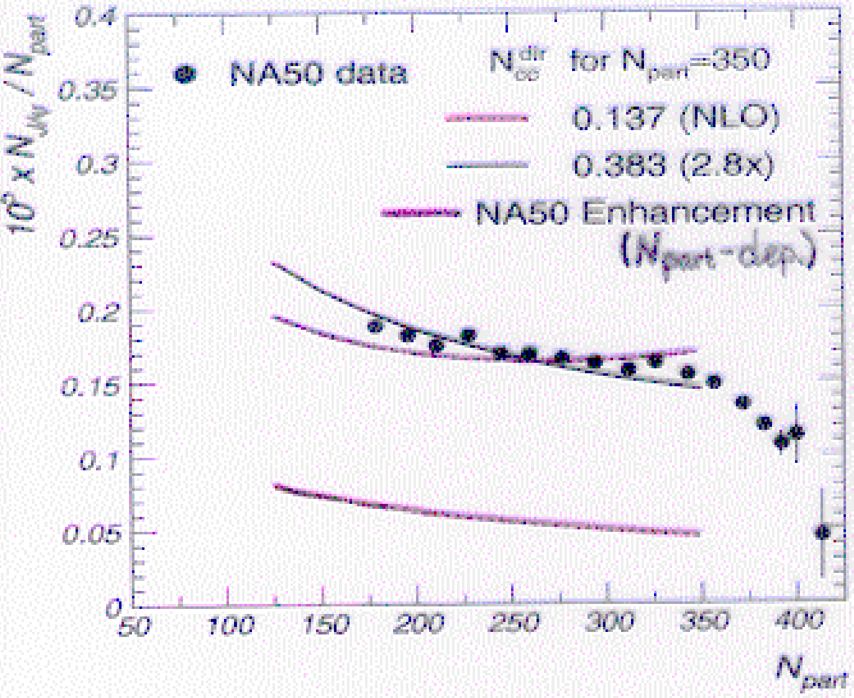
[Redlich + Braun-Munzinger '00]

4.) Model Comparisons to Data

4.1. SPS (Pb-Pb $\sqrt{s}$ = 17 AGeV) : J/Ψ

Statistical Hadronization only

[Andronic, Braun-Munzinger, Stachel + Redlich '02]

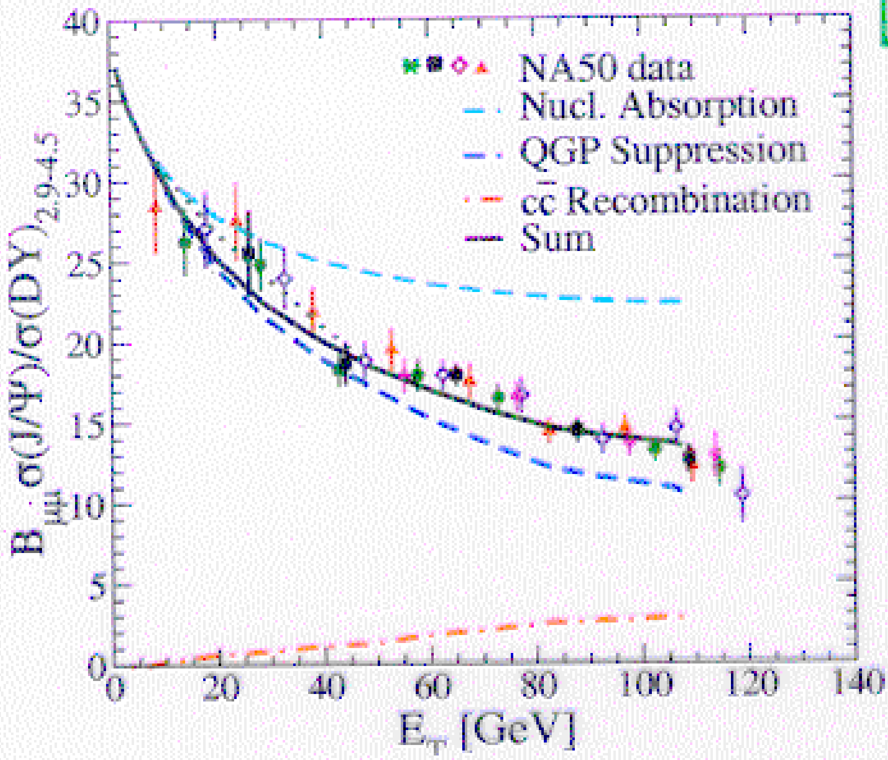


- assumes all direct J/Ψ dissociated
- requires $N_{c\bar{c}}$-excess by factor ~3

(similar: [Gorenstein et al. '01])

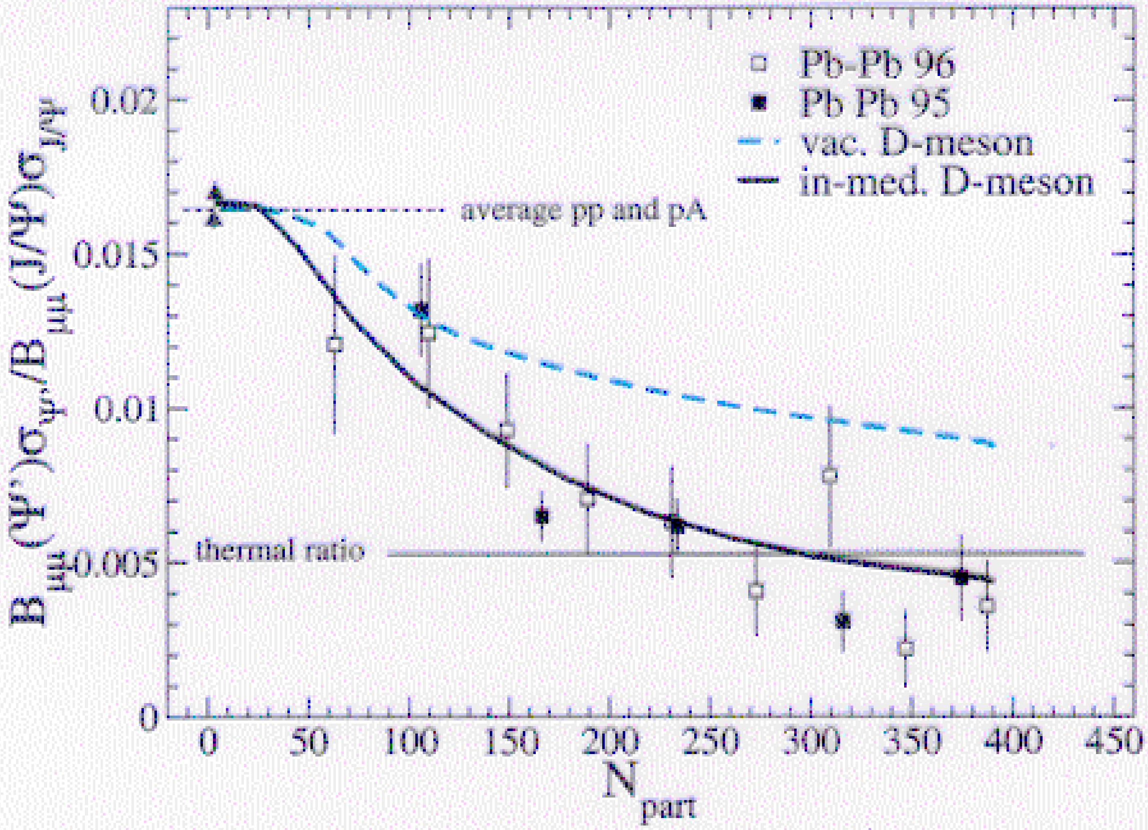
Dynamical Evolution Approach (Rate-Equation)

[Grandchamp, RR + Brown '03]



- no $N_{c\bar{c}}$-excess
- secondary formation ~25%
- main effect: QGP-suppression of direct J/Ψ ! ($T_{ini} \approx$ 210 MeV)

Ψ'/Ψ Ratio at SPS

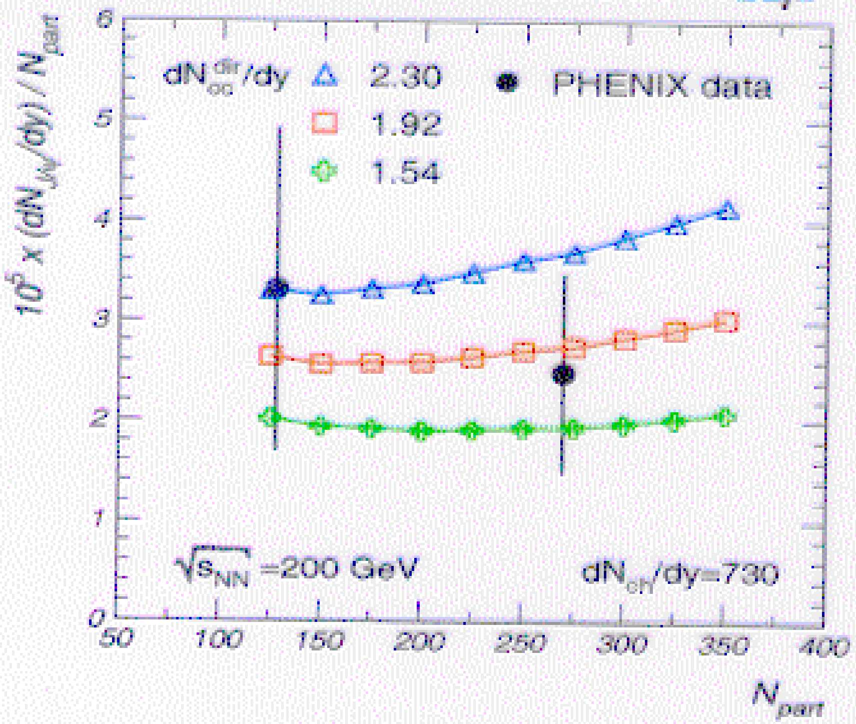


- consistent with Statistical Recombination at T_c for $N_{part} > 150$ [Braun-Munzinger + Stachel '00]
- dynamical evolution approach requires hadronic in-medium effects, opening $\Psi' \rightarrow D\bar{D}$ [Grandchamp, RR + Brown '03]

4.2. J/Ψ Production at RHIC

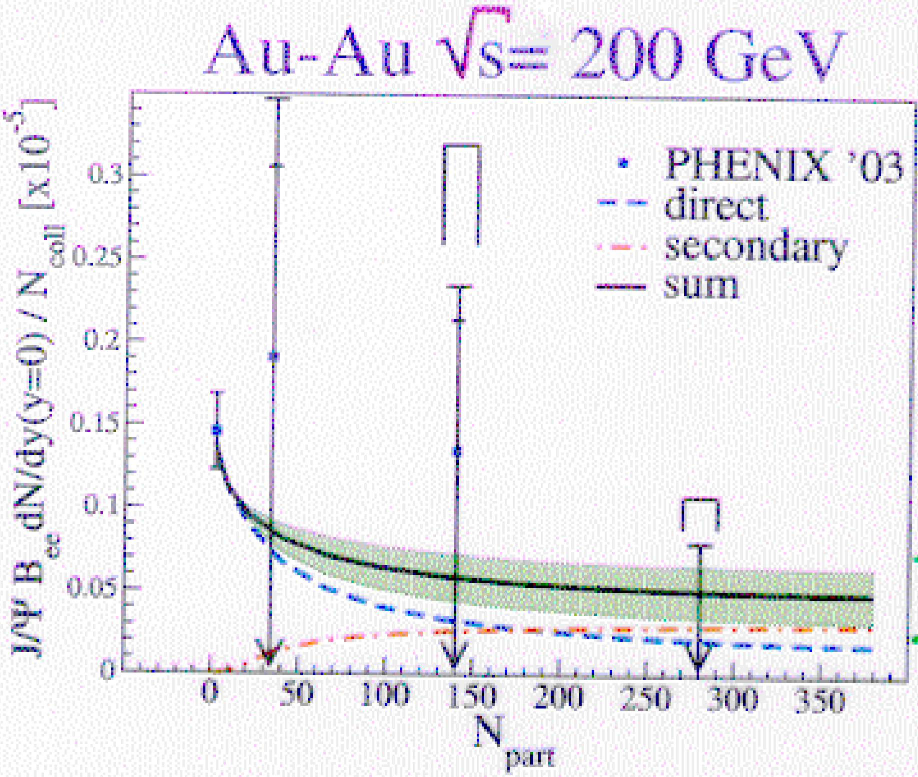
Statistical Hadronization only

[Andronic et al. '02]



$\propto N_{c\bar{c}}^2$ (central)

Dynamical Evolution incl. Medium Effects



[Grandchamp et al. '03]

secondary ≳ direct suppressed

} sensitivity to m_c^*

similar to transport models [Zhang et al. '02, Bratkovskaya et al. '03]

5) Summary + Conclusions

- **QGP**
  - charmonia might survive as resonances (spectral fcts.!)
  - $J/\Psi \leftrightarrow c\bar{c}$ equilibration ?
- Phase Boundary
  - open-charm continuous: $m_c^* \approx m_D^*$ (Chiral Restoration)

    ⇒ reduce equilibrium charmonium numbers
- Hadronic Phase
  - J/Ψ robust, Ψ' sensitive to in-medium effects

⇒ Charmonium Signatures in URHIC's versatile!

- SPS: "suppression" viable
- Collider Energies: if charm sector (partially) equilibrates substantial J/Ψ production inevitable!

observables to disentangle mechanisms:

- charm chemistry (Ψ'/Ψ, D/Λ_c, Ξ_{cc}, ...)
- p_t-spectra (c, Ξ elliptic flow!)
- centrality dependence / excitation function (suppression → regeneration)

...