Heavy Quarkonia Production in p+p Collisions from the PHENIX Experiment

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Quarkonia in p+p Collisions

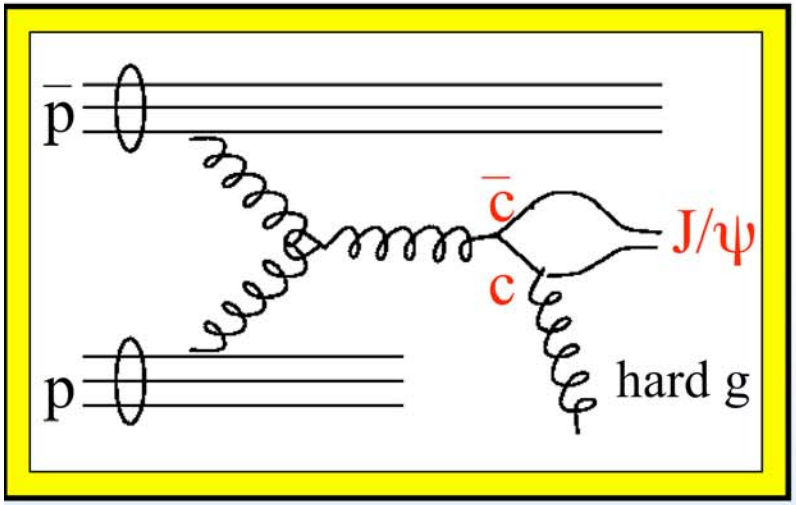
1. Production Mechanism:
   - Heavy quarks predominantly generated in hadronic collisions via gluonic diagrams
   - Details of hadronization process remain unclear
2. Properties of Cold Nuclear Matter (CNM):
   - Initial state energy loss
   - Gluon shadowing
   - Cronin
   - Nuclear absorption

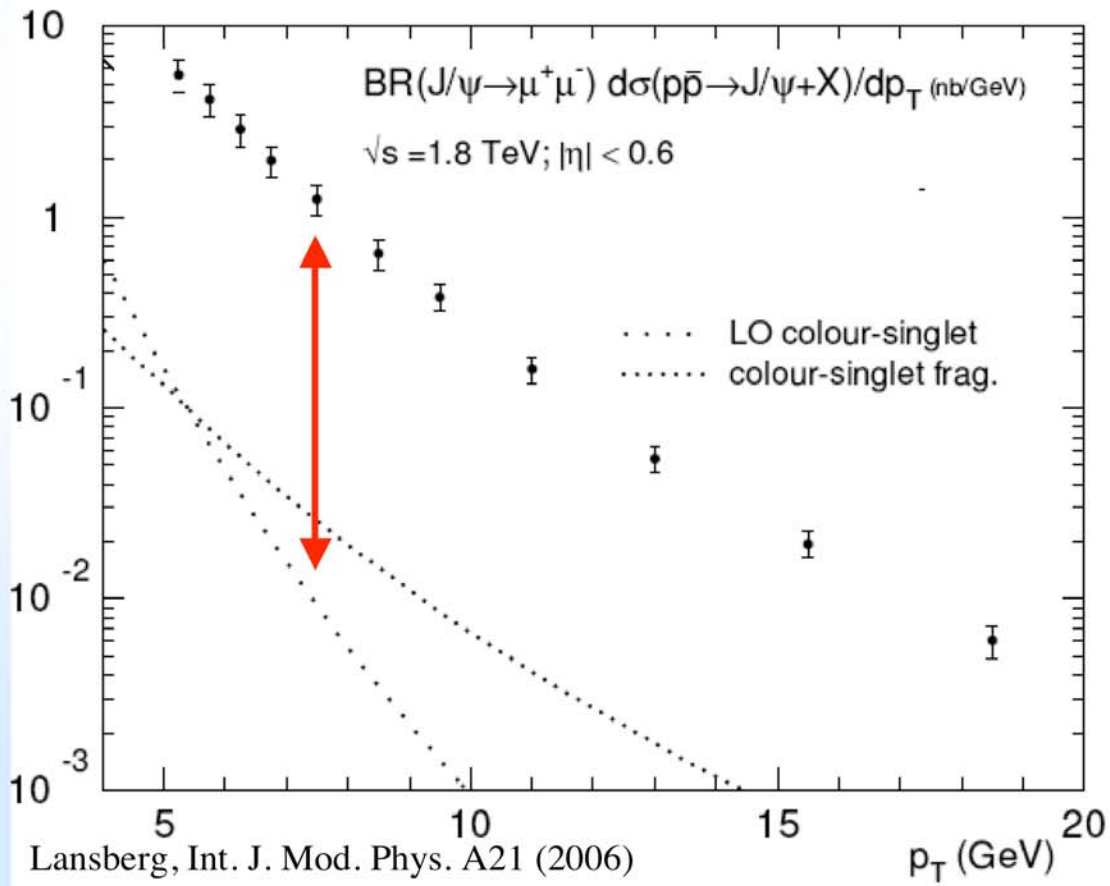
   } Relative influence on yields needs to be determined
3. Reference for Heavy Ion collisions:
   - Provide critical information needed for evaluating the nuclear modification factor
   - Allow degree of in medium modification relative to CNM to be determined

Talks: A. Glenn, T. Gunji

J/ψ Production Mechanism

- Color Singlet Model:
  - Color singlet $c\bar{c}$ pair created in same quantum state as J/ψ
  - Underpredicts J/ψ production cross section by a x10
  - Predicts no polarization

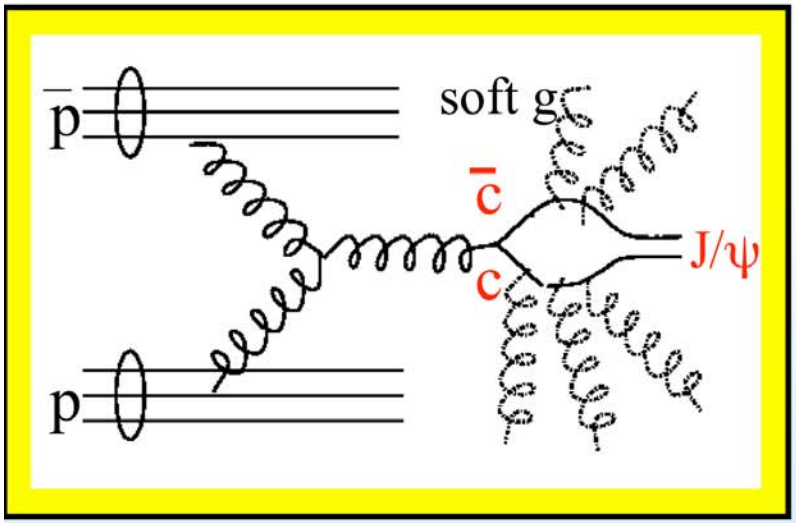


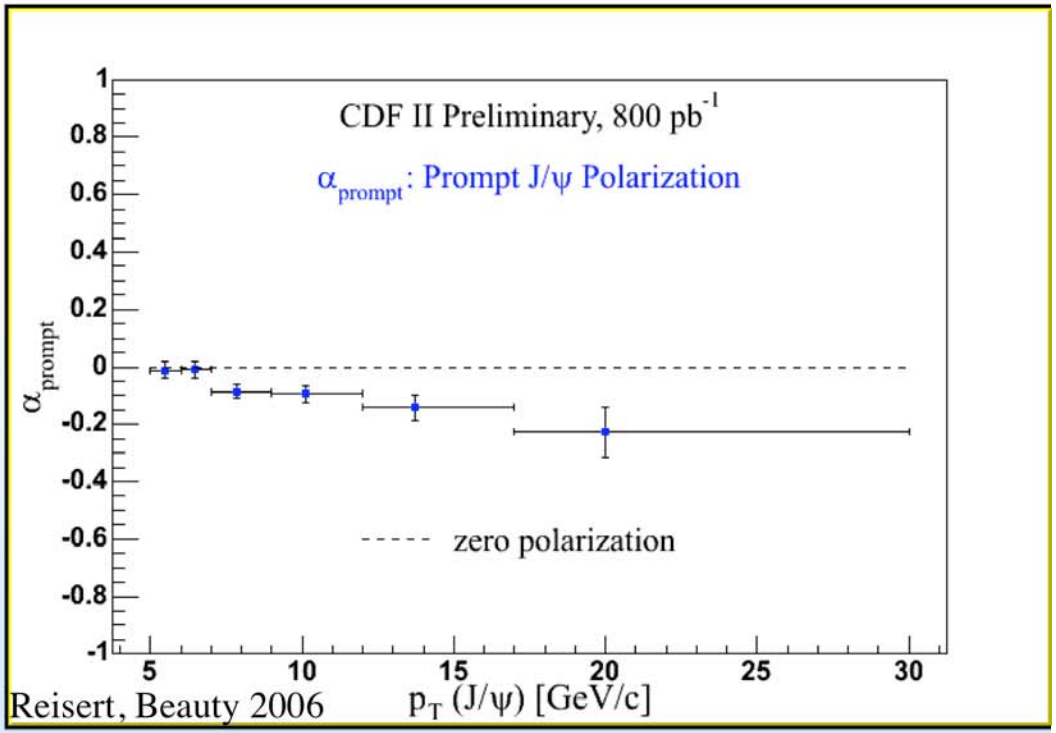


Lansberg, Int. J. Mod. Phys. A21 (2006)

J/ψ Production Mechanism

- Color Singlet Model:
- NRQCD Color Octet Model:
  - Includes octet state $c\bar{c}$ pairs that radiate soft gluons during hadronization
  - Color octet matrix elements derived from experimental data were expected to be universal, but are not
  - Predicts large transverse polarization ($\alpha>0$) at high p_T that is not seen in experimental data



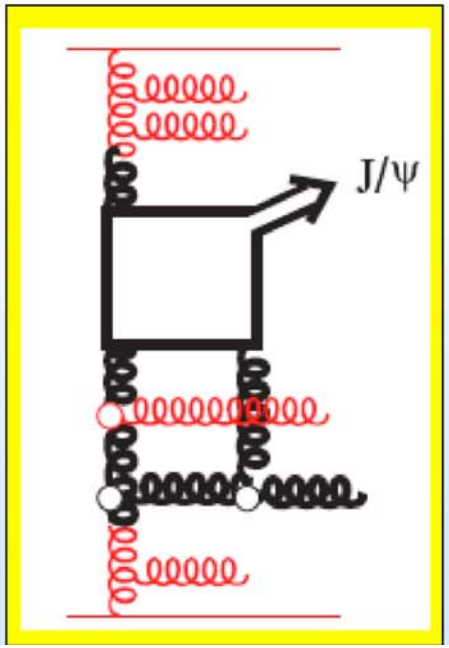


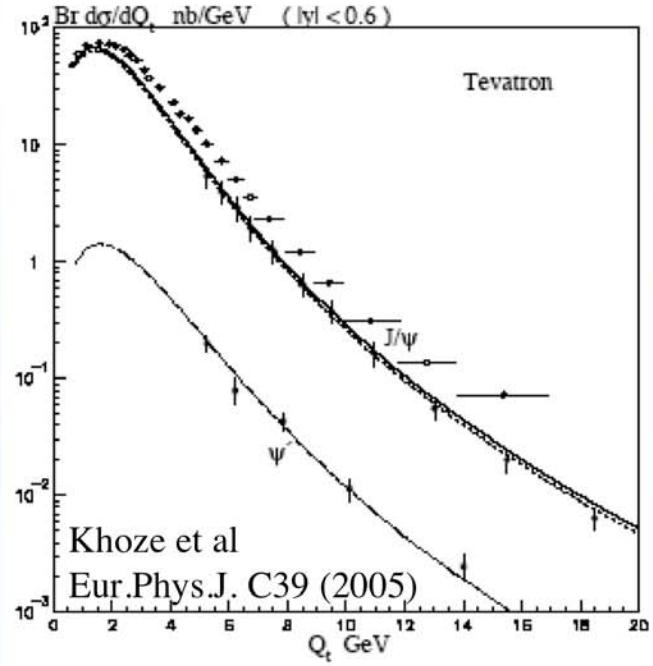
J/ψ Production Mechanism

- Color Singlet Model:
- NRQCD Color Octet Model:
- Color Evaporation Model:
  - Phenomenological approach
  - Charmonium states formed in proportions determined by experimental data for any $c\bar{c}$ pair that has a mass below the $D\bar{D}$ threshold
  - Uses emission of soft gluons to form J/ψ
  - Predicts no polarization

J/ψ Production Mechanism

- Color Singlet Model:
- NRQCD Color Octet Model:
- Color Evaporation Model:
- pQCD involving 3-gluons:
  - Hadronization mechanism includes channel involving the fusion of a symmetric color octet state with an additional gluon
  - Successfully reproduces experimental cross section and polarization measurements

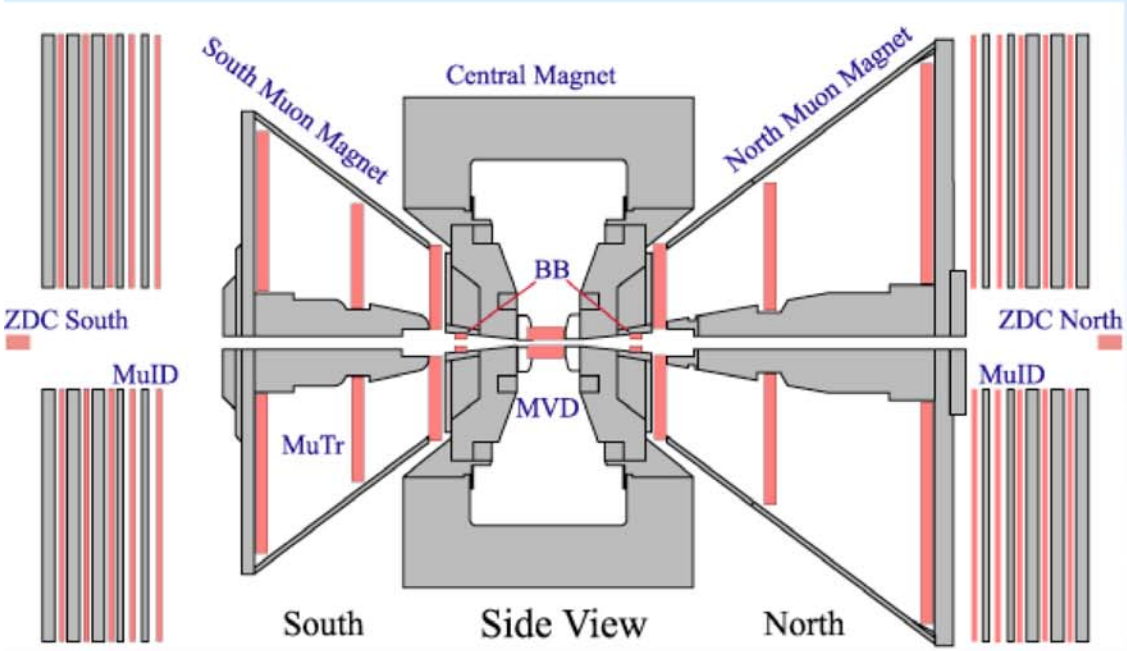




PHENIX Data Compendium

Run	Species	$s^{1/2}$ [GeV]	$\int Ldt$	# J/ψ $\lvert\eta\rvert<0.35$	# J/ ψ $1.2<\lvert y\rvert<2.2$	Reference
01	Au+Au	130	1 μb^{-1}			
02	Au+Au	200	24 μb^{-1}	13		PRC69, 014901 (2004)
	p+p	200	0.15 pb^{-1}	46	65	PRL92, 051802 (2004)
03	d+Au	200	2.74 nb^{-1}	364	1186	PRL96, 012304 (2006)
	p+p	200	0.35 pb^{-1}	130	448	
04	Au+Au	200	241 μb^{-1}	1000	4449	nucl-ex/0611020
	Au+Au	62	9 μb^{-1}			
05	Cu+Cu	200	3 nb^{-1}	2290	9000	coming soon
	Cu+Cu	62	0.19 nb^{-1}		146	
	Cu+Cu	22.5	2.7 μb^{-1}			
	p+p	200	3.8 pb^{-1}	1500	8005	hep-ex/0611020
06	p+p	200	10.7 pb^{-1}			
	p+p	62	0.1 pb^{-1}			

PHENIX Detector: Muon Arms



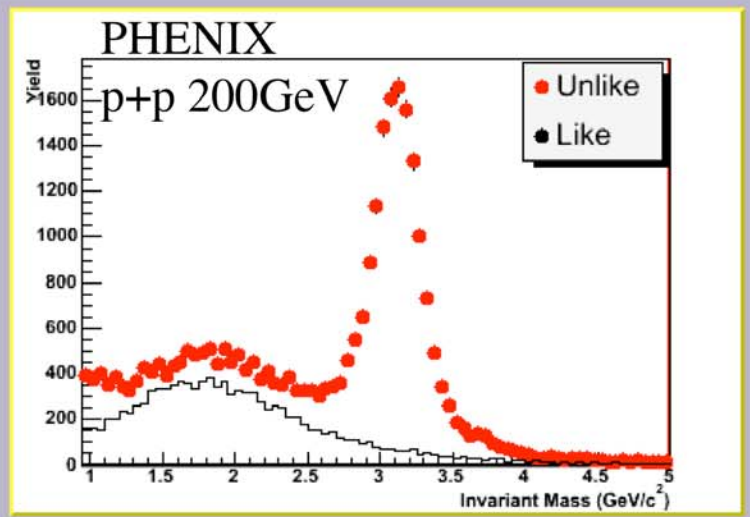
$J/\psi \rightarrow \mu^+ \mu^-$

$p > 2GeV/c$

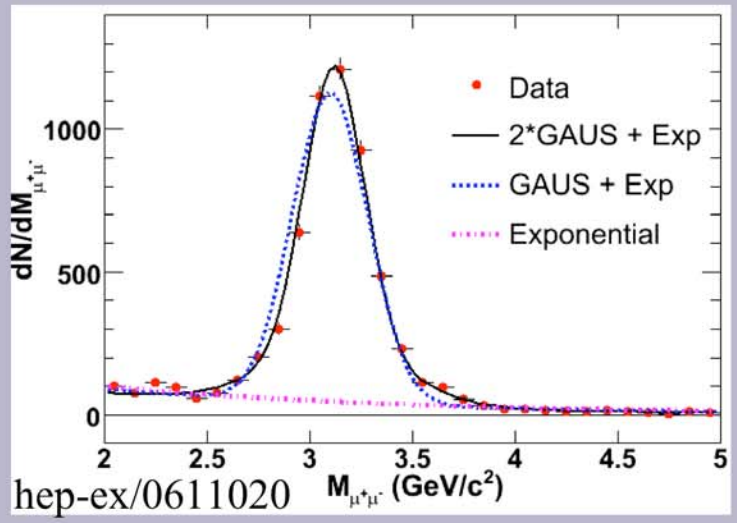
$1.2 < |y| < 2.2$

$\Delta\phi = 2\pi$

Poster #163: Silvestre



Event Mixed Background Subtraction



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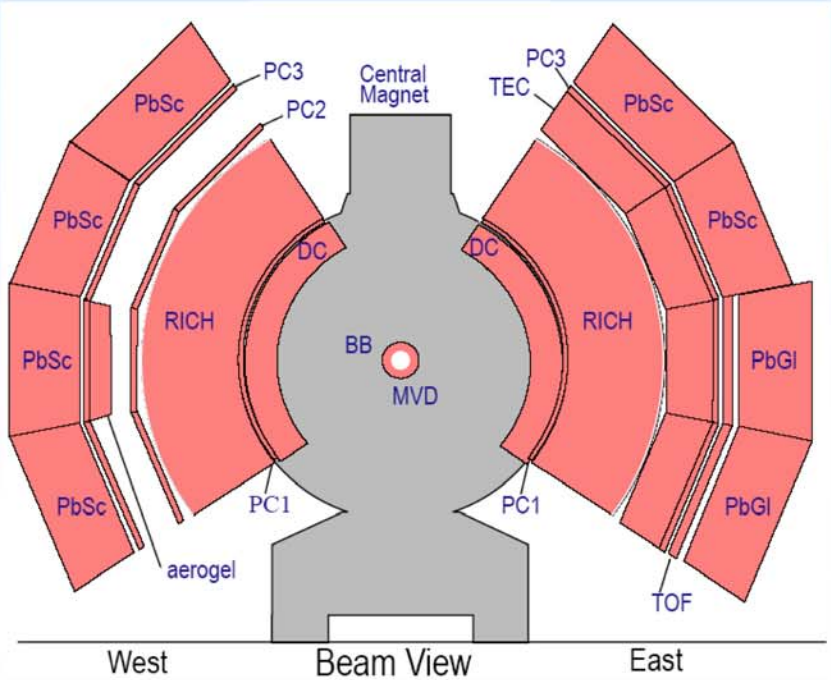
PHENIX Detector: Central Arms

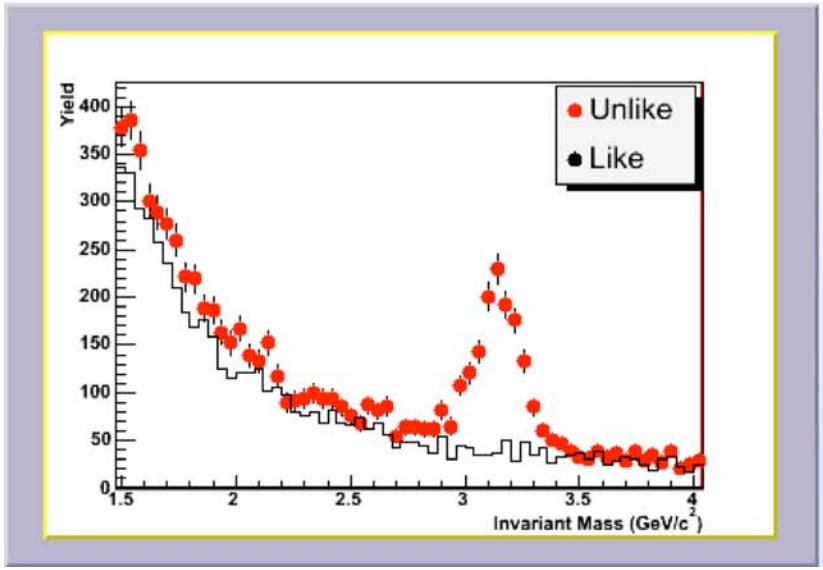


$J/\psi \rightarrow e^+ e^-$

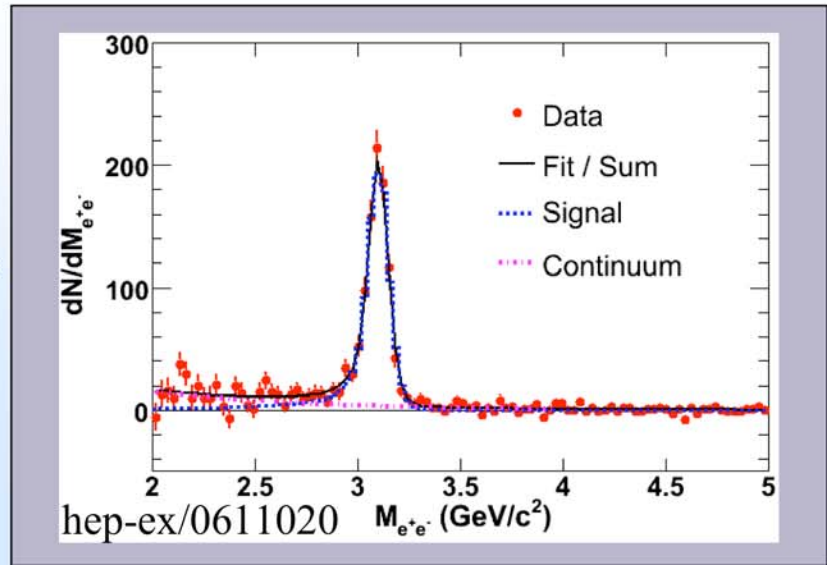
$p > 0.2 GeV/c$

$|\eta| < 0.35$

$\Delta\phi = \pi$



Like Sign Subtraction



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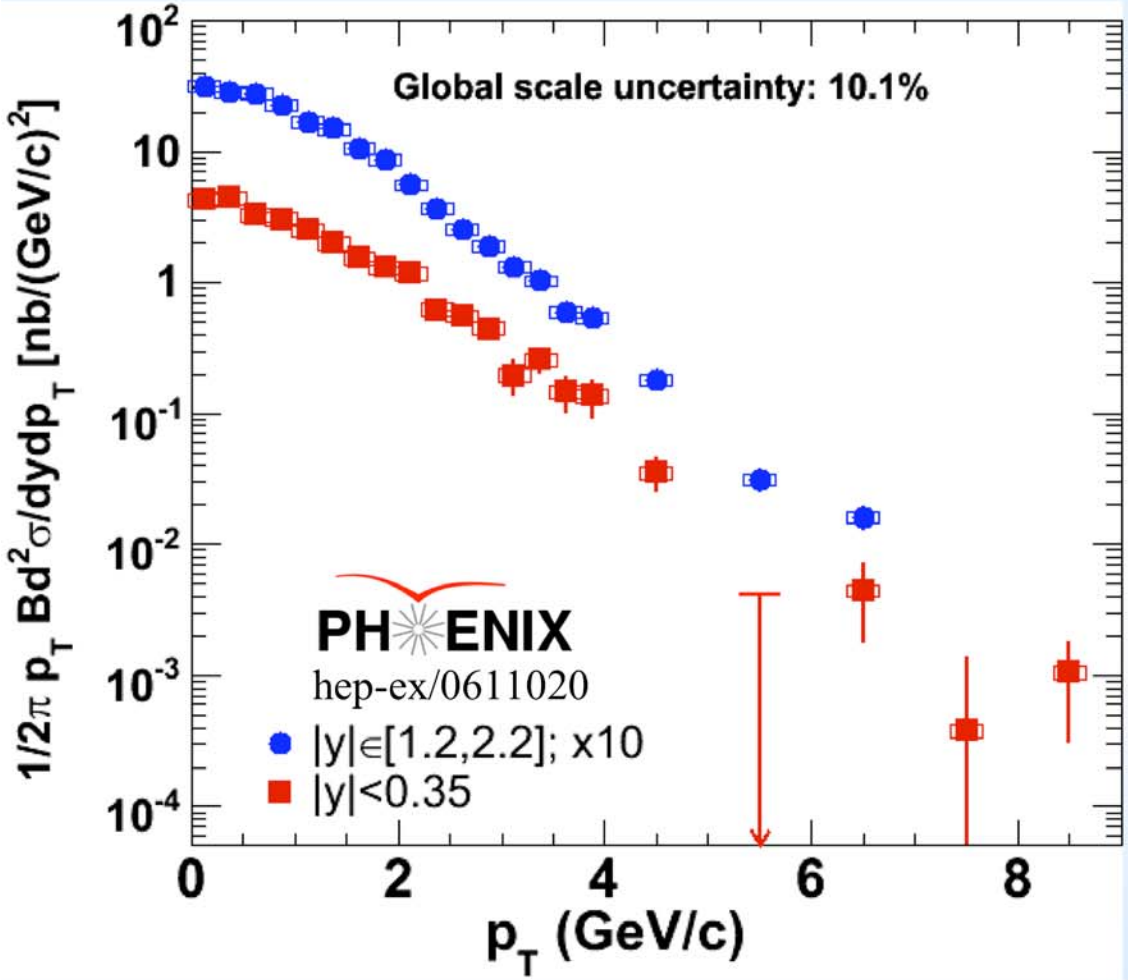
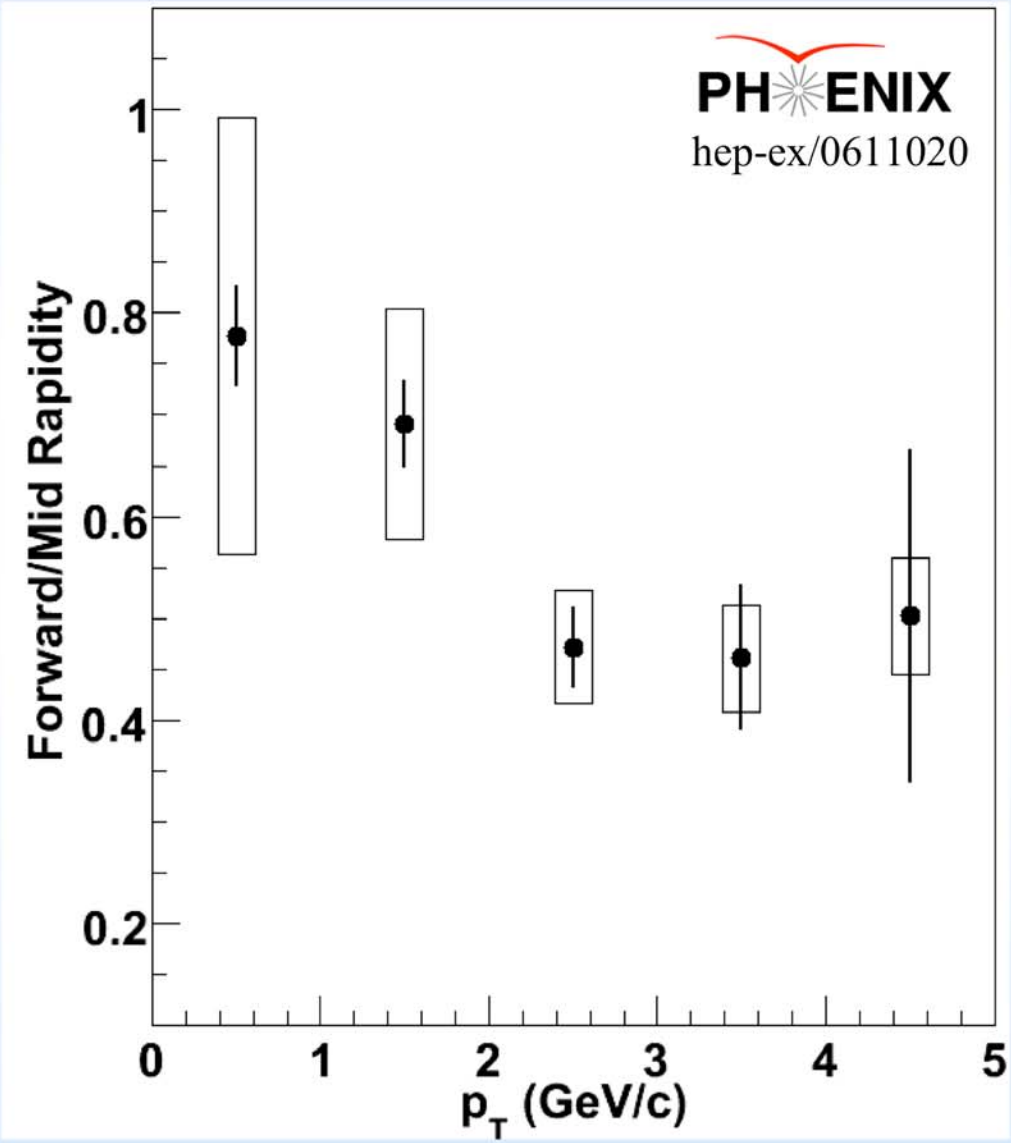
J/ψ Cross Section vs p_T



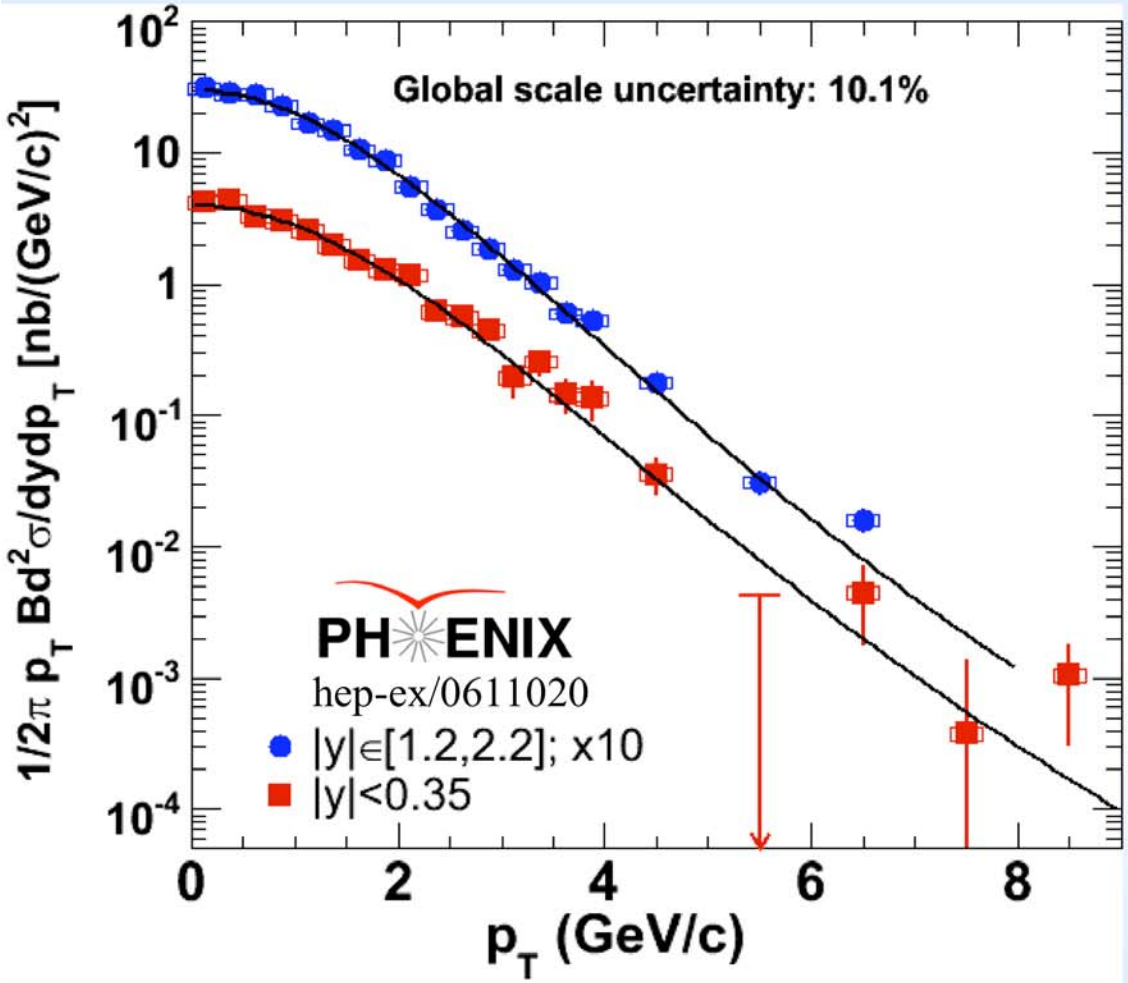
- High statistics of run 5 data set allow p_T spectrum to mapped up to 9 GeV/c
- Vertical error bars:
  - statistical
  - point-to-point uncorrelated (ie signal extraction syst)
- Boxes are the point-to-point correlated systematic error
  - Define maximum allowed shape deviation
  - Acceptance (±10%, ±8%)
  - Run dependent detector efficiency (±8%, ±4%)

Ratio of p_T spectra



- Significant decrease observed in ratio of $|y|<0.35$ and $1.2<|y|<2.2$ p_T spectra
- Indicates forward rapidity p_T spectrum is softer than mid-rapidity
- At forward rapidity longitudinal momentum increased ∴ less energy is available in the transverse direction

J/ψ Cross Section vs p_T



$\langle p_T^2 \rangle$ extracted using Kaplan function integrated to ∞

$$f(p_T) = p_0 \left[1 + \left(\frac{p_T}{p_1} \right)^2 \right]^{-6}$$

Mid-rapidity:

$$\langle p_T^2 \rangle = 4.14 \pm 0.18^{+0.30}_{-0.20}$$

$$\chi^2 / ndf = 23/19$$

Forward rapidity:

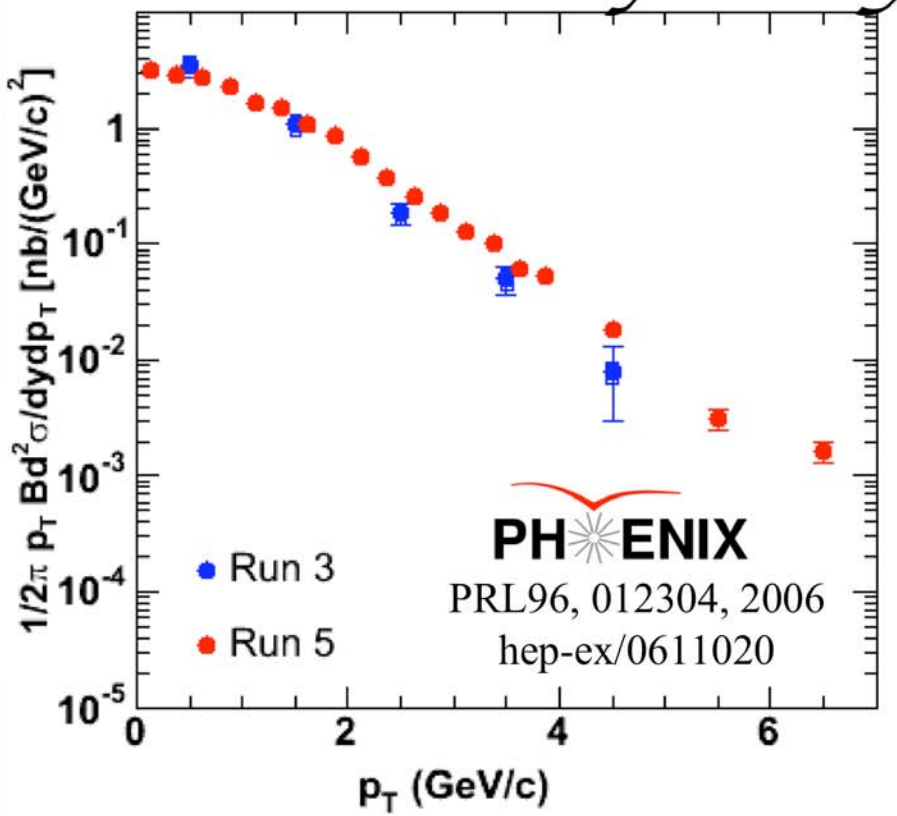
$$\langle p_T^2 \rangle = 3.59 \pm 0.06 \pm 0.16$$

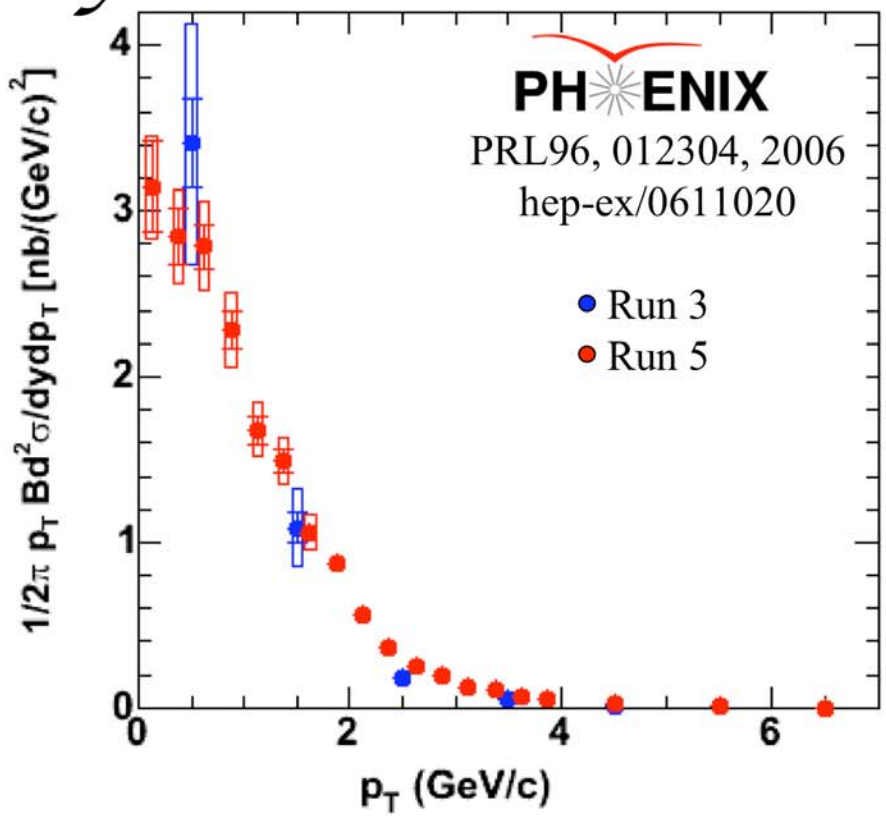
$$\chi^2 / ndf = 28/17$$

If the exponent is allowed to float a slightly better fit is obtained, $\chi^2/ndf = 20/16$

But the $\langle p_T^2 \rangle$ is not significantly modified: $\langle p_T^2 \rangle = 3.68$

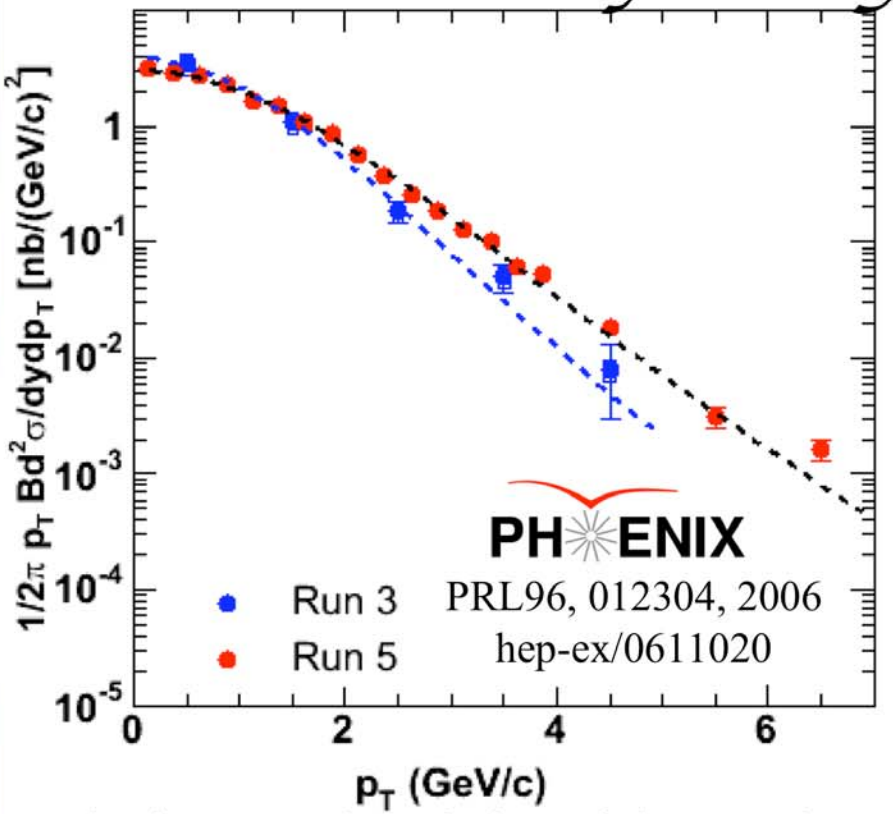
Forward Rapidity $<p_T^2>$: Run 3 vs 5

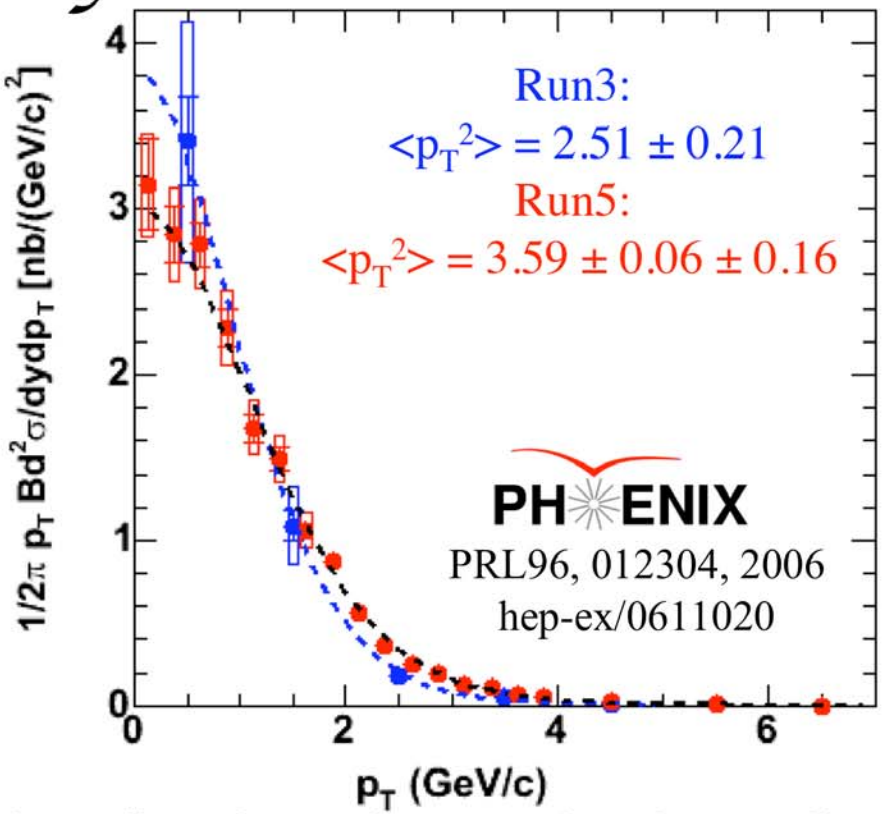




- x10 higher statistics available from run 5 data set relative to run 3
- Allows shape of p_T spectrum to be mapped with high precision
- Within errors the p_T spectra for both runs agree

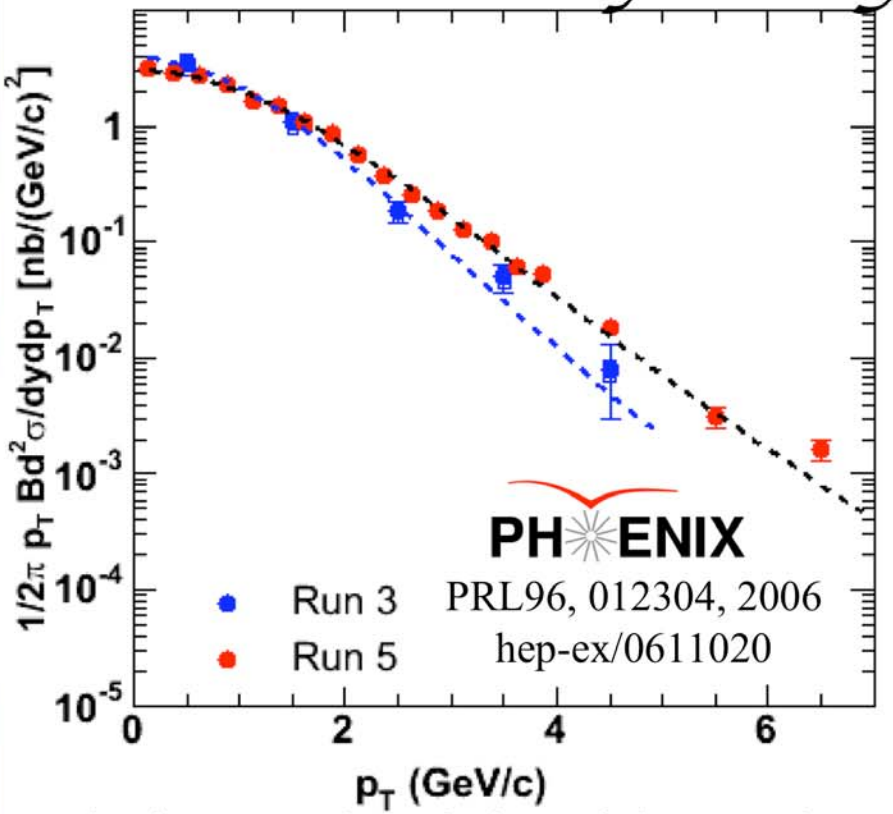
Forward Rapidity $<p_T^2>$: Run 3 vs 5

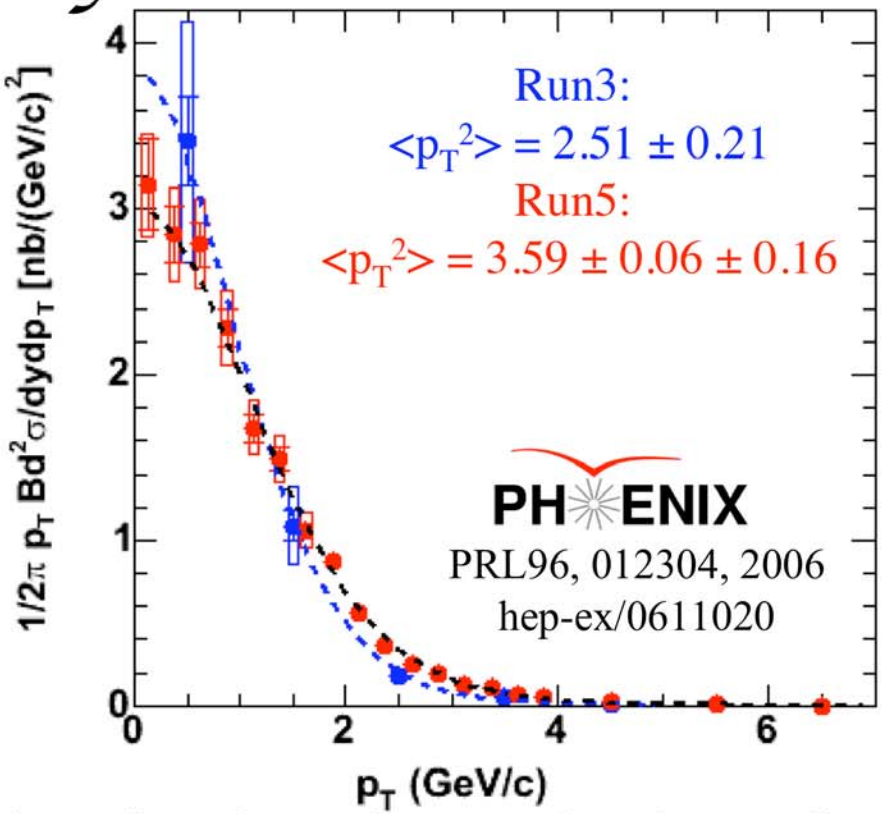




- The increased statistics of the run 5 p+p data allow for an improved understanding of the shape of the p_T spectrum & allow the $<p_T^2>$ to be completely defined ⇒ extrapolation in no longer necessary

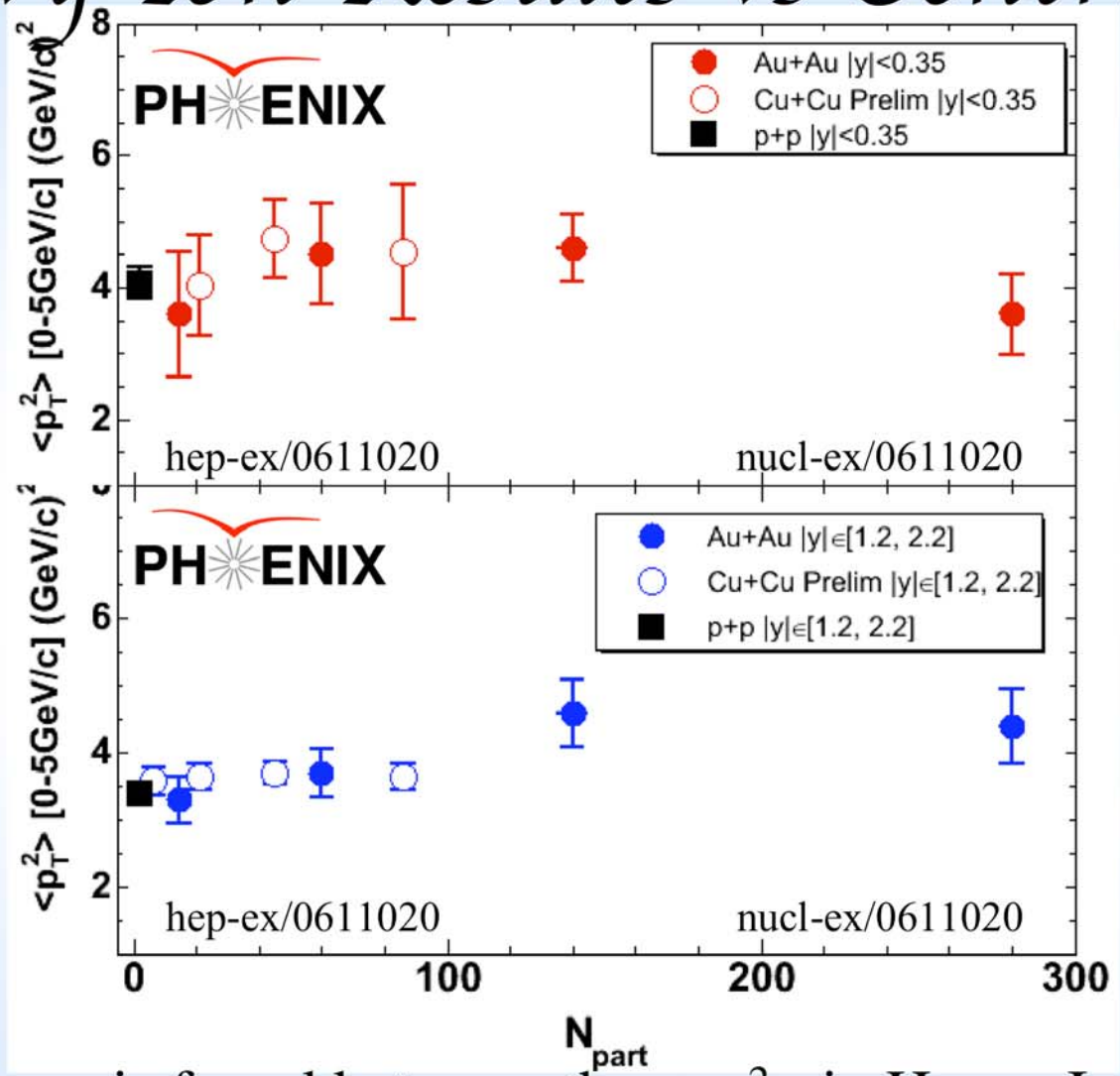
Forward Rapidity $<p_T^2>$: Run 3 vs 5





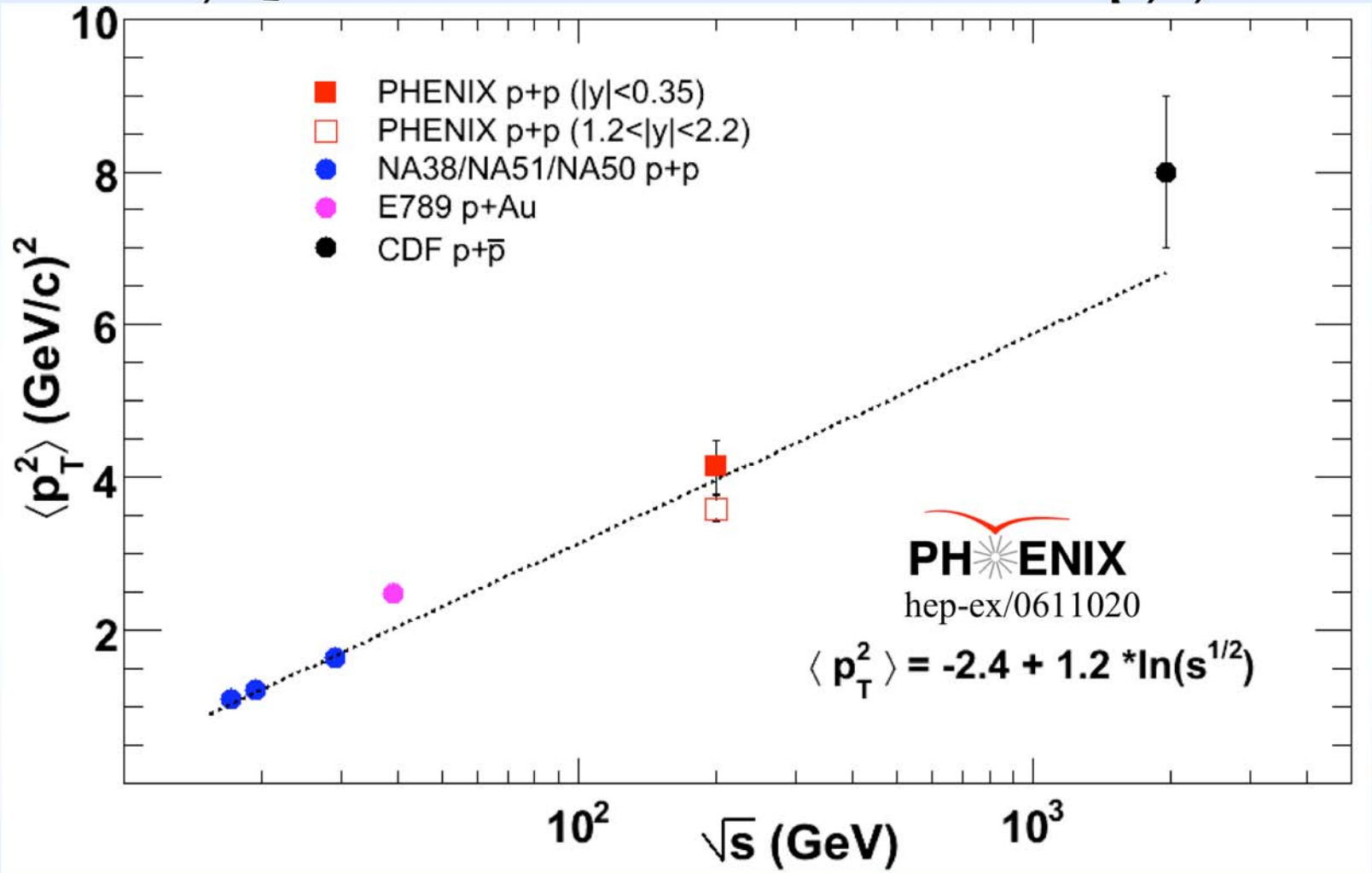
- The increased statistics of the run 5 p+p data allow for an improved understanding of the shape of the p_T spectrum & allow the $<p_T^2>$ to be completely defined ⇒ extrapolation in no longer necessary
- The run 3 p+p results have been revisited and it was found that the systematic error was underestimated.
- A reanalysis of the d+Au is underway to determine how this effects our interpretation of that data set.

Heavy Ion Results vs Centrality



Good consistency is found between the $\langle p_T^2 \rangle$ in Heavy Ion collisions as a function of centrality and the p+p results for the $\langle p_T^2 \rangle$ integrated over $p_T < 5$GeV/c where Heavy Ion data exists.

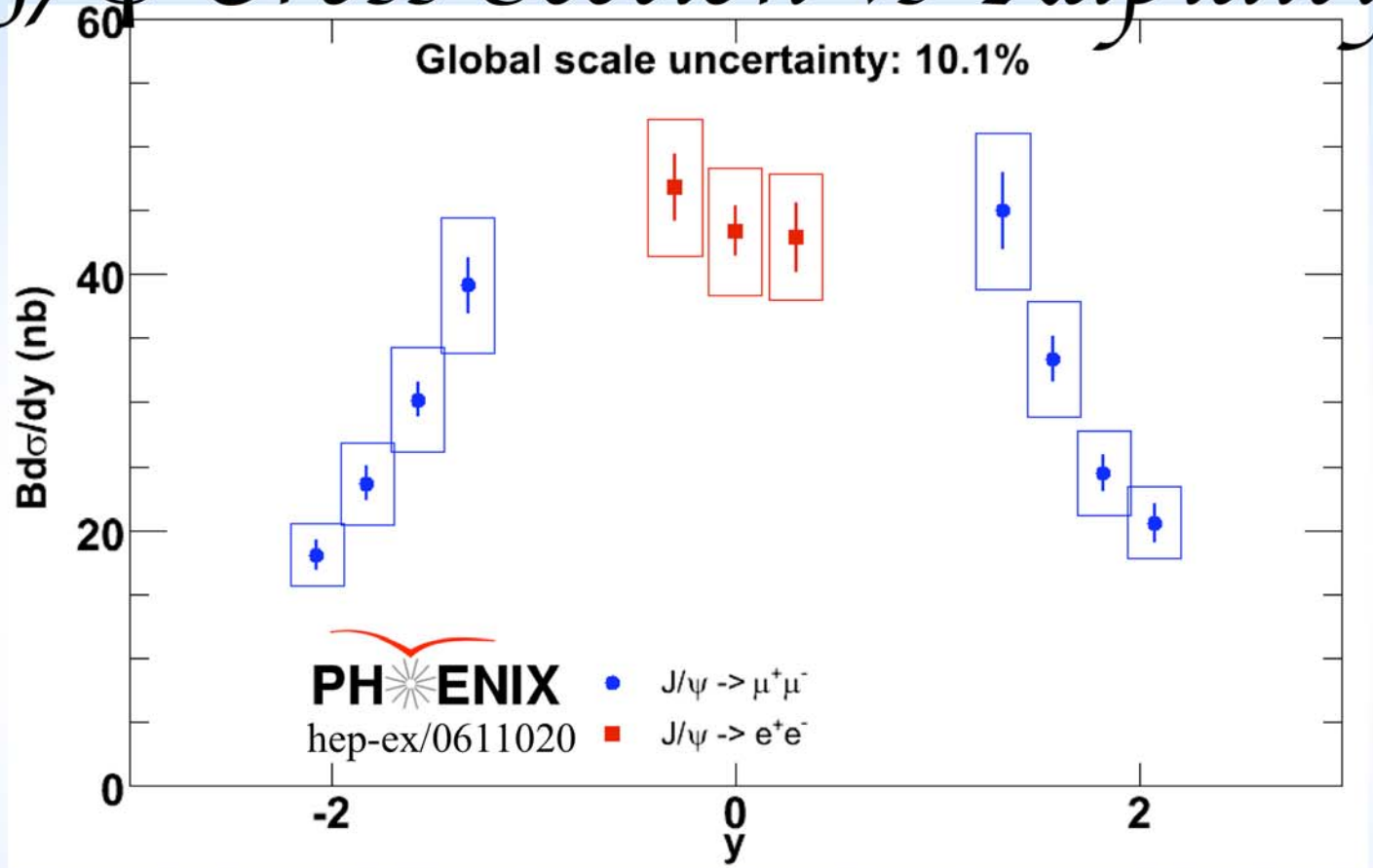
$<p_T^2>$ vs Collision Energy



PHENIX $<p_T^2>$ measurements compared to measurements at other energies.

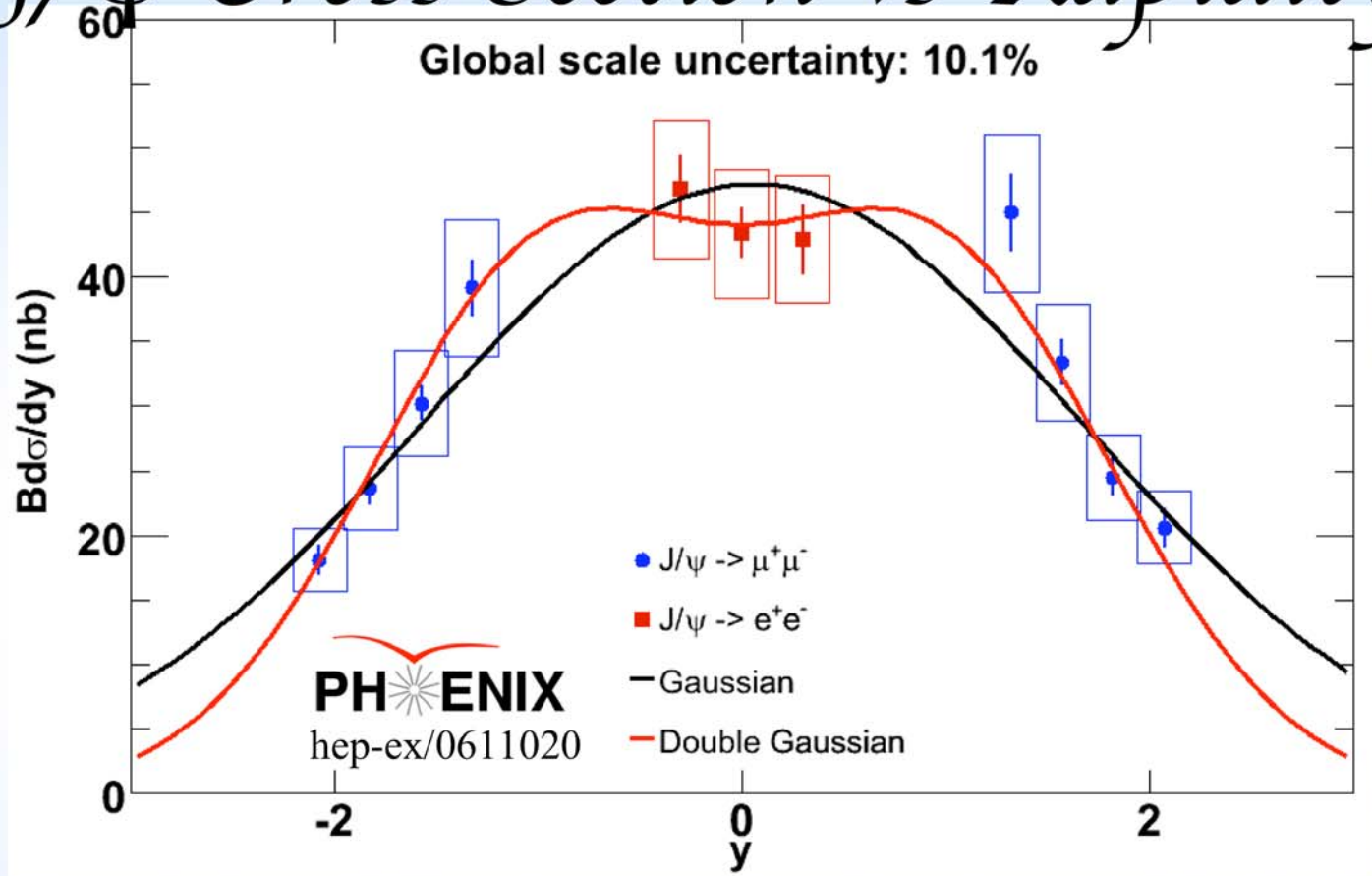
As a function of collision energy the data show a linear dependence on the $\ln(\sqrt{s})$.

J/ψ Cross Section vs Rapidity



- The statistics available are large enough to allow eleven rapidity bins!!
- Data now limited by systematic error not statistics

J/ψ Cross Section vs Rapidity

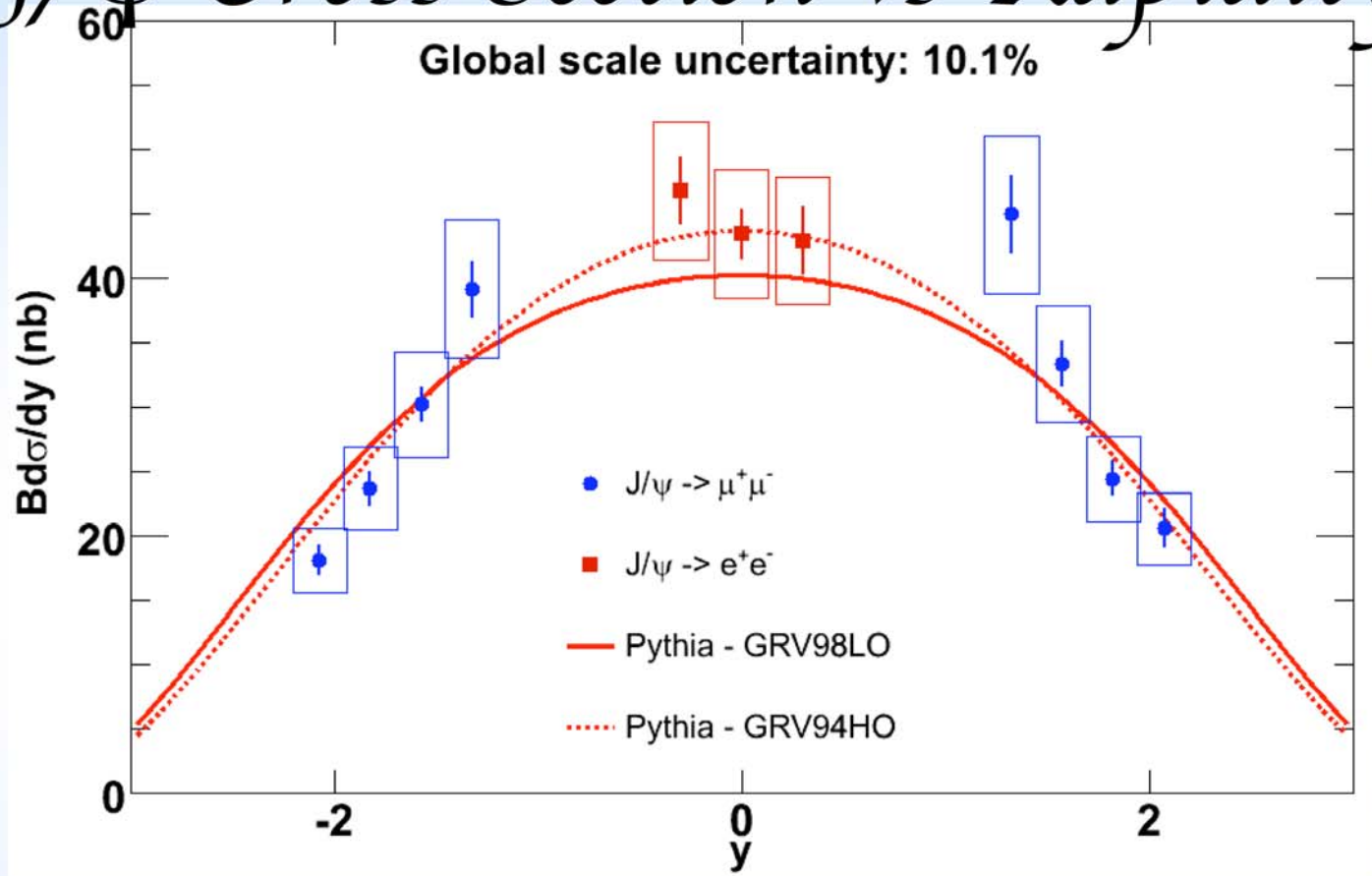


- The statistics available are large enough to allow eleven rapidity bins!!
- Data now limited by systematic error not statistics
- The data slightly favor a flat distribution over the rapidity range |y|<1.5

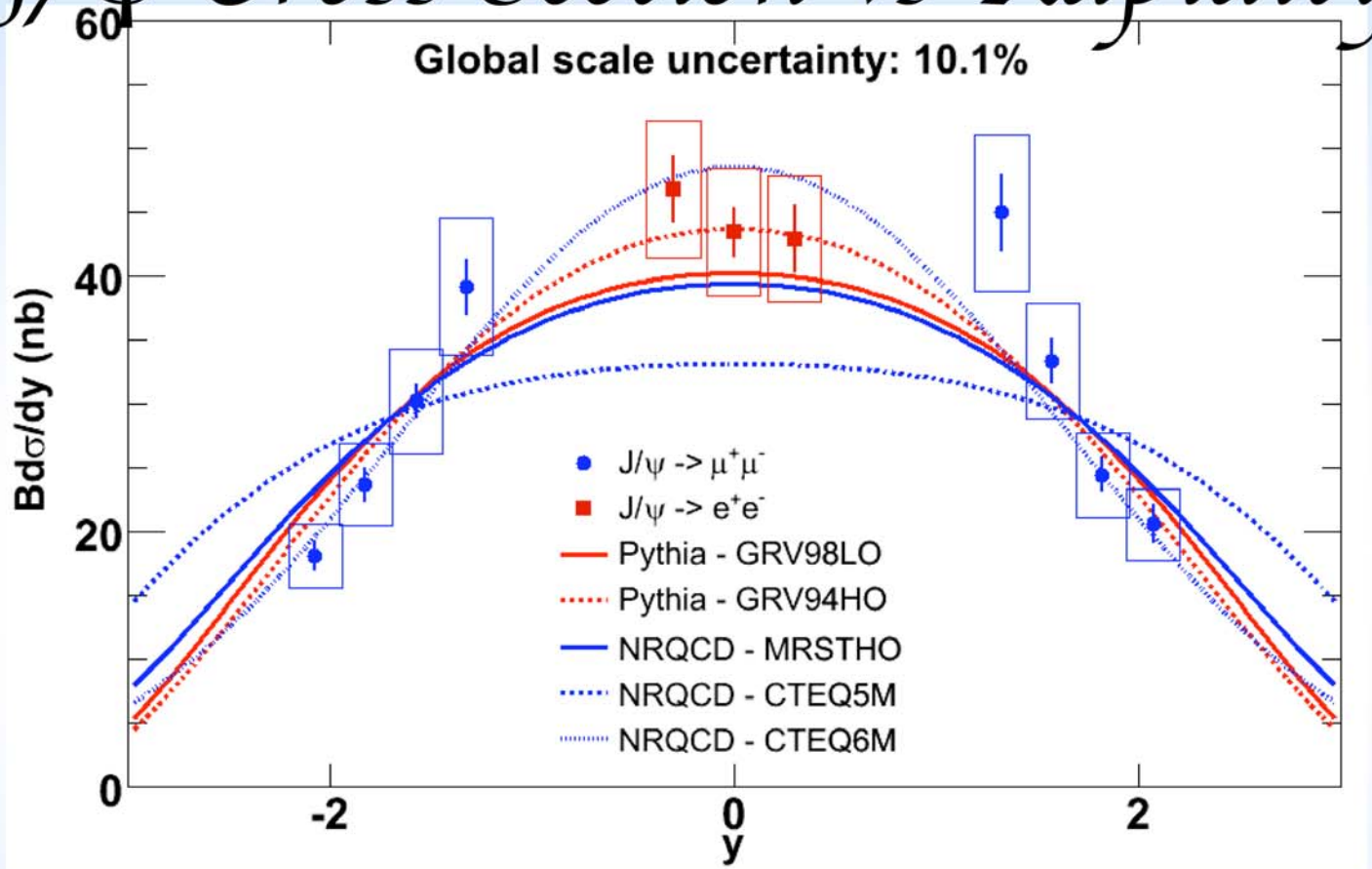
But!

- Remember the systematic errors on the mid and forward rapidity points are independent ∴ a narrower distribution is not excluded.

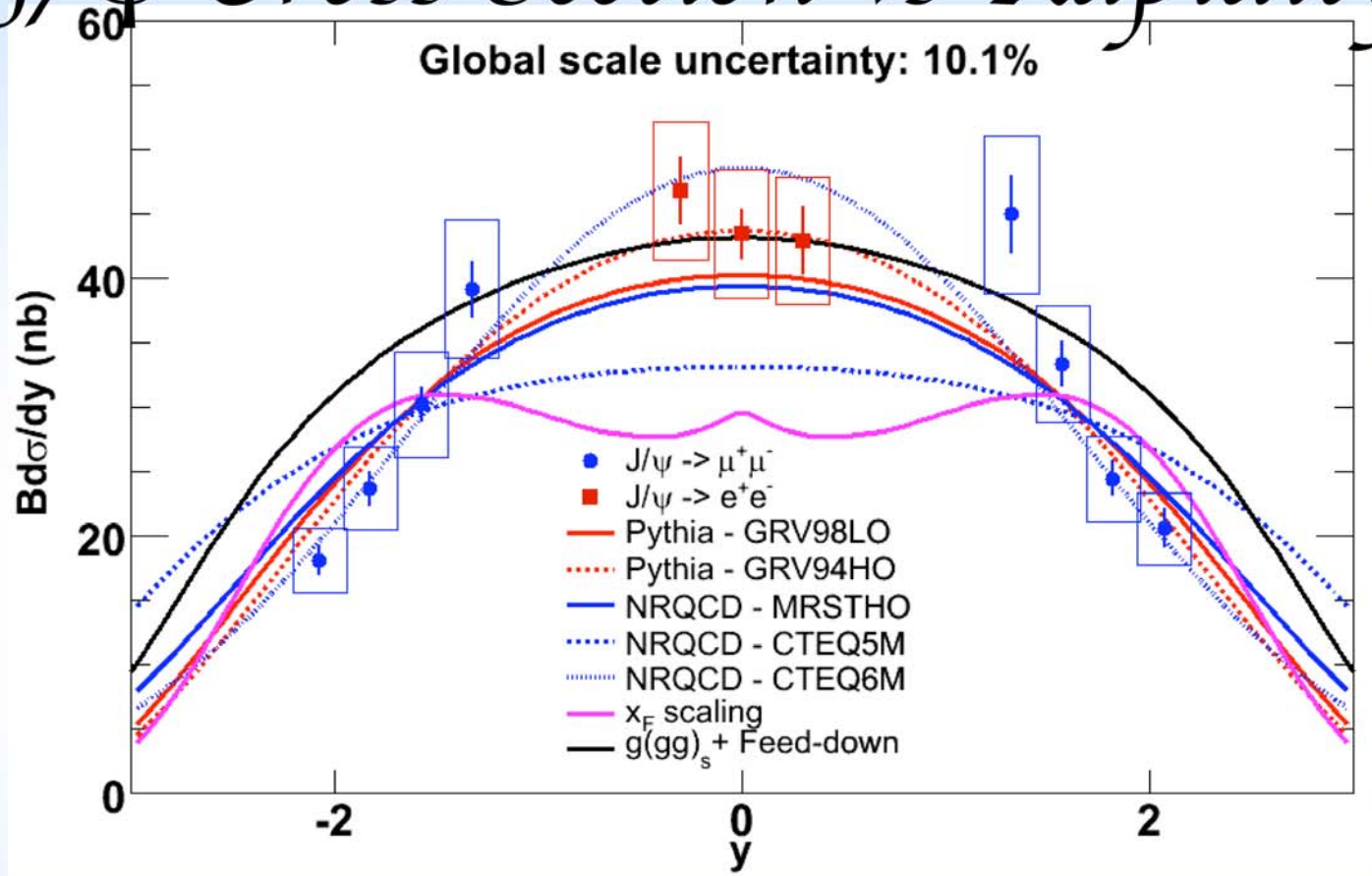
J/ψ Cross Section vs Rapidity



J/ψ Cross Section vs Rapidity



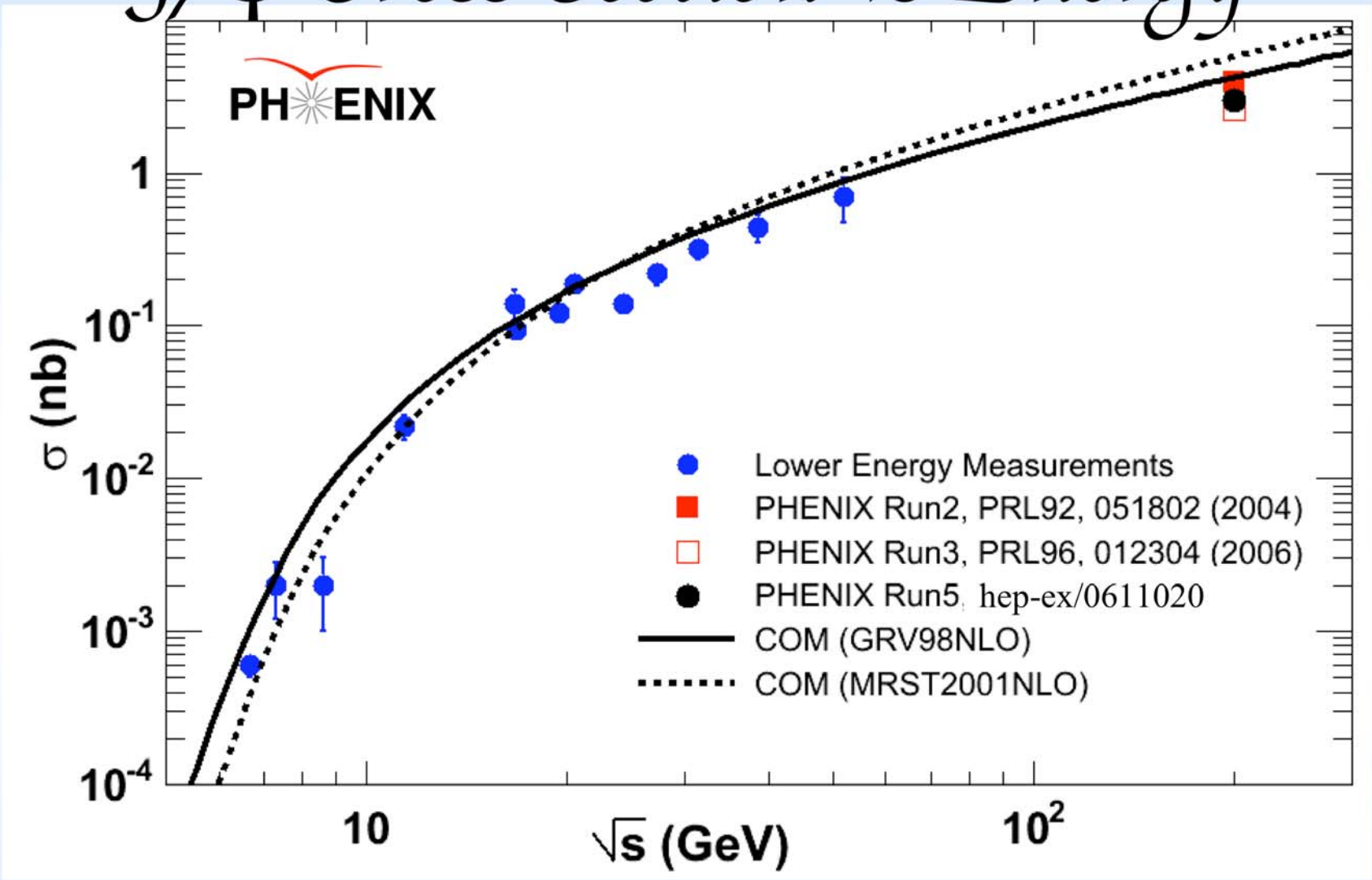
J/ψ Cross Section vs Rapidity



- Comparison with theoretical predictions allows differentiation among the available J/ψ production mechanisms
- Many calculations are inconsistent with the steepness of the slope at forward rapidity and the slight flattening observed at mid-rapidity

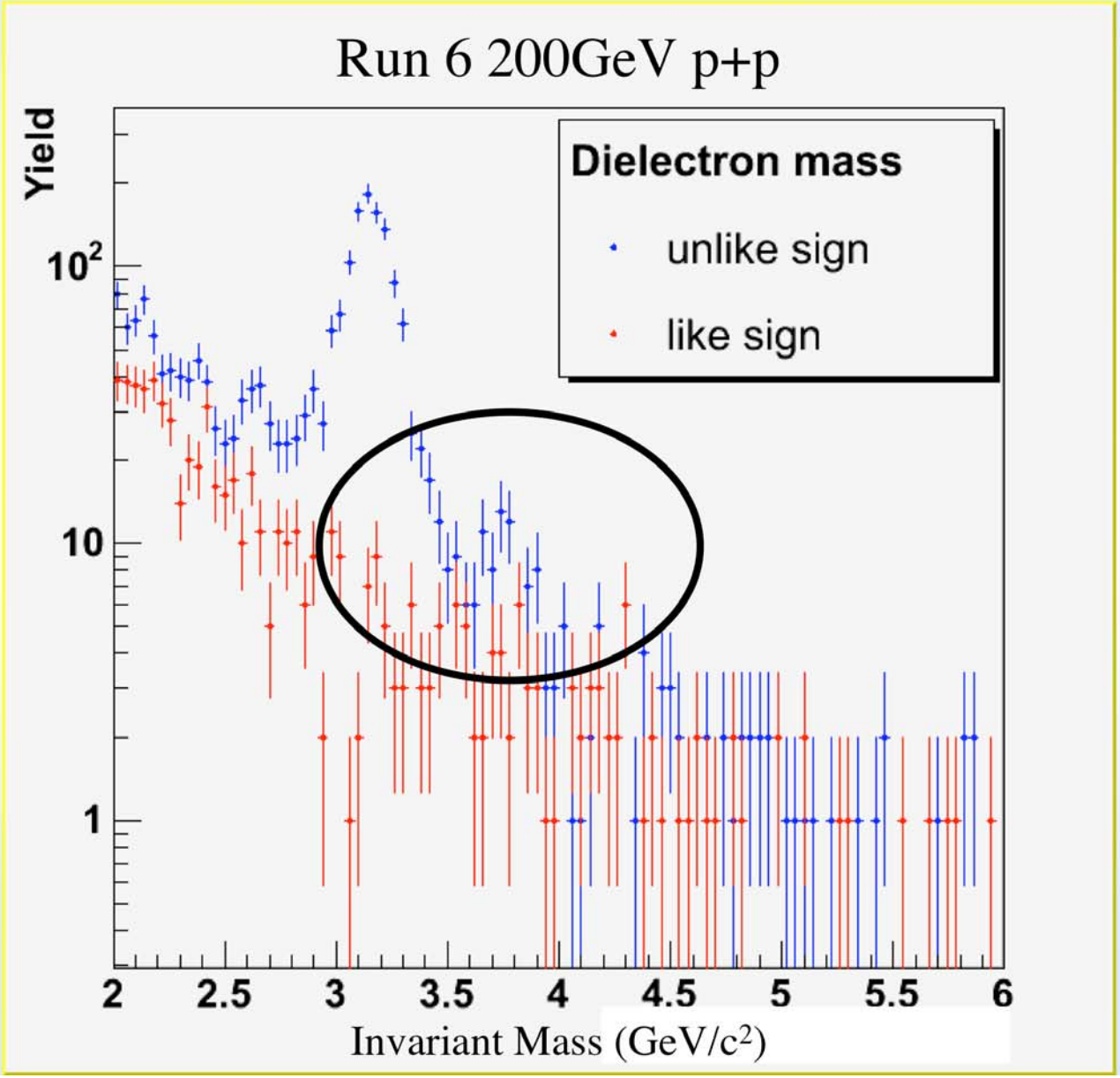
$$\mathbf{B_{ll} * \sigma_{pp}(J/\psi) = 178 \pm 3 \pm 53 \pm 18\ nb}$$

J/ψ Cross Section vs Energy

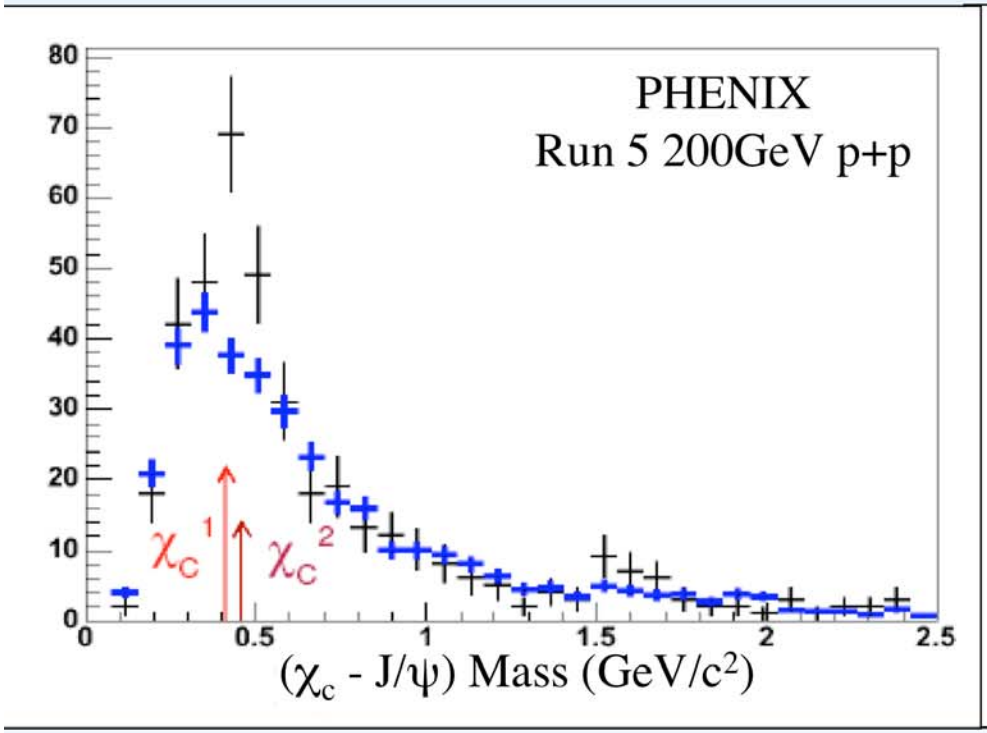


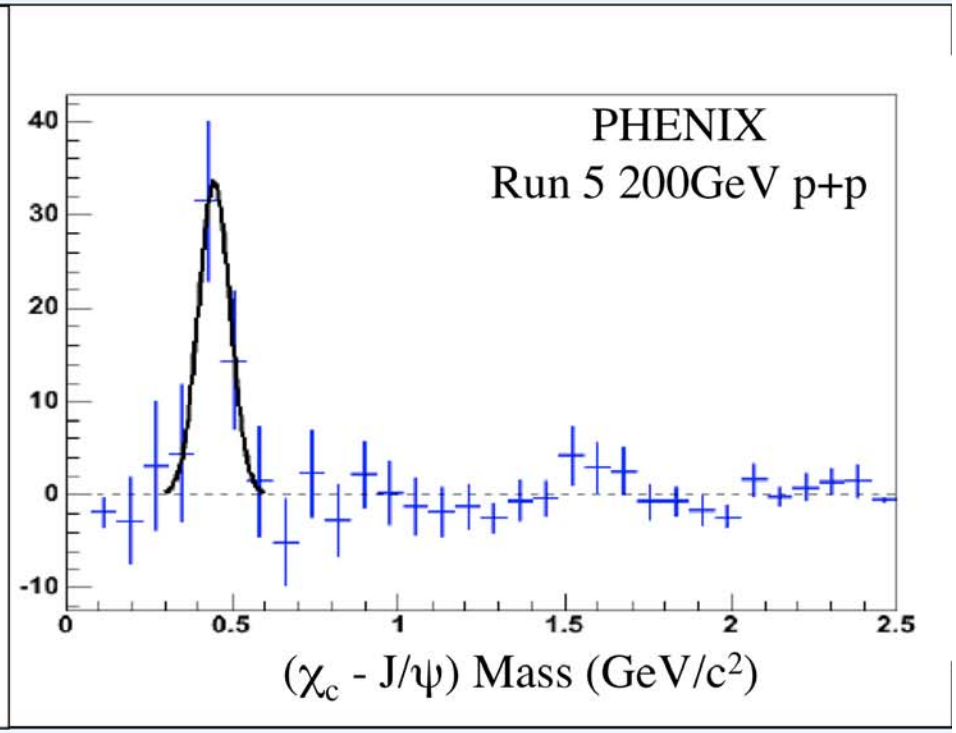
Consistent with trend of world's data and with the COM but unable to differentiate between PDF's

Future Measurements: ψ'



Future Measurements: χ_c





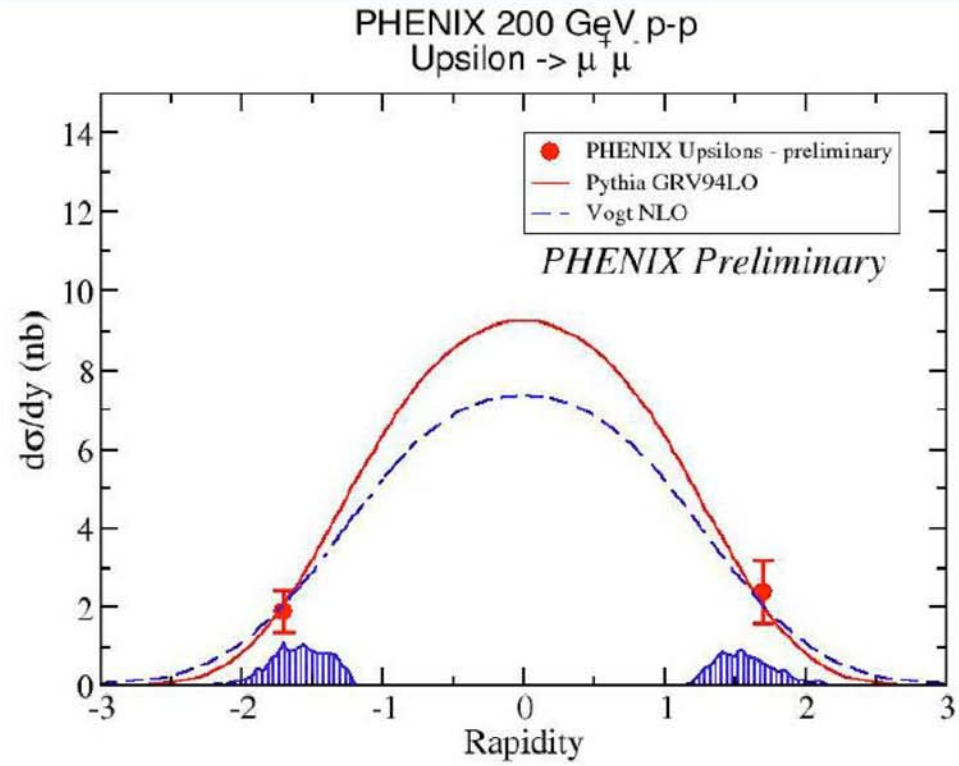
Run 6 data set has a factor of x3 more luminosity

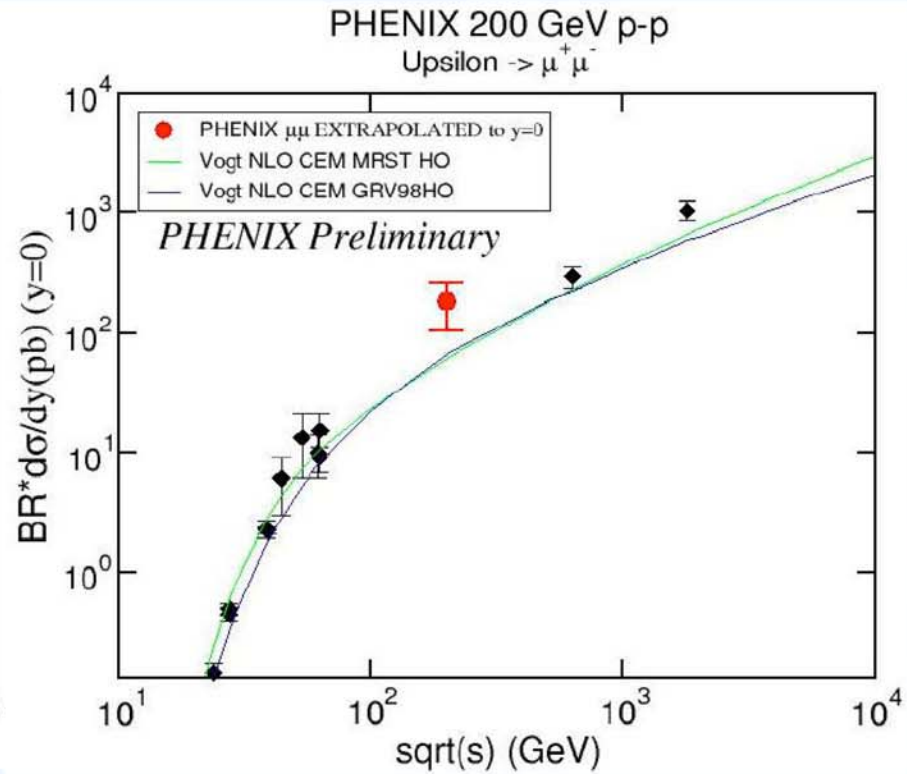
Unveiling the Iceberg

- We have entered an era of precision J/ψ measurements at PHENIX
- Data provide a challenge for production models:
  - p_T spectrum mapped from 0-9 GeV/c
  - Ratio of forward and mid-rapidity p_T distributions show a softening at forward rapidity
  - High statistics data allows an improved assessment of $\langle p_T^2 \rangle$
  - Rapidity distribution slightly flatter than most models and falls off more rapidly at forward rapidity
  - Reanalysis of run3 d+Au will be forthcoming
- Improved measurement of ϒ, ψ'and χ_c to come in p+p collisions
- Future PHENIX data will shed light on these processes and open additional exciting avenues of quarkonia measurements

The End

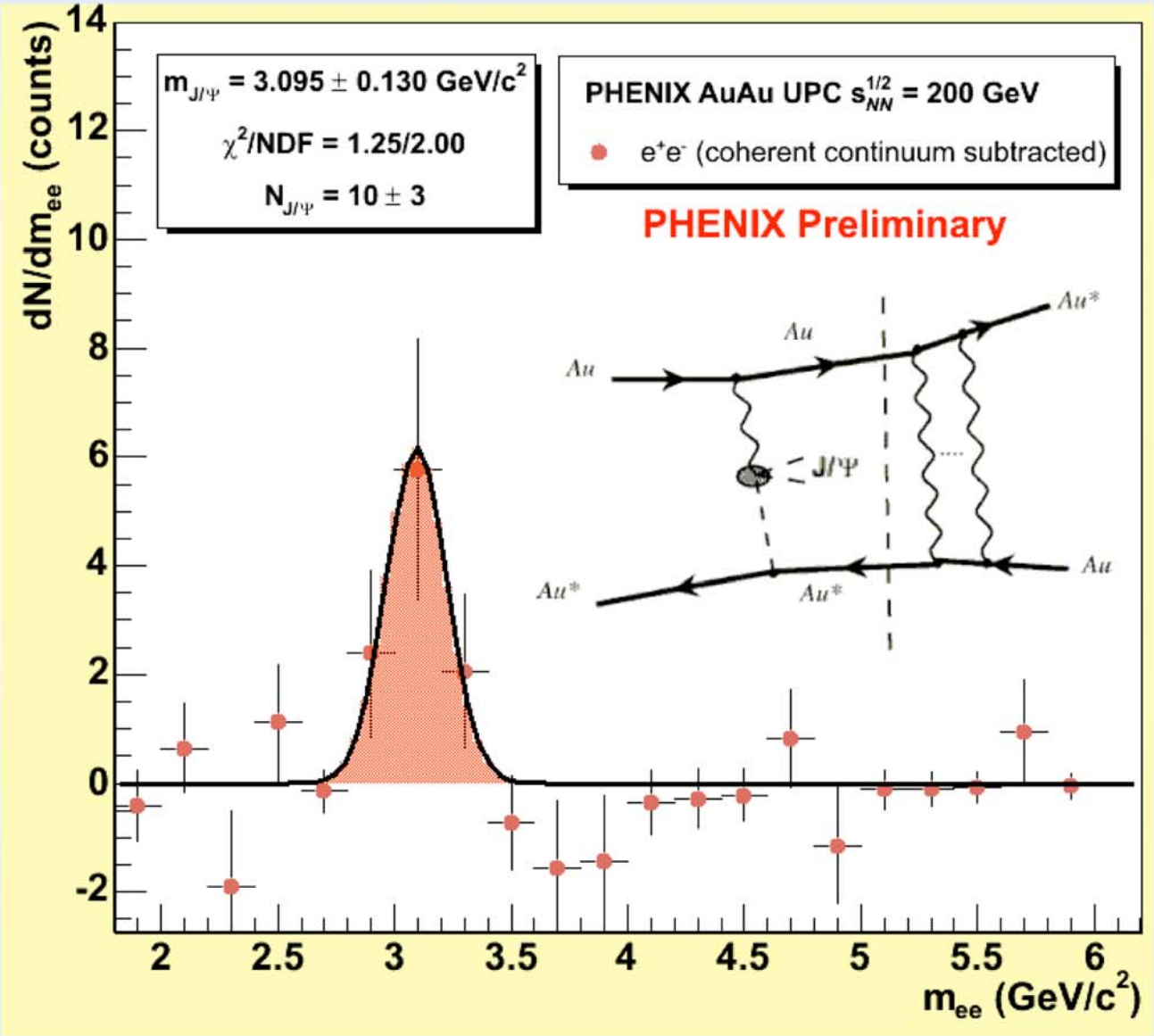
PHENIX Upsilon Measurement





- Signal extraction assumes excess in Υ mass region is strictly from Υ's
- Rapidity dependence requires mid-rapidity point to constrain fit
- Preliminary cross section appears consistent with trend in world's data

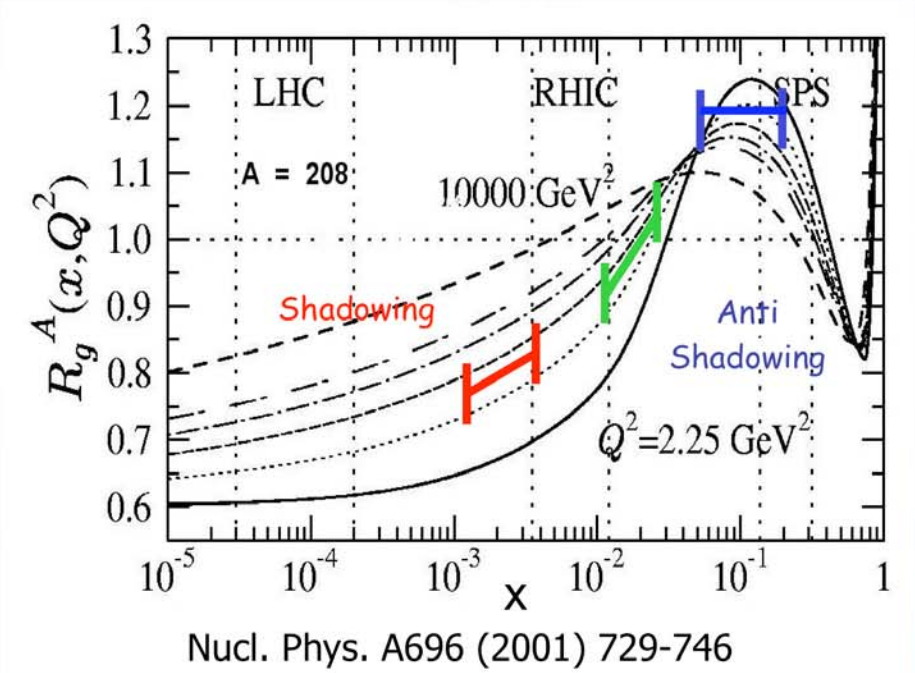
Ultra-Peripheral Collisions



Cold Nuclear Matter - d+Au

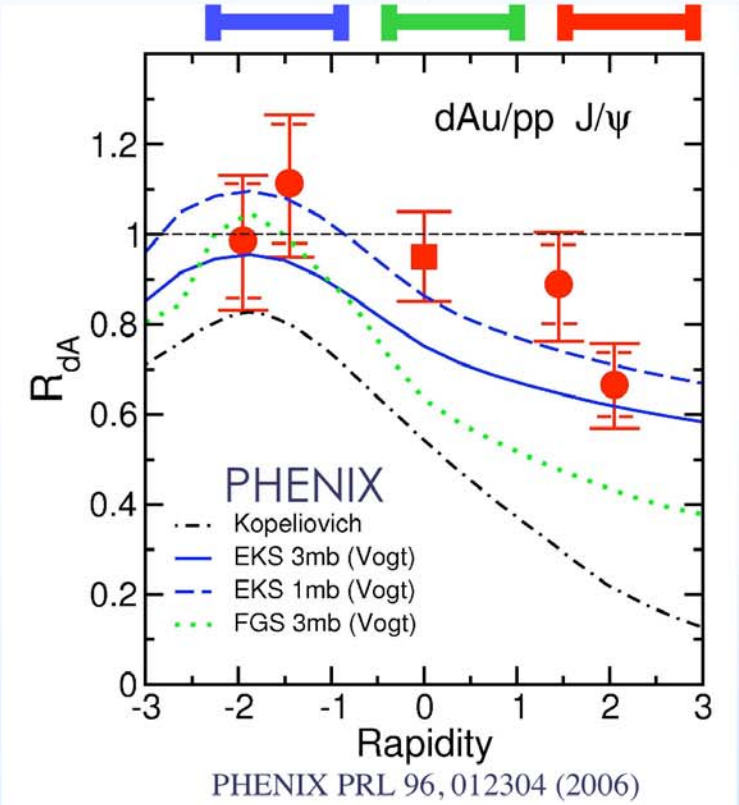
- Absorption of J/ψ by nuclear matter
- Modification of PDF due to gluon shadowing

Models



Nucl. Phys. A696 (2001) 729-746

Data



PHENIX PRL 96, 012304 (2006)

Vogt, PRC71, 054902 (2005), Kopeliovich, NP A696, 669 (2001)

PHENIX data compatible with:
- weak gluon shadowing
- weak absorption : 1 mb (max 3mb)