IN-MEDIUM FORMATION OF J/ψ: PROBE OF CHARM QUARK THERMALIZATION

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WORKSHOP ON QGP THERMALIZATION
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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

Multiple ccbar pairs in high energy AA Collisions

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

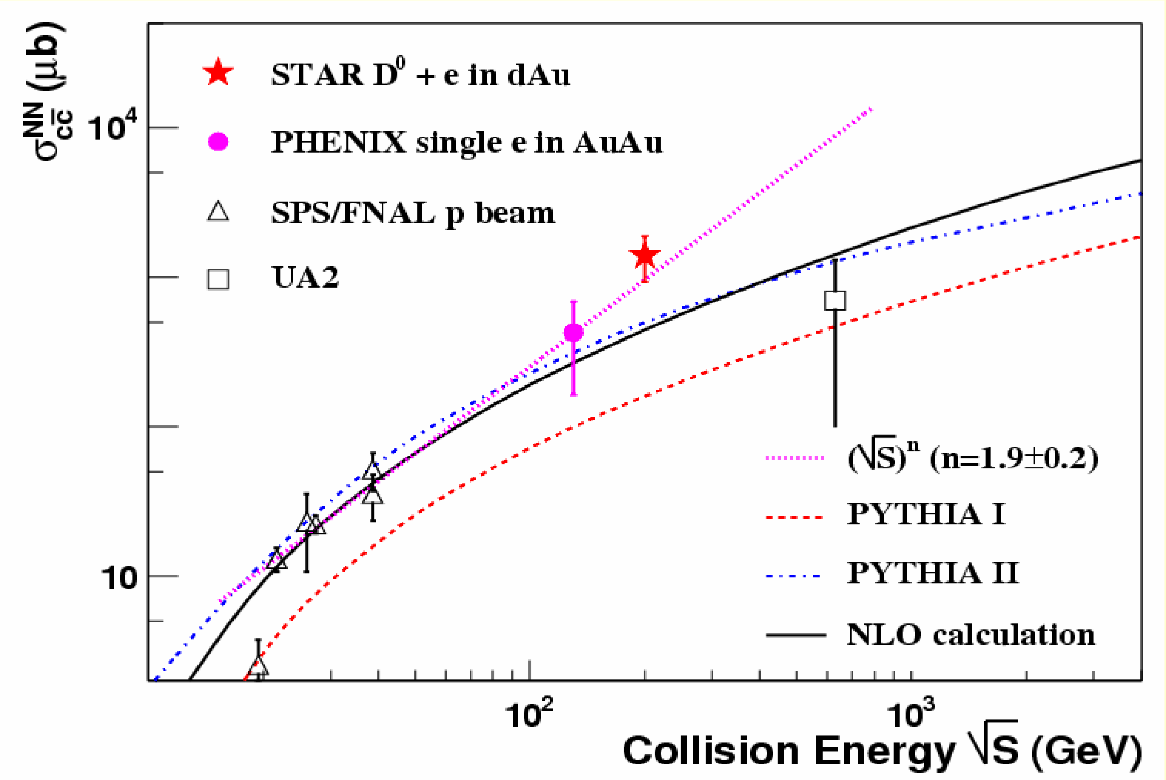
CENTRAL VALUES:

- 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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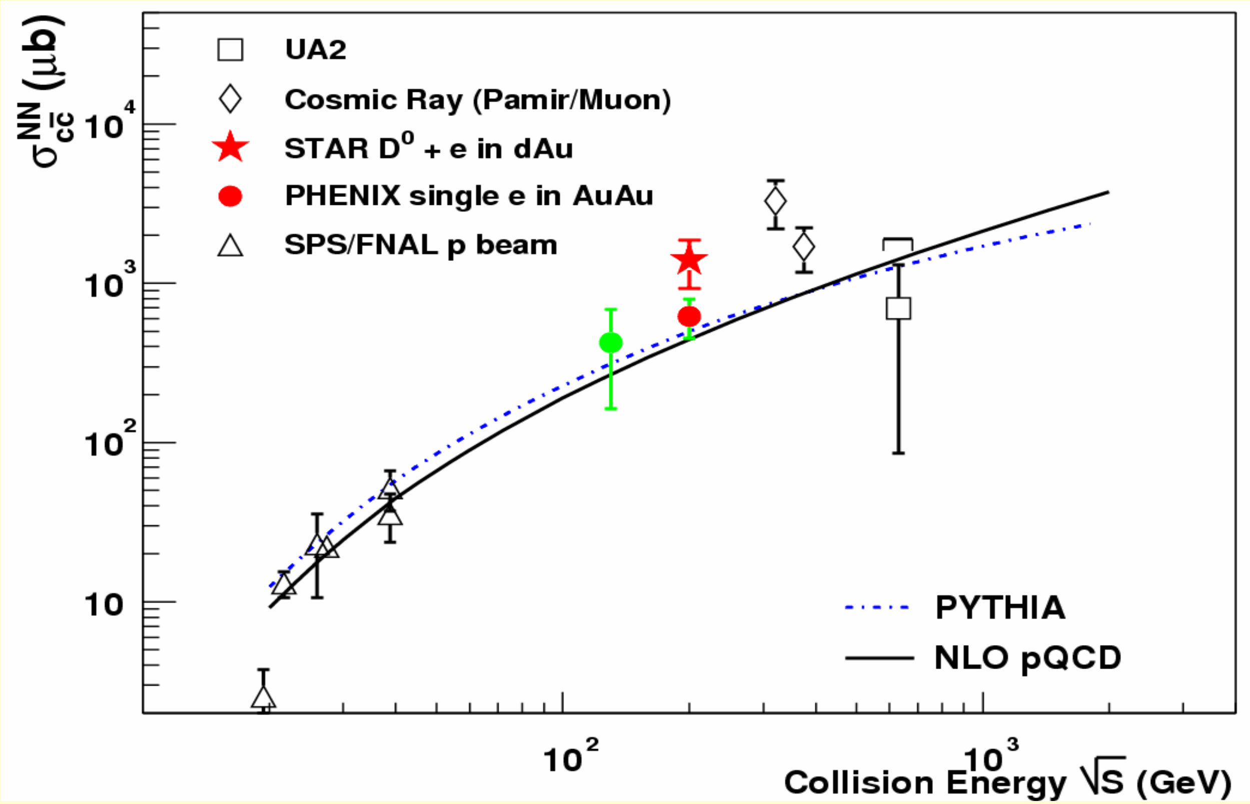


PROBE REGION OF COLOR DECONFINEMENT WITH MULTIPLE PAIRS OF HEAVY QUARKS

Avoids Matsui-Satz Condition

Form Quarkonium directly in the Medium

Formation and Suppression Competition

Scenario supported by lattice calculations of quarkonium spectral functions

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 $\bar{\mathrm{c}}$:

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

Average over fluctuations:

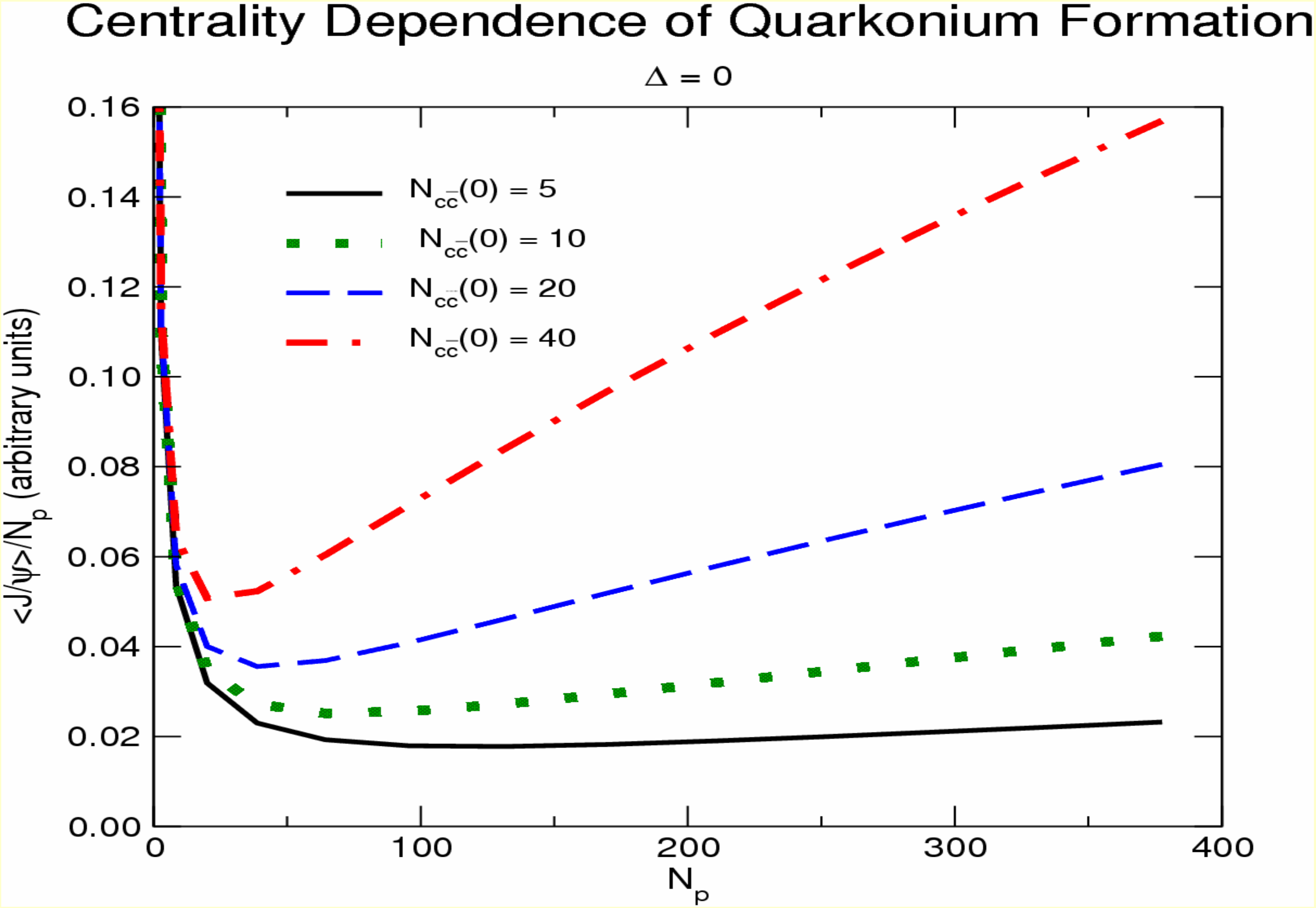
$$< J/\psi >= \lambda \ < N_{c\bar{c}} > (< N_{c\bar{c}} > +1) / N_{ch}$$

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



FORMATION OF QUARKONIUM IN REGION OF COLOR DECONFINEMENT

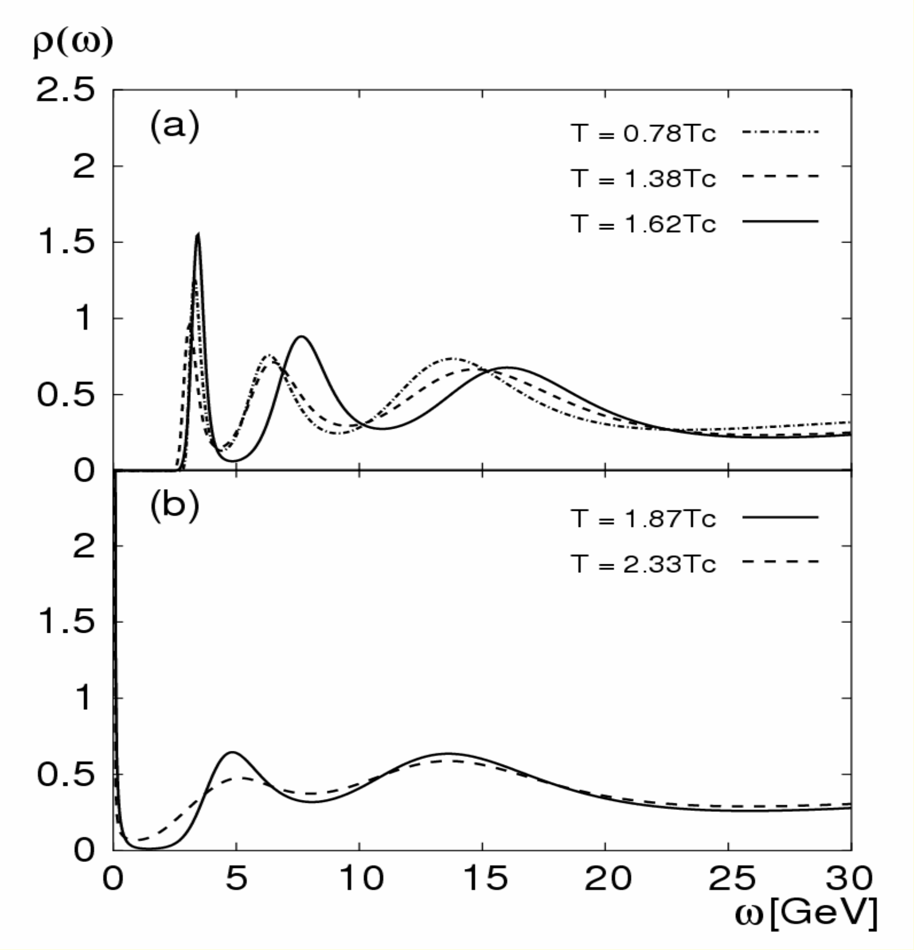
R. L. Thews, M. Schroedter, and J. Rafelski, Phys. Rev. C63:054905 (2001)

Formation process is Inverse of dissociation

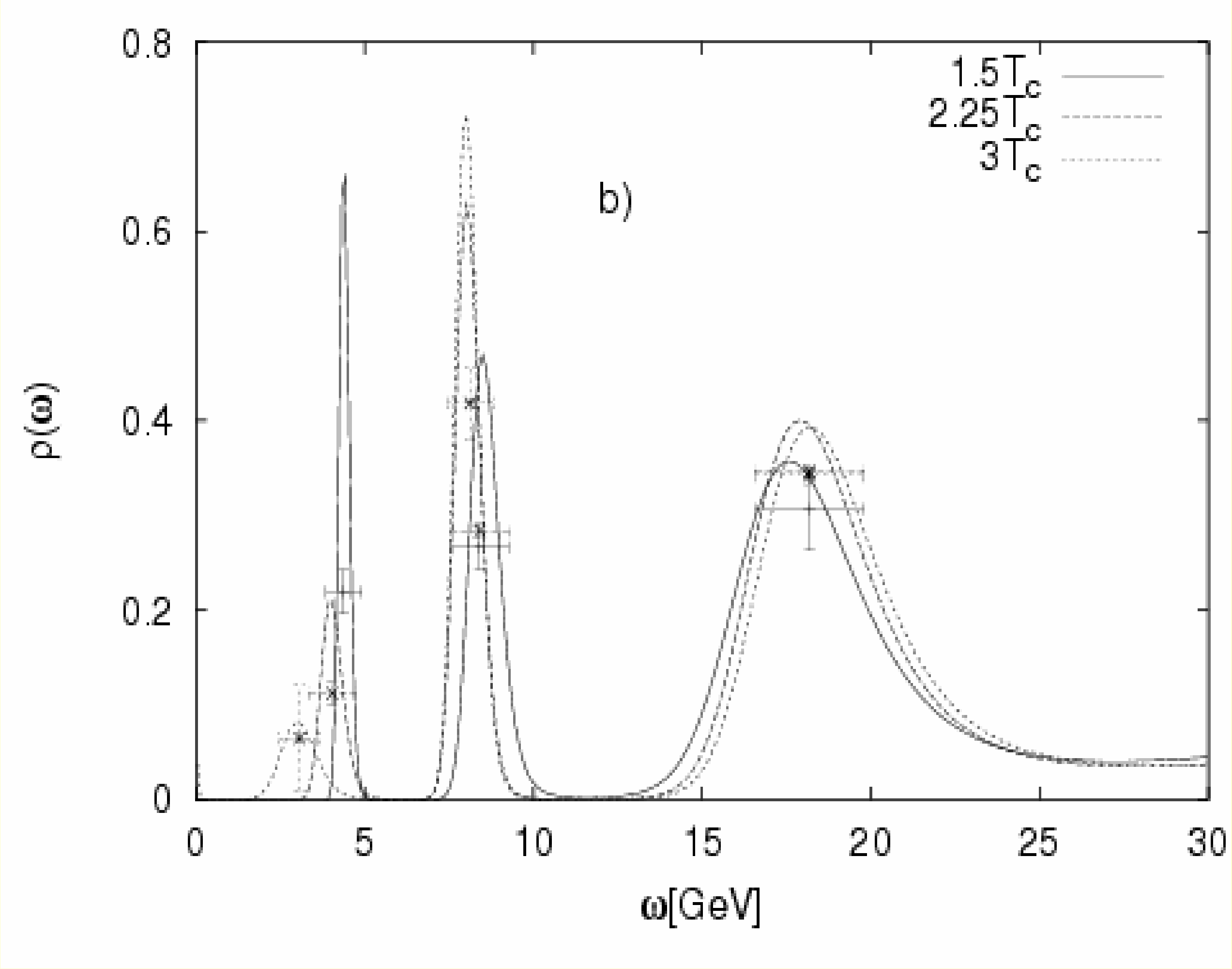
Model evolution of region with initial temperature and isentropic expansion, depends on contours of participant density

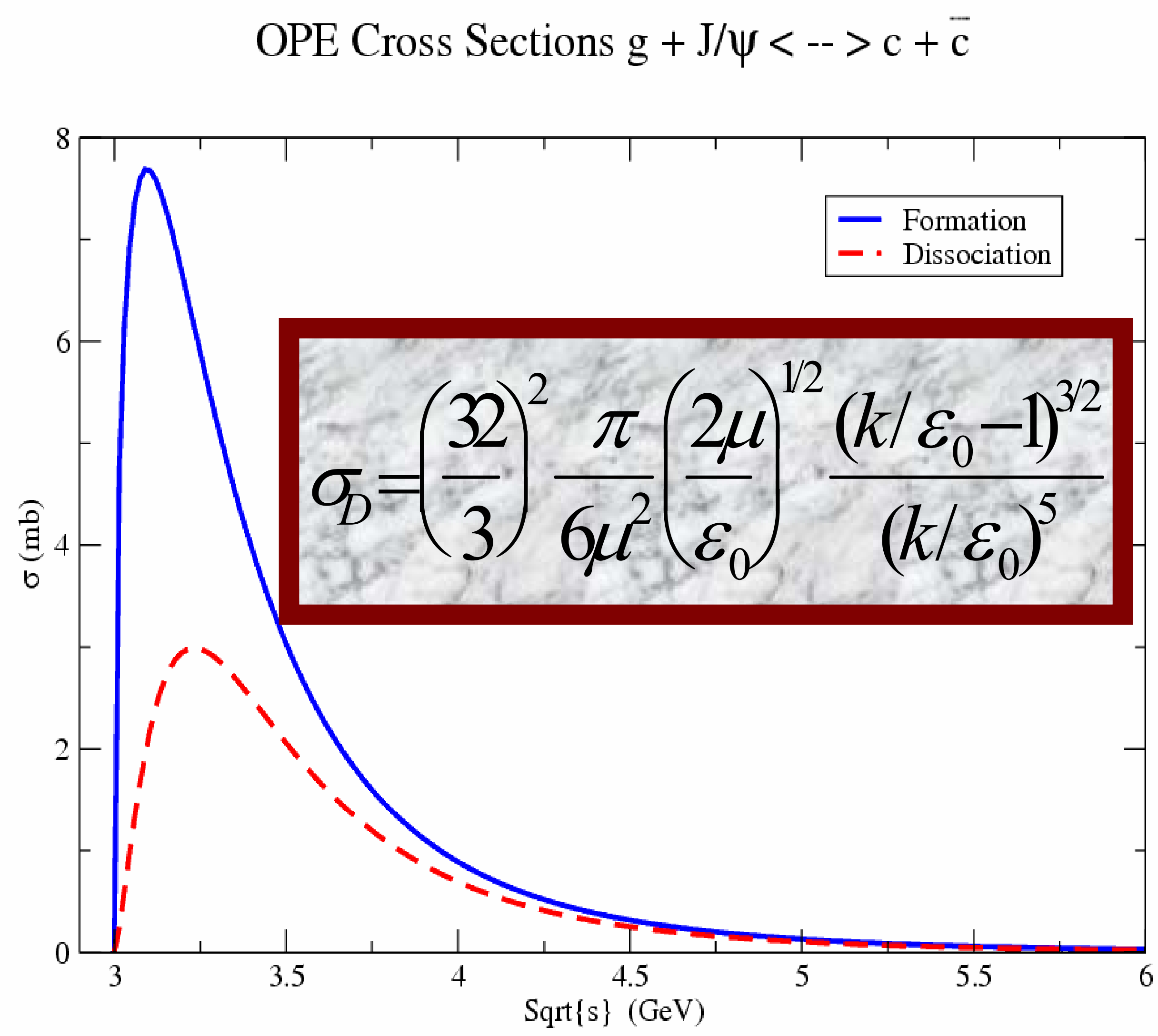
Final population determined by competition between formation and dissociation rates

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



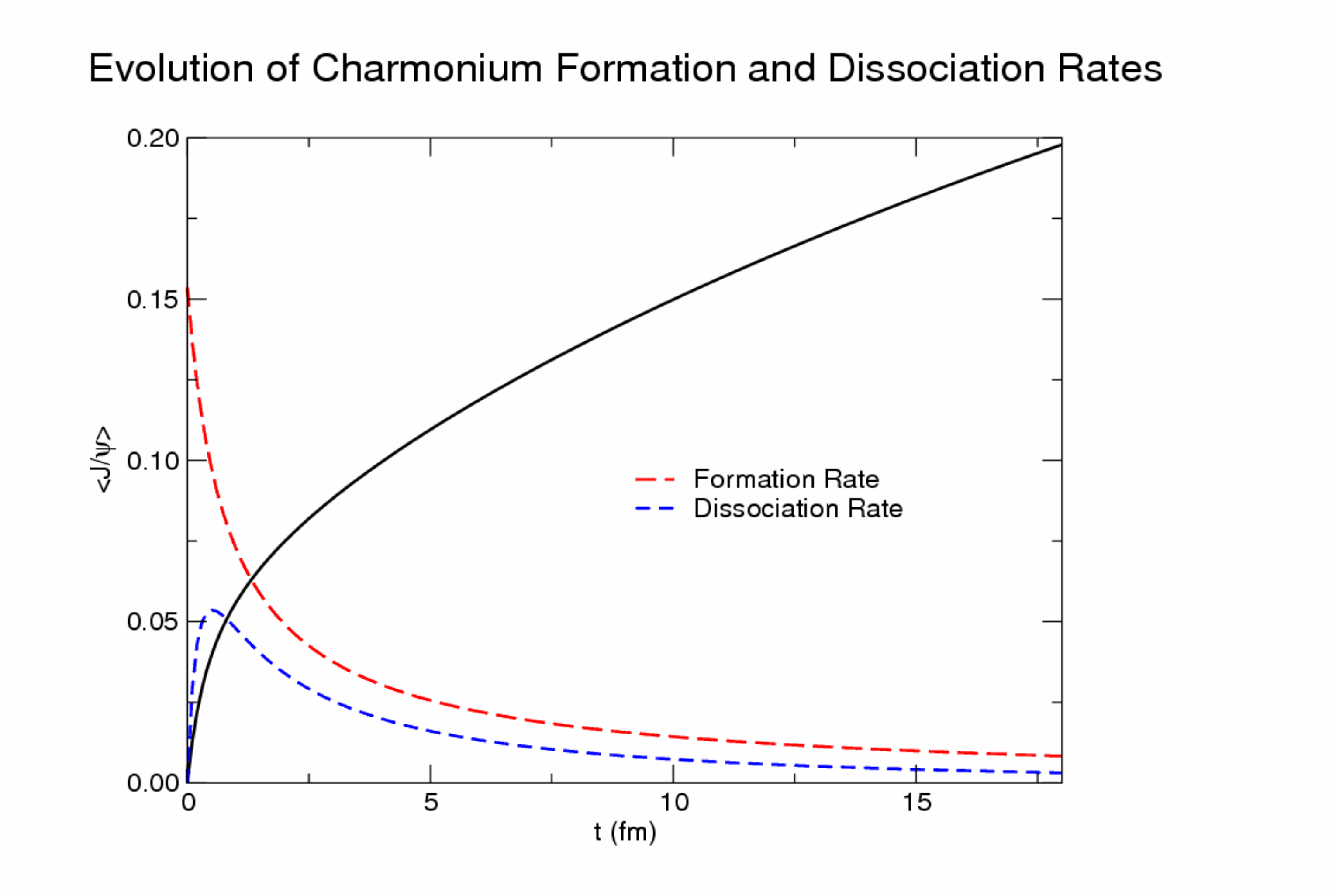
S. Datta, F. Karsch, P. Petreczky, I. Wetzorke, Phys. Rev. D69:094507 (2004)





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

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



J/Psi yield is Quadratic in Total Charm

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

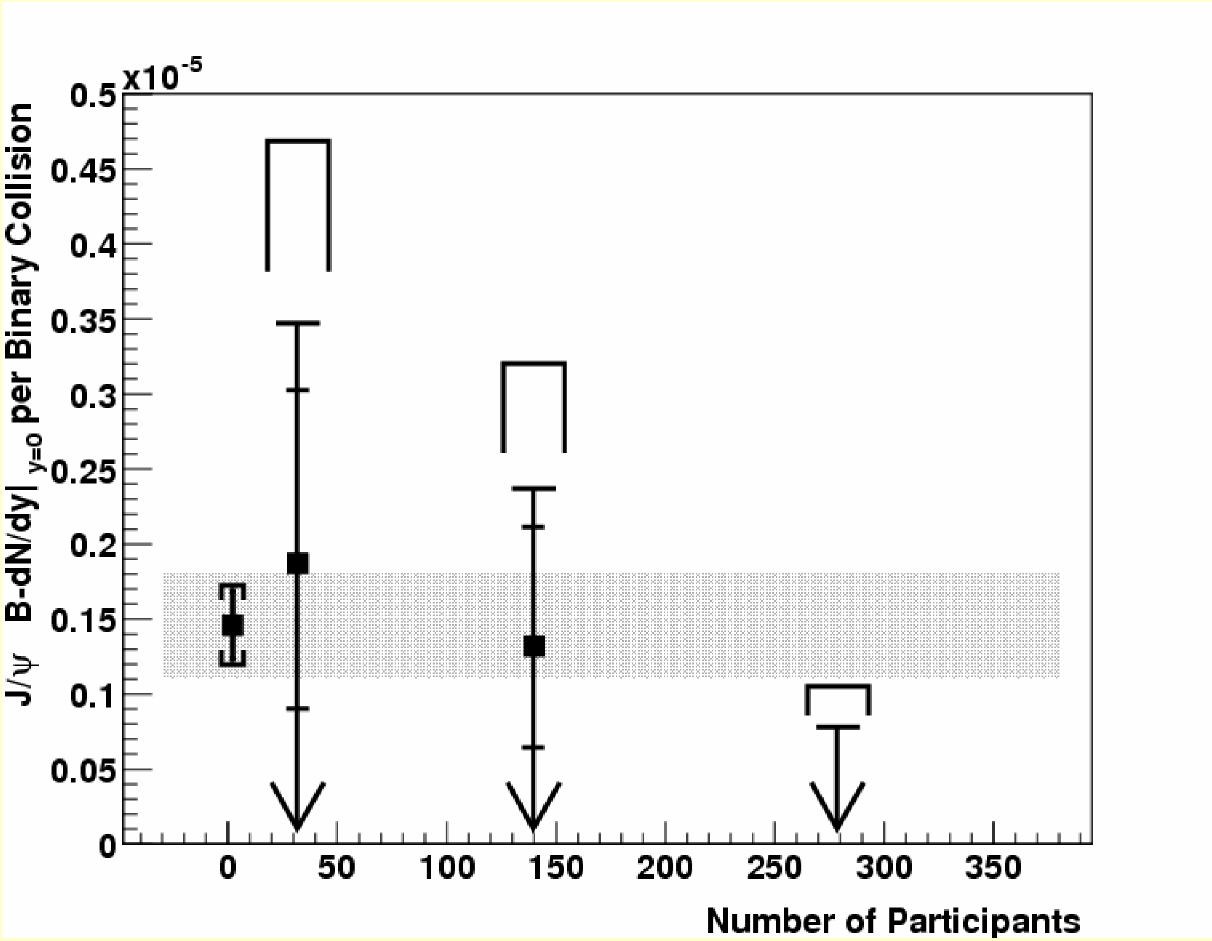
$$\varepsilon(\tau) = \exp[-\int_{\tau_0}^{\tau} \lambda_D \, \rho_g \, d\tau]$$

COMPARISON WITH INITIAL PHENIX DATA AT RHIC 200

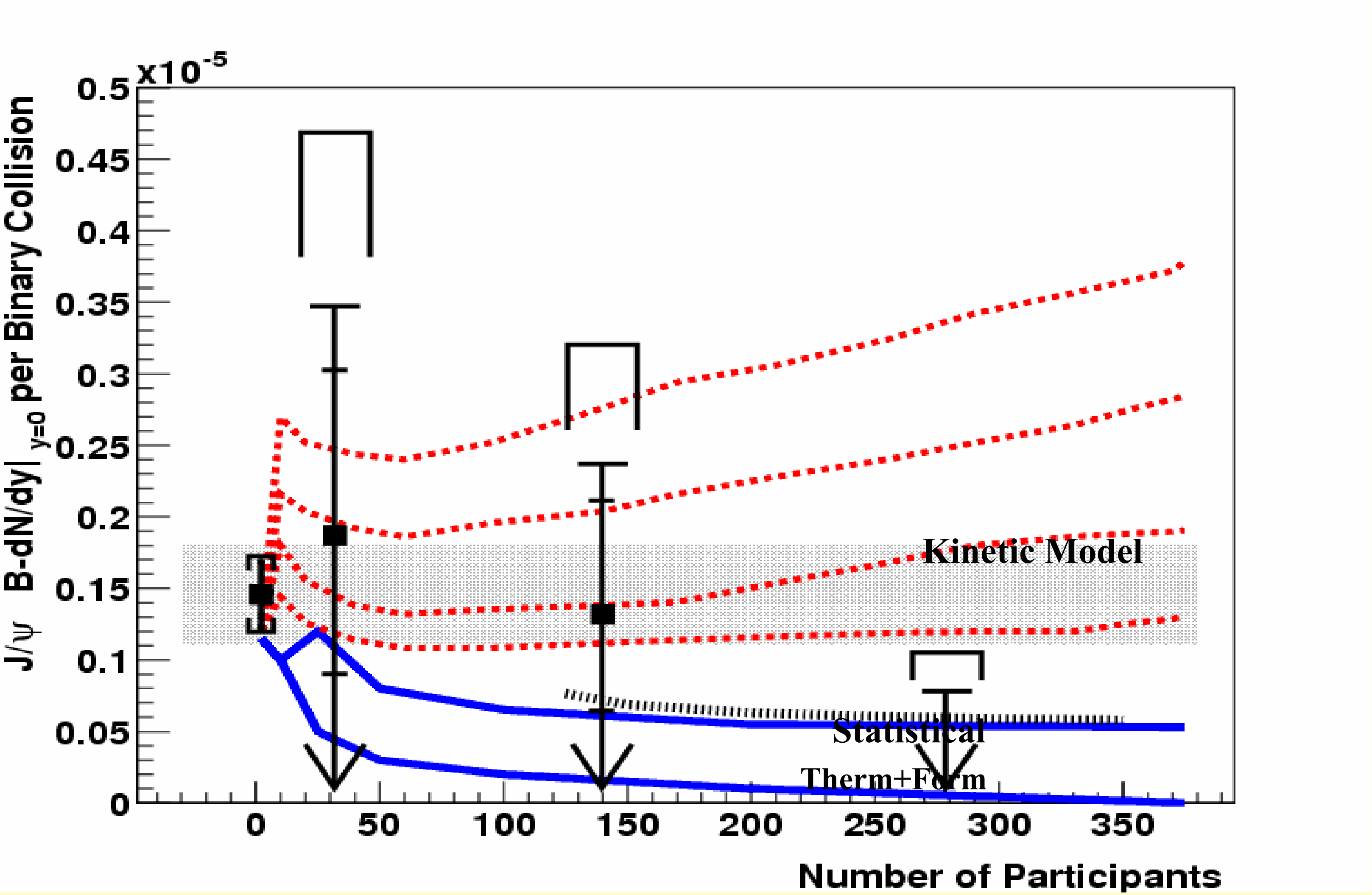
Rates very sensitive to quark momentum distribution

Centrality signature varies with magnitude of N_{cc}

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



Model predictions very sensitive to N_{cc} and distribution



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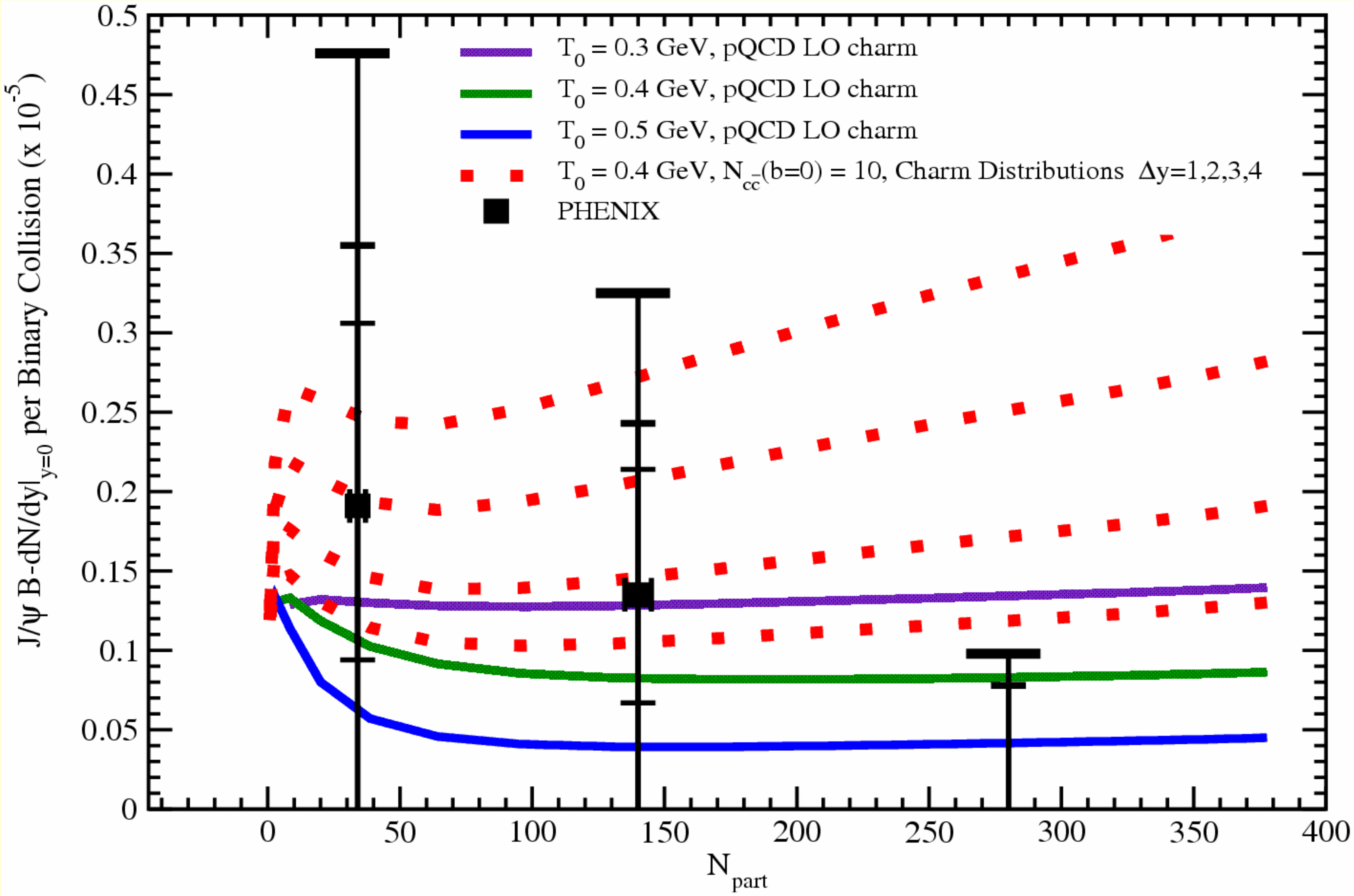
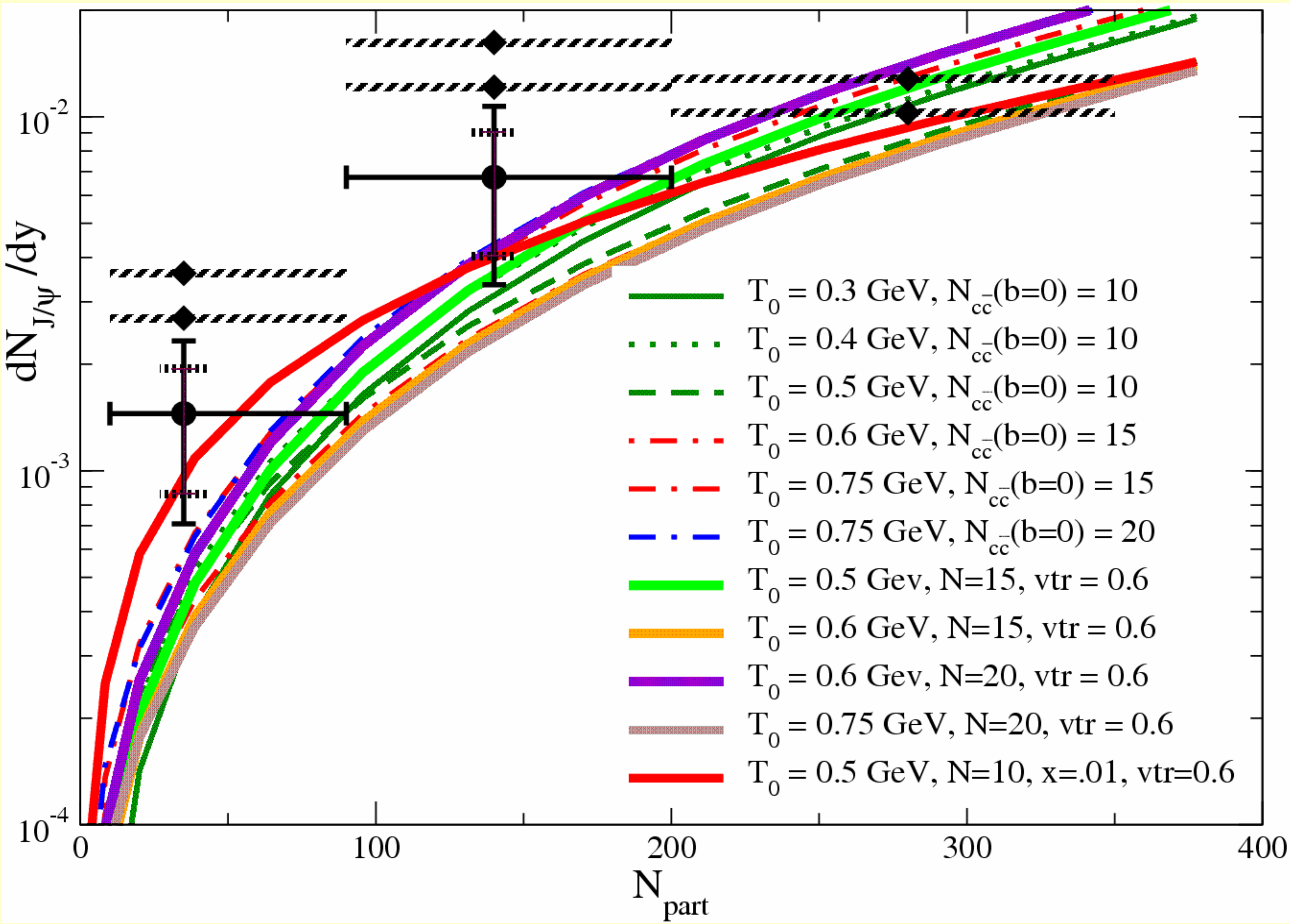




$dN_{J/\psi}/dy$
10^{-2}
10^{-3}
10^{-4}
0
100
200
300
400
N_{part}
T_0 = 0.3 GeV, $N_{c\bar{c}}$(b=0) = 10
T_0 = 0.4 GeV, $N_{c\bar{c}}$(b=0) = 10
T_0 = 0.5 GeV, $N_{c\bar{c}}$(b=0) = 10
T_0 = 0.6 GeV, $N_{c\bar{c}}$(b=0) = 15
T_0 = 0.75 GeV, $N_{c\bar{c}}$(b=0) = 15
T_0 = 0.75 GeV, $N_{c\bar{c}}$(b=0) = 20
T_0 = 0.5 Gev, N=15, vtr = 0.6
T_0 = 0.6 GeV, N=15, vtr = 0.6
T_0 = 0.6 Gev, N=20, vtr = 0.6
T_0 = 0.75 GeV, N=20, vtr = 0.6
T_0 = 0.5 GeV, N=10, x=.01, vtr=0.6

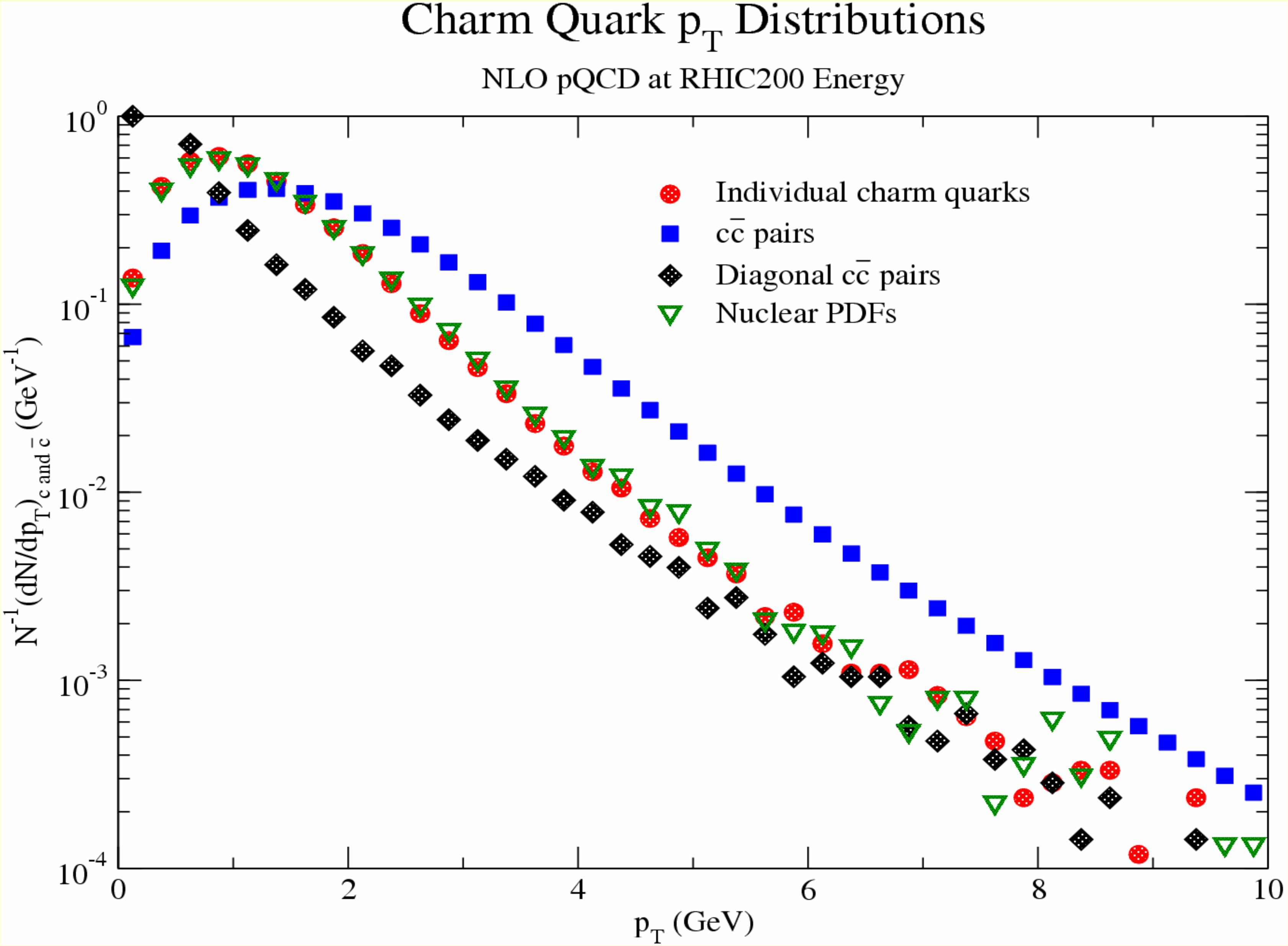
DO THE Y AND P_T SPECTRA PROVIDE A QUARK THERMALIZATION SIGNATURE?

M. Mangano and R. L. Thews: nucl-th/0505055

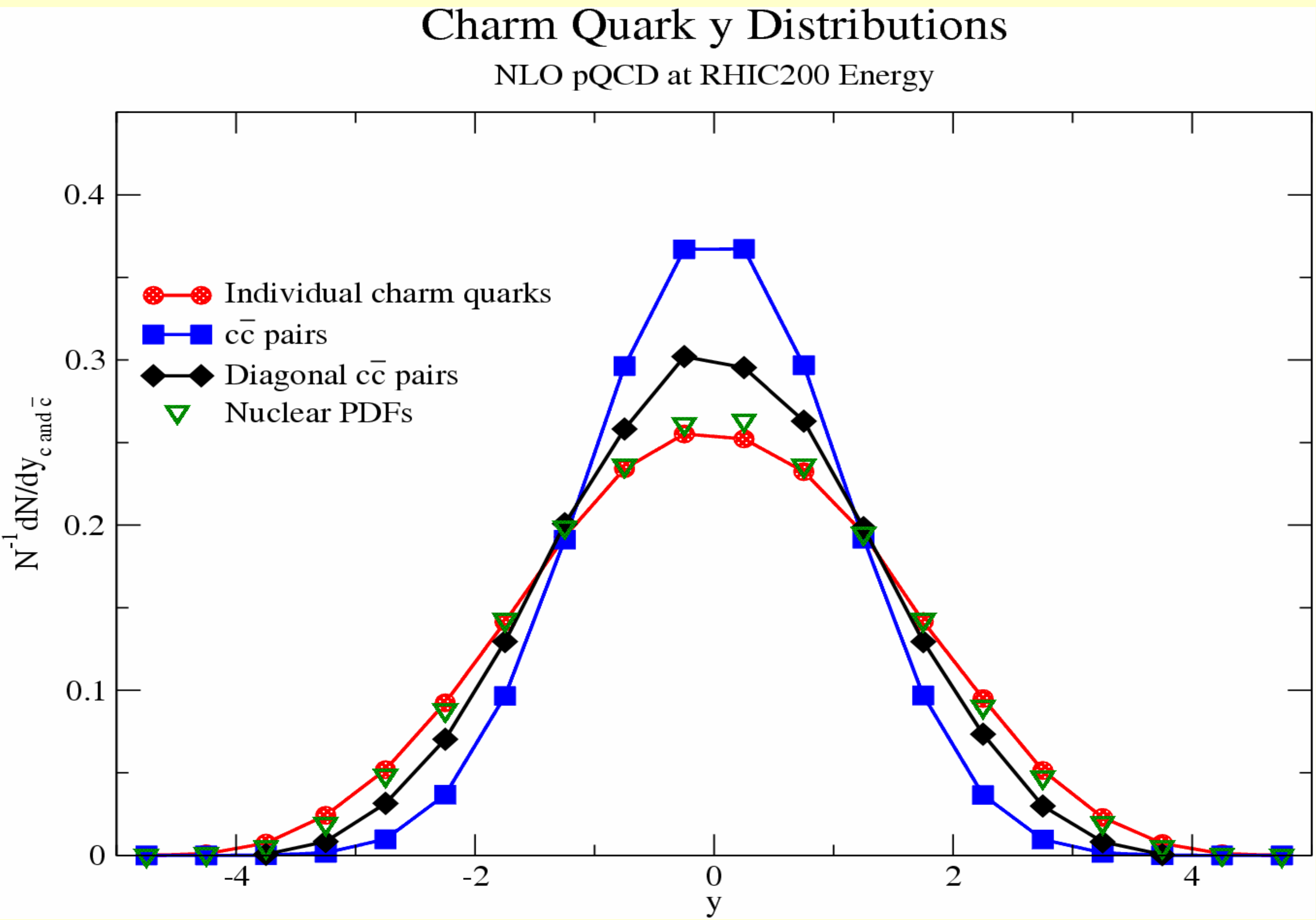
1. Generate sample of ccbar pairs from NLO pQCD (smear LO q_t)
2. Supplement with k_t to simulate initial state and confinement effects
3. Integrate formation rate using these events to define particle distributions (no cquark-medium interaction)
4. Repeat with cquark thermal+flow distribution (maximal cquark-medium interaction)

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

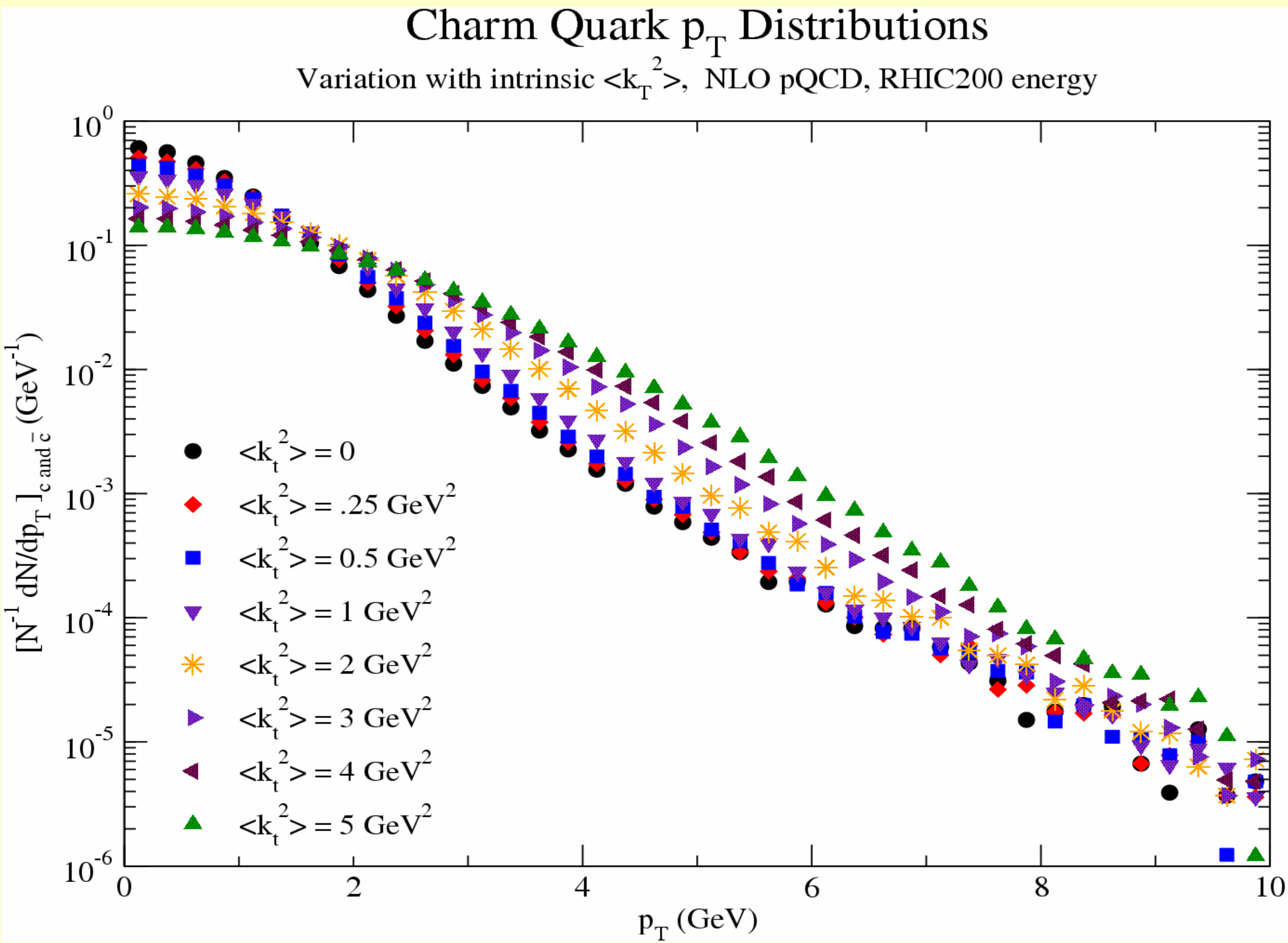
- All combinations of c and cbar contribute
- Total has expected $(N_{ccbar})^2$ / V behavior
- Prefactor is integrated flux per ccbar pair



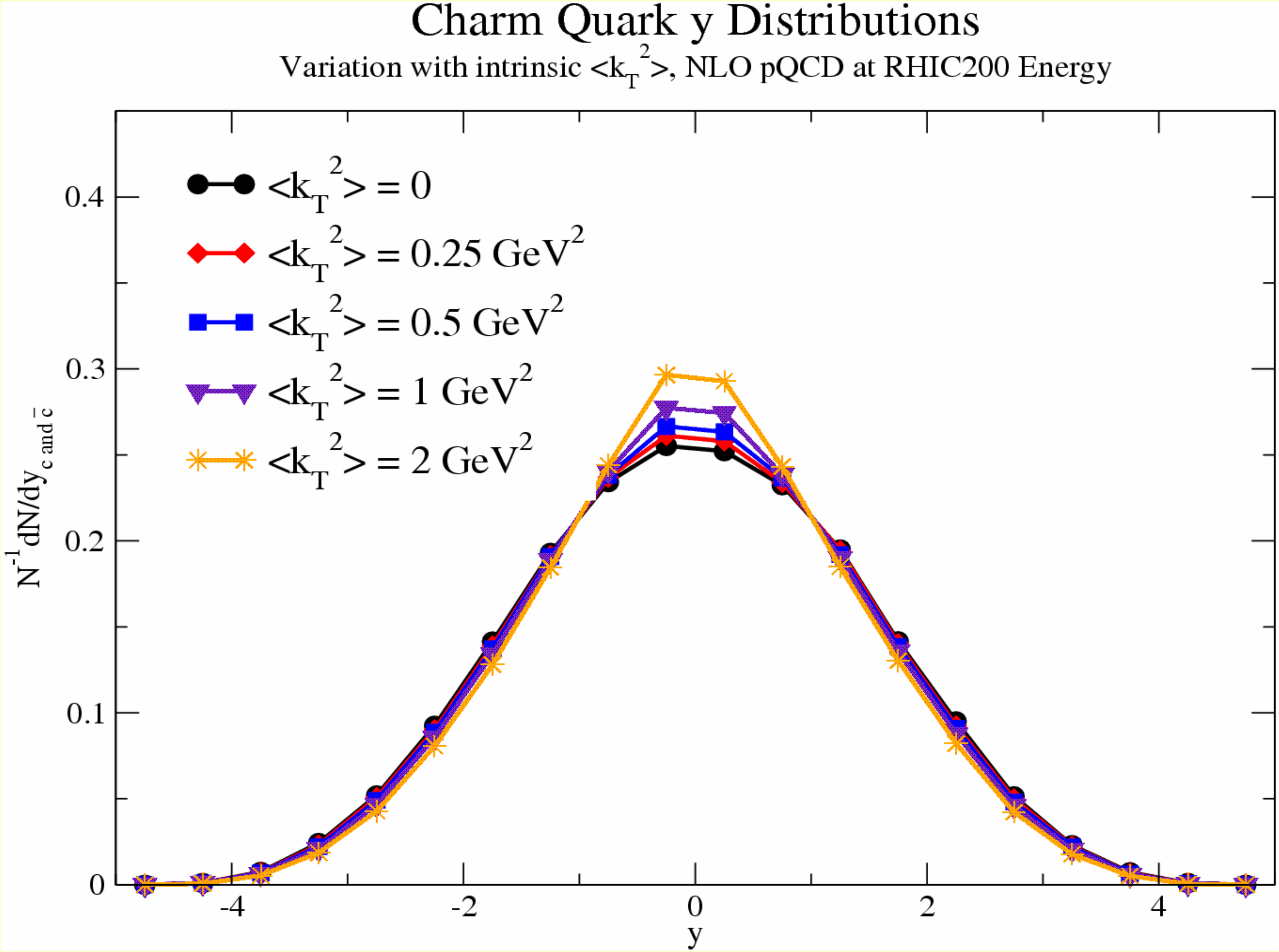
Charm Quark p_T Distributions
NLO pQCD at RHIC200 Energy
Individual charm quarks
$c\bar{c}$ pairs
Diagonal $c\bar{c}$ pairs
Nuclear PDFs
$N^{-1}(dN/dp_T)_{c\text{ and }\bar{c}}$ (GeV^{-1})
p_T (GeV)
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
2
4
6
8
10



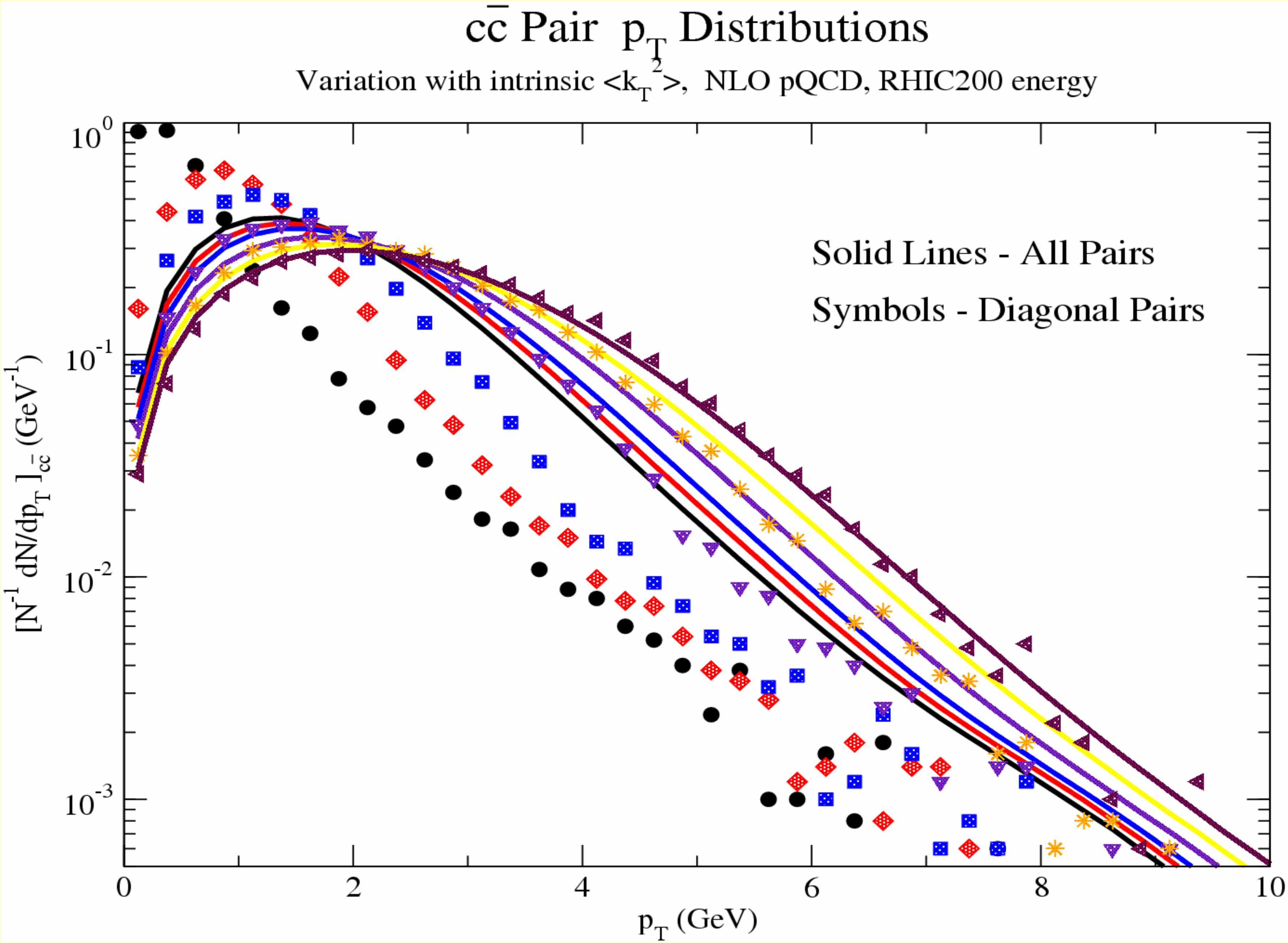
Charm Quark y Distributions
NLO pQCD at RHIC200 Energy
Individual charm quarks
$c\bar{c}$ pairs
Diagonal $c\bar{c}$ pairs
Nuclear PDFs
$N^{-1} dN/dy_{c \text{ and } \bar{c}}$
y
0.4
0.3
0.2
0.1
0
-4
-2
0
2
4



Charm Quark p_T Distributions
Variation with intrinsic $<k_T^2>$, NLO pQCD, RHIC200 energy
$[N^{-1} dN/dp_T]_{c \text{ and } \bar{c}}$ (GeV^{-1})
p_T (GeV)
$<k_t^2> = 0$
$<k_t^2> = .25$ GeV^2
$<k_t^2> = 0.5$ GeV^2
$<k_t^2> = 1$ GeV^2
$<k_t^2> = 2$ GeV^2
$<k_t^2> = 3$ GeV^2
$<k_t^2> = 4$ GeV^2
$<k_t^2> = 5$ GeV^2
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
0
2
4
6
8
10

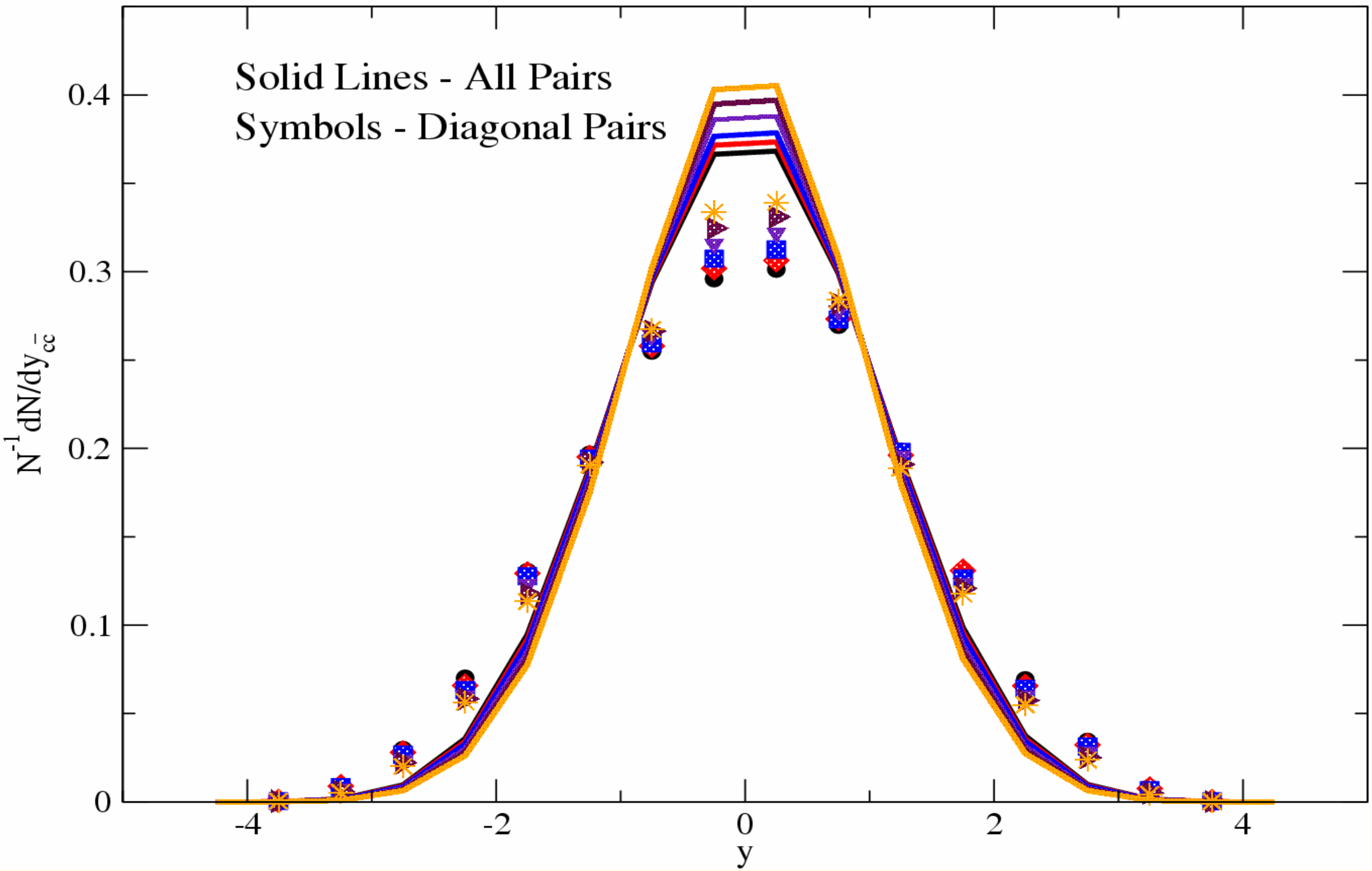


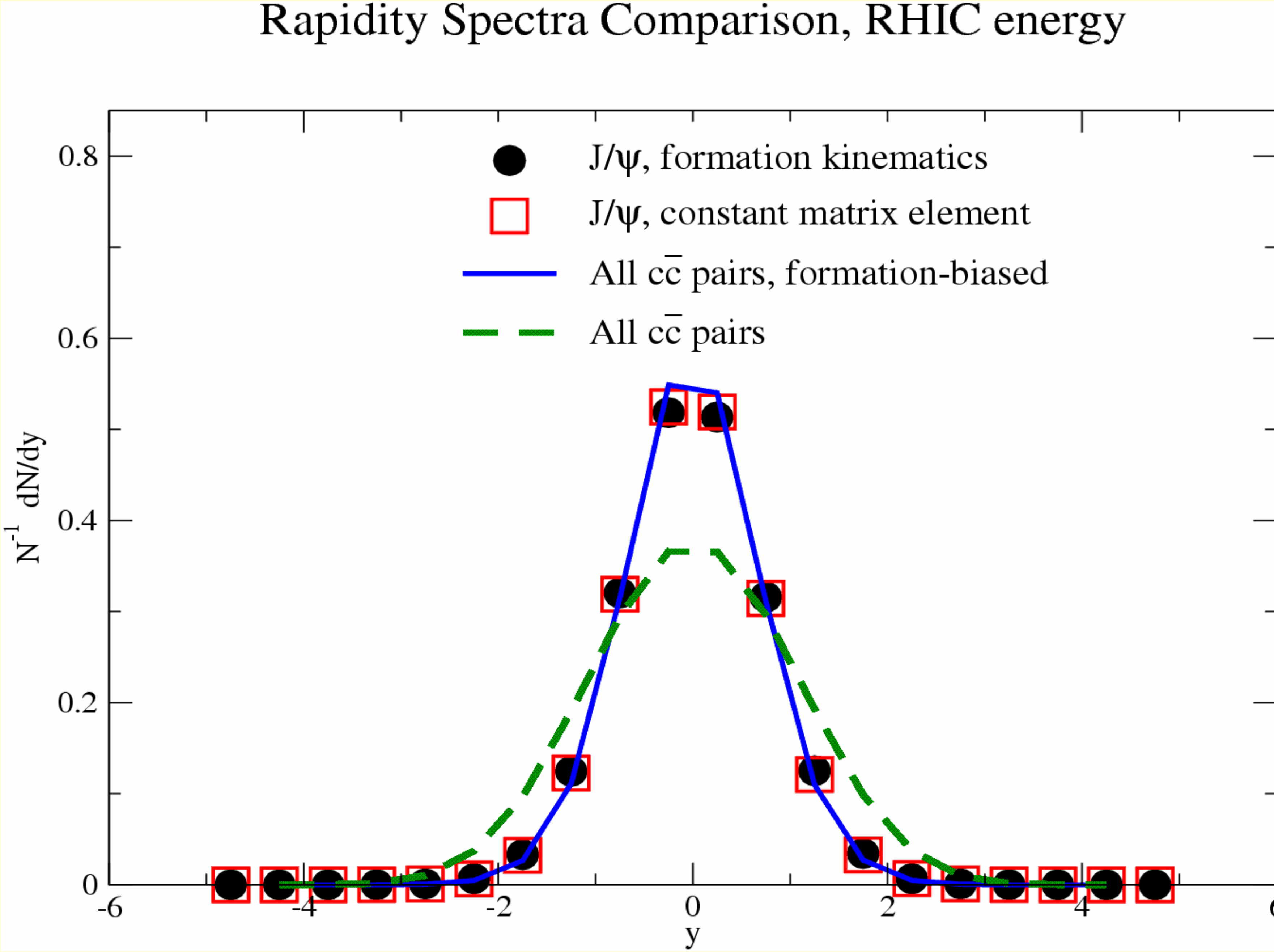
Charm Quark y Distributions
Variation with intrinsic <k_T^2>, NLO pQCD at RHIC200 Energy
<k_T^2> = 0
<k_T^2> = 0.25 GeV^2
<k_T^2> = 0.5 GeV^2
<k_T^2> = 1 GeV^2
<k_T^2> = 2 GeV^2
N^-1 dN/dy_c and c̄
y
0
0.1
0.2
0.3
0.4
-4
-2
0
2
4


$c\bar{c}$ Pair p_T Distributions
Variation with intrinsic $\langle k_T^2 \rangle$, NLO pQCD, RHIC200 energy
Solid Lines - All Pairs
Symbols - Diagonal Pairs
$[N^{-1}\, dN/dp_T\,]_{c\bar{c}}$ (GeV^{-1})
p_T (GeV)
10^0
10^{-1}
10^{-2}
10^{-3}
0
2
4
6
8
10

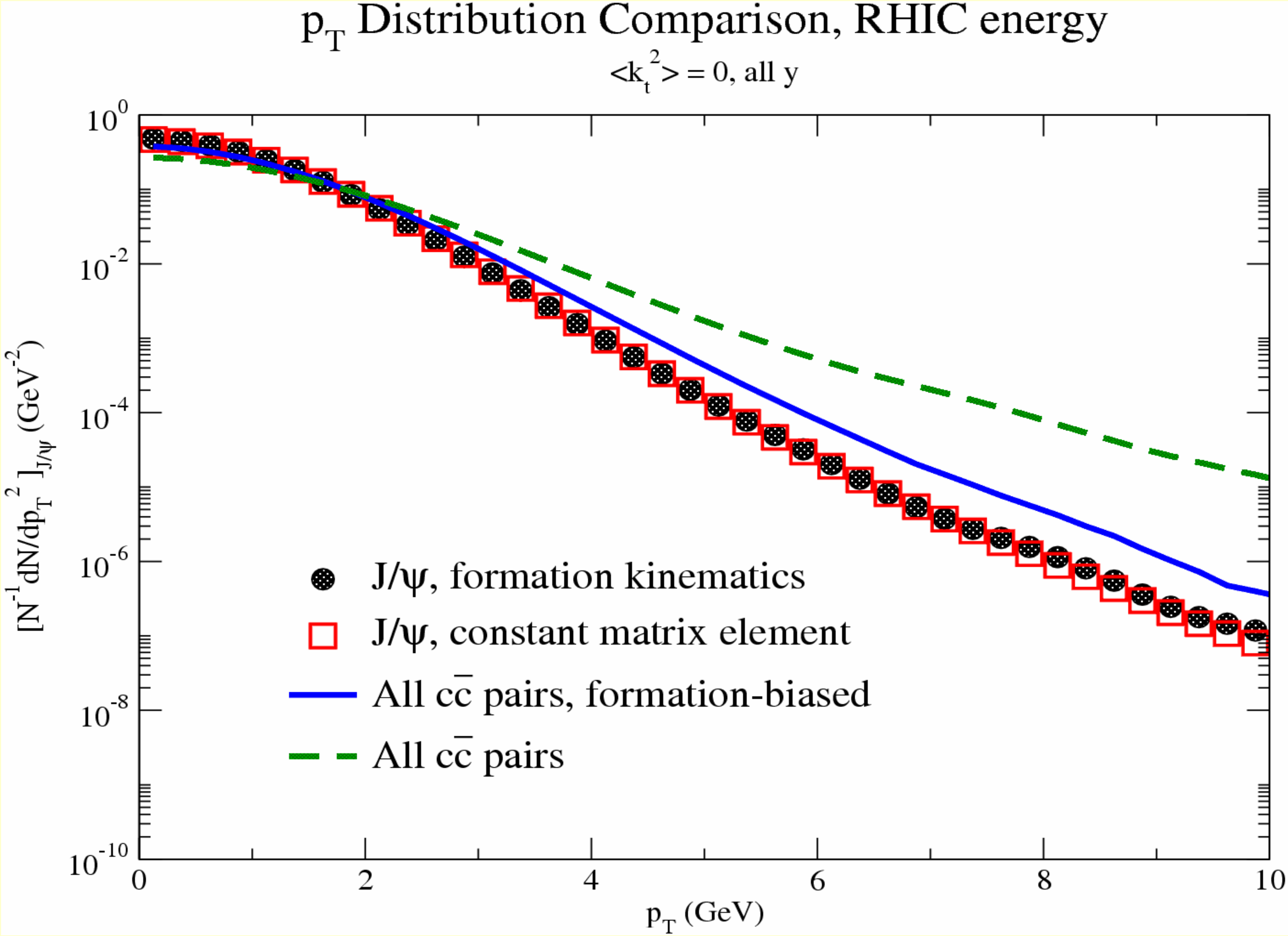
$c\bar{c}$ Pair y Distributions

Variation with intrinsic $\langle k_T^2 \rangle$, NLO pQCD at RHIC200 Energy

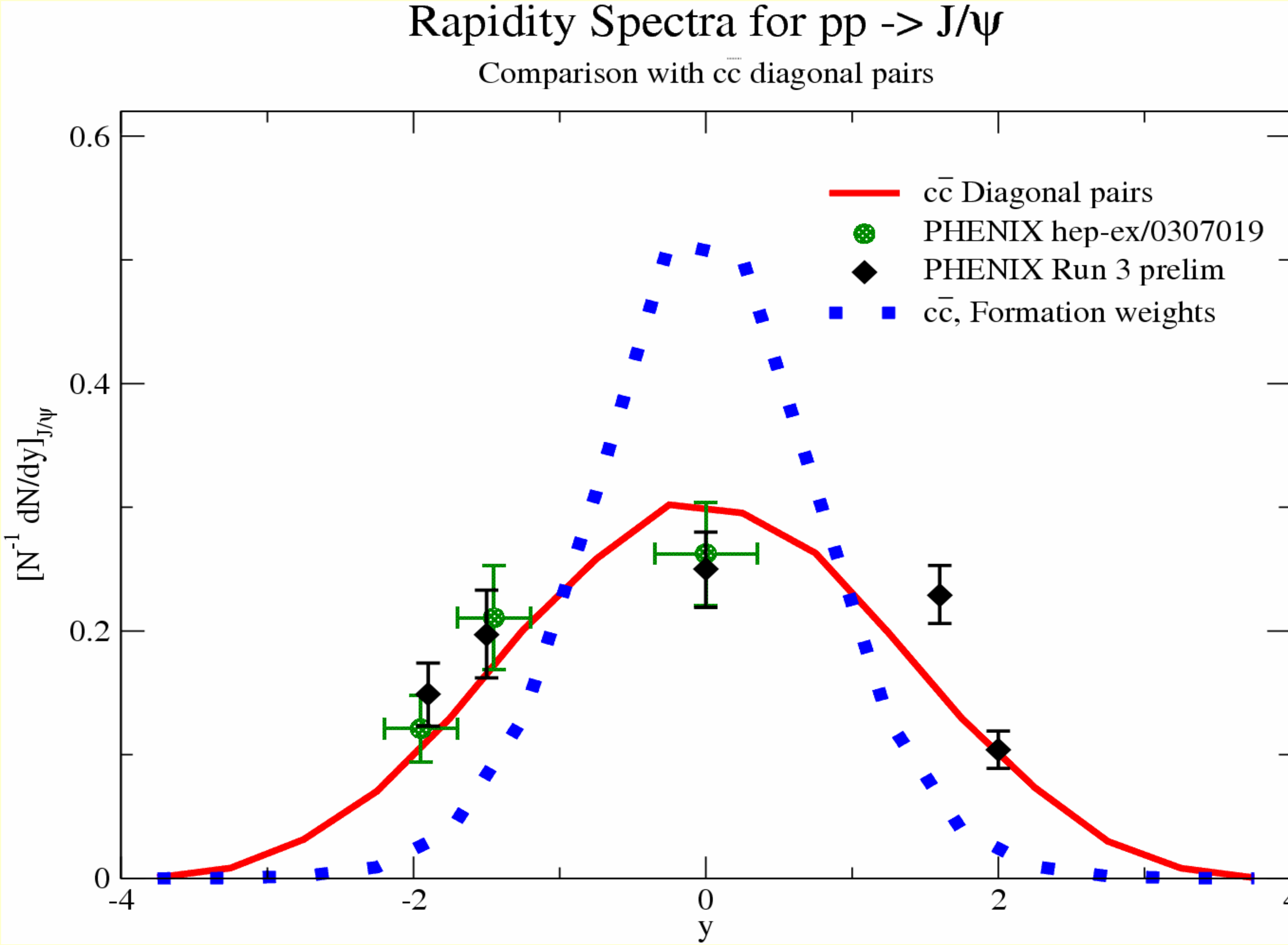




Rapidity Spectra Comparison, RHIC energy
J/ψ, formation kinematics
J/ψ, constant matrix element
All cc̄ pairs, formation-biased
All cc̄ pairs
N^-1 dN/dy
y
0.8
0.6
0.4
0.2
0
-6
-4
-2
0
2
4
6

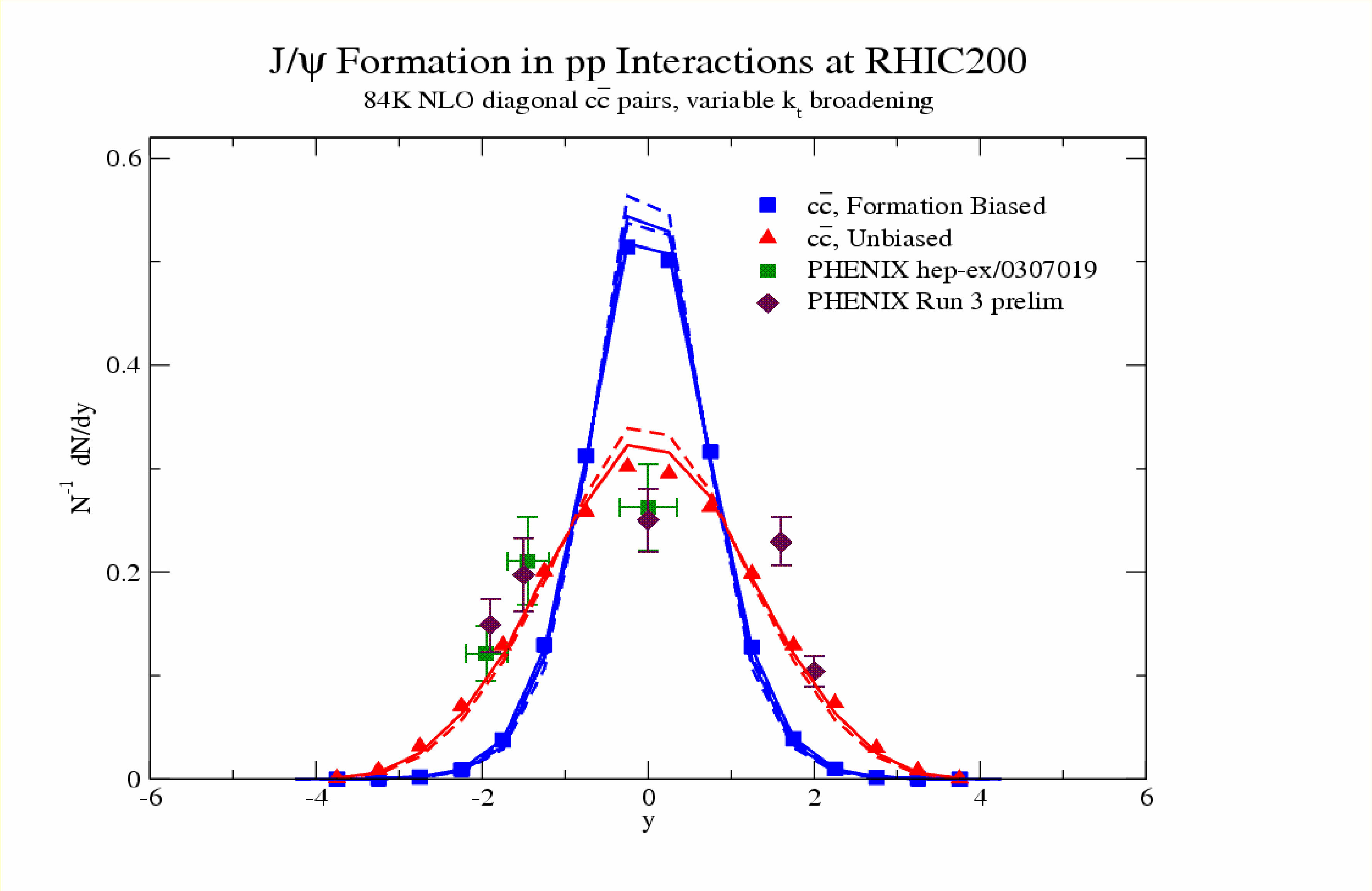


p_T Distribution Comparison, RHIC energy
<k_t^2> = 0, all y
[N^-1 dN/dp_T^2]_J/ψ (GeV^-2)
p_T (GeV)
J/ψ, formation kinematics
J/ψ, constant matrix element
All cc̄ pairs, formation-biased
All cc̄ pairs
10^0
10^-2
10^-4
10^-6
10^-8
10^-10
0
2
4
6
8
10



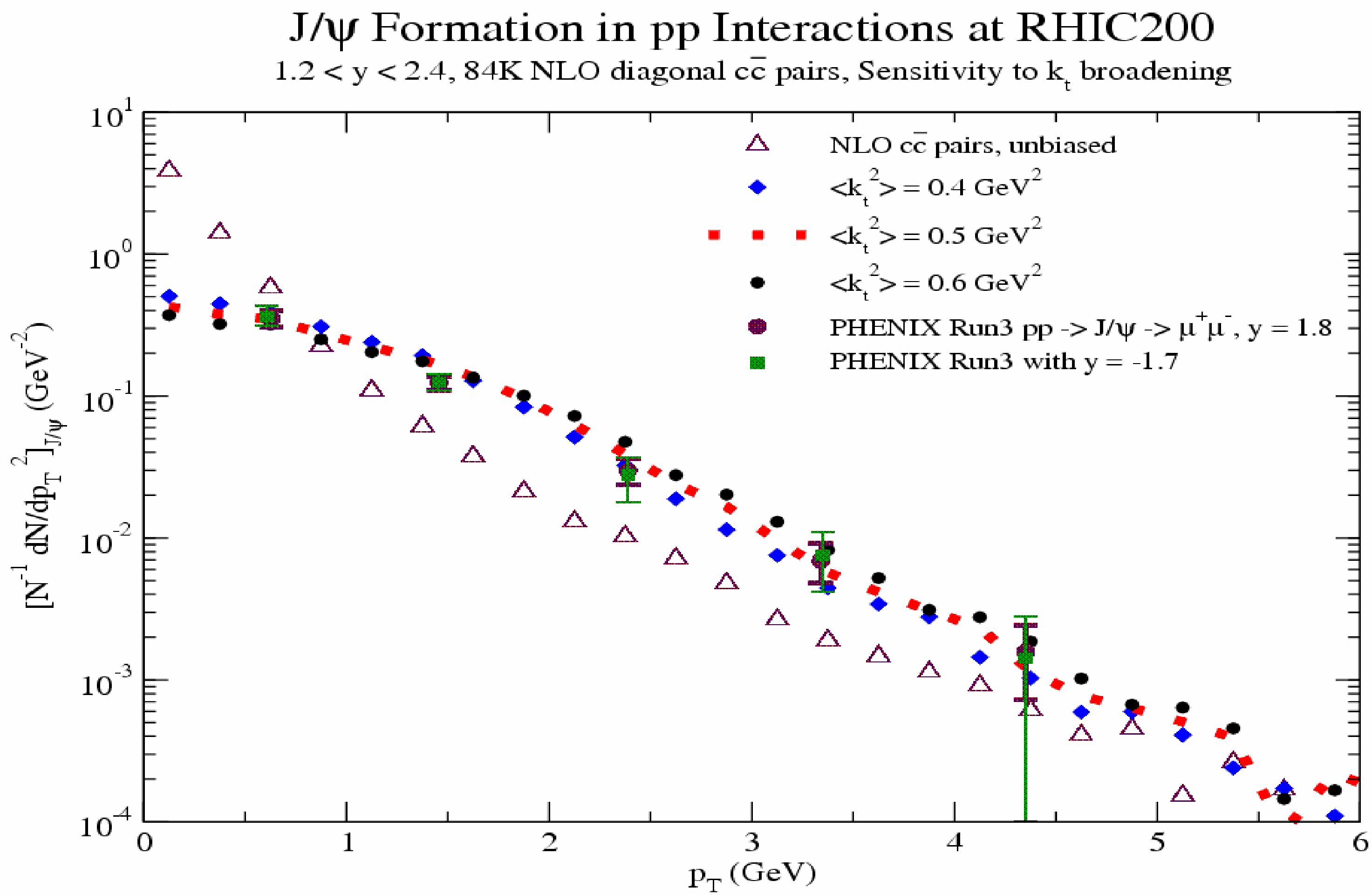
Rapidity Spectra for pp -> J/ψ
Comparison with cc̄ diagonal pairs
cc̄ Diagonal pairs
PHENIX hep-ex/0307019
PHENIX Run 3 prelim
cc̄, Formation weights
[N^-1 dN/dy]_J/ψ
y
0.6
0.4
0.2
0
-4
-2
0
2
4

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



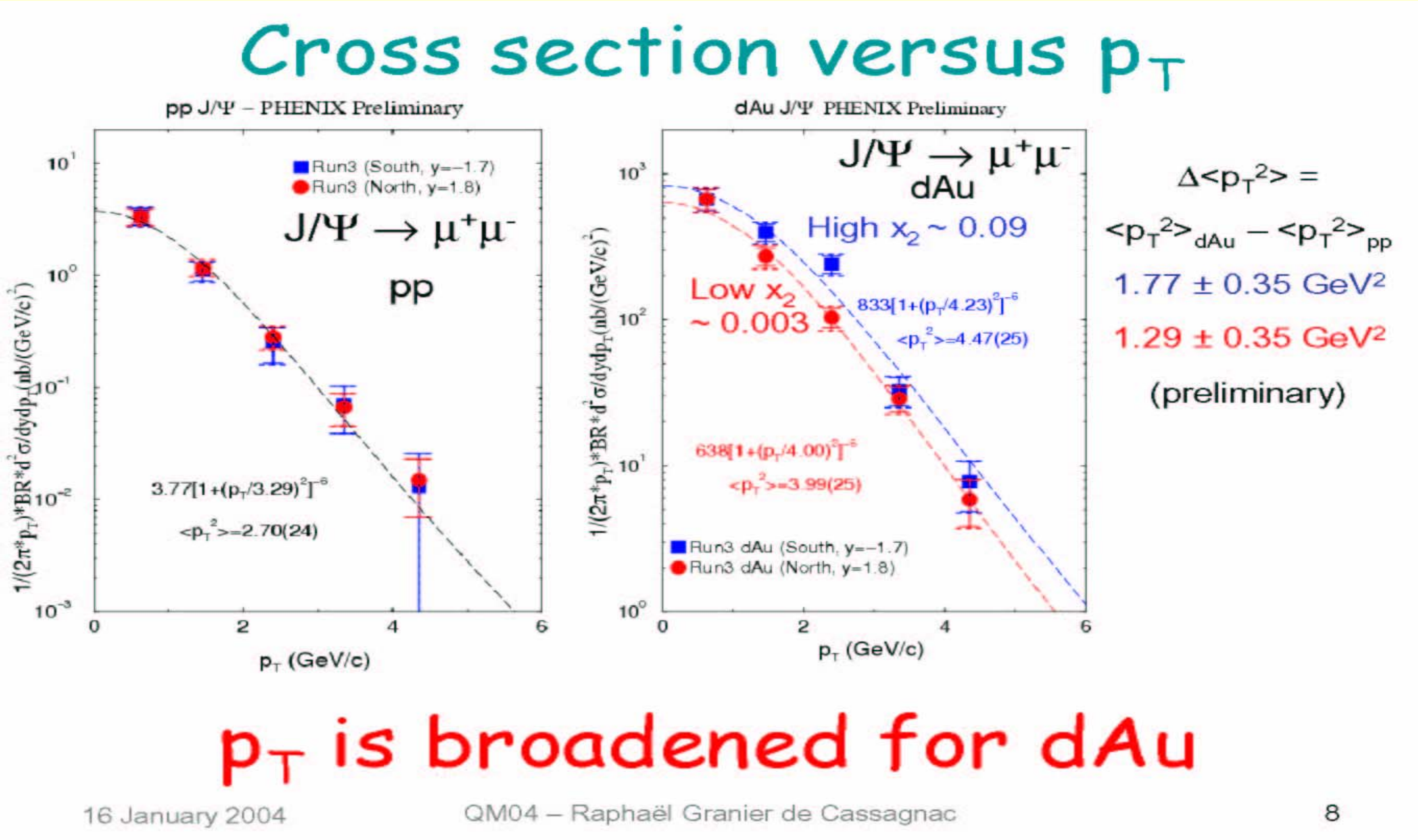
p-p data determine intrinsic k_t

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



Use dAu broadening to determine nuclear k_t

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

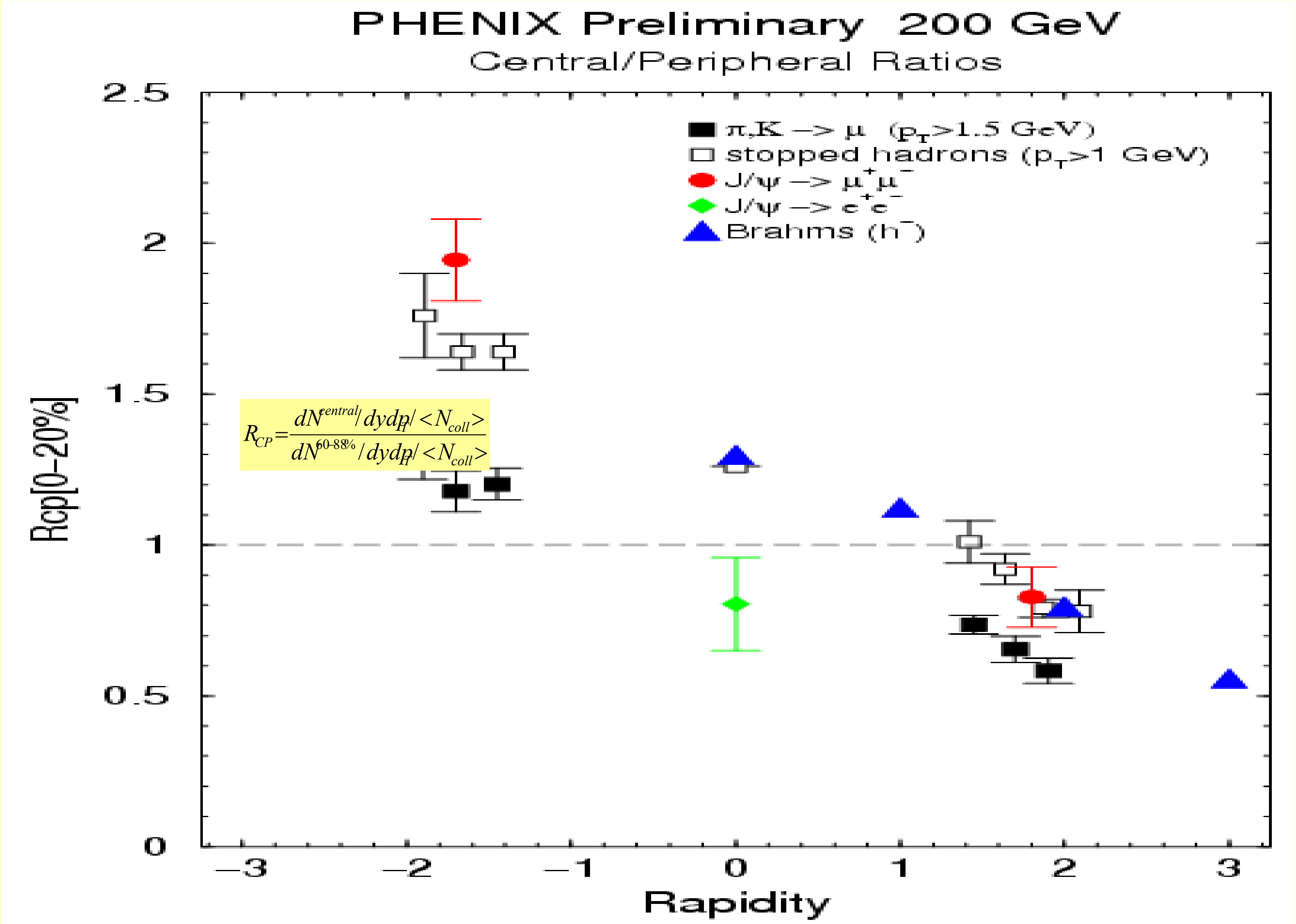


S. Gavin and M. Gyulassy, Phys. Lett. B214 (1988

$$< p_T^2 >_{AB} = < p_T^2 >_{pp} + \lambda^2 \{\bar{n}_A + \bar{n}_B - 2\}$$

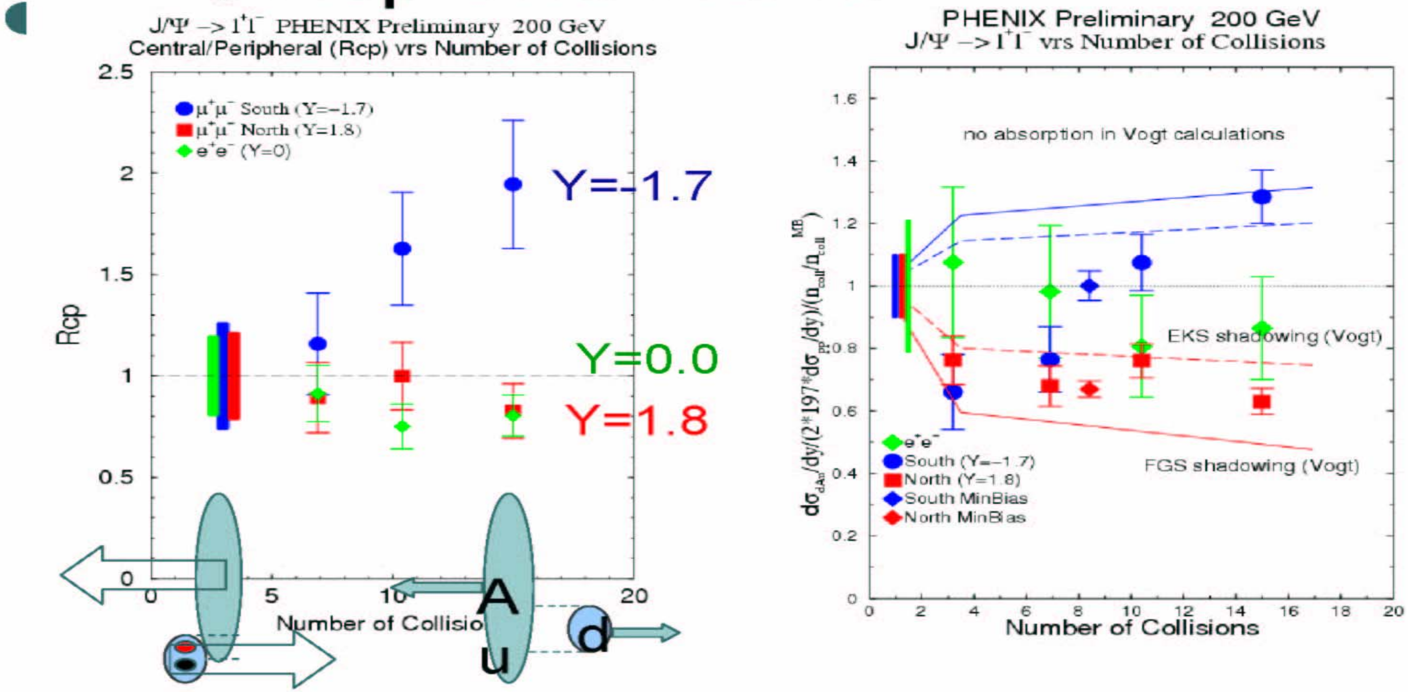
Nuclear broadening from Initial state parton scattering, extract $\lambda^2 =$ 0.35 +/- 0.14 GeV^2 for Au-Au at RHIC, compare with 0.12 +/- .02 GeV^2 at fixed-target energy

P. Steinberg, Hot Quark 2004 Workshop, July 2004



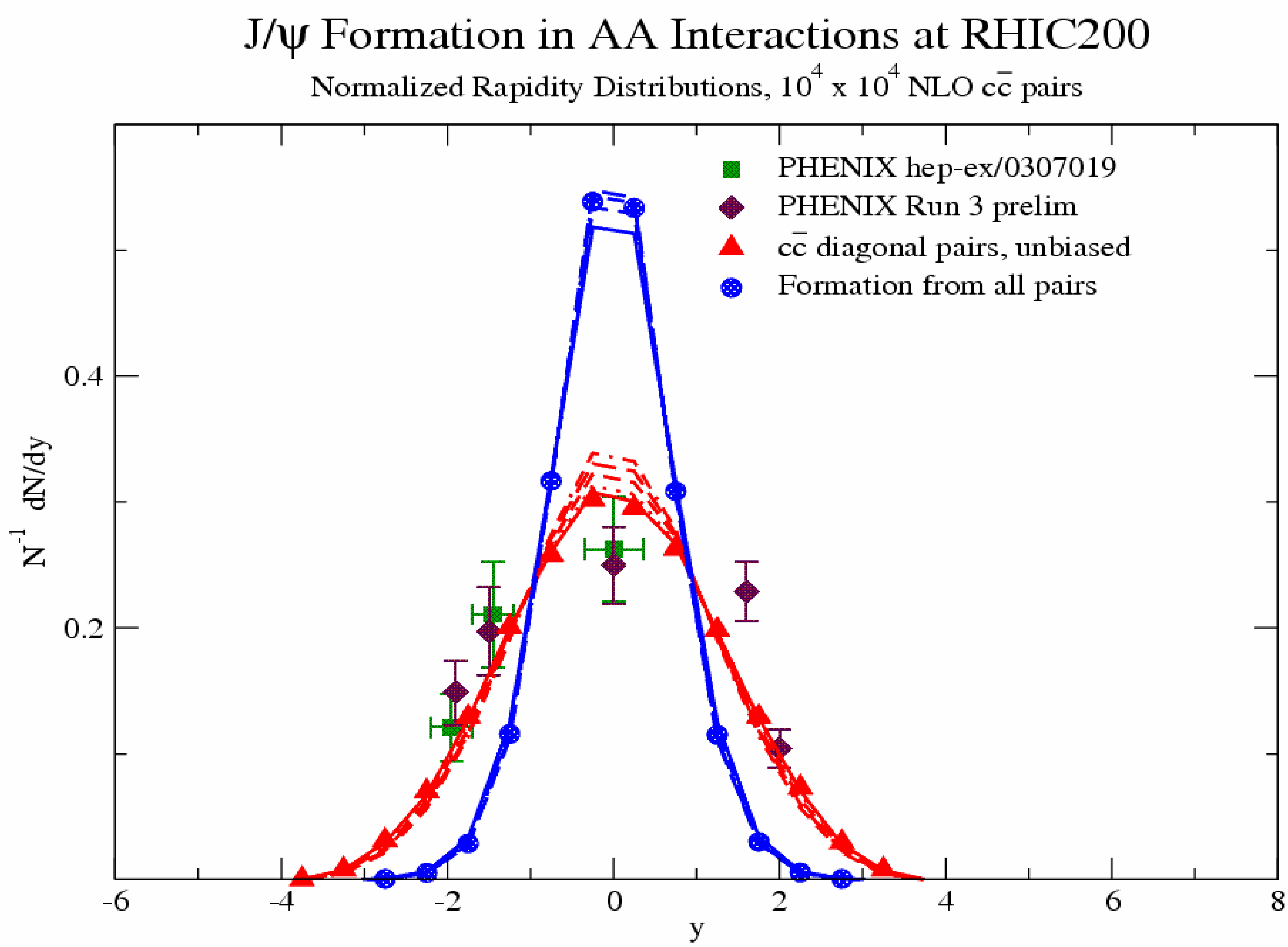
J. Burward-Hoy, Winter Workshop on Nuclear Dynamics, 2004

Rcp and RdAu

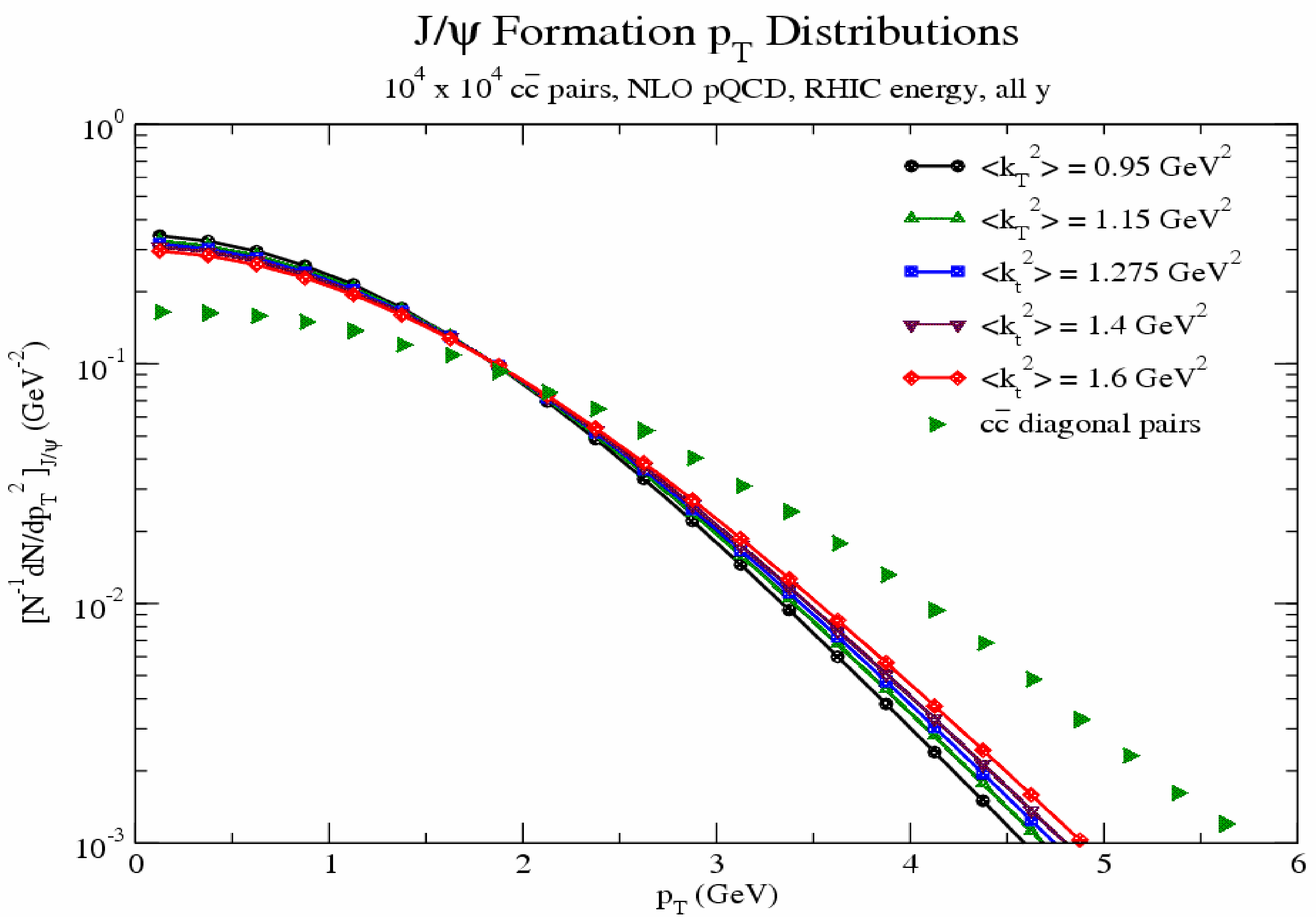


- RdA: average over centrality consistent with minimum bias result.
- Weak nuclear effects at forward rapidities (green points at midrapidity)
- Stronger centrality dependence at backward rapidities

Formation through "off-diagonal" pairs narrows rapidity distribution



Formation through "off-diagonal" pairs narrows p_t distribution

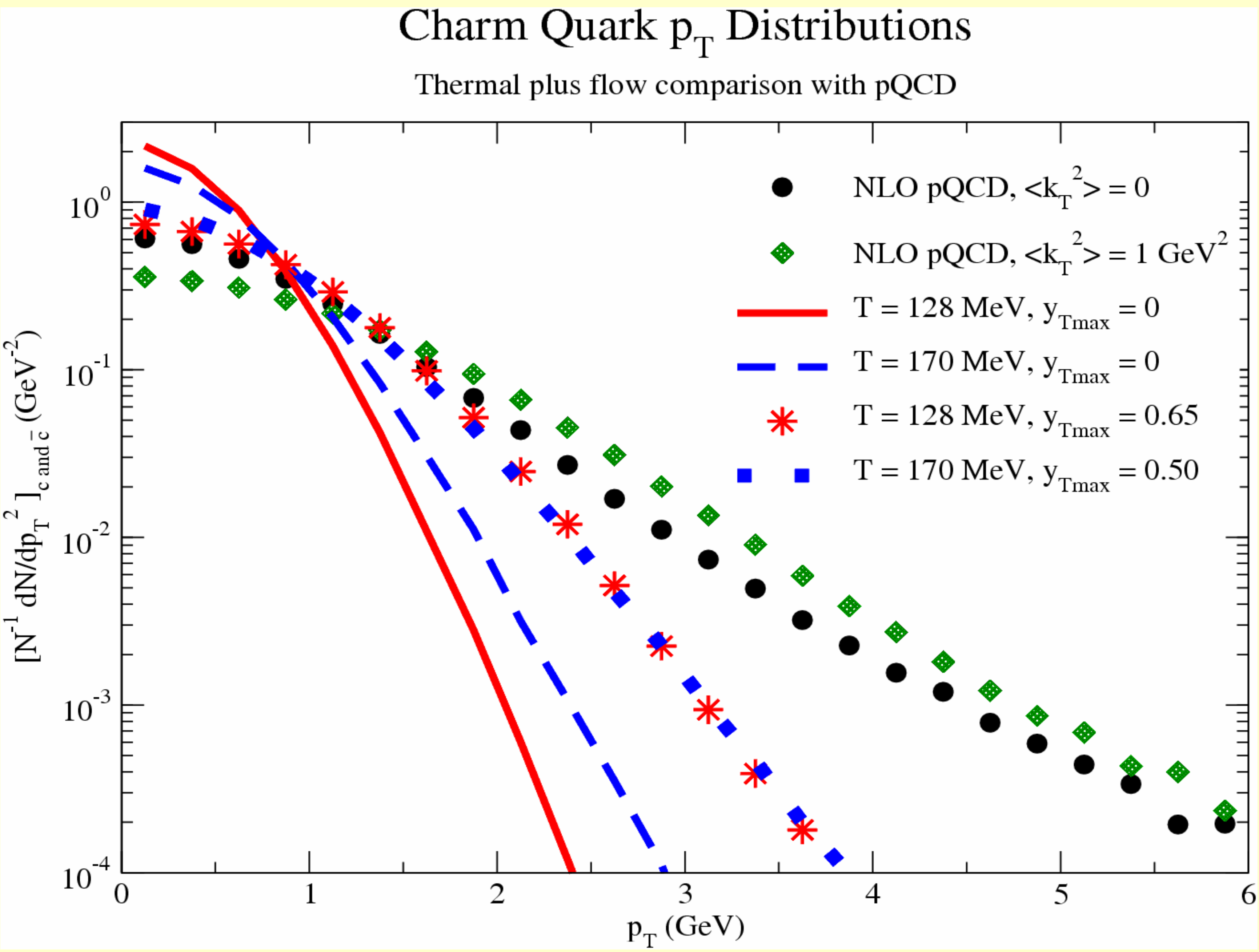


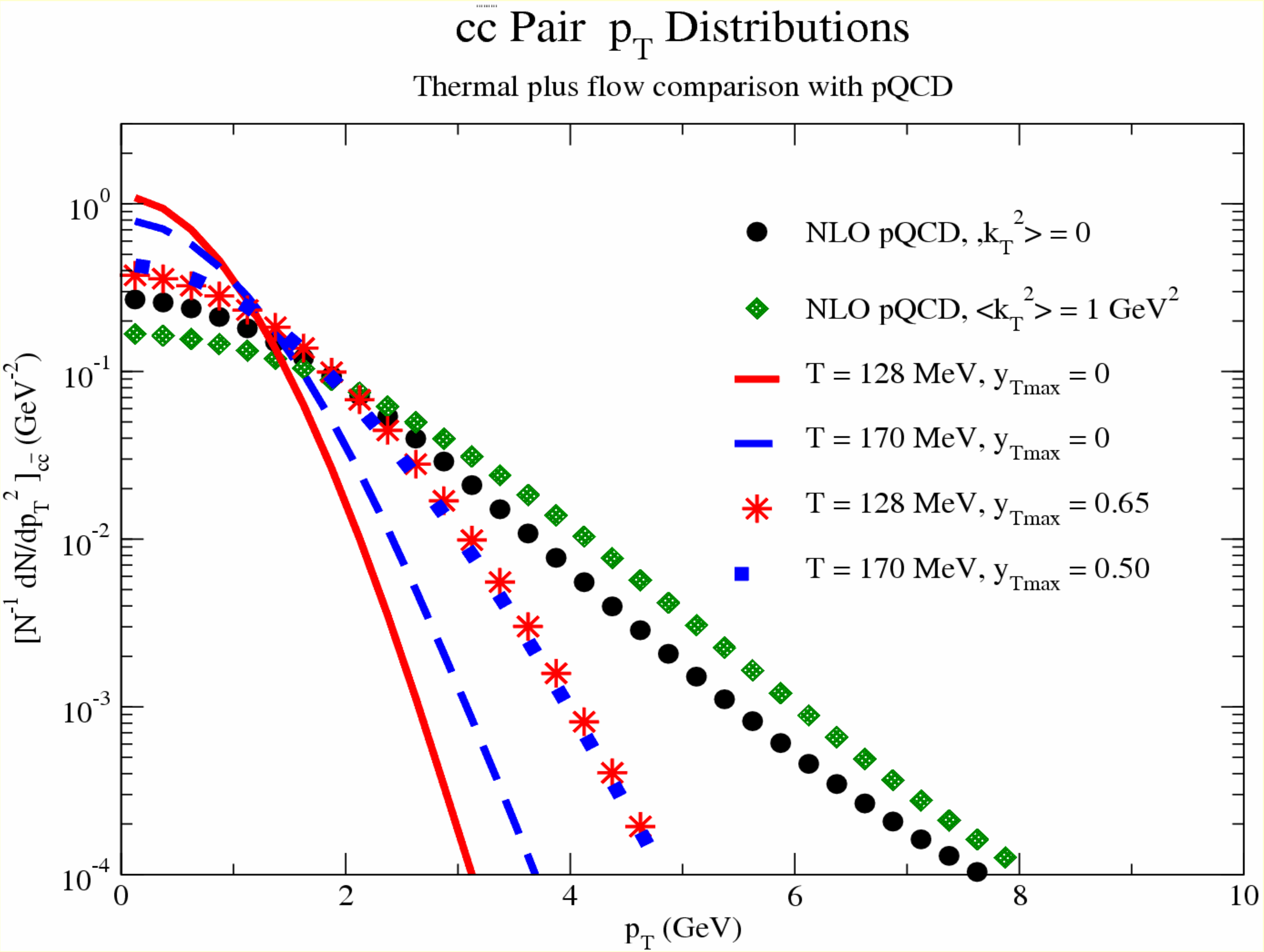
Comparison with Thermal + Transverse Flow c-Quark Distributions

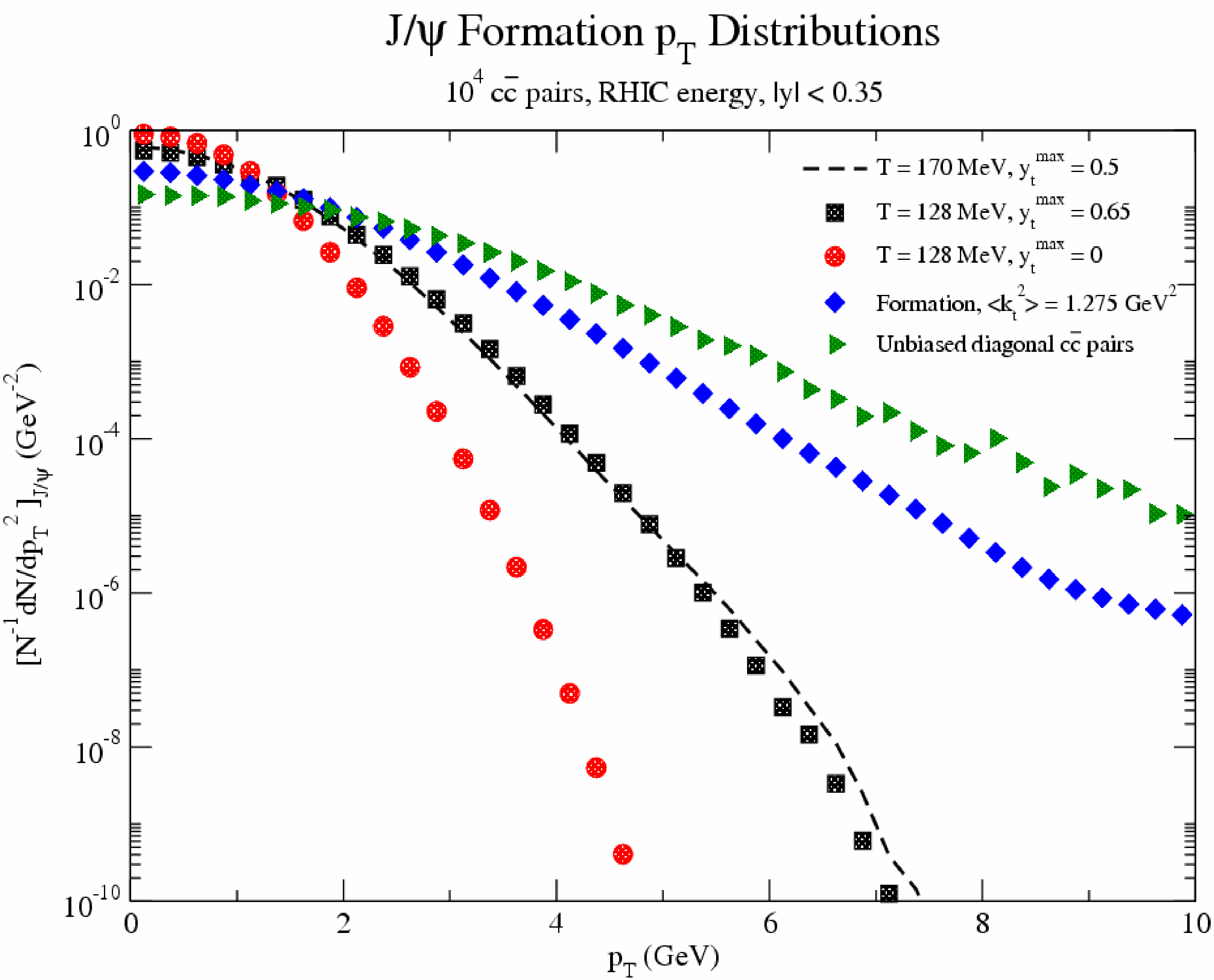
K.A.Bugaev, M. Gazdzicki, M.I.Gorenstein, Phys.Lett.B544,127(2002)

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

$$\frac{dN}{dp_T^2} \propto m_T \int_0^R r\,dr\, I_0\left[\frac{p_T \sinh(\frac{r}{R} y_T^{max})}{T}\right] K_1\left[\frac{m_T \cosh(\frac{r}{R} y_T^{max})}{T}\right]$$

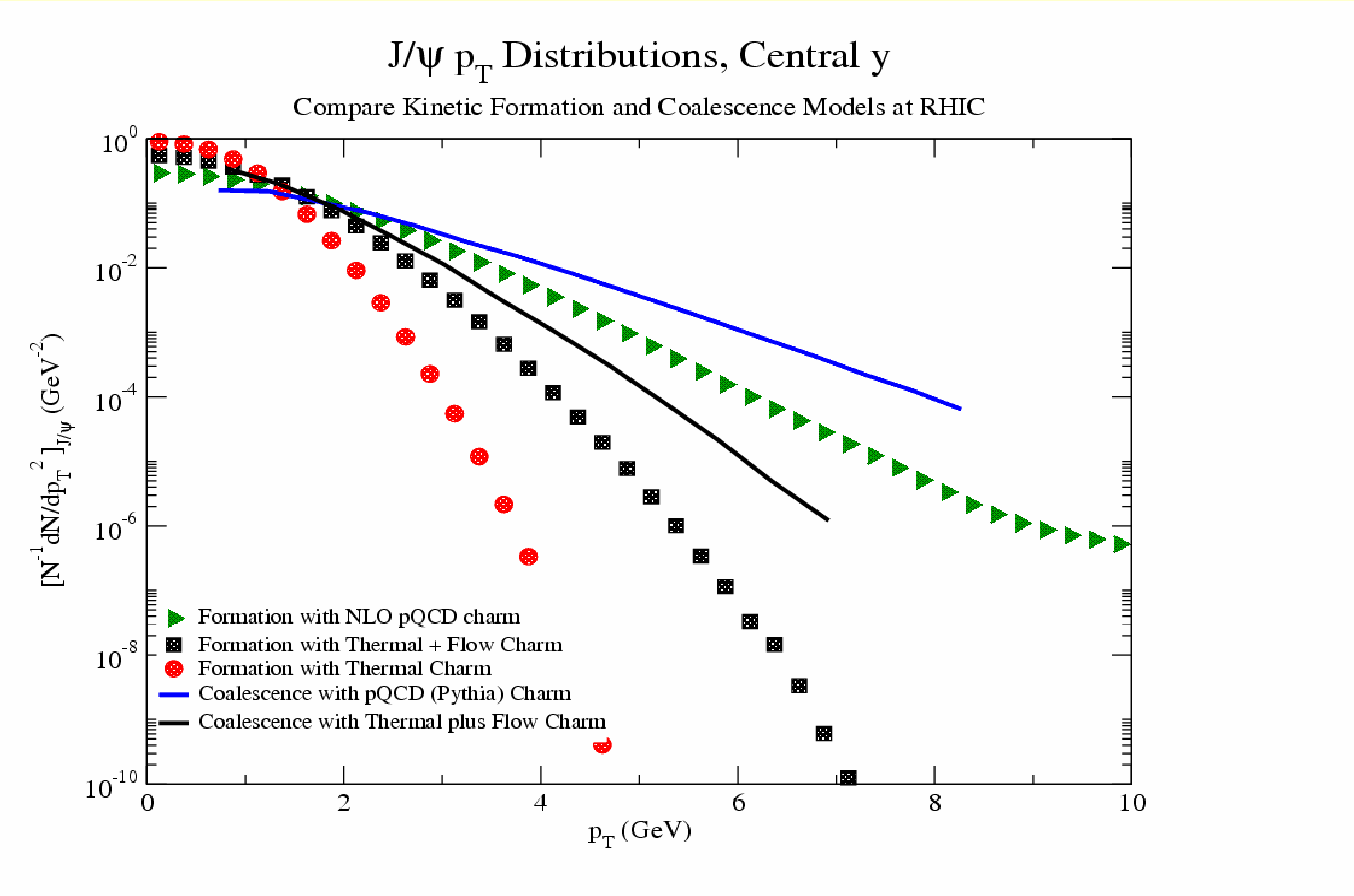

Charm Quark p_T Distributions
Thermal plus flow comparison with pQCD
NLO pQCD, $<k_T^2> = 0$
NLO pQCD, $<k_T^2> = 1\ GeV^2$
T = 128 MeV, $y_{Tmax} = 0$
T = 170 MeV, $y_{Tmax} = 0$
T = 128 MeV, $y_{Tmax} = 0.65$
T = 170 MeV, $y_{Tmax} = 0.50$
$[N^{-1}\ dN/dp_T^2]_{c\ and\ \bar{c}}\ (GeV^{-2})$
p_T (GeV)
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
1
2
3
4
5
6


cc Pair p_T Distributions
Thermal plus flow comparison with pQCD
NLO pQCD, ,k_T^2> = 0
NLO pQCD, <k_T^2> = 1 GeV^2
T = 128 MeV, y_Tmax = 0
T = 170 MeV, y_Tmax = 0
T = 128 MeV, y_Tmax = 0.65
T = 170 MeV, y_Tmax = 0.50
[N^-1 dN/dp_T^2]_cc̄ (GeV^-2)
p_T (GeV)
10^0
10^-1
10^-2
10^-3
10^-4
0
2
4
6
8
10



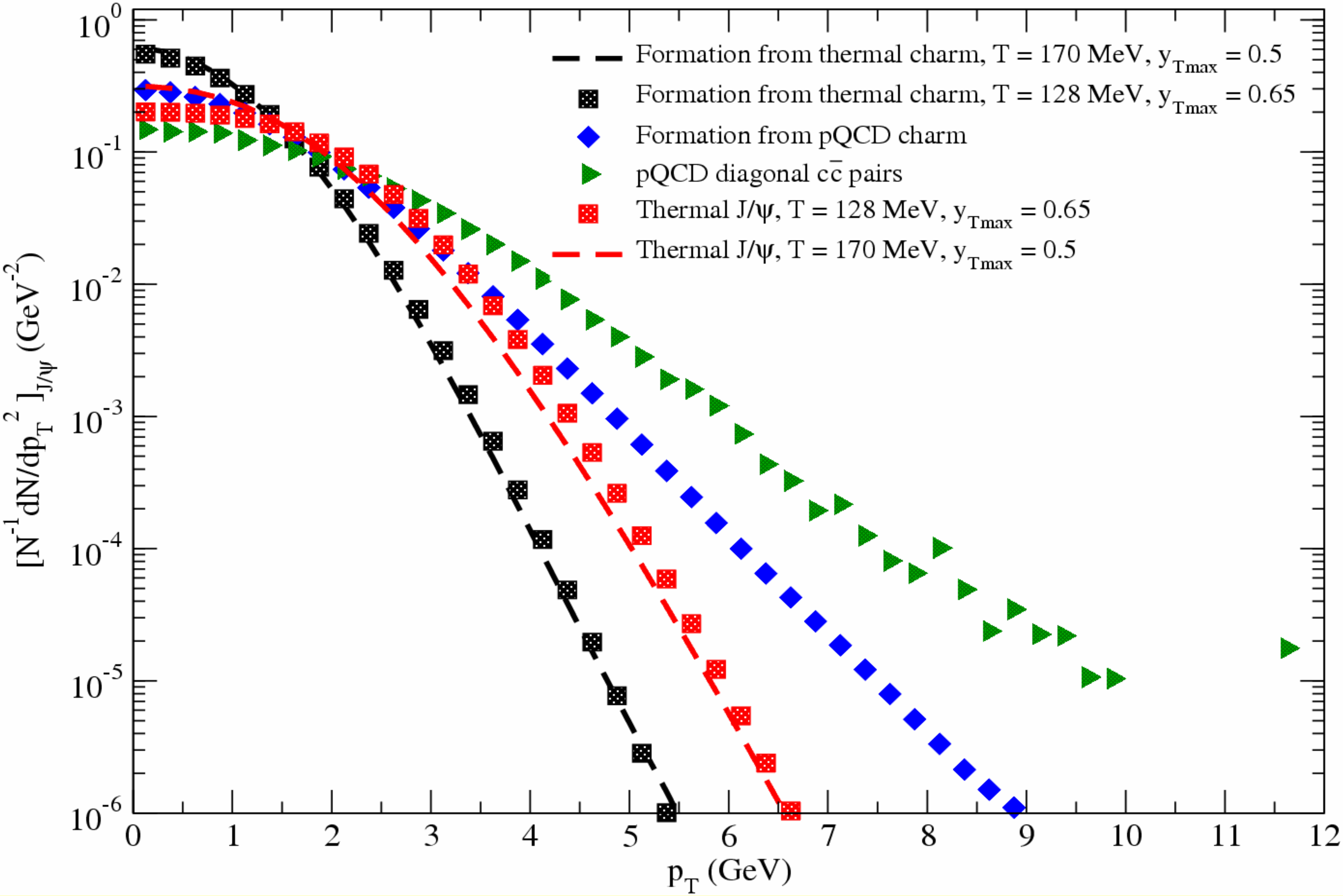
J/ψ Formation p_T Distributions
10^4 $c\bar{c}$ pairs, RHIC energy, |y| < 0.35
$[N^{-1} dN/dp_T^2]_{J/\psi}$ (GeV^{-2})
p_T (GeV)
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
0
2
4
6
8
10
T = 170 MeV, y_t^{max} = 0.5
T = 128 MeV, y_t^{max} = 0.65
T = 128 MeV, y_t^{max} = 0
Formation, $\langle k_t^2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

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

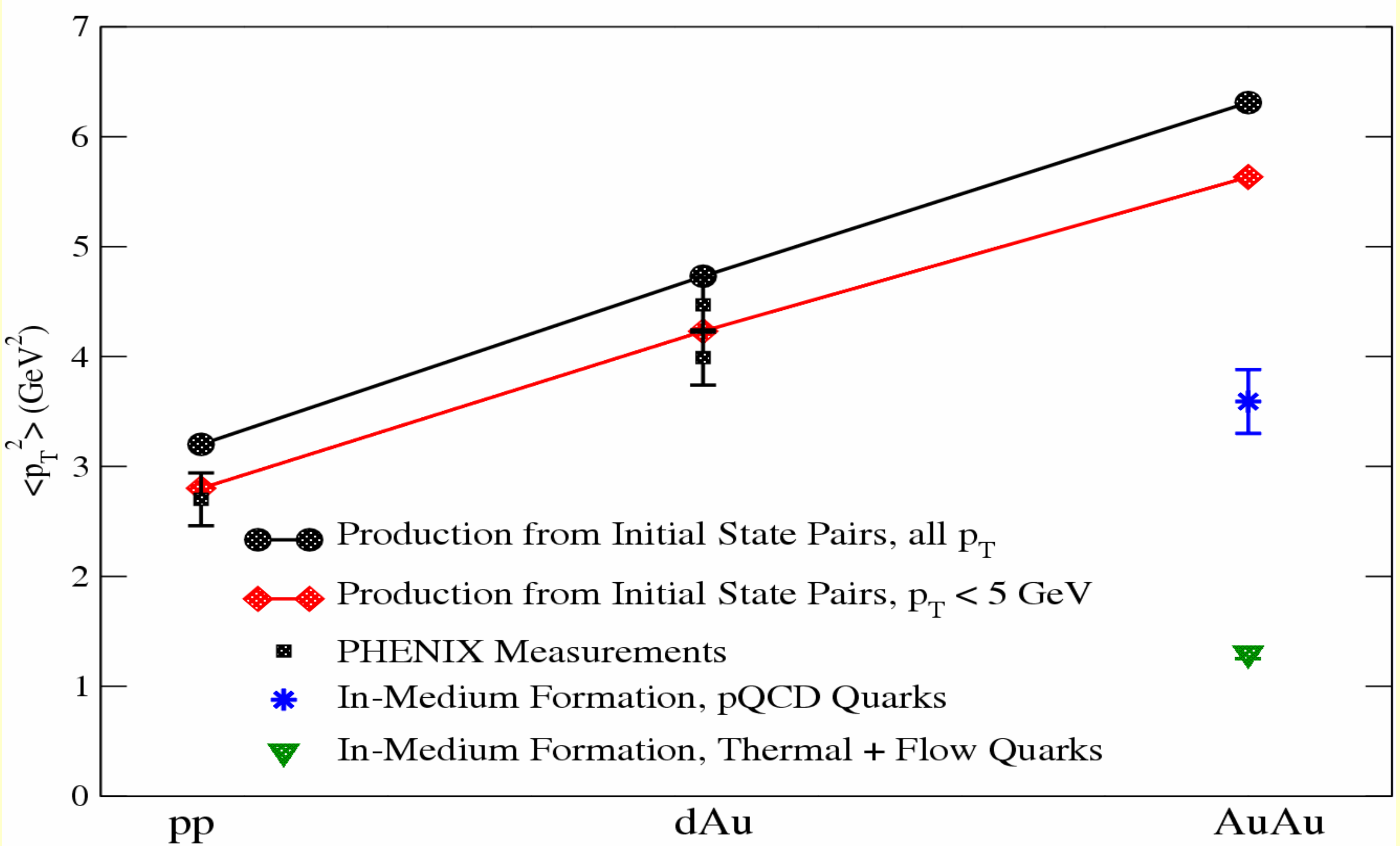


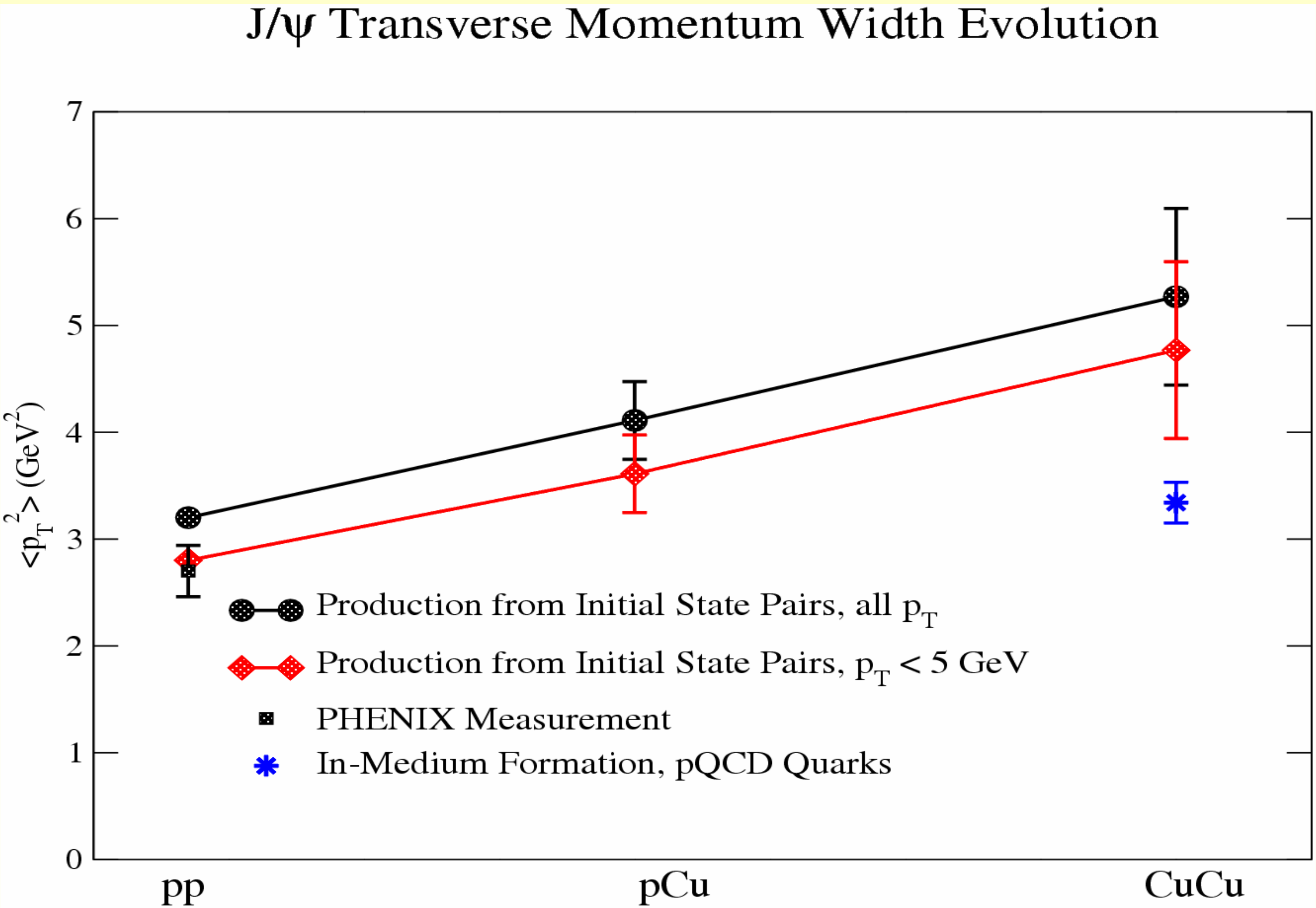
J/ψ Formation p_T Distributions

Comparison with direct Thermal Distribution



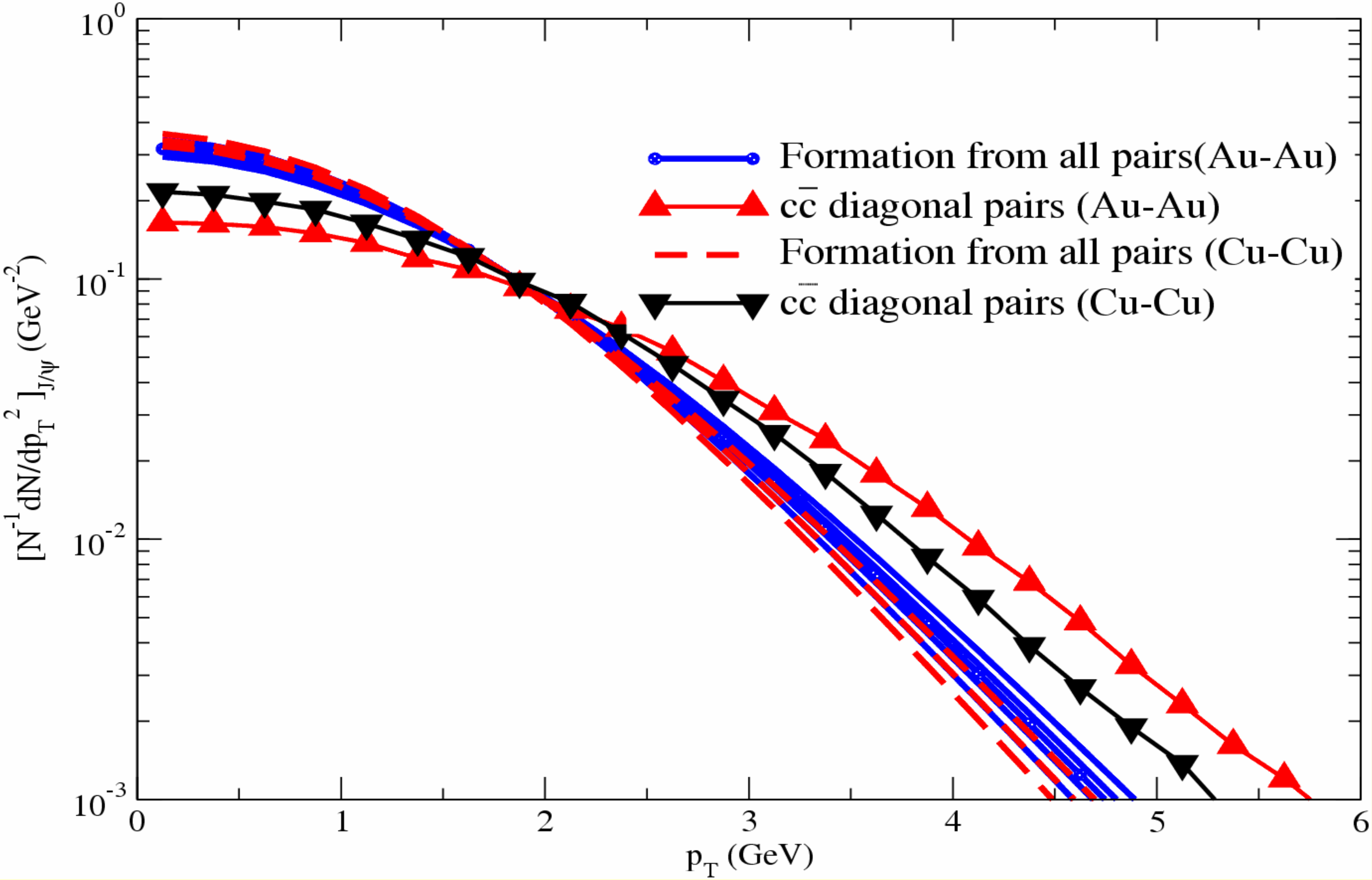
J/ψ Transverse Momentum Width Evolution



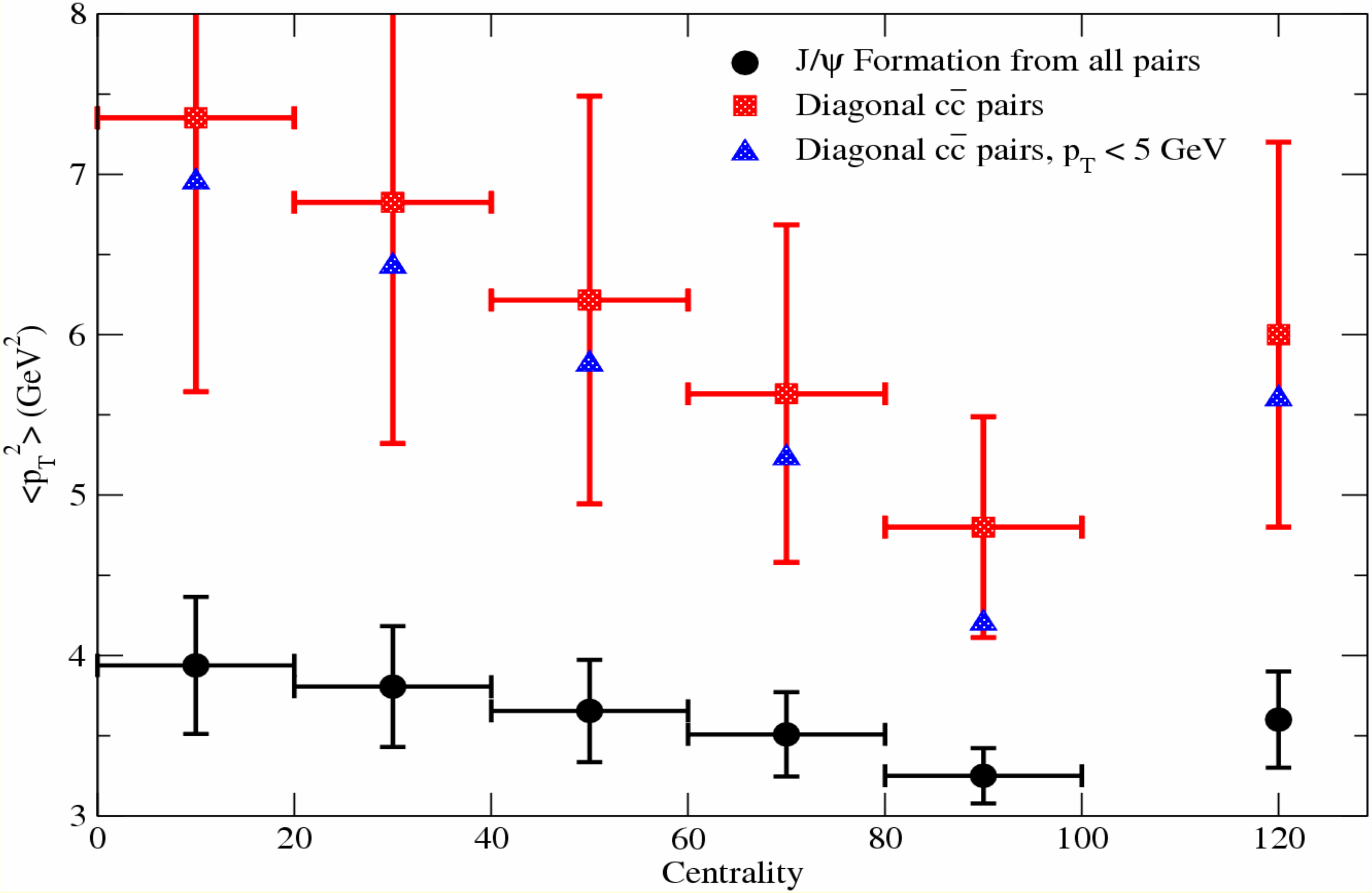


J/ψ Transverse Momentum Width Evolution
$<p_T^2>$ (GeV^2)
0
1
2
3
4
5
6
7
pp
pCu
CuCu
Production from Initial State Pairs, all p_T
Production from Initial State Pairs, p_T < 5 GeV
PHENIX Measurement
In-Medium Formation, pQCD Quarks

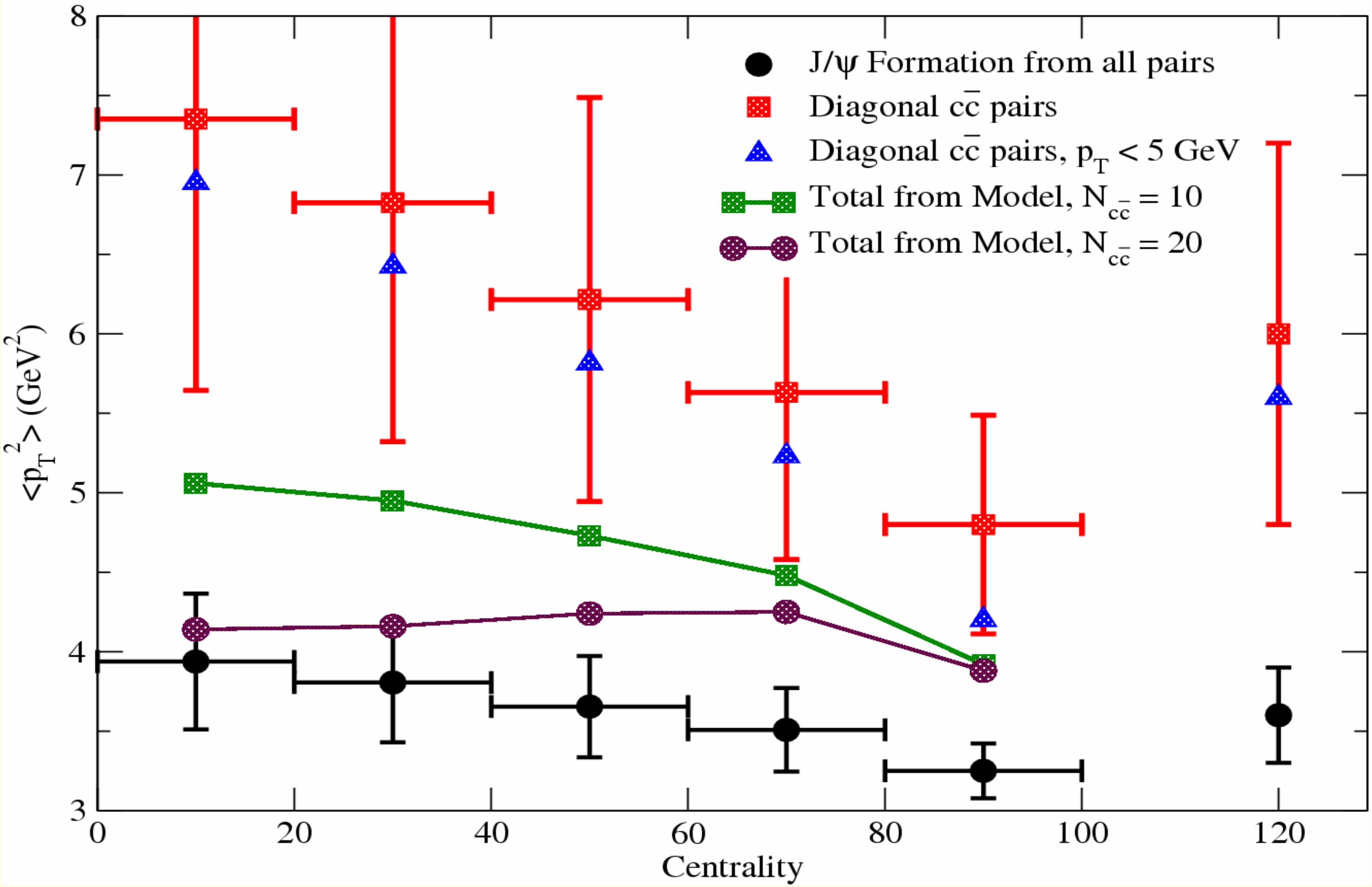
J/ψ Formation Comparison with Initial Production



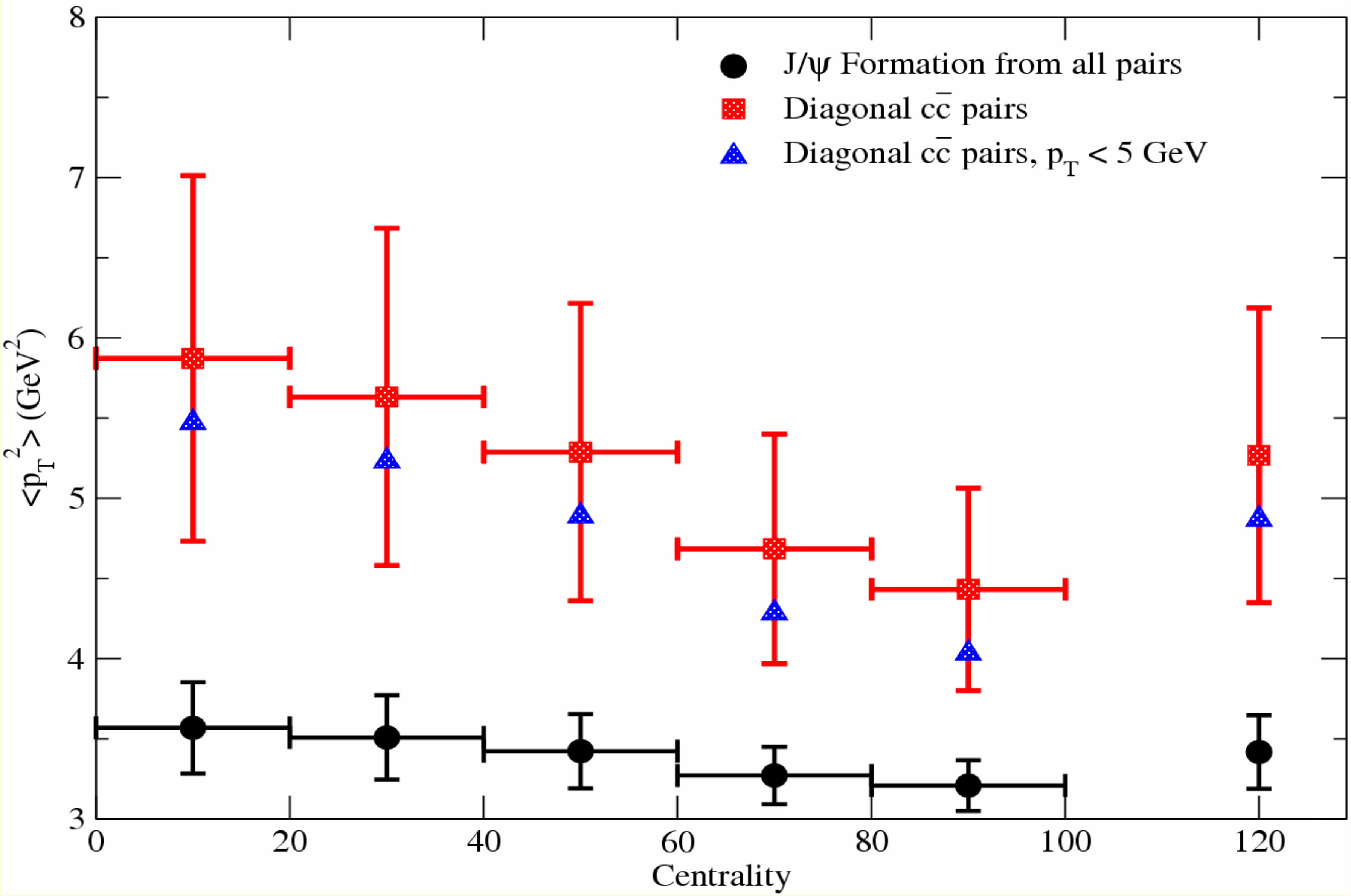
J/ψ p_T width vs centrality for Au-Au at RHIC200



J/ψ p_T width vs centrality for Au-Au at RHIC200

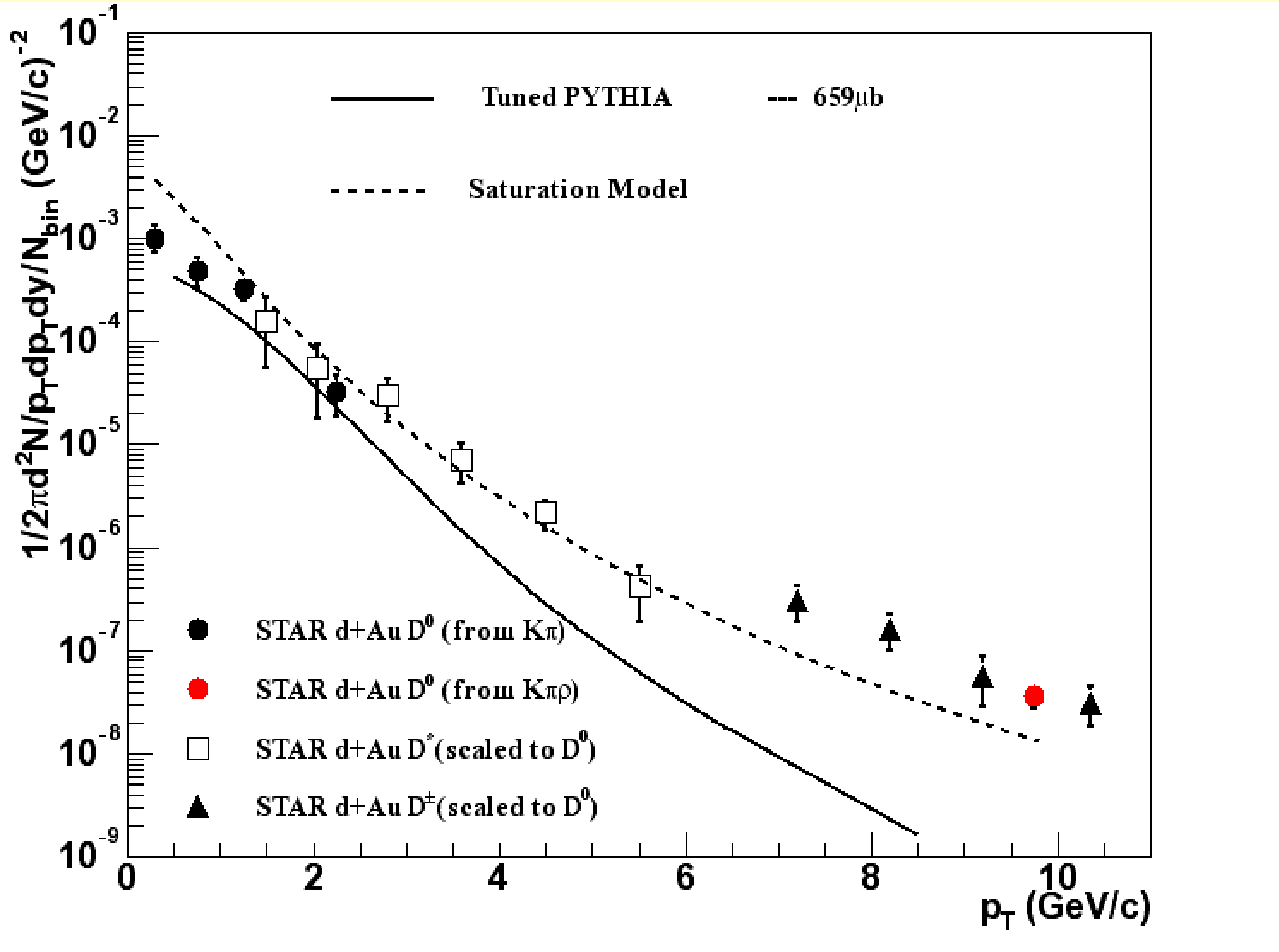


J/ψ p_T width vs centrality for Cu-Cu at RHIC200

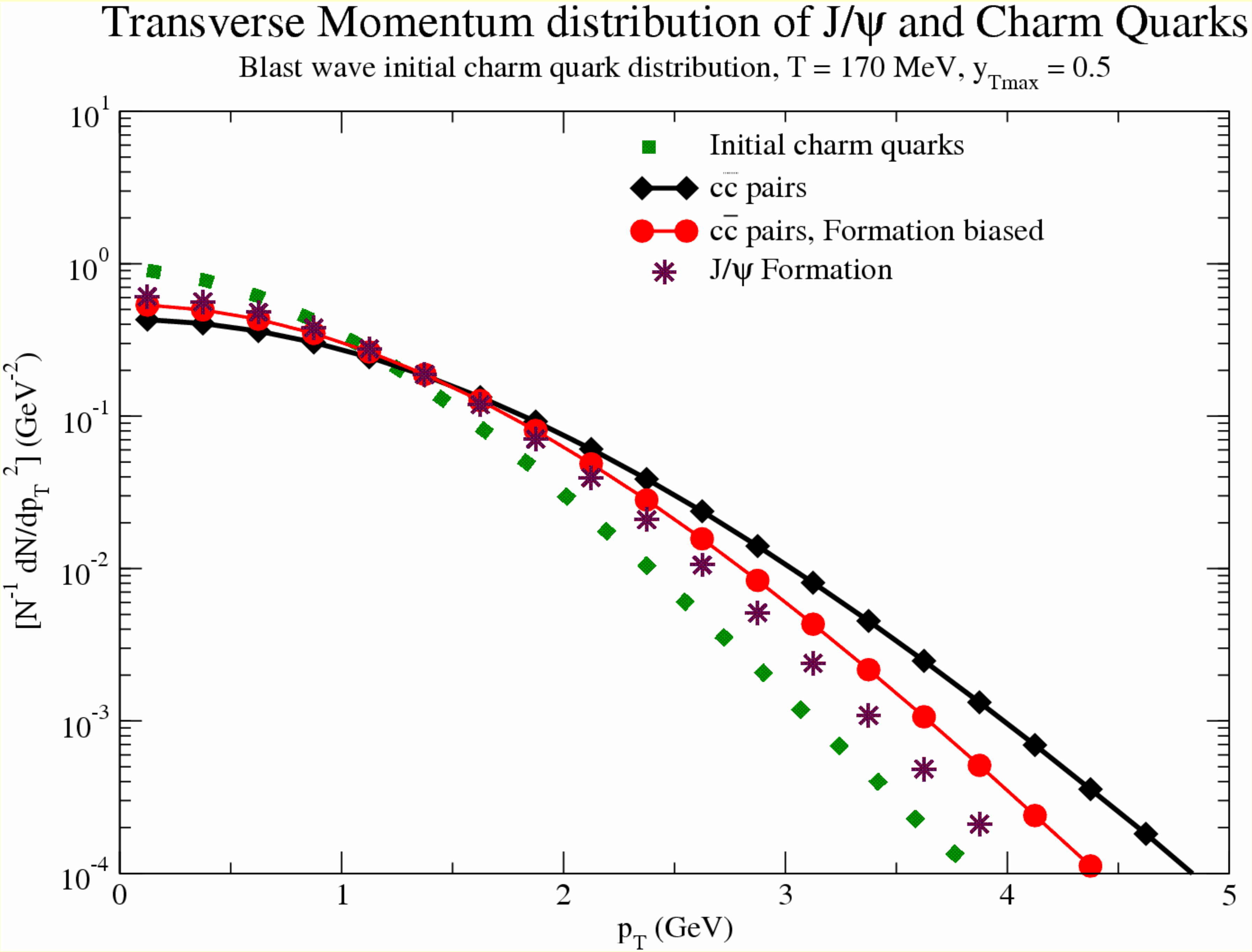


SUMMARY

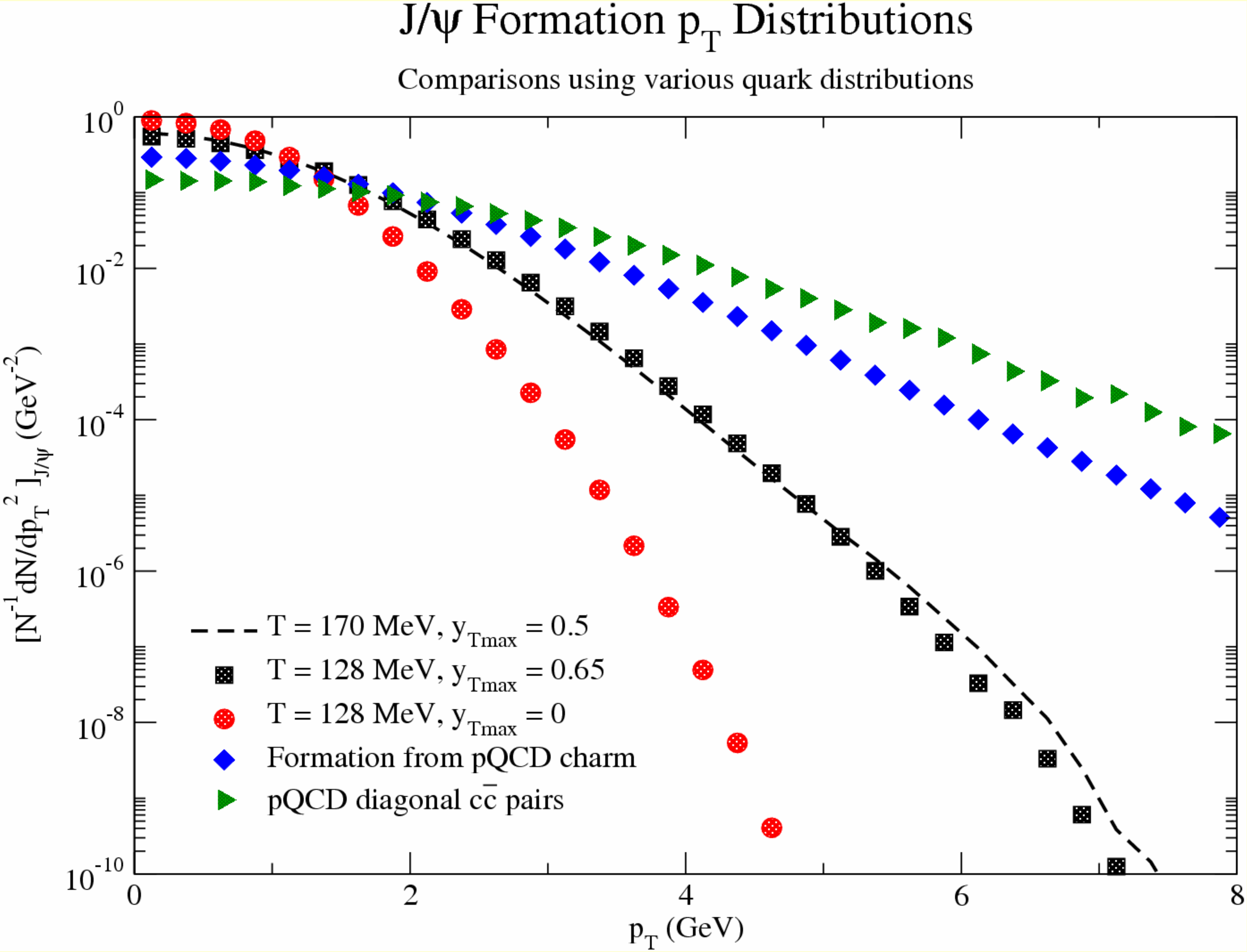
- Absolute magnitude and centrality dependence tests require both open and hidden flavor measurements
- J/Psi p_T and y measurements *alone can* provide signatures of in-medium recombination processes
- The difference of pQCD quark pair spectra for diagonal vs off-diagonal combinations survives in the J/Psi results
- Non-monatonic behavior of widths of transverse momentum spectra signal recombination
- In-medium formation process very sensitive to heavy quark thermalization and flow

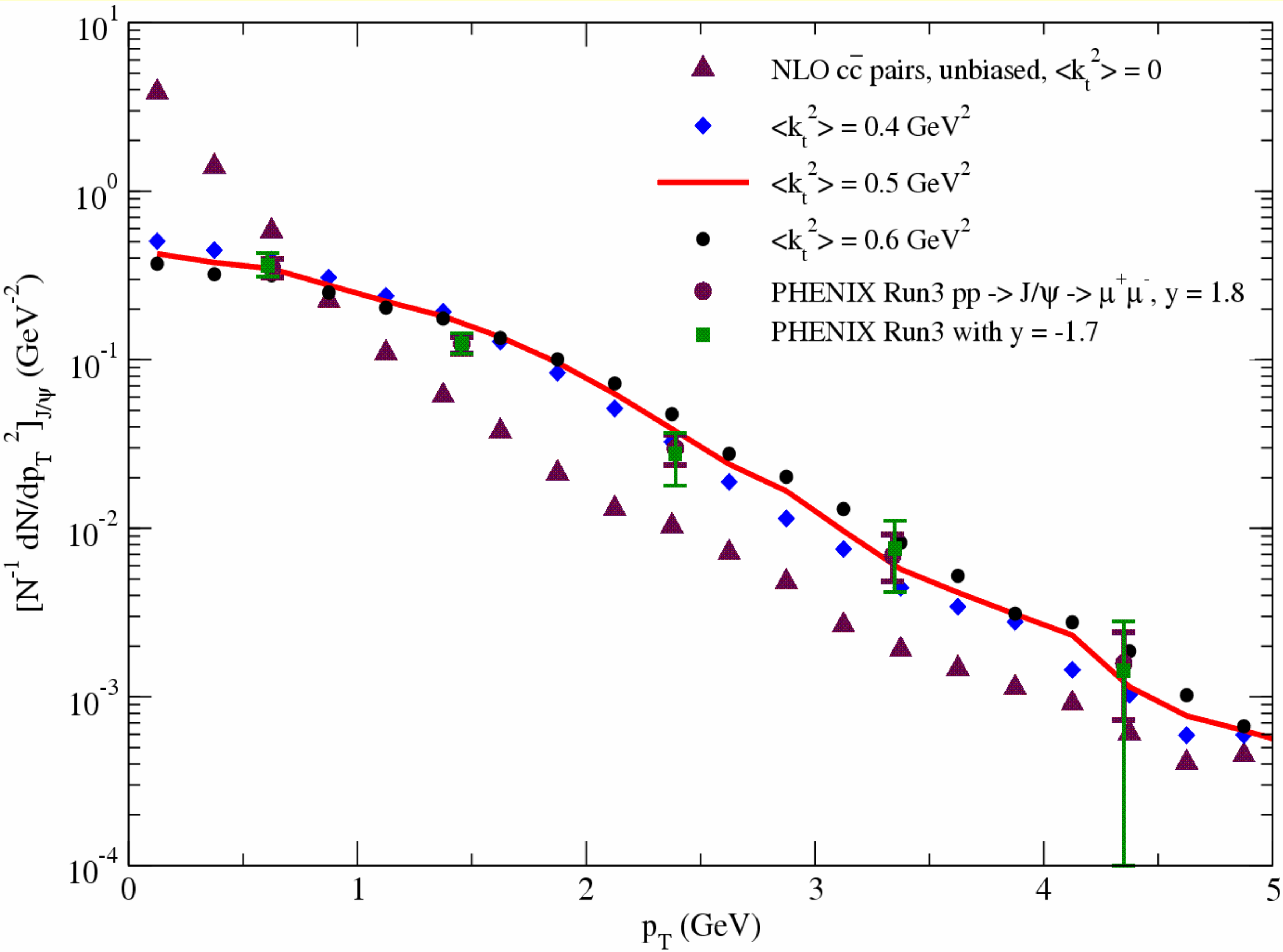


Tuned PYTHIA
--- 659μb
Saturation Model
STAR d+Au D⁰ (from Kπ)
STAR d+Au D⁰ (from Kπρ)
STAR d+Au D*(scaled to D⁰)
STAR d+Au D±(scaled to D⁰)
1/2πd²N/pTdpTdy/Nbin (GeV/c)⁻²
pT (GeV/c)
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
0
2
4
6
8
10

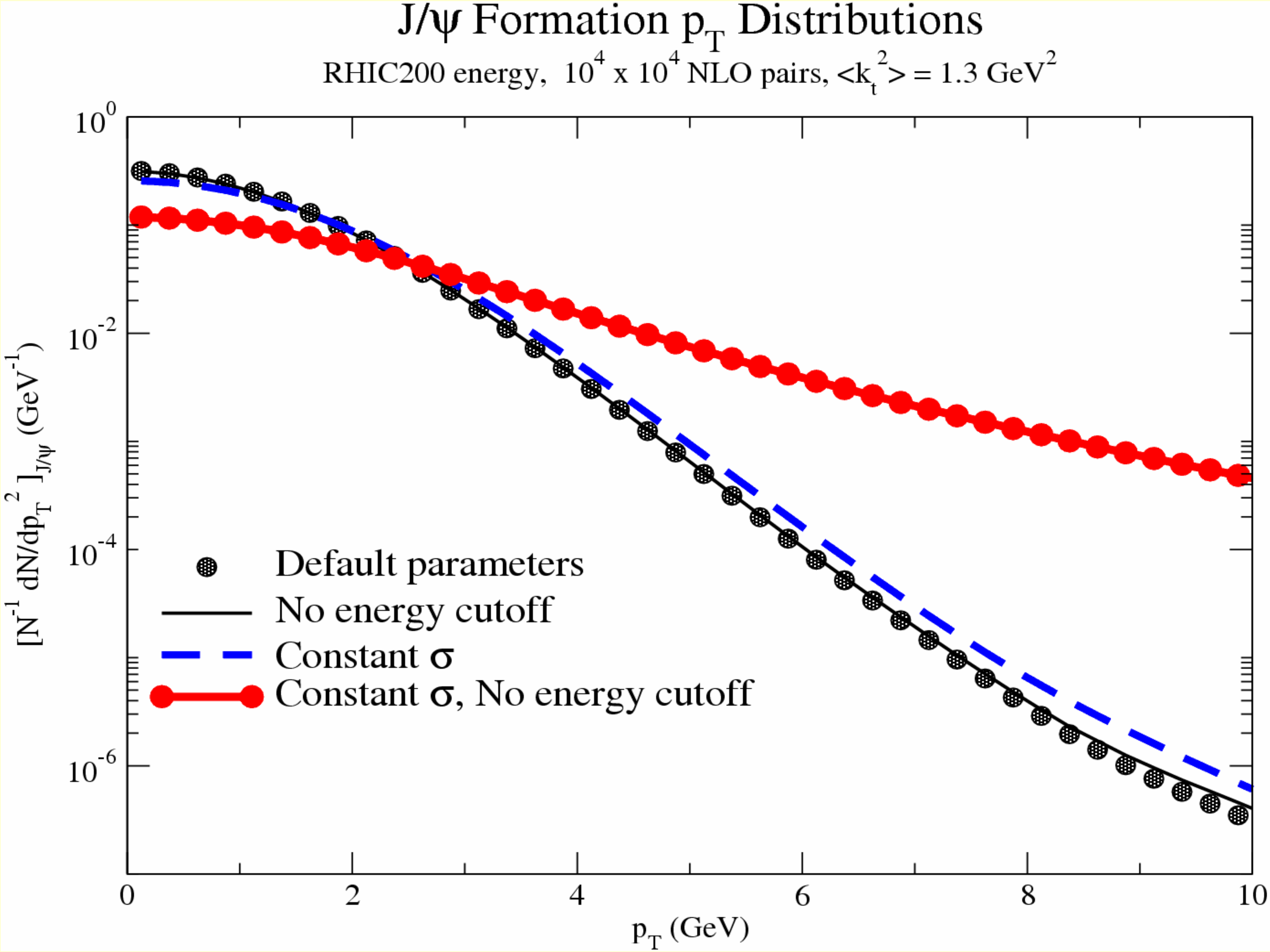


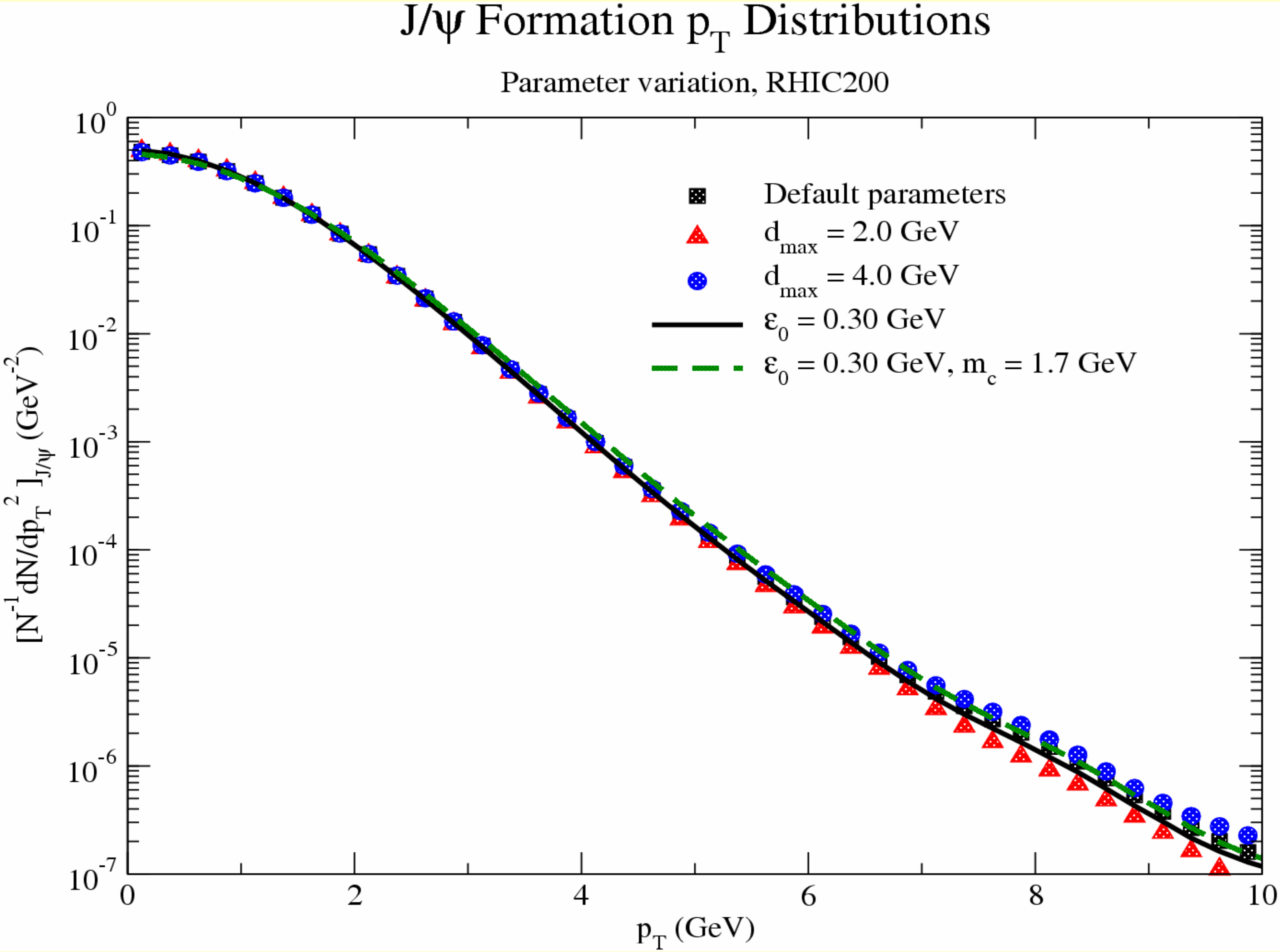
Transverse Momentum distribution of J/ψ and Charm Quarks
Blast wave initial charm quark distribution, T = 170 MeV, y_{Tmax} = 0.5
Initial charm quarks
$c\bar{c}$ pairs
$c\bar{c}$ pairs, Formation biased
J/ψ Formation
$[N^{-1}\, dN/dp_T^{\,2}]\ (GeV^{-2})$
p_T (GeV)
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
1
2
3
4
5

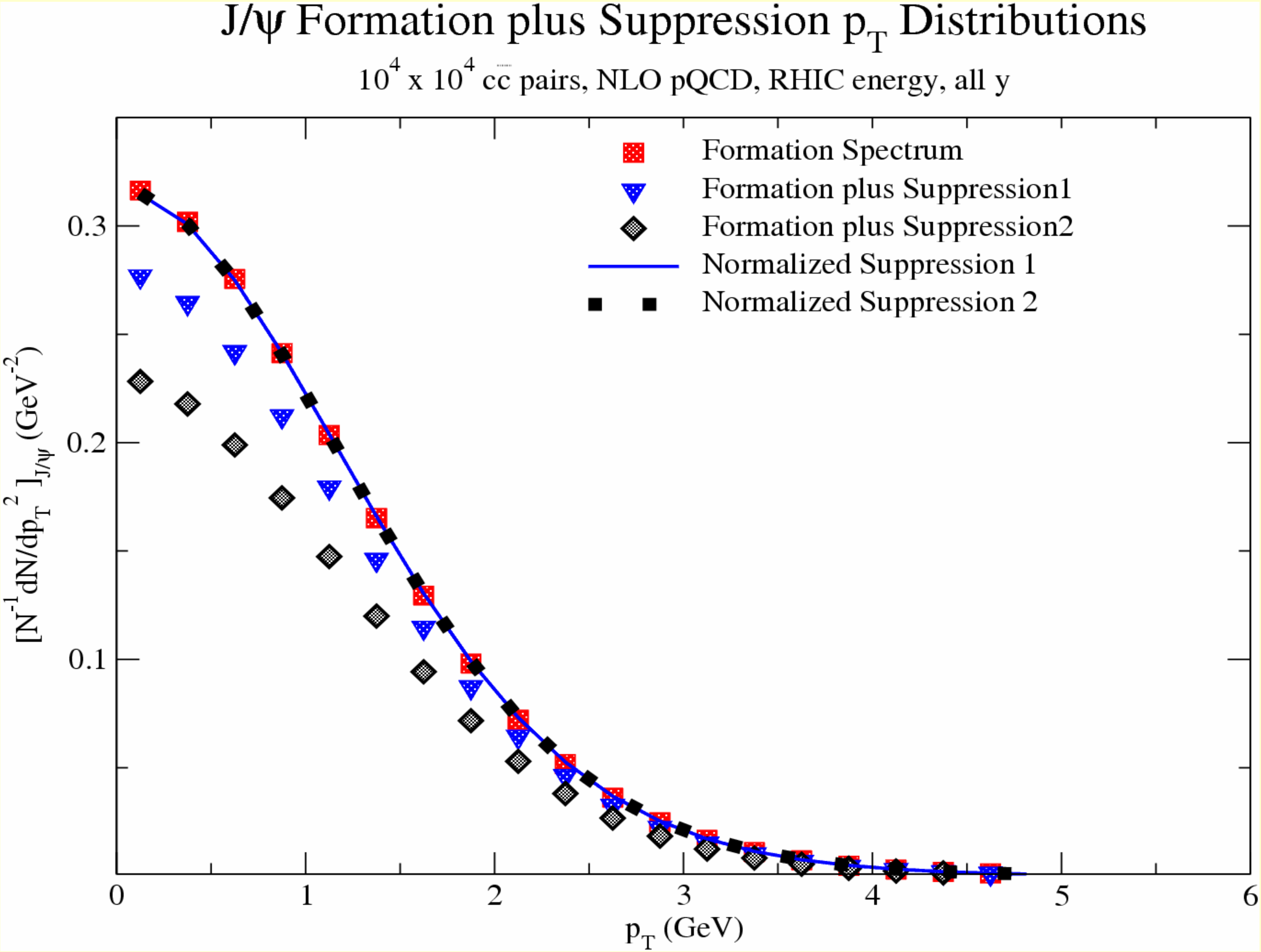

J/ψ Formation p_T Distributions
Comparisons using various quark distributions
[N^-1 dN/dp_T^2]_J/ψ (GeV^-2)
p_T (GeV)
T = 170 MeV, y_Tmax = 0.5
T = 128 MeV, y_Tmax = 0.65
T = 128 MeV, y_Tmax = 0
Formation from pQCD charm
pQCD diagonal cc̄ pairs
10^0
10^-2
10^-4
10^-6
10^-8
10^-10
0
2
4
6
8



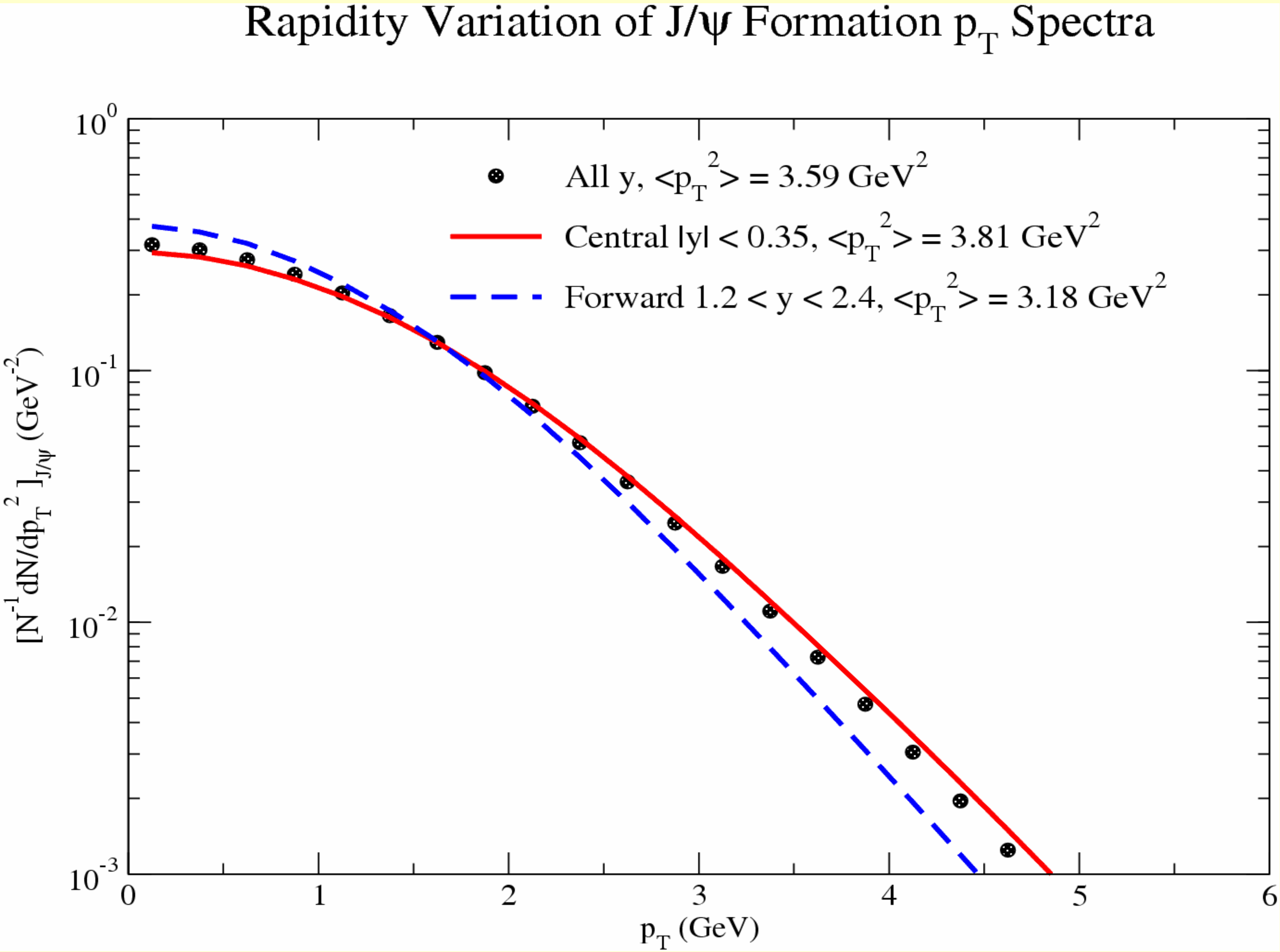
NLO $c\bar{c}$ pairs, unbiased, $<k_t^2> = 0$
$<k_t^2> = 0.4$ GeV^2
$<k_t^2> = 0.5$ GeV^2
$<k_t^2> = 0.6$ GeV^2
PHENIX Run3 pp -> J/ψ -> $\mu^+\mu^-$, y = 1.8
PHENIX Run3 with y = -1.7
$[N^{-1}\, dN/dp_T^{\;2}]_{J/\psi}$ (GeV^{-2})
p_T (GeV)
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
1
2
3
4
5

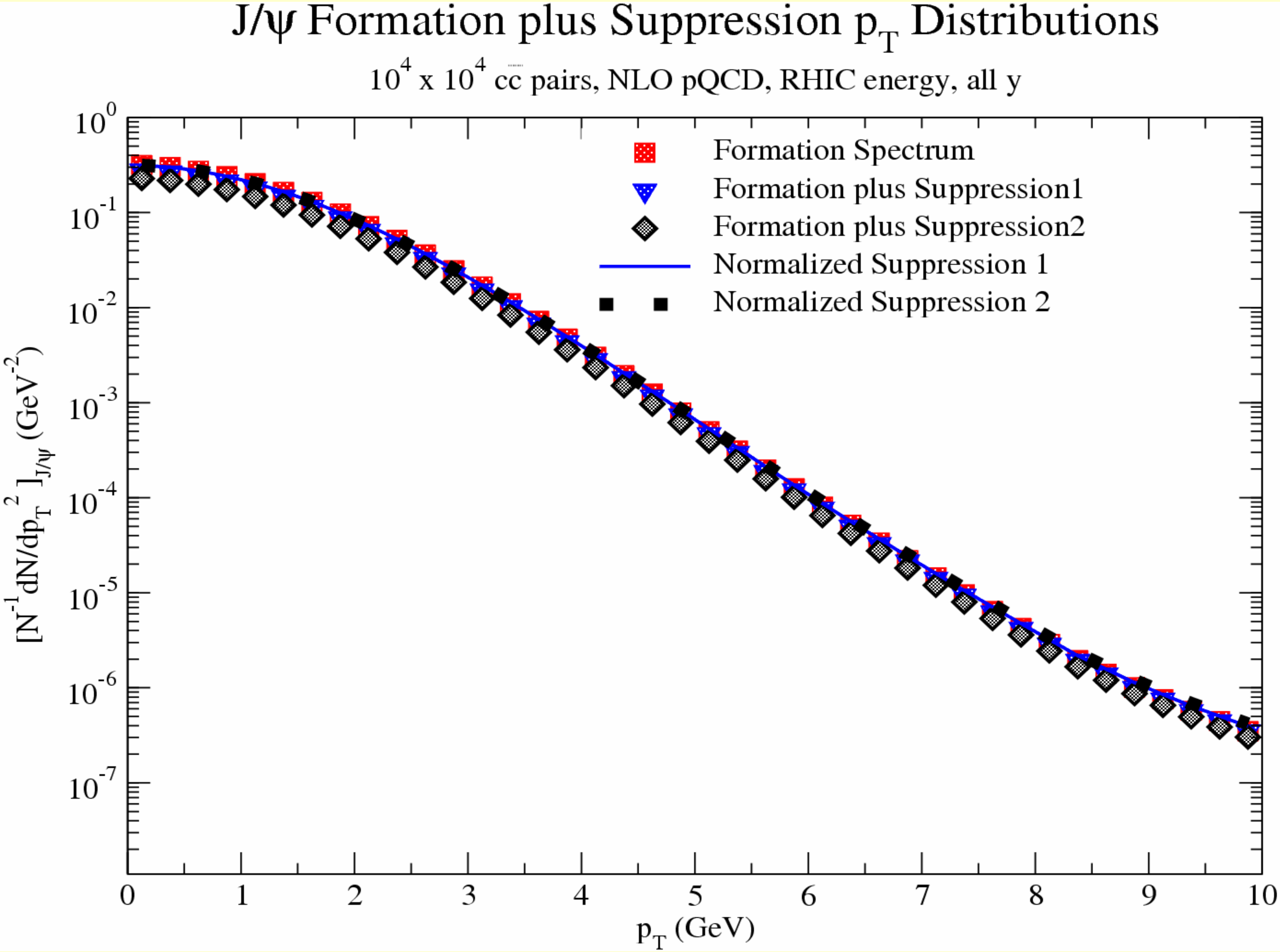

J/ψ Formation p_T Distributions
RHIC200 energy, 10^4 x 10^4 NLO pairs, $<k_t^2> = 1.3$ GeV^2
$[N^{-1}\, dN/dp_T^{\,2}]_{J/\psi}$ (GeV^{-1})
10^0
10^{-2}
10^{-4}
10^{-6}
0
2
4
6
8
10
p_T (GeV)
Default parameters
No energy cutoff
Constant σ
Constant σ, No energy cutoff


J/ψ Formation p_T Distributions
Parameter variation, RHIC200
Default parameters
d_{max} = 2.0 GeV
d_{max} = 4.0 GeV
ε_0 = 0.30 GeV
ε_0 = 0.30 GeV, m_c = 1.7 GeV
$[N^{-1} dN/dp_T^{\,2}]_{J/\psi}$ (GeV^{-2})
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0
2
4
6
8
10
p_T (GeV)



J/ψ Formation plus Suppression p_T Distributions
10^4 x 10^4 cc pairs, NLO pQCD, RHIC energy, all y
Formation Spectrum
Formation plus Suppression1
Formation plus Suppression2
Normalized Suppression 1
Normalized Suppression 2
[N^-1 dN/dp_T^2]_J/ψ (GeV^-2)
p_T (GeV)
0.1
0.2
0.3
0
1
2
3
4
5
6


Rapidity Variation of J/ψ Formation p_T Spectra
All y, <p_T^2> = 3.59 GeV^2
Central |y| < 0.35, <p_T^2> = 3.81 GeV^2
Forward 1.2 < y < 2.4, <p_T^2> = 3.18 GeV^2
[N^-1 dN/dp_T^2]_J/ψ (GeV^-2)
p_T (GeV)
10^0
10^-1
10^-2
10^-3
0
1
2
3
4
5
6


J/ψ Formation plus Suppression p_T Distributions
10^4 x 10^4 $c\bar{c}$ pairs, NLO pQCD, RHIC energy, all y
Formation Spectrum
Formation plus Suppression1
Formation plus Suppression2
Normalized Suppression 1
Normalized Suppression 2
$[N^{-1} dN/dp_T^2]_{J/\psi}$ (GeV^{-2})
p_T (GeV)
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0
1
2
3
4
5
6
7
8
9
10