J/ψ ENHANCEMENT at RHIC

R. L. THEWS
UNIVERSITY OF ARIZONA

20'th Anniversary Workshop on J/ψ Suppression
BNL
MAY 9, 2006

IN-MEDIUM FORMATION

HIGH ENERGY EVOLUTION OF MATSUI-SATZ:

$R_{\text{plasma screening}} < R_{\text{quarkonium}}$ SUPPRESSION in a static medium, or

KHARZEEV-SATZ: Ionization with deconfined gluons

Charm pair diffuse away, will not recombine during deconfinement phase or at hadronization

NEW SCENARIO AT COLLIDER ENERGIES

Multiple ccbar pairs in high energy AA Collisions

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

CENTRAL VALUES AT RHIC:

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

AND AT LHC: 100-200??

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 (J/ψ and η_c)

Probability for charm quark to combine with anticharm:

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

Since $\varepsilon << 1$, 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 $N_{ch} \propto N_p{}^{1+\Delta}$,

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

Suppression of Initially Produced J/ψ

$$N_{J/\psi}^{\text{Initial}}(\tau_f) = \varepsilon(\tau_f)\, N_{J/\psi}^{\text{Initial}}(\tau_i)$$

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

Continuous In-Medium Formation followed by Partial Suppression

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

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

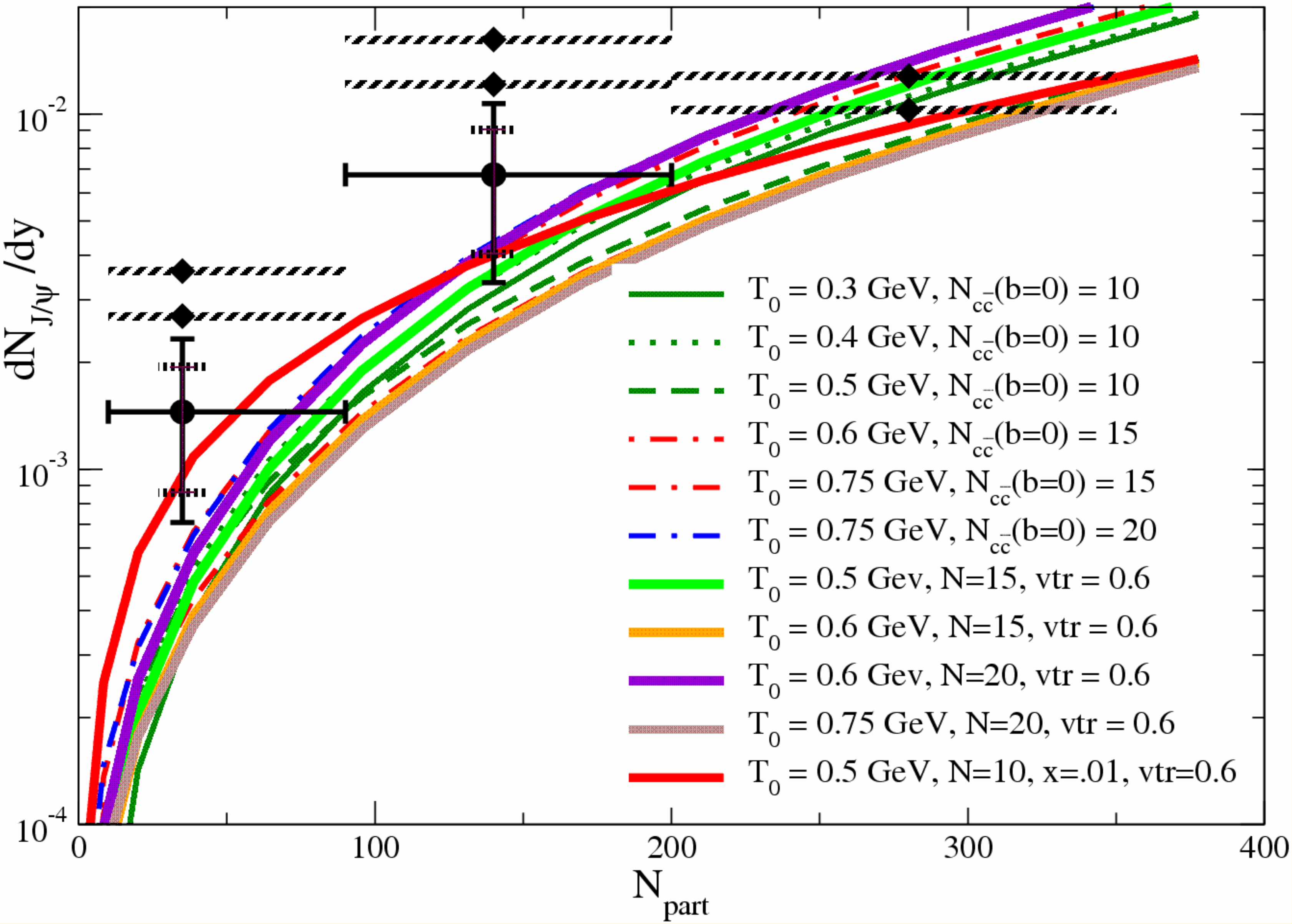
COMPARISON WITH INITIAL PHENIX DATA AT RHIC 200

Rates very sensitive to quark momentum distribution

Centrality signature varies with magnitude of N_{cc}

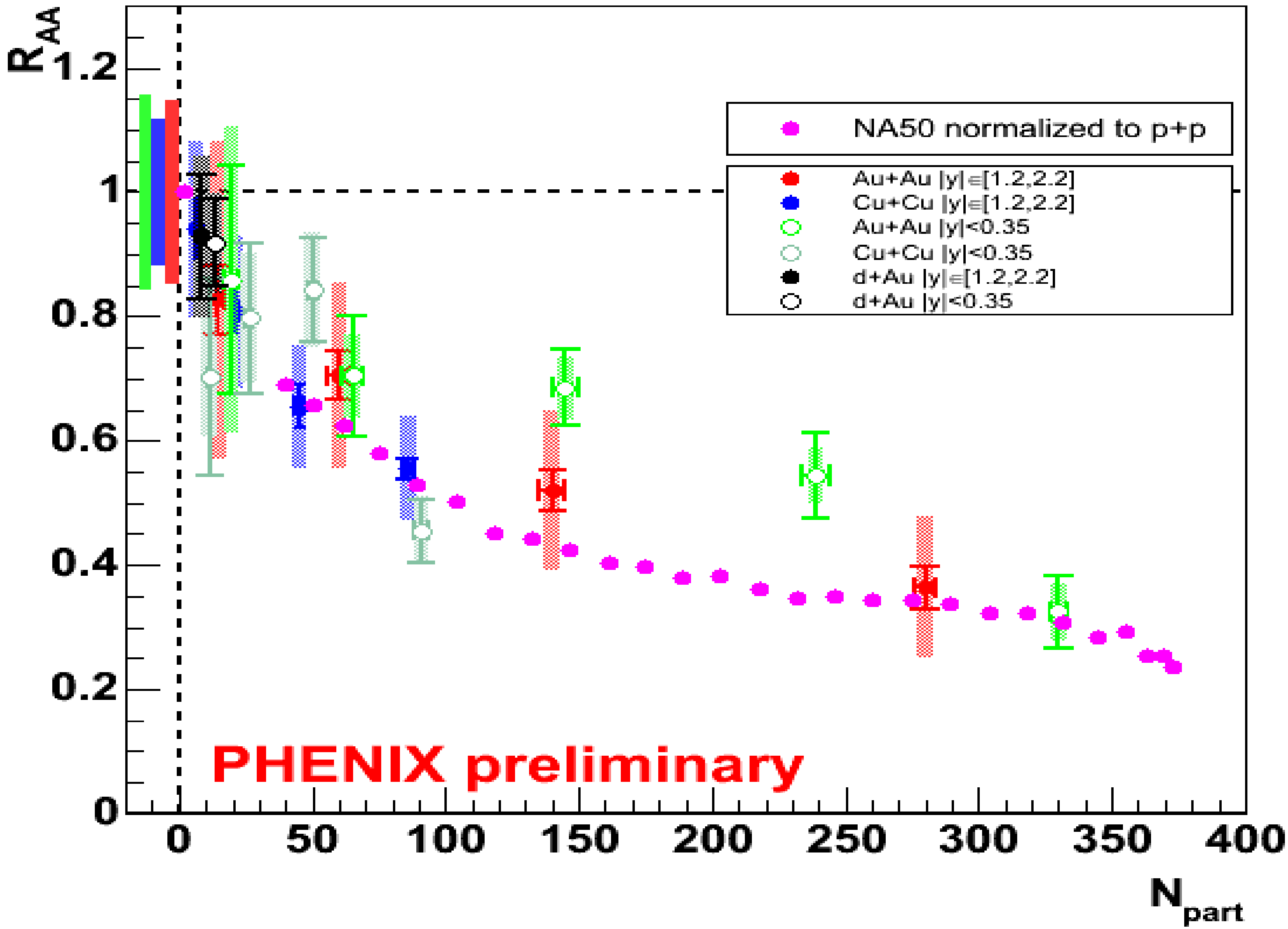
Initial indication for suppression below binary scaling

Agreement within a region of model parameter space

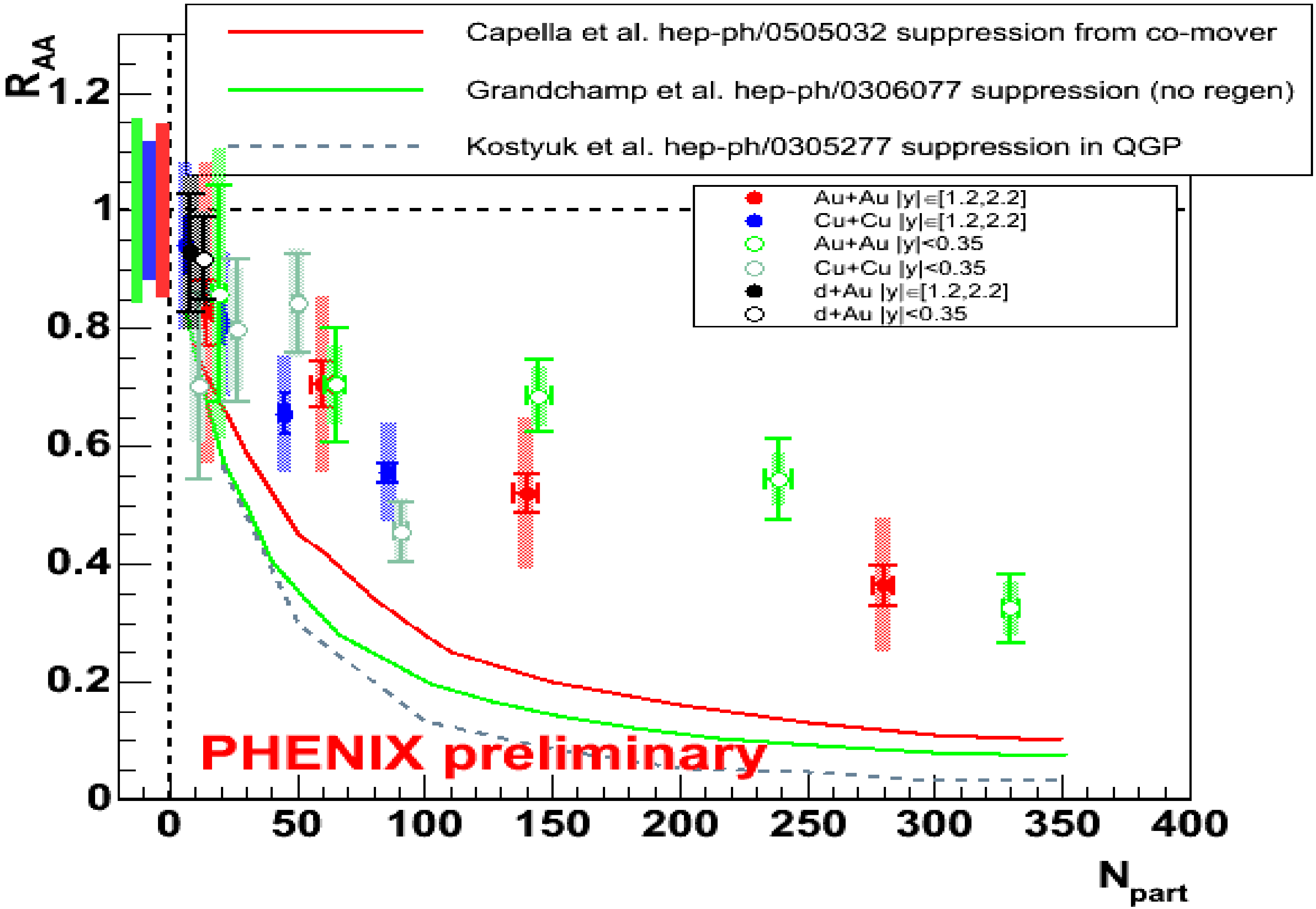


$dN_{J/\psi}/dy$
10^{-2}
10^{-3}
10^{-4}
0
100
200
300
400
N_{part}
T_0 = 0.3 GeV, $N_{c\bar{c}}$(b=0) = 10
T_0 = 0.4 GeV, $N_{c\bar{c}}$(b=0) = 10
T_0 = 0.5 GeV, $N_{c\bar{c}}$(b=0) = 10
T_0 = 0.6 GeV, $N_{c\bar{c}}$(b=0) = 15
T_0 = 0.75 GeV, $N_{c\bar{c}}$(b=0) = 15
T_0 = 0.75 GeV, $N_{c\bar{c}}$(b=0)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

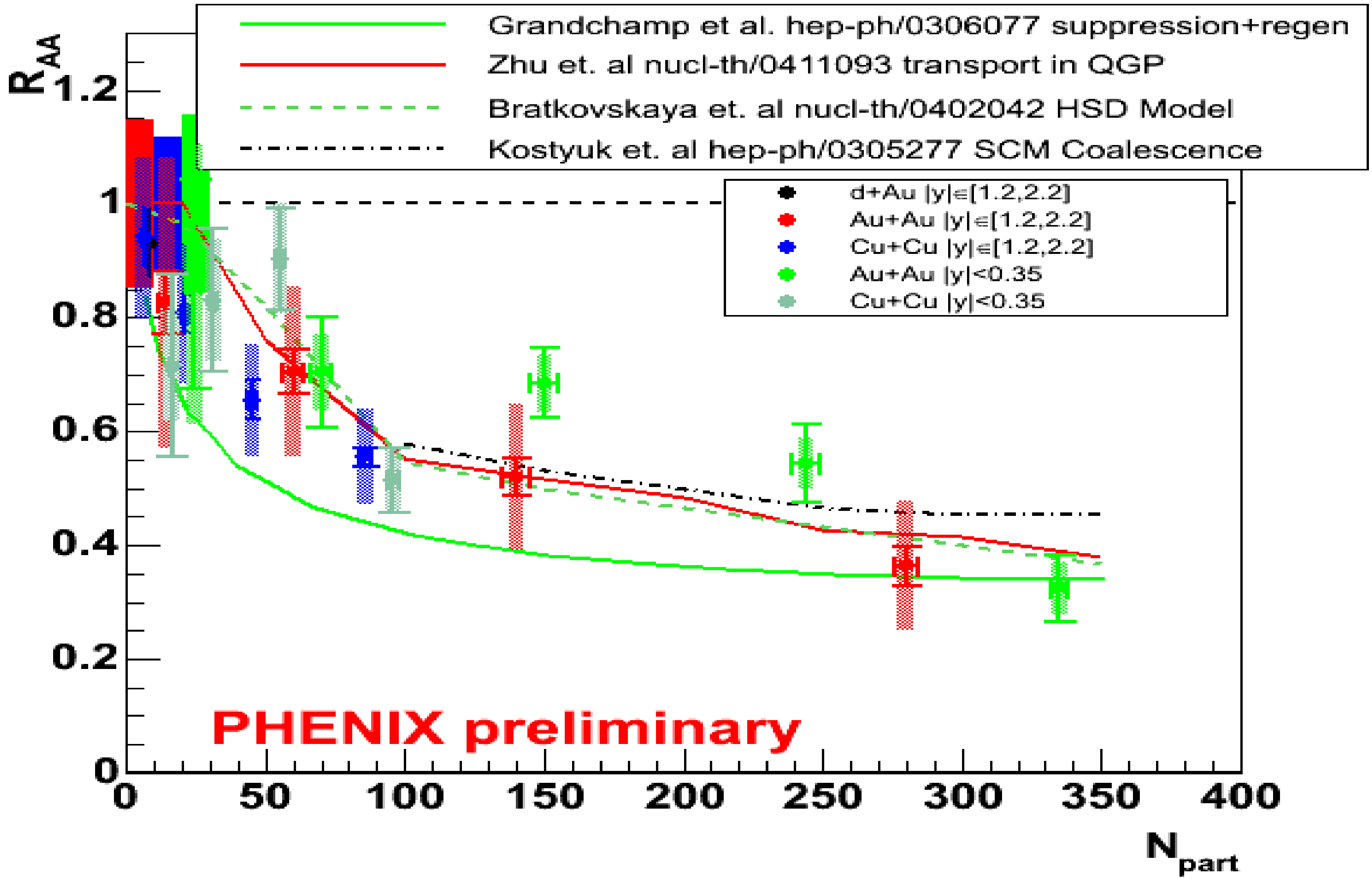
J/ψ nuclear modification factor R_{AA}

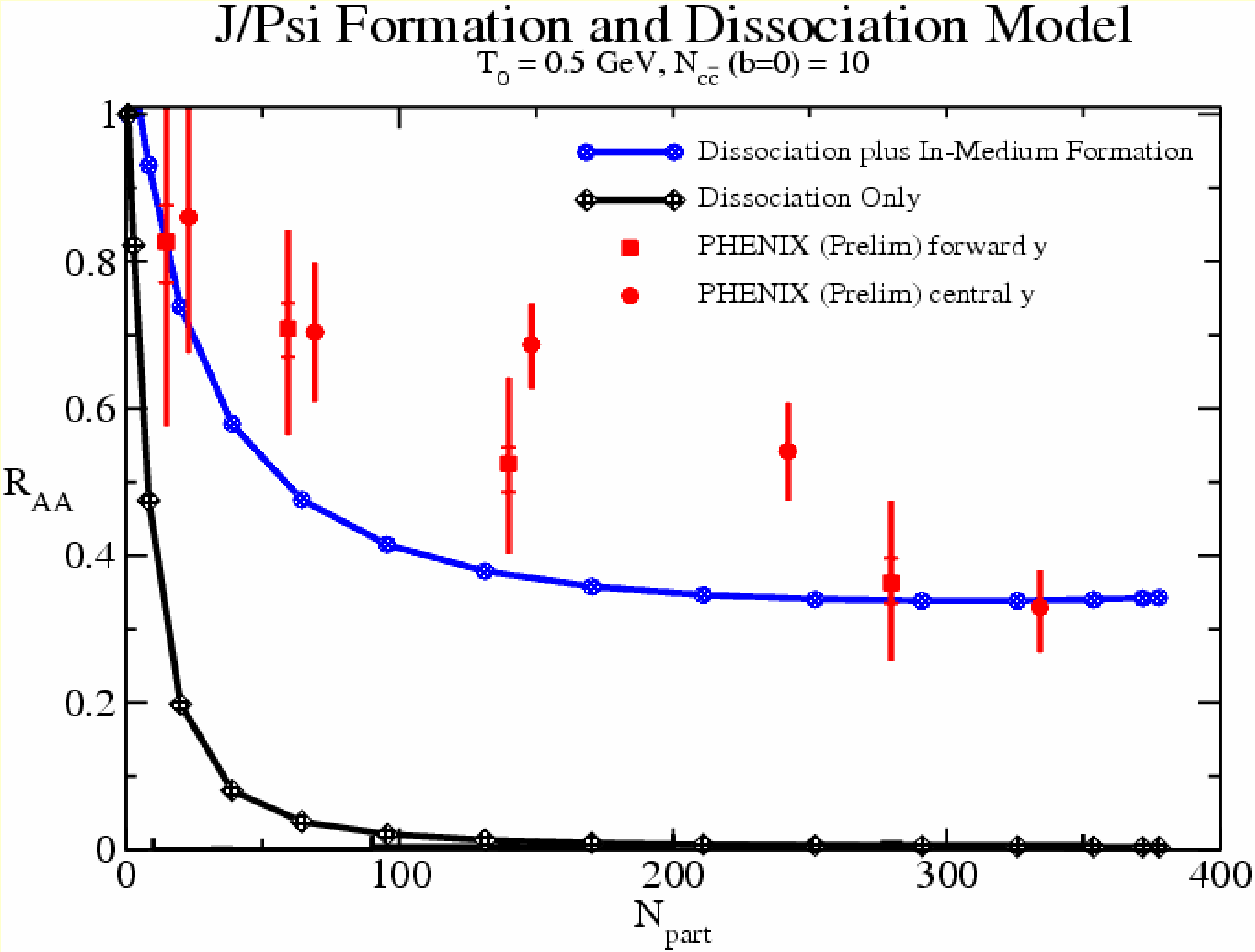


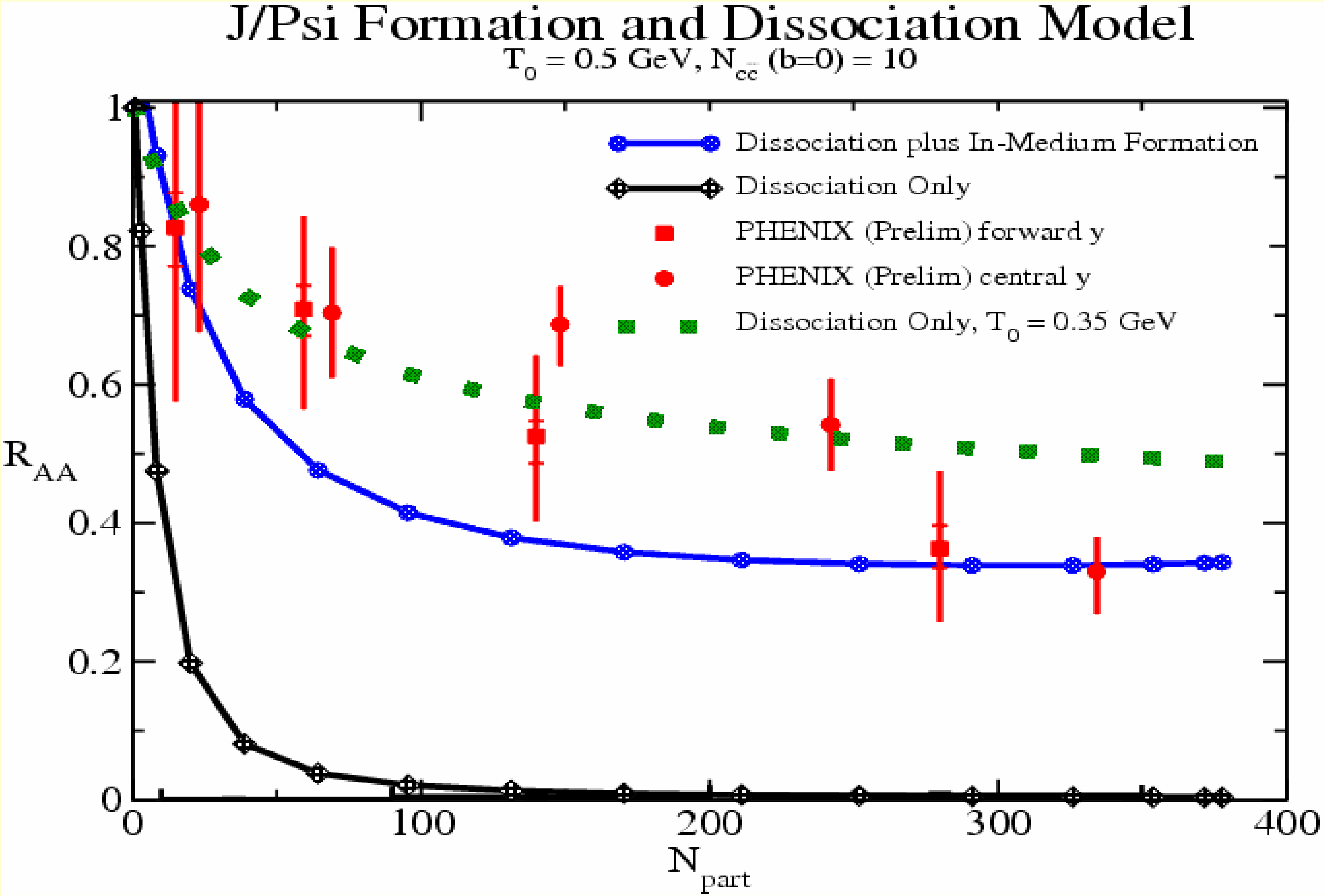
J/ψ nuclear modification factor R_{AA}



J/ψ nuclear modification factor R_{AA}




J/Psi Formation and Dissociation Model
T0 = 0.5 GeV, Ncc̄ (b=0) = 10
Dissociation plus In-Medium Formation
Dissociation Only
PHENIX (Prelim) forward y
PHENIX (Prelim) central y
RAA
Npart
0
0.2
0.4
0.6
0.8
1
0
100
200
300
400



J/Psi Formation and Dissociation Model
T0 = 0.5 GeV, Ncc (b=0) = 10
Dissociation plus In-Medium Formation
Dissociation Only
PHENIX (Prelim) forward y
PHENIX (Prelim) central y
Dissociation Only, T0 = 0.35 GeV
RAA
Npart
0
0.2
0.4
0.6
0.8
1
0
100
200
300
400

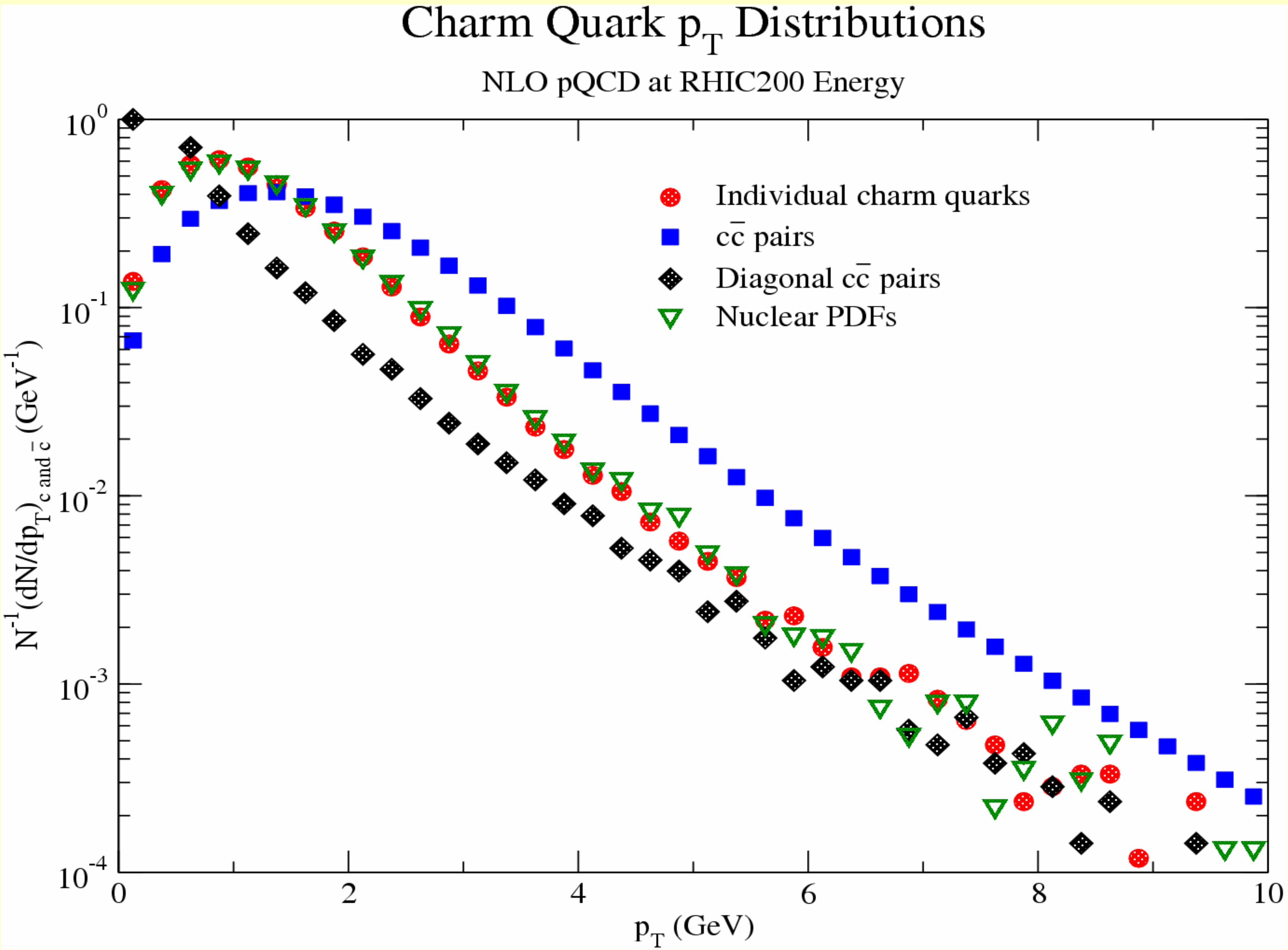
CAN Y AND P_T SPECTRA PROVIDE SIGNATURES OF IN-MEDIUM FORMATION?

R. L. Thews and M. L. Mangano Phys. Rev. C73, 014904 (2006) [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)

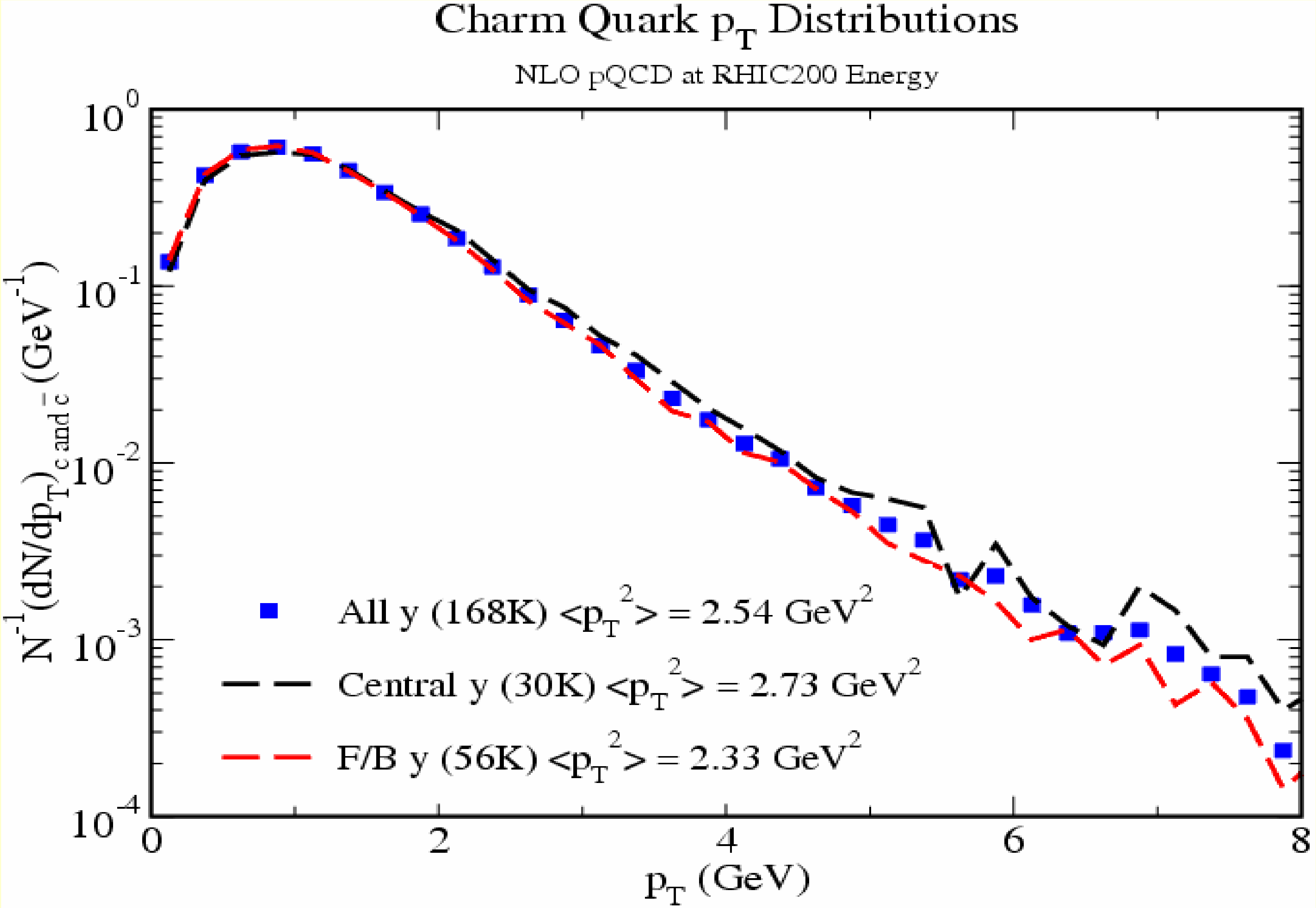
$$\frac{dN_{J/\psi}}{d^3p_{J/\psi}} = \int \frac{dt}{V(t)} \sum_{i=1}^{N_{c\bar{c}}} \sum_{j=1}^{N_{c\bar{c}}} v_{rel} \frac{d\sigma(p_i + p_j \rightarrow p_{J/\psi} + X)}{d^3p_{J/\psi}}$$

- All combinations of c and cbar contribute
- Total has expected $(N_{ccbar})^2$ / V behavior
- Prefactor is integrated flux per ccbar pair
- "Off-Diagonal" Pair y and p_T distributions differ from "Diagonal", should survive in J/ψ
- Weighting with in-medium formation probability introduces additional modification



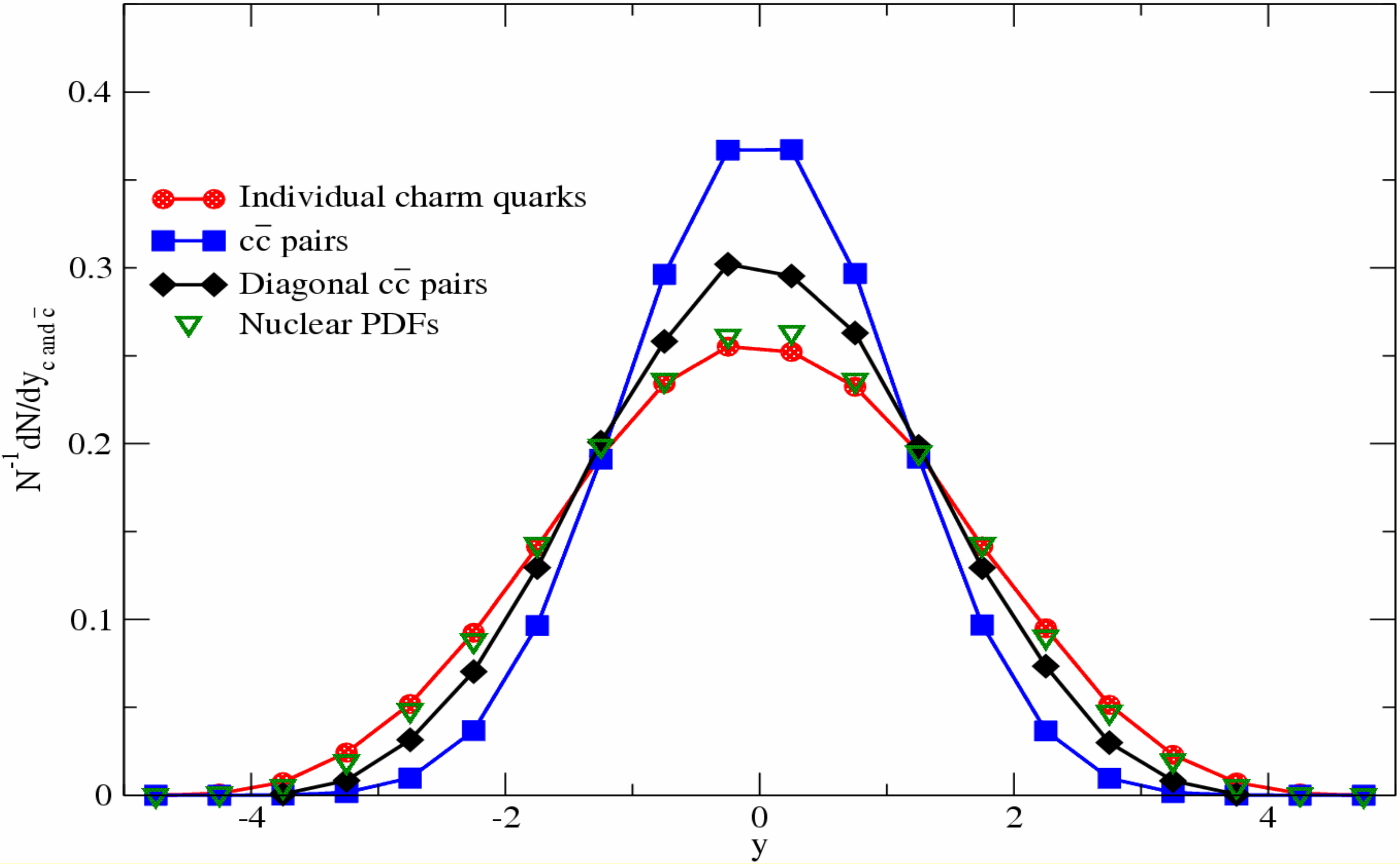
Charm Quark p_T Distributions
NLO pQCD at RHIC200 Energy
Individual charm quarks
$c\bar{c}$ pairs
Diagonal $c\bar{c}$ pairs
Nuclear PDFs
$N^{-1}(dN/dp_T)_{c \text{ and } \bar{c}}$ (GeV^{-1})
p_T (GeV)
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
2
4
6
8
10

P_T distribution shows minimal variation with y interval

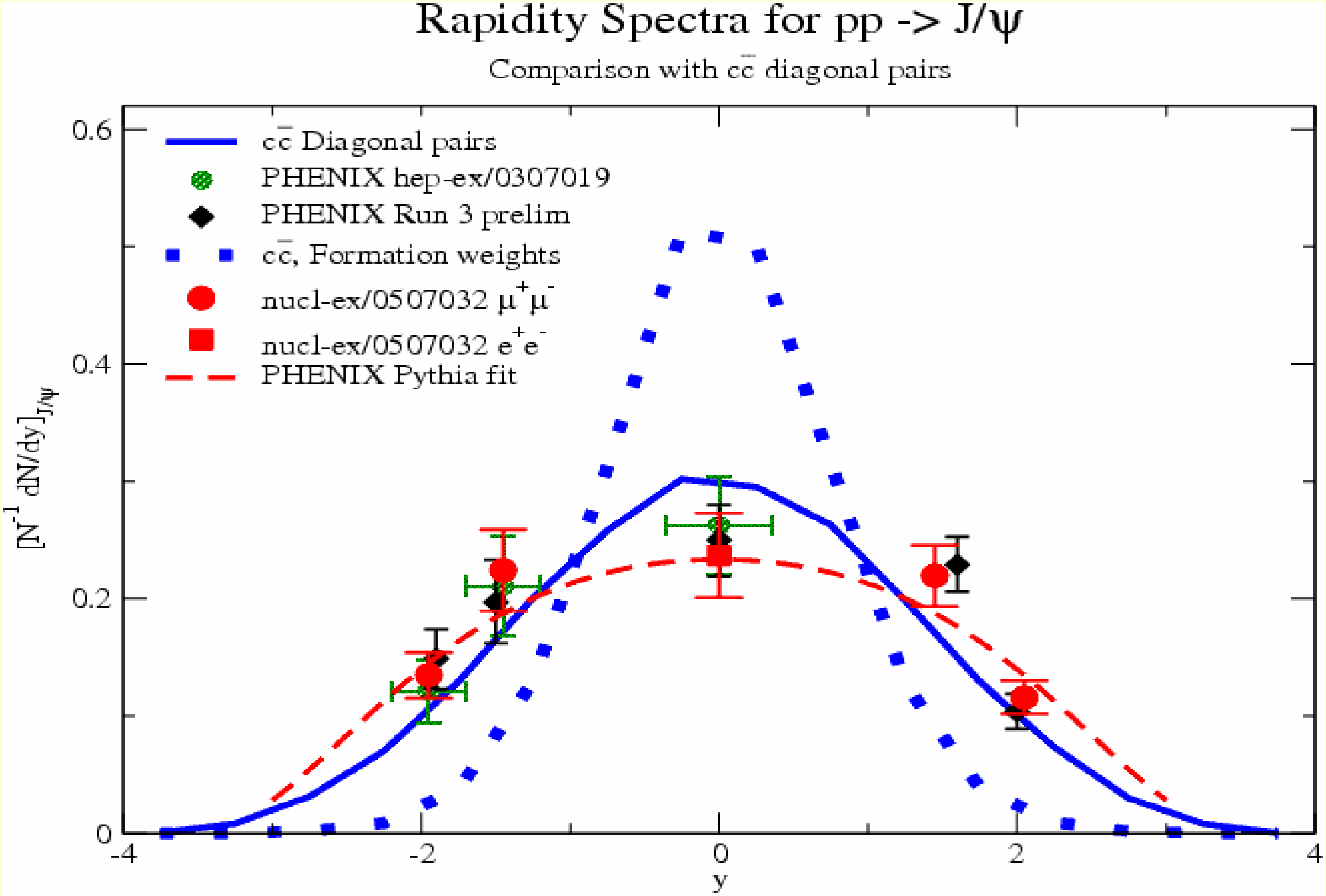


Charm Quark y Distributions

NLO pQCD at RHIC200 Energy

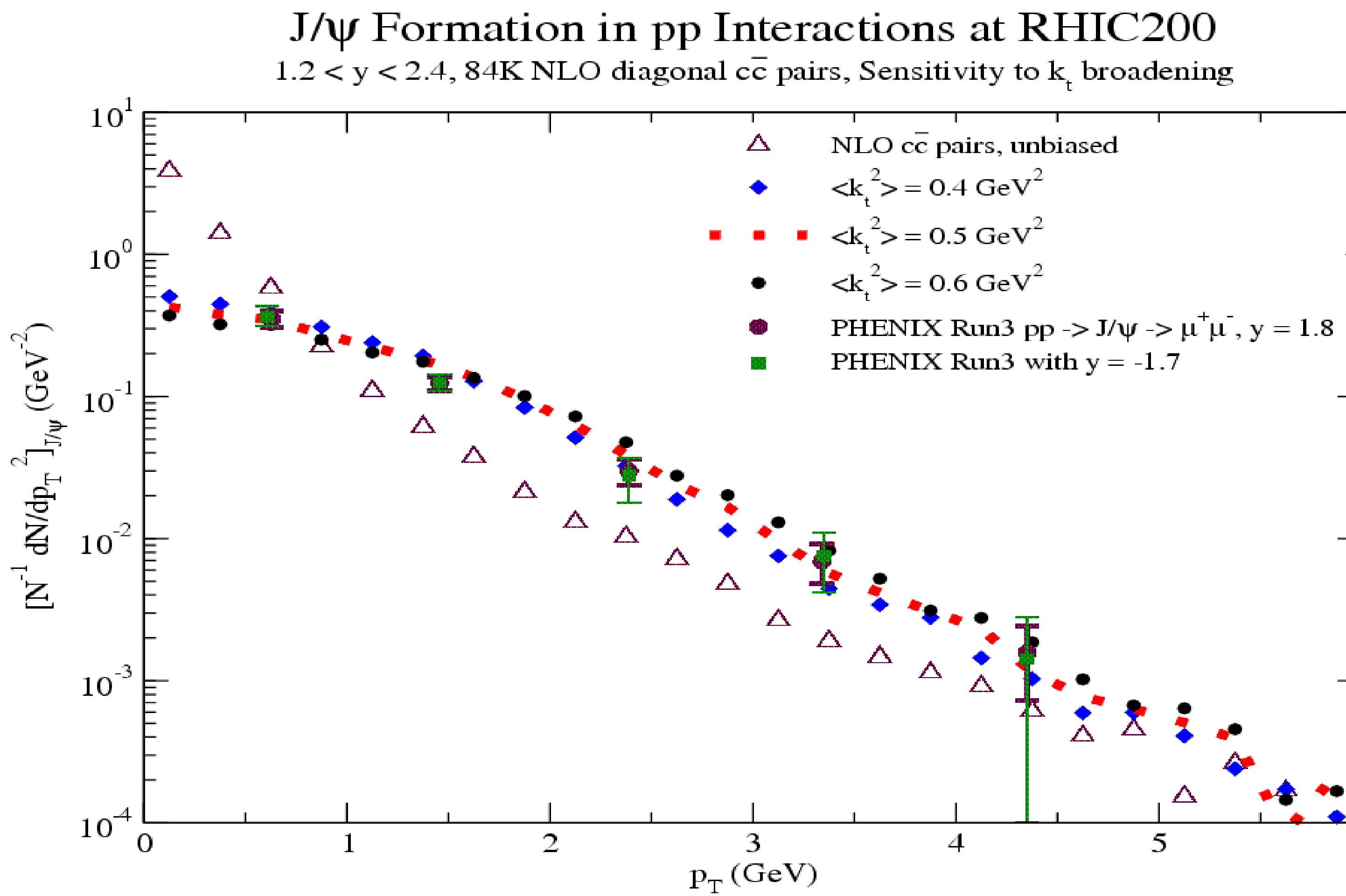


p-p data "select" unbiased diagonal c-cbar pairs



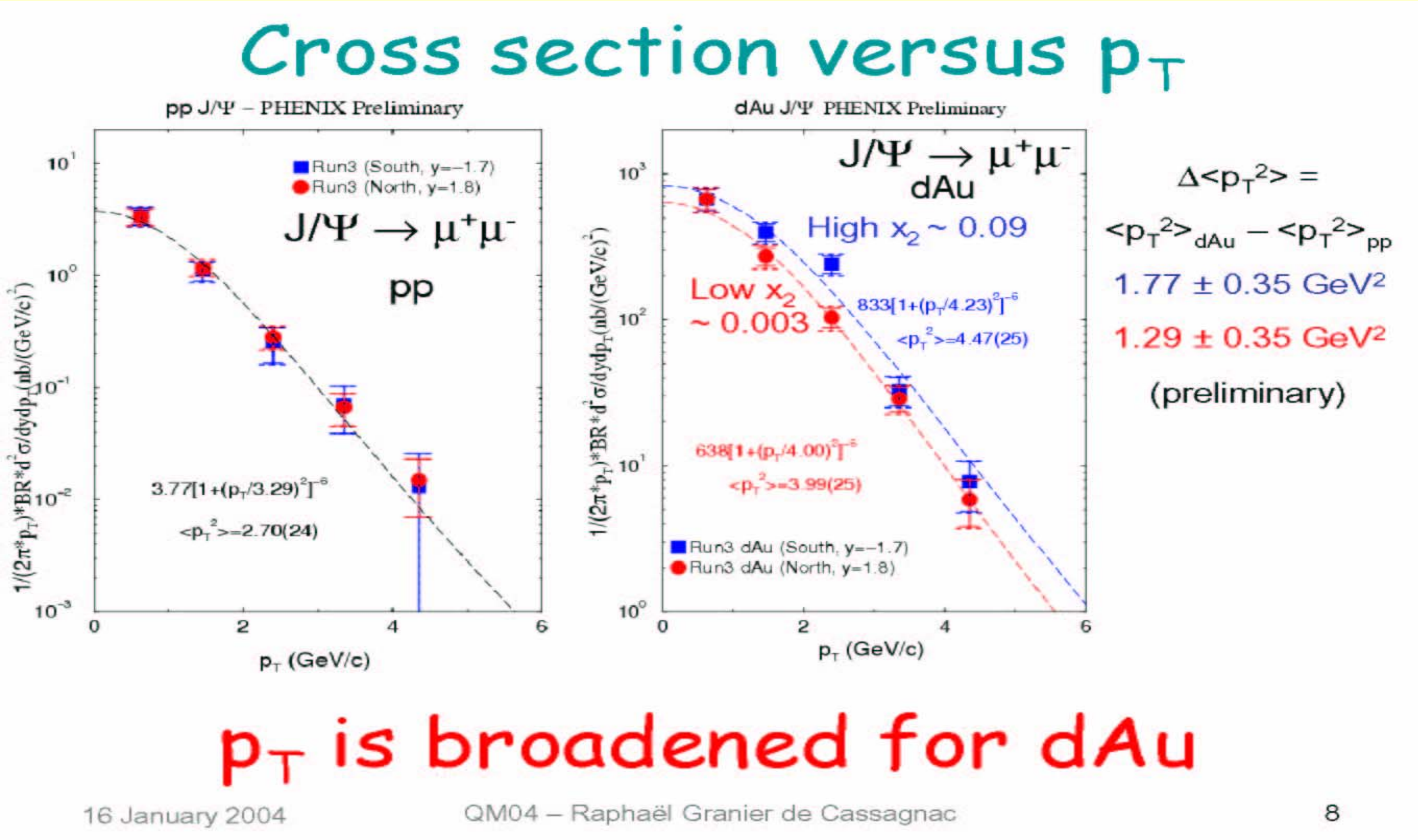
p-p data determine intrinsic k_t

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



Use dAu broadening to determine nuclear k_t

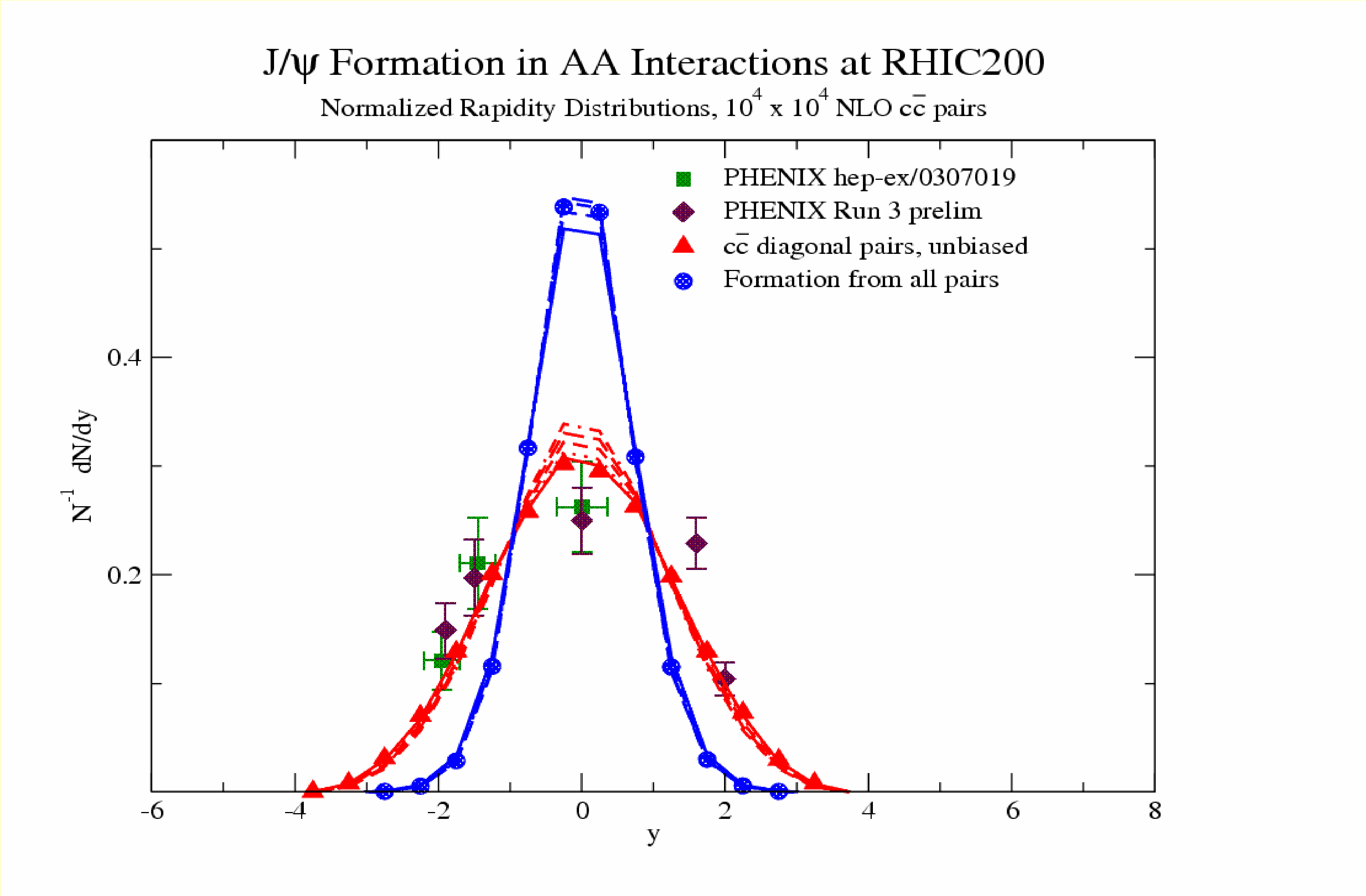
$$\Rightarrow \quad \langle k_t^{\,2} \rangle_{AA} = 1.3 \pm 0.3 \text{ GeV}^2$$

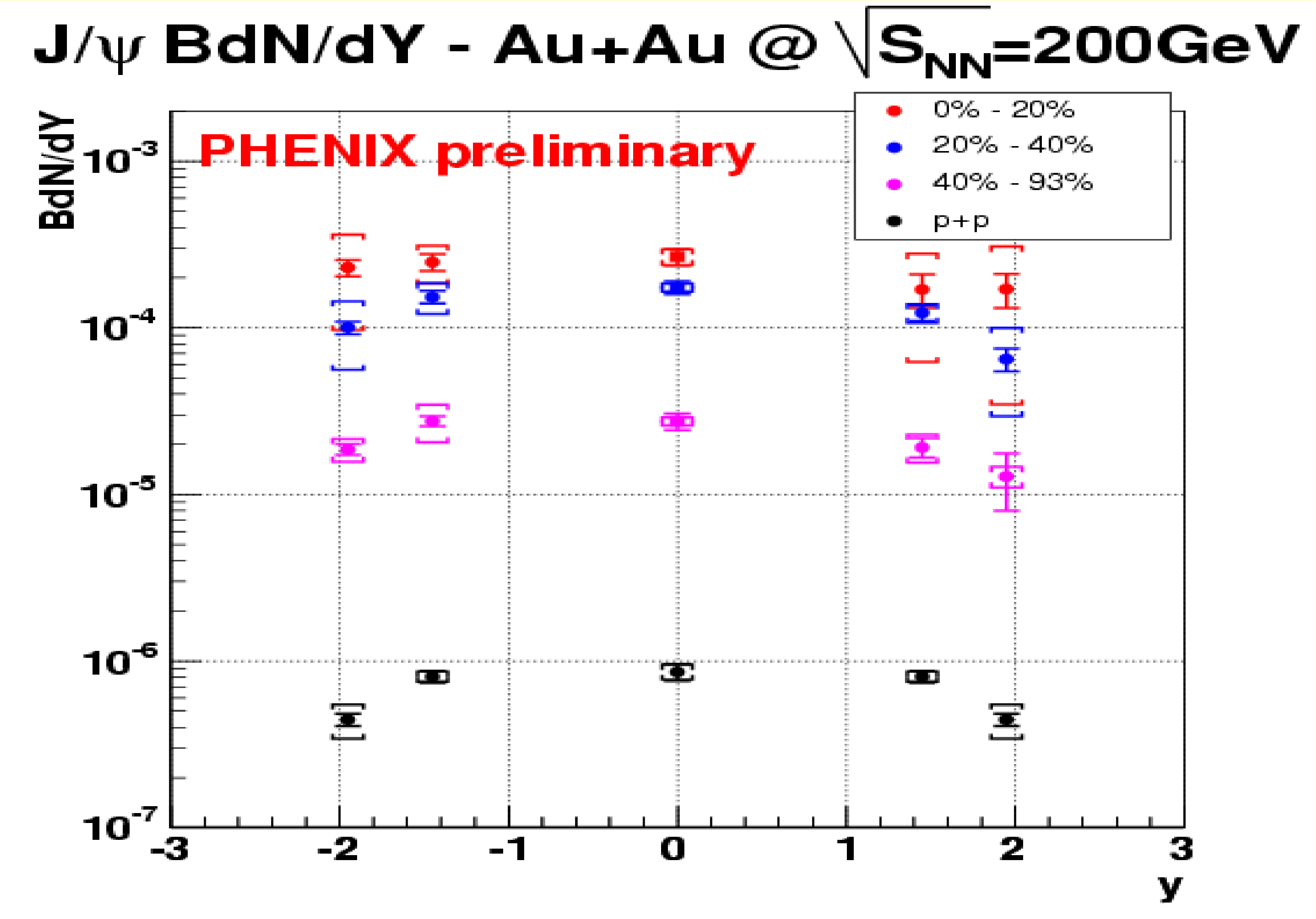


$$< p_T^2 >_{AB} = < p_T^2 >_{pp} + \lambda^2 \{\bar{n}_A + \bar{n}_B - 2\}$$

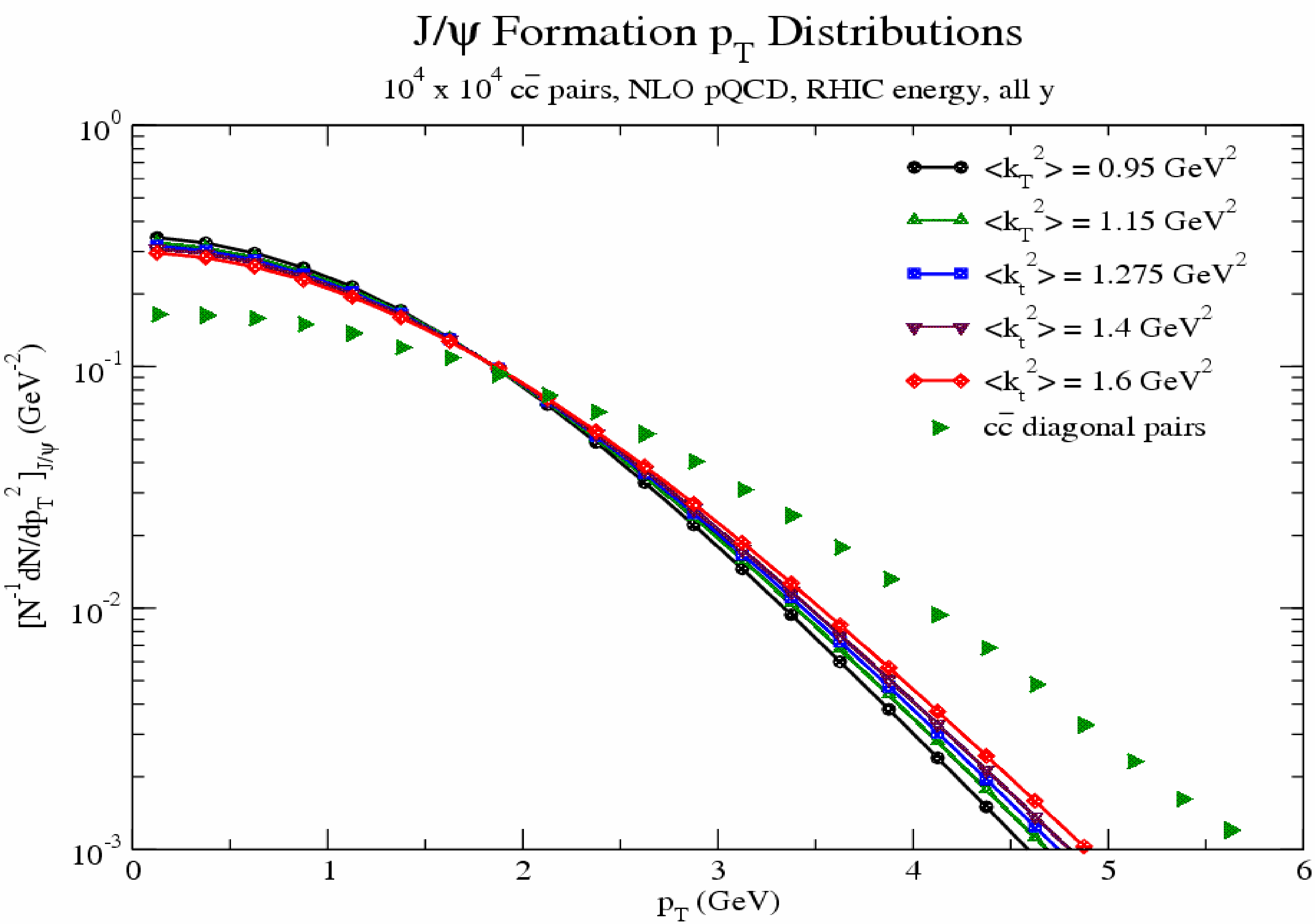
Nuclear broadening from Initial state parton scattering, extract $\lambda^2 =$ 0.56 +/- 0.08 GeV^2 for Au-Au at RHIC, compare with 0.12 +/- .02 GeV^2 at fixed-target energy. Note: λ and n are correlated within given nuclear geometry.

Formation through "off-diagonal" pairs narrows rapidity distribution

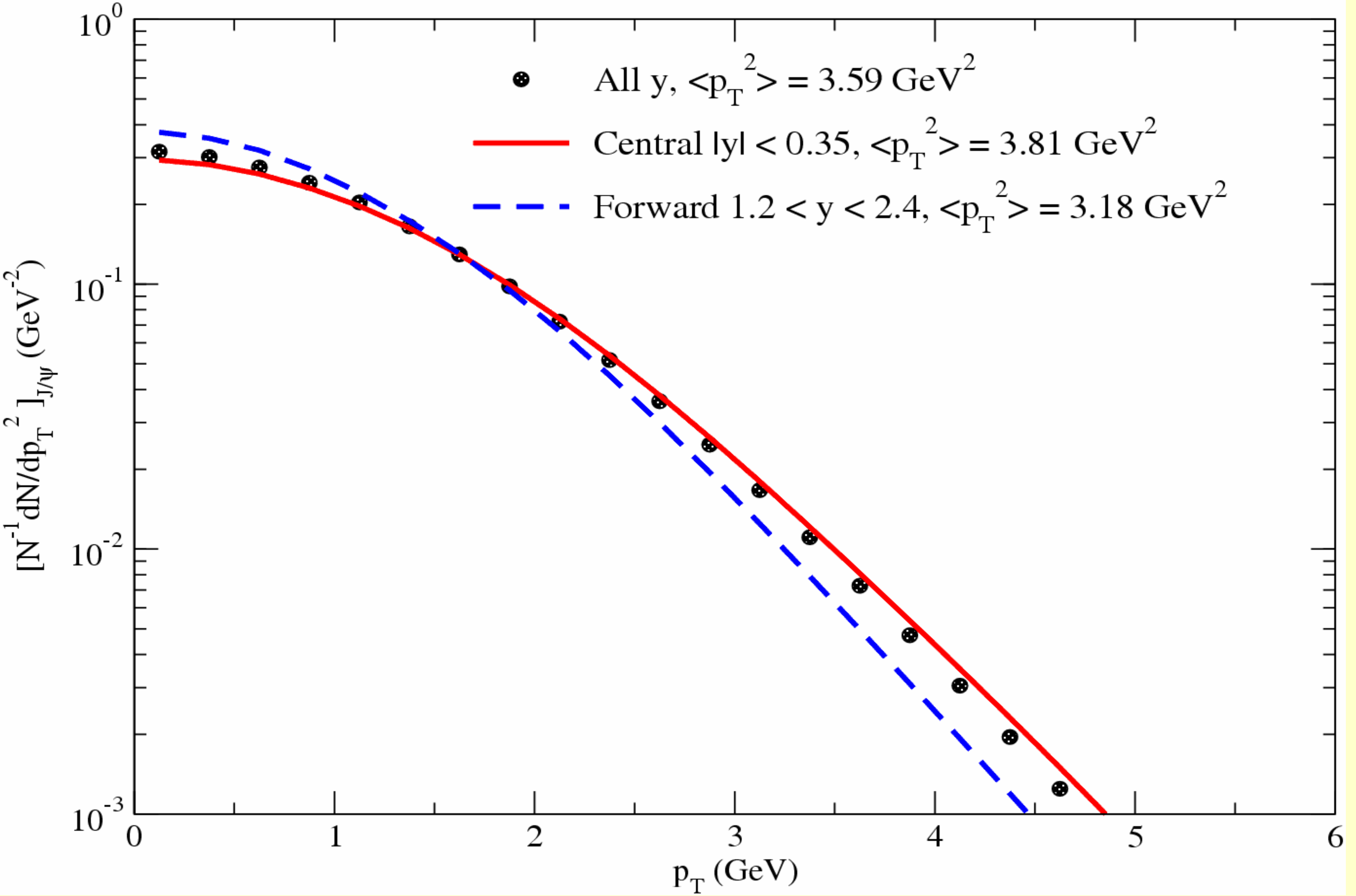


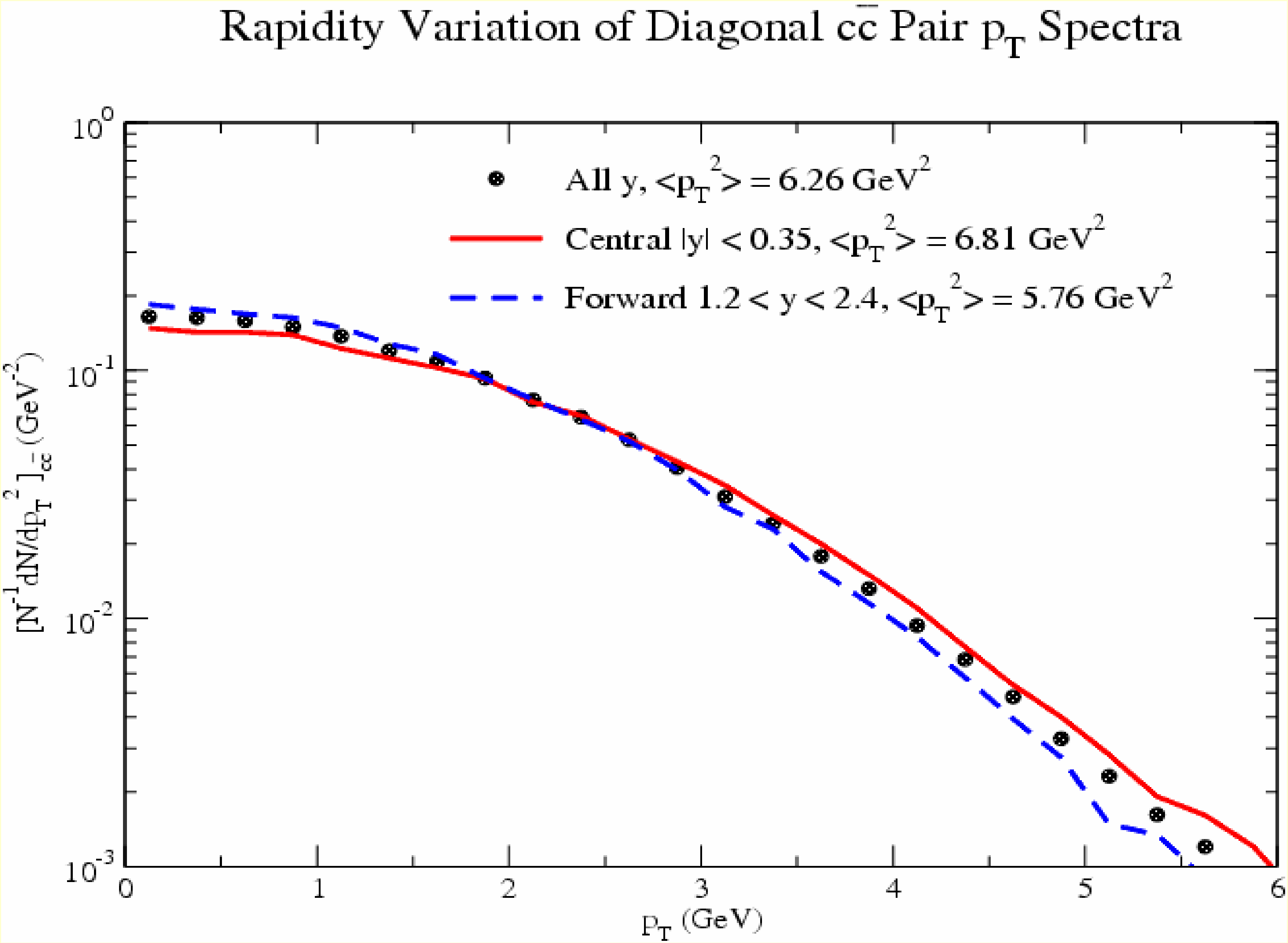

J/ψ BdN/dY - Au+Au @ √S_NN=200GeV
PHENIX preliminary
0% - 20%
20% - 40%
40% - 93%
p+p
BdN/dY
10^-3
10^-4
10^-5
10^-6
10^-7
-3
-2
-1
0
1
2
3
y

Formation through "off-diagonal" pairs narrows p_t distribution



Rapidity Variation of J/ψ Formation p_T Spectra

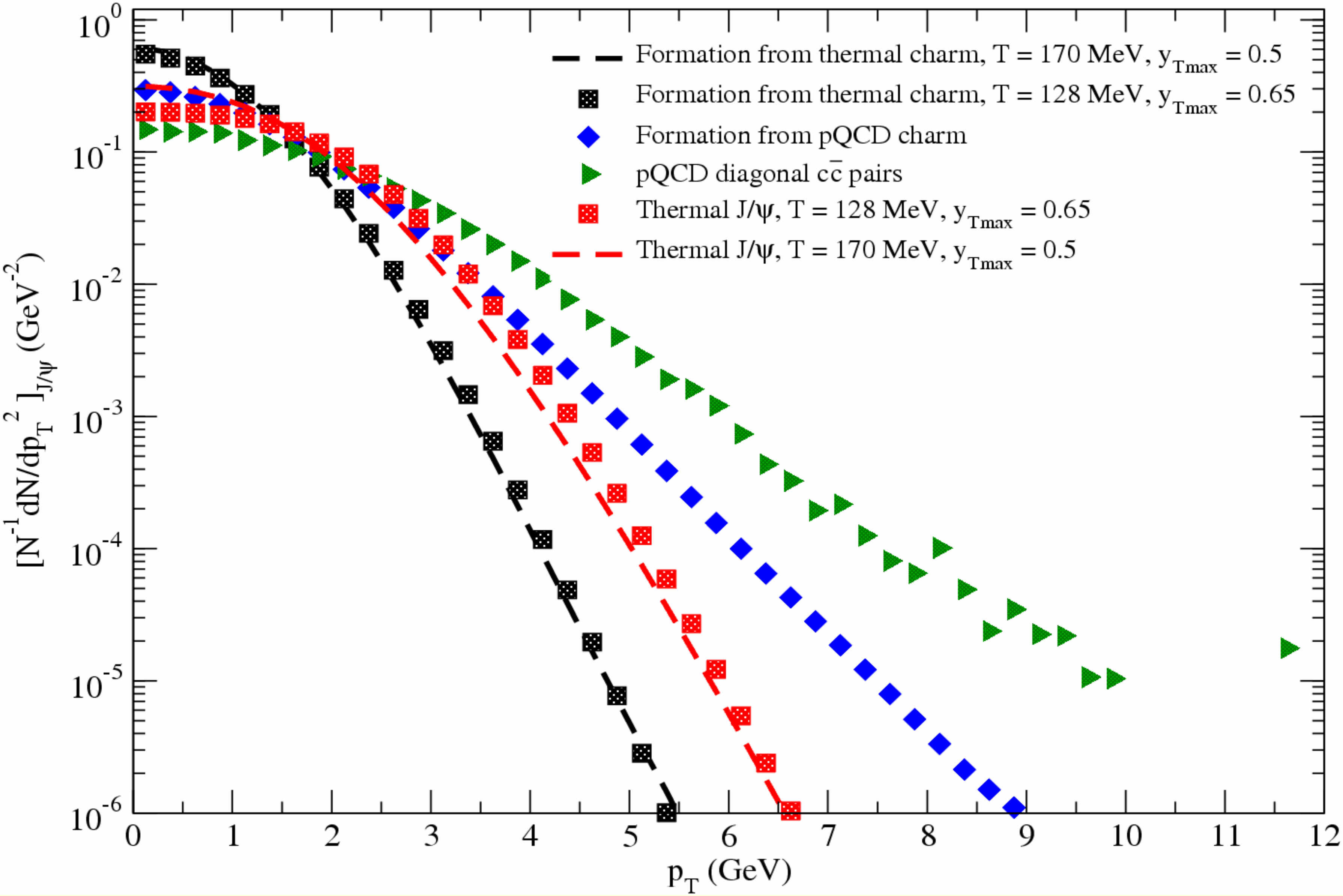


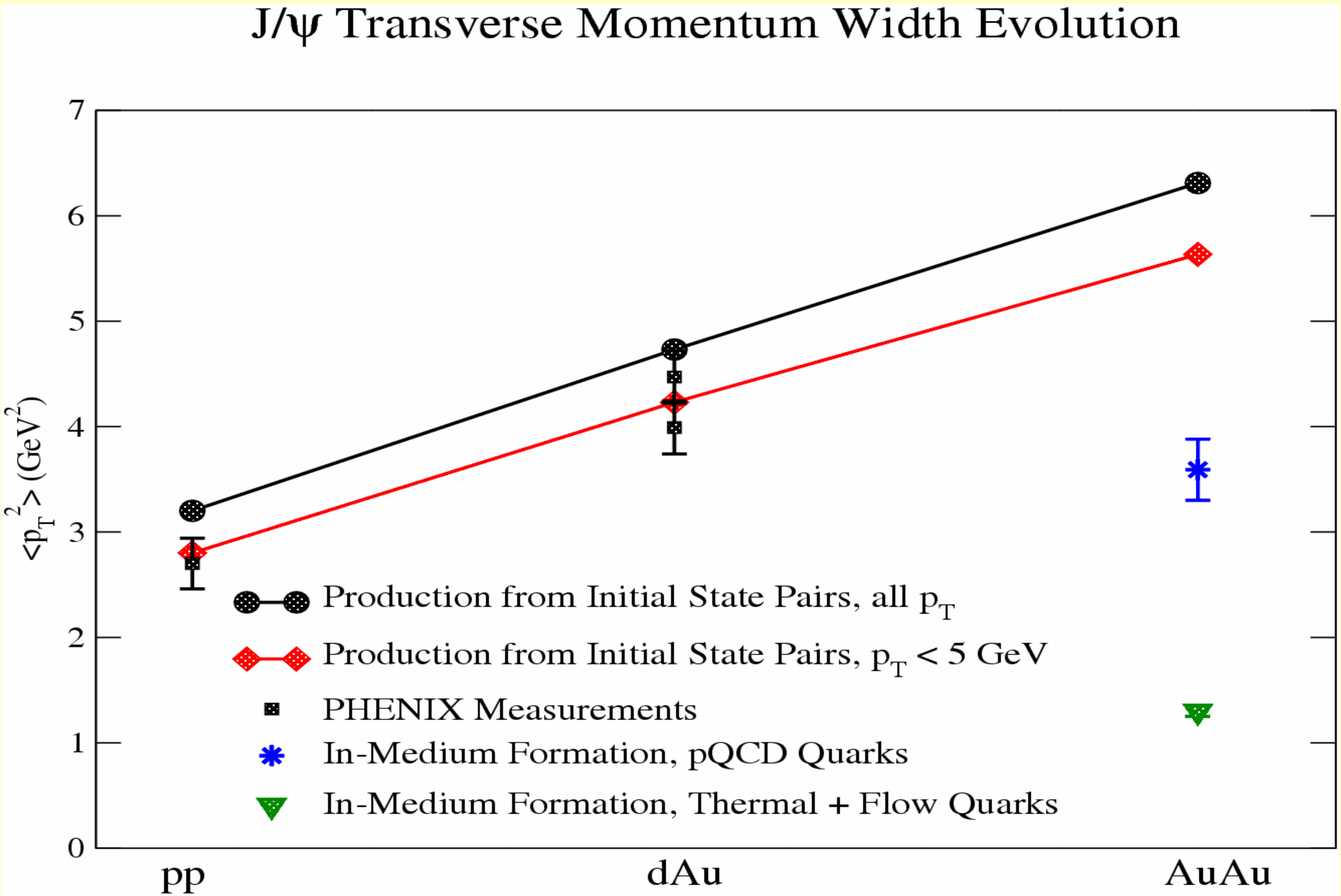


Rapidity Variation of Diagonal $c\bar{c}$ Pair p_T Spectra
All y, $<p_T^2> = 6.26$ GeV^2
Central $|y| < 0.35$, $<p_T^2> = 6.81$ GeV^2
Forward $1.2 < y < 2.4$, $<p_T^2> = 5.76$ GeV^2
$[N^{-1} dN/dp_T^2]_{c\bar{c}}$ (GeV^{-2})
p_T (GeV)
10^0
10^{-1}
10^{-2}
10^{-3}
0
1
2
3
4
5
6

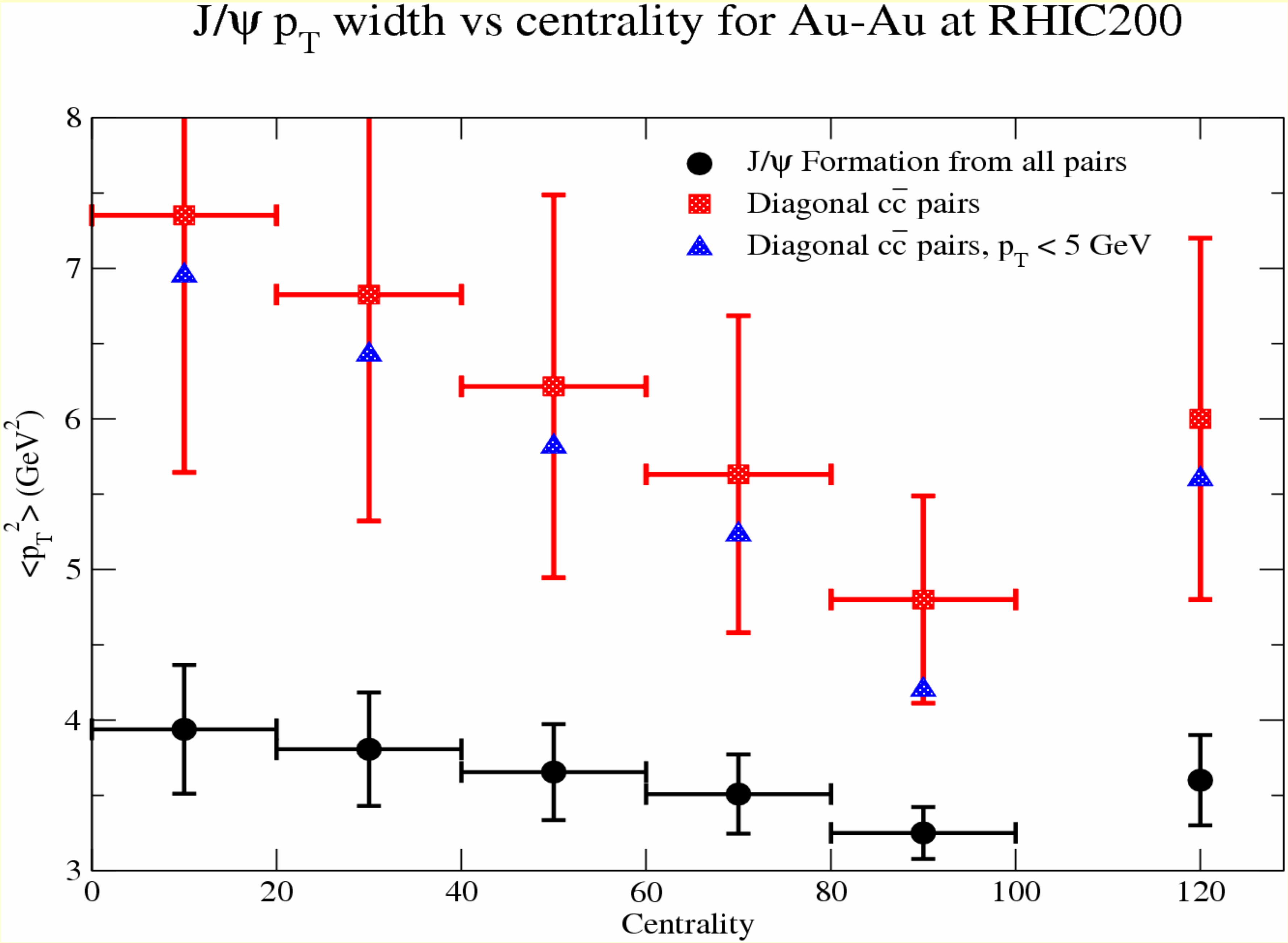
J/ψ Formation p_T Distributions

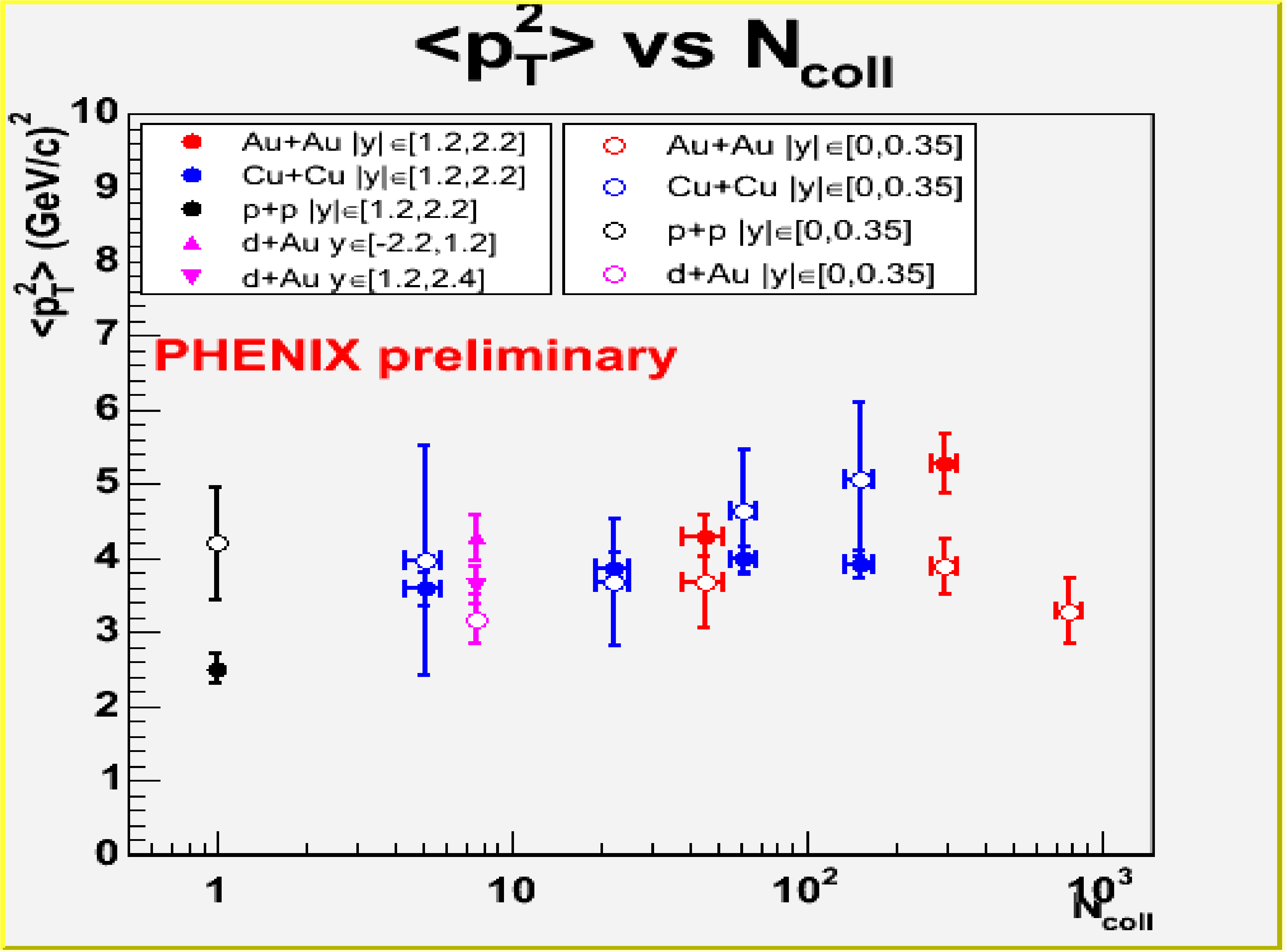
Comparison with direct Thermal Distribution



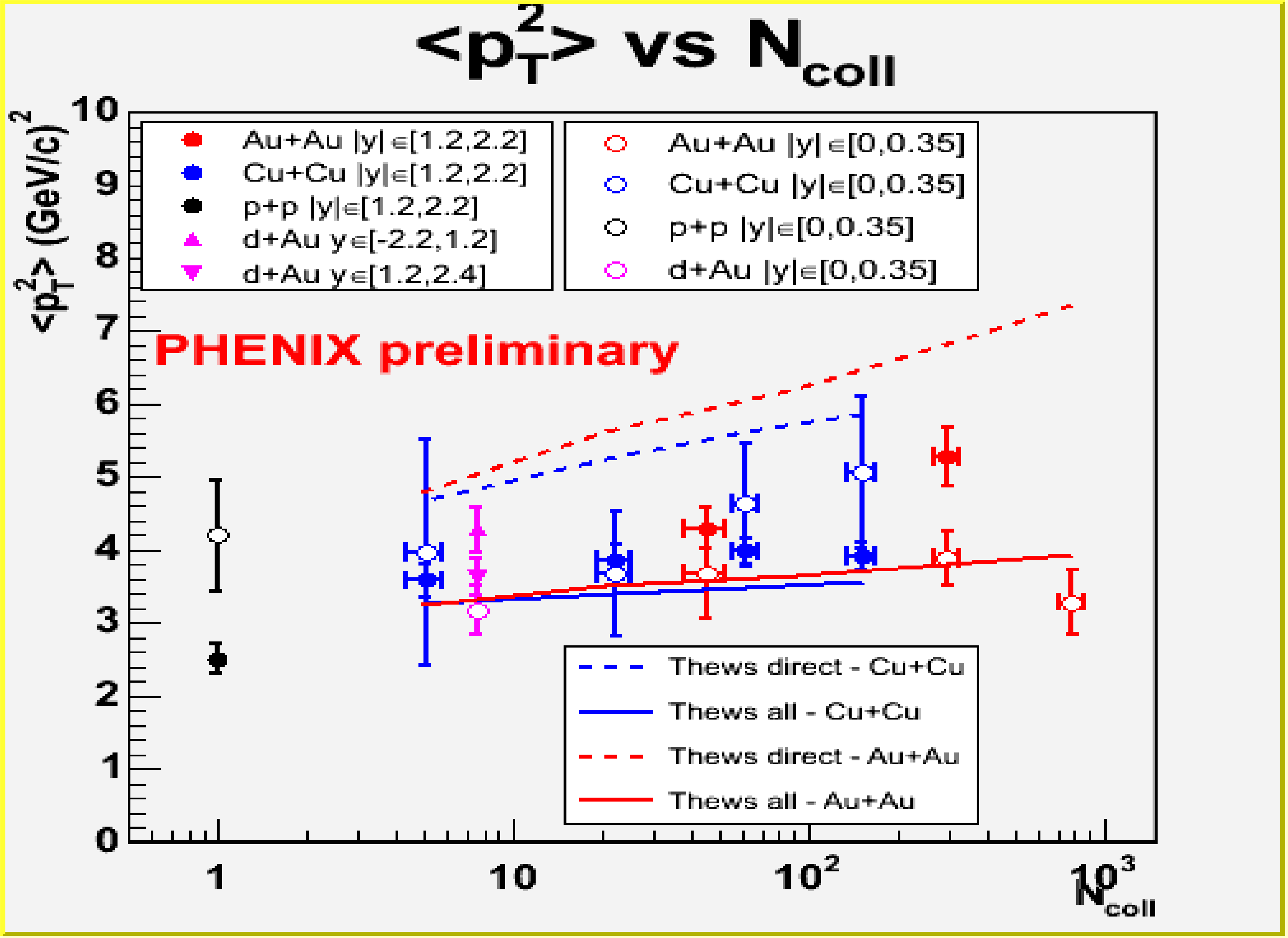


J/ψ Transverse Momentum Width Evolution
$<p_T^2>$ (GeV^2)
0
1
2
3
4
5
6
7
pp
dAu
AuAu
Production from Initial State Pairs, all p_T
Production from Initial State Pairs, p_T < 5 GeV
PHENIX Measurements
In-Medium Formation, pQCD Quarks
In-Medium Formation, Thermal + Flow Quarks

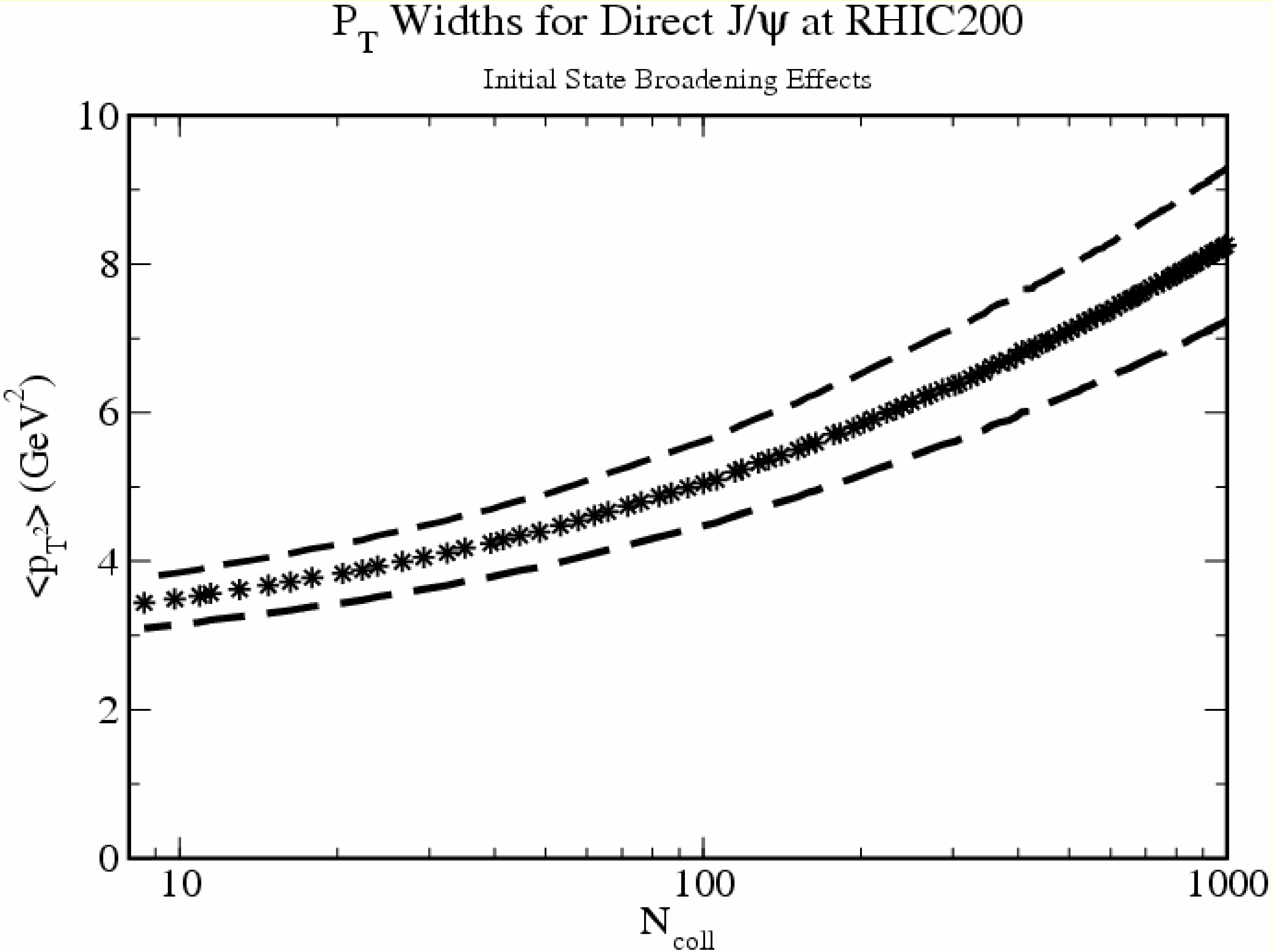

J/ψ p_T width vs centrality for Au-Au at RHIC200
J/ψ Formation from all pairs
Diagonal cc̄ pairs
Diagonal cc̄ pairs, p_T < 5 GeV
<p_T^2> (GeV^2)
Centrality
3
4
5
6
7
8
0
20
40
60
80
100
120



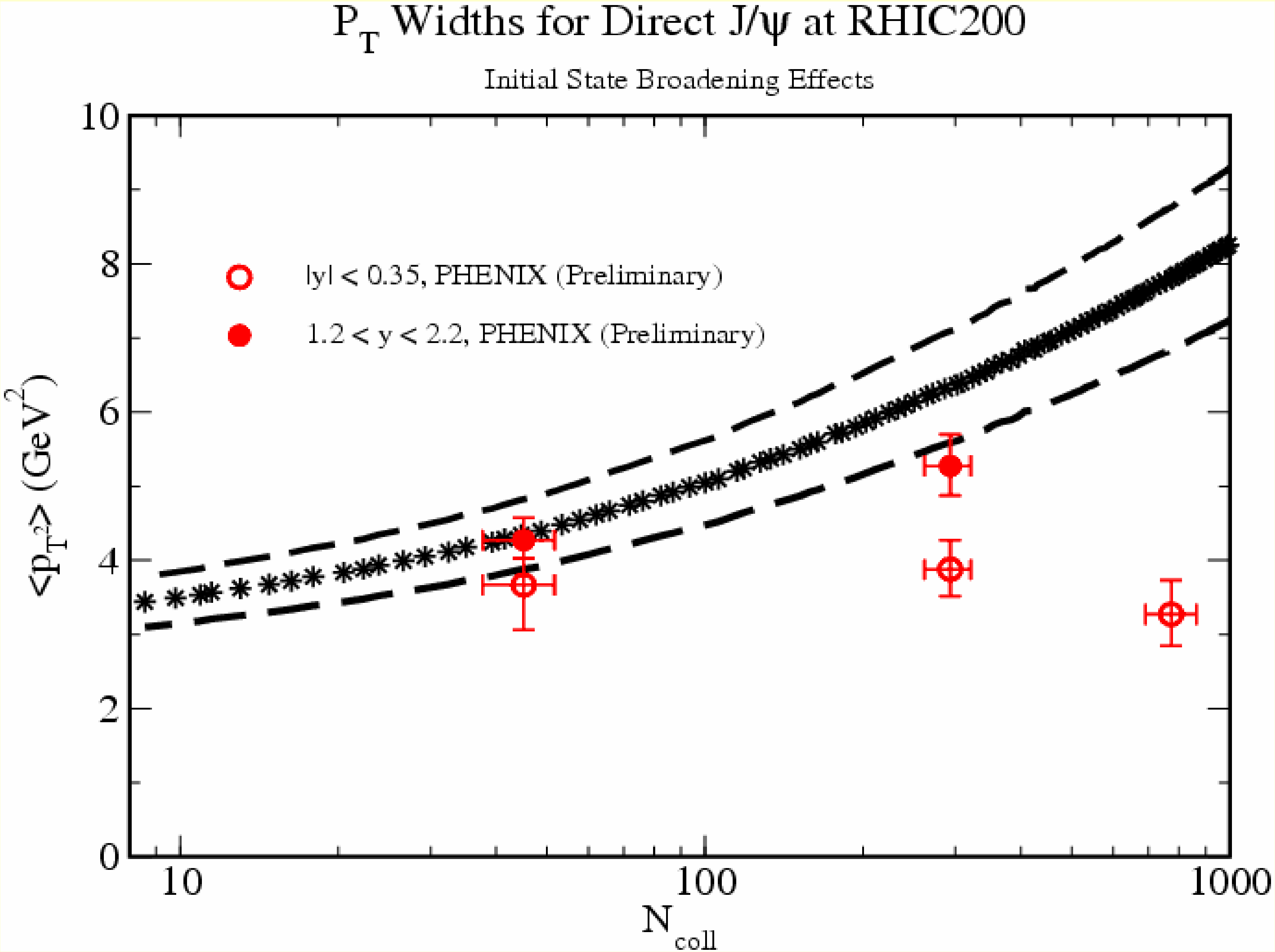
<p_T^2> vs N_coll
<p_T^2> (GeV/c)^2
Au+Au |y|∈[1.2,2.2]
Cu+Cu |y|∈[1.2,2.2]
p+p |y|∈[1.2,2.2]
d+Au y∈[-2.2,1.2]
d+Au y∈[1.2,2.4]
Au+Au |y|∈[0,0.35]
Cu+Cu |y|∈[0,0.35]
p+p |y|∈[0,0.35]
d+Au |y|∈[0,0.35]
PHENIX preliminary
0
1
2
3
4
5
6
7
8
9
10
1
10
10^2
10^3
N_coll



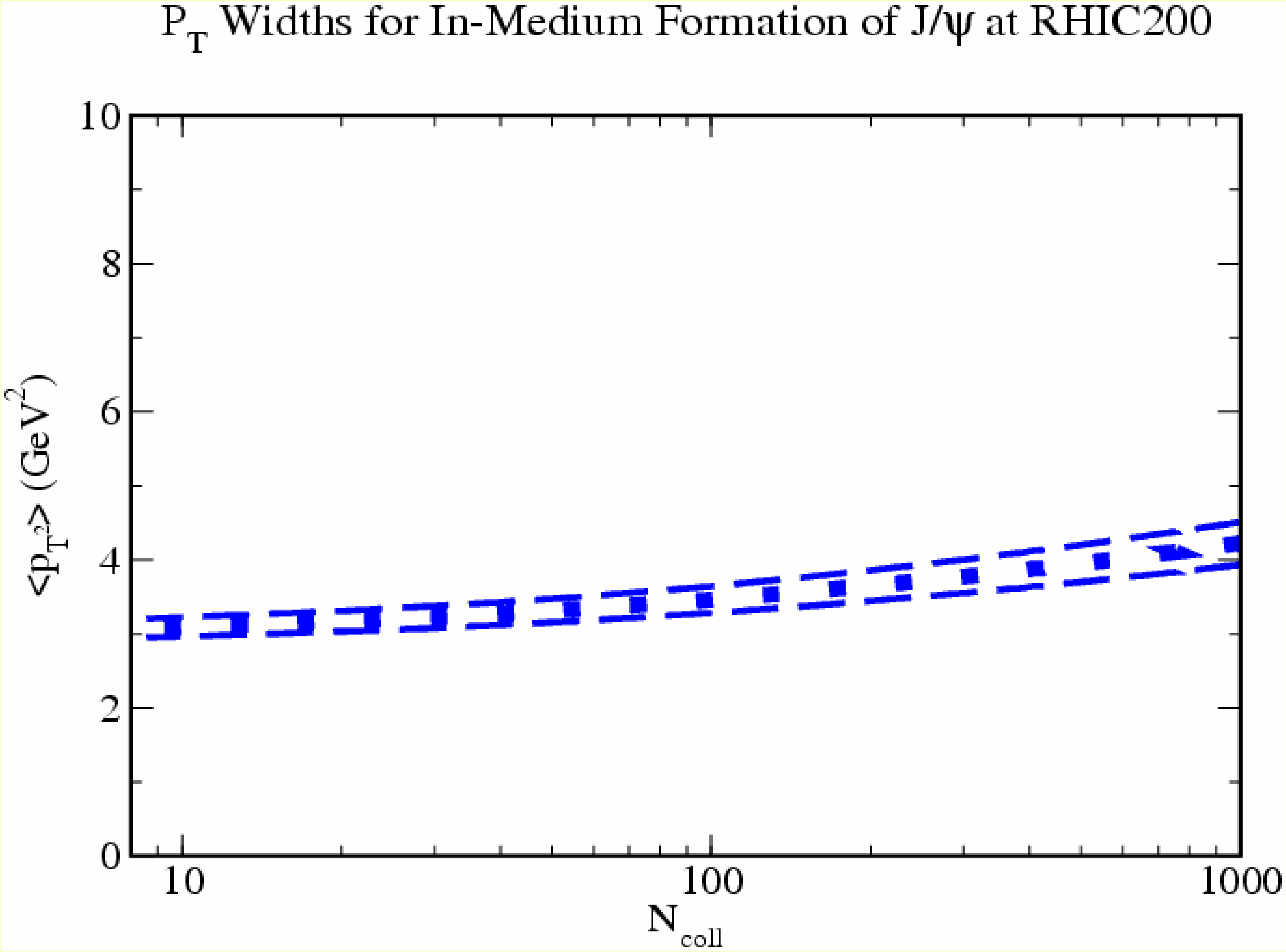
<p_T^2> vs N_coll
10
9
8
7
6
5
4
3
2
1
0
<p_T^2> (GeV/c)^2
Au+Au |y|∈[1.2,2.2]
Cu+Cu |y|∈[1.2,2.2]
p+p |y|∈[1.2,2.2]
d+Au y∈[-2.2,1.2]
d+Au y∈[1.2,2.4]
Au+Au |y|∈[0,0.35]
Cu+Cu |y|∈[0,0.35]
p+p |y|∈[0,0.35]
d+Au |y|∈[0,0.35]
PHENIX preliminary
Thews direct - Cu+Cu
Thews all - Cu+Cu
Thews direct - Au+Au
Thews all - Au+Au
1
10
10^2
10^3
N_coll



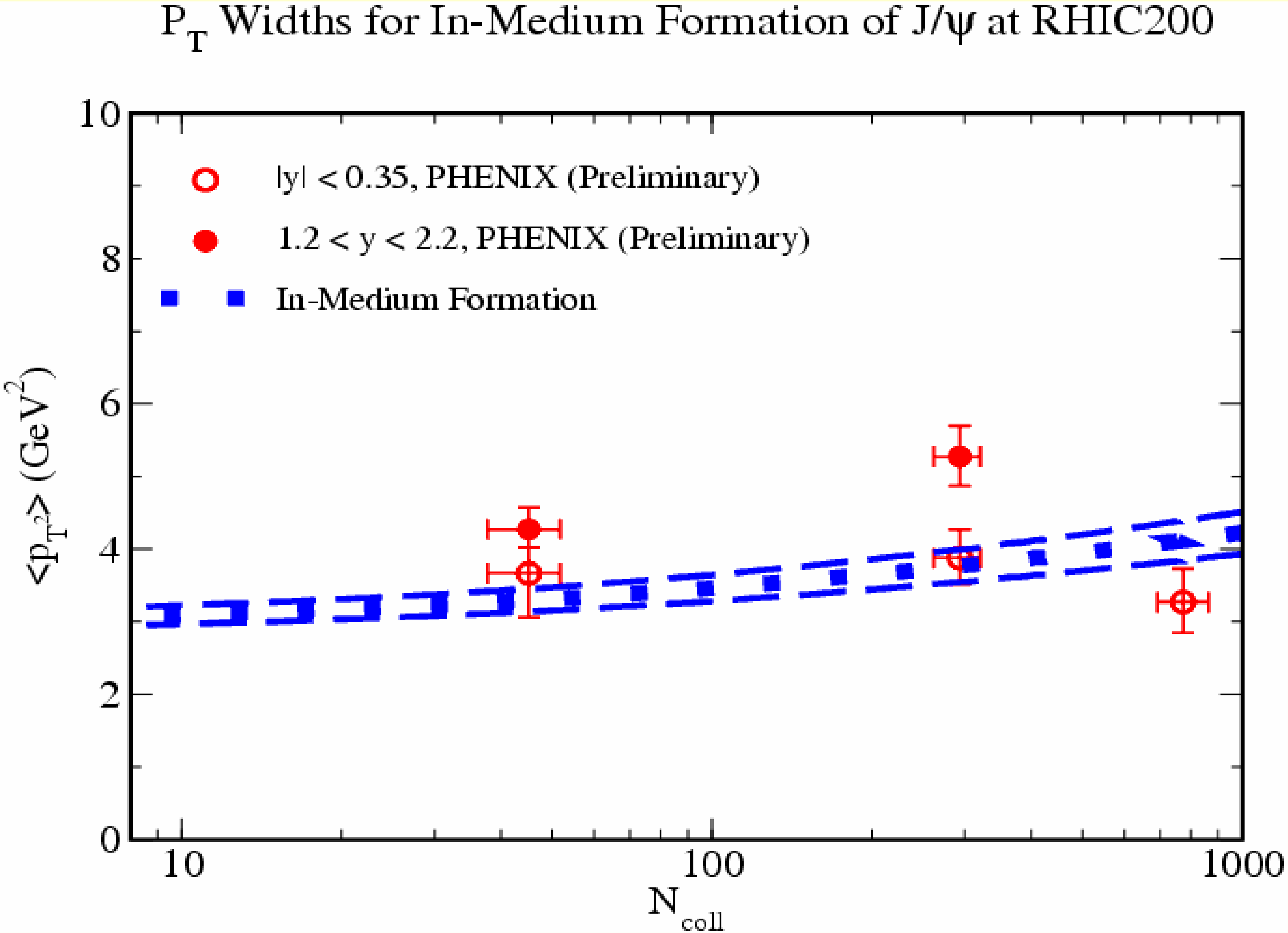
P_T Widths for Direct J/ψ at RHIC200
Initial State Broadening Effects
<p_T²> (GeV²)
N_coll
0
2
4
6
8
10
10
100
1000



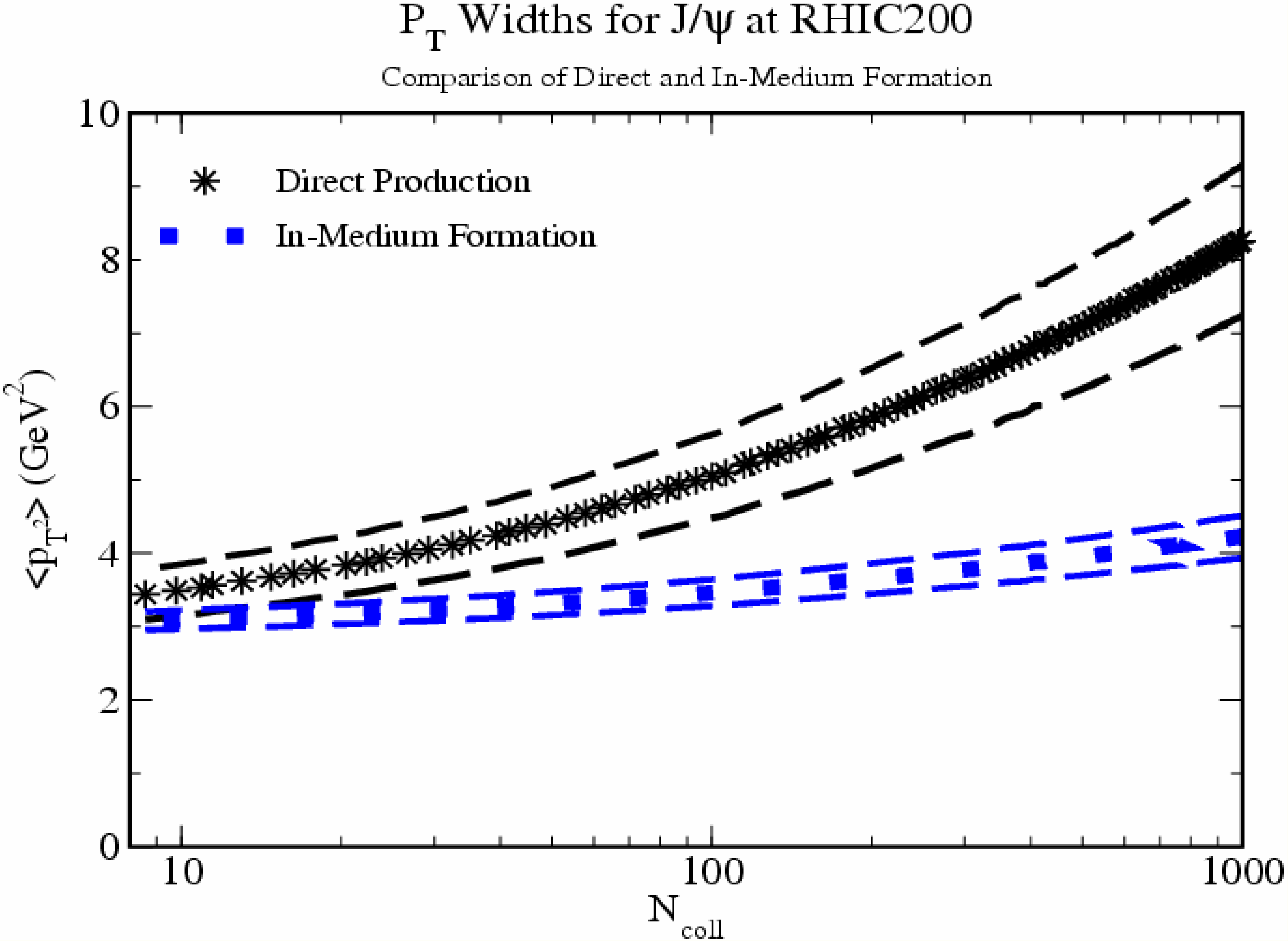
P$_T$ Widths for Direct J/ψ at RHIC200
Initial State Broadening Effects
|y| < 0.35, PHENIX (Preliminary)
1.2 < y < 2.2, PHENIX (Preliminary)
$\langle p_T^2 \rangle$ (GeV^2)
N$_{coll}$
0
2
4
6
8
10
10
100
1000



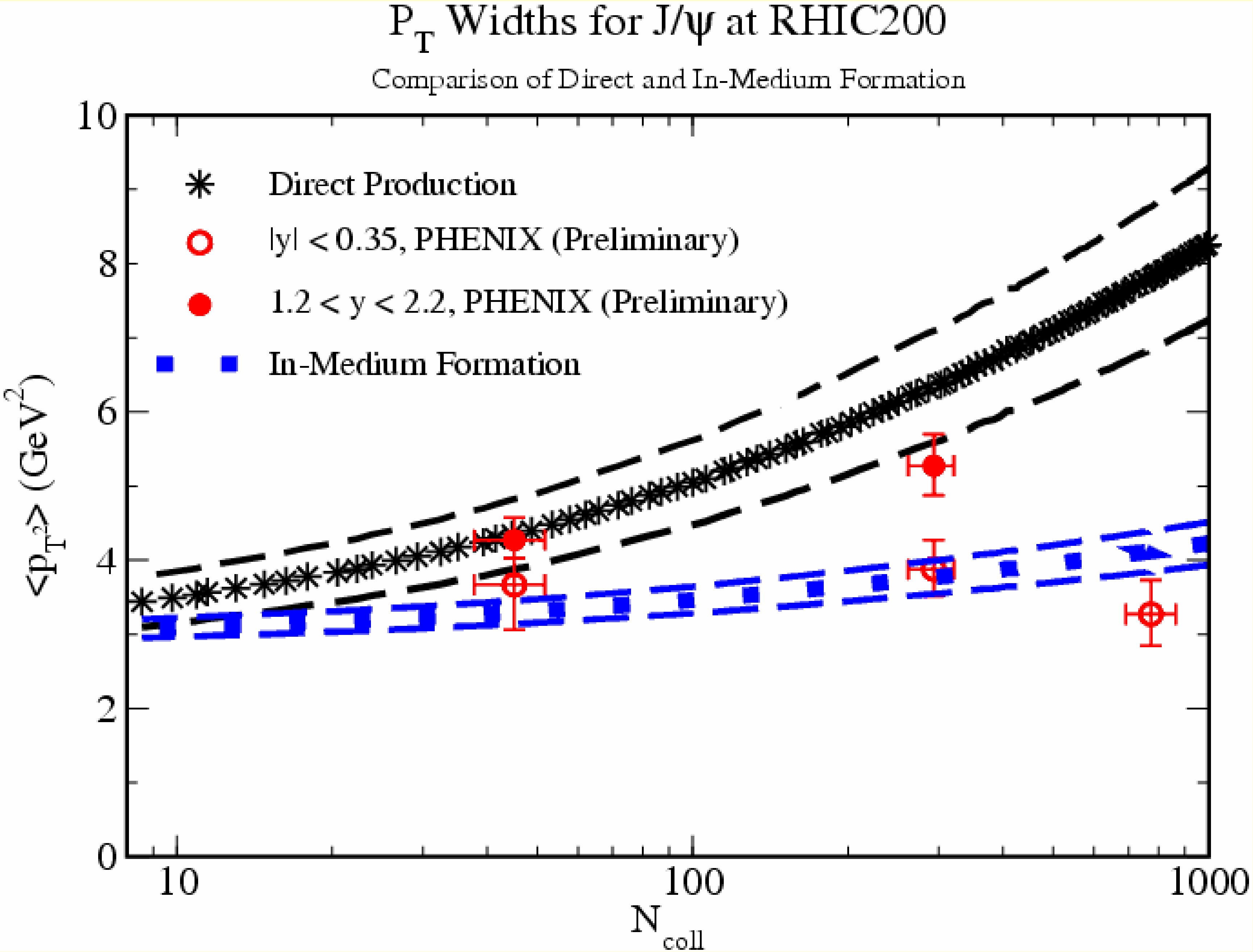
P_T Widths for In-Medium Formation of J/ψ at RHIC200
$\langle p_T^2 \rangle$ (GeV^2)
0
2
4
6
8
10
10
100
1000
N_{coll}



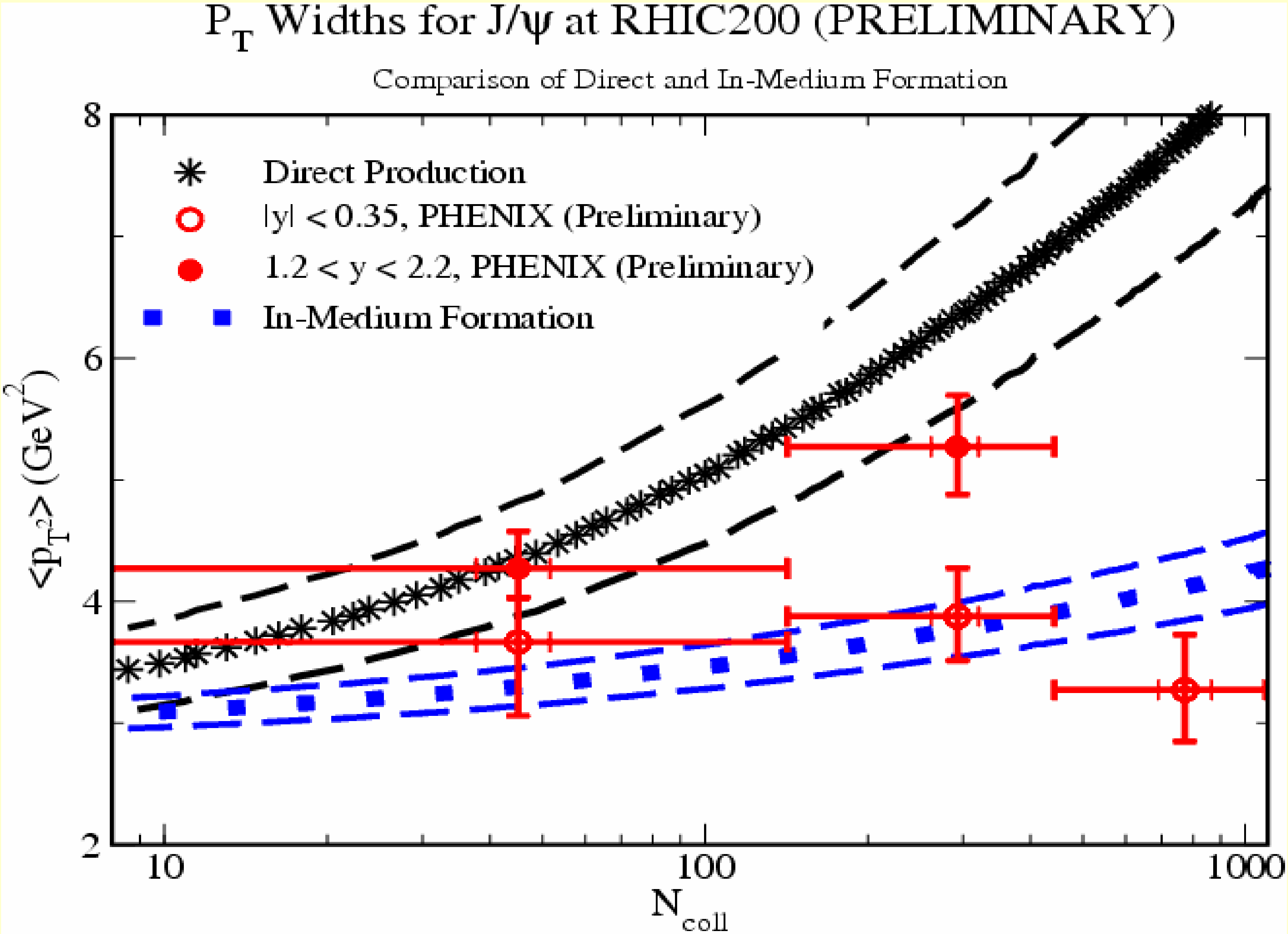
P_T Widths for In-Medium Formation of J/ψ at RHIC200
|y| < 0.35, PHENIX (Preliminary)
1.2 < y < 2.2, PHENIX (Preliminary)
In-Medium Formation
<p_T^2> (GeV^2)
N_coll
0
2
4
6
8
10
10
100
1000



P_T Widths for J/ψ at RHIC200
Comparison of Direct and In-Medium Formation
Direct Production
In-Medium Formation
<p_T^2> (GeV^2)
N_coll
0
2
4
6
8
10
10
100
1000



P_T Widths for J/ψ at RHIC200
Comparison of Direct and In-Medium Formation
Direct Production
|y| < 0.35, PHENIX (Preliminary)
1.2 < y < 2.2, PHENIX (Preliminary)
In-Medium Formation
<p_T^2> (GeV^2)
N_coll
0
2
4
6
8
10
10
100
1000



P_T Widths for J/ψ at RHIC200 (PRELIMINARY)
Comparison of Direct and In-Medium Formation
Direct Production
|y| < 0.35, PHENIX (Preliminary)
1.2 < y < 2.2, PHENIX (Preliminary)
In-Medium Formation
<p_T^2> (GeV^2)
N_coll
2
4
6
8
10
100
1000

Combine Initial-State Broadening with Final-State Nuclear Absorption

- Nuclear absorption biases production point toward the later stages of the initial state collision sequence
- Average number of initial-state collisions increases, resulting in larger p_T broadening
- In-medium formation takes place after the nuclear absorption, not subject to this effect

Mean Number of Initial-State Collisions

$$<n> = \frac{1}{n}\sum_{m=1}^{n}(m-1) = (n-1)/2$$

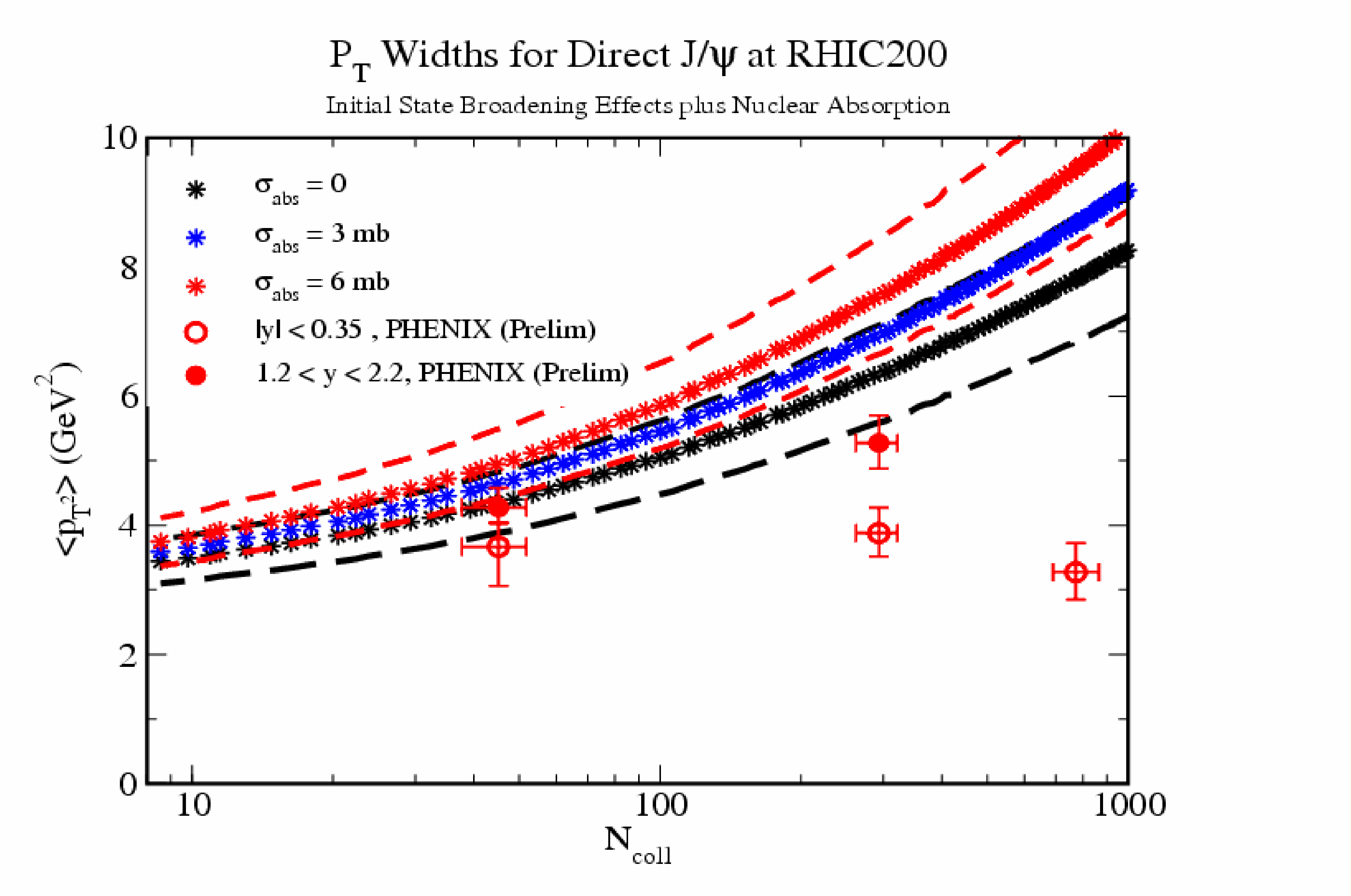
Include Final-State Nuclear Absorption

$$<n>_{abs} = \frac{1}{P_{tot}}\sum_{m=1}^{n}(m-1)P_{mn}$$

Path Length Model

$$P_{mn} = x^{n-m} \qquad x \equiv \exp^{-(\rho\sigma/n)L_{\max}}$$

$$< n >_{abs} = \frac{x-1}{x^{n}-1}\sum_{m=1}^{n}(m-1)x^{n-m}$$



P$_T$ Widths for Direct J/ψ at RHIC200
Initial State Broadening Effects plus Nuclear Absorption
$\sigma_{abs} = 0$
$\sigma_{abs} = 3$ mb
$\sigma_{abs} = 6$ mb
|y| < 0.35 , PHENIX (Prelim)
1.2 < y < 2.2, PHENIX (Prelim)
$\langle p_T^2 \rangle$ (GeV^2)
N$_{coll}$
0
2
4
6
8
10
10
100
1000

SUMMARY

- R_{AA} (N_{coll}) points toward In-Medium Formation (AKA regeneration, coalescence, recombination) as the mechanism for J/ψ production in central Au-Au at RHIC. However, sequential supression remains viable option.
- Normalized p_T and y spectra *alone can* provide signatures of in-medium recombination processes
- Variation of $\langle p_T^2 \rangle$ with system size and centrality provides characteristic signals of in-medium formation

- Initial PHENIX measurements of <p_T^2> differ between rapidity intervals, not allowed if J/ψ reflects underlying ccbar pair distributions. Subject to large uncertainties, the in-medium scenario may be preferred.
- Initial PHENIX measurements of y spectra do not exhibit narrowing predicted by in-medium formation
- What about sQGP? Can we retain a scenario of binary interactions? Perhaps charm quarks will not even propagate in the medium.
- Correlation of J/ψ and charm quark flow in progress