QUARKONIUM FORMATION IN STATISTICAL AND KINETIC MODELS

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WHAT DO HEAVY FLAVORS PROVIDE?

MASS SCALES: M_c = 1.5 GeV, M_b = 5.0 GeV

DISTANCE SCALES: 0.07 fm, 0.02 fm

BOUND STATE SCALES: 0.30 fm, 0.13 fm

HARD PROBES: $M_Q >> \Lambda_{QCD}$

CALCULATIONS: LO + NLO pQCD

NUCLEAR COLLISIONS:
SHADOWING, SATURATION, k_t broadening

POINTLIKE PROCESS: SCALES WITH BINARY COLLISIONS:

$$N_{coll} \propto N_p^{\frac{4}{3}}$$

QUARKONIUM FORMATION

MATSUI-SATZ: $R_{\text{plasma screening}} < R_{\text{quarkonium}}$: SUPPRESSION

KHARZEEV-SATZ: Ionization with deconfined gluons

NA50: Anomalous Suppression

ALTERNATIVES: Dense hadronic medium, comovers

M. Sitta (NA50), hep-ex/0405056

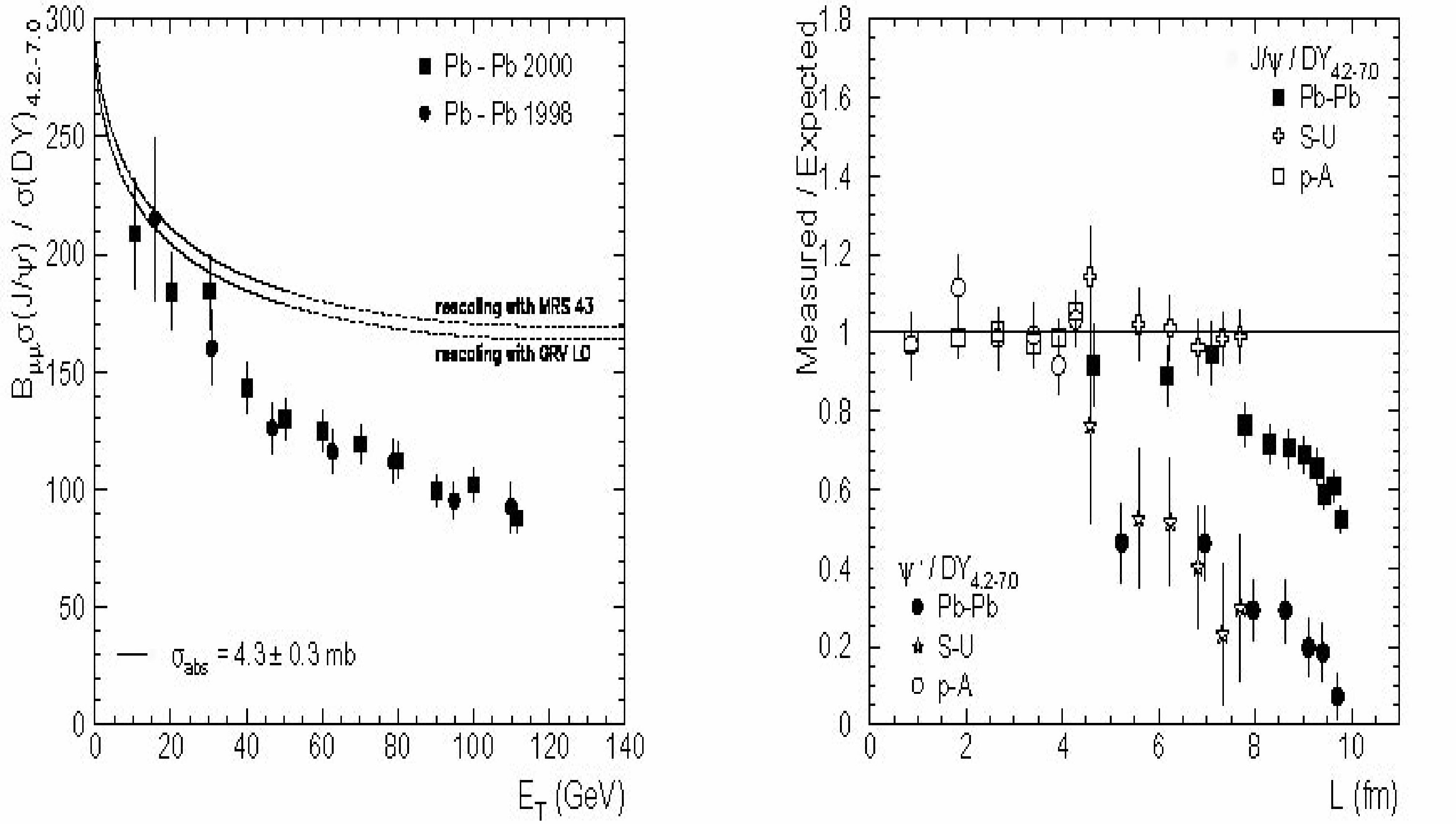


Figure 3: $B_{\mu\mu}\sigma(J/\psi)/\sigma(DY)$ as a function of E_T (left) and the ratio "measured value"/"expected value" for the relative yields $B_{\mu\mu}\sigma(J/\psi)/\sigma(DY)$ and $B'_{\mu\mu}\sigma(\psi')/\sigma(DY)$ as a function of L (right).

Multiple ccbar pairs in high energy AA Collisions

$$N_{c\bar{c}}(b=0) \approx 30\sigma_{c\bar{c}}^{pp}(mb)$$

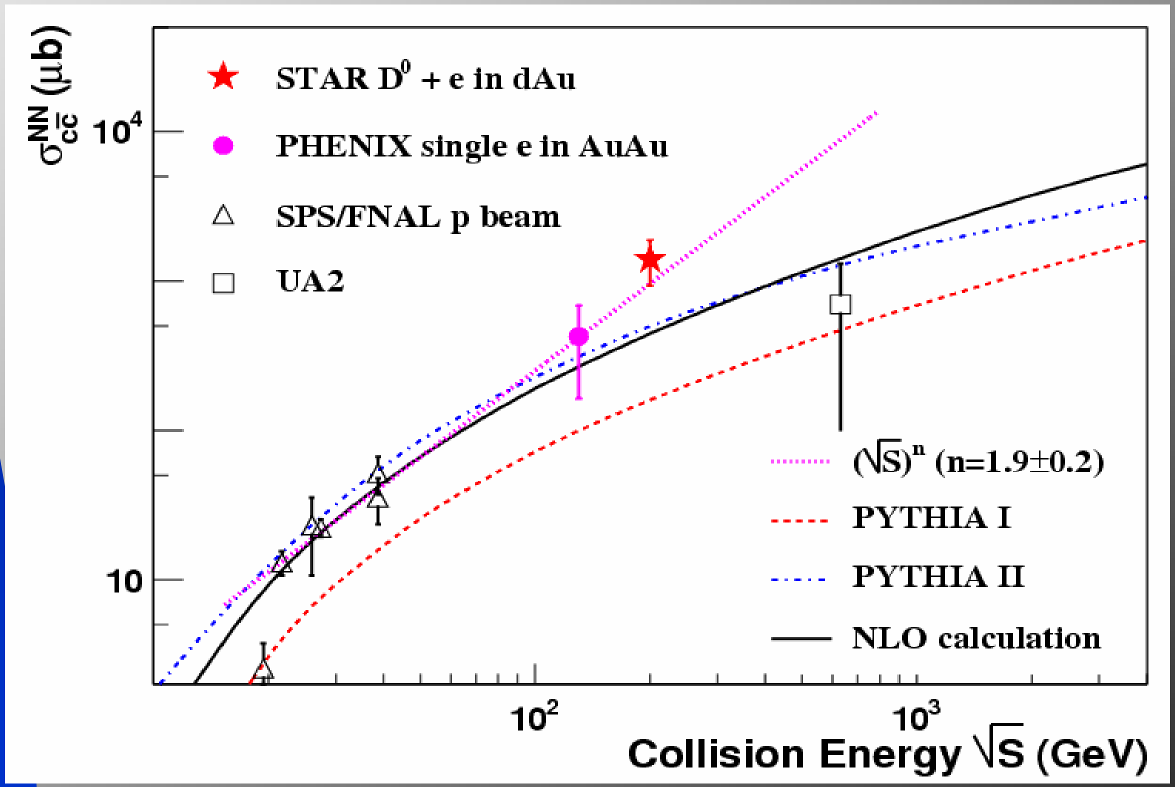
CENTRAL VALUES:

- 10-15 from extrapolation of low energy
- 20 from PHENIX electrons
- 40 from STAR electrons and Kπ

$$709 \pm 85 \pm {}^{332}_{281} \mu b$$: PHENIX nucl-ex/0403057 (pp)

$$622 \pm 57 \pm 160 \mu b$$: PHENIX nucl-ex/0409028 (Au-Au)

$$1.4 \pm 0.2 \pm 0.4\, mb$$: STAR nucl-ex/0407006 (d-Au)



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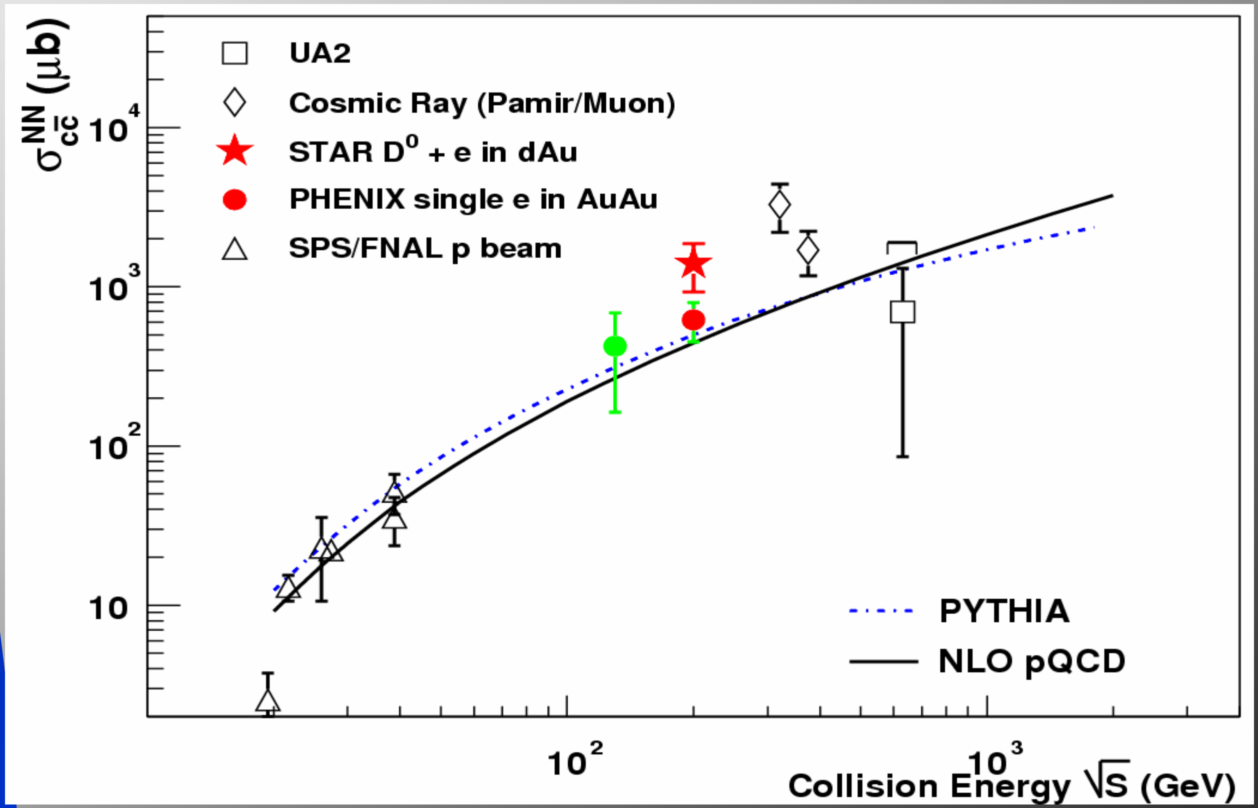


PROBE REGION OF COLOR DECONFINEMENT WITH MULTIPLE PAIRS OF HEAVY QUARKS

Avoids Matsui-Satz Condition

Distribute Heavy Flavor at hadronization (statistical)

Form Quarkonium in the medium: inverse suppression

IF THE INCOHERENT RECOMBINATION OF HEAVY QUARKS DETERMINES FINAL HADRONIC ABUNDANCES:

Probability for charm quark to combine with anticharm:

$$\varepsilon = N_c / N_{u,d} \propto N_{c\bar{c}} / N_{ch}$$

Since ε << 1, sum for each $\bar{\text{c}}$:

$$N_{quarkonium} \propto N_{c\bar{c}}{}^2 / N_{ch}$$

Average over fluctuations:

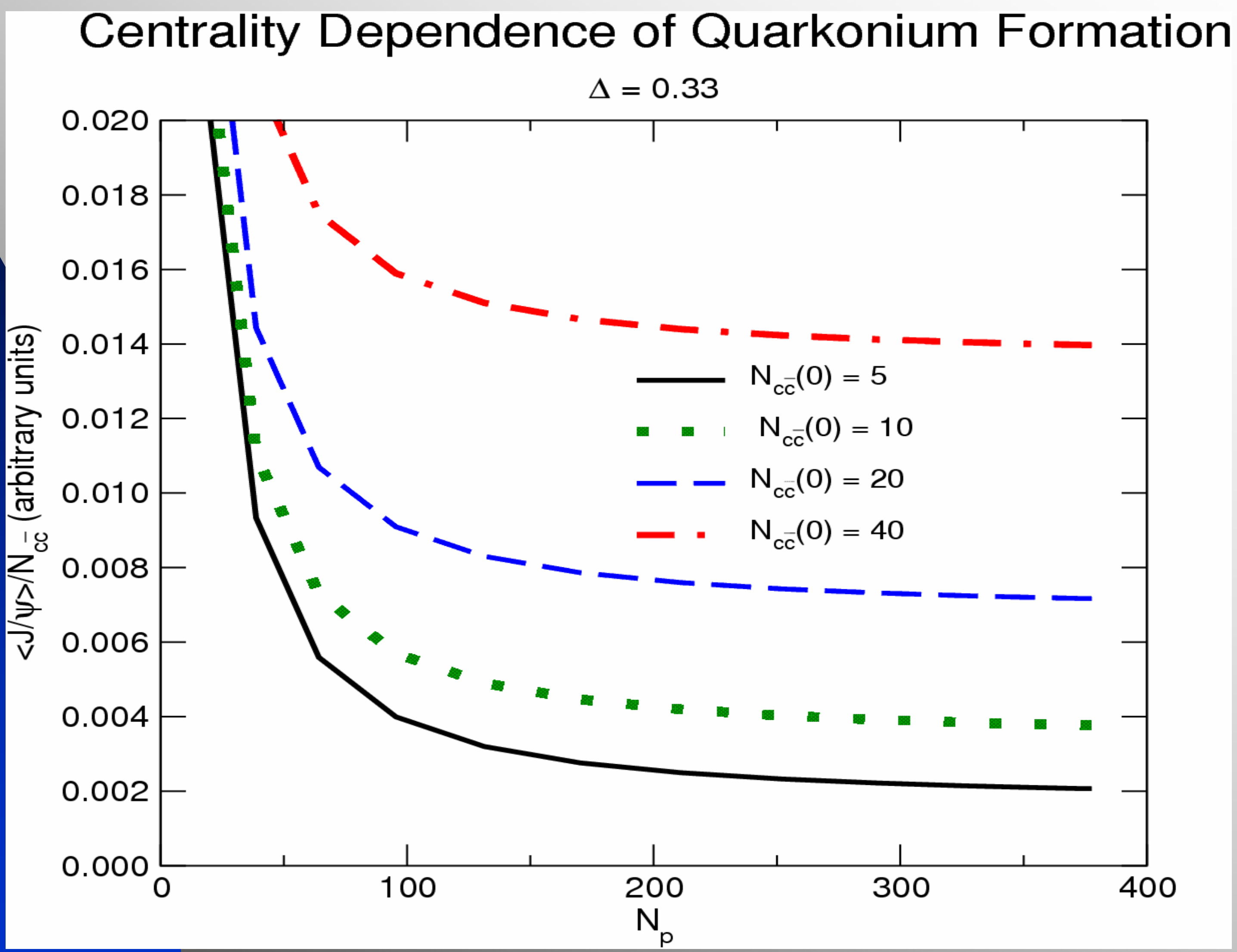
$$< J/\psi >= \lambda \ < N_{c\bar{c}} > (< N_{c\bar{c}} > +1) / N_{ch}$$

Centrality dependence in terms of participants $\mathrm{N_p}$:

Parameterize $N_{ch} \propto N_p{}^{1+\Delta}$,

$$< J/\psi > / < N_{c\bar{c}}(binary) > = aN_p{}^{\frac{1}{3}-\Delta} + bN_p{}^{-1-\Delta}$$

FORMATION CENTRALITY SIGNATURES



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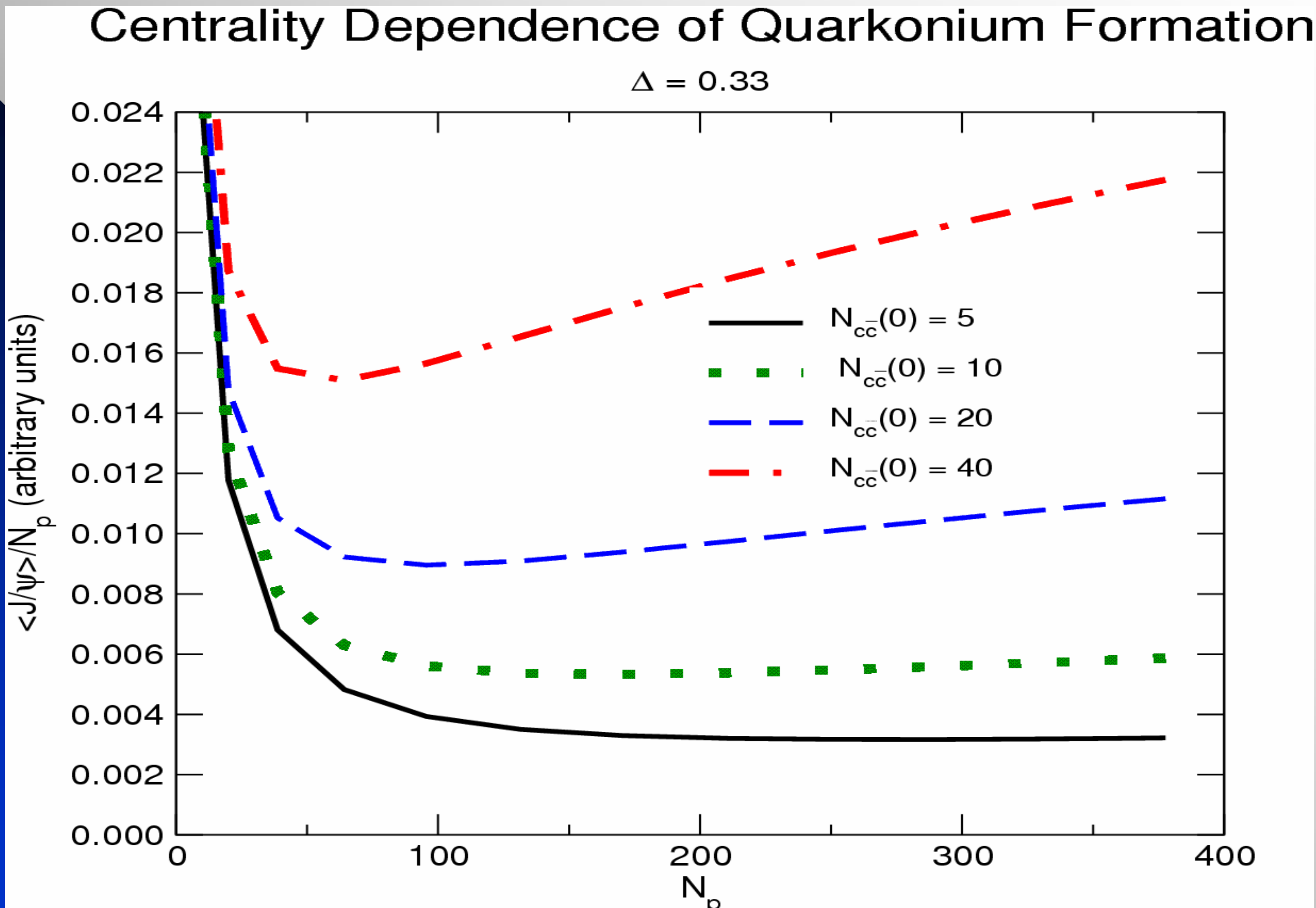

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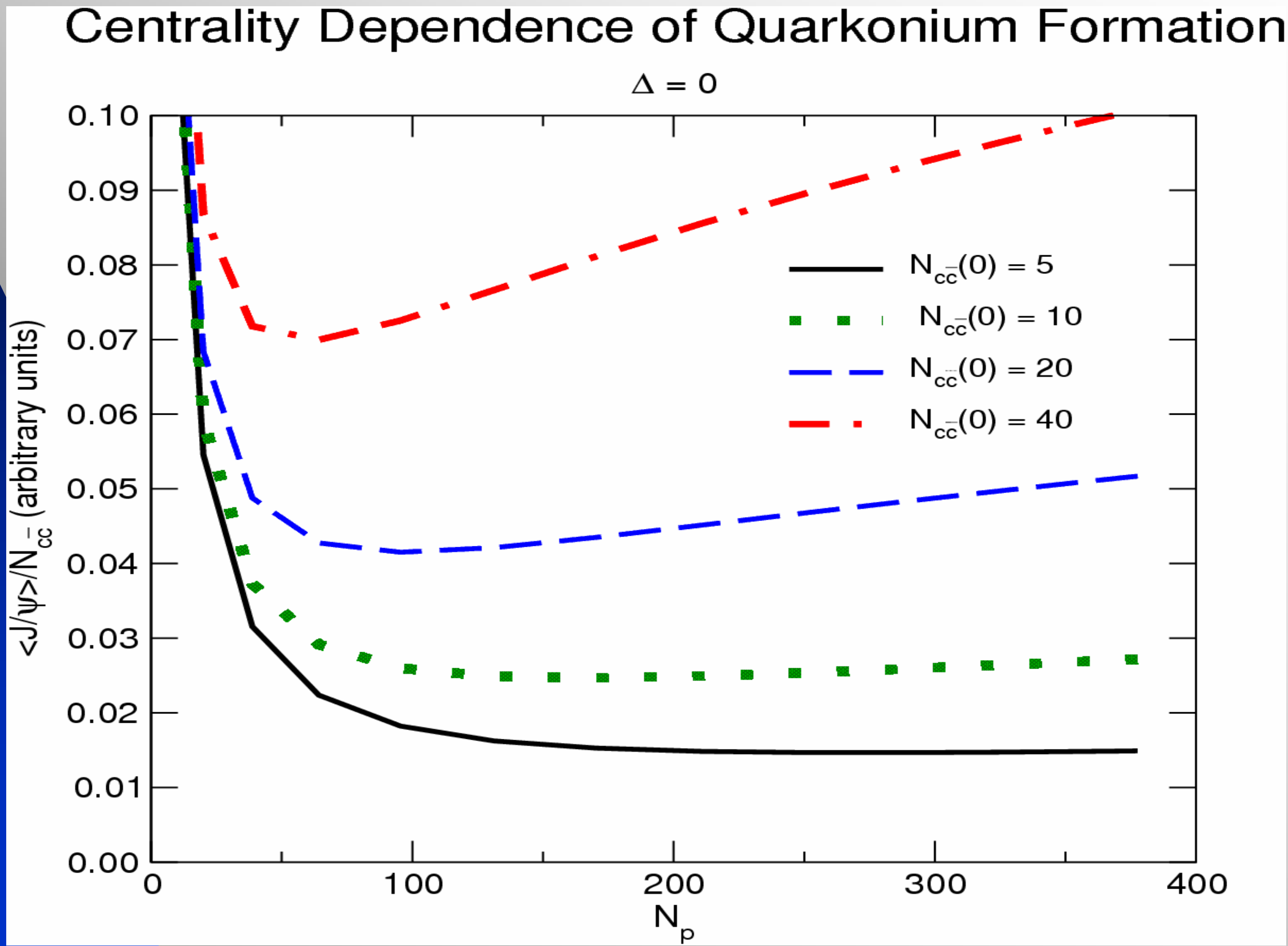

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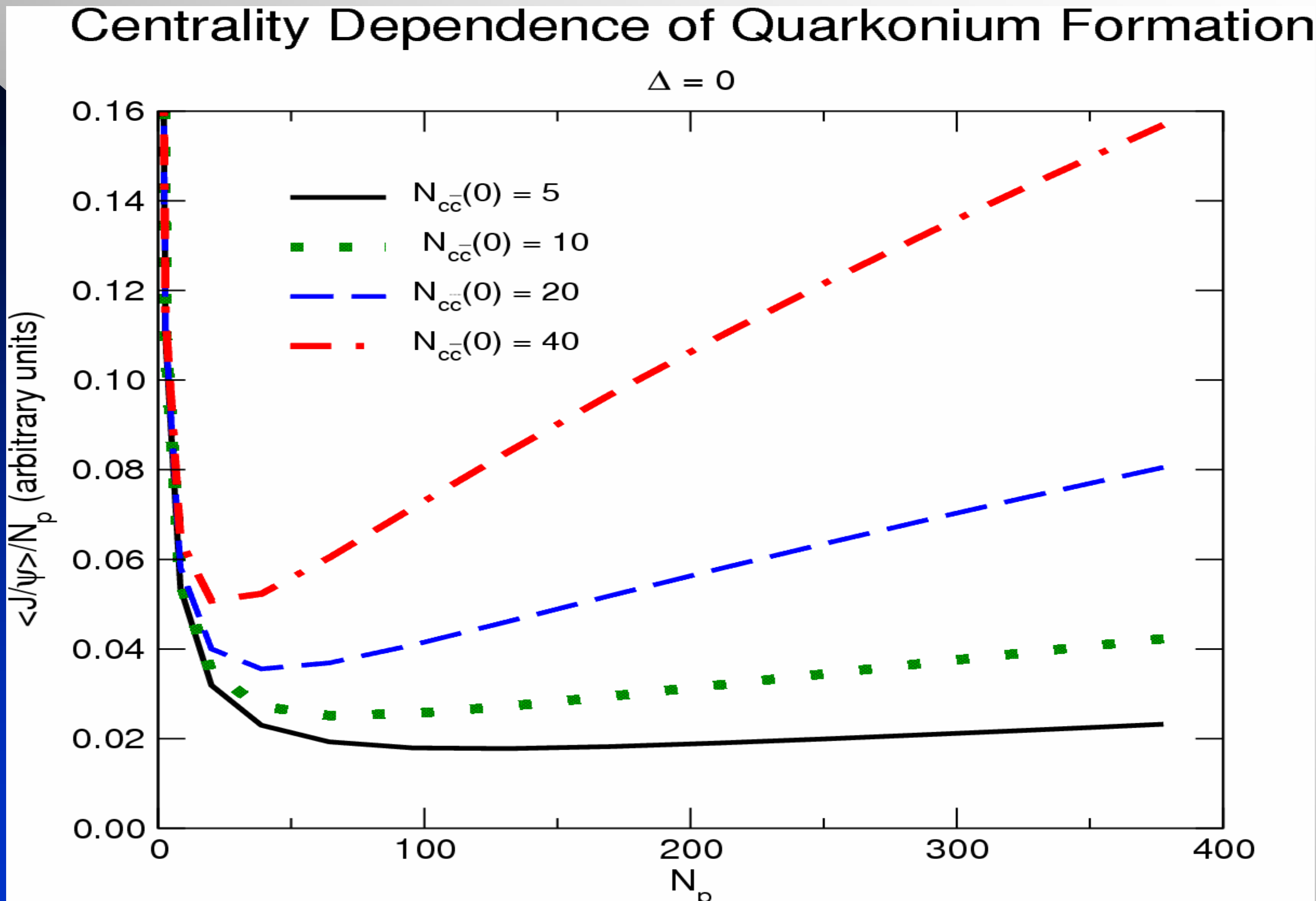

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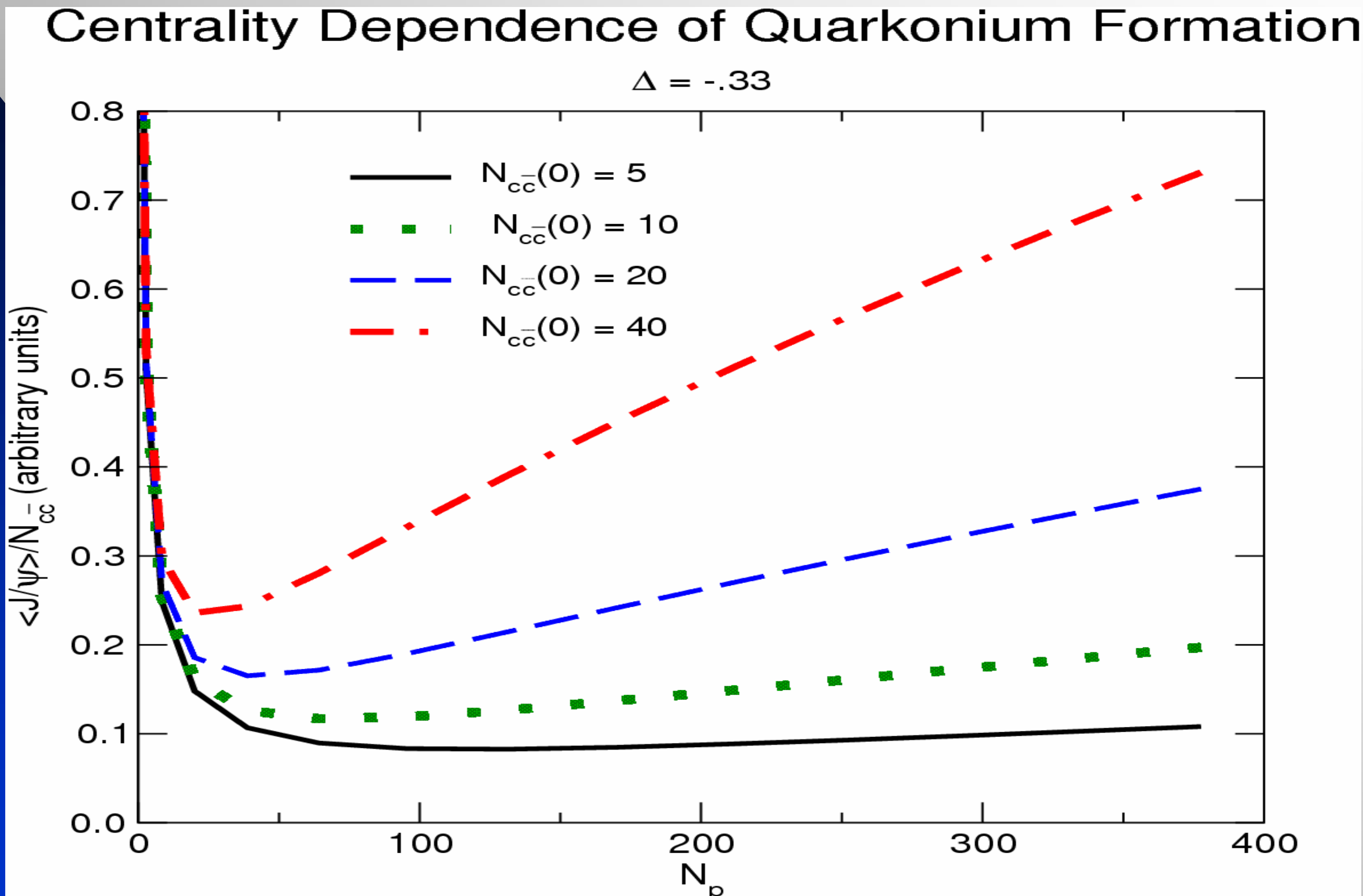

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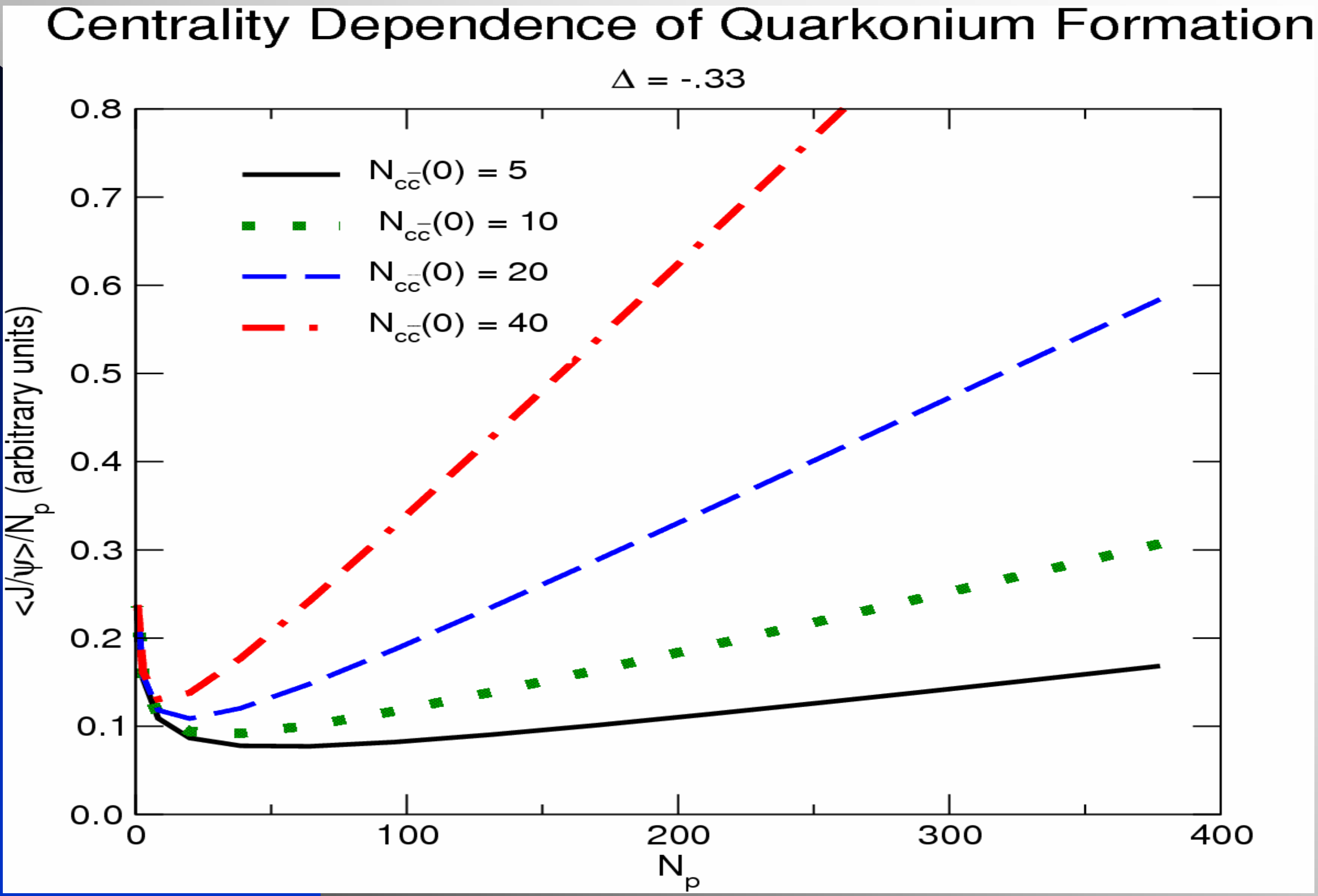
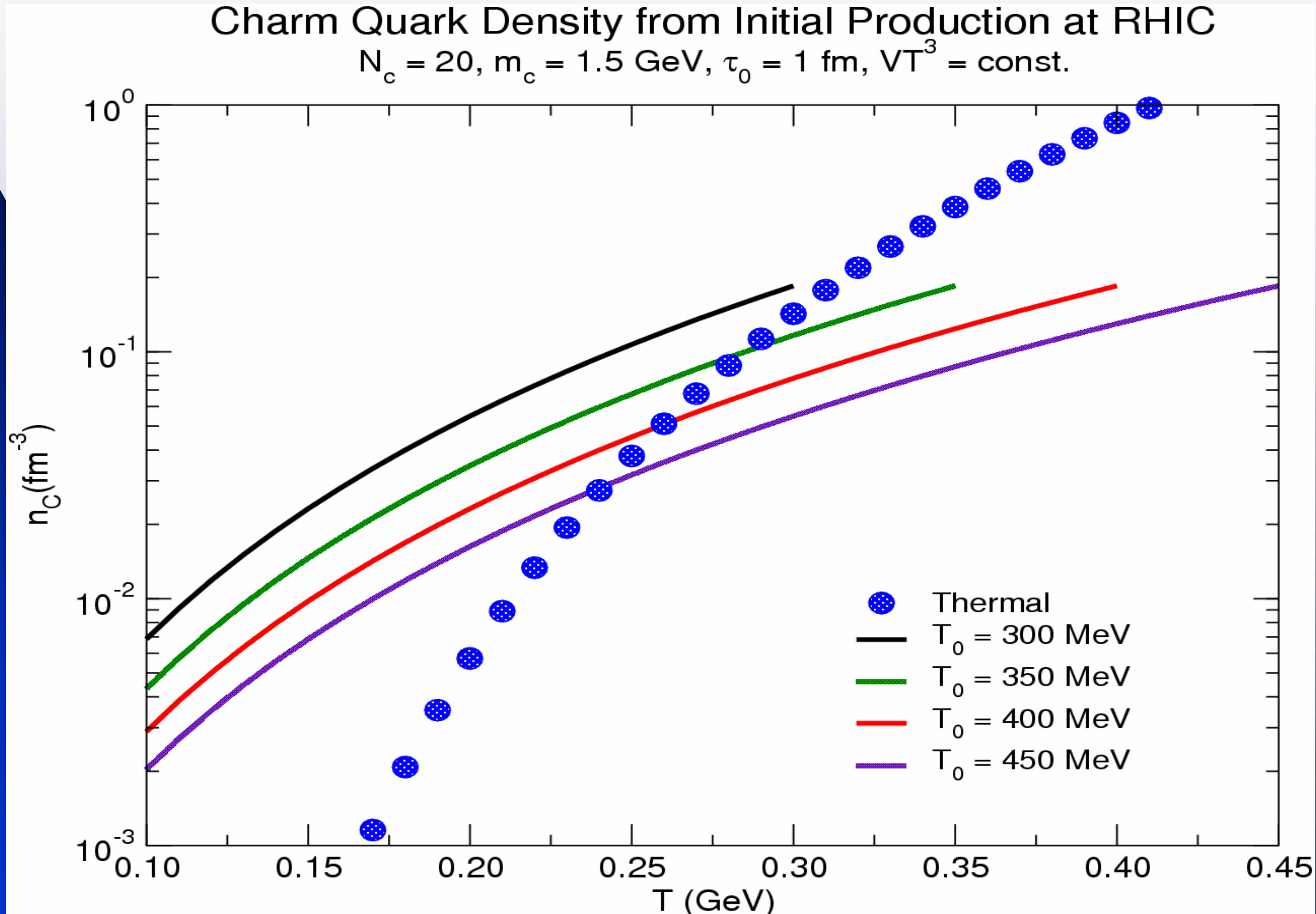


STATISTICAL HADRONIZATION MODEL

P. Braun-Munzinger, J. Stachel, Phys. Lett. B490, 196 (2000)

Chemical abundance of light hadrons fit with statistical model, parameters T, V, μ.
Hadrons with heavy quarks underpredicted.
Initial production of heavy quarks oversaturates chemical equilibrium.
Introduce charm enhancement factor γ_C, which is fixed by conservation of charm.
Then distribute charm quarks into hadrons according to statistical weights.

Charm density from Initial Production exceeds chemical equilibrium density for all $T < T_C$

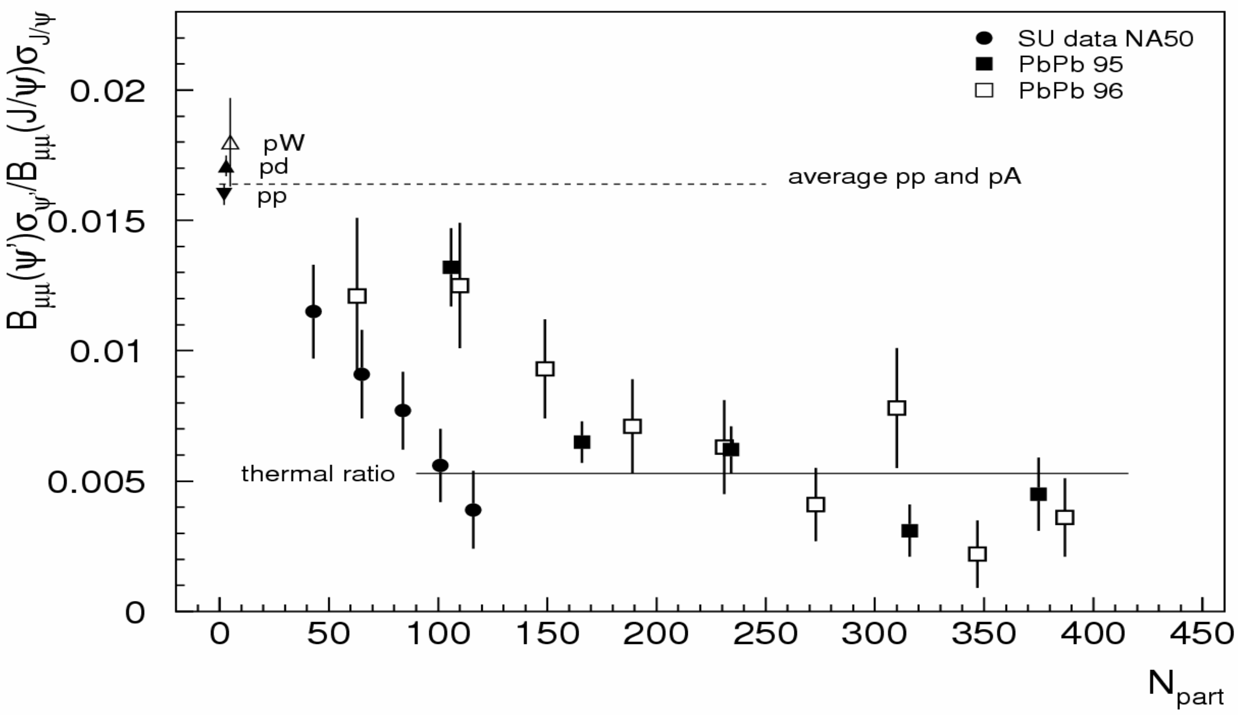


$$N_{cc} = \tfrac{1}{2}\gamma_c N_{open}^{thermal} + \gamma_c^2 N_{hidden}^{thermal}$$

$$N_{J/\psi} = \gamma_c^2 N_{J/\psi}^{thermal}$$

$$N_{canonical} = N_{gc} I_1(N_{gc}) / I_0(N_{gc})$$
$$\rightarrow N_{gc}, N_{gc} >> 1$$
$$\rightarrow \tfrac{1}{2} N_{gc}^2, N_{gc} << 1.$$

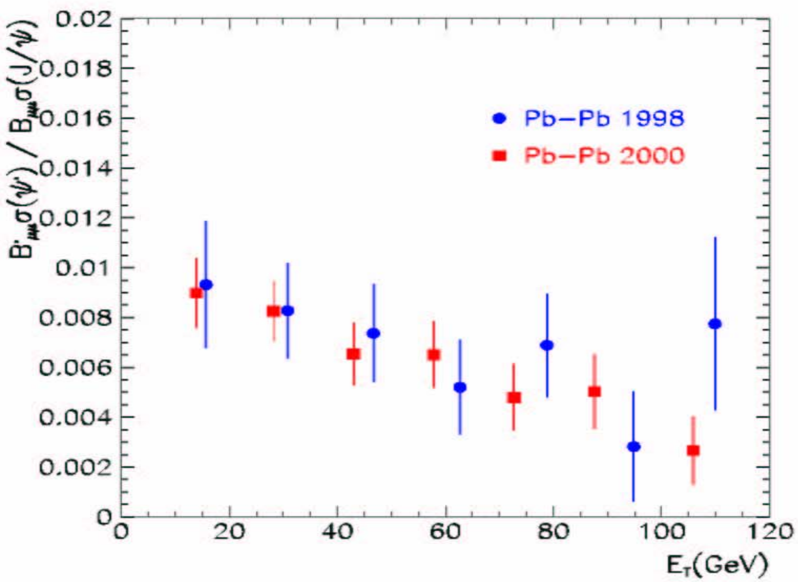
$$\gamma_c \rightarrow 2 N_{cc} / N_{open}^{thermal}, \text{gc limit}$$
$$\rightarrow 2\sqrt{N_{cc}} / N_{open}^{thermal}, \text{canonical limit}$$



SU data NA50
PbPb 95
PbPb 96
pW
pd
pp
average pp and pA
thermal ratio
$B_{\mu\mu}(\psi')\sigma_{\psi'}/B_{\mu\mu}(J/\psi)\sigma_{J/\psi}$
0.02
0.015
0.01
0.005
0
0
50
100
150
200
250
300
350
400
450
N_{part}

H. Santos (NA50), J. Phys. G30, 1175 (Proceedings Quark Matter 2004)

ψ'/ψ as a function of E_T



The ratio of the two charmonium states decreases with centrality by a factor of 2.5 between peripheral and central collisions

The ψ' is more suppressed than the J/ψ in Pb-Pb collisions

H. Santos, NA50 Coll.

Quark Matter 2004 - Oakland, January 11-17 – p.11

$$N_{J/\psi} = 4[n_{ch}^{therm} n_{J/\psi}^{therm} / (n_{open}^{therm})^2] \frac{N_{cc}^2}{N_{ch}}$$

Hadronization Volume $(N_{ch}/n_{ch})^{therm}$ is physical parameter

Ratio of thermal densities slowly-varying with Temperature

SPS (NA50): Requires charm enhancement approx 3x

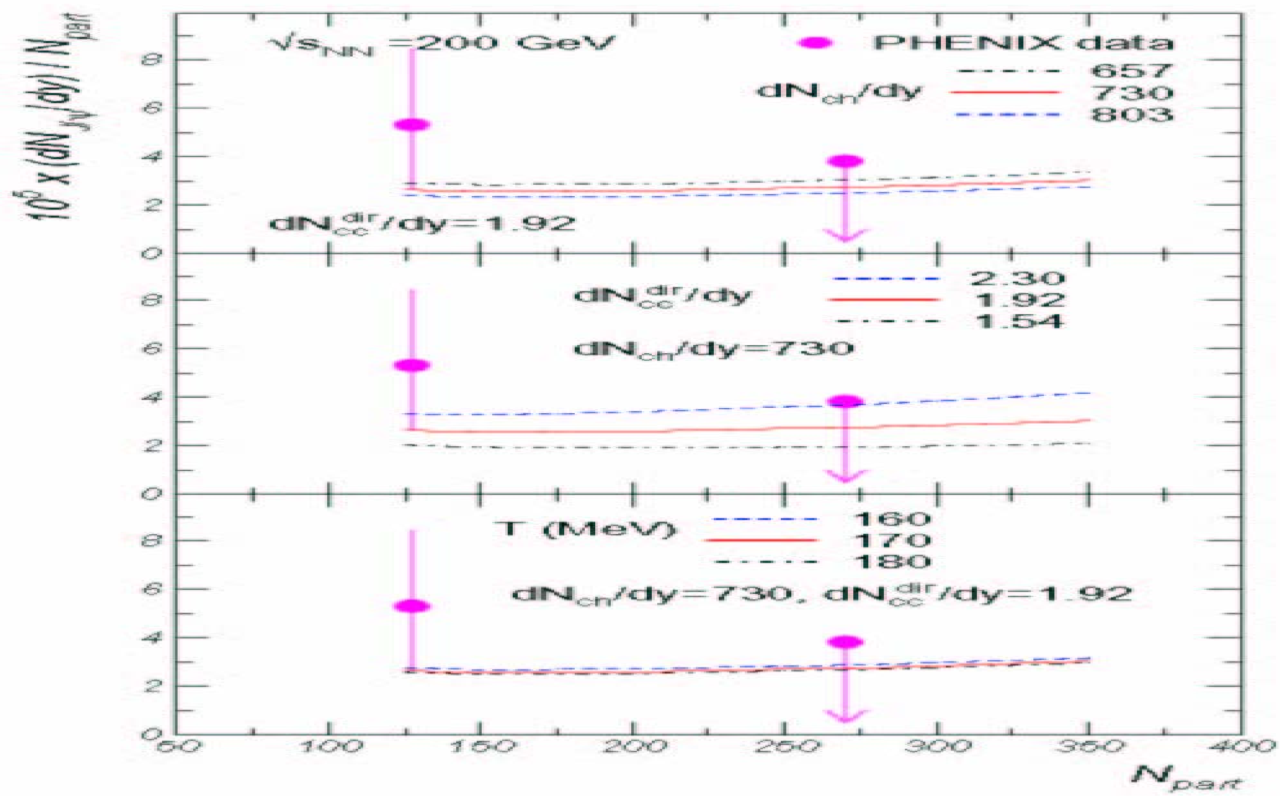
RHIC & LHC: Express in terms of rapidity densities

Additional predictions: Open charm mesons and baryons

A Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel,

Phys. Lett. B571:36-44, 2003

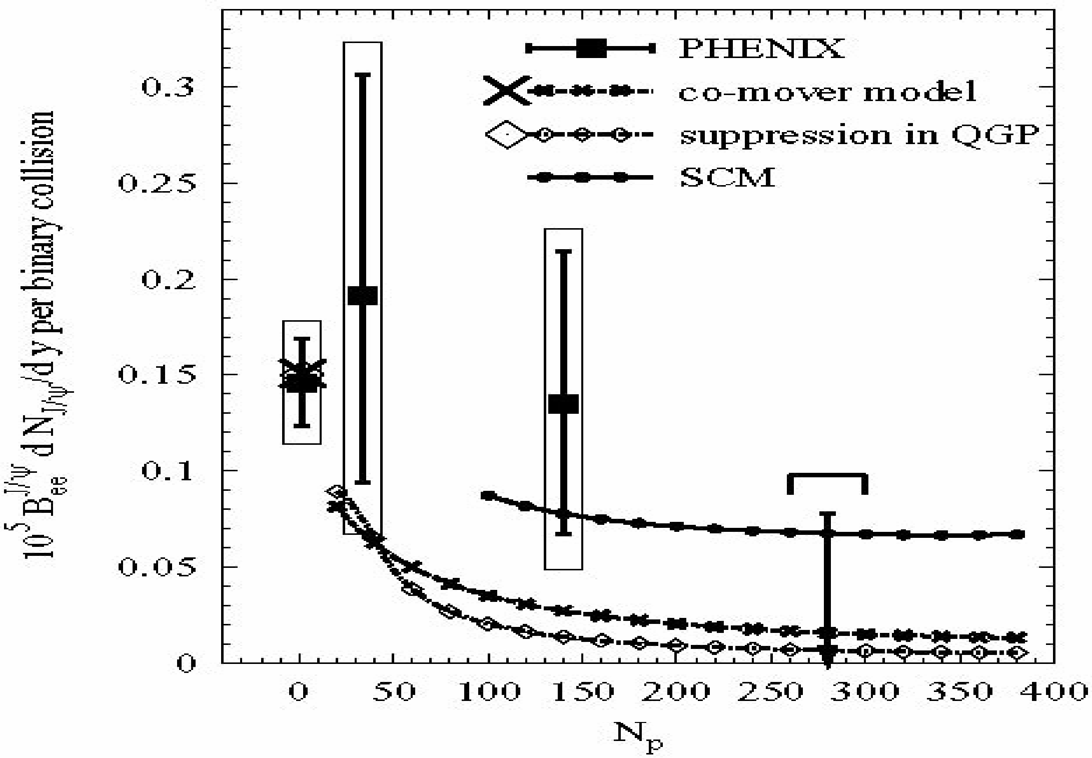
$\sigma_{cc} = 390\ \mu b$



A.P. Kostyuk, M.I. Gorenstein, H. Stocker, W. Greiner

Phys. Rev. C68: 041902, 2003

σ_{cc} = 650 μb



FORMATION OF QUARKONIUM IN REGION OF COLOR DECONFINEMENT

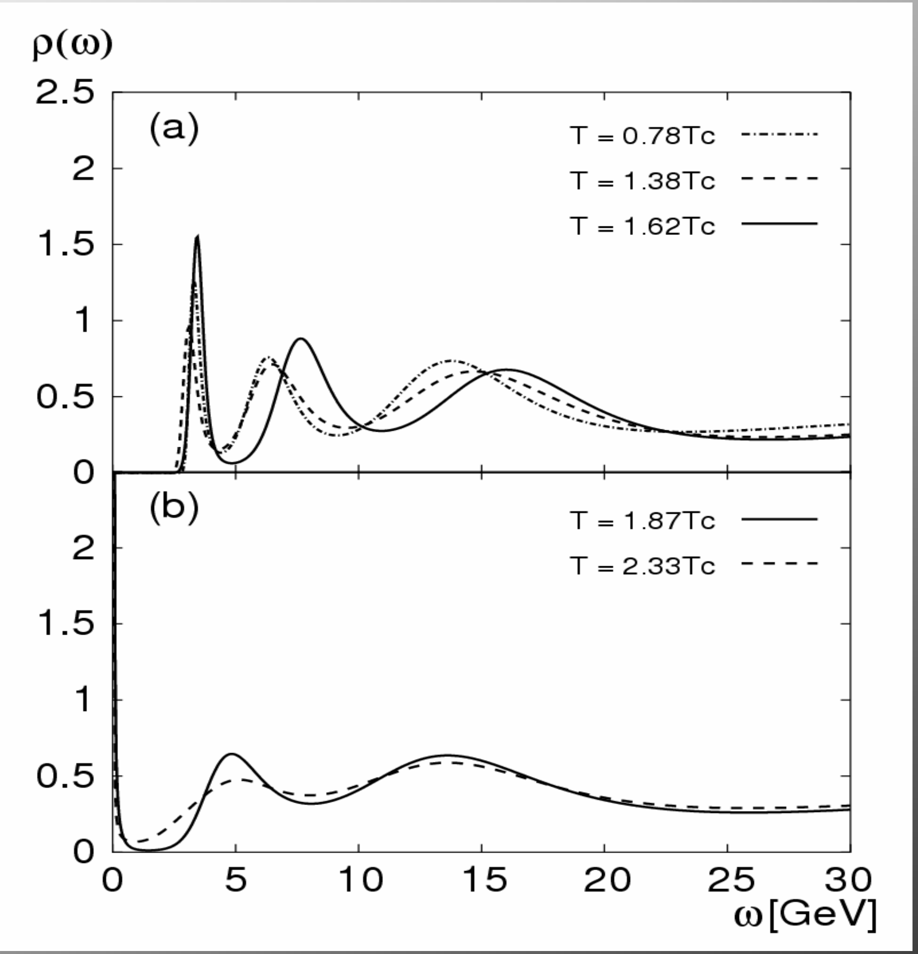
R. L. Thews, M. Schroedter, J. Rafelski, Phys. Rev. C63:054905, 2001

Formation process is Inverse of dissociation

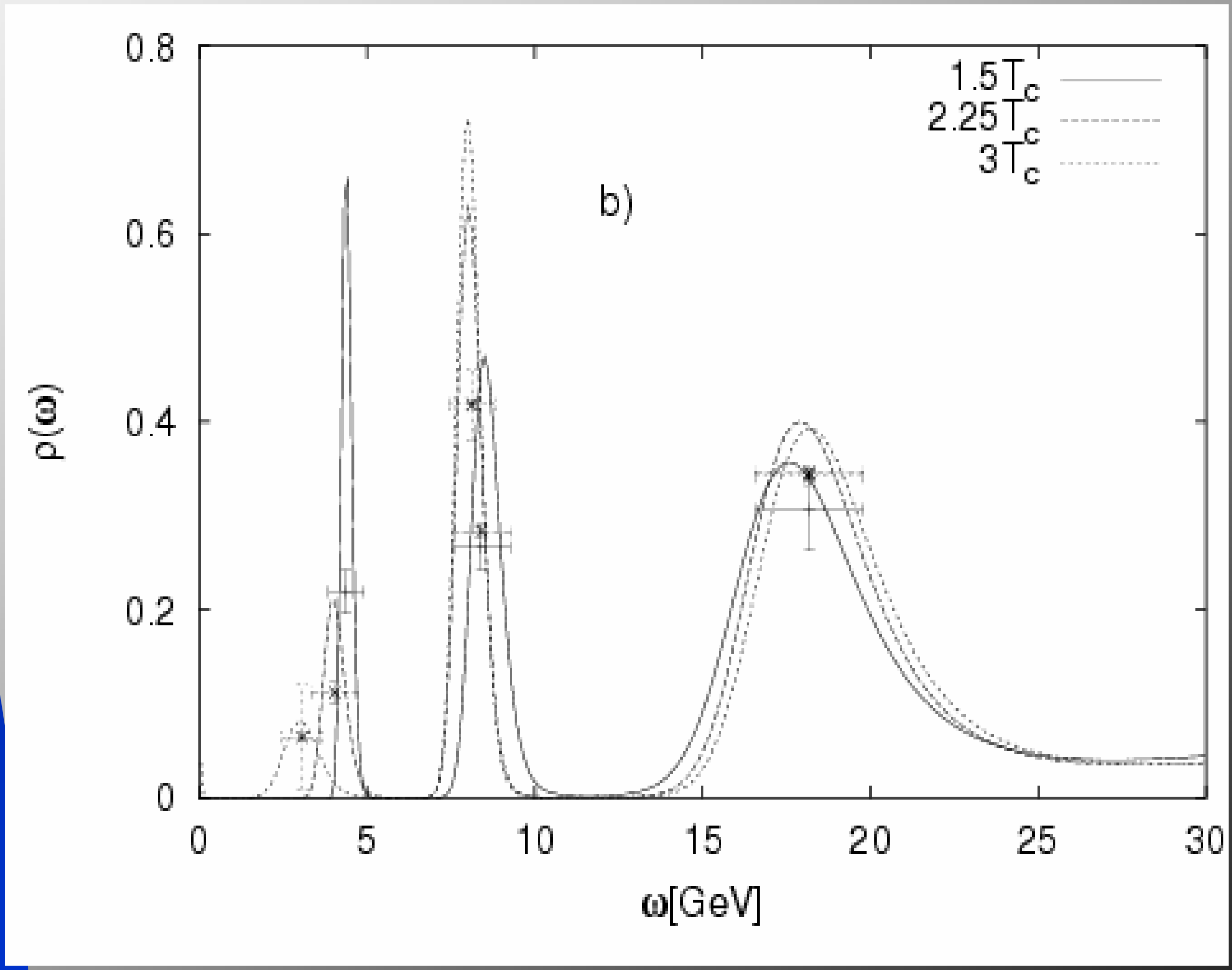
Model evolution of region with initial temperature and isentropic expansion, depends on contours of participant density

Final population determined by competition between formation and dissociation rates

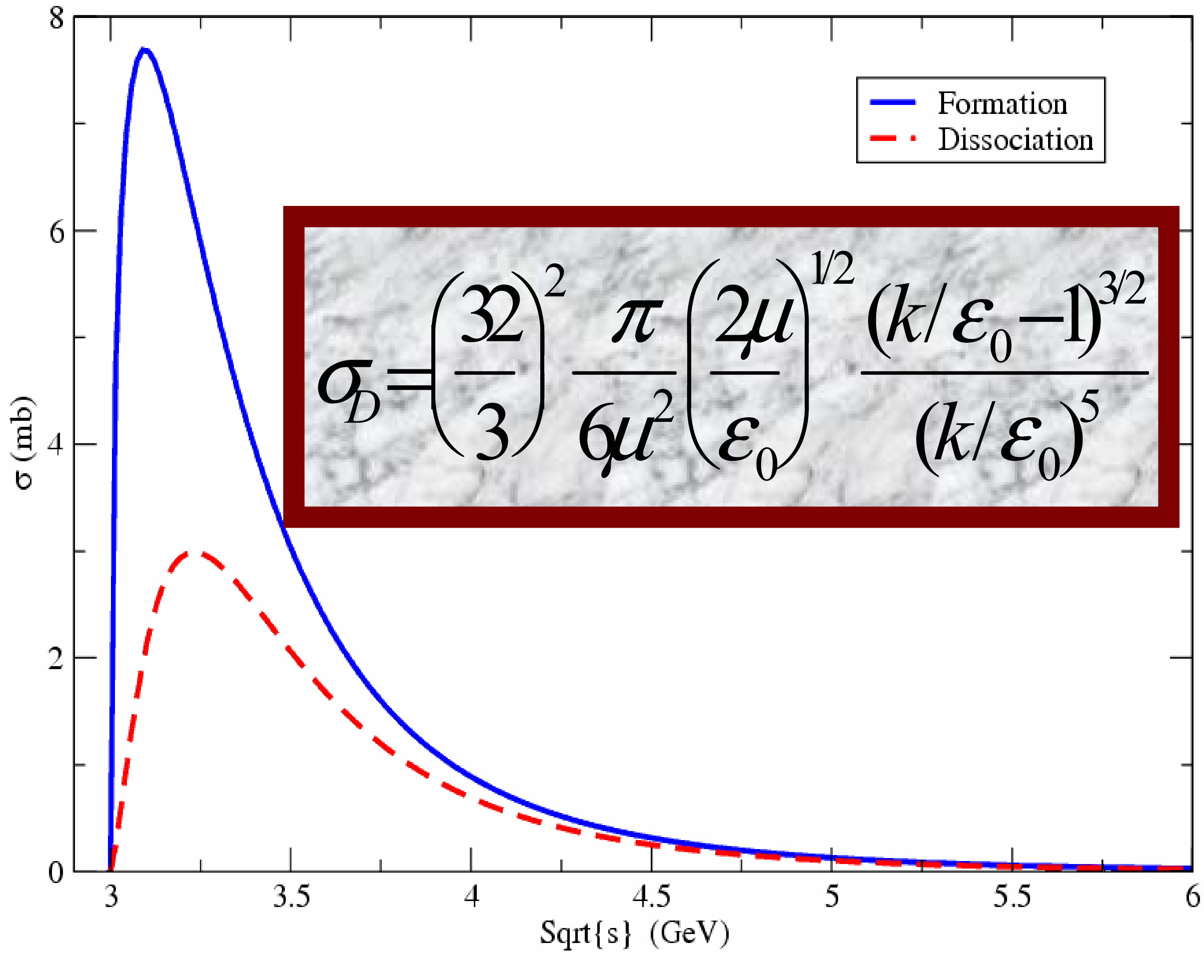
M. Asakawa and T. Hatsuda, Phys. Rev. Lett: 012001 (2004)



S. Datta, F. Karsch, P. Petreczky, I. Wetzorke, Phys. Rev. D69:094507 (2004)

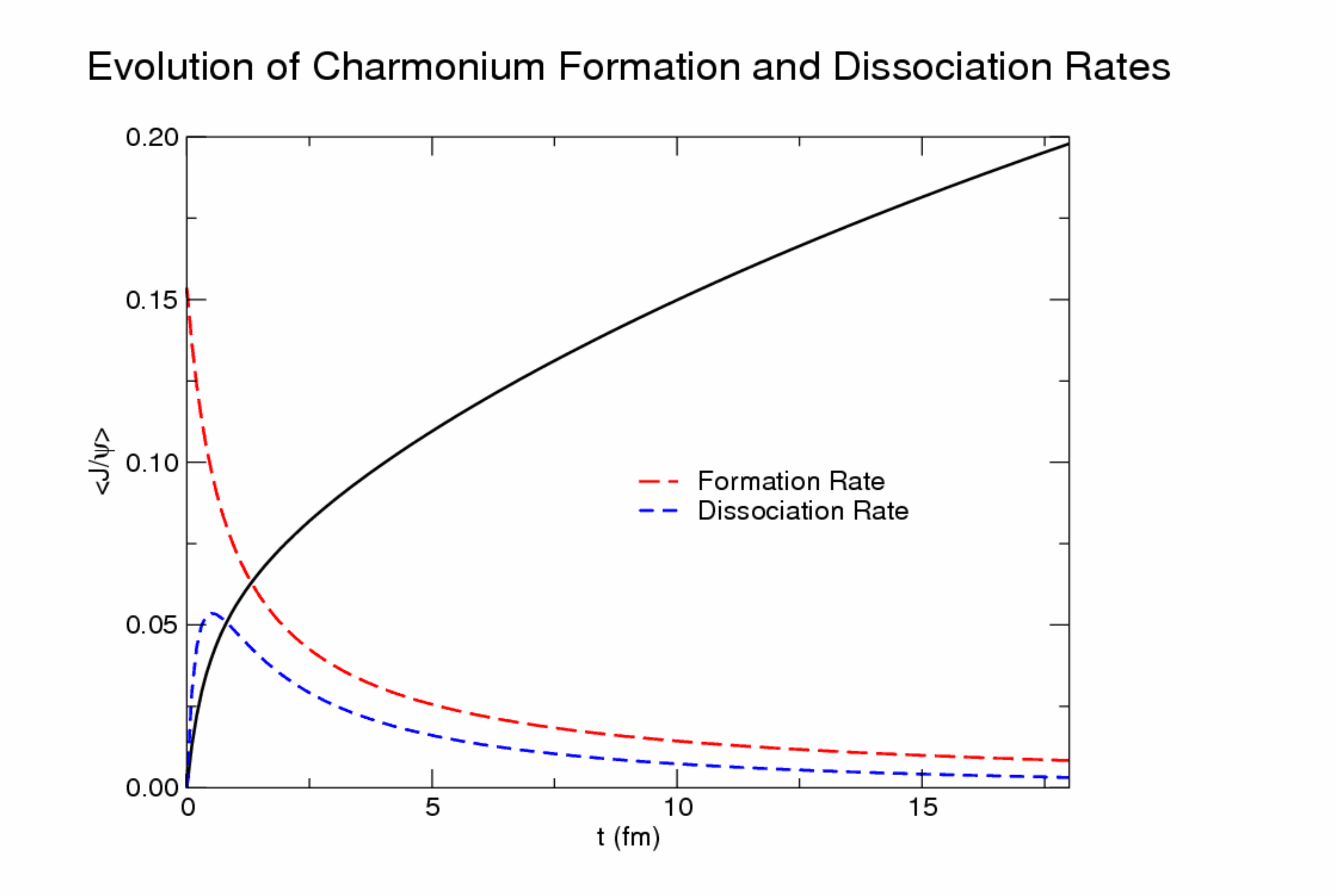


OPE Cross Sections g + J/ψ < -- > c + $\bar{c}$



$$\sigma_D = \left(\frac{32}{3}\right)^2 \frac{\pi}{6\mu^2} \left(\frac{2\mu}{\varepsilon_0}\right)^{1/2} \frac{(k/\varepsilon_0 - 1)^{3/2}}{(k/\varepsilon_0)^5}$$

$$\frac{dN_{J/\psi}}{d\tau} = <v\sigma_F> \rho_c N_c - <v\sigma_D> \rho_g N_{J/\psi}$$



If $N_{J/\psi} << N_{cc}$, solution is:

$$N_{J/\psi}(\tau_f) = \varepsilon(\tau_f) \times N_{cc}^2 \int_{\tau_0}^{\tau_f} \lambda_F [V(\tau)\,\varepsilon(\tau)]^{-1} d\tau$$

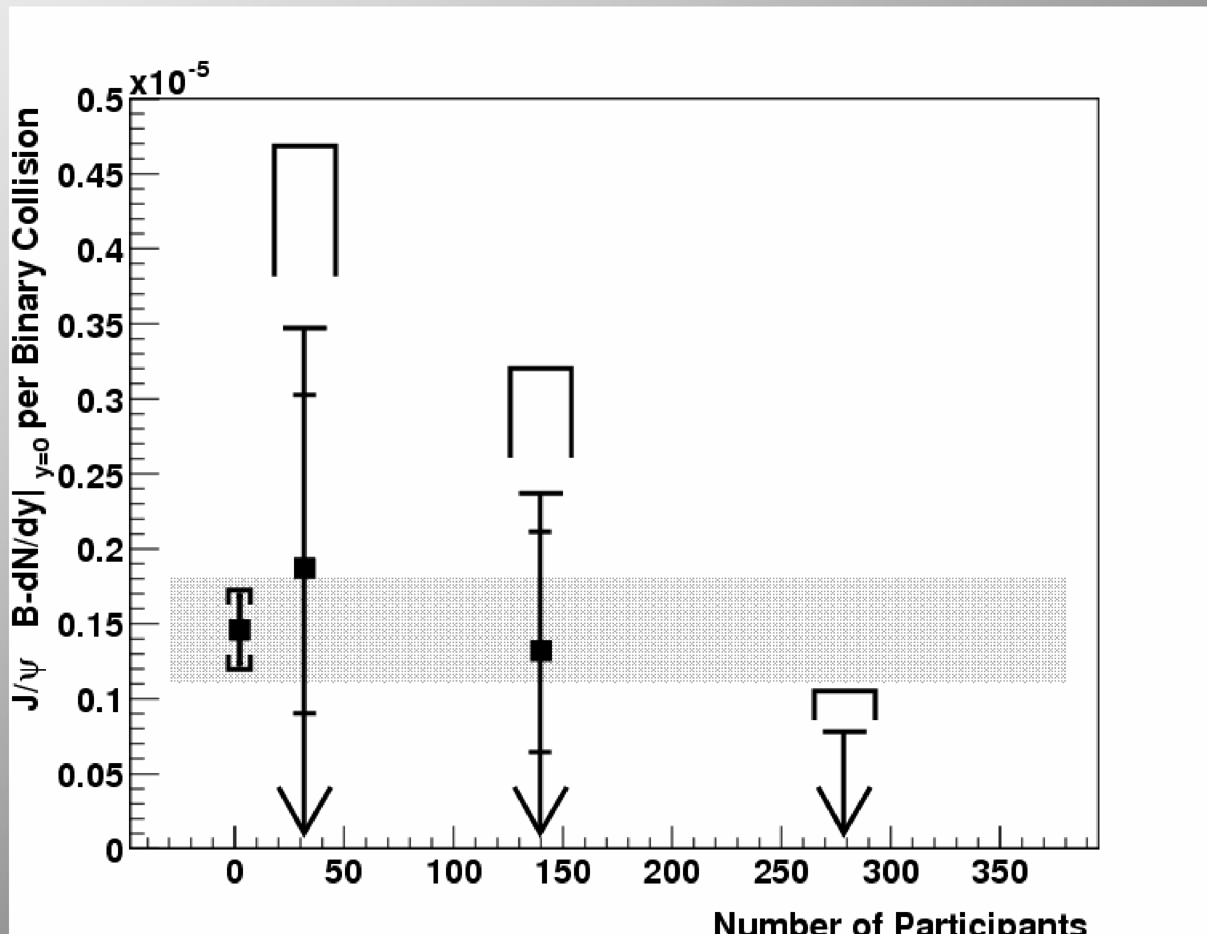
$$\varepsilon(\tau) = \exp[-\int_{\tau_0}^{\tau} \lambda_D \rho_g \, d\tau]$$

COMPARISON WITH INITIAL PHENIX DATA AT RHIC 200

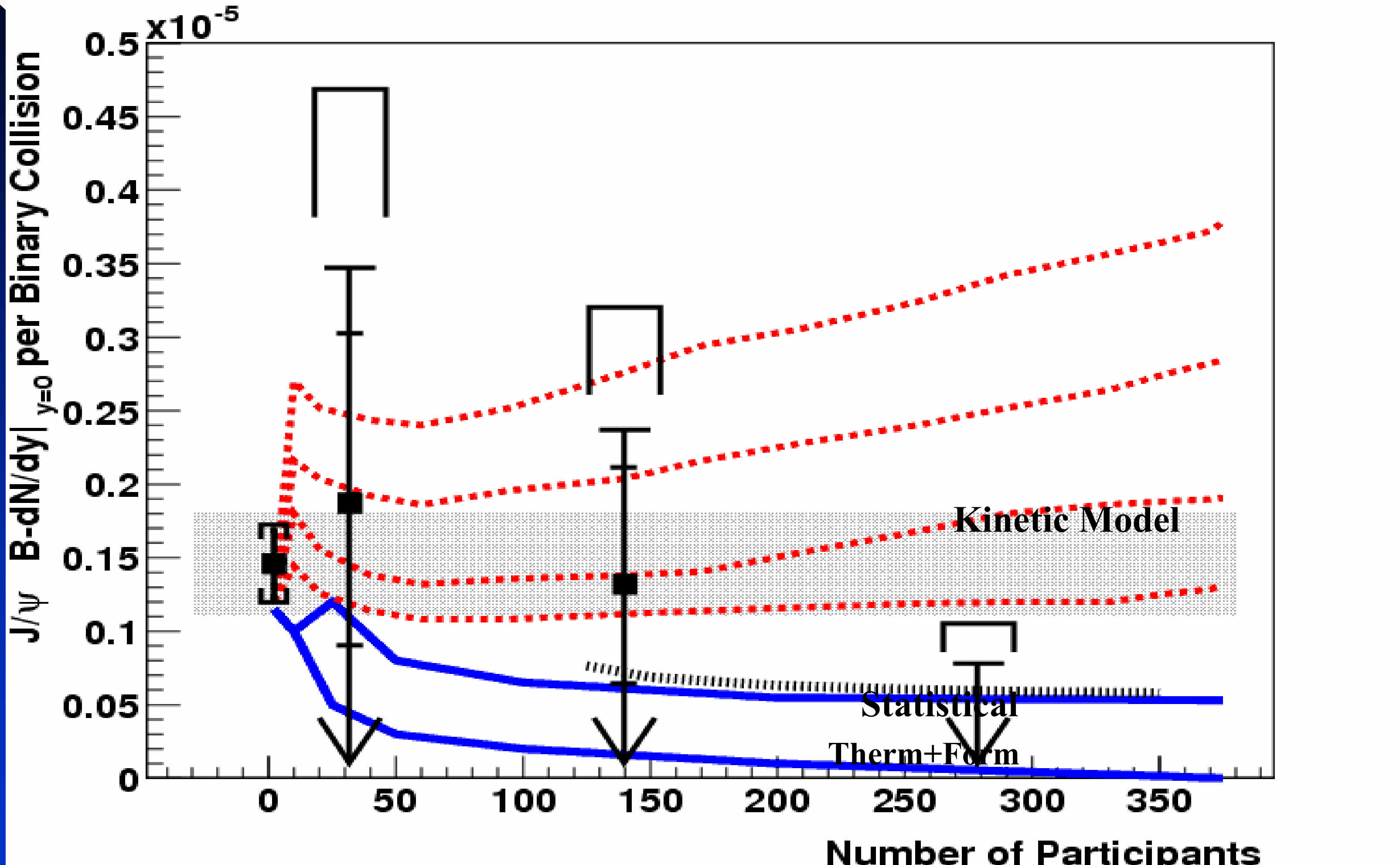
Rates very sensitive to quark momentum distribution

Centrality signature varies with magnitude of N_{cc}

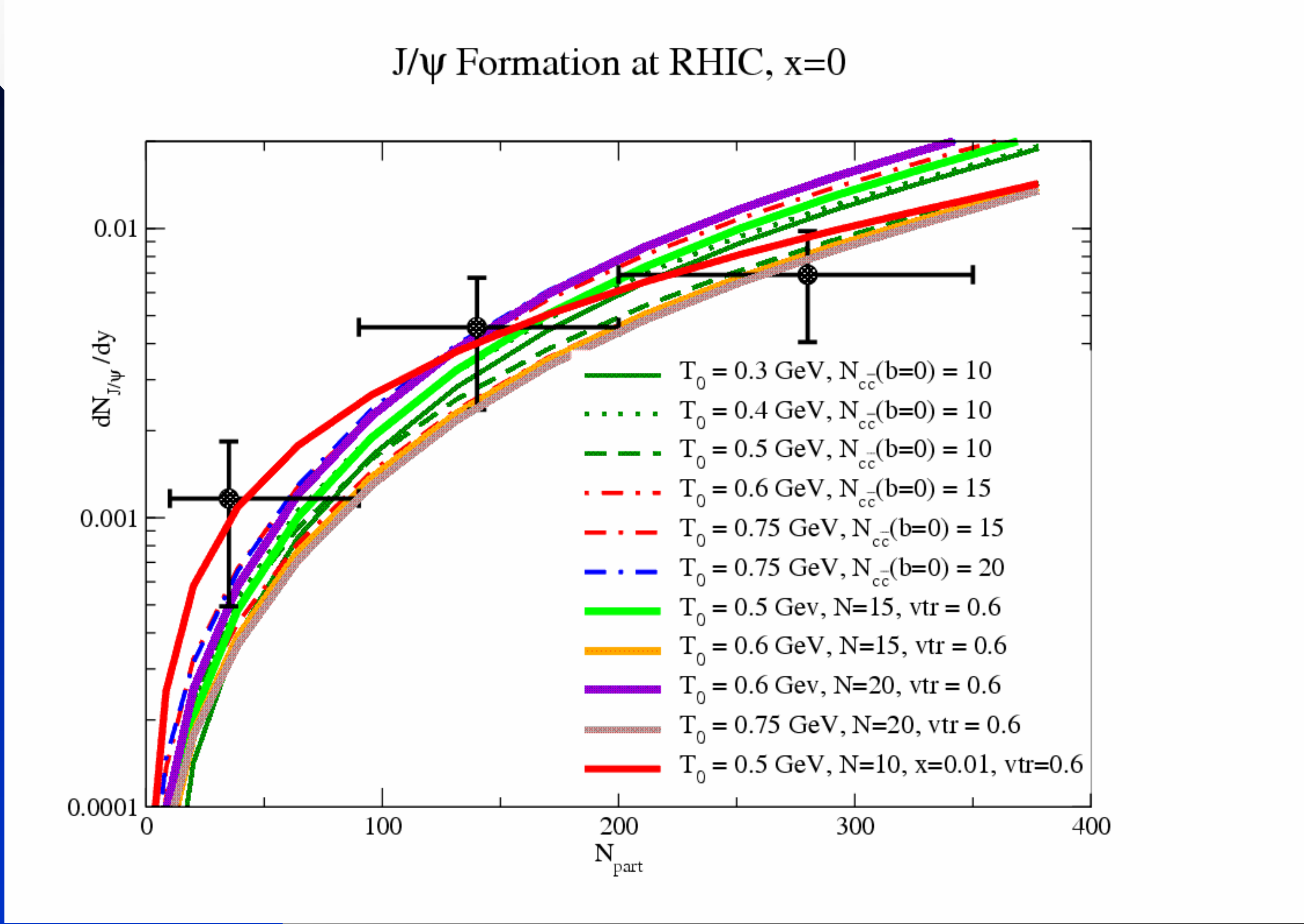
PHENIX – Phys. Rev. C69, 014901 (2004)



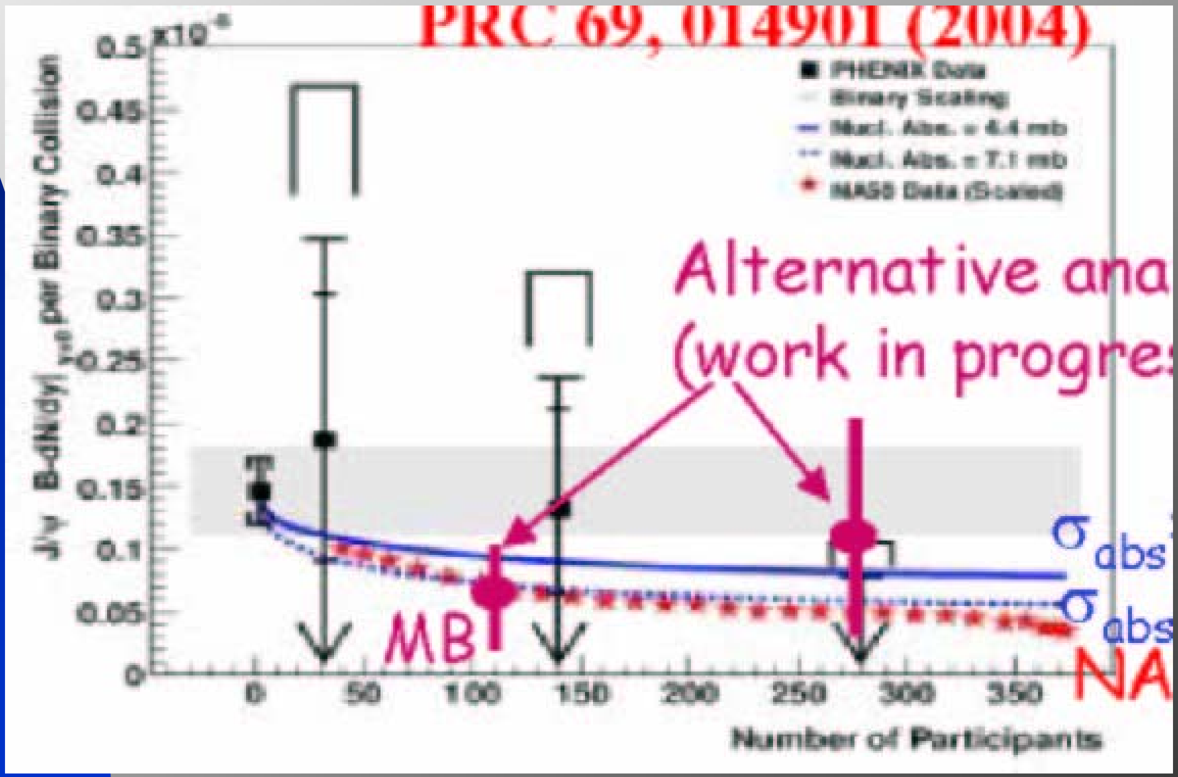
Model predictions very sensitive to N_{cc} and distribution



R. L. Thews, J. Phys. G30: S369 (2004)



T. Gunji, JPS 2004, PHENIX (prelim)



DO THE Y AND P_T SPECTRA PROVIDE A FORMATION SIGNATURE?

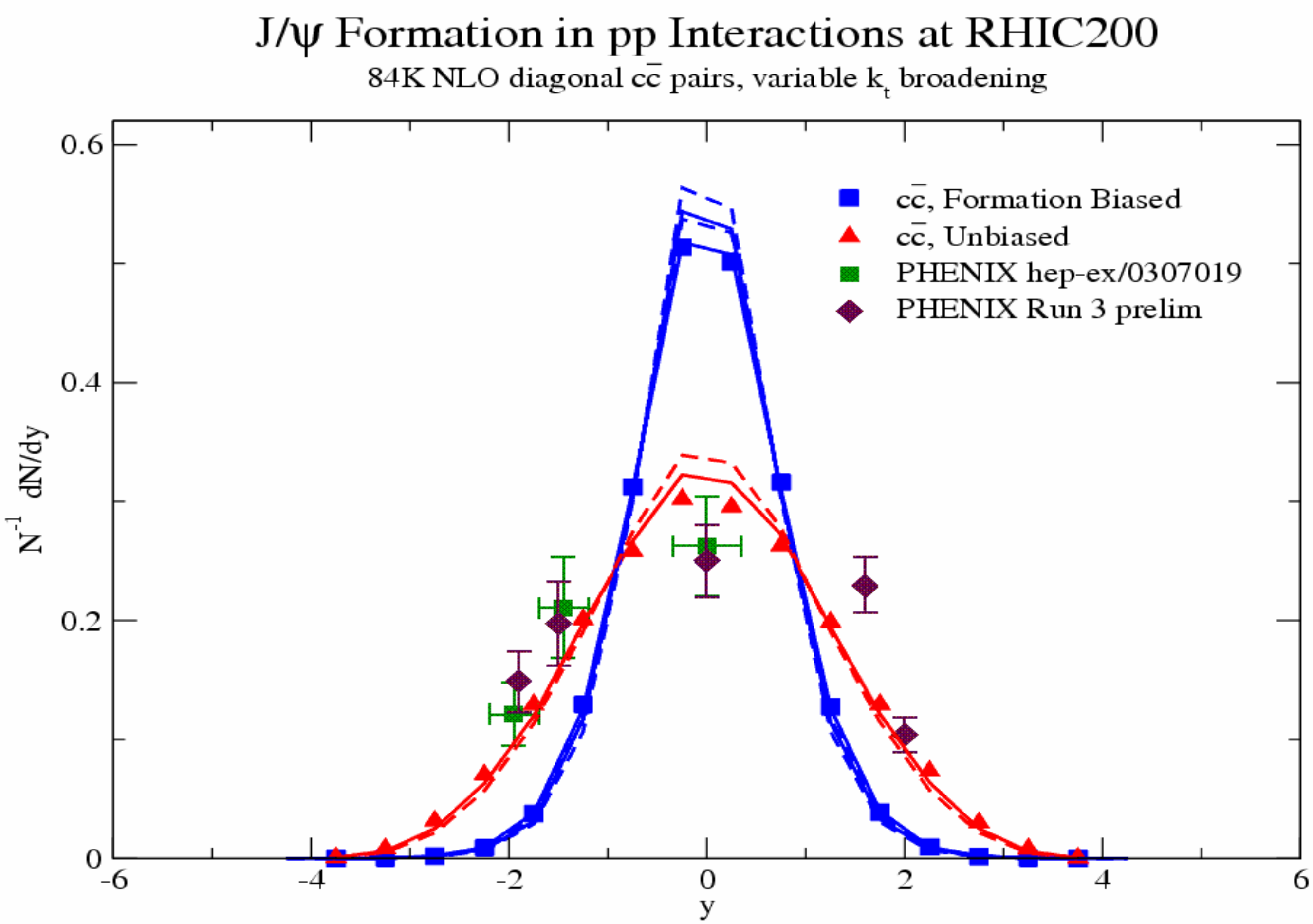
M. Mangano and R. L. Thews (work in progress)

1. Generate sample of ccbar pairs from NLO pQCD (smear LO q_t)
2. Supplement with k_t to simulate initial state and confinement effects
3. Integrate formation rate using these events to define particle distributions

$$\frac{dN_{J/\psi}}{d^3p_{J/\psi}} = \int \frac{dt}{V(t)} \sum_{i=1}^{N_{c\bar{c}}} \sum_{j=1}^{N_{c\bar{c}}} v_{rel} \frac{d\sigma(p_i + p_j \to p_{J/\psi} + X)}{d^3p_{J/\psi}}$$

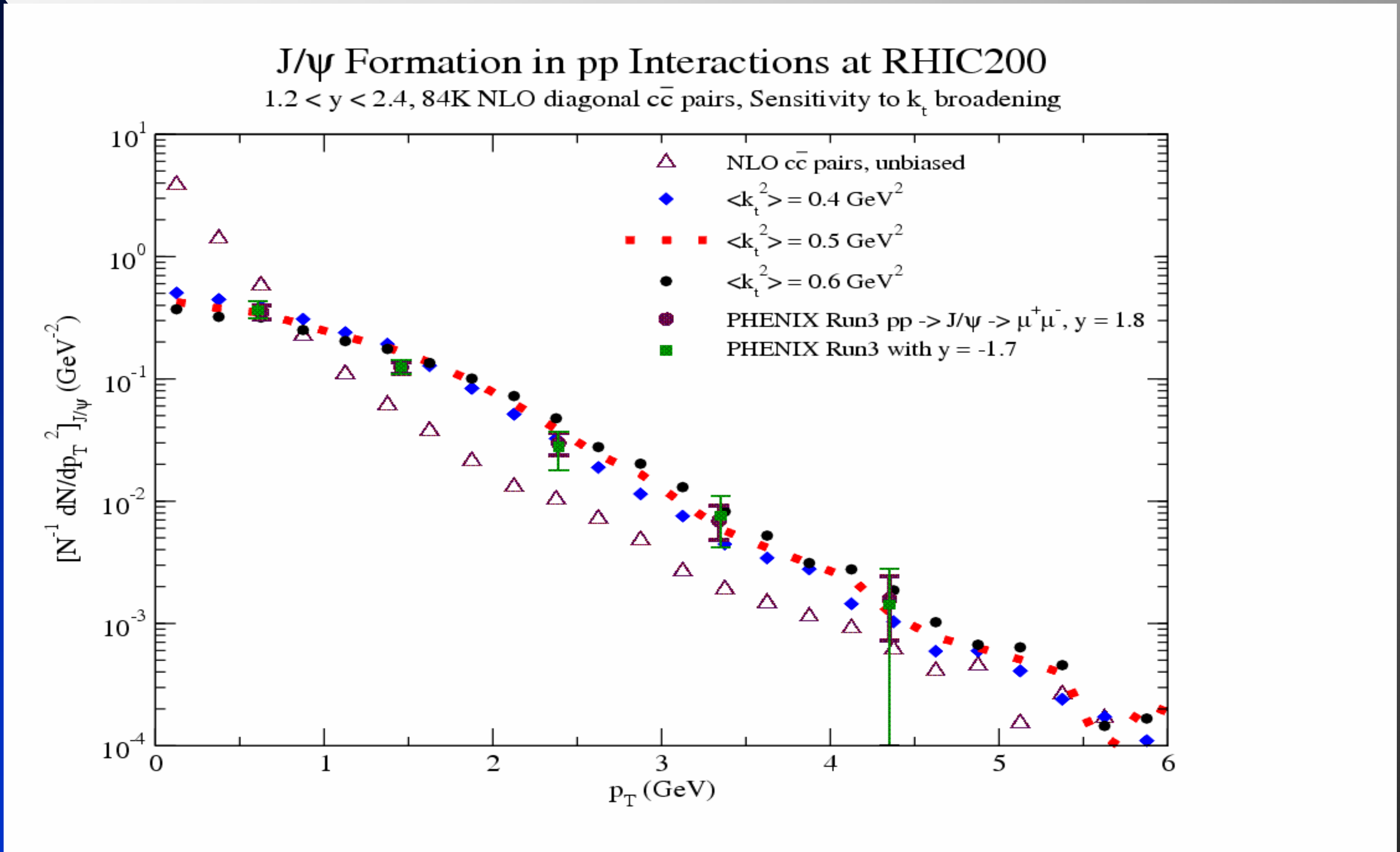
- All combinations of c and cbar contribute
  - Prefactor is integrated flux for given pair
- Total has expected $(N_{ccbar})^2$ / V behavior

p-p data "select" unbiased diagonal c-cbar pairs



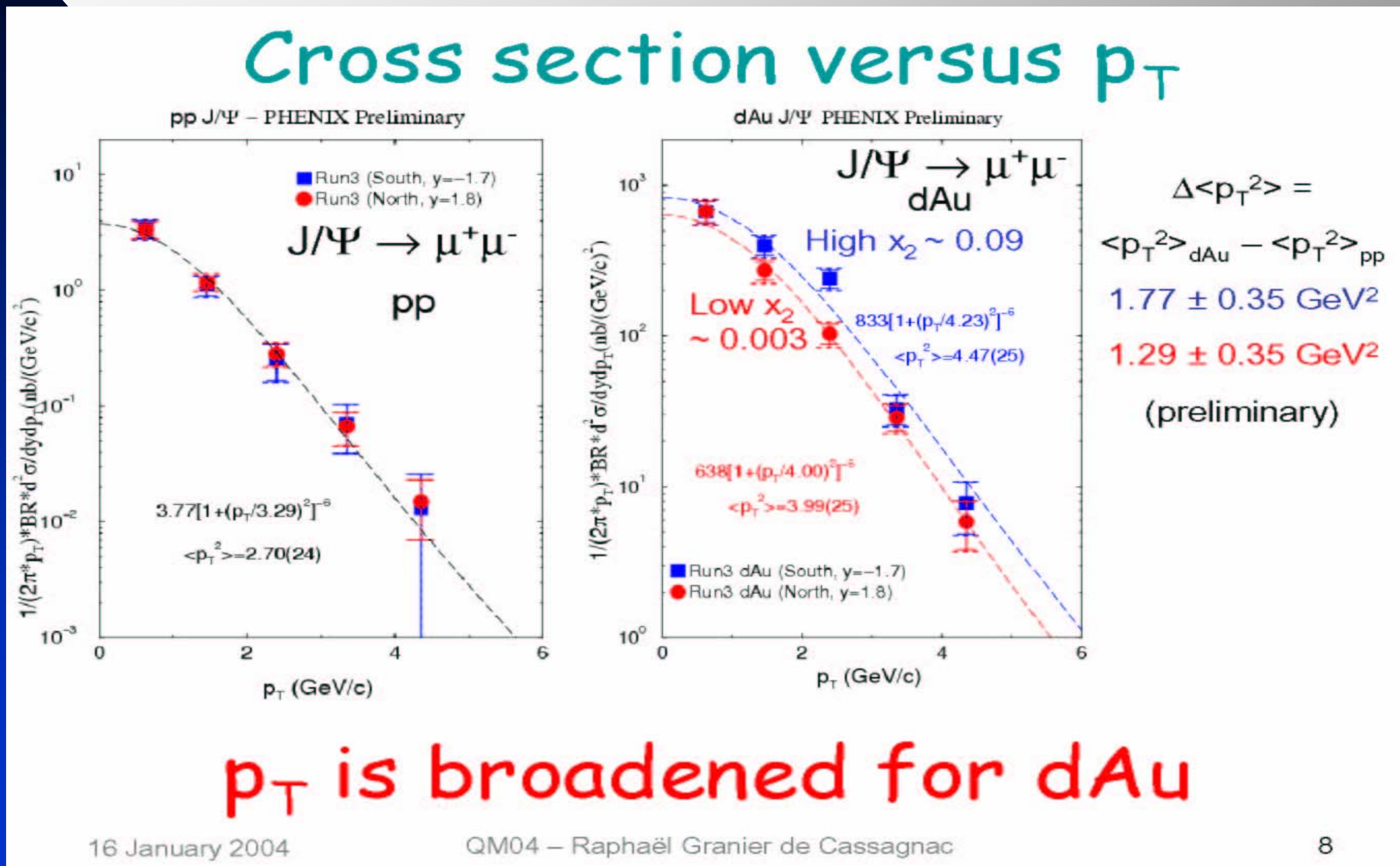
p-p data determine intrinsic k_t

$$< k_t^2 >_{c-quarks} = 0.5 \pm 0.1 \ GeV^2$$

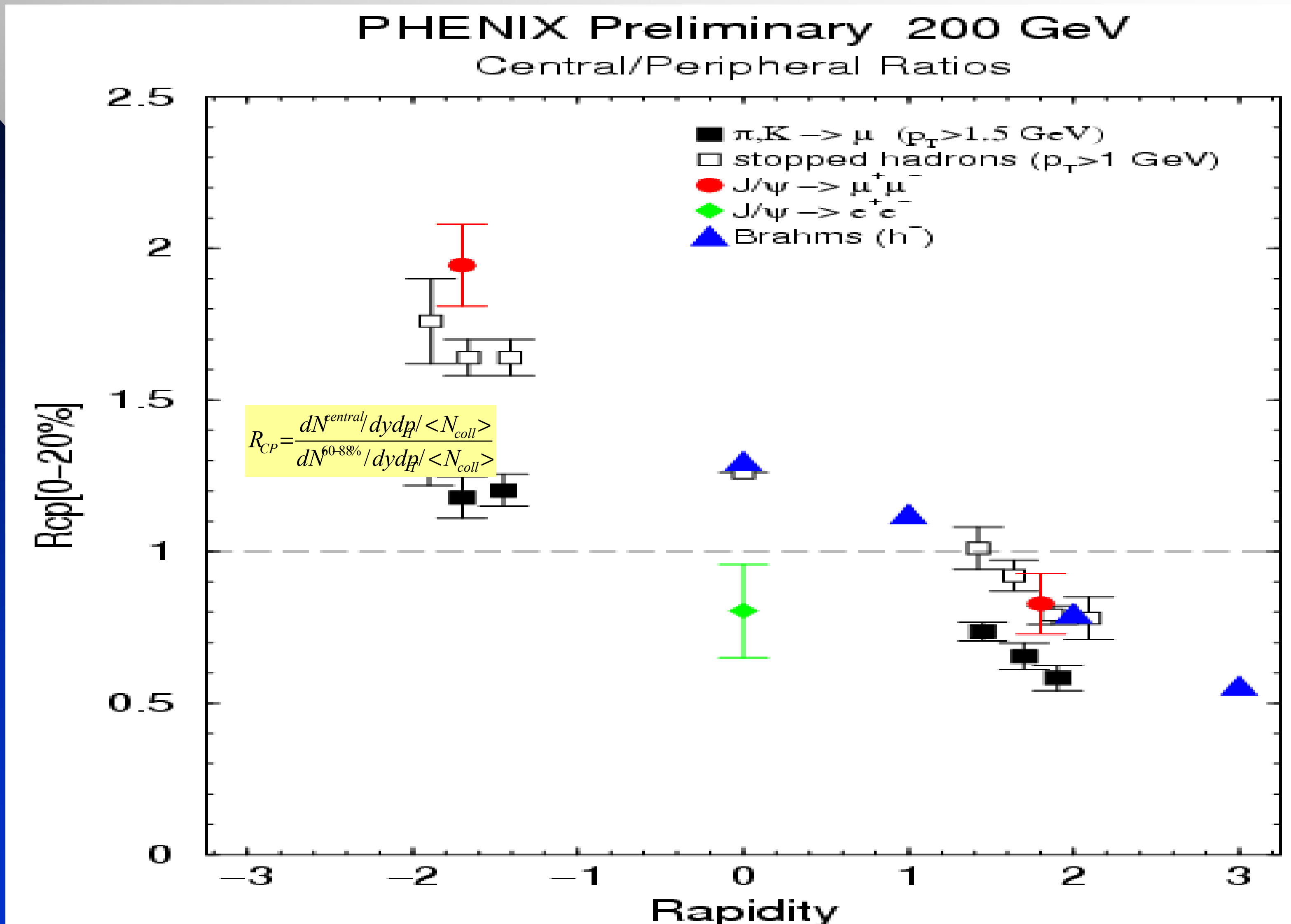


Use dAu broadening to determine nuclear k_t

$$\Rightarrow \quad < k_t^{\,2} >_{AA} = 1.3 \pm 0.3 \text{ GeV}^2$$

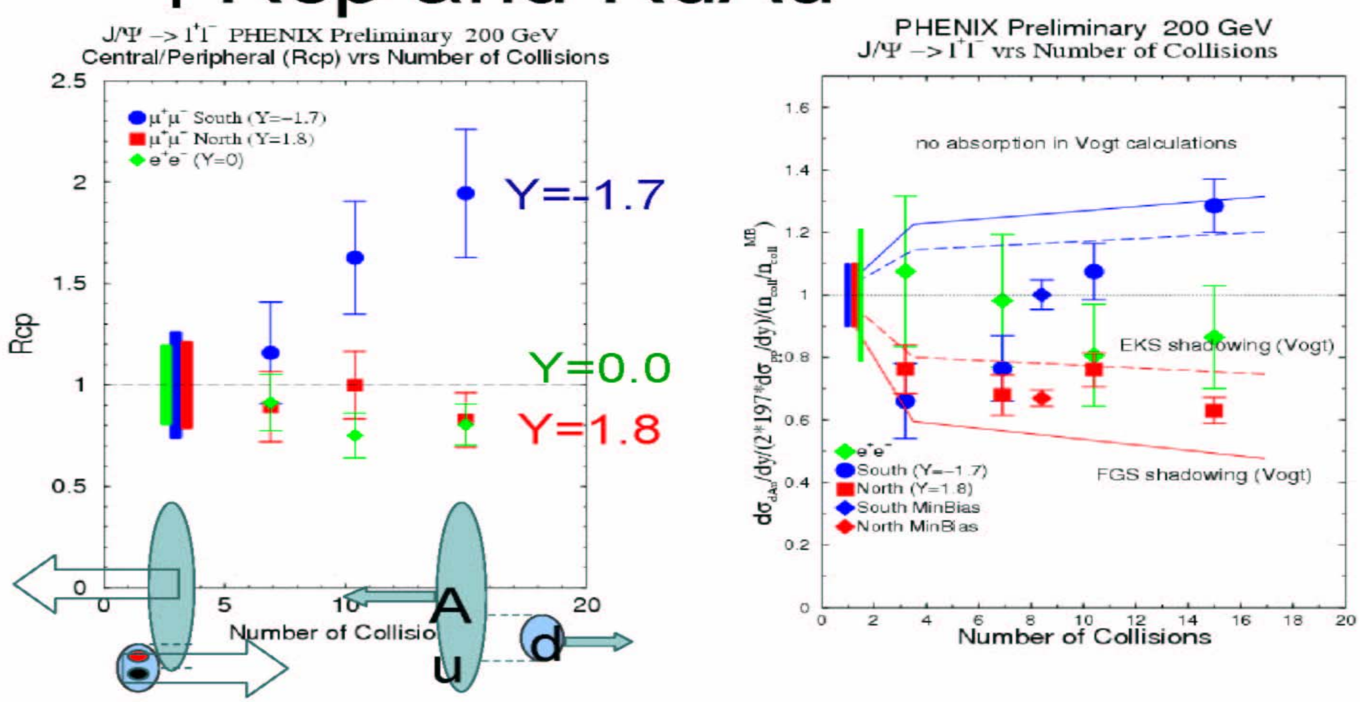


P. Steinberg, Hot Quark 2004 Workshop, July 2004



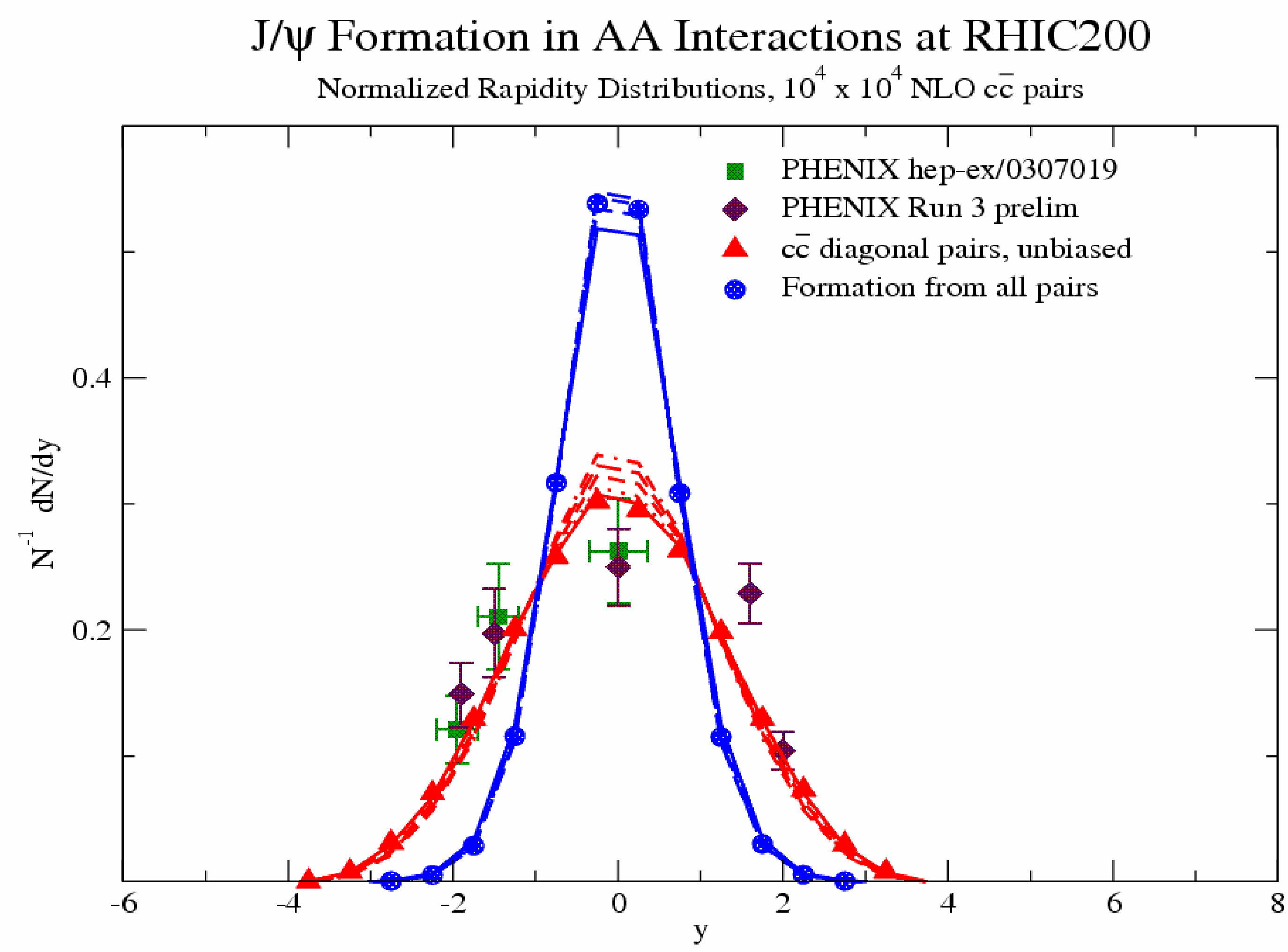
J. Burward-Hoy, Winter Workshop on Nuclear Dynamics, 2004

Rcp and RdAu

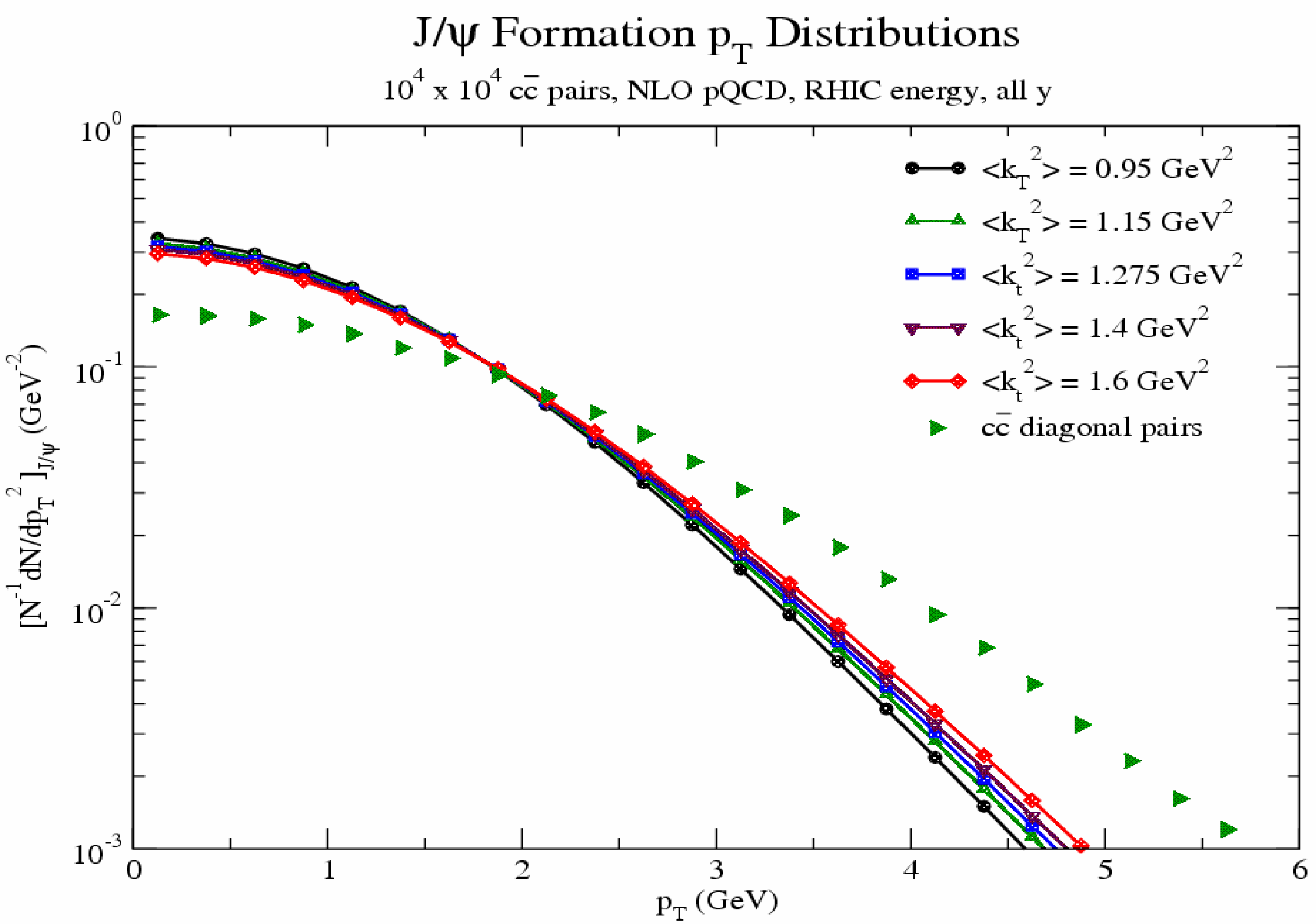


- RdA: average over centrality consistent with minimum bias result.
- Weak nuclear effects at forward rapidities (green points at midrapidity)
- Stronger centrality dependence at backward rapidities

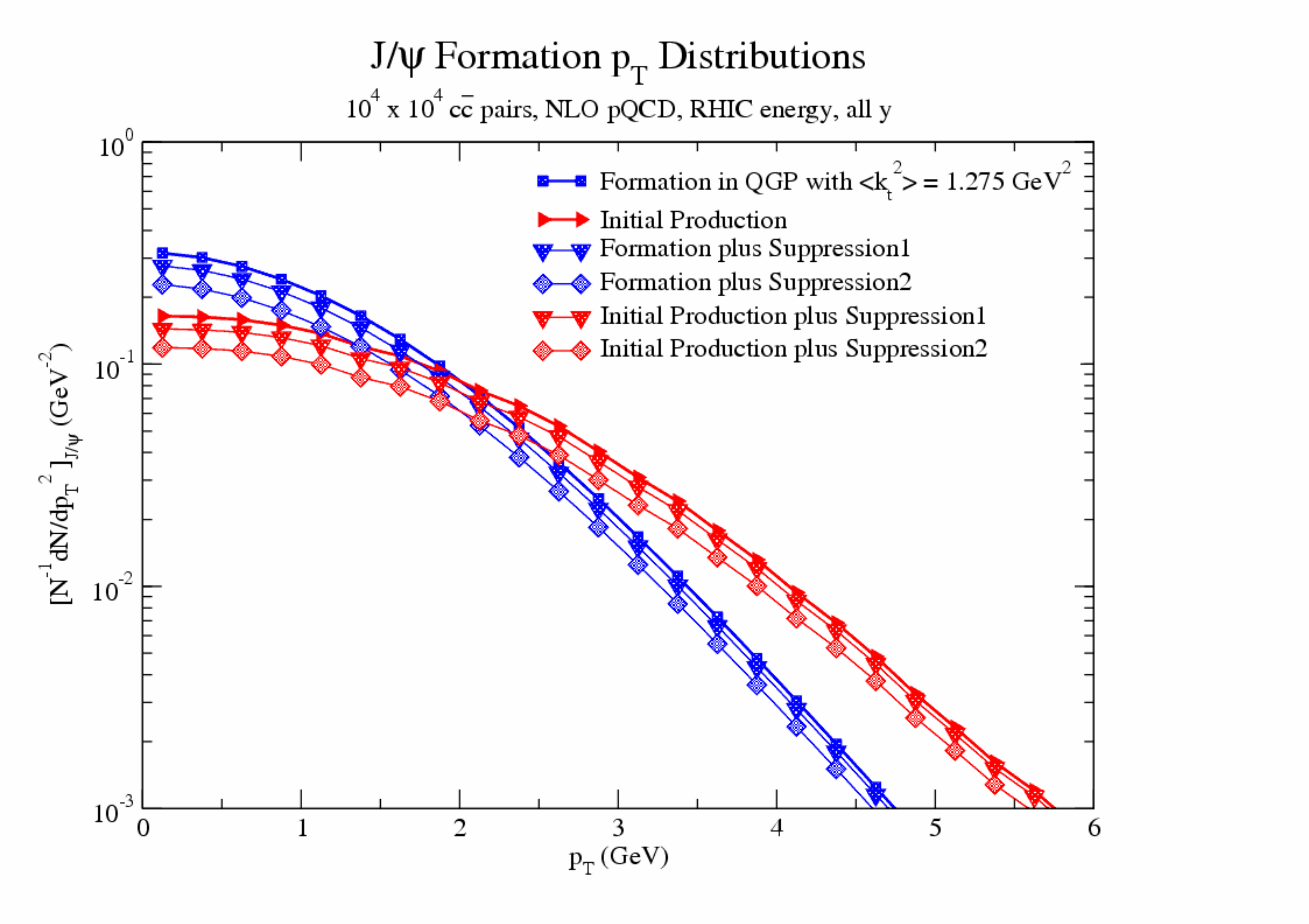
Formation through "off-diagonal" pairs narrows rapidity distribution



Formation through "off-diagonal" pairs narrows p_t distribution



Suppression of formed or initial J/ψ in partonic medium

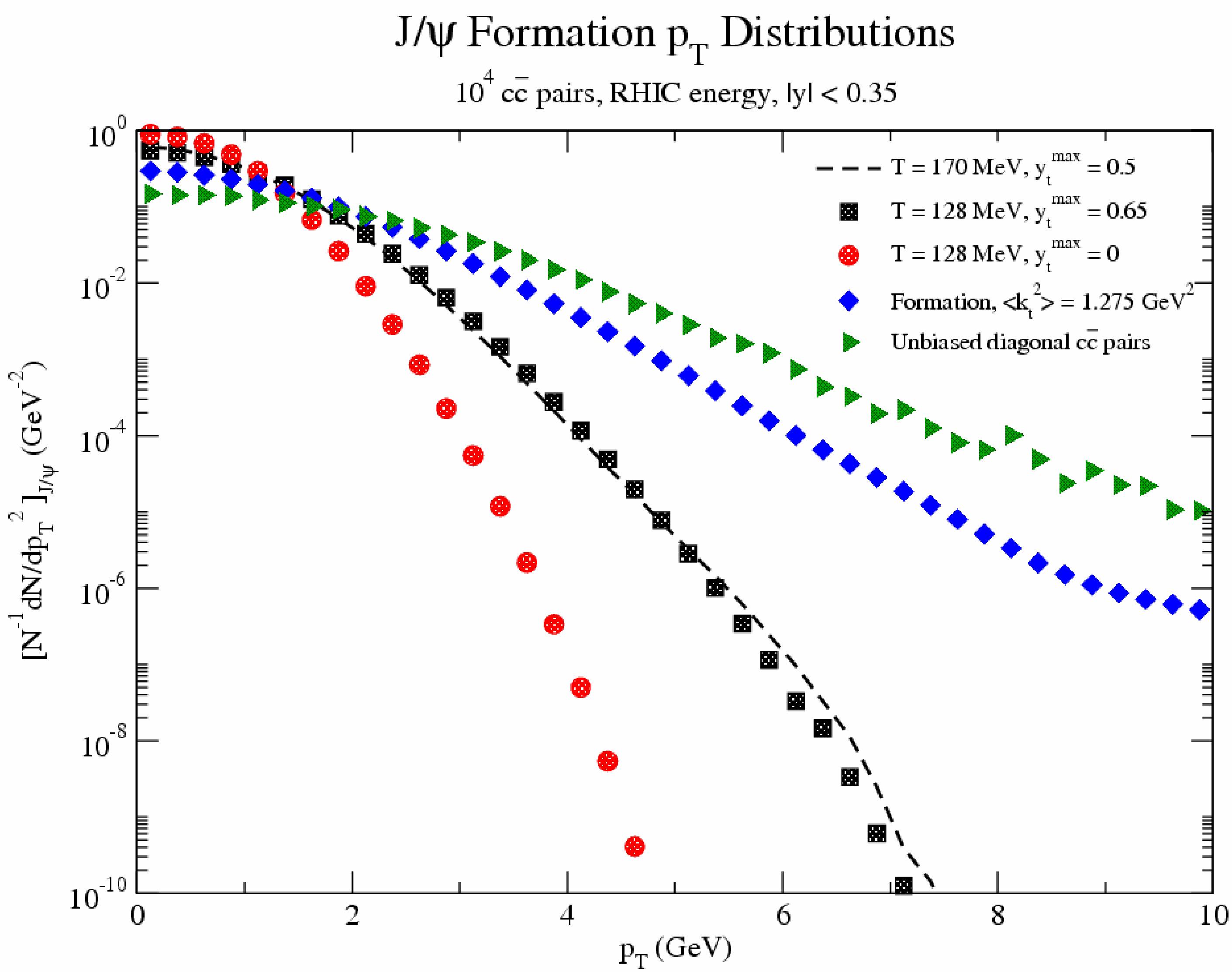


Comparison with Thermal + Transverse Flow c-Quark Distributions

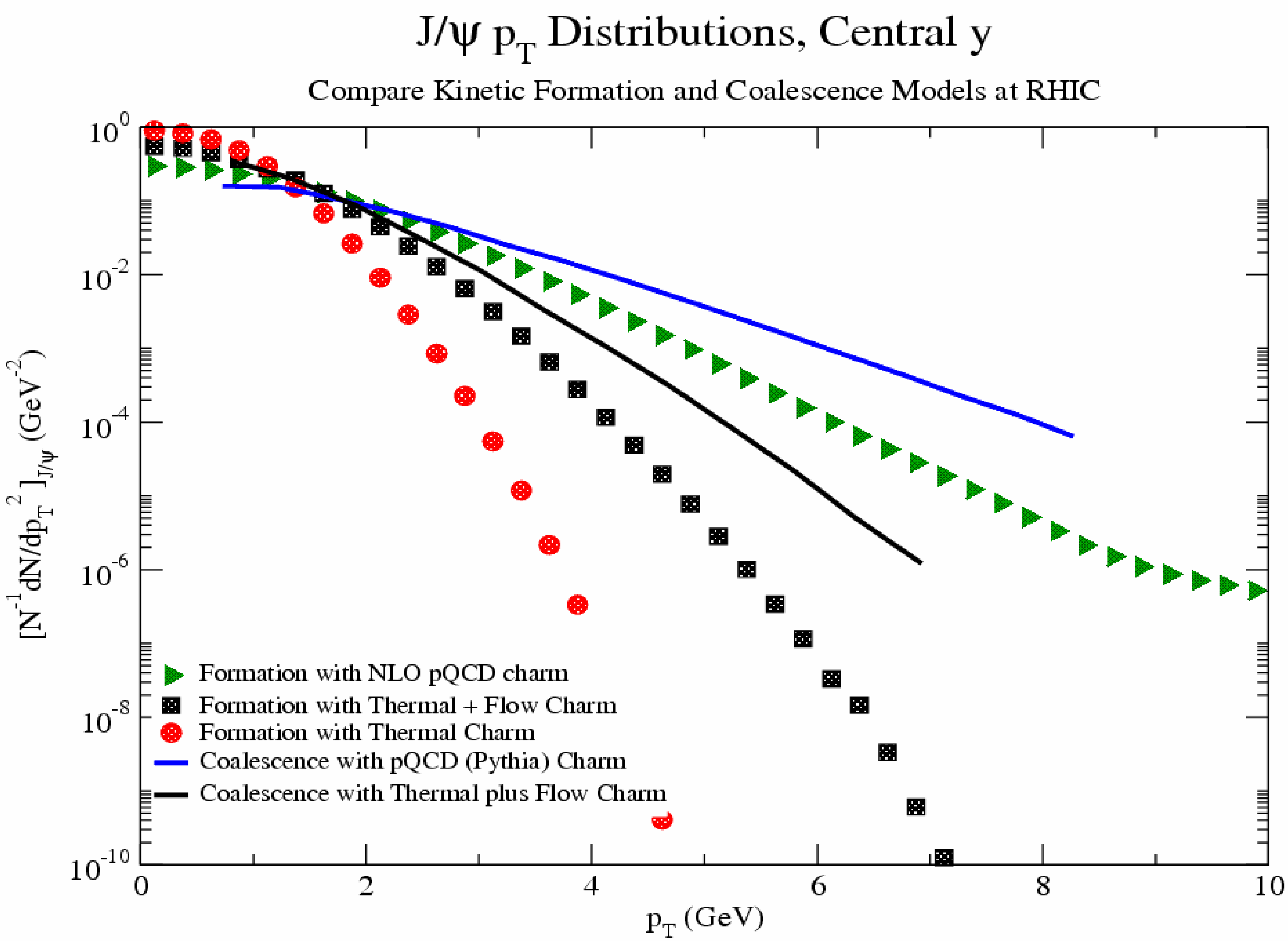
K.A.Bugaev, M. Gazdzicki, M.I.Gorenstein, Phys.Lett.B544,127(2002)

S.Batsouli, S.Kelly, M.Gyulassy, J.L.Nagle, Phys.Lett.B557,26 (2003)

$$\frac{dN}{dp_t^2} \propto m_t \int_0^R r\, dr\, I_0\left[\frac{p_t \sinh(\frac{r}{R} y_t^{\max})}{T}\right] K_1\left[\frac{m_t \cosh(\frac{r}{R} y_t^{\max})}{T}\right]$$

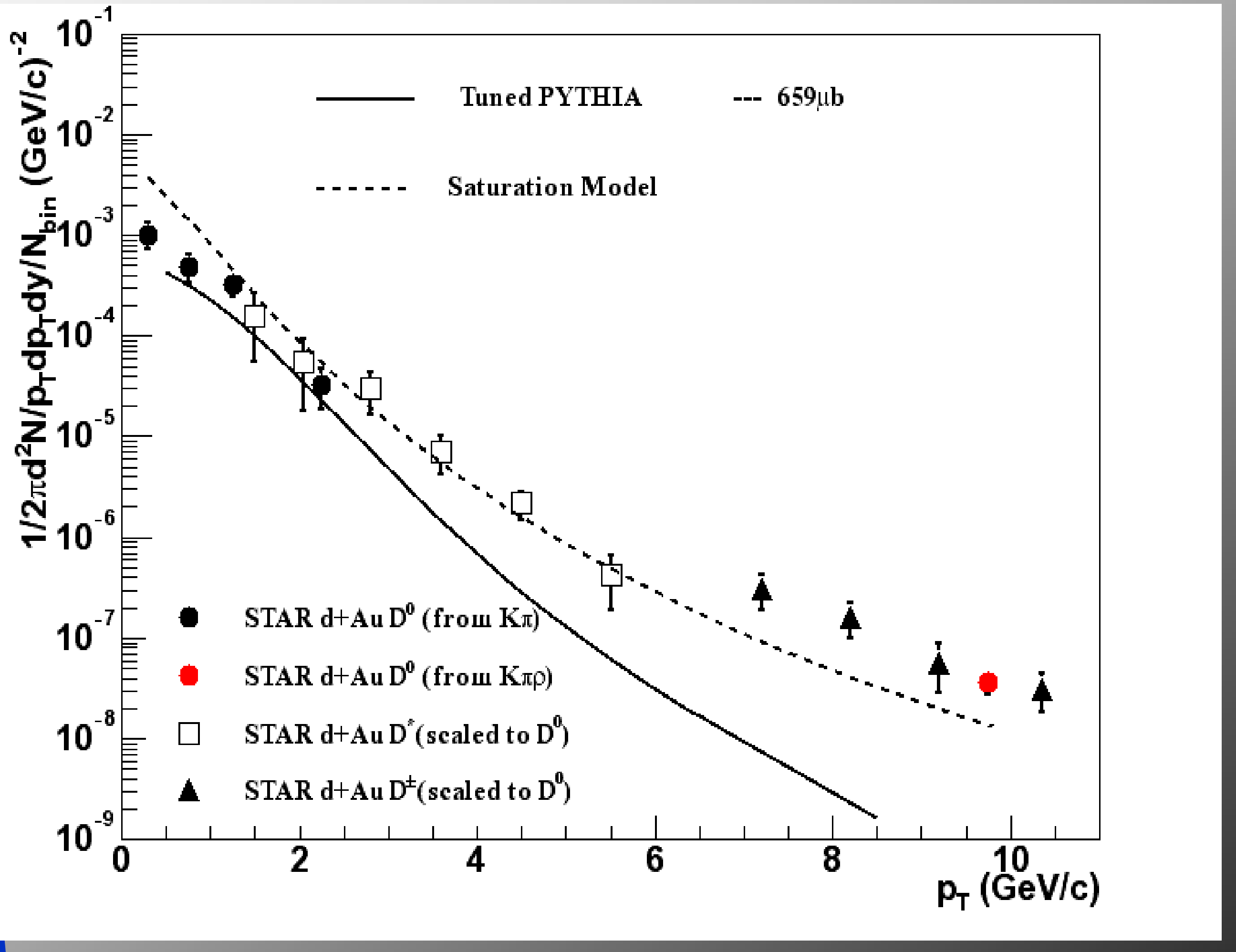

J/ψ Formation p_T Distributions
10^4 $c\bar{c}$ pairs, RHIC energy, |y| < 0.35
$[N^{-1} dN/dp_T^2]_{J/\psi}$ (GeV^{-2})
p_T (GeV)
T = 170 MeV, y_t^{max} = 0.5
T = 128 MeV, y_t^{max} = 0.65
T = 128 MeV, y_t^{max} = 0
Formation, $\langle k_t^2 \rangle$ = 1.275 GeV^2
Unbiased diagonal $c\bar{c}$ pairs
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
0
2
4
6
8
10

Comparison with coalescence model: V Greco, C. M. Ko, R. Rapp, Phys. Lett. B595:202 (2004)



SUMMARY

- Absolute magnitude and centrality dependence tests require both open and hidden flavor
- Pt and y signature of kinetic process
- Both mechanisms contribute to total production
- Stat hadronization also predicts open/hidden
- Formation process very sensitive to quark flow



Tuned PYTHIA
--- 659μb
Saturation Model
STAR d+Au D⁰ (from Kπ)
STAR d+Au D⁰ (from Kπρ)
STAR d+Au D*(scaled to D⁰)
STAR d+Au D±(scaled to D⁰)
1/2πd²N/p_T dp_T dy/N_bin (GeV/c)^-2
p_T (GeV/c)