In-Medium Effects on Charmonium Production in Heavy-Ion Collisions

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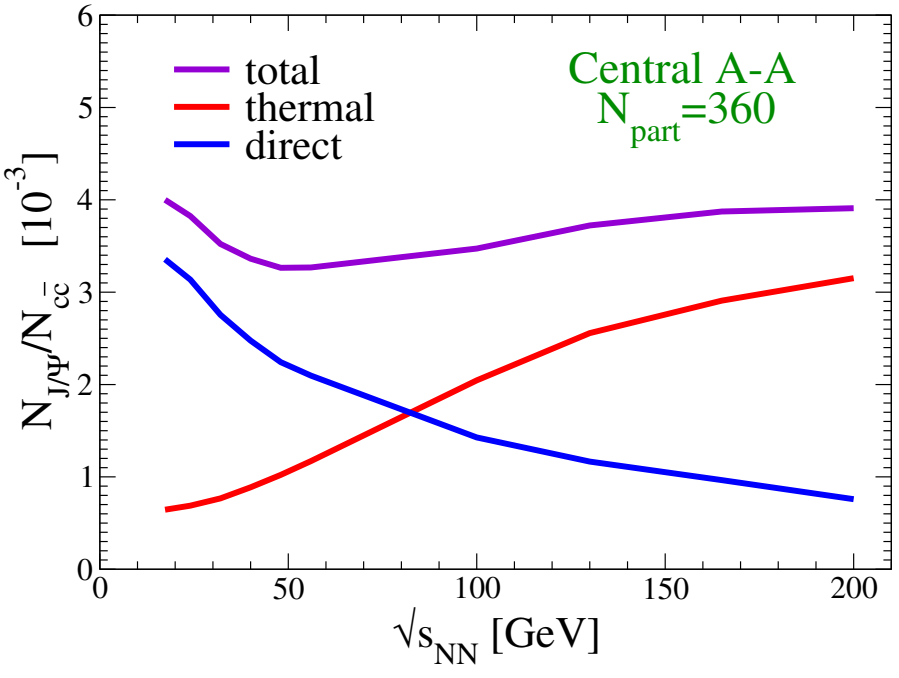
Outline

- Introduction & motivations
- Equilibrium properties of charm in matter
  Lattice QCD, in-medium effects, equilibrium abundances
- Charmonium interactions in QGP and HG
- Kinetic approach in heavy-ion collisions
- SPS results & predictions, charmonium at RHIC
  J/Ψ centrality dependence, Ψ'/Ψ ratio
- Conclusions & outlook

Introduction & Motivations

- Charmonia in Heavy-Ion Collisions [Matsui & Satz '86]
  - produced in hard N-N collisions
  - charmonia (J/ψ, ψ', χ) suppressed due to reinteractions
    nuclear absorption, QGP suppression, HG interactions
  - statistical regeneration at T_c [Braun-Munzinger & Stachel '00]
    $\Rightarrow$ 2-component model [LG & R. Rapp '01]



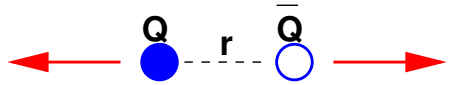
- Underpredict Ψ' suppression
  (Ψ'/Ψ ratio)

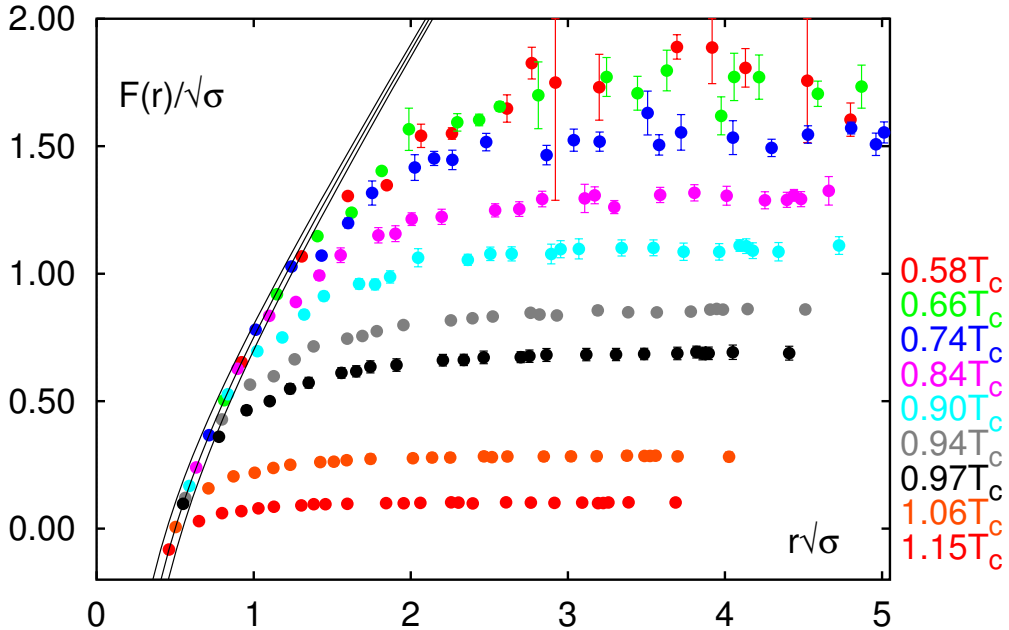
- Lattice QCD
  - Heavy quark potential modified in the medium
  - J/Ψ spectral functions: J/Ψ survives in QGP

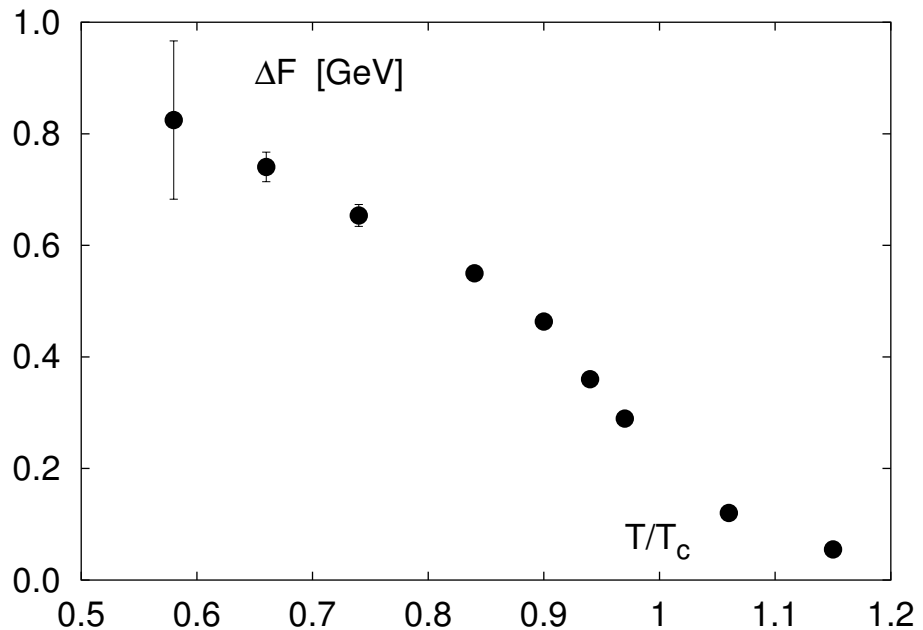
- Improved approach
  - Infer in-medium properties of charm from Lattice QCD
    $\Psi + X_1 \rightleftharpoons X_2 + c + \bar{c}\ (D + \bar{D})$
  - Solve rate equations
    $\Rightarrow$ J/Ψ regeneration in QGP & HG

Equilibrium Properties of Charm in Matter

- Lattice QCD: heavy quark free energy [Karsch et al. '00]



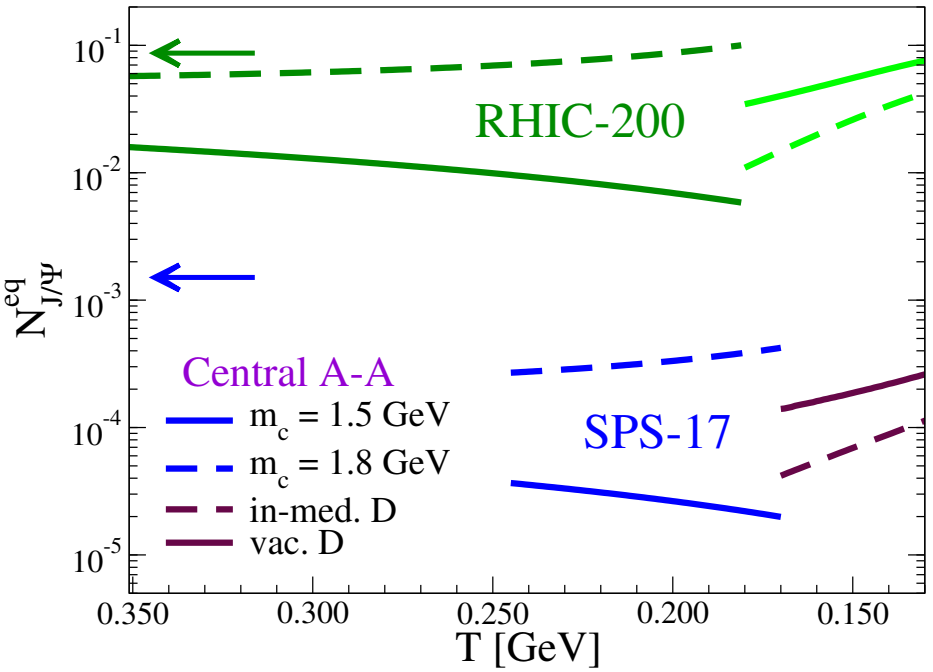


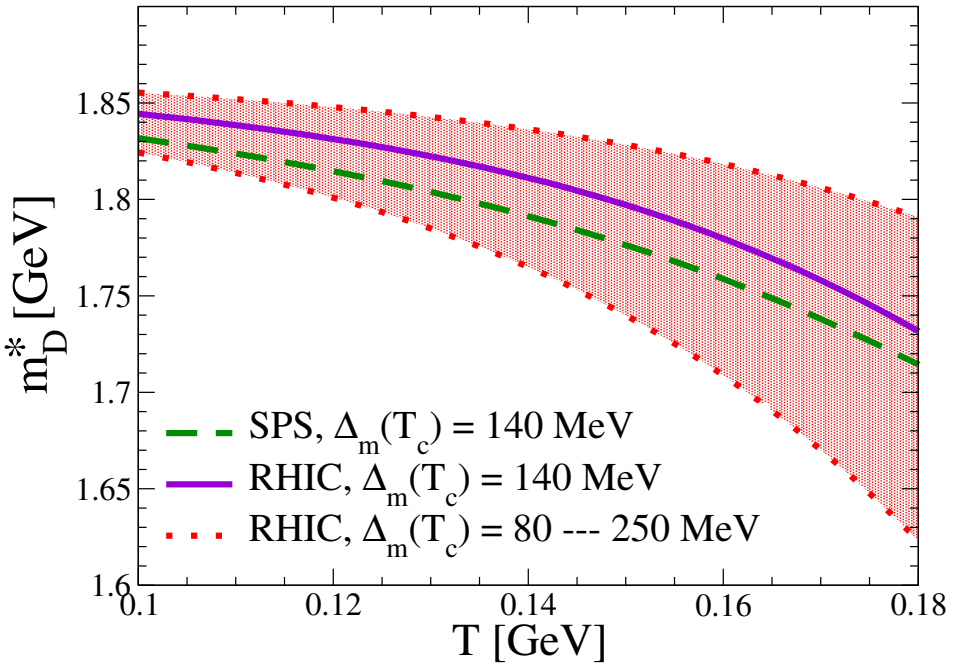


- Plateau at large distances $\sim$ Open-Charm threshold
- Reduced Open-Charm threshold
  $\Rightarrow$ charm thermal correlation, χ-symmetry restoration m_D^*
- Smooth transition across T_c
- Consequences on equilibrium charm chemistry

J/Ψ Equilibrium Abundances

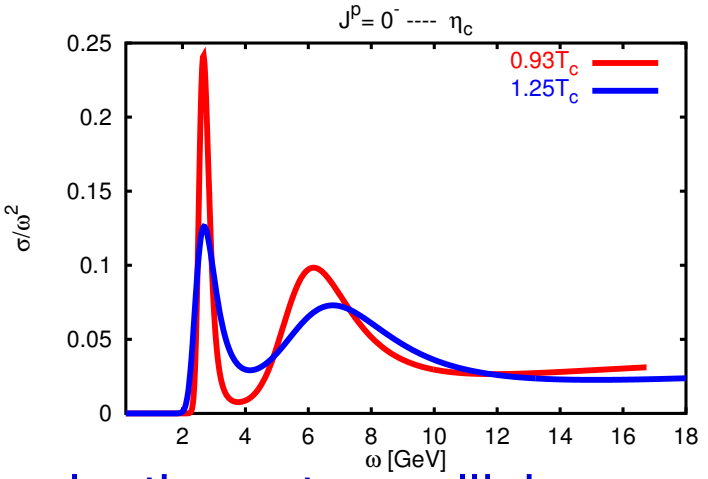
- m_c^*: thermal correlation
- $N_{op} = 2V\gamma_c n_c(T, m_c^*)$
- m_D^*: χ-restoration
- $N_{op} = V\gamma_c \sum_\alpha n_\alpha(T, \mu_B)$
- Continuity hypothesis: open-charm degeneracies matched
- Charm chemical off-equilibrium: $N_{c\bar{c}} = \frac{1}{2} N_{op} \frac{I_1(N_{op})}{I_0(N_{op})} + N_{hid}$
- $N_{c\bar{c}}$: <u>no</u> open-charm enhancement. $\sigma_{c\bar{c}}^{pp}(\sqrt{s} = 200) \simeq 650\mu b$ [Phenix]
- J/Ψ equilibrium number: $N_{J/\Psi}^{eq} = V\gamma_c^2 n_\psi^{eq}(T)$

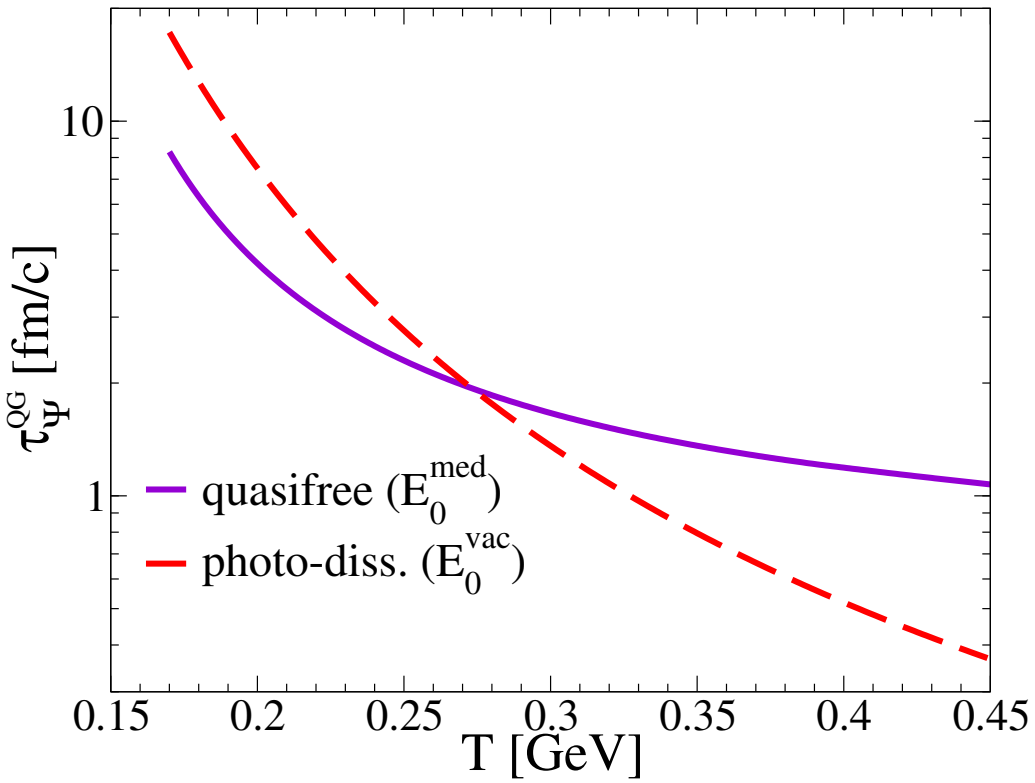




Charmonium in the QGP

- Spectral functions from Lattice
  [Karsch et al. '02]
  $\Rightarrow$ low-lying charmonia in QGP
- Large width increase across T_c
  [Umeda et al. '02], mass $\equiv$ constant



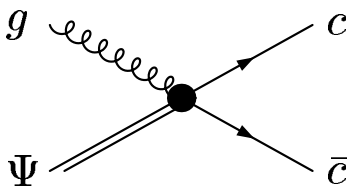


- Inelastic parton collisions

$$(\tau_\Psi)^{-1} = \sum_{i=q,g} \int \frac{d^3k}{(2\pi)^3} f^i(T) \sigma_\Psi^{QG} v_{rel}$$

- gluo-dissociation

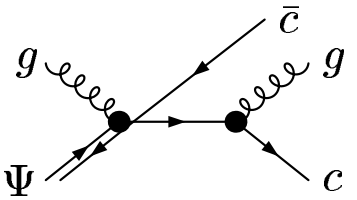
$E_b >> \Lambda_{QCD}$



- quasifree [L.G., R. Rapp '01]

$E_b \lesssim \Lambda_{QCD}$

ψ', χ

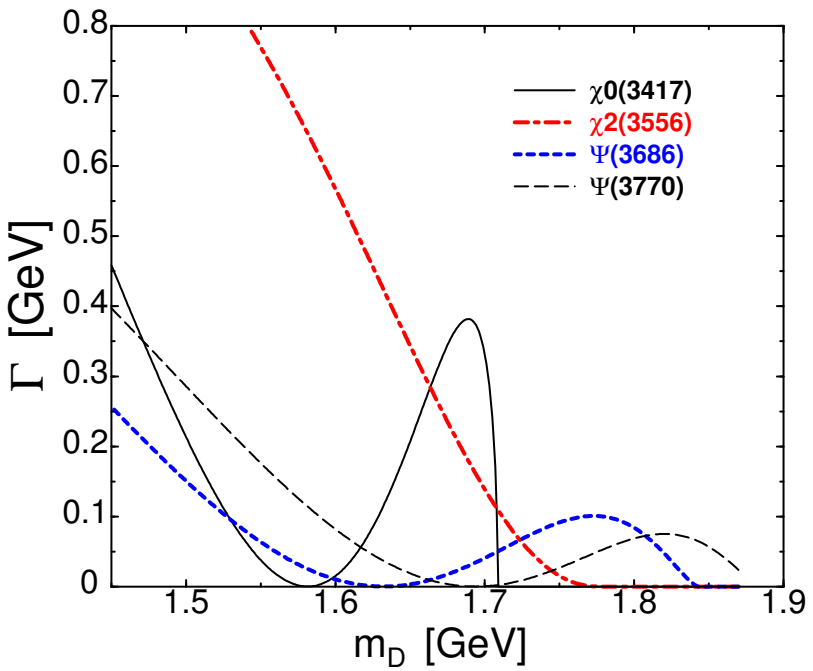


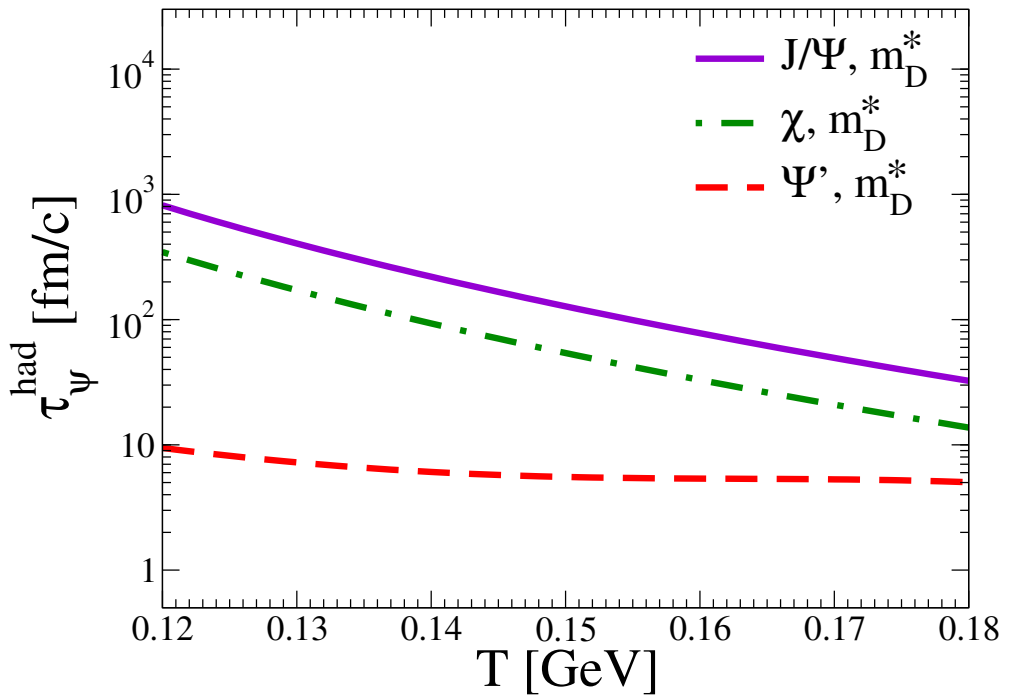
Charmonium Interactions in Hadron Gas

- SU(4) effective lagrangian [Haglin '99, Lin and Ko '99]

$$J/\Psi + \pi, \rho \rightarrow D\bar{D}^{(*)}$$

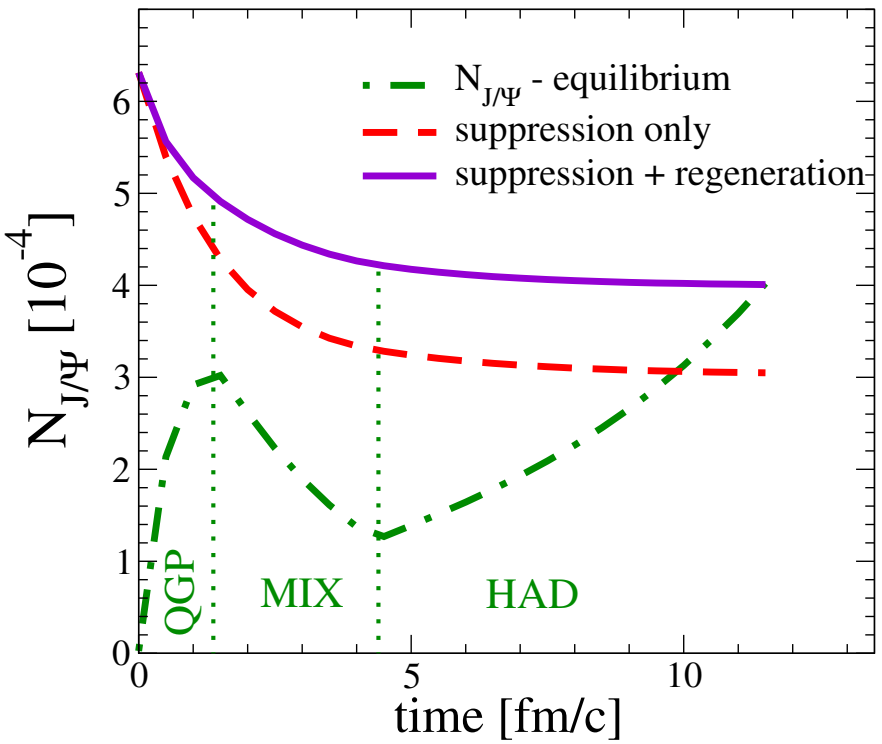
- Geometric scaling, $\left(\frac{r_i}{r_\Psi}\right)^2$ for $i = \Psi', \chi$ Form factors $\Lambda = 1\ GeV$
- In-medium effects - lower equilibrium numbers
  - accelerate inelastic reactions
  - lower open charm threshold
- direct decays $\Psi' \rightarrow D\bar{D}$ but: wavefunction nodes ! [Friman '01]

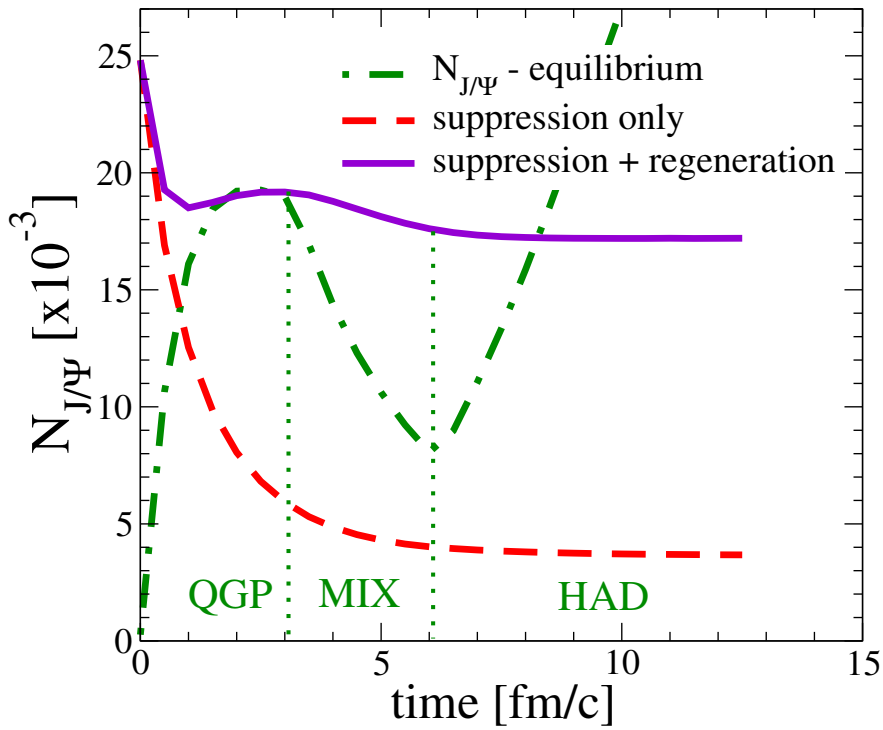




Kinetic Approach in HI Collisions

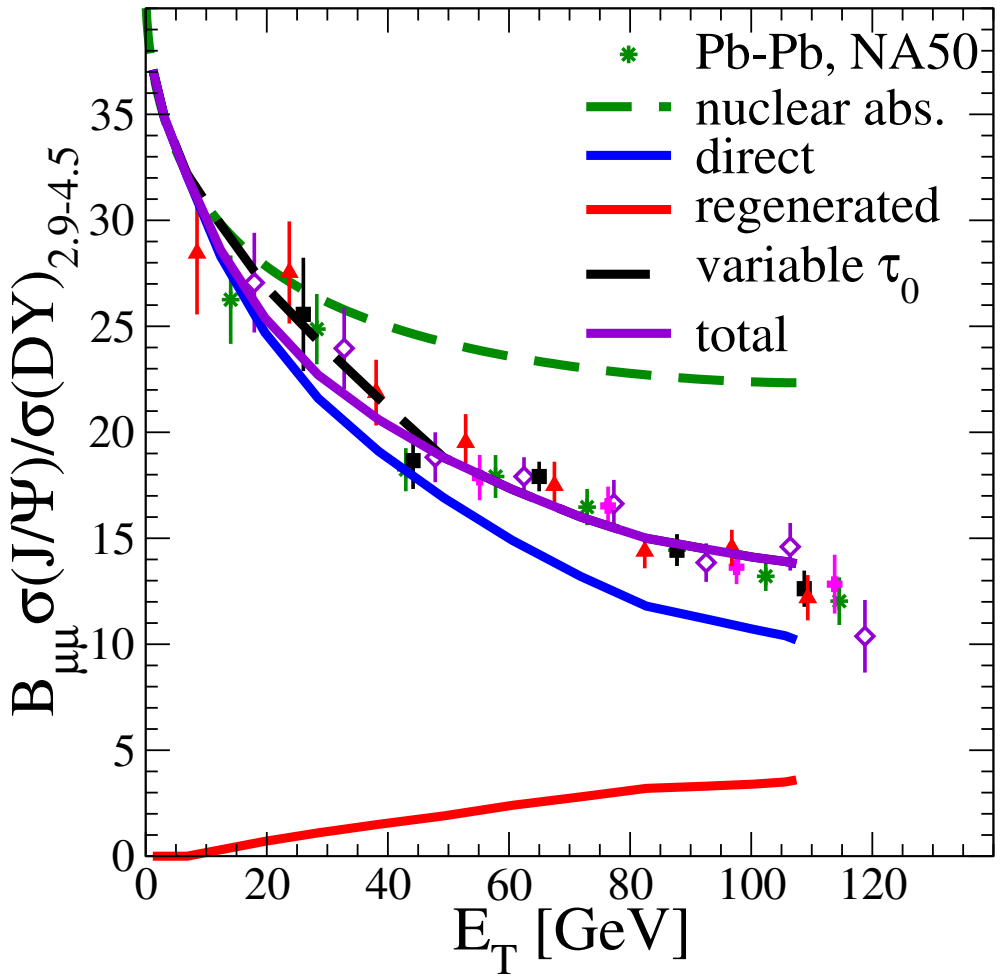
- Kinetic approach - Rate eqs: $\frac{dN_\Psi}{d\tau} = -\frac{1}{\tau_\Psi}[N_\Psi - N_\Psi^{eq}]$
- N_Ψ^{eq} and τ_Ψ include In-medium effects
- Convolute over thermal fireball evolution, include feeddown
- Off-equilibrium features in the evolution
  - chemical off-equilibrium: γ_c, local charm conservation: V_{corr}
  - incomplete thermalization: $\mathcal{R} = 1 - \exp(-\int d\tau/\tau_c^{therm})$





Pb(158 AGeV)-Pb Results at SPS

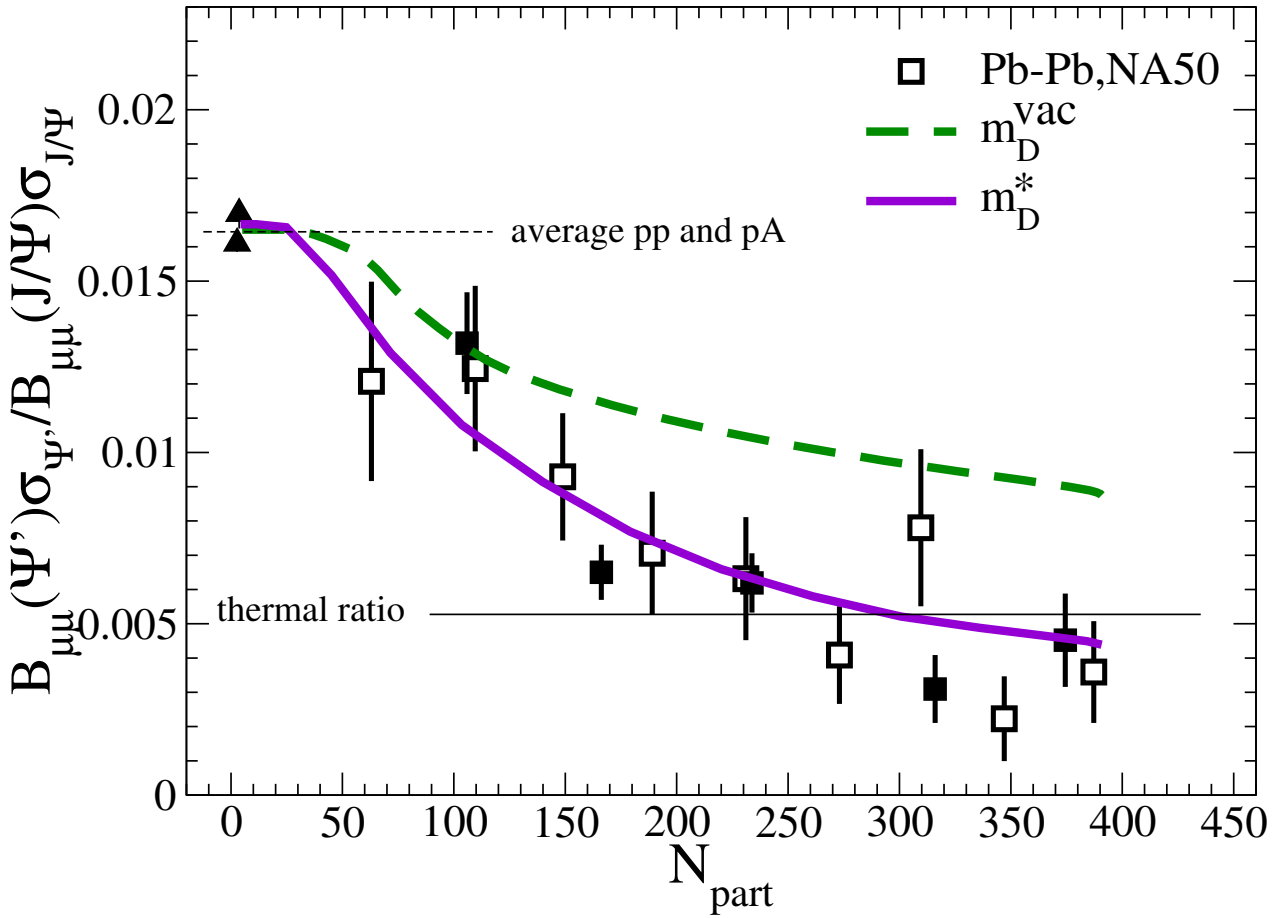
- J/ψ centrality dependence
  - $N_\Psi^{hard} >> N_\Psi^{eq}$
  - Suppression mechanism dominates



- Large E_T: E_T fluctuations & trigger energy loss (not included)

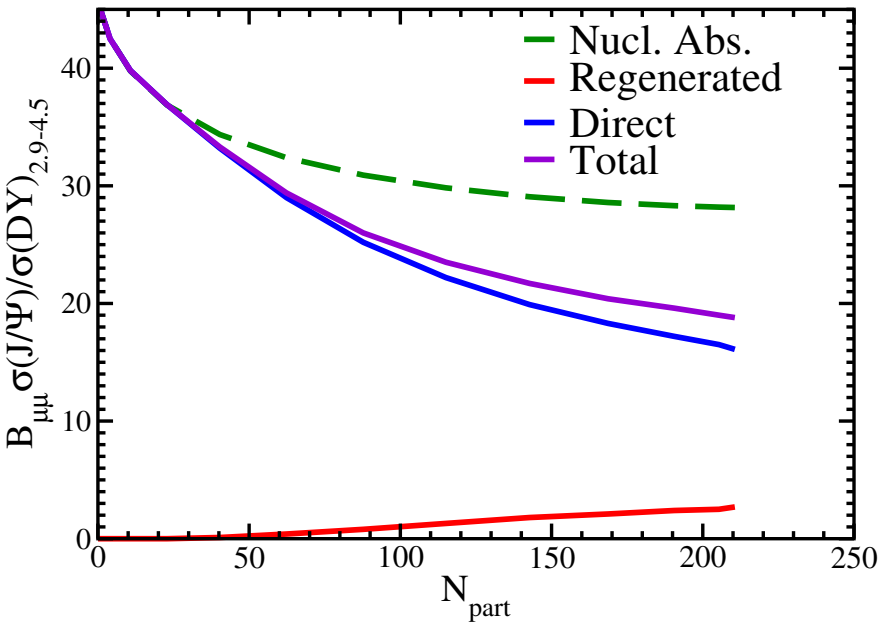
Pb(158 AGeV)-Pb Results at SPS

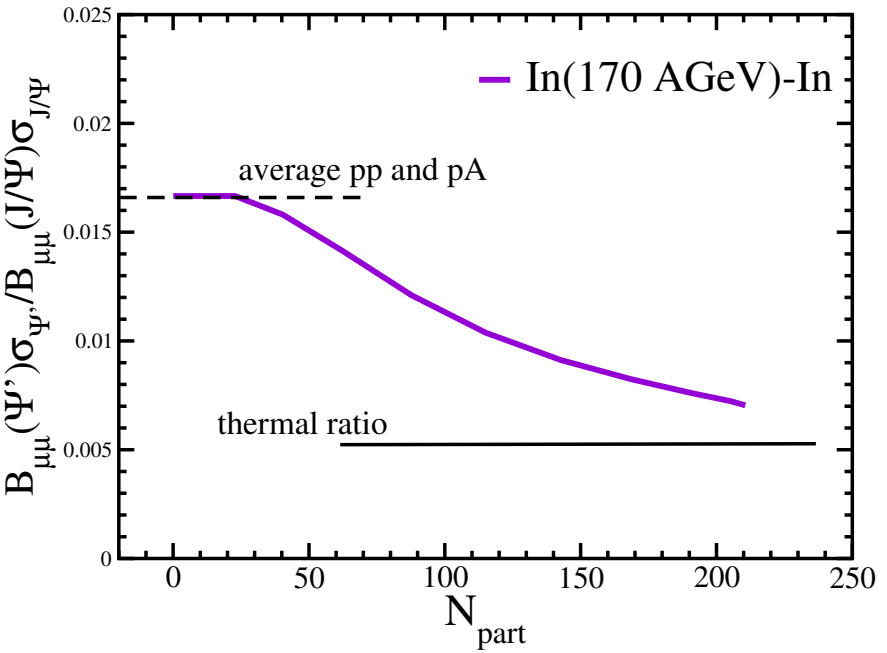
- ψ'/ψ ratio
  - $\Psi' \to D\bar{D}$ in the medium
  - Substantial $\Gamma^{HG}_{\Psi'}$ increase



In(170 AGeV)-In Predictions at SPS

- NA60
- J/ψ centrality dependence
- ψ'/ψ ratio

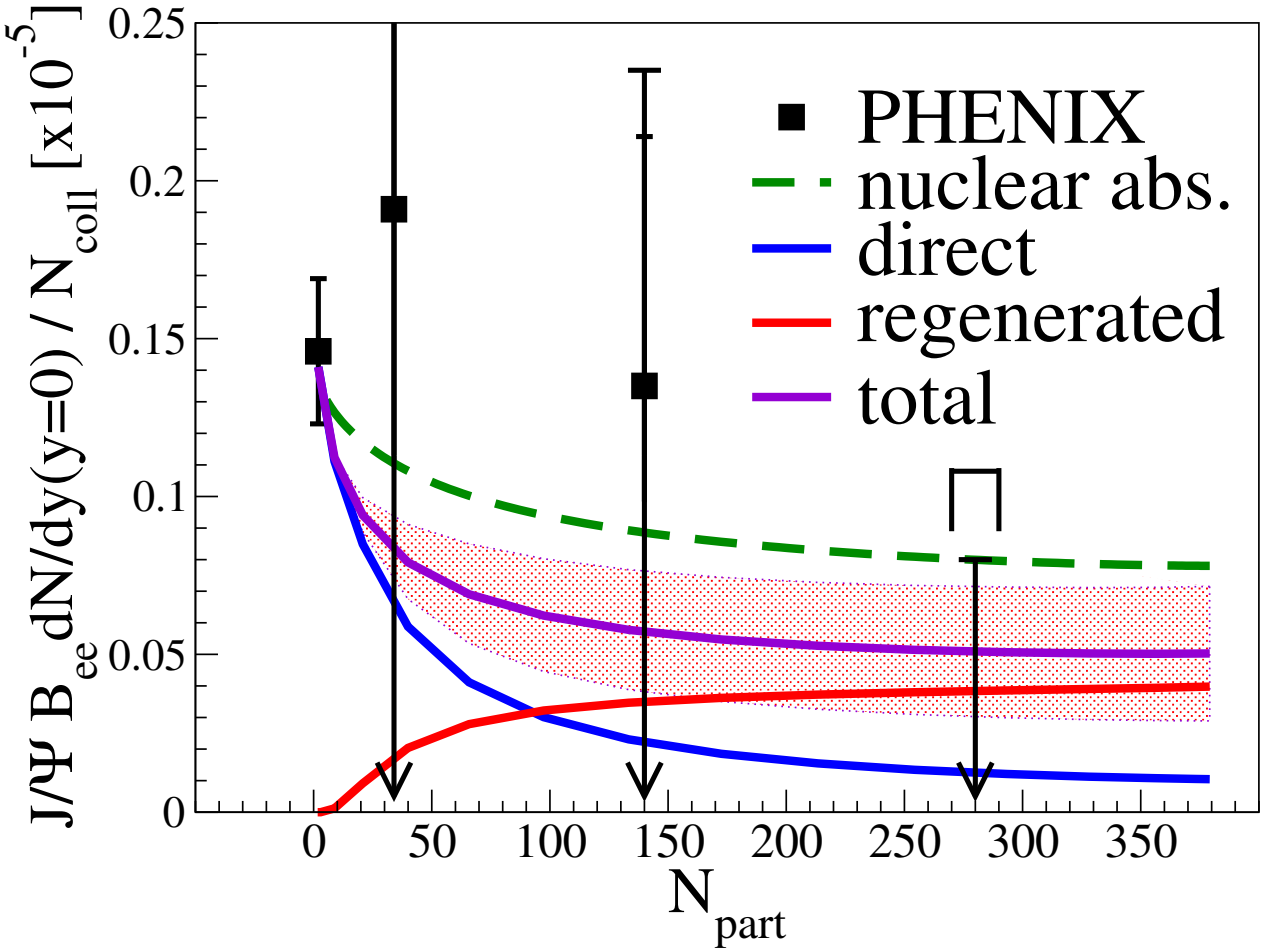




- Departure from nuclear absorption ($\sigma_{abs} = 4.4\ mb$)
- Little regeneration
- E_T effects not included

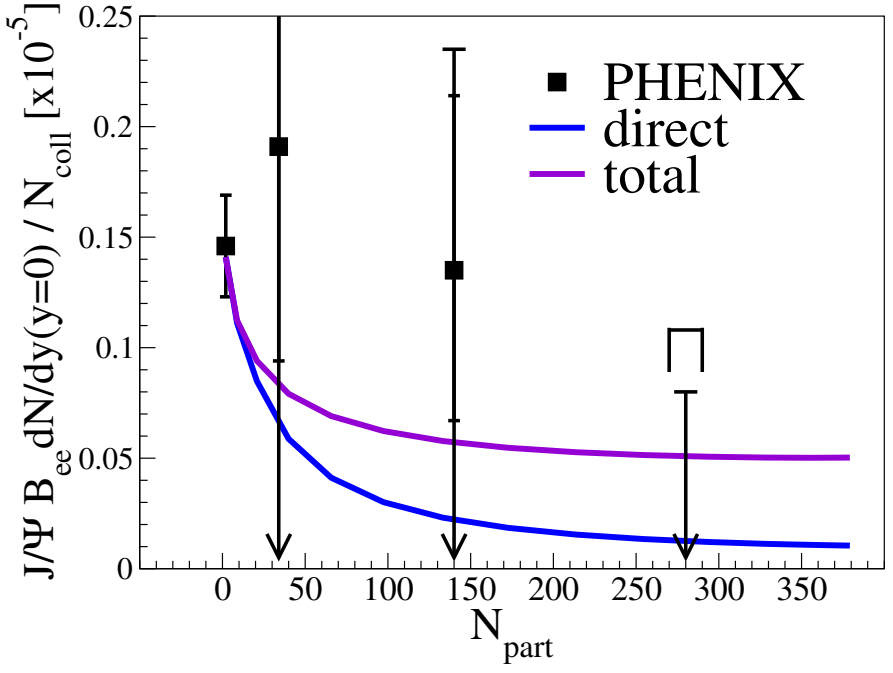
Au-Au at RHIC ($\sqrt{s} = 200$ AGeV)

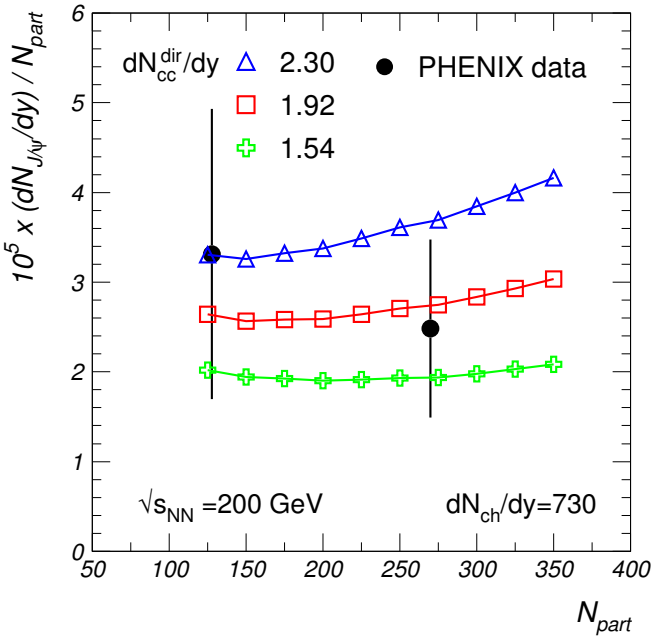
- J/ψ centrality dependence

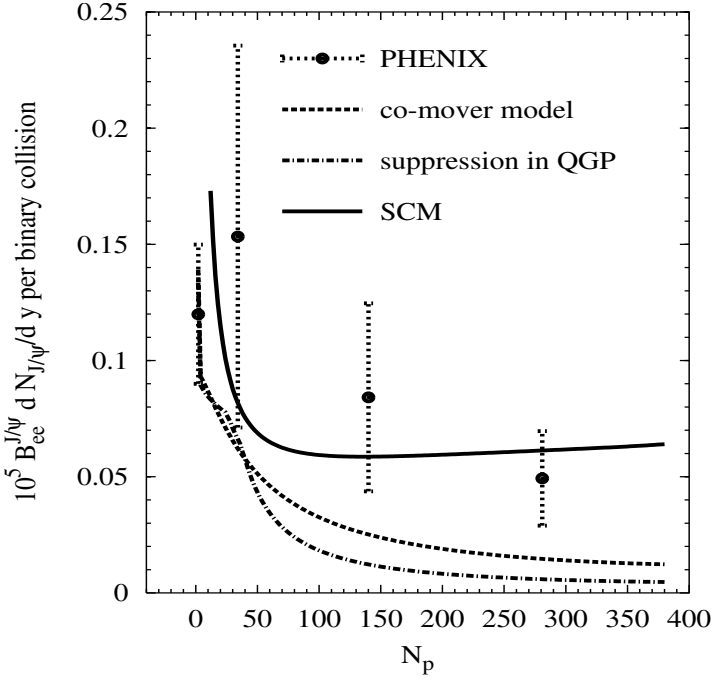


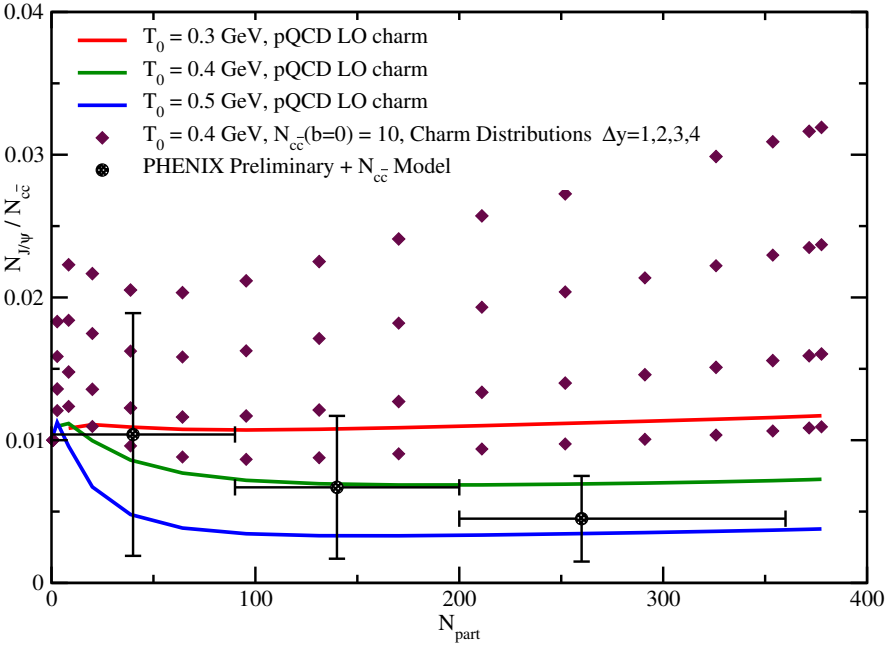
- Significant regeneration in central collisions
- Sensitive to in-medium masses

Au-Au at RHIC ($\sqrt{s} = 200$ AGeV)



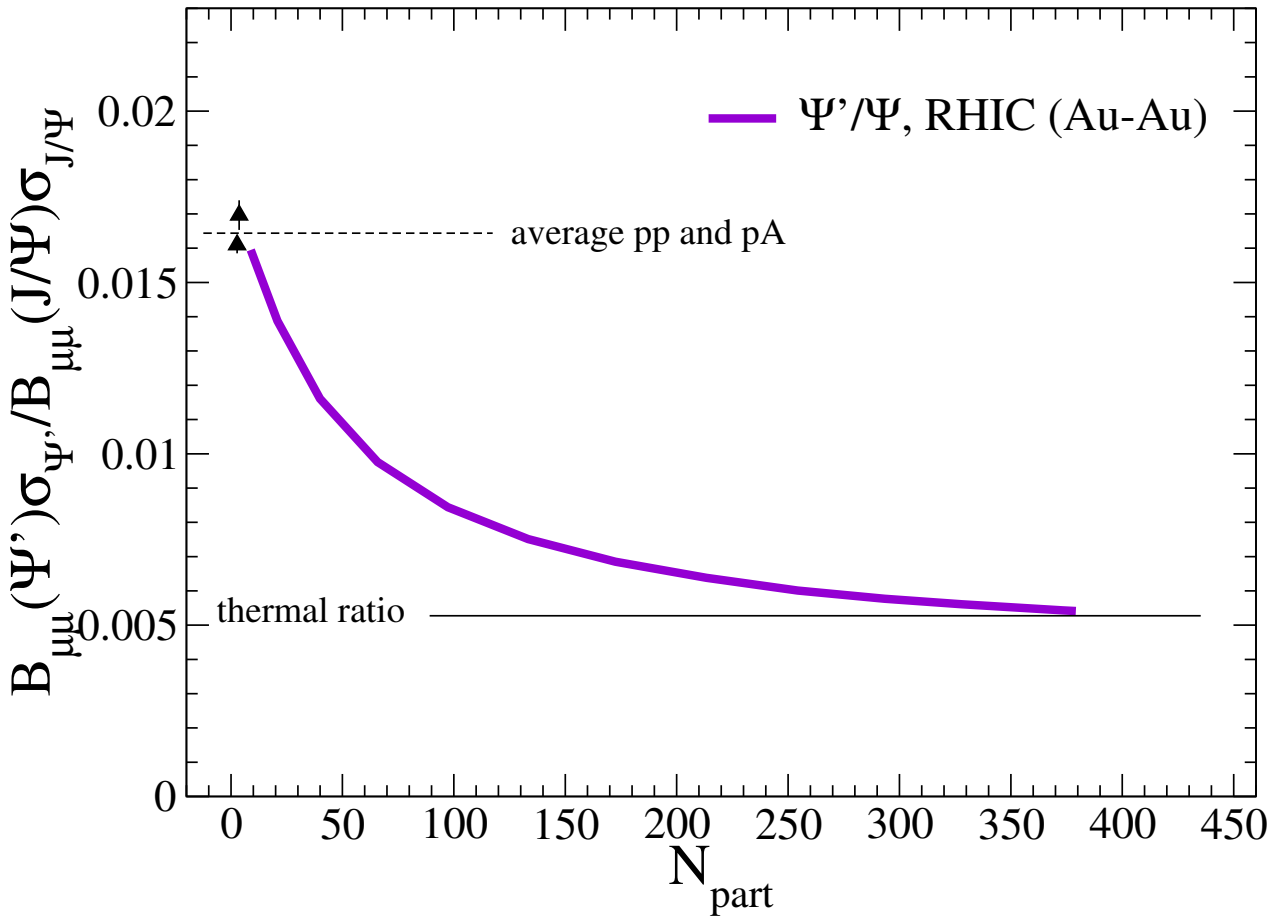






Au-Au at RHIC ($\sqrt{s} = 200$ AGeV)

- ψ'/ψ ratio



- Ψ'/Ψ ratio similar going from SPS to RHIC
  but composition in terms of direct & regenerated very different

Conclusions

- Model of charmonium production in A-A
  - Continuous reduction of the open charm threshold
    QGP: m_c^*, HG: m_D^*
  - Survival of charmonia above T_c
  - Rate equations + in-medium effects
    SPS: suppression
    RHIC: significant regeneration
- Charmonium signatures complex !

Outlook

- Observables to disentangle mechanisms
  - charm chemistry
  - p_T spectra, c (D) elliptic flow
  - centrality dependence
  - excitation function

Extra Slides

High E_T Effects in NA50

- Transverse energy fluctuations at $b = 0$
  [Capella, Ferreiro & Kaidalov '00]
  [Blaizot, Dinh & Ollitrault '00]

- $E_T > 100\ GeV$

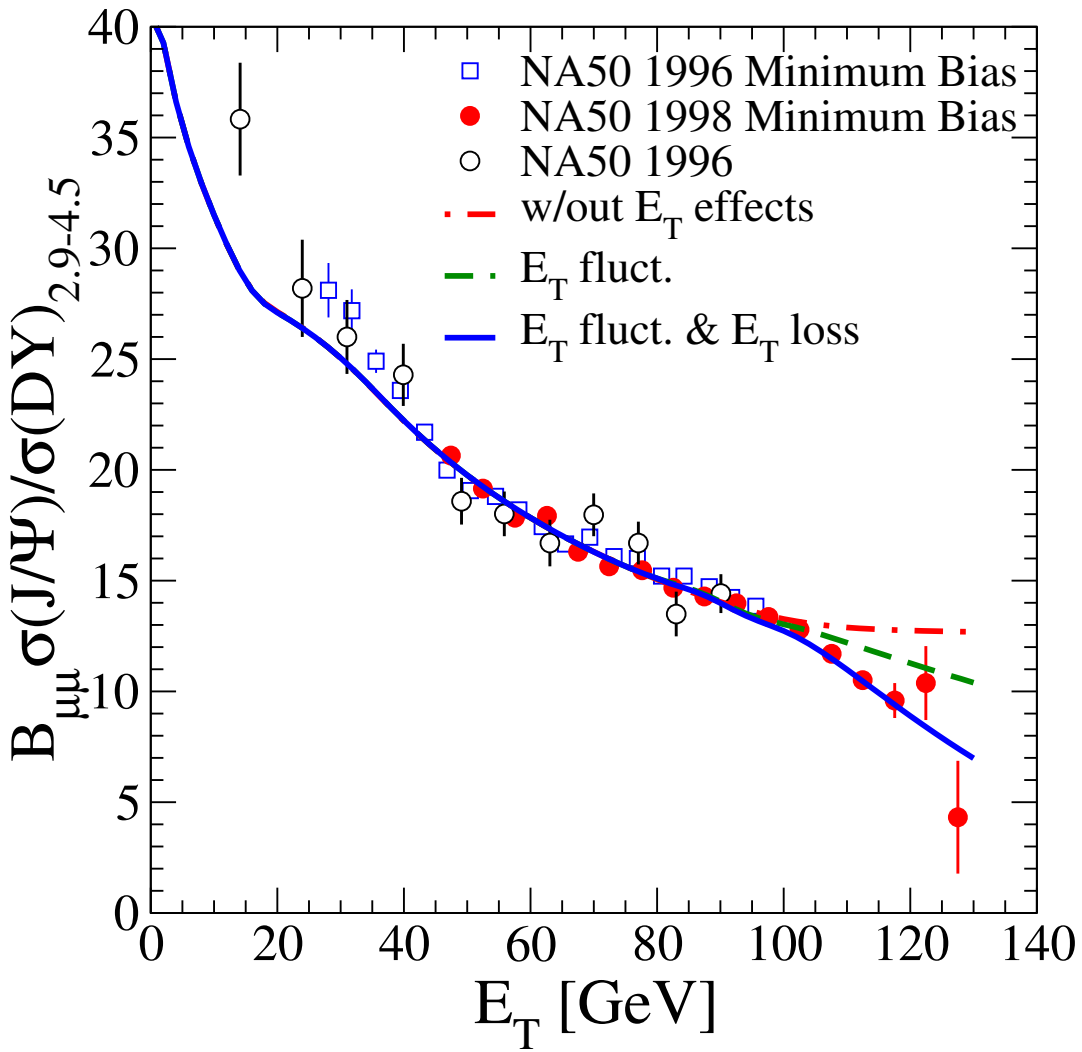
$$S_{tot}(b) \rightarrow S_{tot}(b)\frac{E_T}{E_T(b)}$$

$\Rightarrow$ extra suppression

- Minimum Bias analysis
  [Capella, Kadailov & Sousa '01]

Trigger energy loss ?

$$E_T(b) \rightarrow E_T(b)\frac{N_{part}-2}{N_{part}}$$



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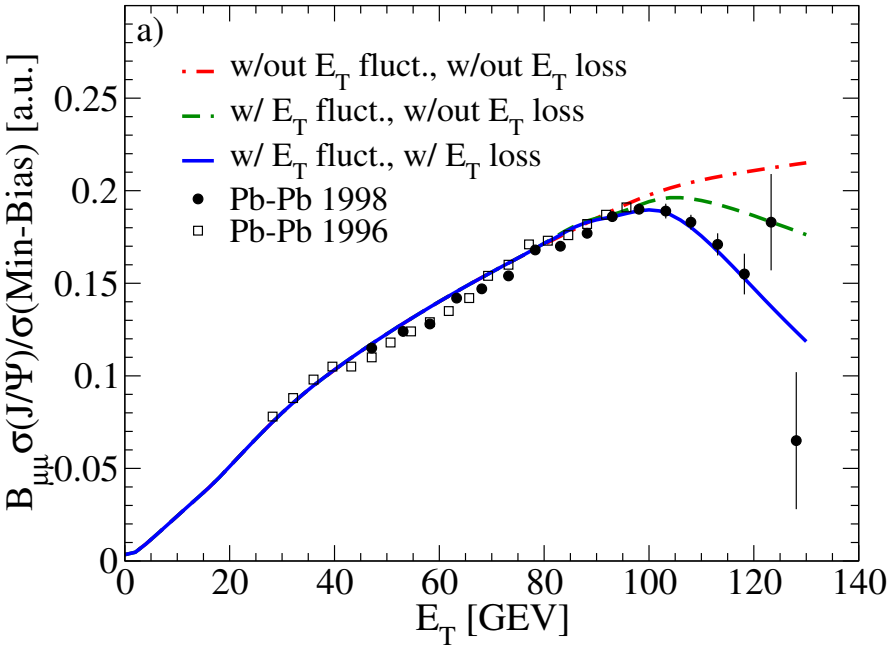
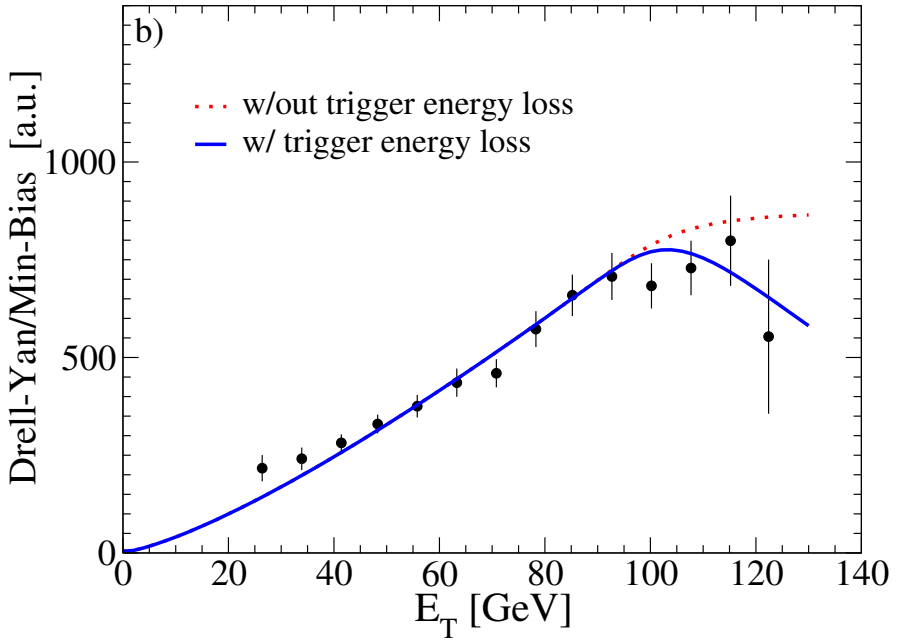
Minimum Bias Analysis





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Open Charm Production

- pN collisions

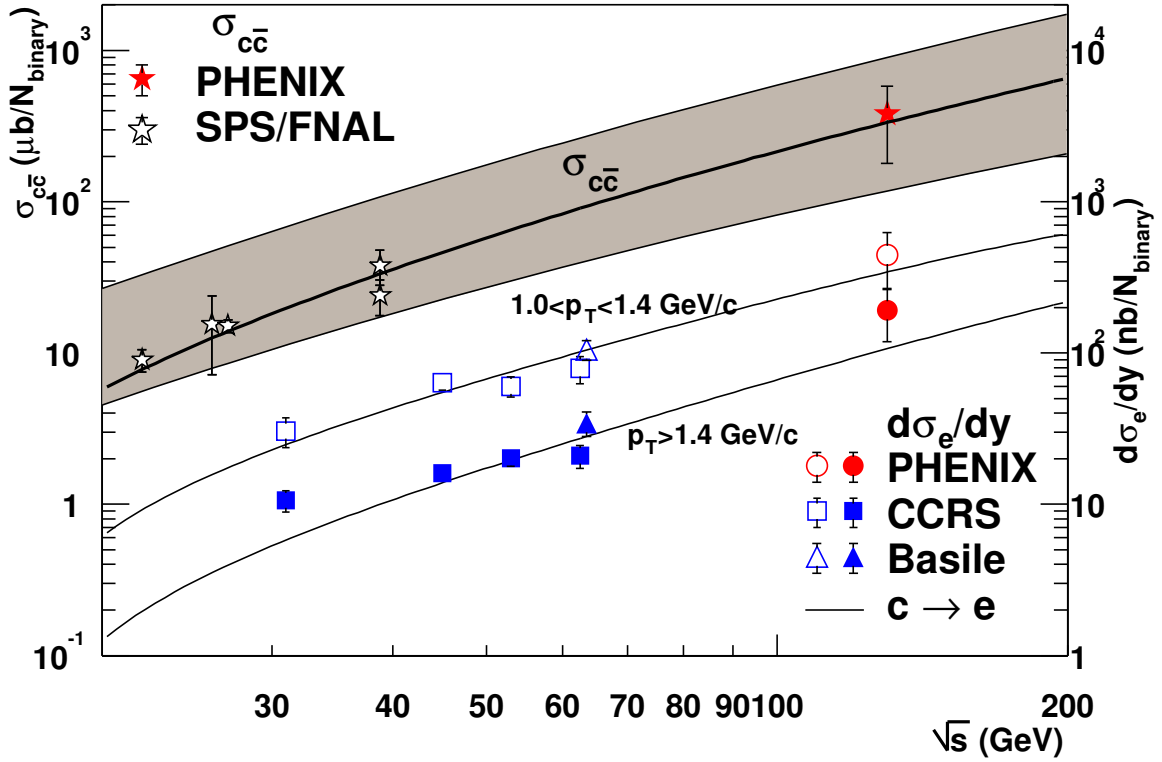
  LO pQCD $\Rightarrow K \sim 4-7$

  NLO $\Rightarrow K \sim 2.5$
- pA collisions

  $\sigma_{c\bar{c}}(pA) = A^{\alpha}\sigma_{c\bar{c}}(pN)$ $\alpha = 1.02 \pm 0.03$ [E789, NA50]
- AA collisions

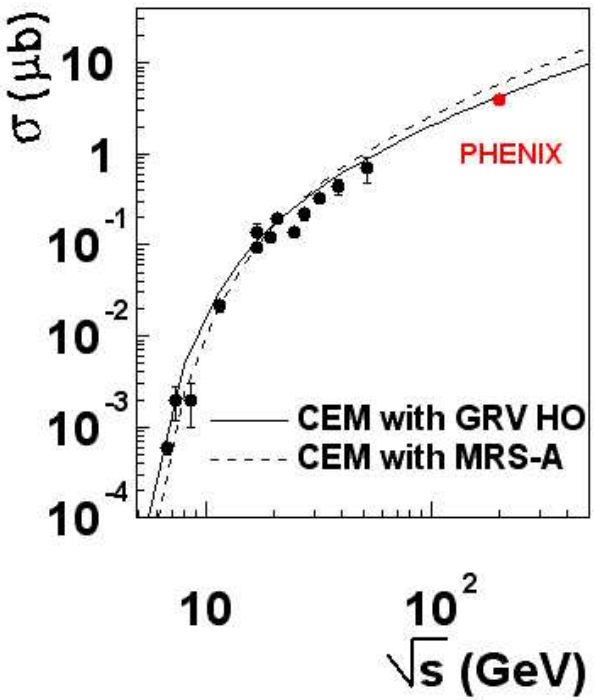
  - SPS[NA50]:
  $M_{\mu^+\mu^-}$ spectrum
  Open charm ($\times 3$)? or
  thermal dimuons
  [Rapp & Shuryak '00]

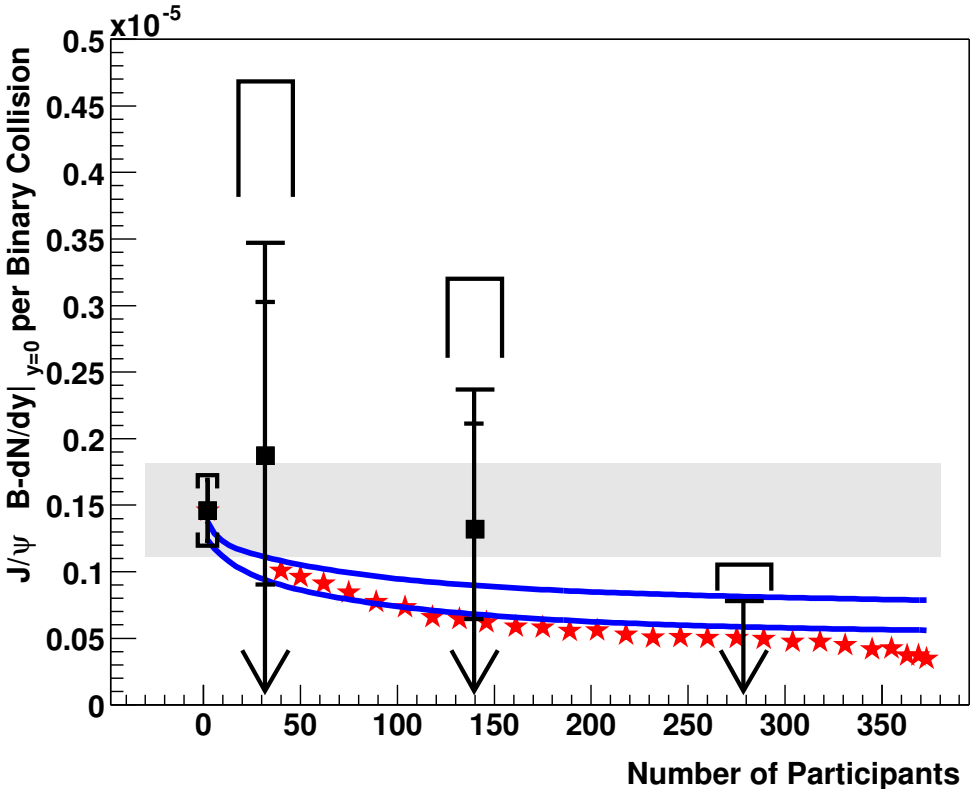
  - RHIC[Phenix]:
  single $e^{\pm}$ p_t spectra
  consistent w/
  $\sigma_{c\bar{c}}(AB) = A.B.\sigma_{c\bar{c}}(pN$

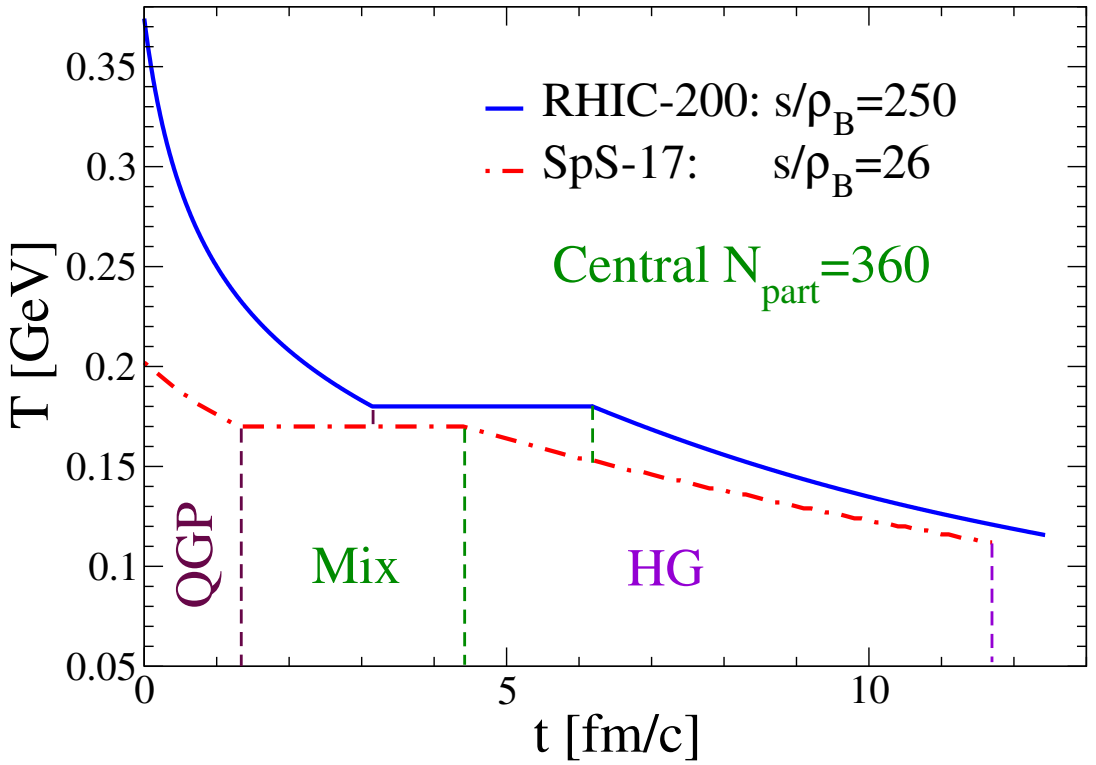


Primordial Charmonium + Pre-Eq. Effects

- pN collisions $\sim 1\%$ of $c\bar{c}$ pairs form a quarkonium state
- pA collisions $\sigma_{J/\Psi}(pA) = A^{\alpha}\sigma_{J/\Psi}(pN)$ $\alpha \simeq 0.92$ [NA50]
- AA collisions $\sigma_{J/\Psi}(AB) = (AB)^{\alpha}\sigma_{J/\Psi}(pN)$
- Glauber: nuclear path length L, $S_{nuclear} = e^{-\rho_0 \sigma_{nuc} L}$, σ_{nuc}=4.4 mb
- nuclear absorption at RHIC (d-AU)





Thermal Fireball Model

- Expanding thermal fireball consistent with:
  - hadro-chemistry
  - hydro-dynamical evolution
  - electromagnetic probes
- Trajectory in (μ_B, T) plane at constant S and N_B
- Quasiparticle-QGP/ resonance-HG equation of state