QUARKONIUM PRODUCTION VIA RECOMBINATION

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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)

Suppression of Initially Produced J/ψ

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

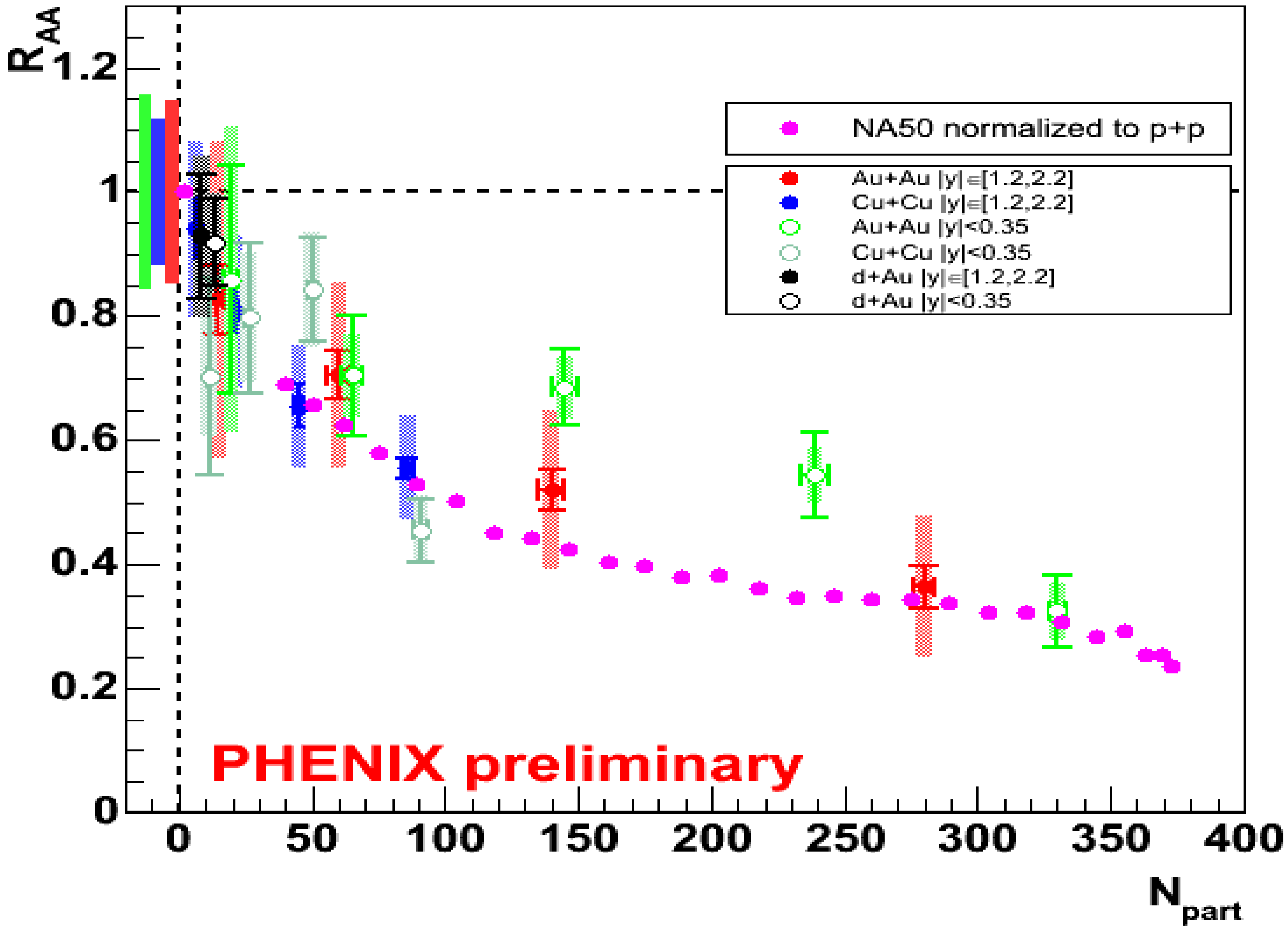
$$\varepsilon(\tau) = \exp[-\int_{\tau_0}^{\tau} \lambda_D \rho_g \, d\tau]$$

Continuous In-Medium Formation followed by Partial Suppression

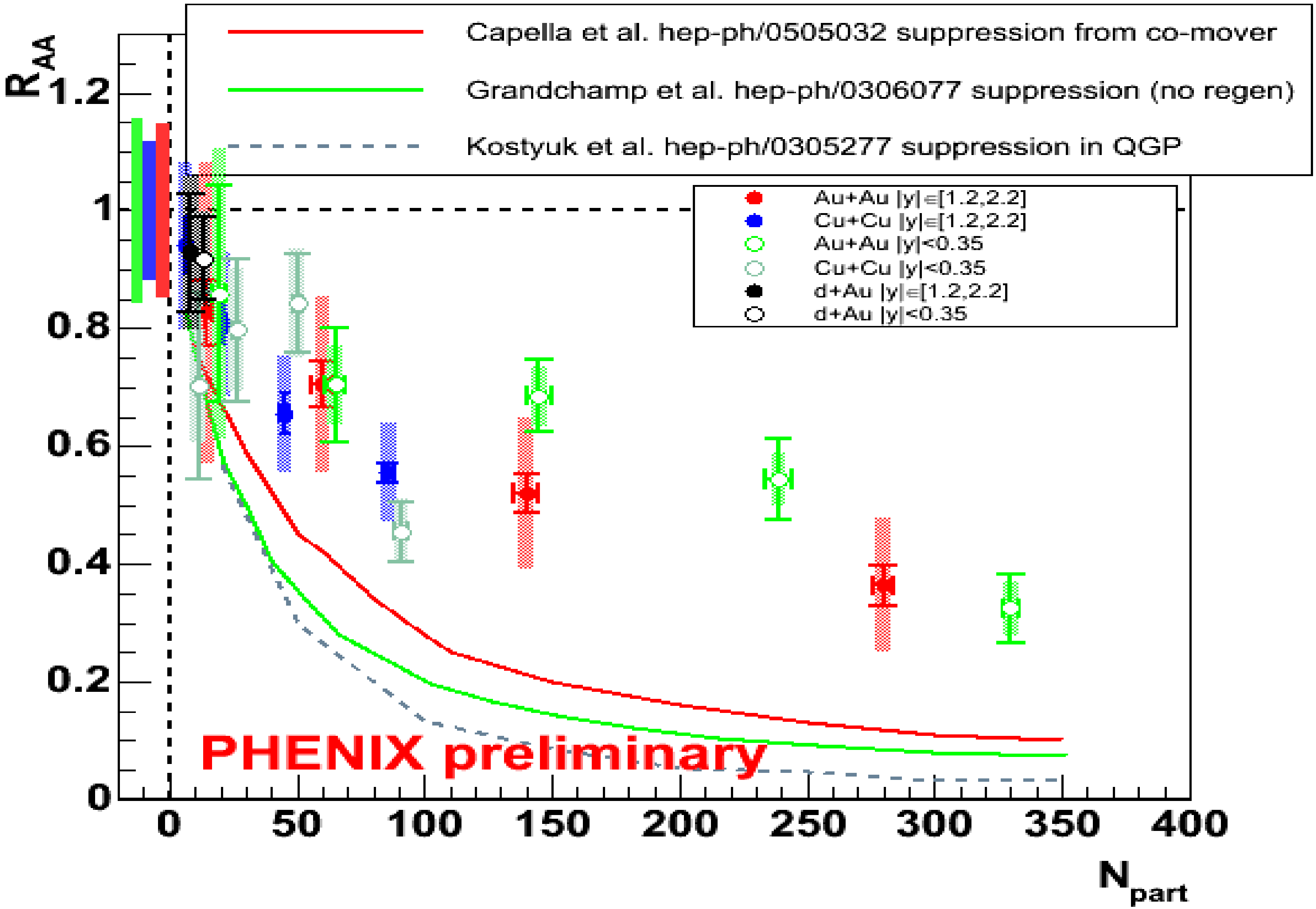
$$N_{J/\psi}^{Form}(\tau_f) = N_{cc}^2 \int_{\tau_0}^{\tau_f} \lambda_F \, V^{-1}(\tau)\,\gamma(\tau)\, d\tau$$

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

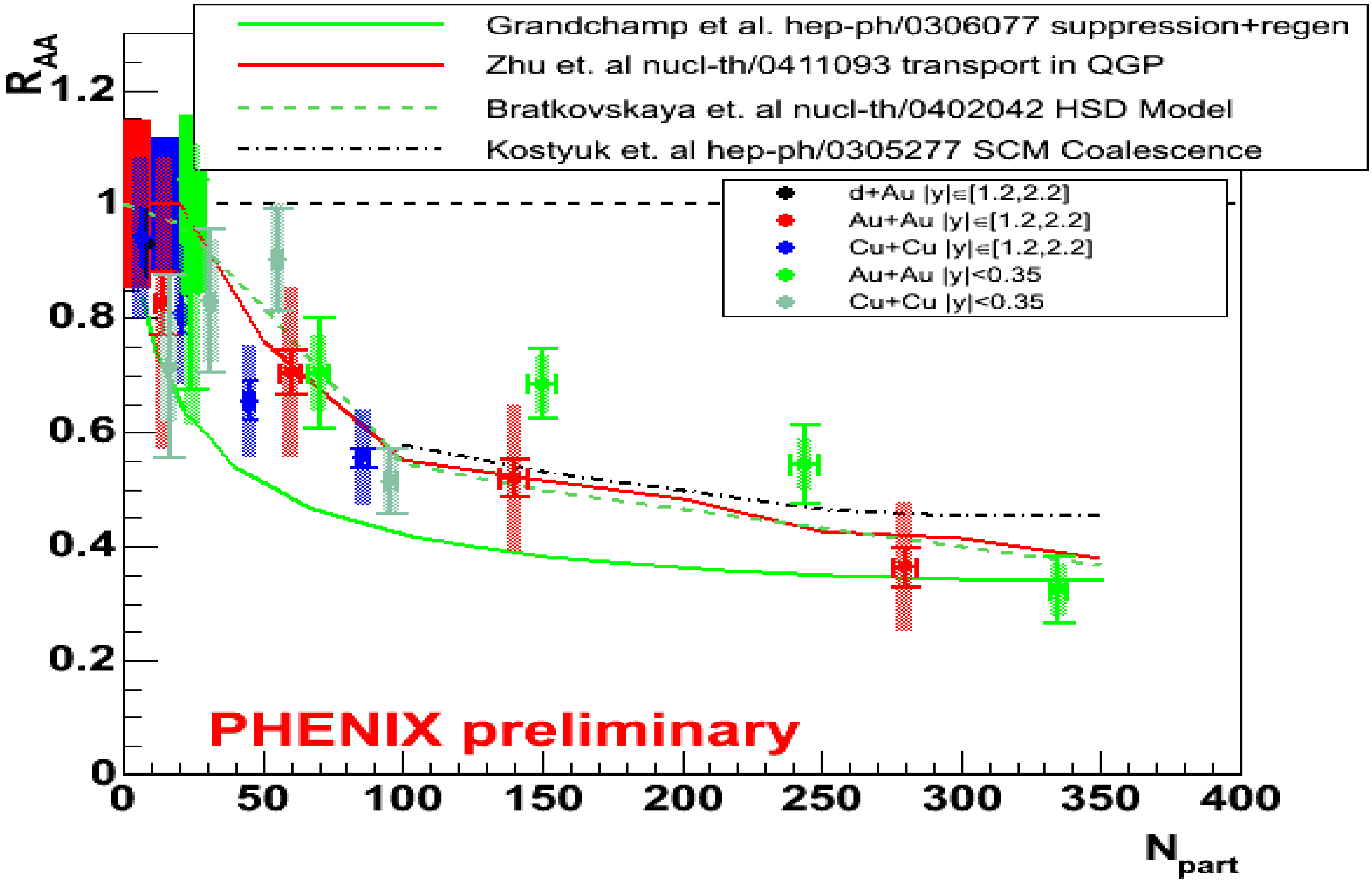
J/ψ nuclear modification factor R_{AA}



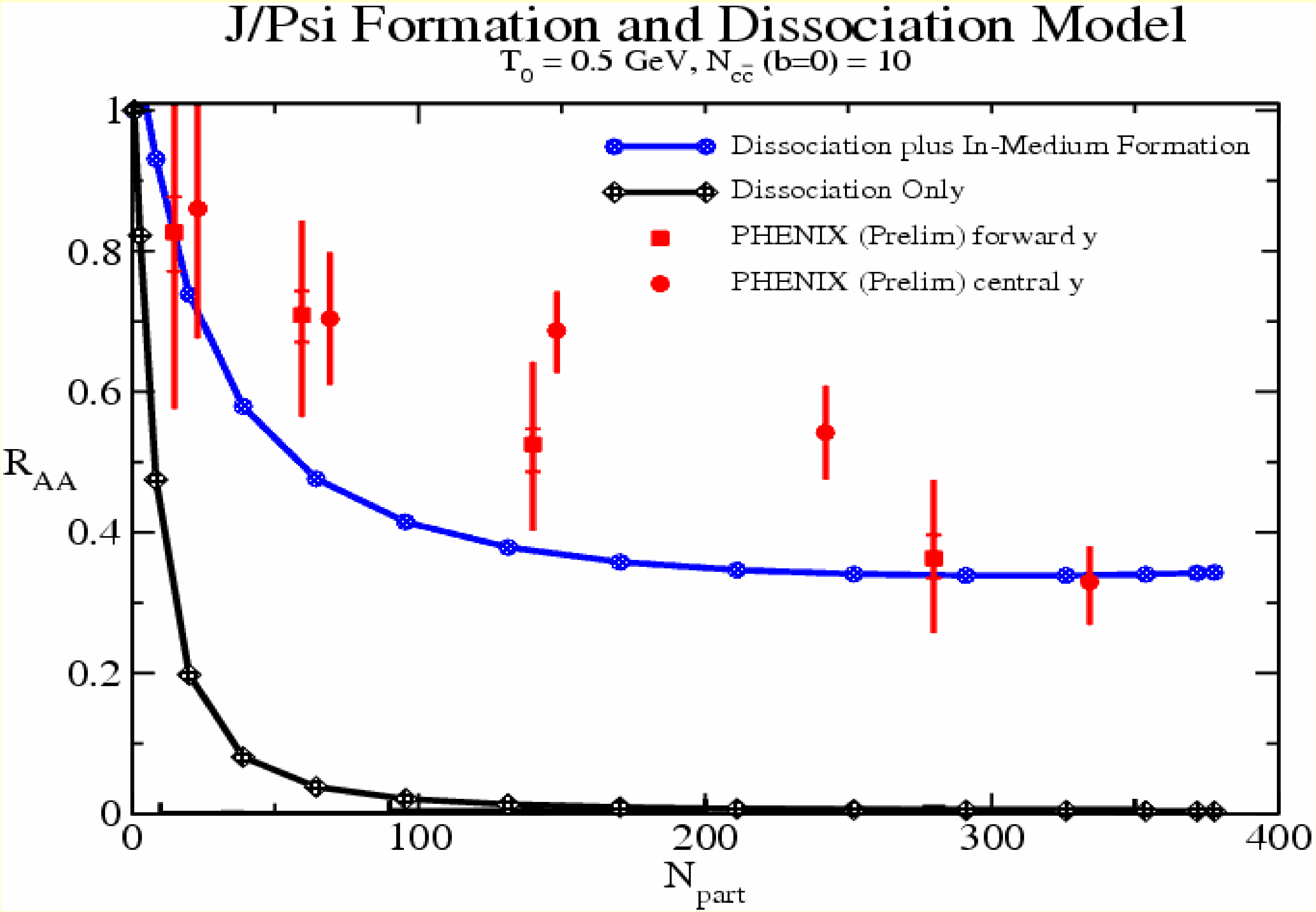
J/ψ nuclear modification factor R_{AA}



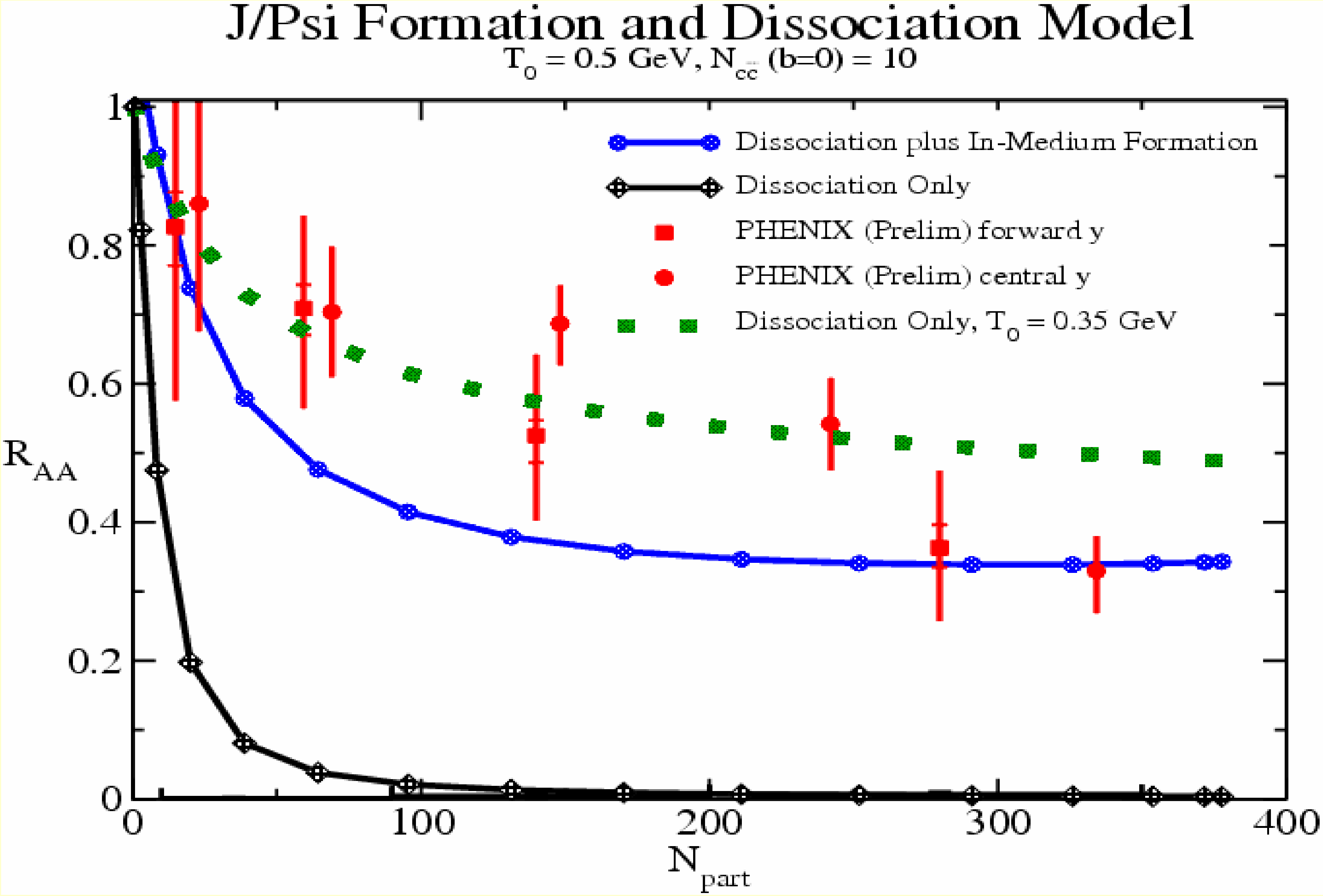
J/ψ nuclear modification factor R_{AA}



Kinetic Model Recombination Predictions Consistent with data



but Dissociation Alone is still a contender



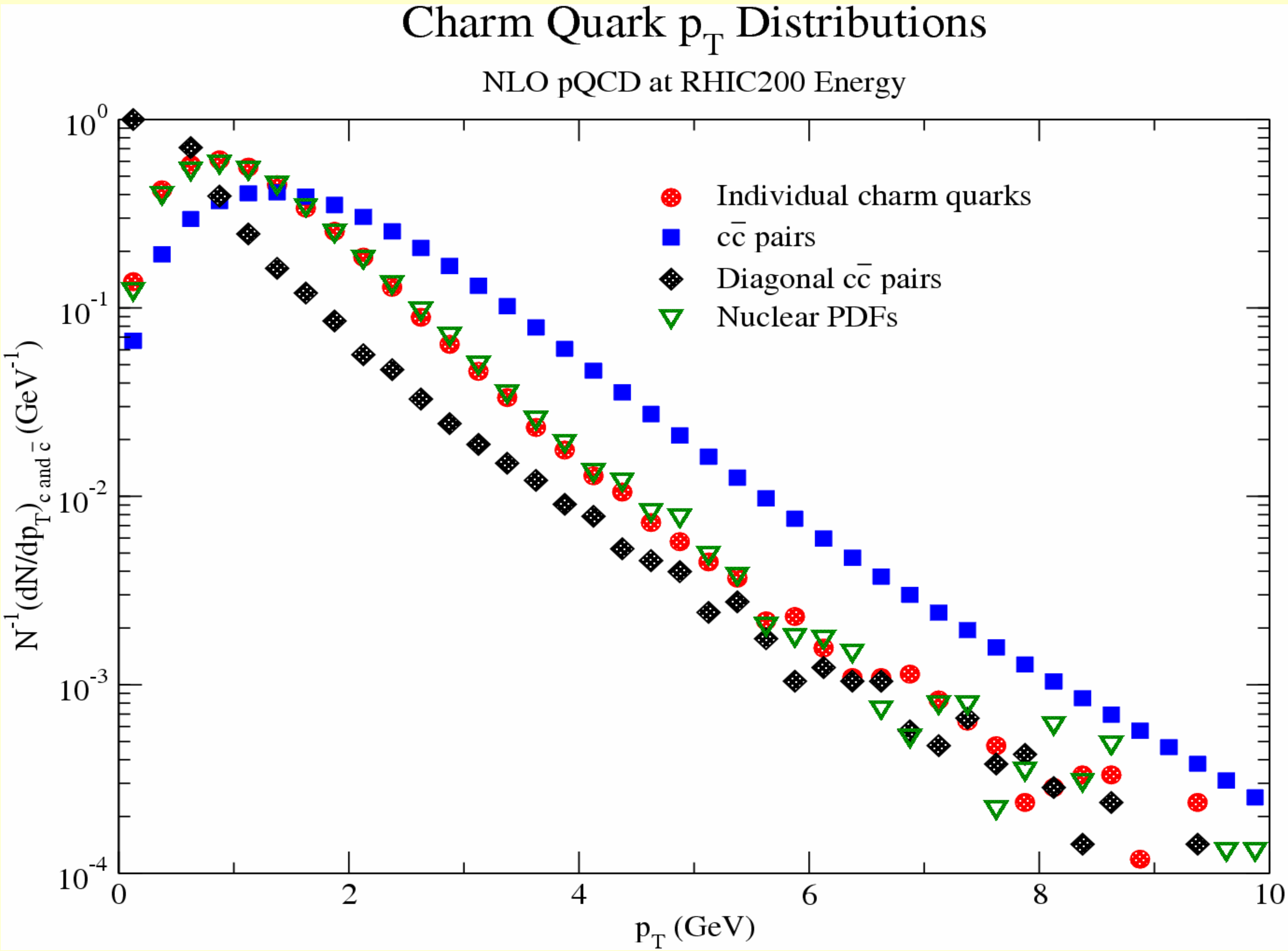
CAN Y AND P_T SPECTRA PROVIDE SIGNATURES OF IN-MEDIUM FORMATION?

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)

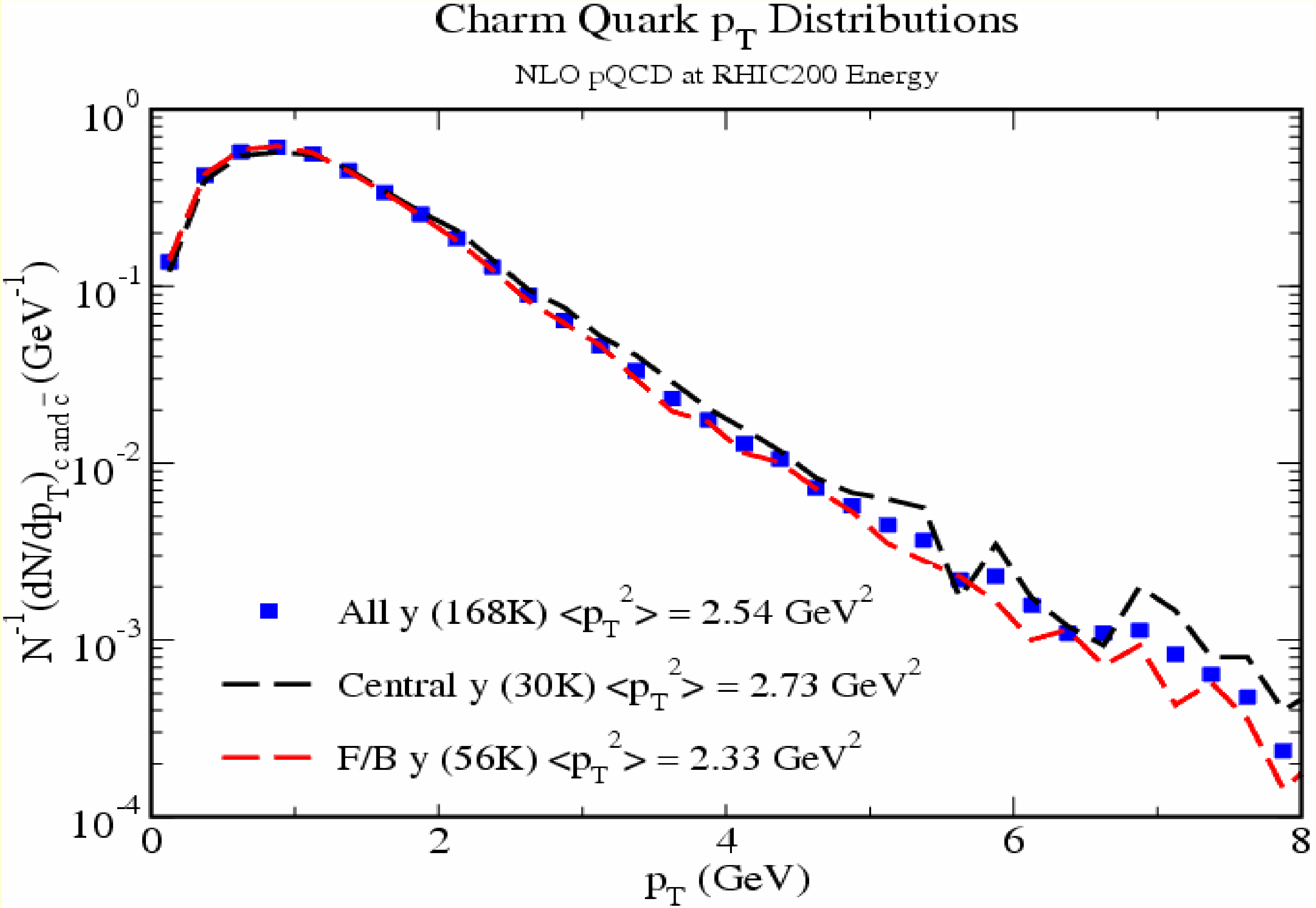
$$\frac{dN_{J/\psi}}{d^3p_{J/\psi}} = \int \frac{dt}{V(t)} \sum_{i=1}^{N_{c\bar{c}}} \sum_{j=1}^{N_{c\bar{c}}} v_{rel} \frac{d\sigma(p_i + p_j \rightarrow p_{J/\psi} + X)}{d^3p_{J/\psi}}$$

- 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



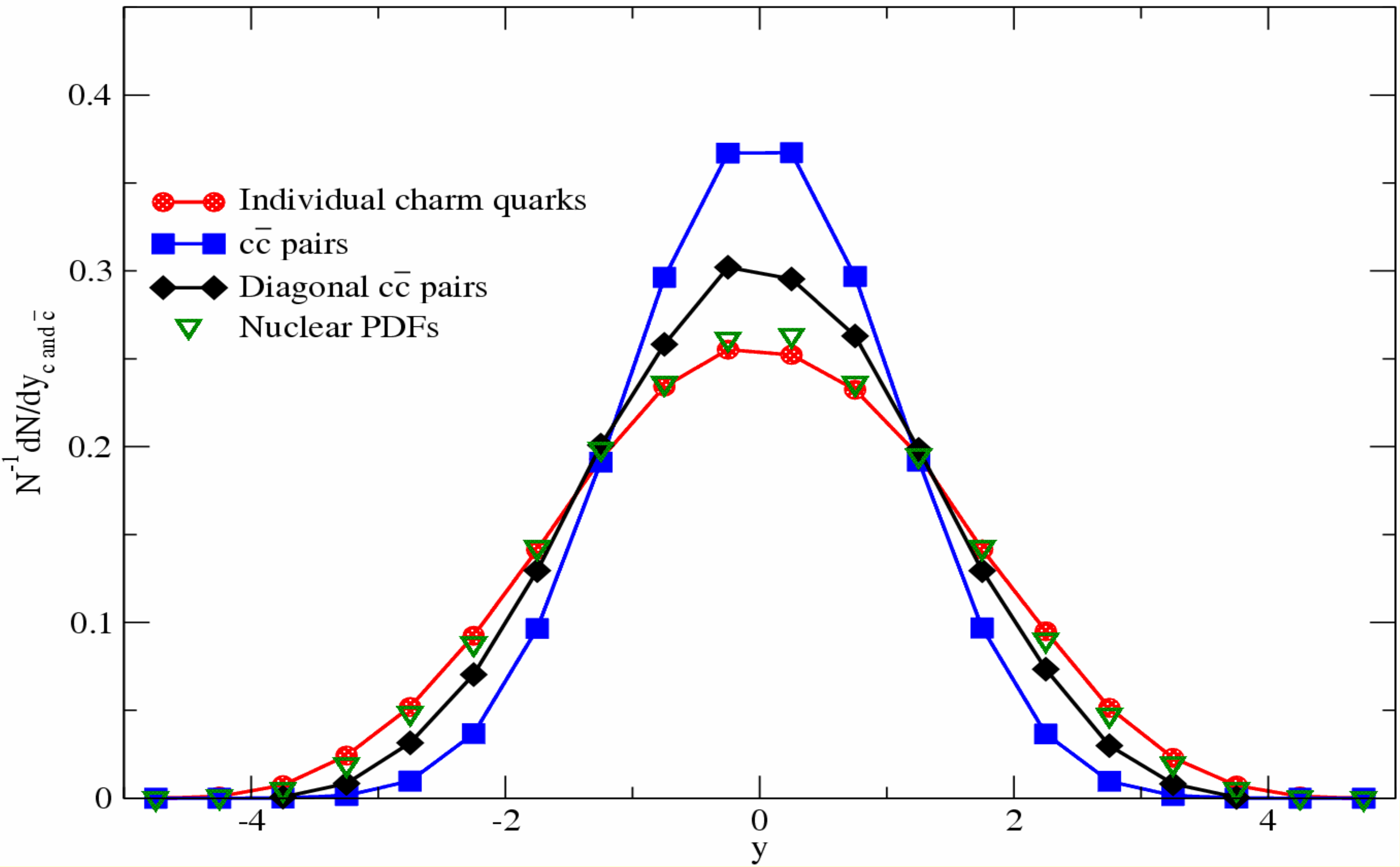
Charm Quark p_T Distributions
NLO pQCD at RHIC200 Energy
Individual charm quarks
$c\bar{c}$ pairs
Diagonal $c\bar{c}$ pairs
Nuclear PDFs
$N^{-1}(dN/dp_T)_{c\ and\ \bar{c}}\ (GeV^{-1})$
p_T (GeV)
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
2
4
6
8
10

P_T distribution shows minimal variation with y interval

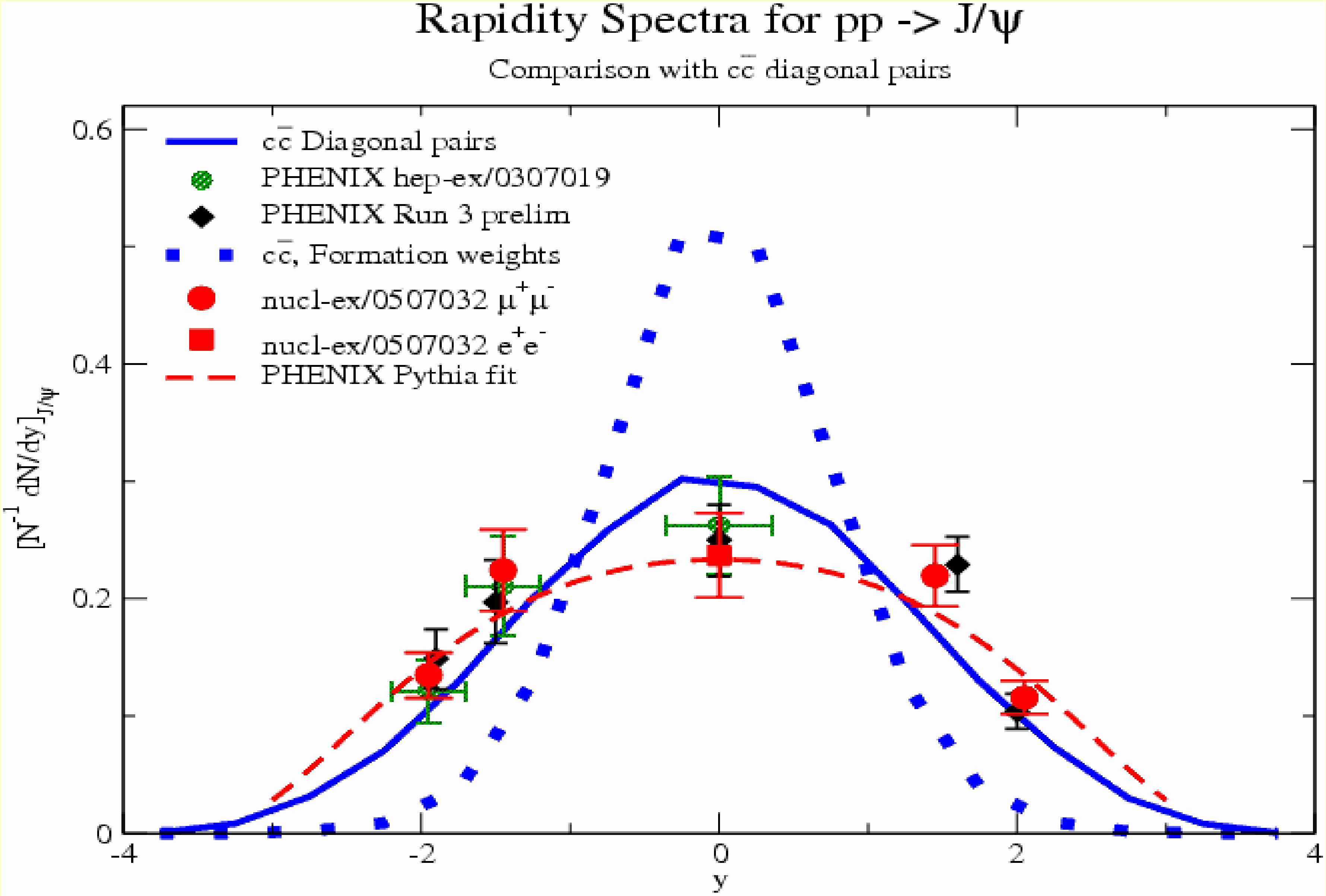


Charm Quark y Distributions

NLO pQCD at RHIC200 Energy

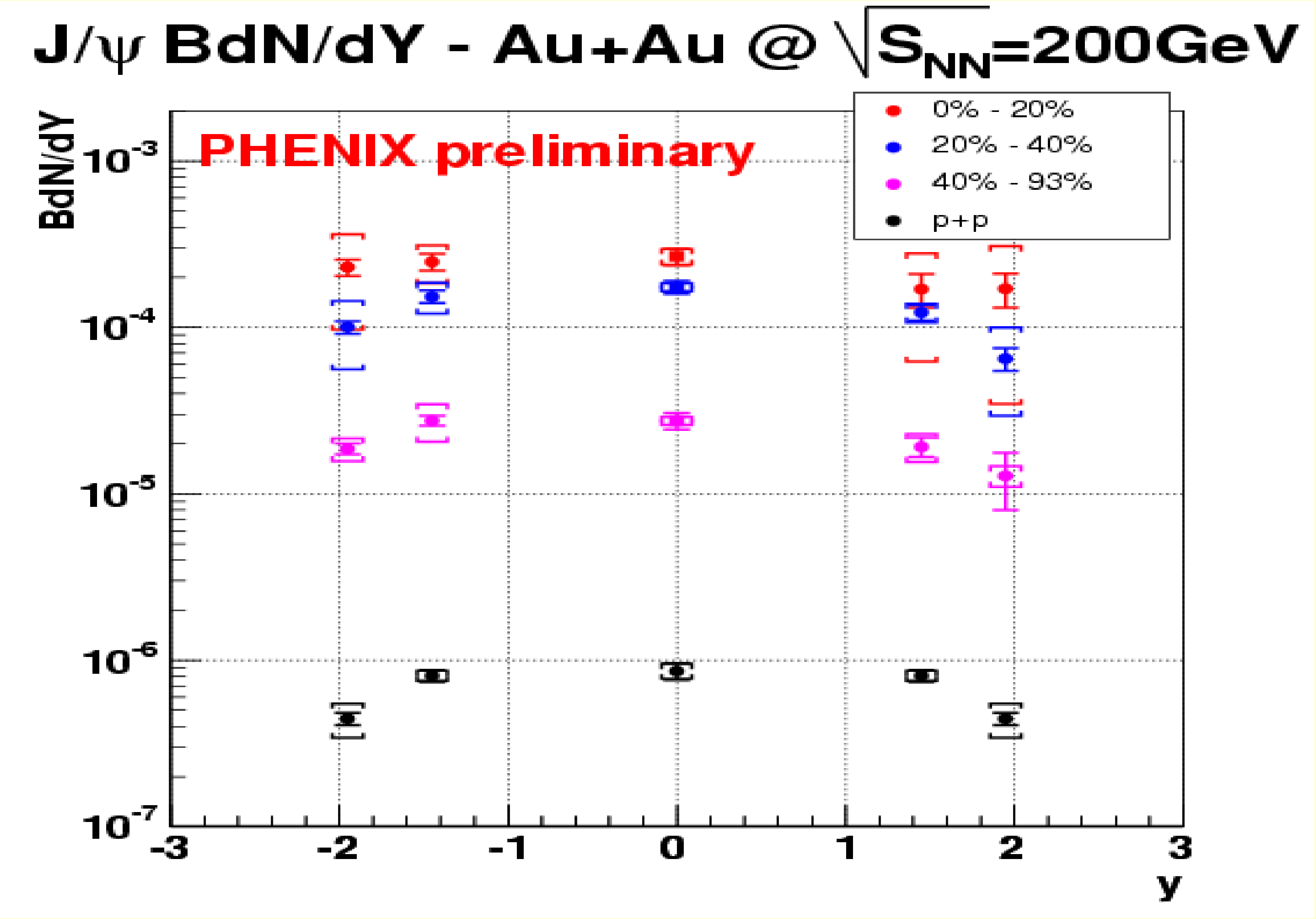


p-p data “select” unbiased diagonal c-cbar pairs

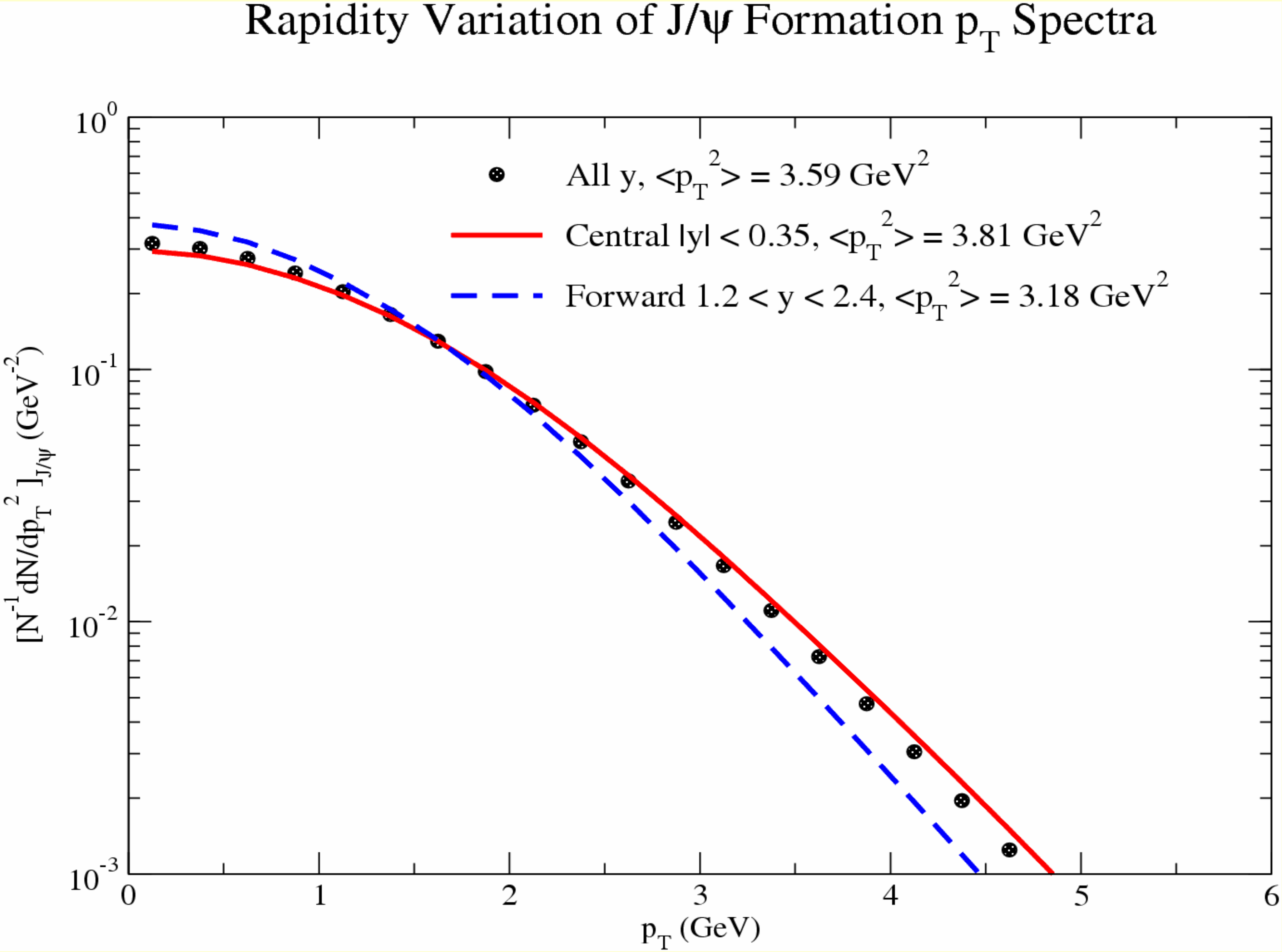


$$< p_T^2 >_{AB} = < p_T^2 >_{pp} + \lambda^2 \{\bar{n}_A + \bar{n}_B - 2\}$$

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

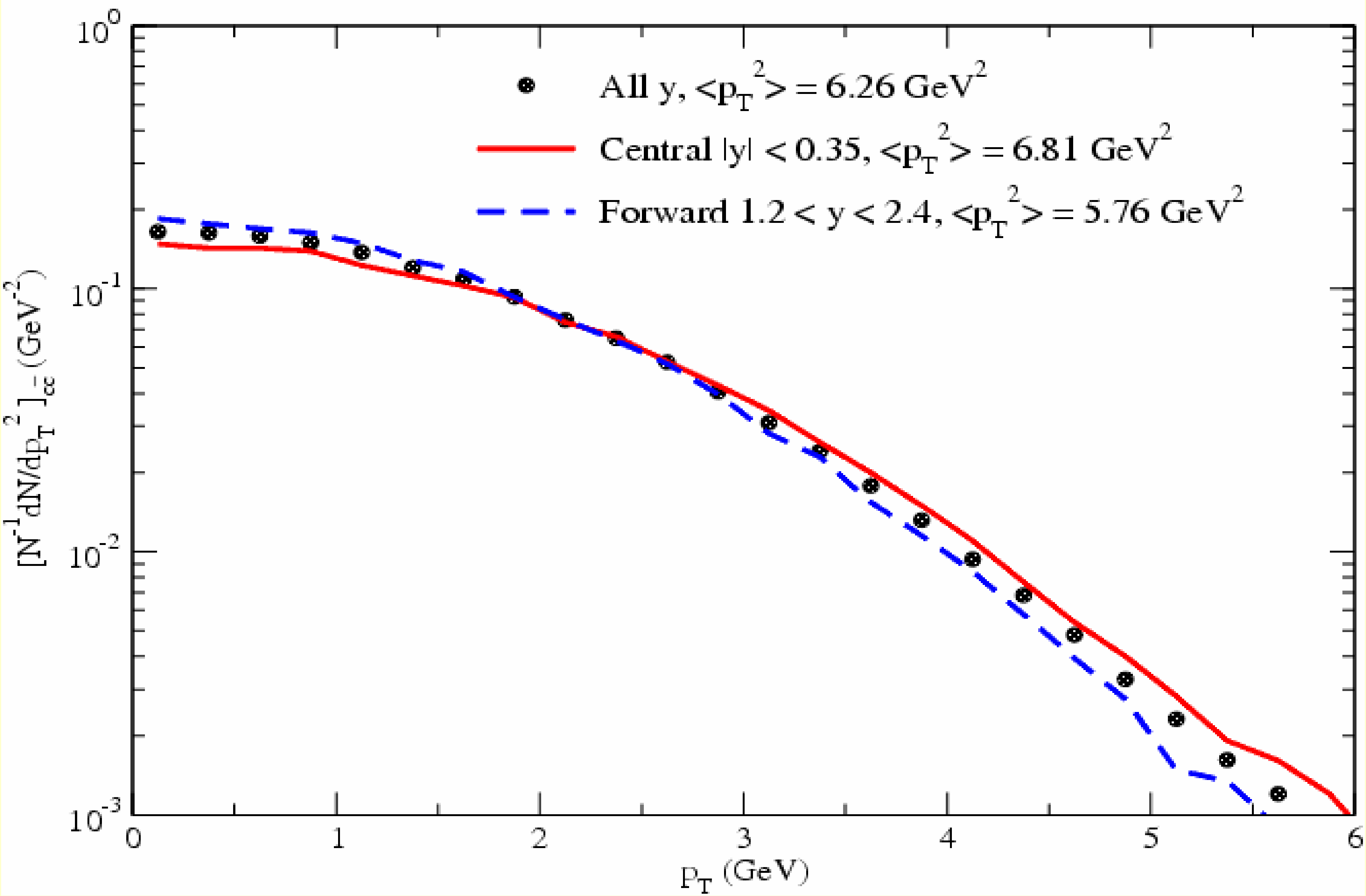


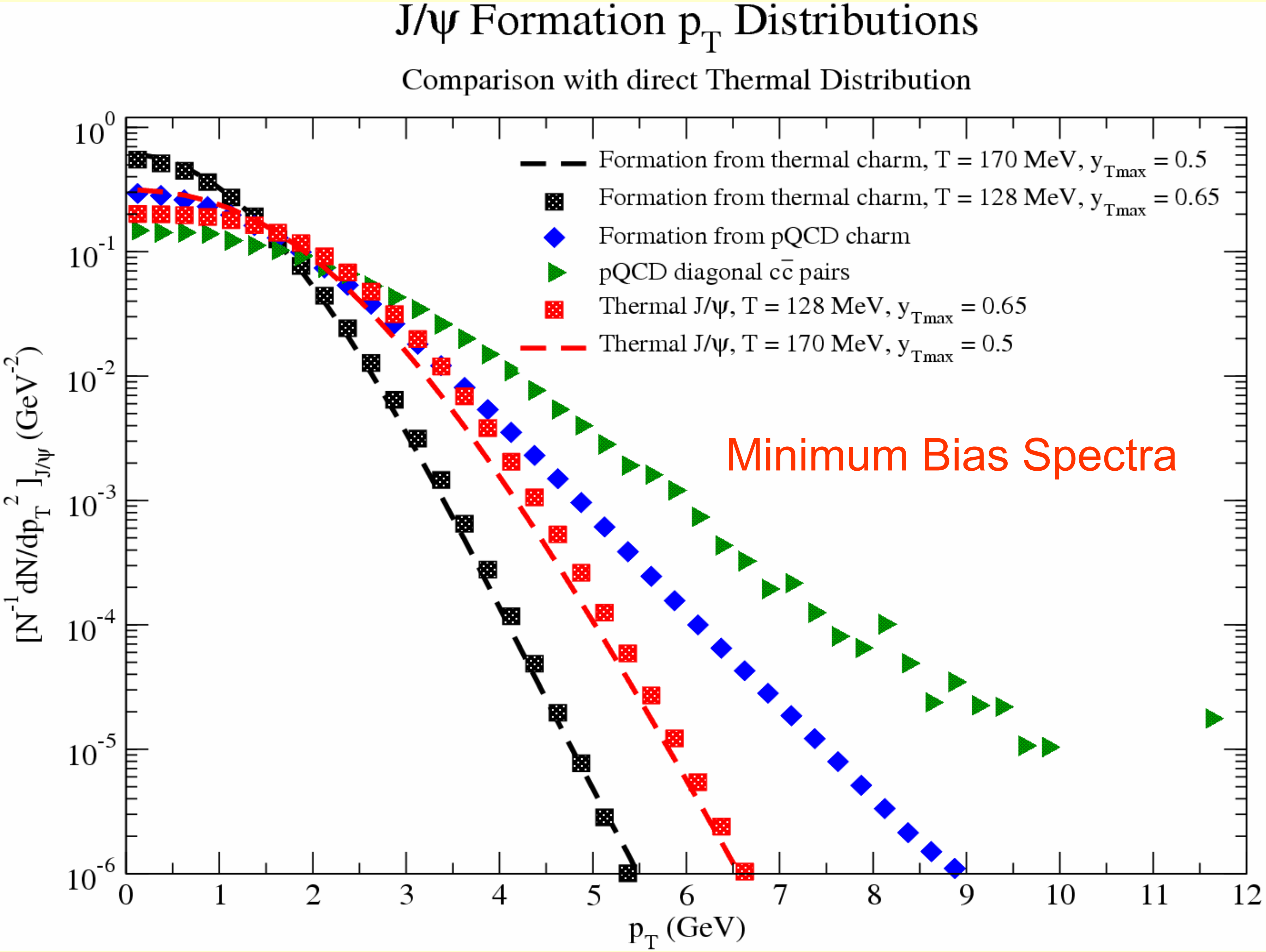
J/ψ BdN/dY - Au+Au @ √S_NN=200GeV
BdN/dY
PHENIX preliminary
0% - 20%
20% - 40%
40% - 93%
p+p
10^-3
10^-4
10^-5
10^-6
10^-7
-3
-2
-1
0
1
2
3
y



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

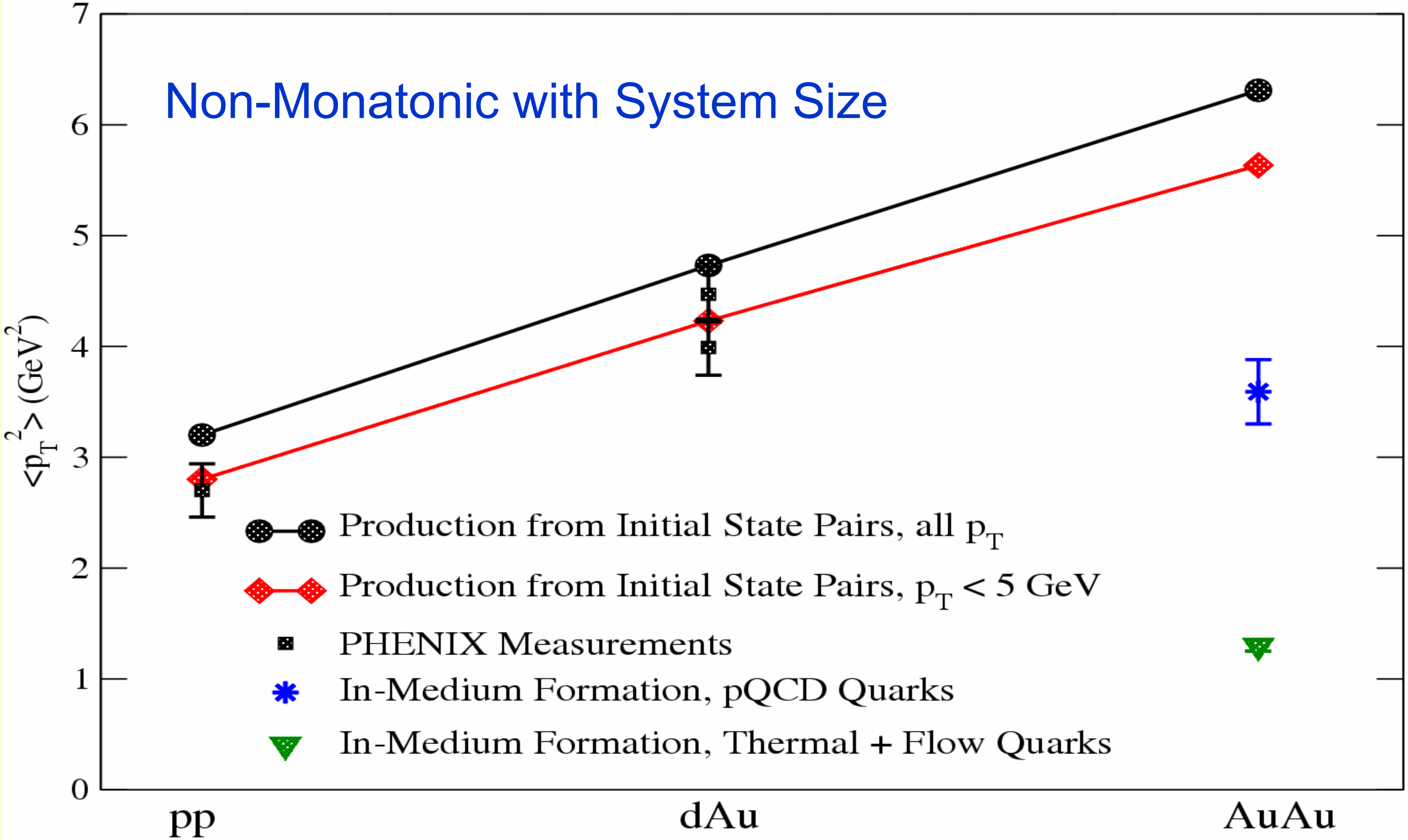
Rapidity Variation of Diagonal $c\bar{c}$ Pair p_T Spectra

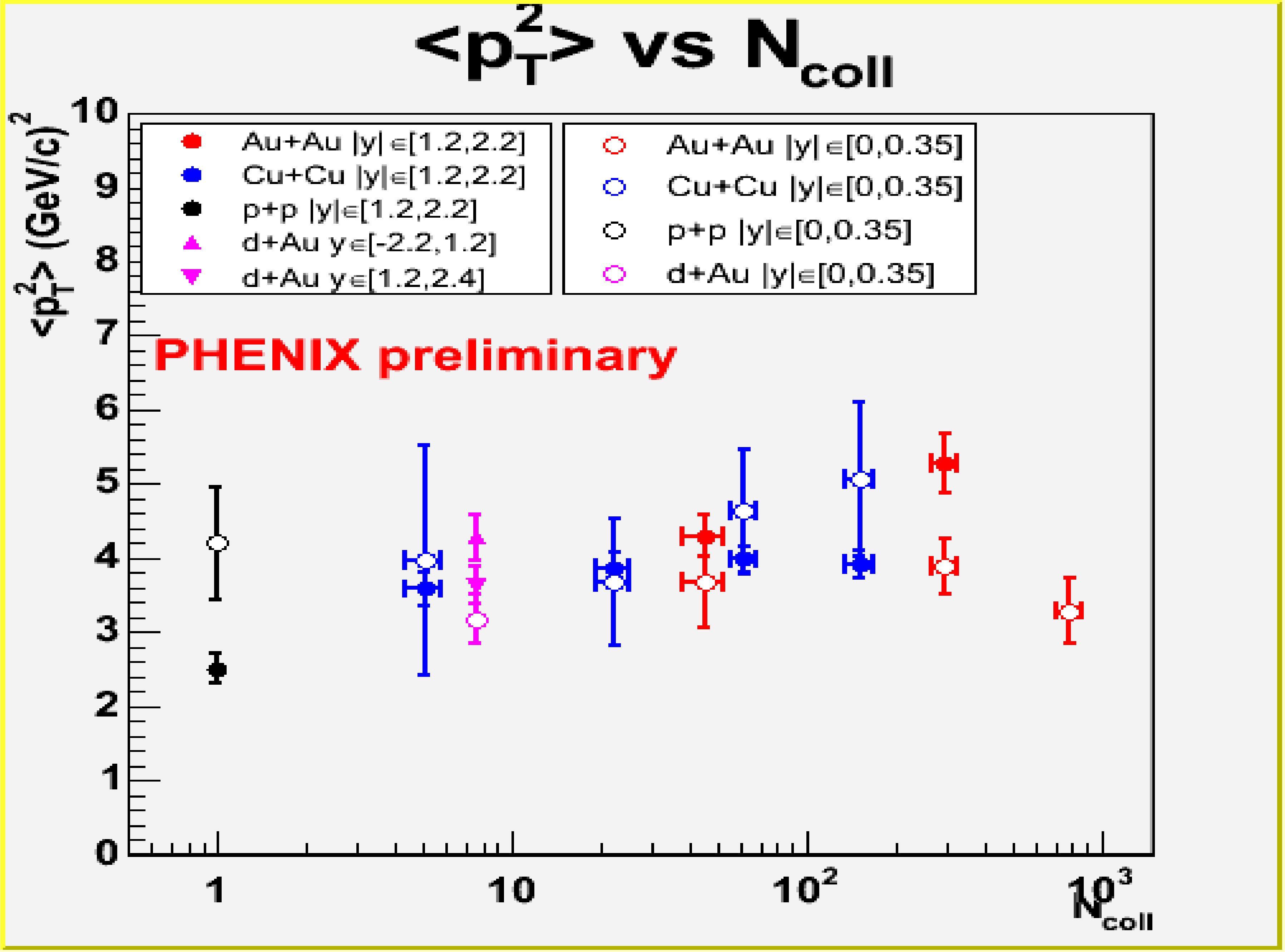




J/ψ Formation p_T Distributions
Comparison with direct Thermal Distribution
Formation from thermal charm, T = 170 MeV, y_{Tmax} = 0.5
Formation from thermal charm, T = 128 MeV, y_{Tmax} = 0.65
Formation from pQCD charm
pQCD diagonal $c\bar{c}$ pairs
Thermal J/ψ, T = 128 MeV, y_{Tmax} = 0.65
Thermal J/ψ, T = 170 MeV, y_{Tmax} = 0.5
Minimum Bias Spectra
$[N^{-1} dN/dp_T^2]_{J/\psi}$ (GeV^{-2})
p_T (GeV)

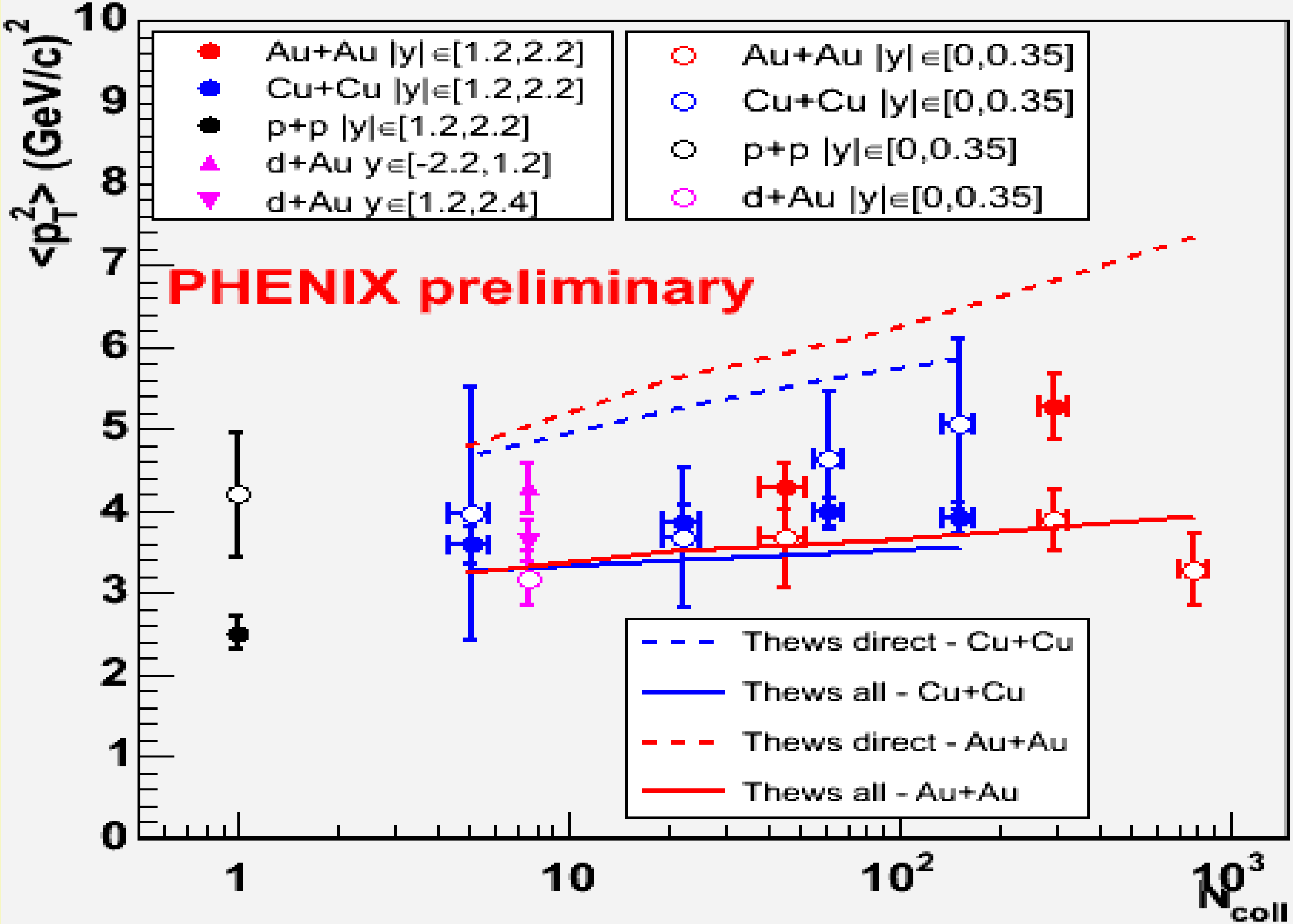
J/ψ Transverse Momentum Width Evolution

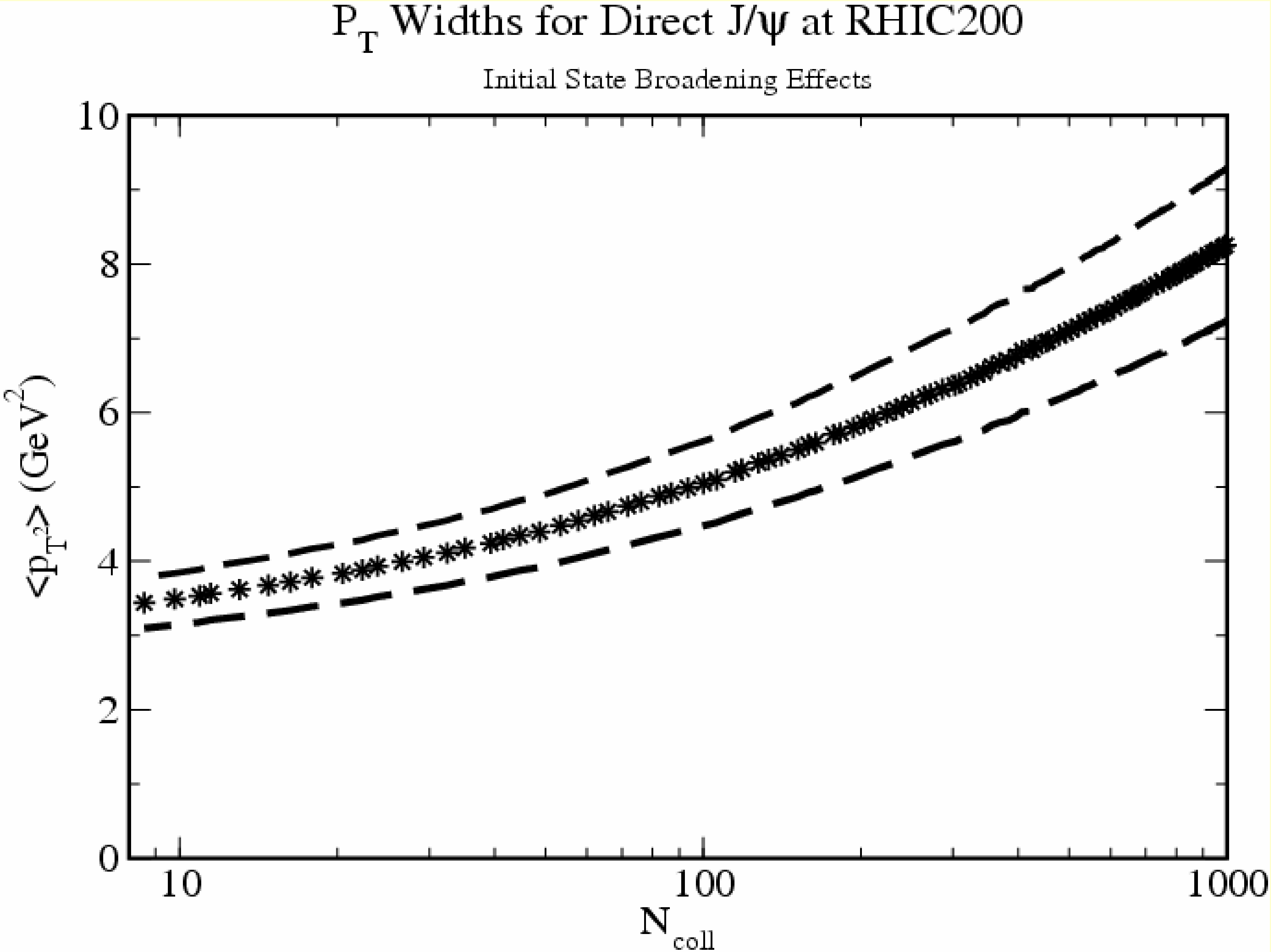




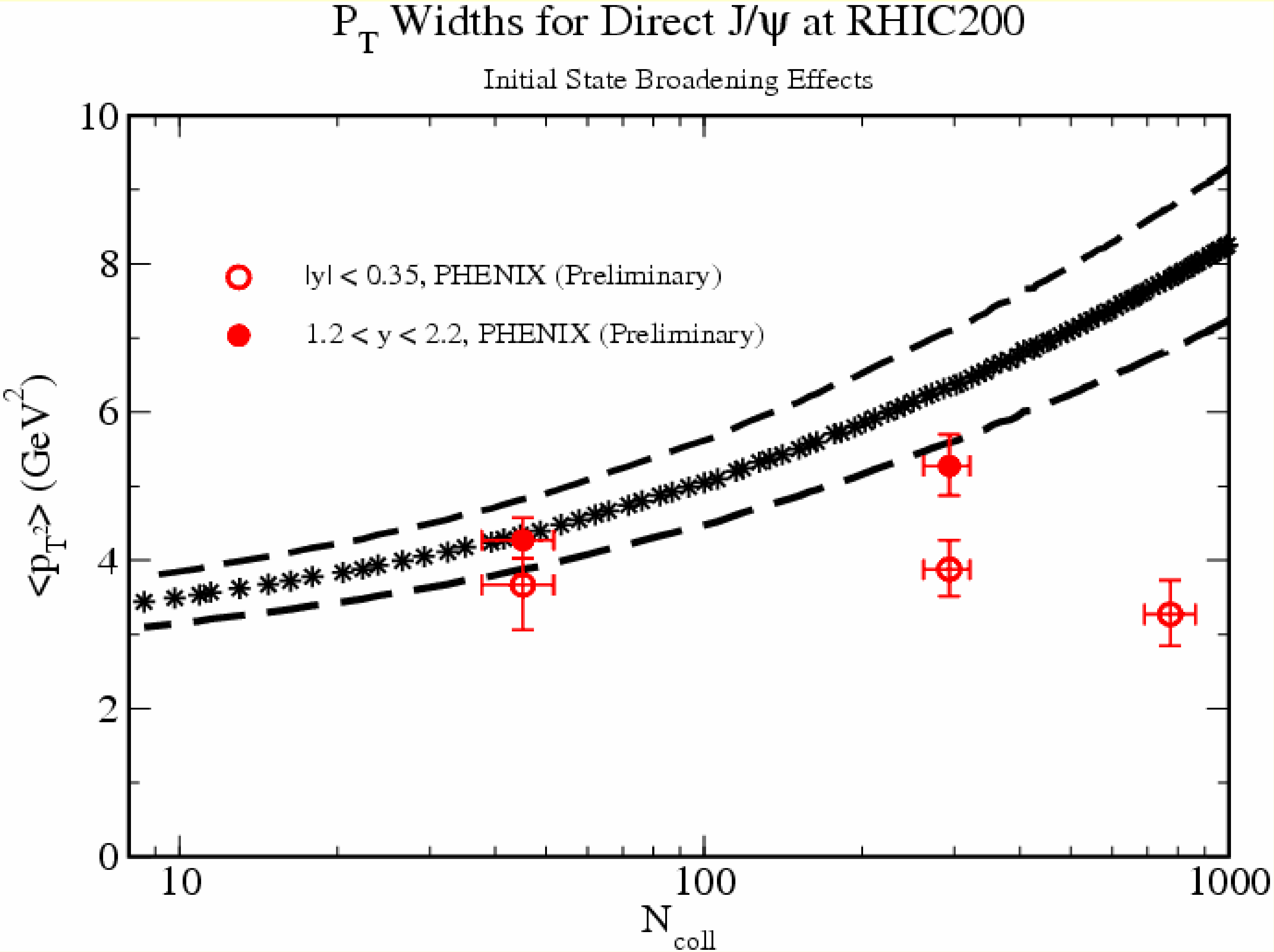
$<p_T^2>$ vs N_{coll}
$<p_T^2>$ (GeV/c)^2
Au+Au |y|∈[1.2,2.2]
Cu+Cu |y|∈[1.2,2.2]
p+p |y|∈[1.2,2.2]
d+Au y∈[-2.2,1.2]
d+Au y∈[1.2,2.4]
Au+Au |y|∈[0,0.35]
Cu+Cu |y|∈[0,0.35]
p+p |y|∈[0,0.35]
d+Au |y|∈[0,0.35]
PHENIX preliminary
N_{coll}

$\langle p_T^2 \rangle$ vs N_{coll}

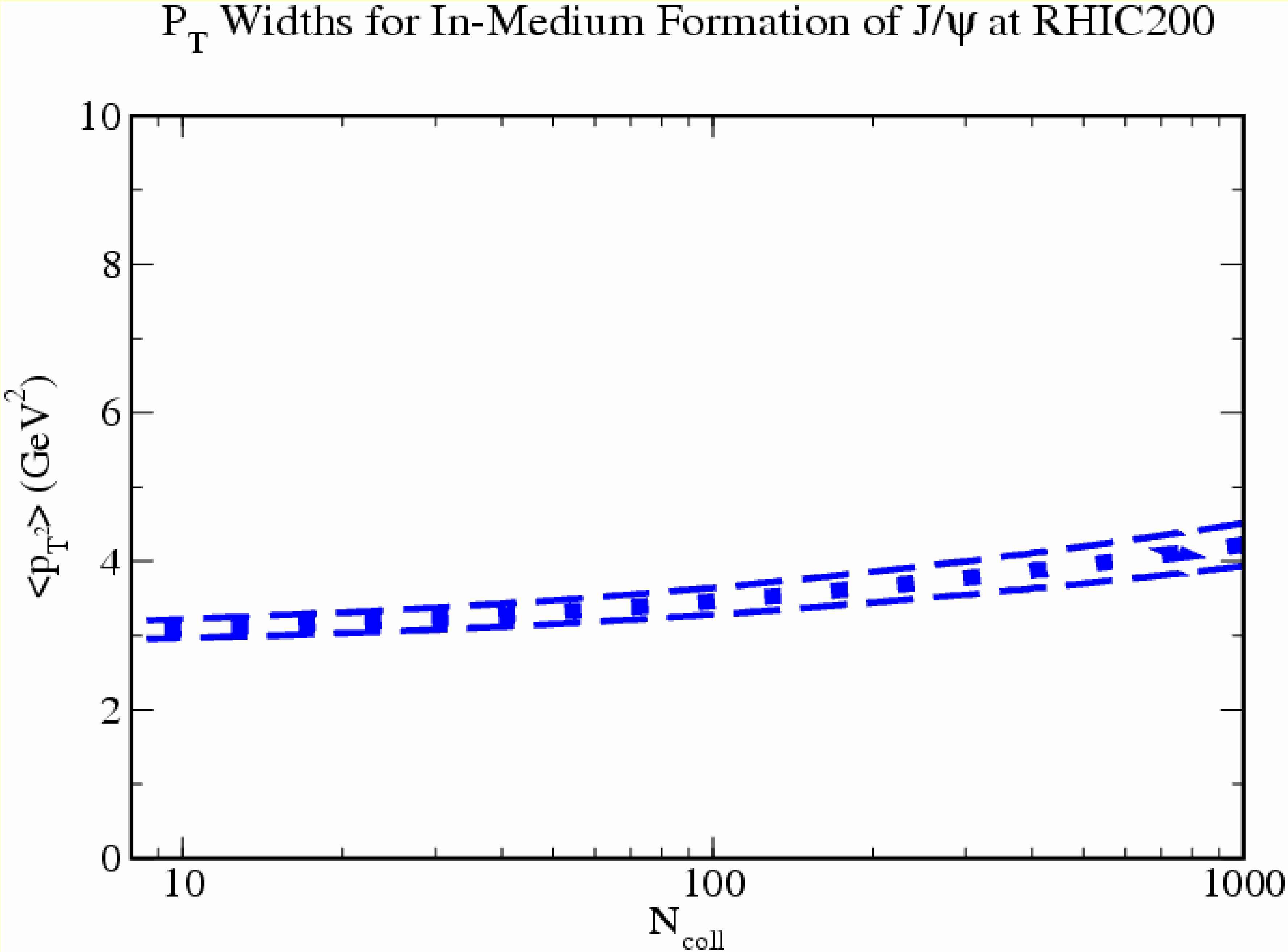




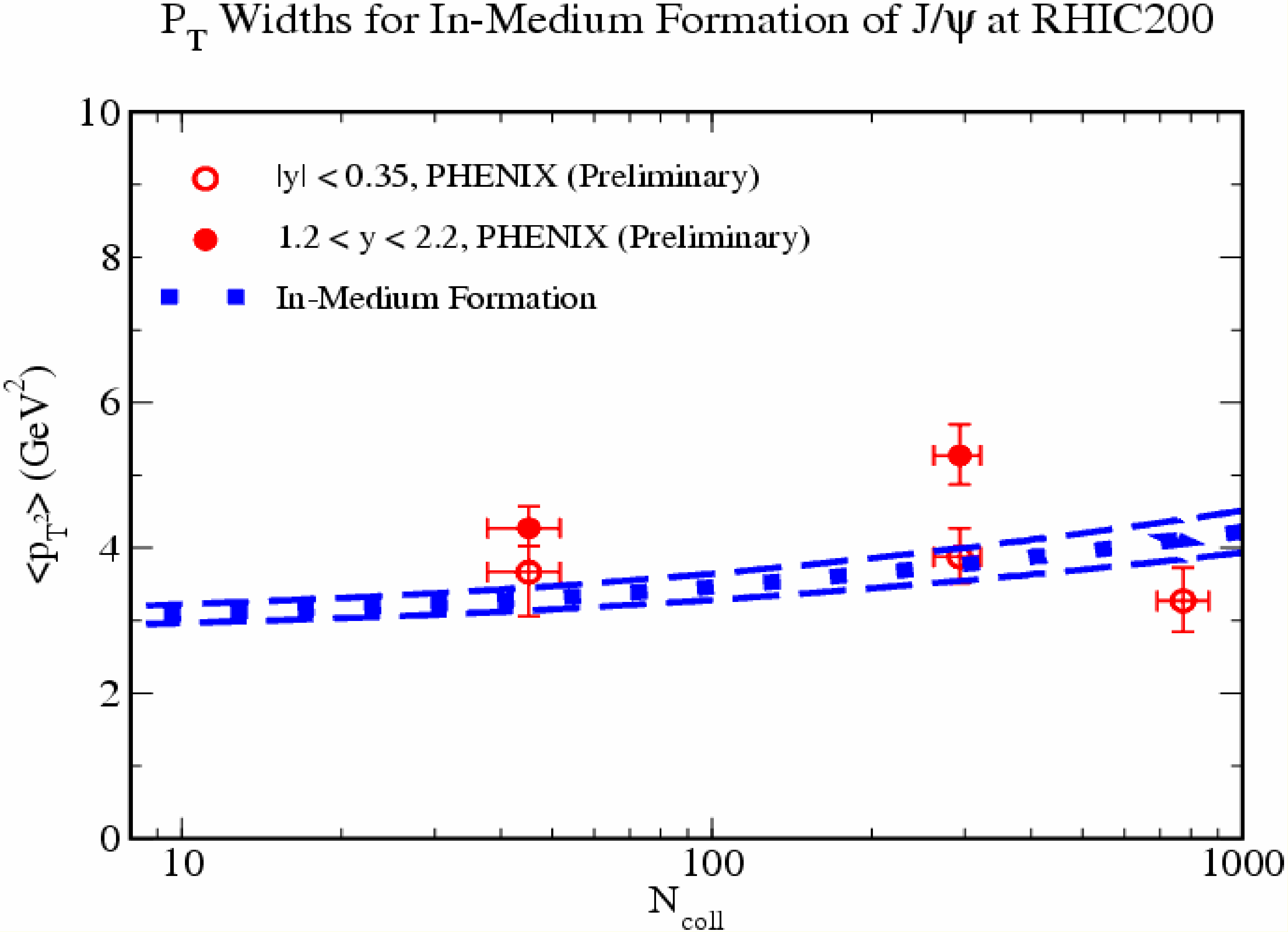
P_T Widths for Direct J/ψ at RHIC200
Initial State Broadening Effects
<p_T^2> (GeV^2)
N_coll
0
2
4
6
8
10
10
100
1000



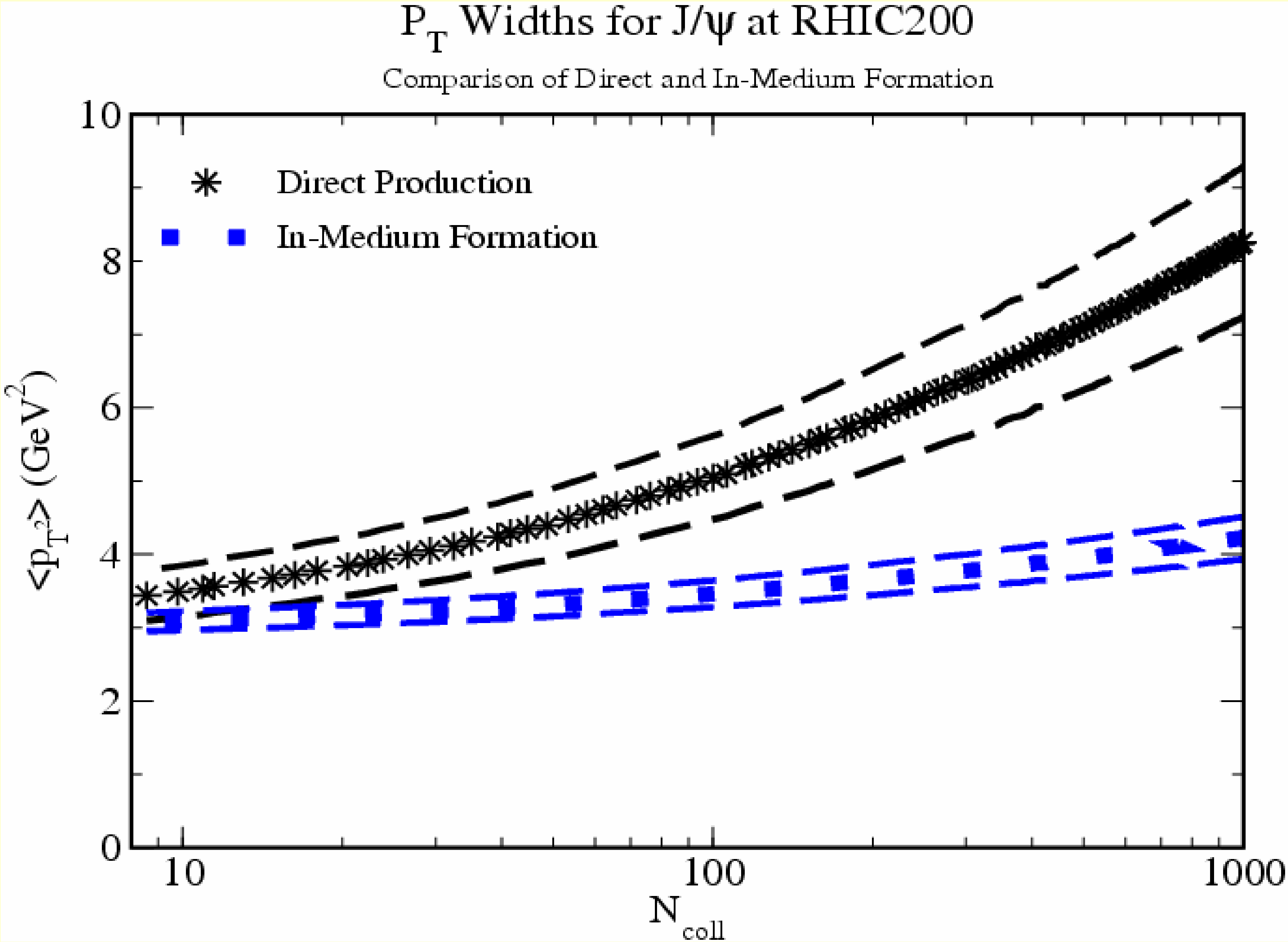
P_T Widths for Direct J/ψ at RHIC200
Initial State Broadening Effects
|y| < 0.35, PHENIX (Preliminary)
1.2 < y < 2.2, PHENIX (Preliminary)
$<p_T^2>$ (GeV^2)
N_{coll}
0
2
4
6
8
10
10
100
1000

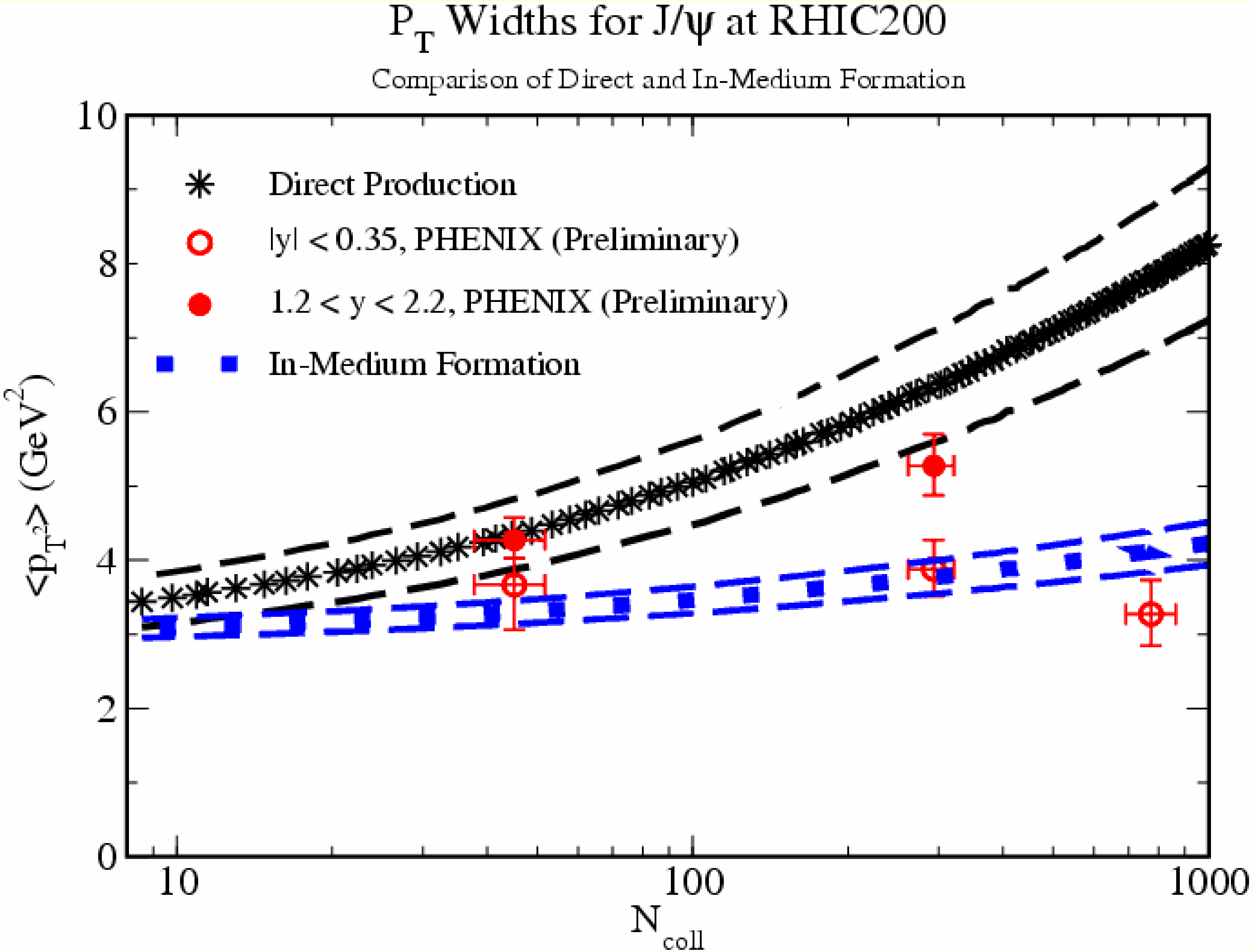


P_T Widths for In-Medium Formation of J/ψ at RHIC200
$<p_T^2>$ (GeV^2)
0
2
4
6
8
10
10
100
1000
N_{coll}

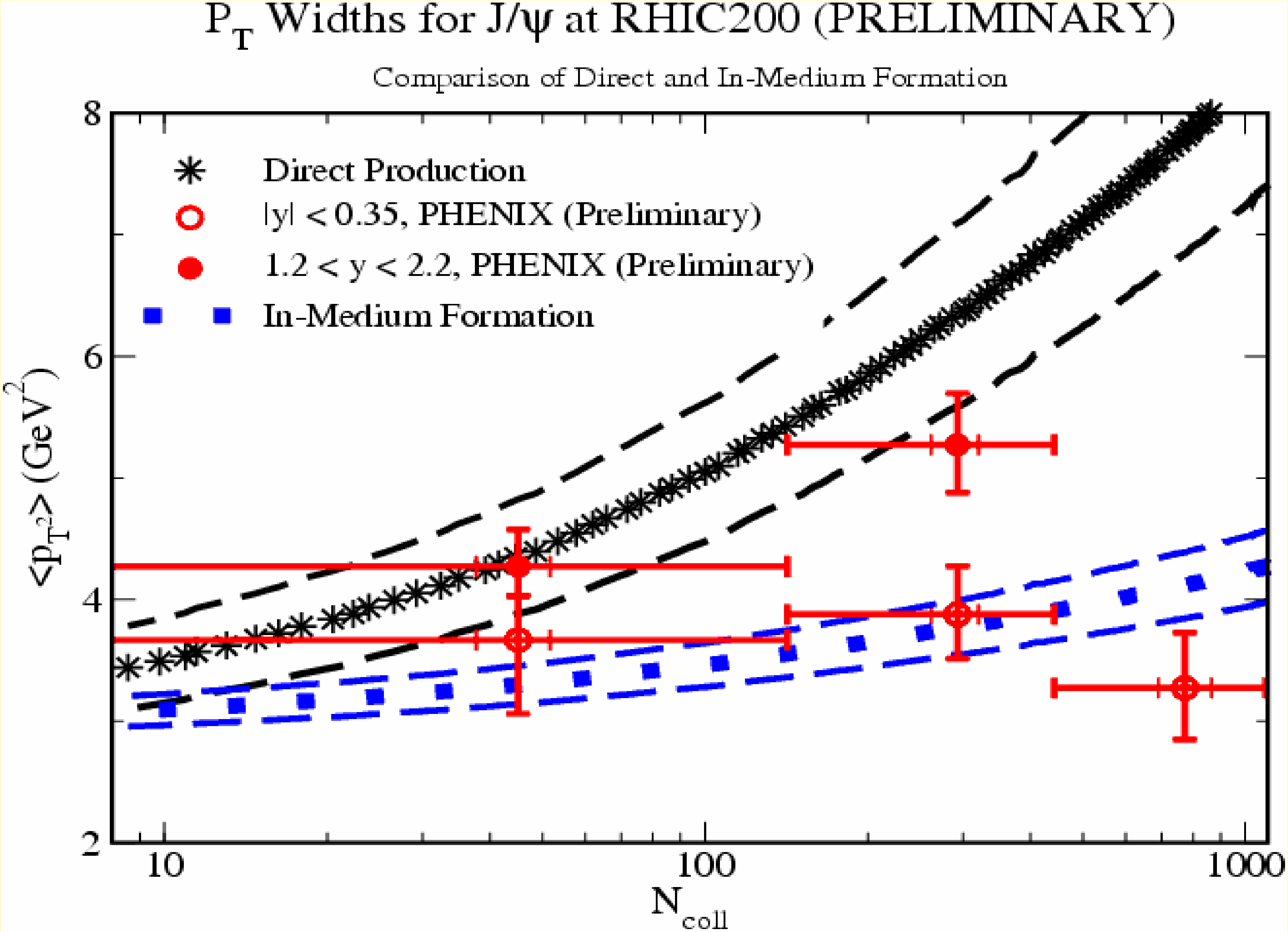


P_T Widths for In-Medium Formation of J/ψ at RHIC200
|y| < 0.35, PHENIX (Preliminary)
1.2 < y < 2.2, PHENIX (Preliminary)
In-Medium Formation
<p_T^2> (GeV^2)
N_coll
0
2
4
6
8
10
10
100
1000

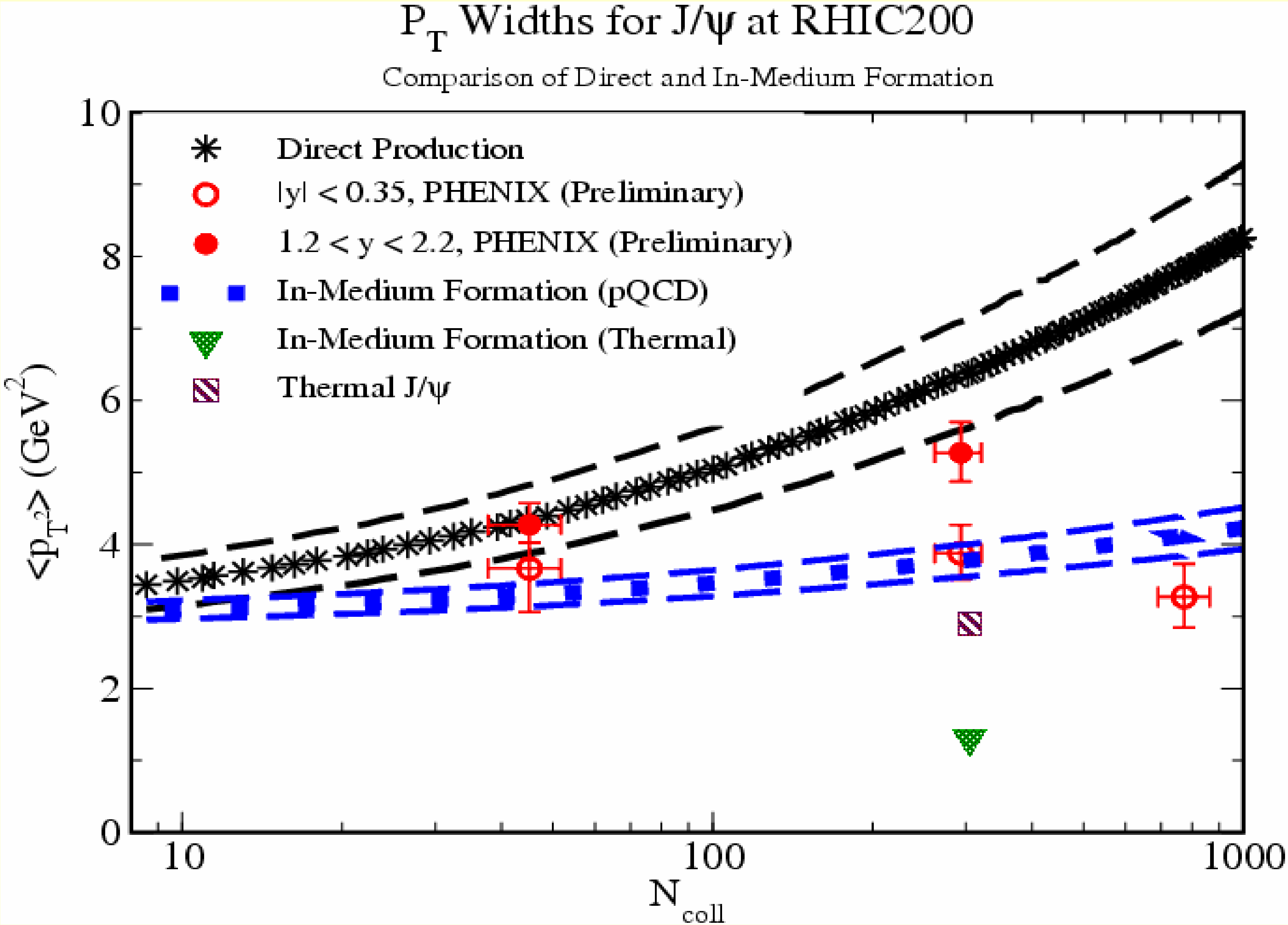

P_T Widths for J/ψ at RHIC200
Comparison of Direct and In-Medium Formation
Direct Production
In-Medium Formation
<p_T^2> (GeV^2)
N_coll
0
2
4
6
8
10
10
100
1000



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
$\langle p_T^2 \rangle$ (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



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 (pQCD)
In-Medium Formation (Thermal)
Thermal J/ψ
<p_T^2> (GeV^2)
N_coll
0
2
4
6
8
10
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

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

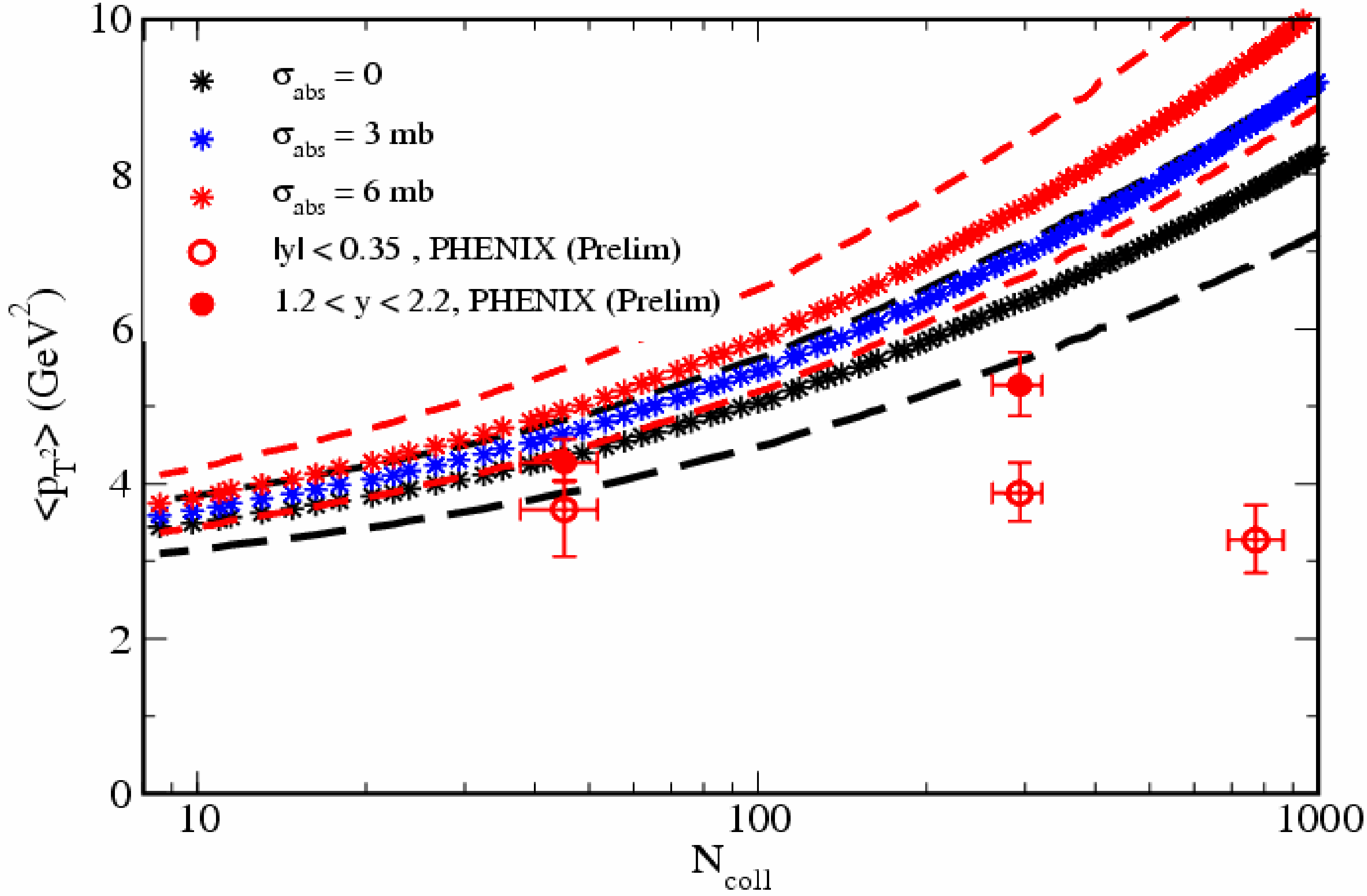
Path Length Model

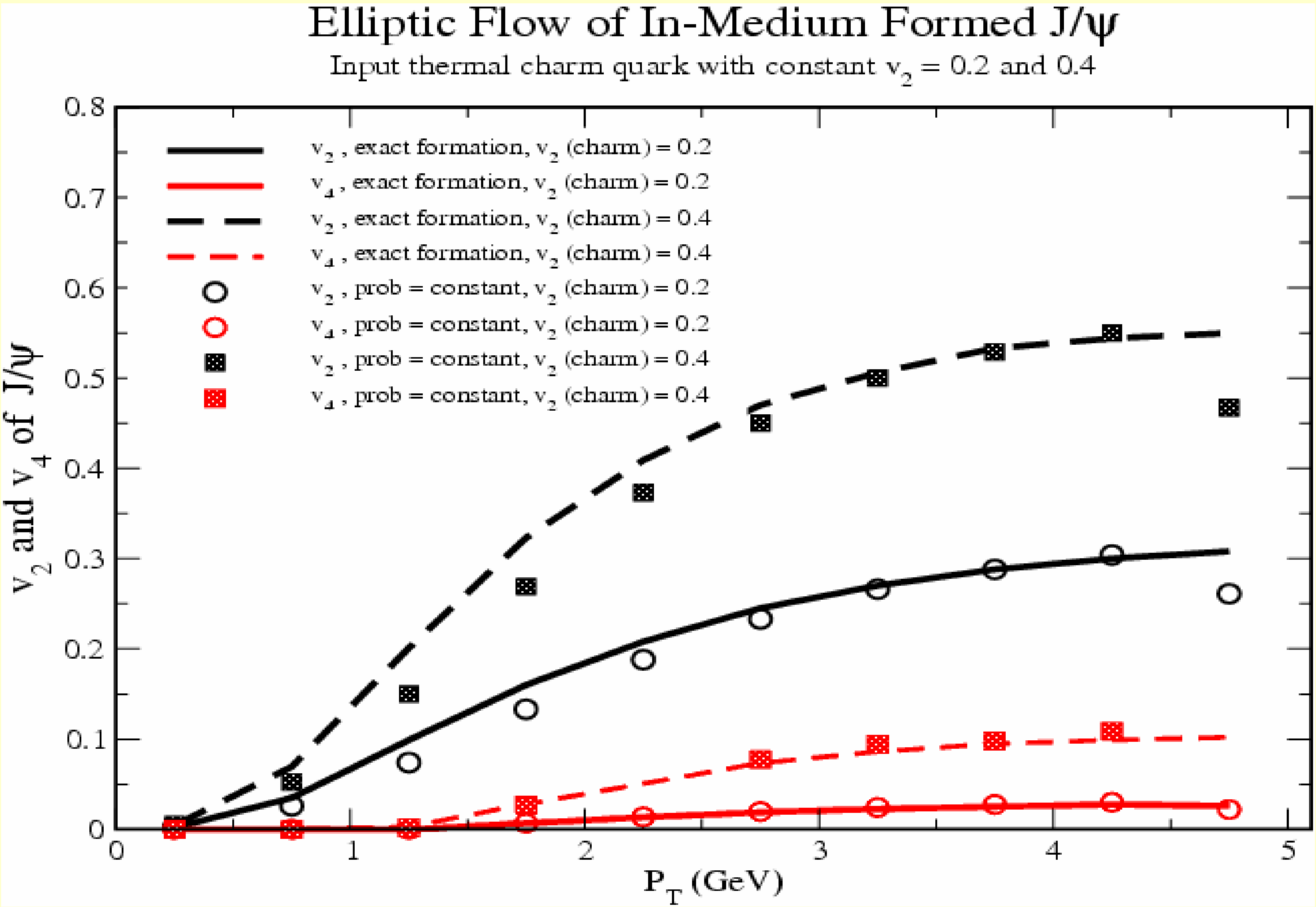
$$P_{mn} = x^{n-m} \qquad x \equiv \exp^{-(\rho\sigma/n)L_{\max}}$$

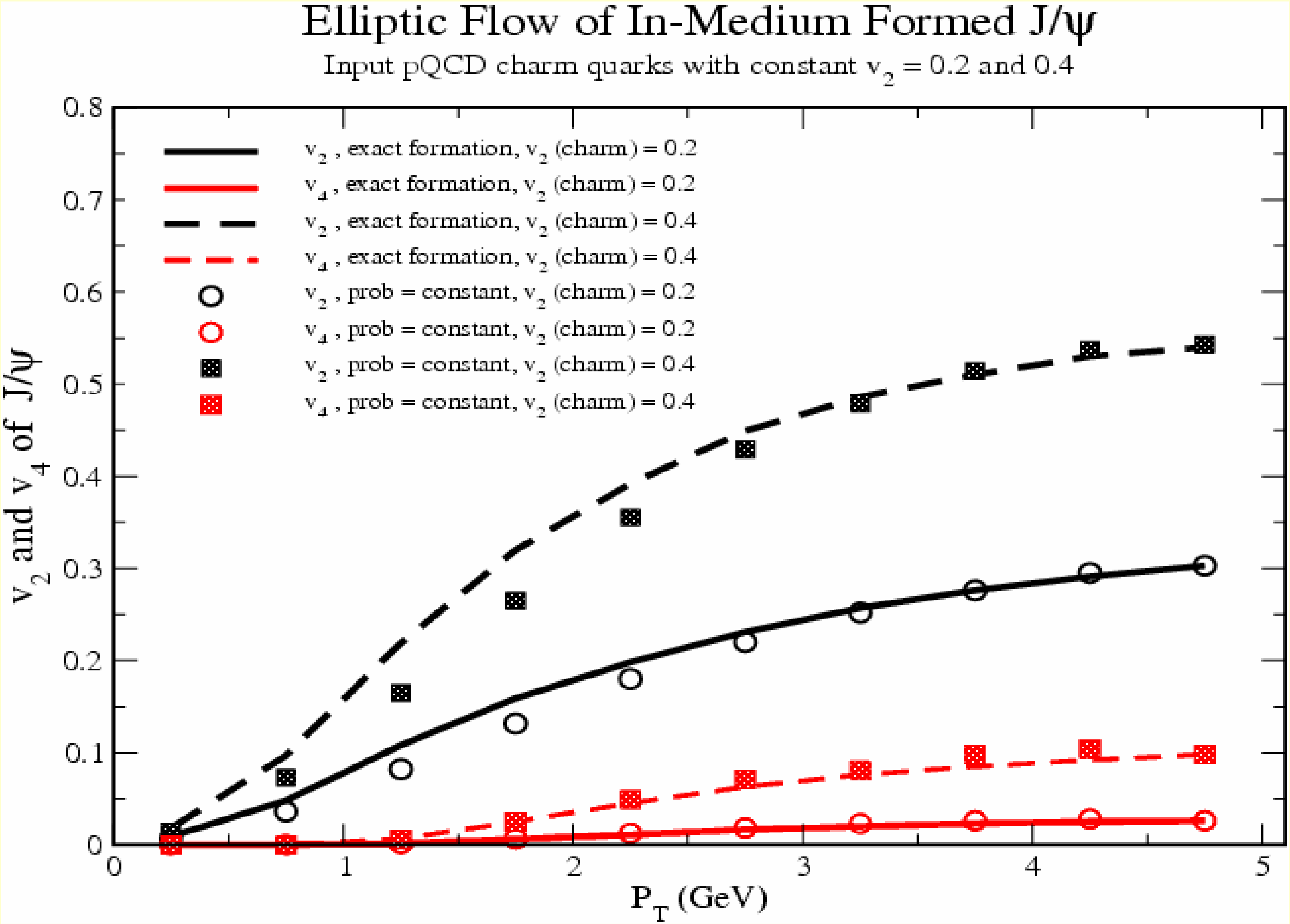
$$<n>_{abs} = \frac{x-1}{x^{n}-1}\sum_{m=1}^{n}(m-1)x^{n-m}$$

P_T Widths for Direct J/ψ at RHIC200

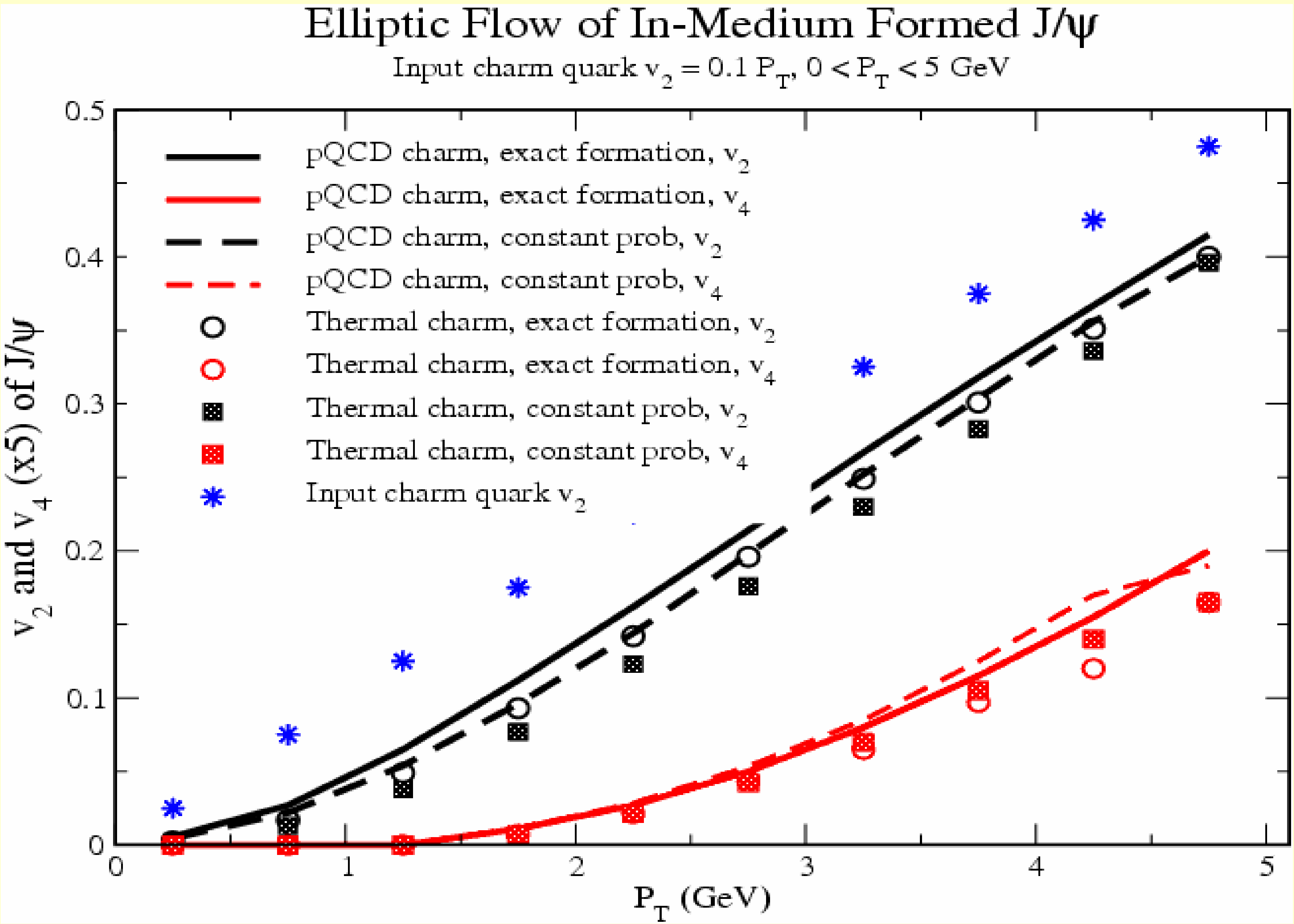
Initial State Broadening Effects plus Nuclear Absorption




Elliptic Flow of In-Medium Formed J/ψ
Input thermal charm quark with constant v2 = 0.2 and 0.4
v2 , exact formation, v2 (charm) = 0.2
v4 , exact formation, v2 (charm) = 0.2
v2 , exact formation, v2 (charm) = 0.4
v4 , exact formation, v2 (charm) = 0.4
v2 , prob = constant, v2 (charm) = 0.2
v4 , prob = constant, v2 (charm) = 0.2
v2 , prob = constant, v2 (charm) = 0.4
v4 , prob = constant, v2 (charm) = 0.4
v2 and v4 of J/ψ
PT (GeV)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
1
2
3
4
5



Elliptic Flow of In-Medium Formed J/ψ
Input pQCD charm quarks with constant v2 = 0.2 and 0.4
v2 , exact formation, v2 (charm) = 0.2
v4 , exact formation, v2 (charm) = 0.2
v2 , exact formation, v2 (charm) = 0.4
v4 , exact formation, v2 (charm) = 0.4
v2 , prob = constant, v2 (charm) = 0.2
v4 , prob = constant, v2 (charm) = 0.2
v2 , prob = constant, v2 (charm) = 0.4
v4 , prob = constant, v2 (charm) = 0.4
v2 and v4 of J/ψ
PT (GeV)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
1
2
3
4
5



Elliptic Flow of In-Medium Formed J/ψ
Input charm quark v2 = 0.1 PT, 0 < PT < 5 GeV
pQCD charm, exact formation, v2
pQCD charm, exact formation, v4
pQCD charm, constant prob, v2
pQCD charm, constant prob, v4
Thermal charm, exact formation, v2
Thermal charm, exact formation, v4
Thermal charm, constant prob, v2
Thermal charm, constant prob, v4
Input charm quark v2
v2 and v4 (x5) of J/ψ
PT (GeV)
0
0.1
0.2
0.3
0.4
0.5
1
2
3
4
5

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> depend on rapidity intervals, not understood 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/Psi and charm quark flow in progress