Charmonium Production in Heavy-Ion Collisions

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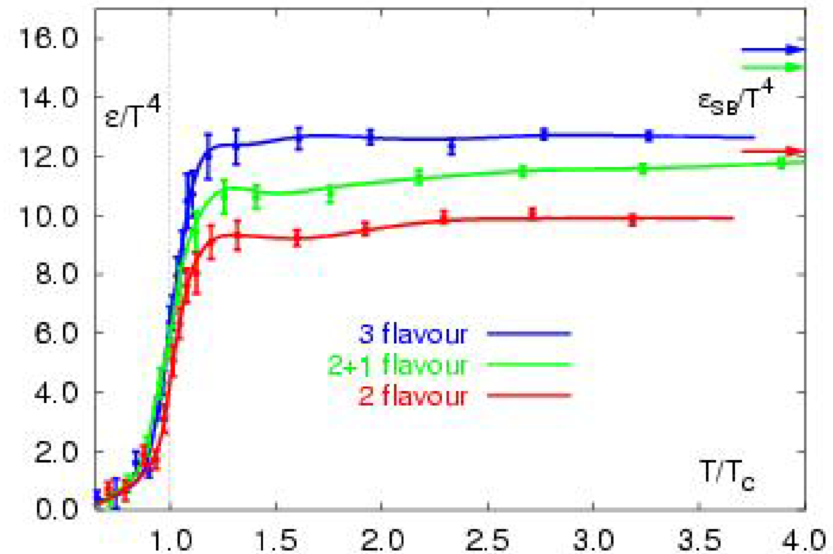
Observing Deconfinement

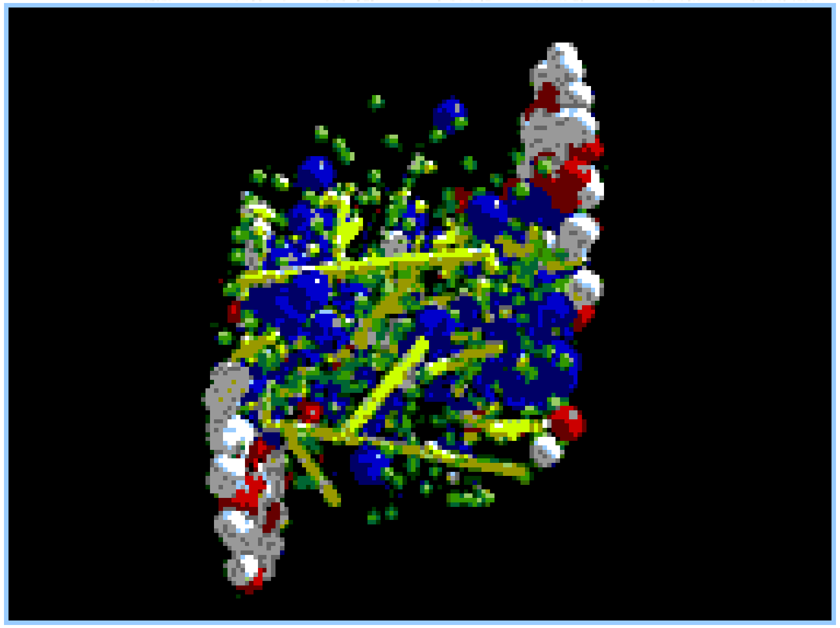
- Lattice QCD
  $T_c \sim 170$ MeV
  $\varepsilon_c \sim 1$ GeV/fm^3



Is the medium produced in HI collisions deconfined in its early stage ?

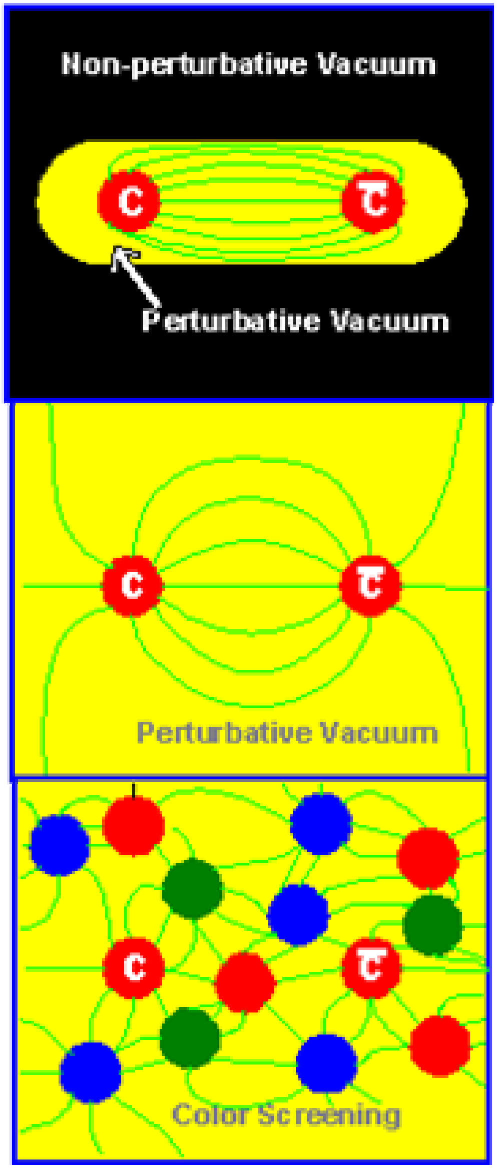
- Deconfinement probe

- present early
- retain memory of collision
- distinguish conf. vs deconf.



Look at the J/Ψ

J/Ψ: a Promising QGP Signature

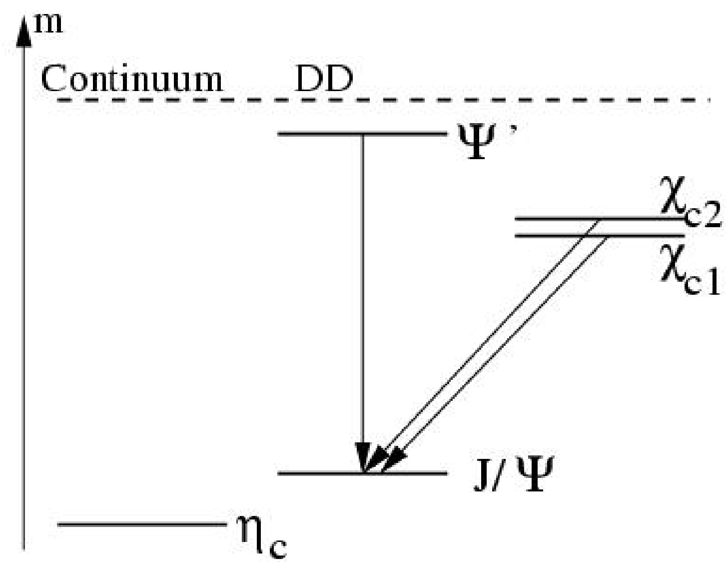


- J/Ψ
  - Small: r ~ 0.2 fm
  - Tightly bound: E_b ~ 640 MeV

$$J/\Psi \rightarrow \boxed{\text{HG}} \rightarrow J/\Psi$$

$$J/\Psi \rightarrow \boxed{\text{QGP}} \rightarrow \cancel{J/\Psi}$$

- Observed in dileptons invariant mass spectrum
- Other charmonia
  - Ψ' ~ 8%
  - χ ~ 32%



Charmonium in HI Collisions

❖ J/Ψ Suppression in plasma

[Matsui & Satz

- Increase wi
- Increase wi
- J/Ψ yield d
  - Cms energy
  - Centrality

❖ Statistical Coalescence at T_c

inger & Stachel '00]

rmalization ?

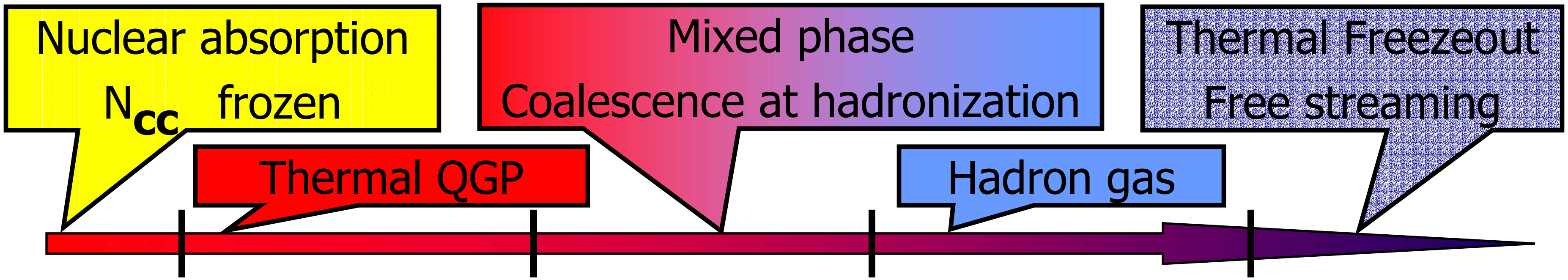
ation of c-quarks

increases with:

- Cms energy
- Centrality

Suppression vs. Regeneration

2-component model



$$N^{dir}_{J/\Psi} \xrightarrow{S_{nuc}\times S_{QG}} \left.\begin{matrix} N^{dir}_{J/\Psi}(T_c) \\ N^{th}_{J/\Psi}(T_c) \end{matrix}\right\} \xrightarrow{S_{HG}} N^{final}_{J/\Psi}$$

Outline

- Motivations/Introduction ☑
- Open charm production
- Direct charmonium production

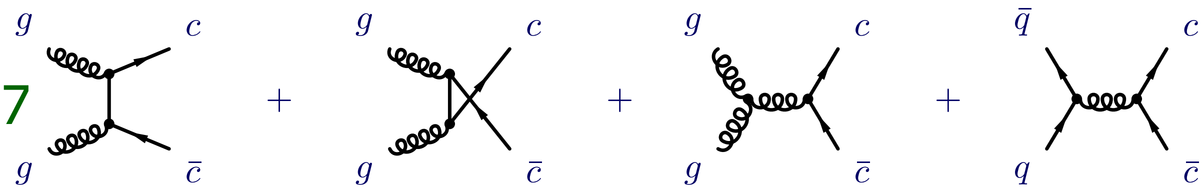
  Nuclear, QGP, Hadronic interactions
- Statistical charmonium production
- Thermal 2-component model

  SPS results, RHIC predictions, excitation function
- In-medium effects

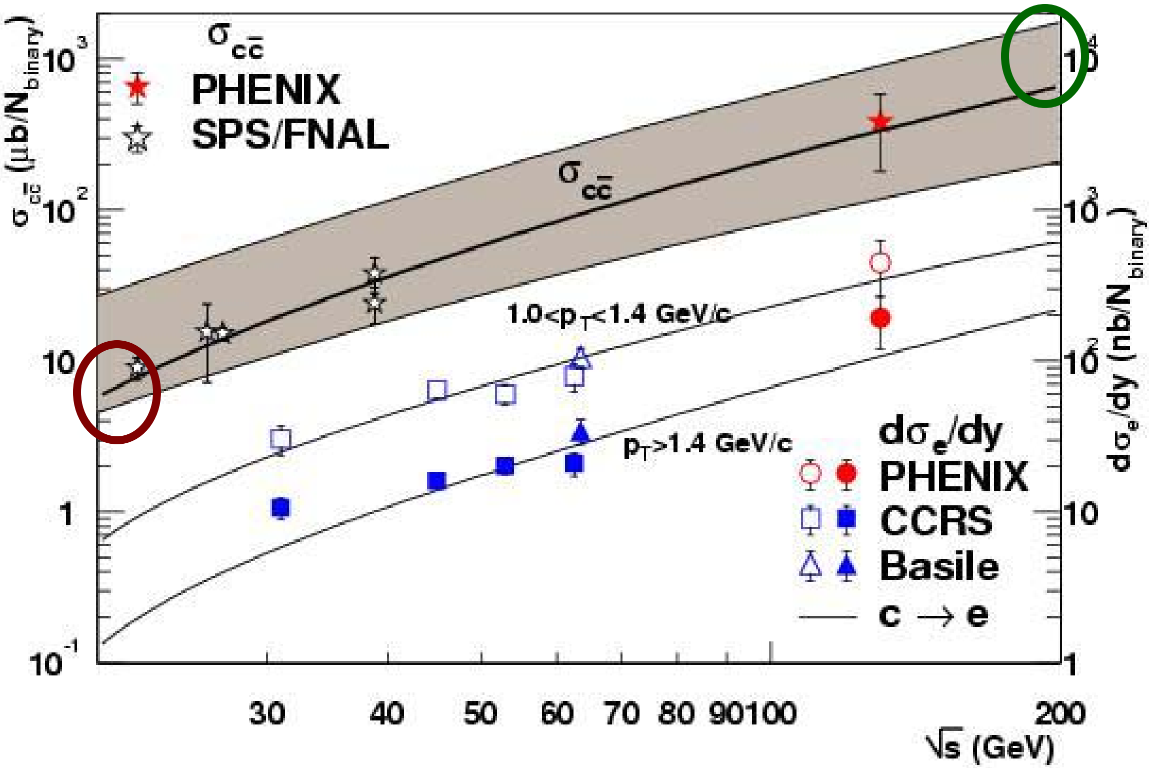
  Lattice QCD, Rate equations
- Conclusions & outlook

Open Charm Production

- NN collisions
  - LO pQCD: K ~ 4-7
  - NLO: K ~ 2-3

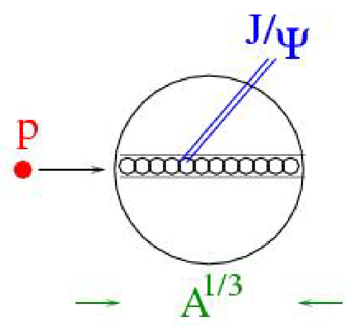


- pA collisions
  - Scaling $\sigma_{c\bar{c}}(pA) = A^{\alpha}\sigma_{c\bar{c}}(pN)$ $\alpha = 1.02 \pm 0.03$ [E789]
- AA collisions
  - SPS central Pb-Pb $N_{c\bar{c}} \sim 0.2$ per collision
  - RHIC central Au-Au $N_{c\bar{c}} \sim 10-20$ per collision



Primordial J/Ψ: Pre-Eq Effects

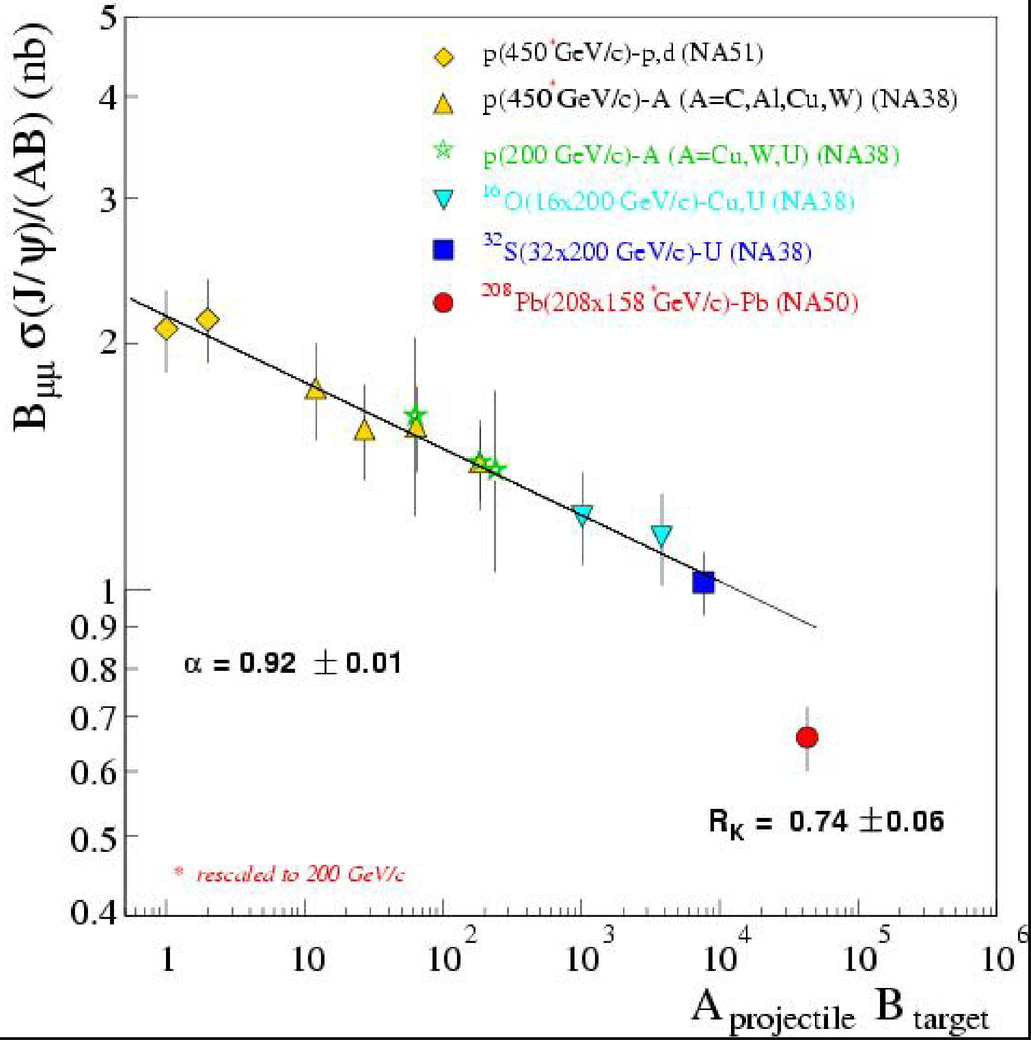
- NN collisions: ~ 1% of cc pairs form a quarkonium state
- pA collisions: $\sigma_{J/\Psi}(pA) = A^{\alpha}\sigma_{J/\Psi}(NN)$ $\alpha \simeq 0.92$ [NA50]
- Nuclear absorption



- AA collisions

$$S_{nuclear} \simeq e^{-\rho_0 \sigma_{nuc} L}$$

- L: nuclear path length
- σ_{nuc}: 4.4 mb
- 50% effect in Pb-Pb at SPS



- RHIC Nuclear absorption ?

Charmonia Interactions in QGP

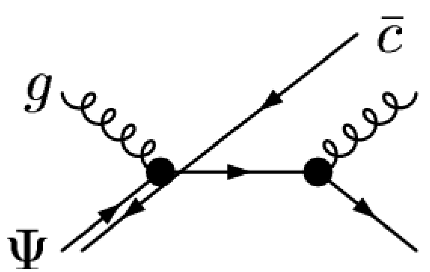
- Schrödinger Eq. + screened cc potential [Karsch et al, '88]

$$V_{c\bar{c}} = \frac{\sigma}{\mu_D}(1 - e^{\mu_D}) - \frac{\alpha}{r} e^{-\mu_D r}, \;\; \mu_D \sim gT \;\; \Rightarrow E_{diss}$$

- Inelastic parton collisions

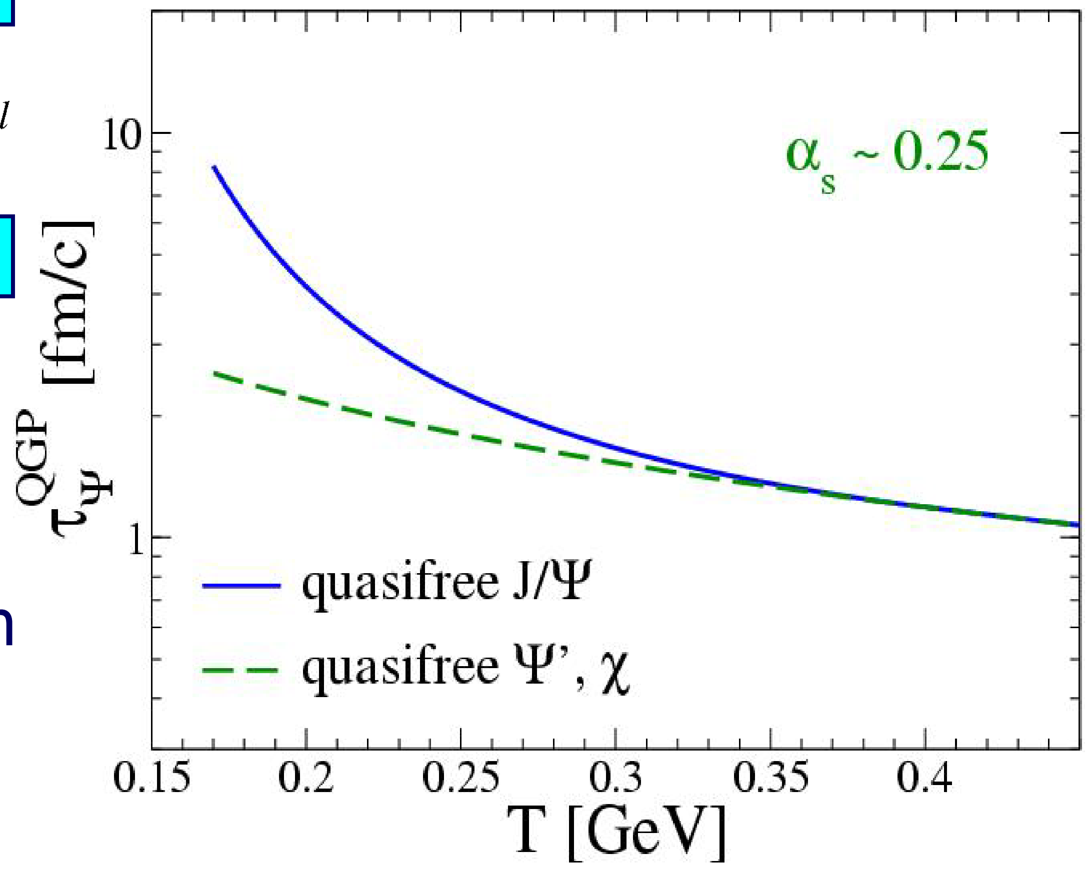
$$(\tau_\Psi)^{-1} = \sum_{i=q,g} \int \frac{d^3k}{(2\pi)^3} f^i(k_0, T) \sigma_\Psi^{QG} v_{rel}$$

- Quasifree approximation



- Convolute over expansion

$$S_\Psi^{QG} = \exp\left(-\int_{\tau_0}^{\tau(T_c)} \frac{d\tau}{\tau_\Psi}\right)$$



Charmonia Interactions in HG

- SU(4) effective Lagrangian [Haglin '99, Lin & Ko '99]

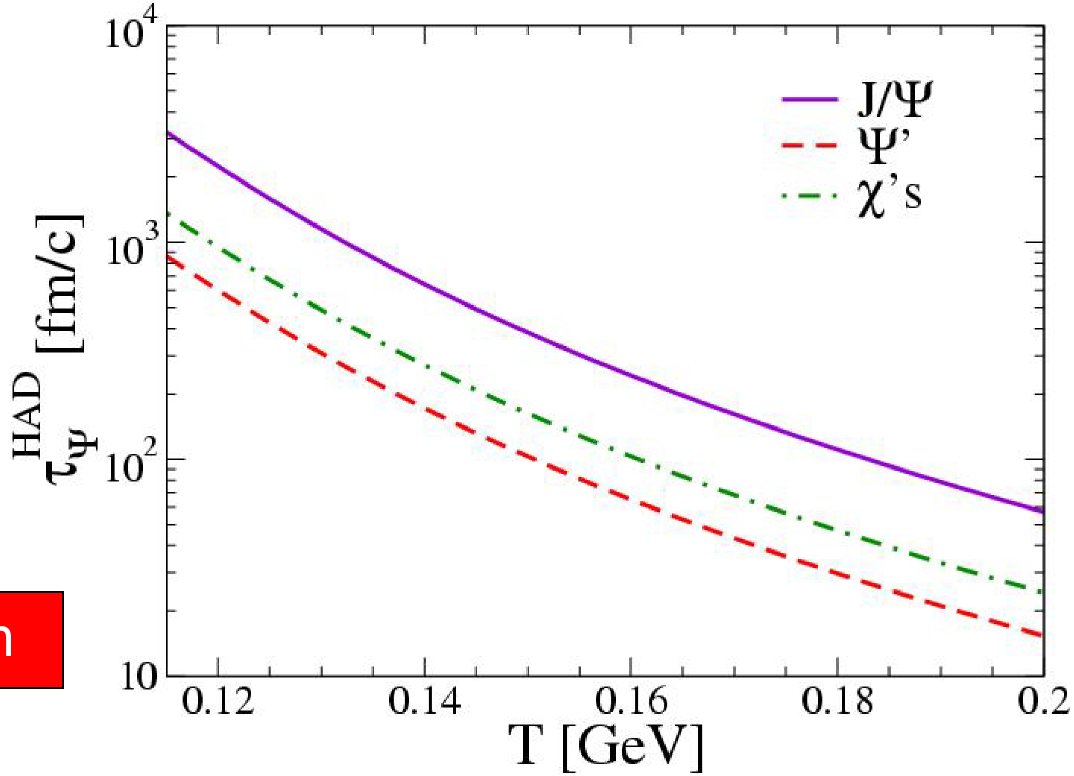
$$J/\Psi + \pi, \rho \rightarrow D\overline{D}^{(*)}$$

- Geometric scaling

$$\left(\frac{r_i}{r_\Psi}\right)^2 \text{ for } i = \Psi', \chi$$

- Form factors Λ = 1 GeV
- Convolute w/ expansion

$$\mathcal{S}_\Psi^{HG} = \exp\left(-\int_{\tau(T_c)}^{\tau_{fo}} d\tau/\tau_\Psi^{HG}\right)$$



- Small hadronic suppression

- Direct J/Ψ's

$$N_{J/\Psi}^{dir}(b) = \sigma_{pp}^{J/\Psi} A B T_{AB}(b) \mathcal{S}_{nuc}(0.6\mathcal{S}^{J/\Psi} + 0.08\mathcal{S}^{\Psi'} + 0.32\mathcal{S}^{\chi})$$

Statistical J/Ψ Production at T_c

- Charm states populated according to thermal phase space at chemical freeze-out (V_H,T_c)

$$n = \frac{d}{2\pi^2}\int_0^\infty p^2 dp (\exp(\frac{\sqrt{p^2+m^2}-\mu}{T}) \pm 1)^{-1}$$

- Thermal densities: $n_{op} = \sum n_i, \quad i = D, D^*, \cdots$

$$n_{hid} = \sum n_j, \quad j = \eta_c, \Psi, \cdots$$

- Ncc from primordial (hard) production
  - c-quark fugacity γ_c solution of

$$N_{c\bar{c}} = \frac{1}{2}\gamma_c V_H n_{op} \frac{I_1(\gamma_c V_H n_{op})}{I_0(\gamma_c V_H n_{op})} + \gamma_c^2 V_H n_{hid}$$

- γ_c : 0.8 → 6 from SPS to RHIC
- Statistical J/Ψ's

$$\boxed{N^{th}_{J/\Psi} = V_H \gamma_c^2 \left[n_{J/\Psi}(T_c) + \sum_j \mathcal{BR}_{j\to J/\Psi} n_j(T_c) \right] \mathcal{R}}$$

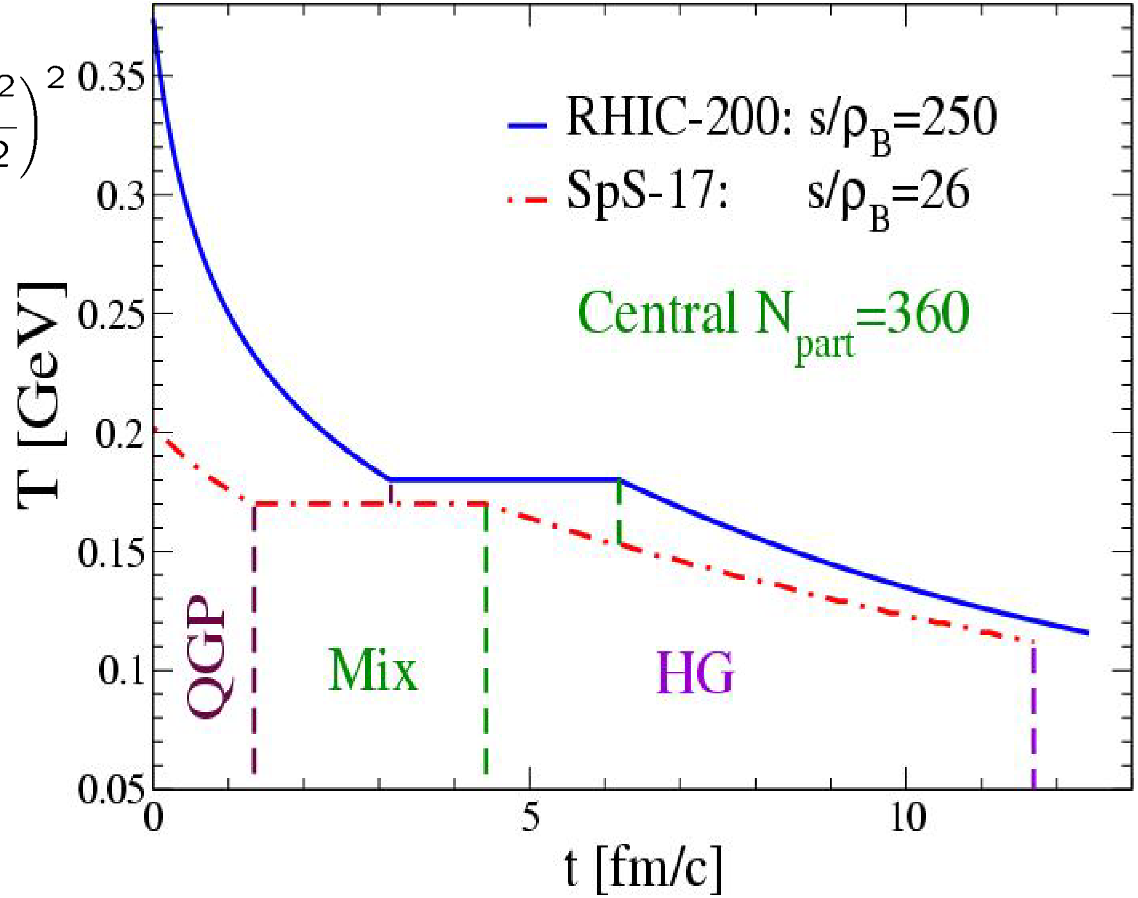
- Thermal equilibration of charm ?
  - Relaxation time approach $\quad \mathcal{R} = (1 - \exp(-\int d\tau/\tau_{eq})) < 1$

Thermal Fireball evolution

- Expanding thermal fireball
  - Trajectory in (μ_B, T) plane at constant *S* and N_B
  - Quasiparticle-QGP / resonance HG equation of state
- Cylindrical expansion

$$V = 2\left(z_0 + v_\parallel t + a_\parallel \frac{t^2}{2}\right)\pi\left(r_\perp + a_\perp \frac{t^2}{2}\right)^2$$

- Parameters fitted to
  - Final flow velocities
  - Hadro-chemistry
- Consistency with
  - Chemistry
  - Hydrodynamics
  - Dilepton yields

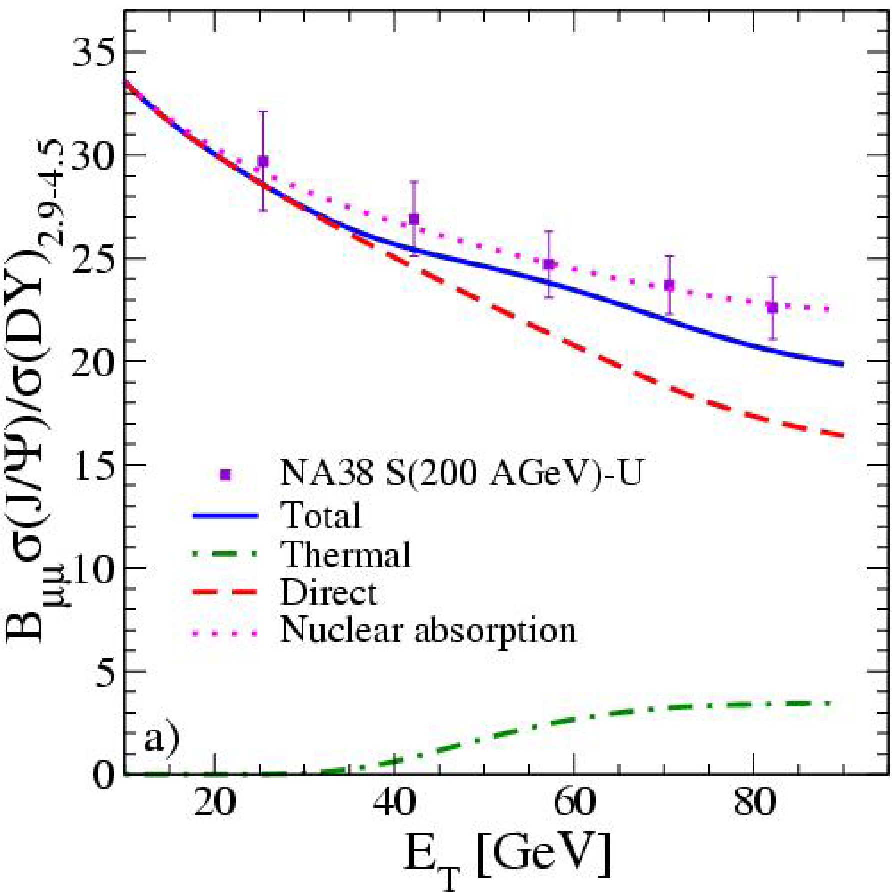


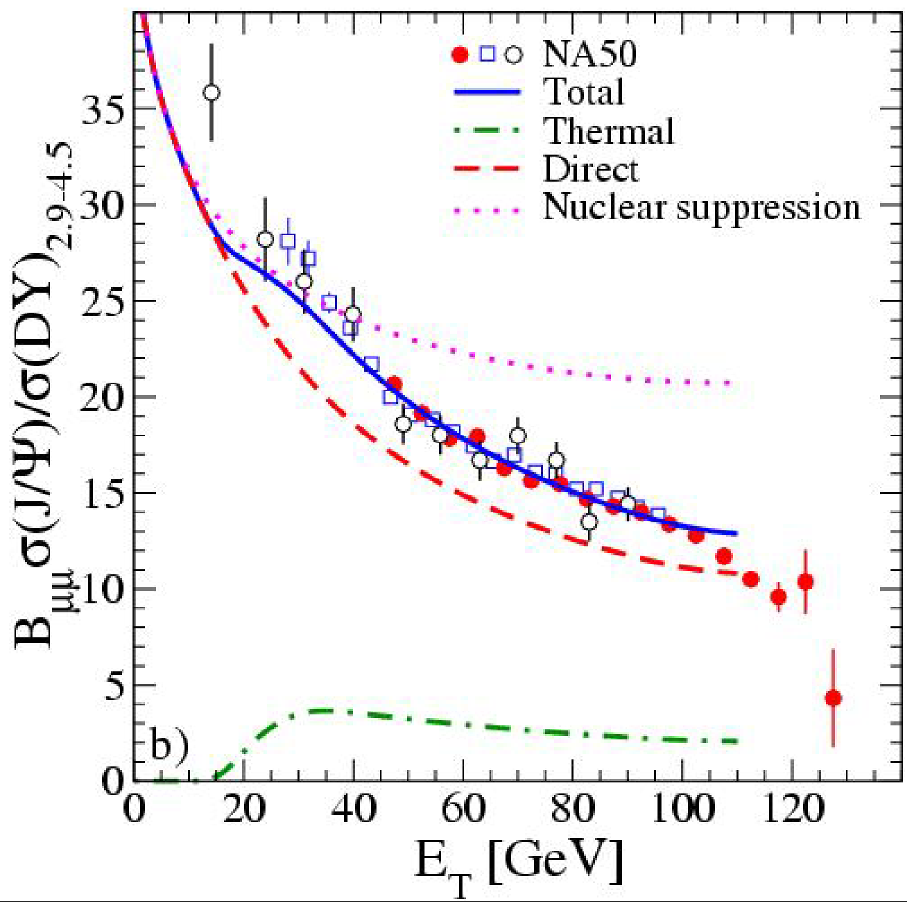
Centrality Dependence at SPS

$$N_{J/\Psi} = N^{dir}_{J/\Psi} + N^{th}_{J/\Psi}$$

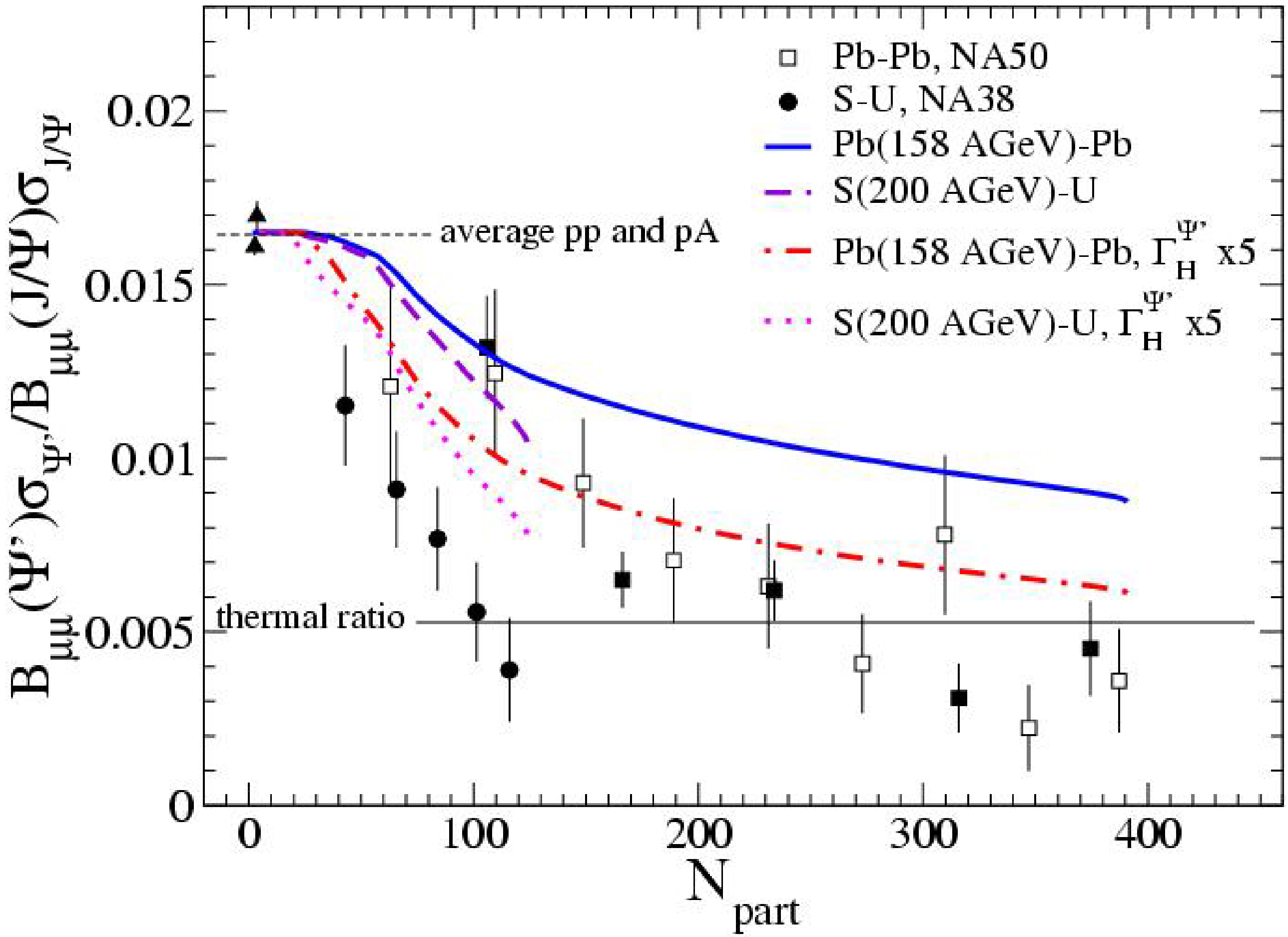
$$\boxed{N^{0}_{J/\Psi} S_{nuc} S_{QG} S_{HG}} \qquad \boxed{N^{th}_{J/\Psi}(T_c) S_{HG}}$$

- Thermal production $\leftrightarrow$ QGP onset
- Moderate contribution at SPS
  Assuming no cc enhancement





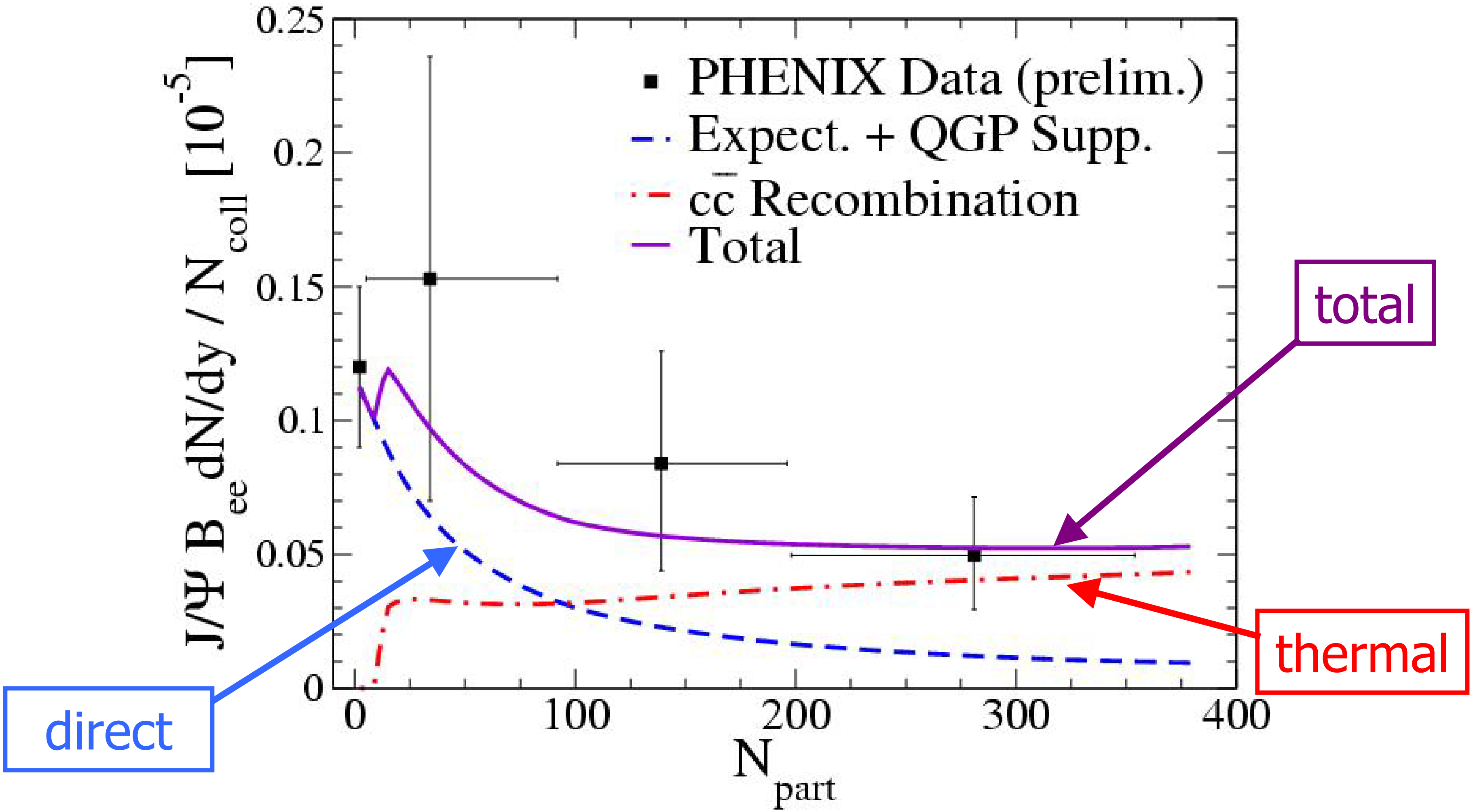
Ψ'/Ψ Ratio



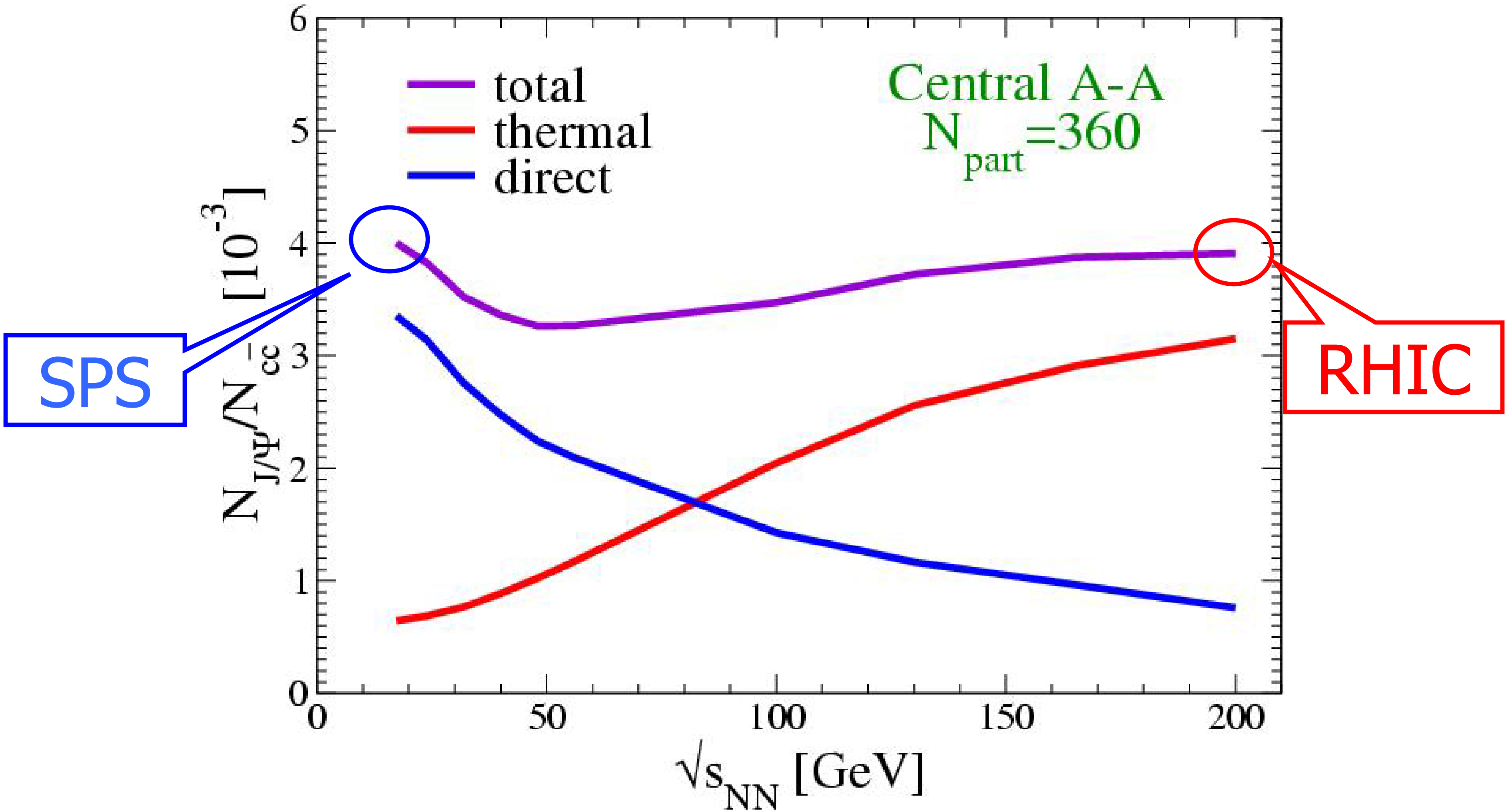
- Suggestive for strong Ψ' dissociation in HG
- Hadronic in-medium effects ?
  - χ –restoration ↔ lower DD threshold → Ψ' above threshold

Centrality Dependence at RHIC

- Thermal J/Ψ's dominate for central collisions
- Composition direct vs. thermal very different from SPS



Excitation Function

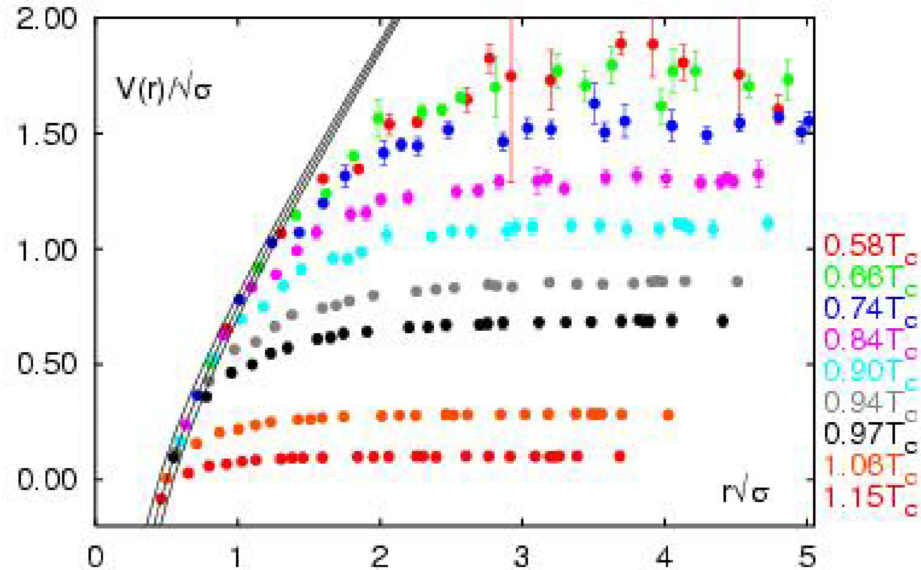


- Transition "direct suppressed" → "statistical"

minimum at $\sqrt{s} \sim (50 - 100)$ GeV

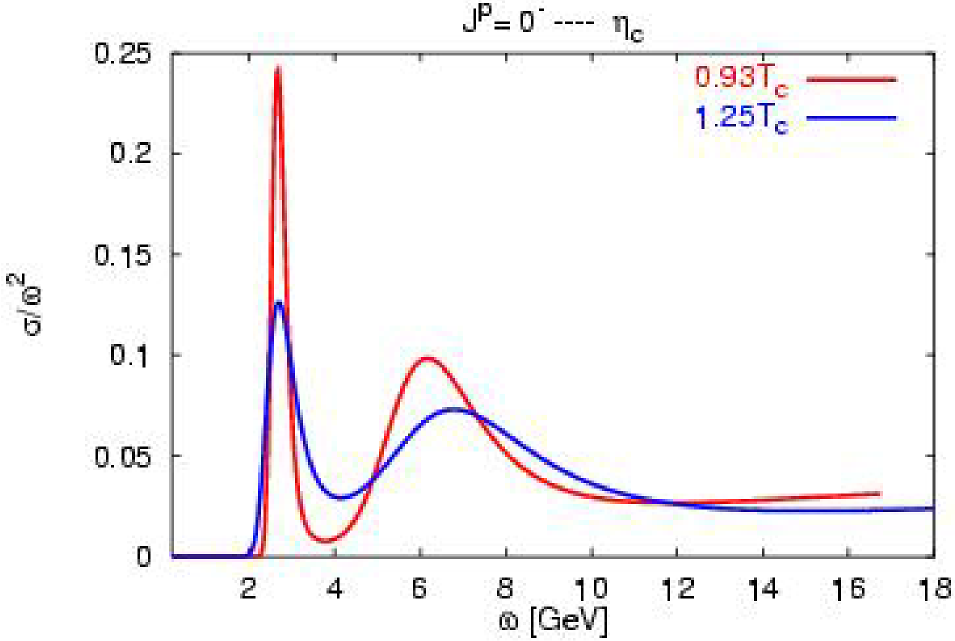
In-Medium Effects

- Lattice QCD heavy quark Free energy [Karsch et al. '00]
  - Reduction of the open charm threshold
  - Even below T_c
  - Smooth transition across T_c



- Spectral functions from Lattice [Karsch et al. '02]
  - Low-lying charmonia survive in the QGP
  - Mass ≡ constant
  - Large width increase across T_c

  [Umeda et al. '02]

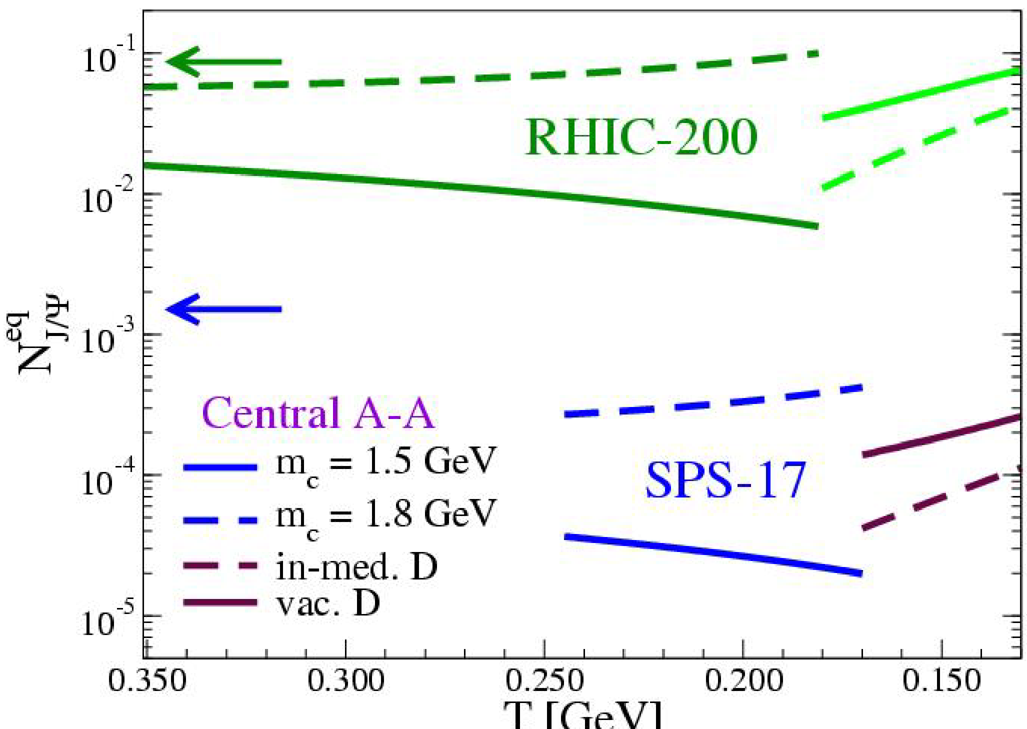


Charm in Matter

❖ J/Ψ Equilibrium abundances

- In-medium charm quark mass
- In-medium D-meson mass

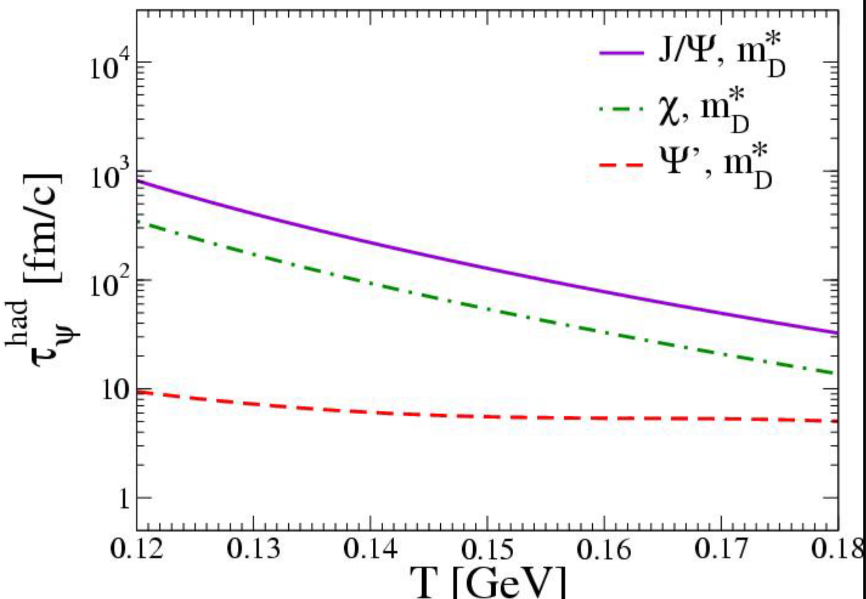
$N^{eq}_{J/\Psi}$ very sensitive to $m^*_{c,D}$



❖ Lower DD threshold

- Increases inelastic reactions

$$\Psi' \rightarrow D\,\overline{D}$$

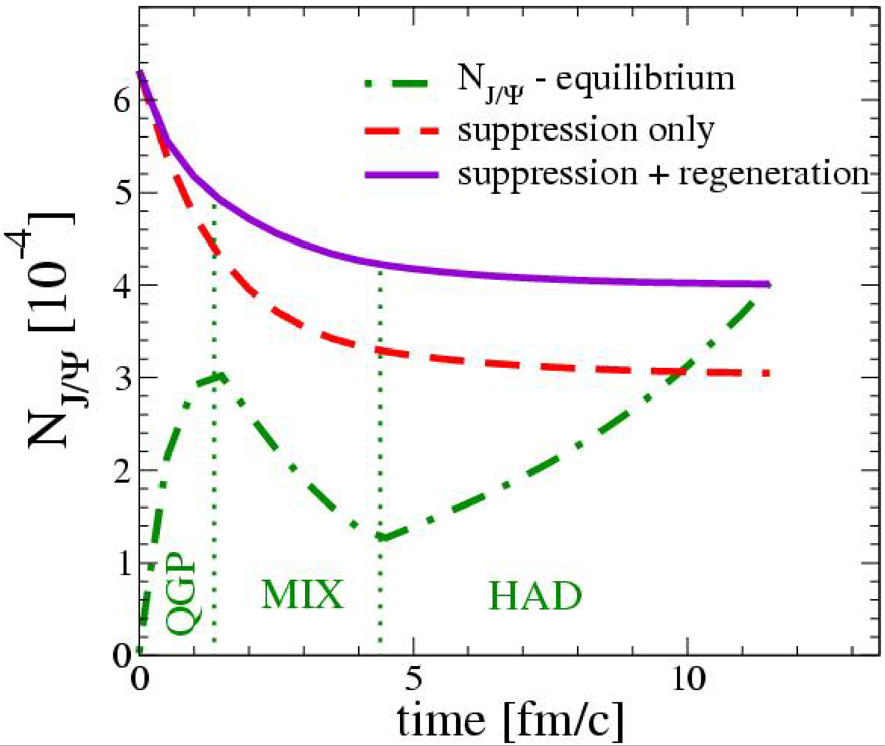


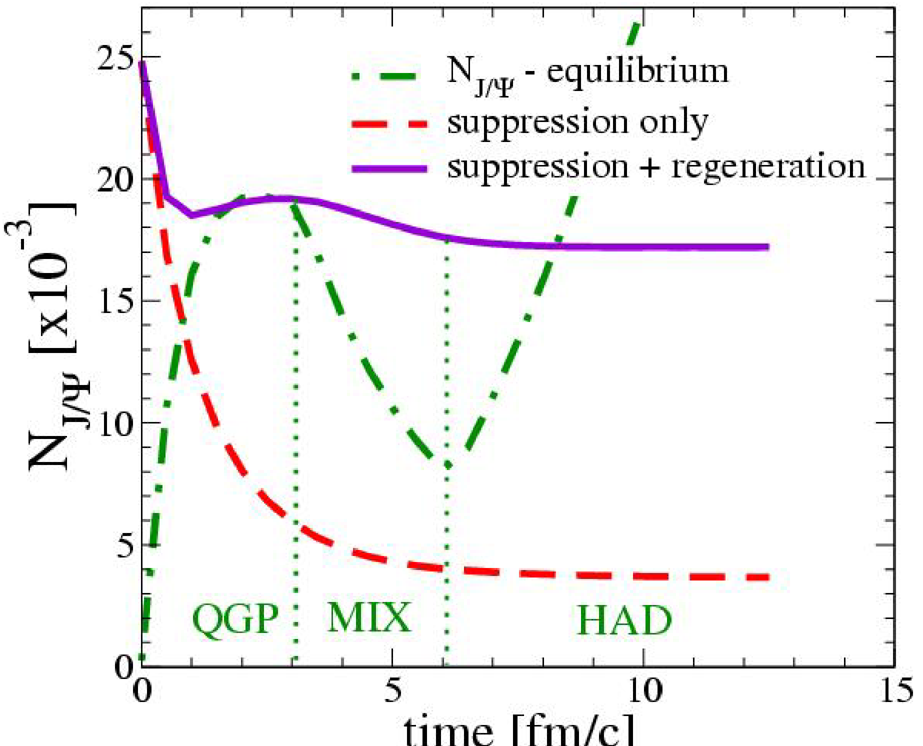
Kinetic Evolution in HI Collisions

- Kinetic approach – Rate equations:

$$\frac{dN_\Psi}{d\tau} = -\frac{1}{\tau_\Psi}\left[N_\Psi - N_\Psi^{eq}\right]$$

- τ_Ψ, N_Ψ^{eq} include in-medium effects
- Off-equilibrium features in the evolution
  - Chemical off-equilibrium: γ_c
  - local charm conservation: V_{corr}
  - Incomplete thermalization



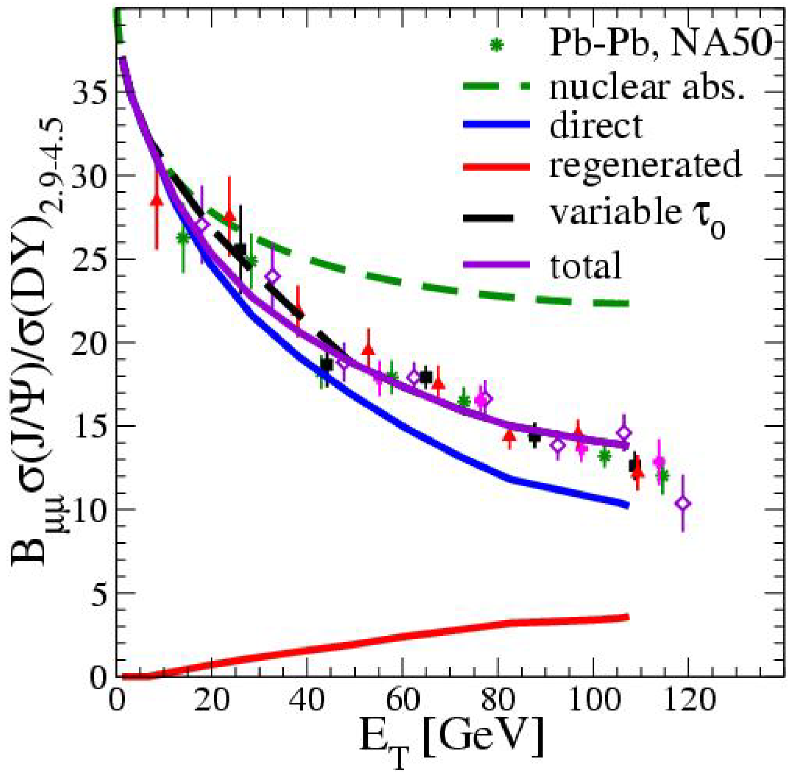


SPS Results

❖ J/Ψ centrality dependence

$$N_\Psi^{hard} >> N_\Psi^{eq}$$

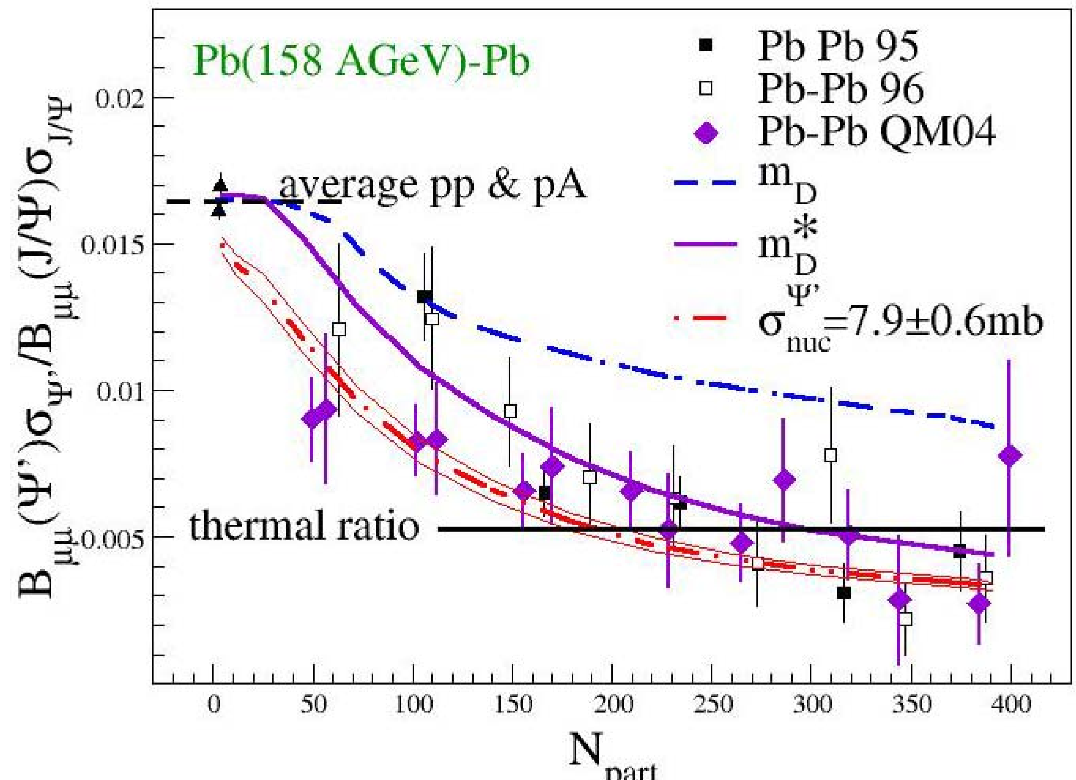
Suppression



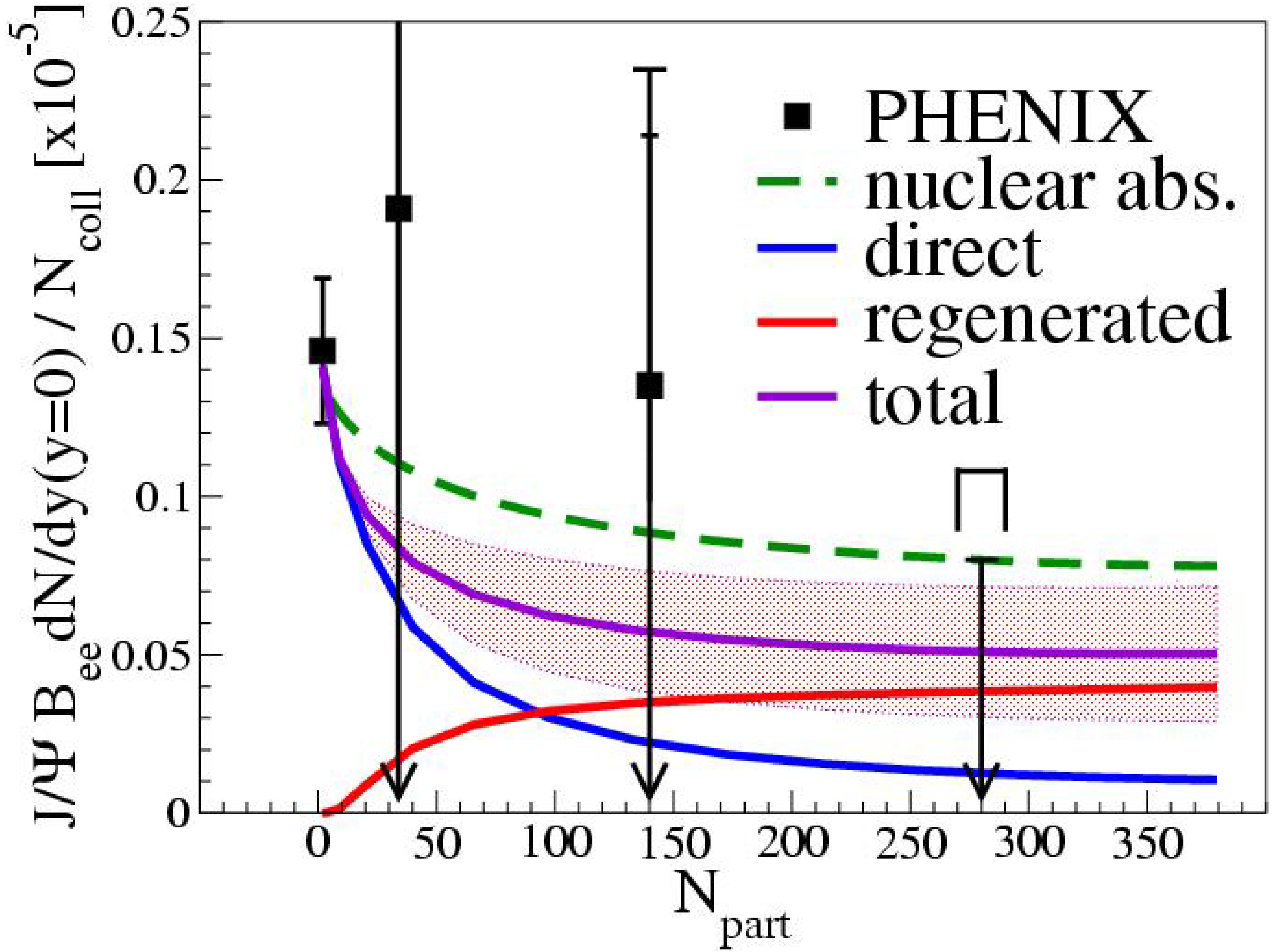
❖ Ψ'/Ψ ratio

$$\Psi' \rightarrow D\overline{D}$$

Medium effects crucial



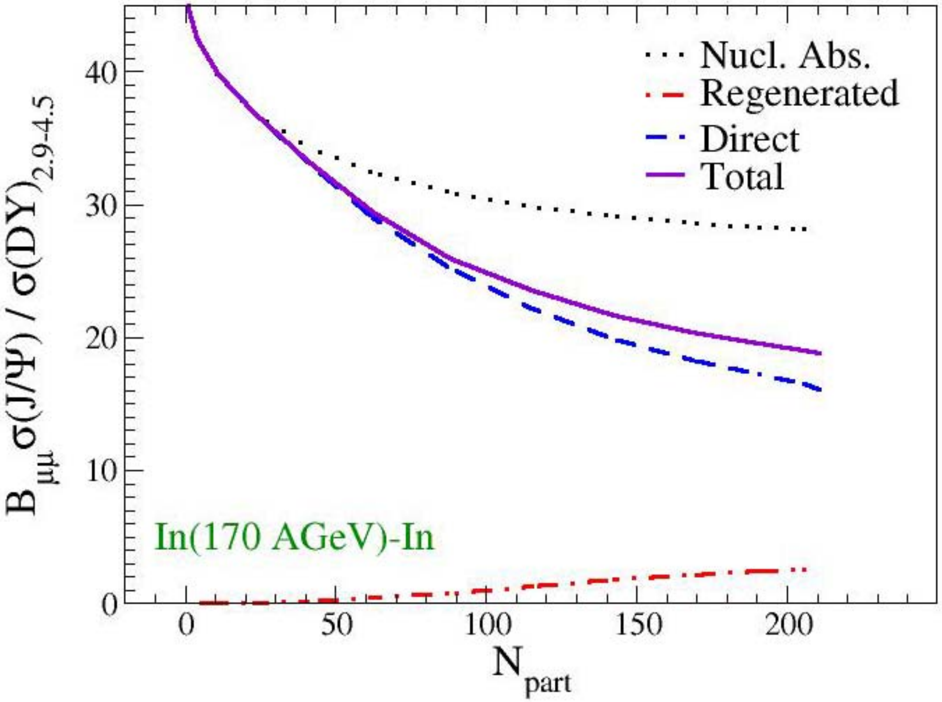
RHIC Results

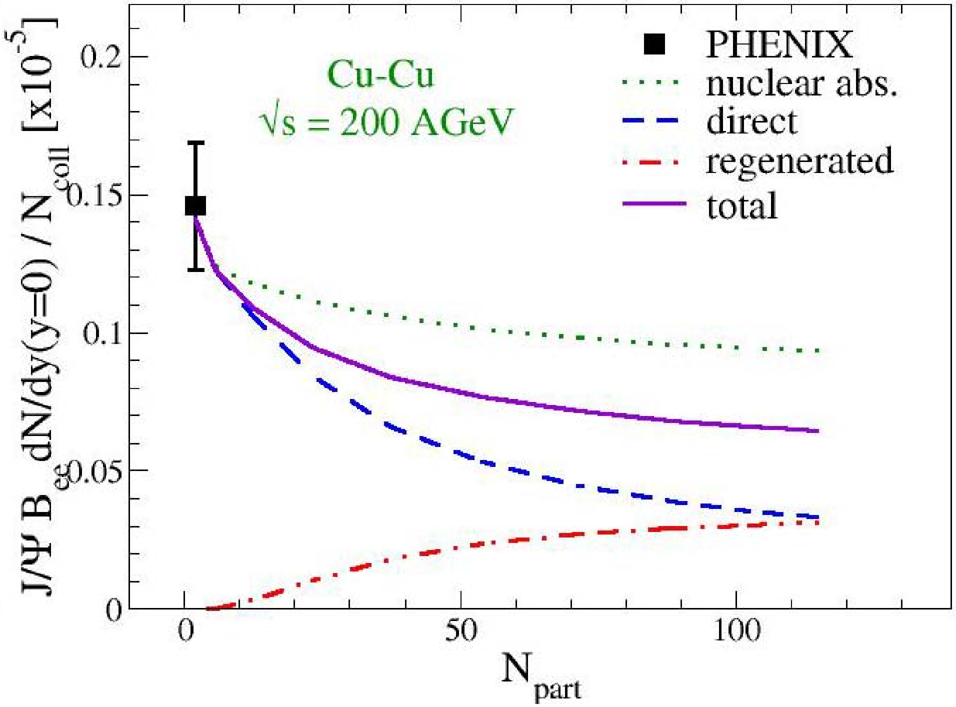


❖ Sensitivity to the magnitude of in-medium effects

Systematics

❖ Energy & system size dependence





Conclusions

- Thermal 2-component approach for charmonium production
  - "Direct" J/Ψ 's
    - QGP: Debye screening & parton diss. $\Rightarrow$ quasifree
    - HG: SU(4) effective theory + geometric scaling
  - "Statistical" J/Ψ 's (no open charm enhancement)
  - Common thermal evolution scenario
  - Consistent with SPS data and preliminary RHIC results
- J/Ψ excitation function
  - "direct suppressed" (SPS) $\Rightarrow$ "statistical coalescence" (RHIC)
- Improved approach
  - In-medium effects inferred from Lattice QCD
    - J/Ψ regeneration in QGP / open-charm threshold reduced
  - Improves the Ψ'/Ψ ratio description

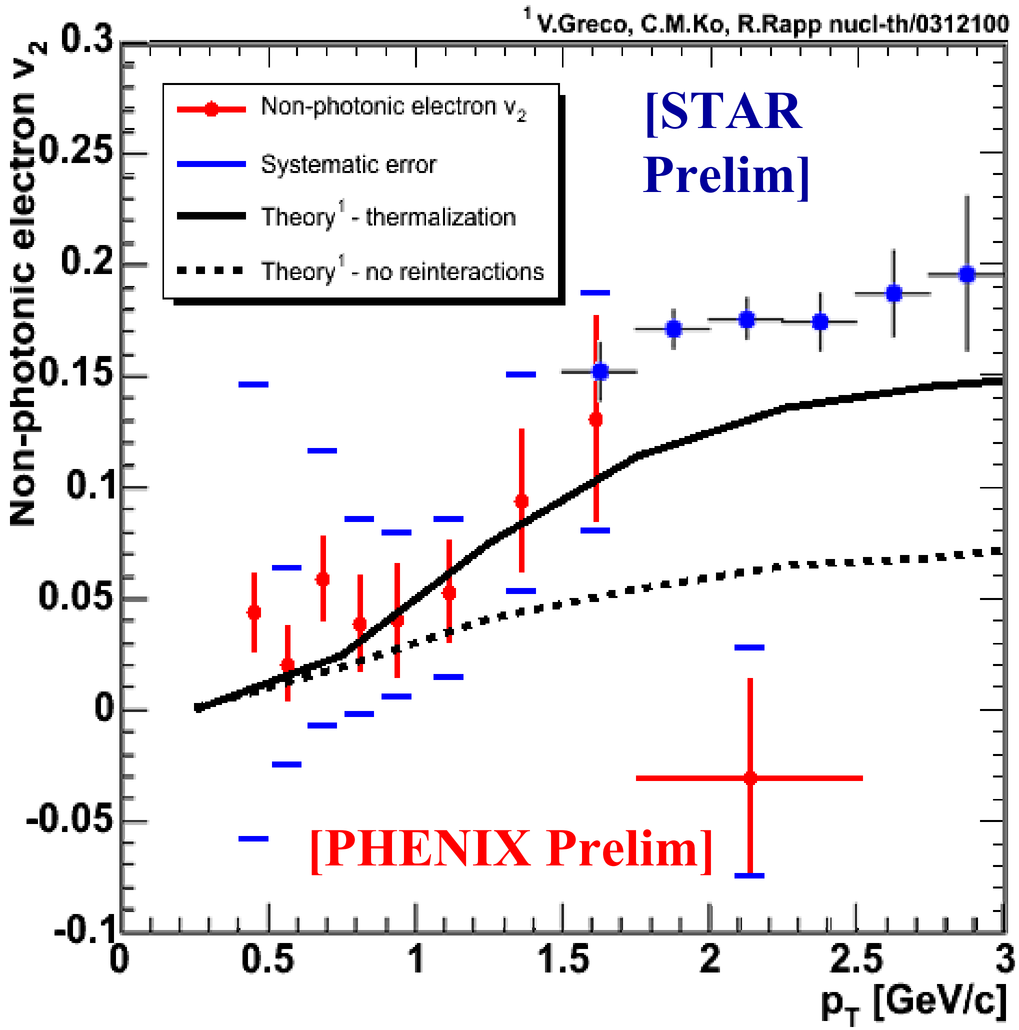
J/Ψ suppression
SPS

QGP formation

J/Ψ regeneration
RHIC

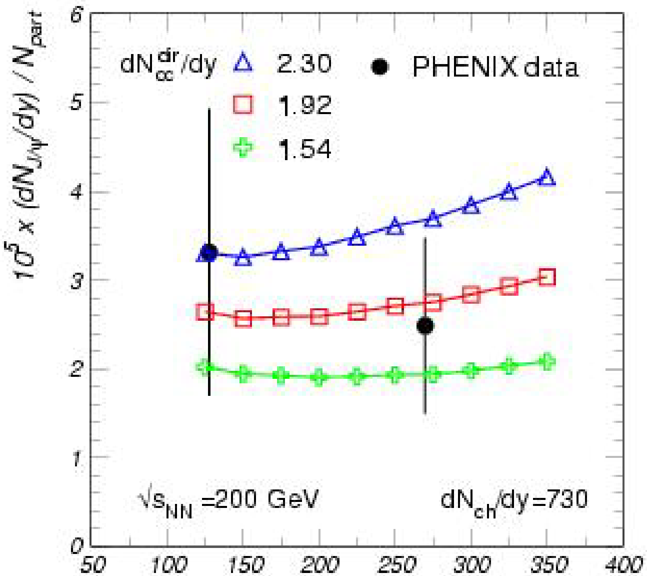
Outlook

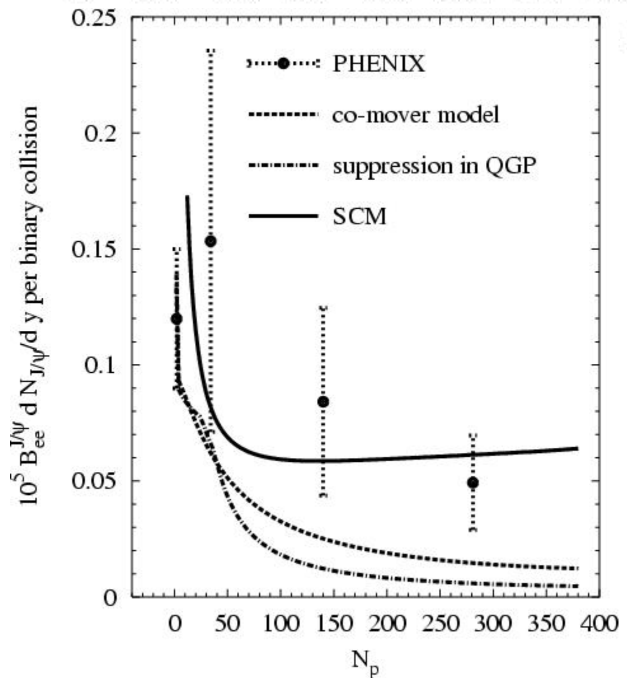
- Observables to disentangle mechanisms
  - Charm chemistry
  - P_T spectra
  - c (D) elliptic flow
  - Excitation function
- Bottomonium system
- LHC

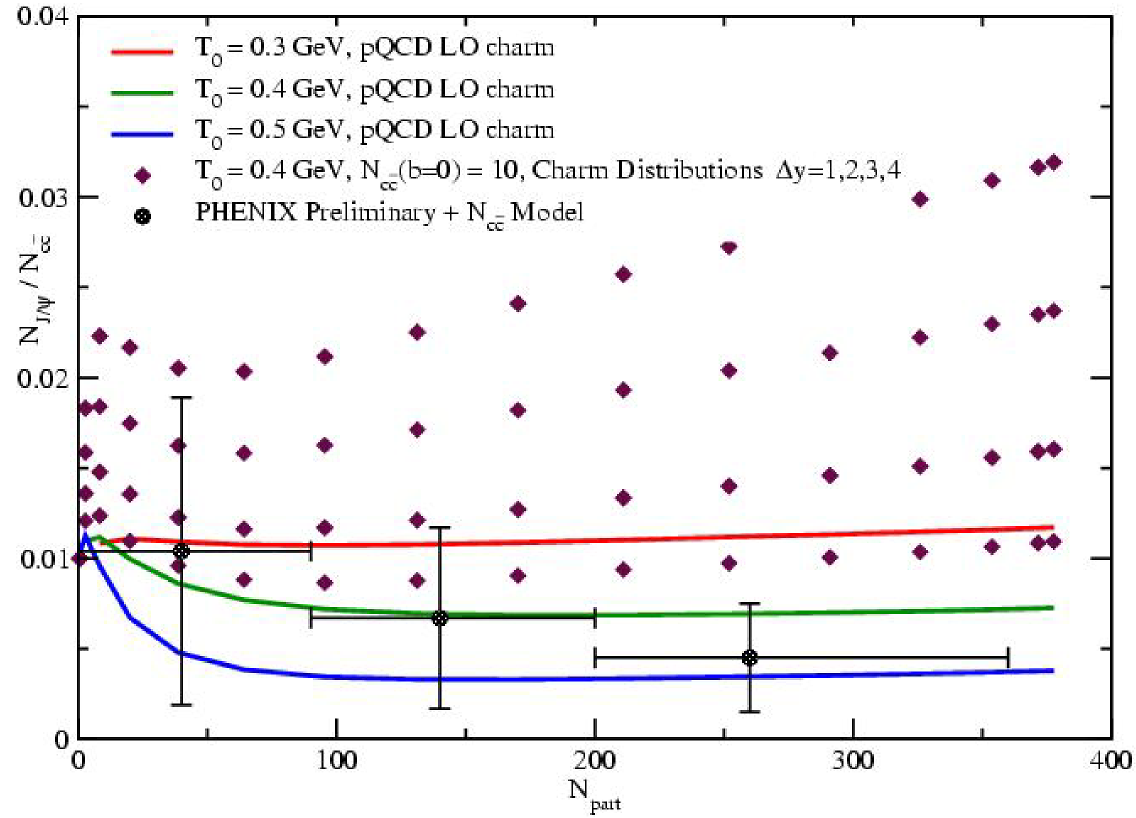


Extra Slides

Model Comparison at RHIC







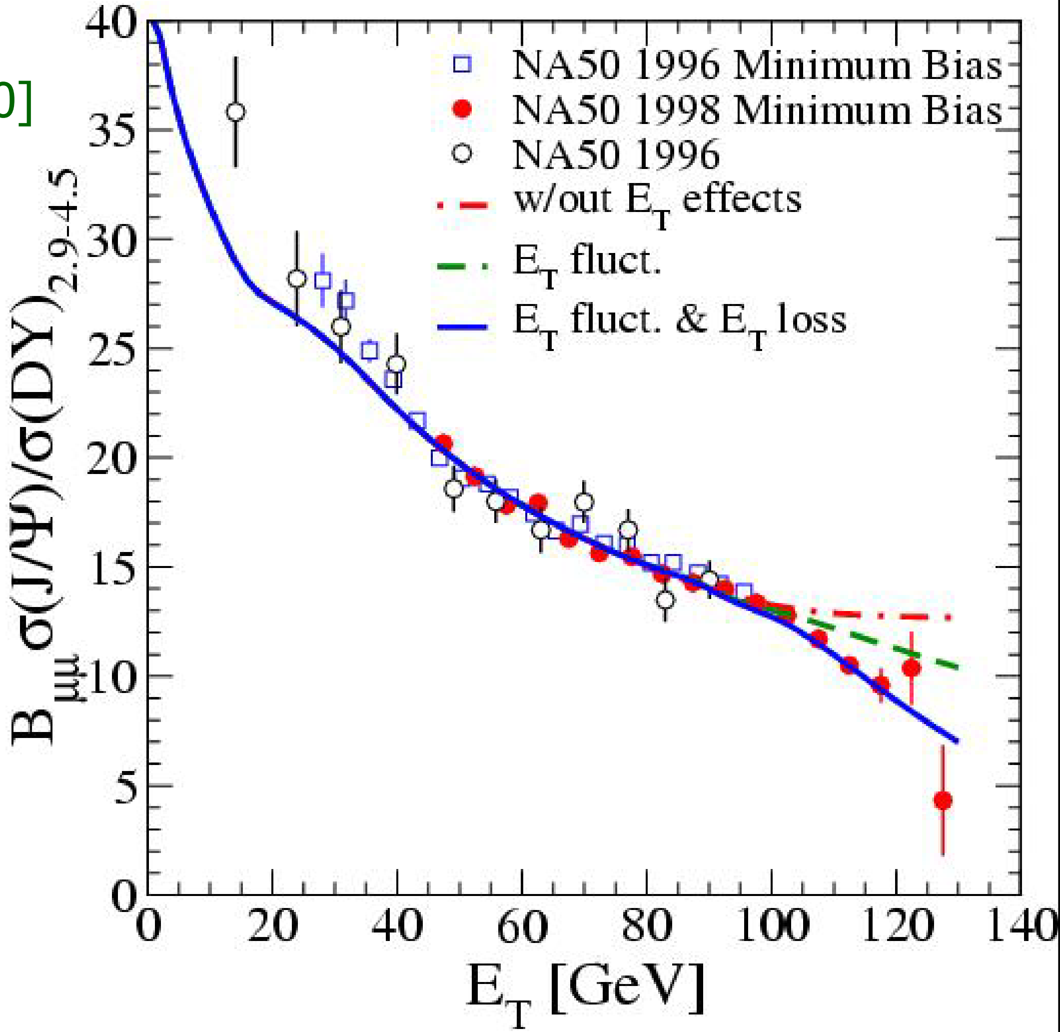
High E_T Effects in NA50

- Transverse energy fluctuations at b=0
  - [Capella, Ferreiro & Kaidalov '00]
  - [Blaizot, Dinh & Ollitrault '00]
- ET > 100 GeV

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

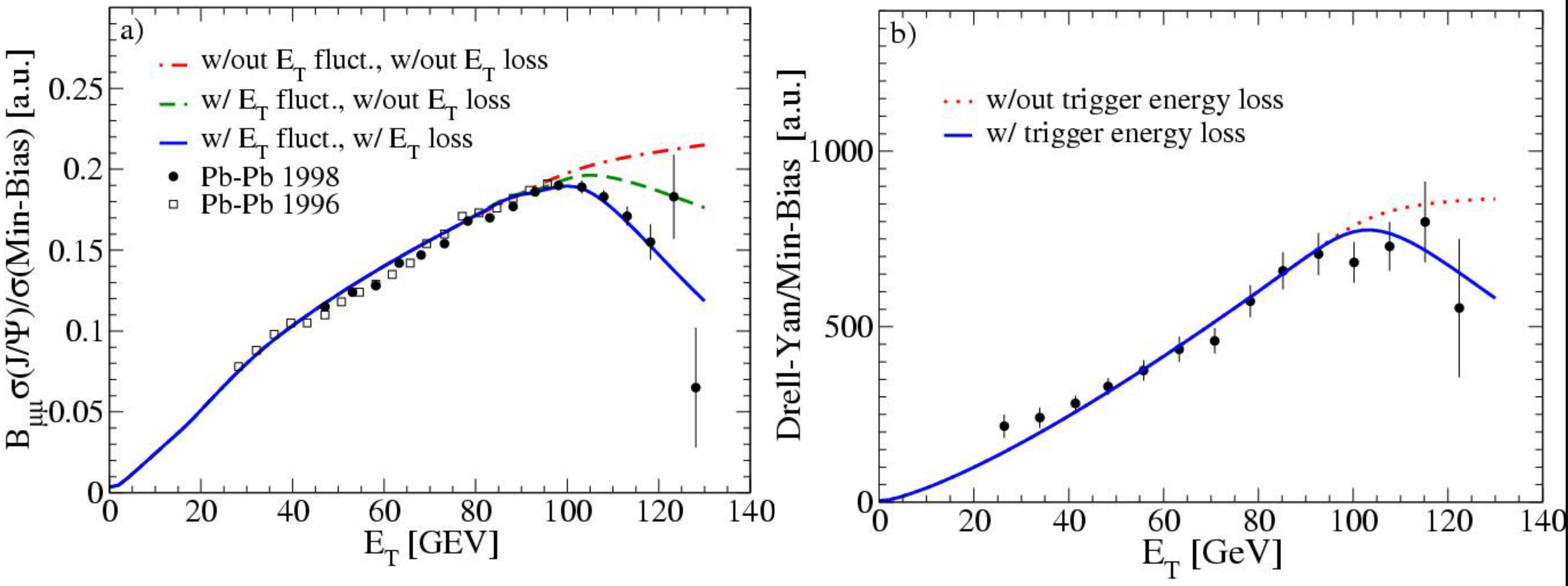
  - Extra suppression
- Minimum Bias analysis
  - [Capella, Kaidalov & Sousa '01]
  - Trigger energy loss ?

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

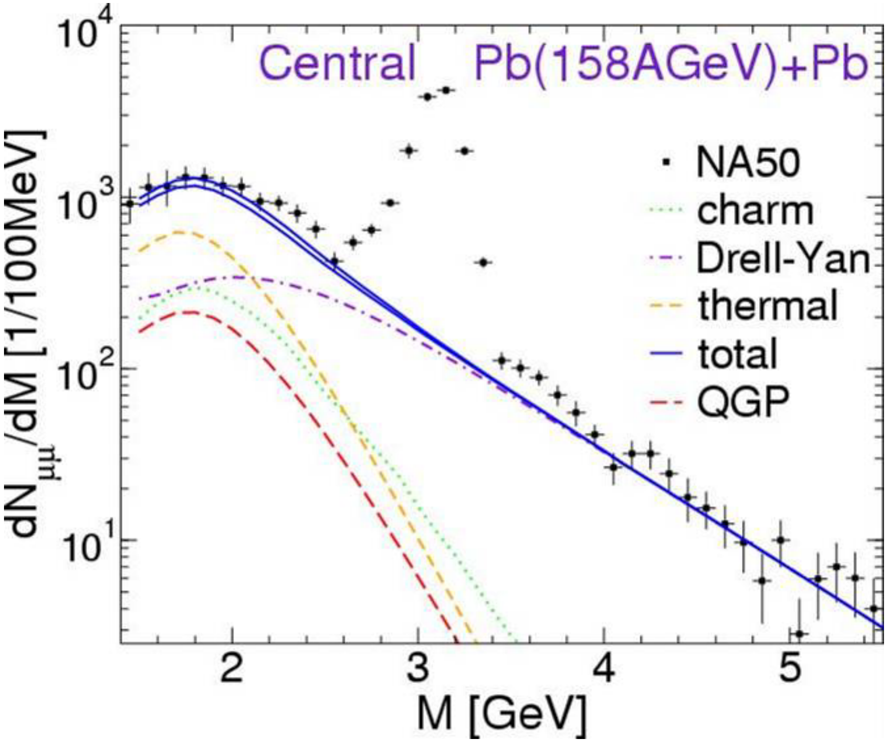


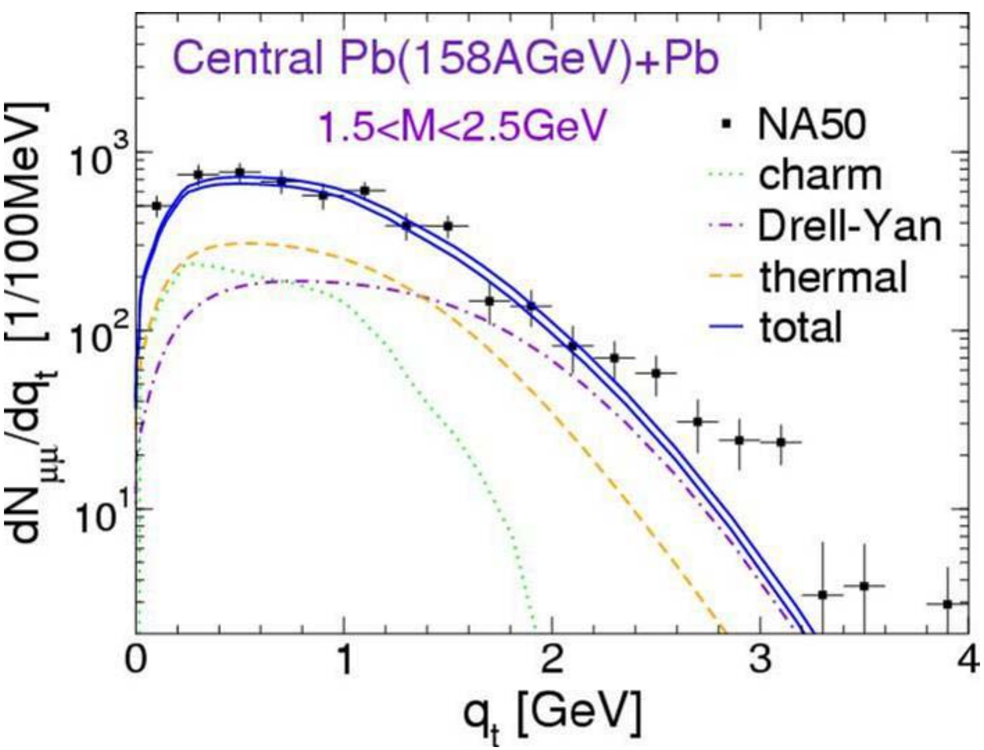
Minimum Bias Analysis

$$\left.\frac{\sigma_{J/\Psi}}{\sigma_{DY}}\right|_{Min.Bias} = \left.\frac{\sigma_{J/\Psi}}{\sigma_{MB}}\right|_{exp.} \times \left.\frac{\sigma_{DY}}{\sigma_{MB}}\right|_{th}^{-1}$$

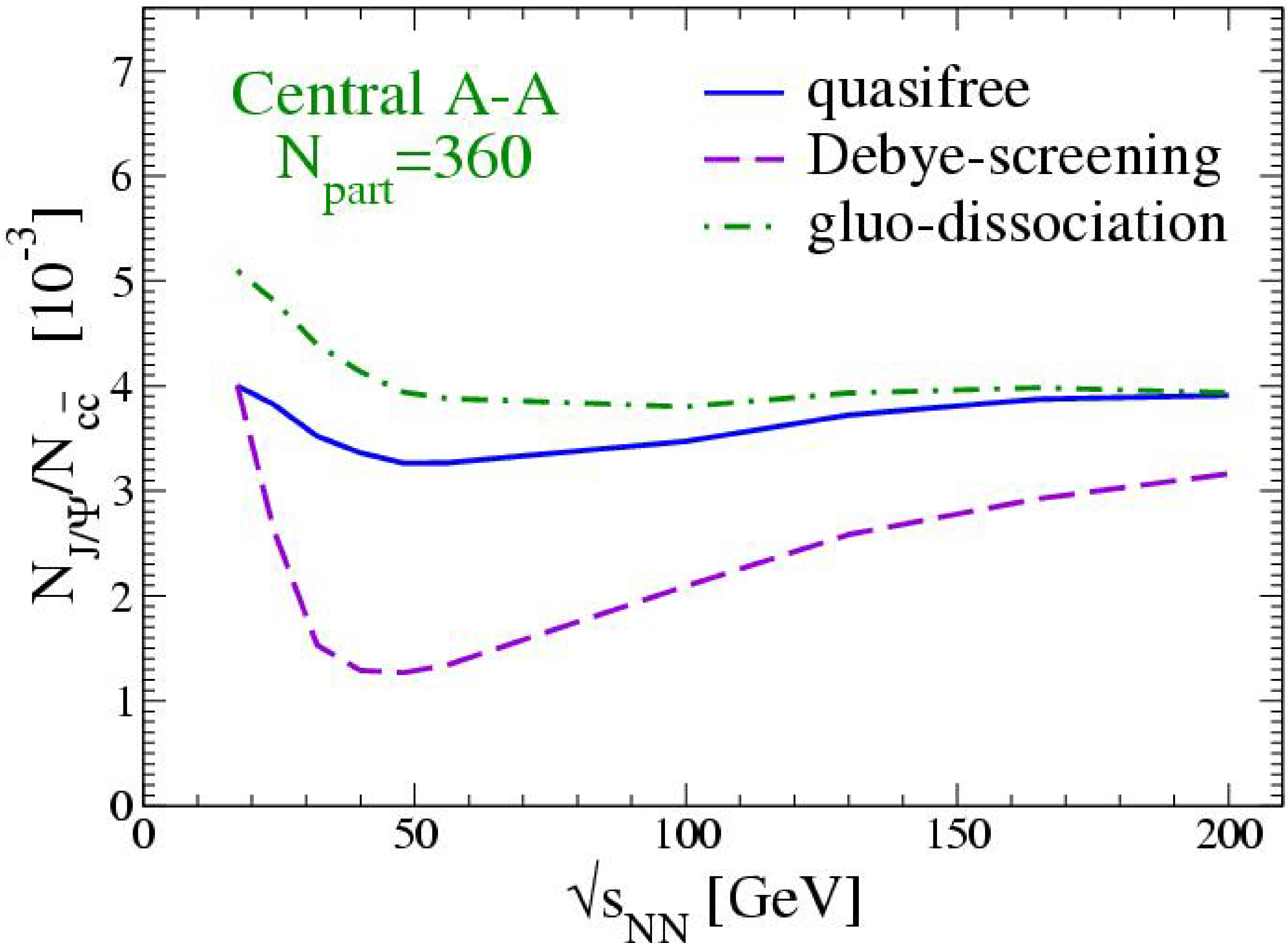


Dilepton Spectra

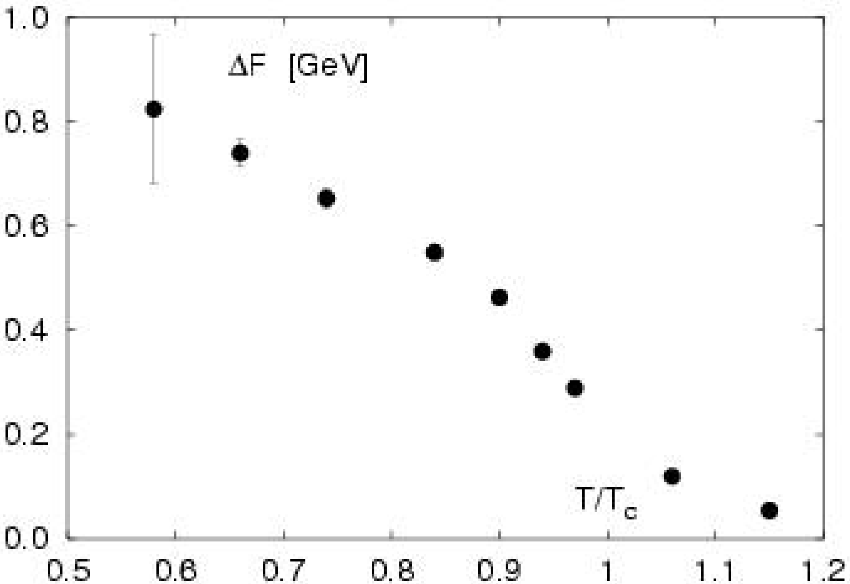


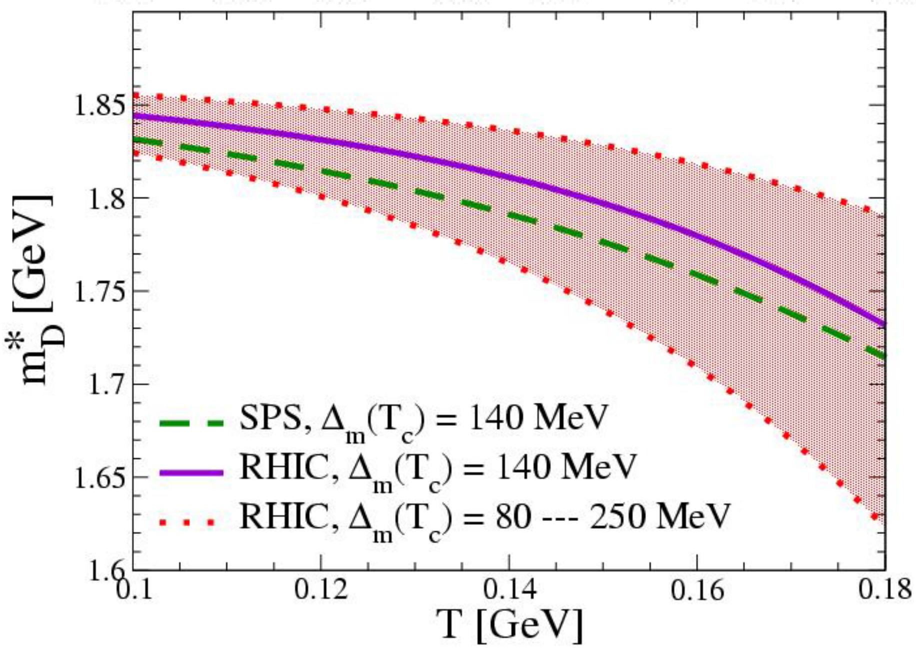


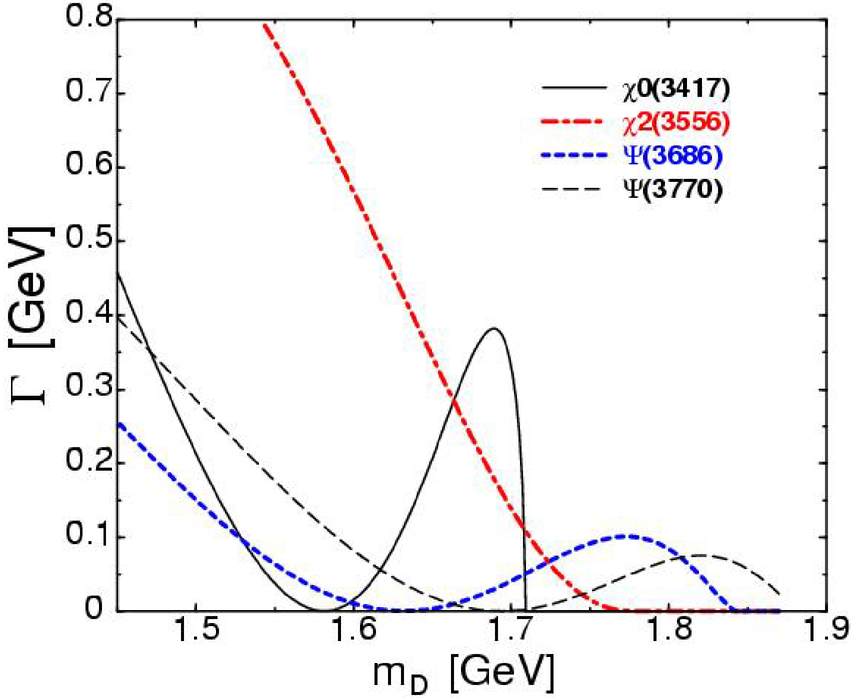
Other QGP Suppression Mechanisms



In-Medium Effects - II







Indium Predictions for NA60