# $J/\psi$ Production in $\sqrt{s} = 200$ GeV p+p Collisions with the PHENIX Detector at RHIC

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15th International Spin Physics Symposium

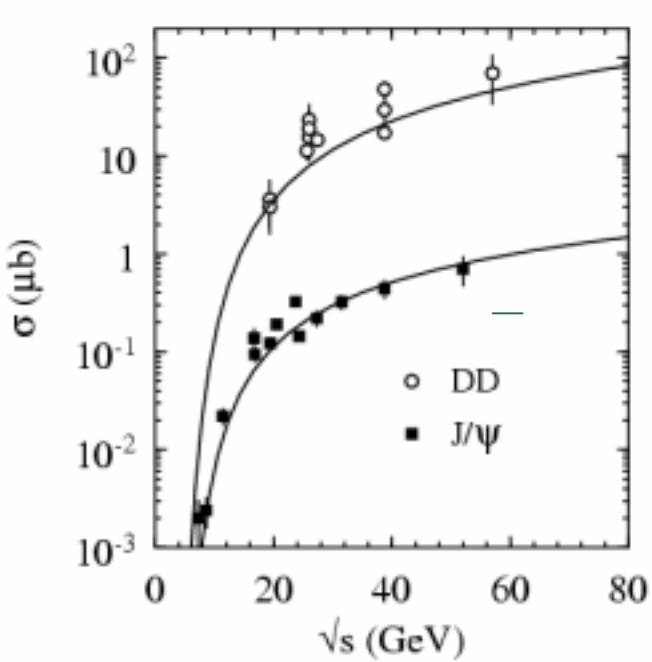
(SPIN 2002)

Brookhaven National Laboratory, Upton, NY

September 9, 2002

# $J/\psi$ production in p+p collisions at $\sqrt{s}$ = 200 GeV

- The highest energy measurement of the production cross section of $J/\psi$
- Discriminate theoretical models for the production mechanism $\rightarrow$ critical to extract $\Delta G(x)$ from $A_{LL}$ of $\vec{p}+\vec{p} \rightarrow J/\psi + X$
- Reference point for Au+Au data to discuss suppression or enhancement of $J/\psi$ production in heavy ion collisions



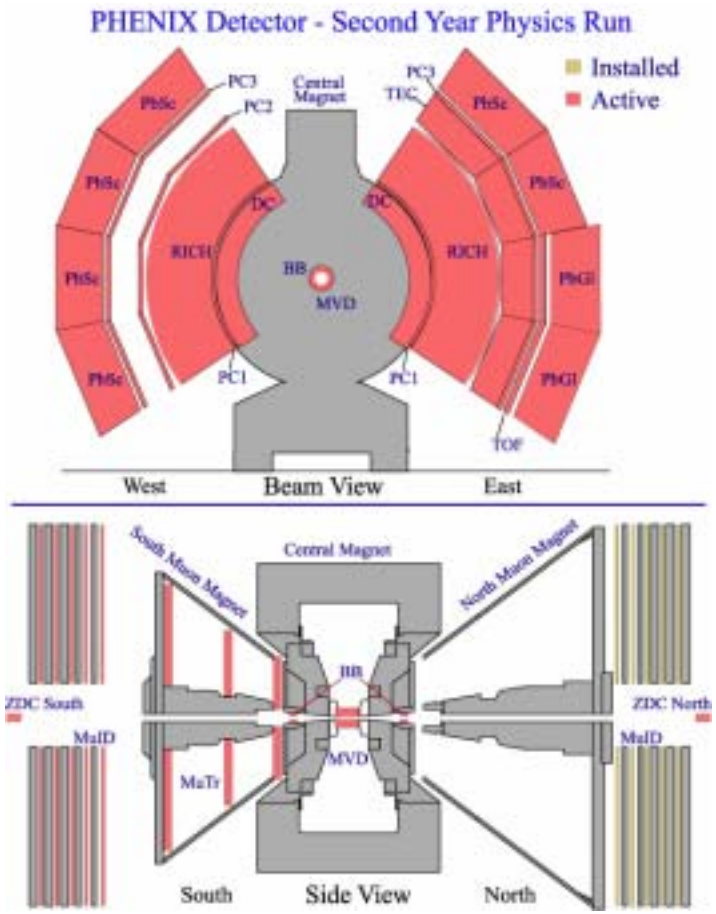

√s dependence of the J/ψ production cross section with previous lower-energy experiments

# Theoretical models for the $J/\psi$ production

- Color-Evaporation Model (CEM)
  - "Ignore" color and other quantum numbers of an intermediate $c\bar{c}$ pair
  - Certain fraction (free parameter) of all produced $c\bar{c}$ pairs form each charmonium
- Color-Single Model (CSM)
  - A $c\bar{c}$ pair needs to be the color-single state and have the same quantum numbers as the charmonium to be formed
  - No free parameter
  - Cross section disagrees with Tevatron data especially at high $p_T$.
- Color-Octet Model (COM)
  - Different state of a $c\bar{c}$ pair (including color-octet states) can form a charmonium with (a) soft gluon emission(s).
  - Color-octet matrix elements are extracted from data $\rightarrow$ still in controversial
  - Polarization of the high-$p_T$ $J/\psi$ disagrees with Tevatron data

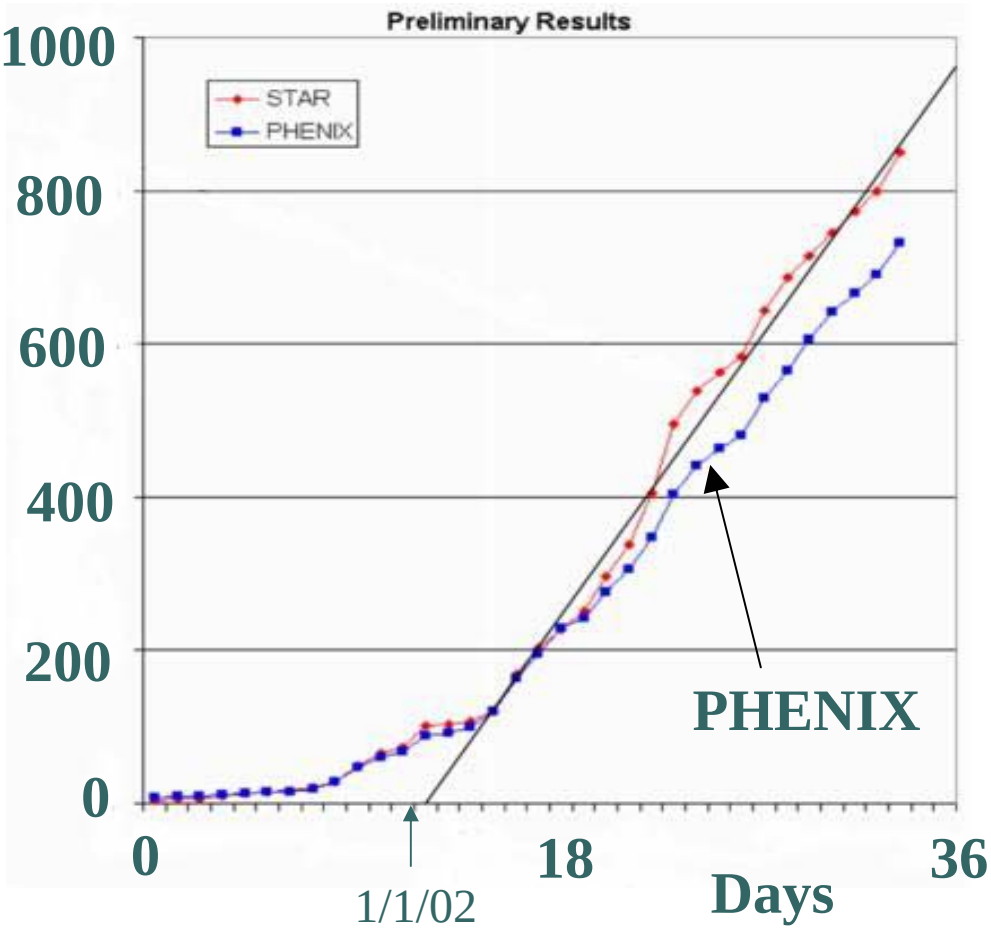
# The PHENIX Detector in Run-2

- Central Arms to detect hadrons, electrons and photons
  - $|\eta| < 0.35$, $\Delta\varphi = \pi$
  - $p_T > 0.2$ GeV/$c$
- South Muon Arm to detect muons in the forward region
  - $1.2 < \eta < 2.2$, $\Delta\varphi = 2\pi$
  - $p_{tot} > 2$ GeV/$c$
- Beam-Beam Counter (BBC) to trigger p+p interactions
  - $3.0 < |\eta| < 3.9$
  - Trigger efficiency ~ 50% for p+p inelastic events




Independent measurements of J/ψ using both $e^+e^-$ channel and $\mu^+\mu^-$ channel

# RHIC Integrated p+p luminosity



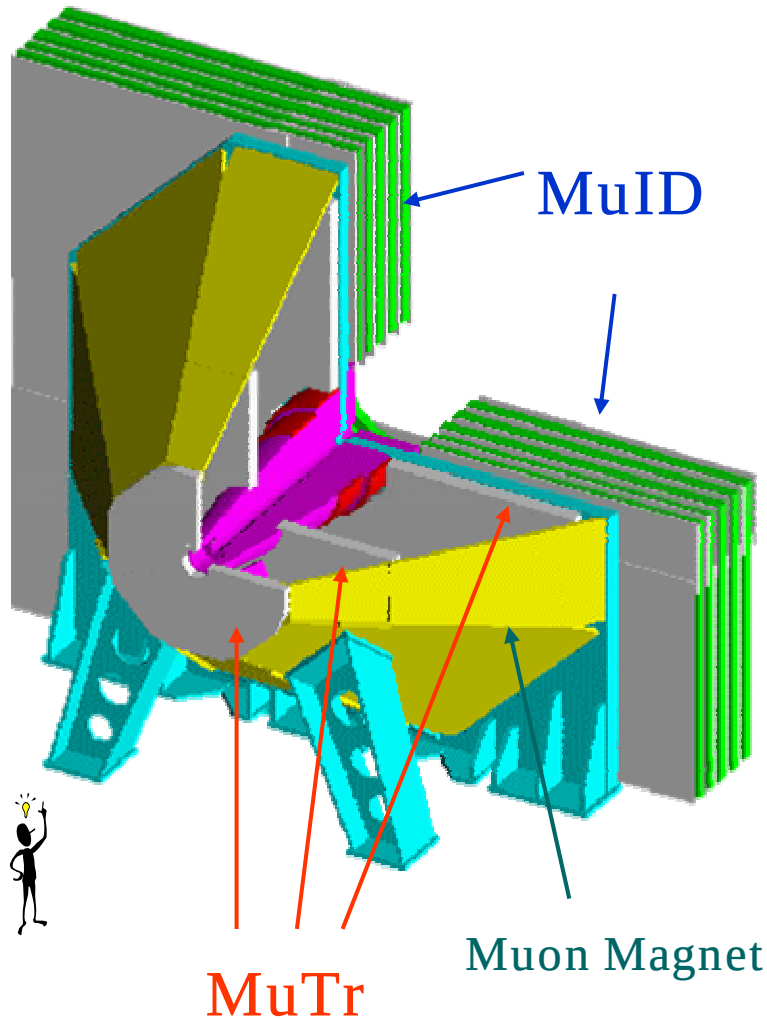

RHIC delivered 700nb$^{-1}$ to PHENIX

After an online vertex cut, PHENIX recorded 150 nb$^{-1}$

Present preliminary analysis used data from:
81 nb$^{-1}$ (1.7 x 10$^{9}$) $\mu^+\mu^-$
48 nb$^{-1}$ (1.0 x 10$^{9}$) $e^+e^-$

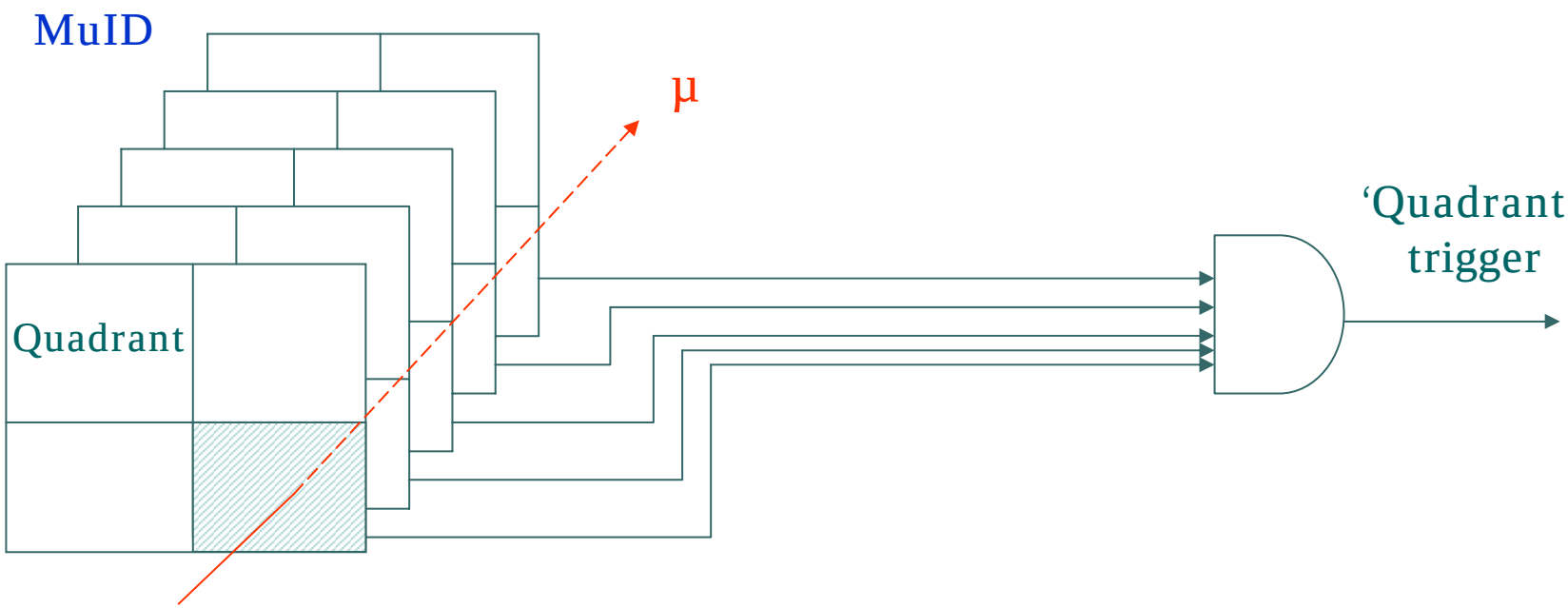
# The PHENIX Muon Arm

- Detect muons with $p_{tot}$ >2 GeV/$c$, 1.2<$\eta$ <2.2 (South Arm)
- Pre-hadron-rejection with Central Magnet steel ($\lambda_{int}$ ~5)
- Muon Tracking Chamber (MuTr)
  - Measure momentum of muons with cathode-readout strip chambers at 3 stations inside Muon Magnet
- Muon Identifier (MuID)
  - $\pi/\mu$ separation with 5-layer sandwich of chambers (Iarocci tubes) and steel
  - Trigger muons
- Successfully operated first time during Run-2

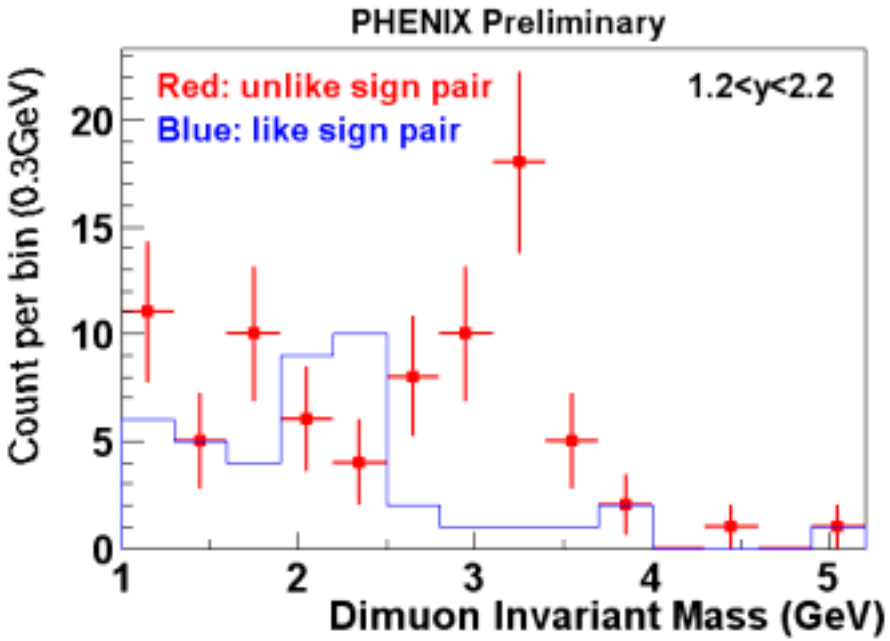


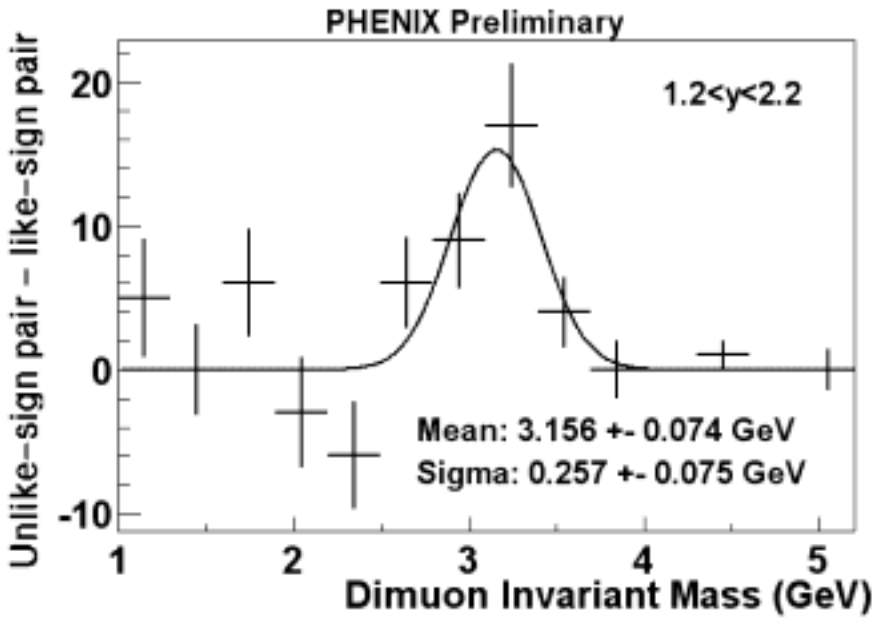
# Muon LVL-1 Trigger

- Coincidence of fired MuID planes of each "quadrant"
- One quadrant for "single-muon trigger" and more than one quadrant for "dimuon trigger" → used for this analysis
- Inefficiencies from hardware dead time is 1~2%



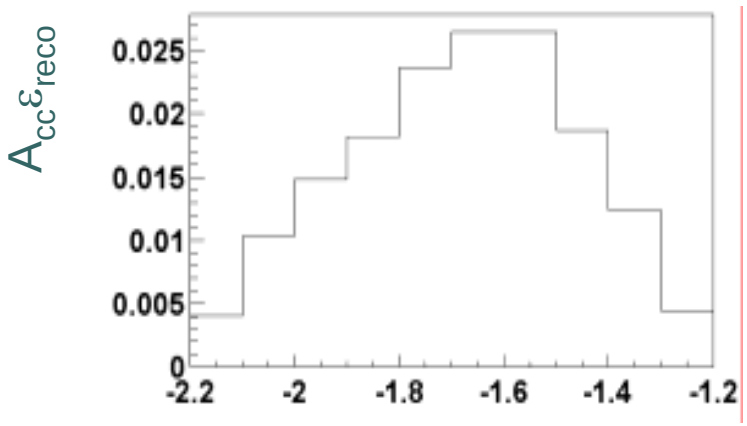
# $J/\psi \rightarrow \mu^+\mu$ signal

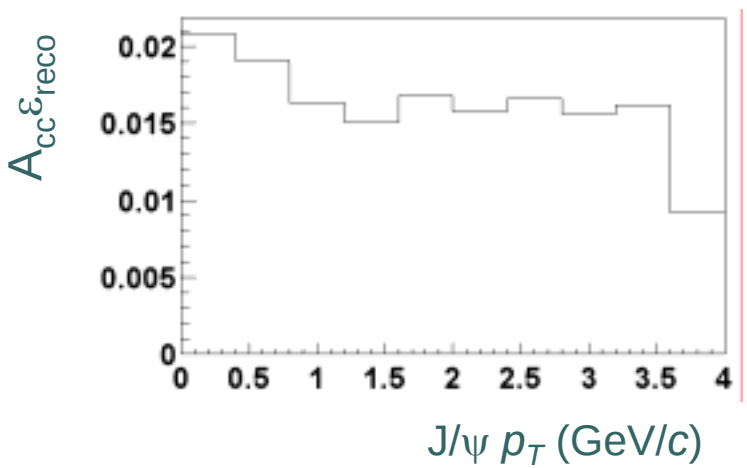



- Significant enhancement of unlike-sign pair in the J/ψ mass region
  - Peak ($3156 \pm 74$ MeV/$c^2$) is consistent with J/ψ mass
  - Mass width ($257 \pm 75$ MeV/$c^2$) is consistent with expectation → further improvement is expected
- $N_{J/\psi} = 36$ in 2.5<mass<3.7GeV/c assuming same count of unlike and like-sign pairs from background (confirmed with simulation)
- Systematic error on the count ~10 % by changing mass cut

# $J/\psi \rightarrow \mu^+\mu^-$ Acceptance and Reconstruction efficiency




$<A_{cc}\varepsilon_{reco}>_{1.2<y<2.2}$
$= 0.0163 \pm 0.031$

- $p_T$ dependence is small
- Including MuID trigger efficiency (~0.62)
- Major uncertainties
  - MuID efficiency → 11 %
  - MuTr efficiency → 10 %
  - J/ψ polarization(λ) → 10% (|λ|<0.3 is assumed)

# BBC efficiency and luminosity

$$\varepsilon_{BBC}^{J/\psi} L = \frac{\varepsilon_{BBC}^{J/\psi}}{\varepsilon_{BBC}^{inela}} \frac{N_{int}}{\sigma_{inela}} = \frac{0.74}{0.51} \frac{1.73\times10^{9}}{42mb} = 60nb^{-1}$$

- $\sigma_{inela}$: p+p inelastic cross section (PYTHIA, $\sqrt{s}$ fit)
- $\varepsilon_{BBC}^{J/\psi}$: BBC efficiency for p+p $\rightarrow$ J/ψ+X$\rightarrow$ μ+μ- events
  - $p_T$ (J/ψ) dependence is small
  - consistent with p+p $\rightarrow$ J/ψ+X$\rightarrow$ e+e- (0.73) and p+p $\rightarrow \pi^0$ X (0.75)

  } simulation
- $\varepsilon_{BBC}^{inela}$: BBC efficiency for p+p inelastic events
- $N_{int}$: Number of interaction triggers with vertex cut (|z|<38cm) — Real data

Analysis of $\varepsilon_{BBC}^{inela}\sigma_{inela}$ is still in progress

↓

Assign conservative 20% error on it

# Br $d\sigma/dy|_{y=1.7}$ result and its uncertainties

$$B_r \left.\frac{d\sigma_{J/\psi}}{dy}\right|_{y=1.7} = \frac{N_{J/\psi}}{A_{cc}\varepsilon_{reco}\varepsilon_{BBC}^{J/\psi} L\Delta y}$$

- $N_{J/\psi} = 36 \pm 7\ (\text{stat.}) \pm 4\ (\text{syst.})$
- $A_{cc}\varepsilon_{reco} = 0.0163 \pm 0.031$
- $\varepsilon_{BBC}^{J/\psi} L = 0.60 \pm 0.12\ \text{nb}^{-1}$
- $\Delta y$: rapidity coverage = 1.0

Br $(J/\psi \rightarrow \mu^+\mu^-)\ d\sigma_{J/\psi}/dy|_{y=1.7.} = 37 \pm 7\ (\text{stat.}) \pm 11\ (\text{syst.})$ nb

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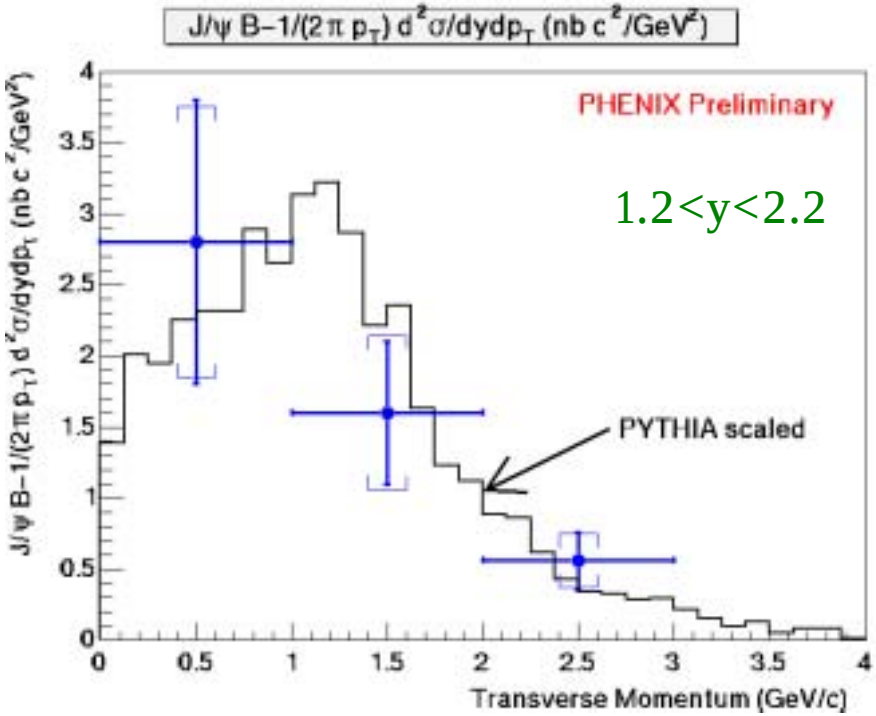
# $J/\psi$ $p_T$ distribution and $\langle p_T \rangle$




- $p_T$ shape is consistent with the PYTHIA (color-singlet model) prediction

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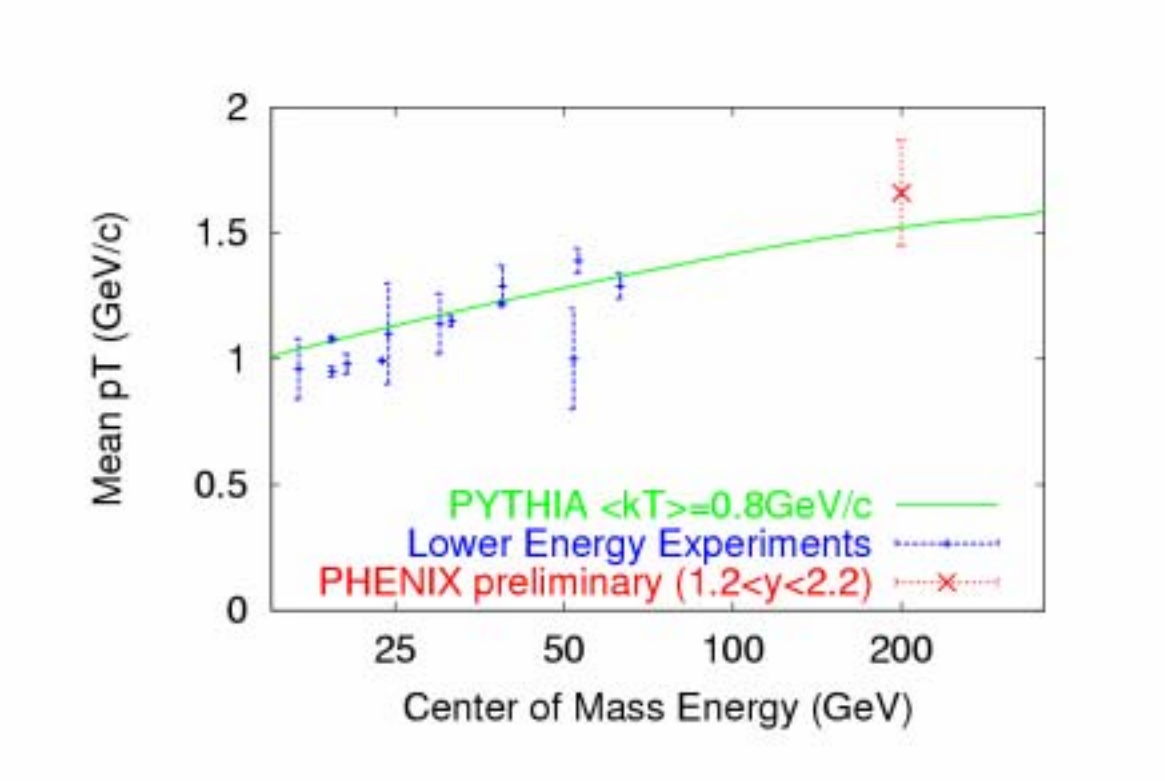
$\langle p_T \rangle_{y=1.7} = 1.66 \pm 0.18$ (stat.) $\pm 0.09$ (syst.) GeV/$c$ ($p_T$<5 GeV/$c$)

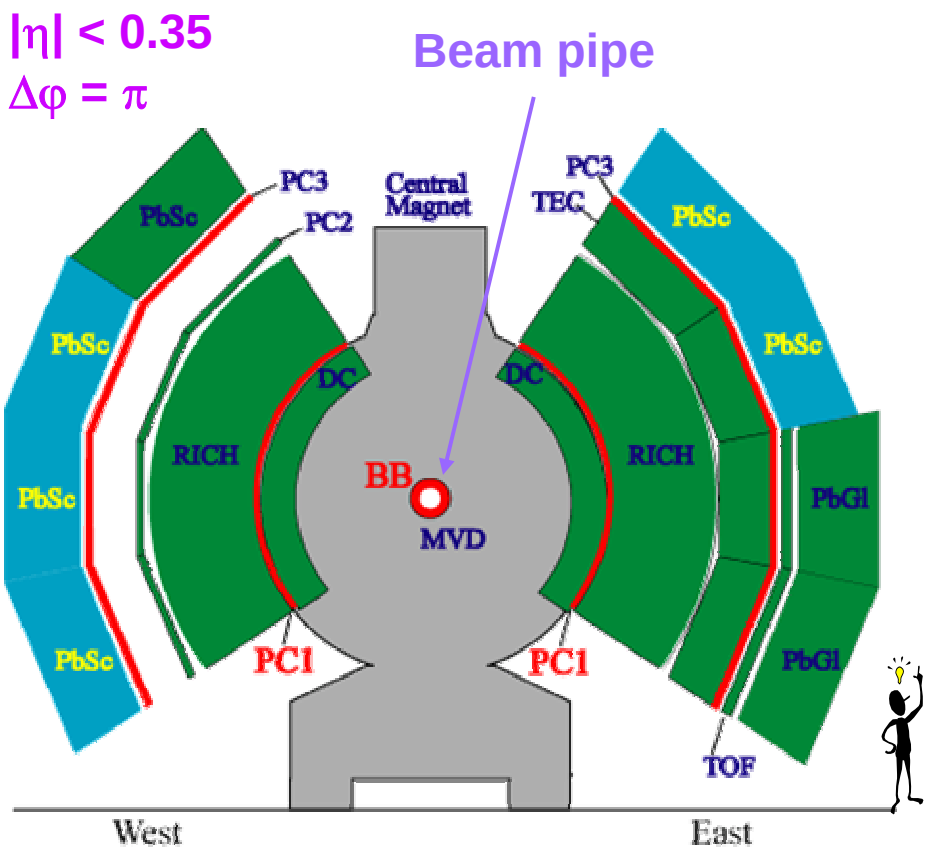
High $p_T$ contribution is expected to be small (~3%) assuming $p_T$ function shape consistent with Tevatron data

# $\langle p_T \rangle$ comparison with lower energy experiments




- Our result of $\langle p_T \rangle$ is slightly higher than lower energy experiments
- Our result is consistent with PYTHIA prediction including $\langle k_T \rangle$ tuned to reproduce $\langle p_T \rangle$ and $p_T$ spectrum of E672/E706 experiments at $\sqrt{s}$ = 39 GeV (Phys. Rev. D62, 012001)

# Electron Measurement with the Central Arms

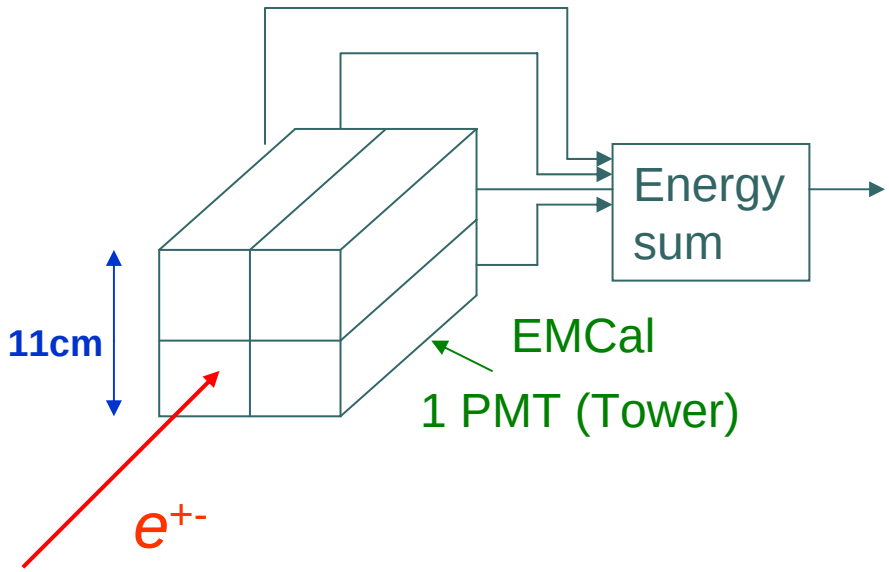



Cross section of the PHENIX Central Arms

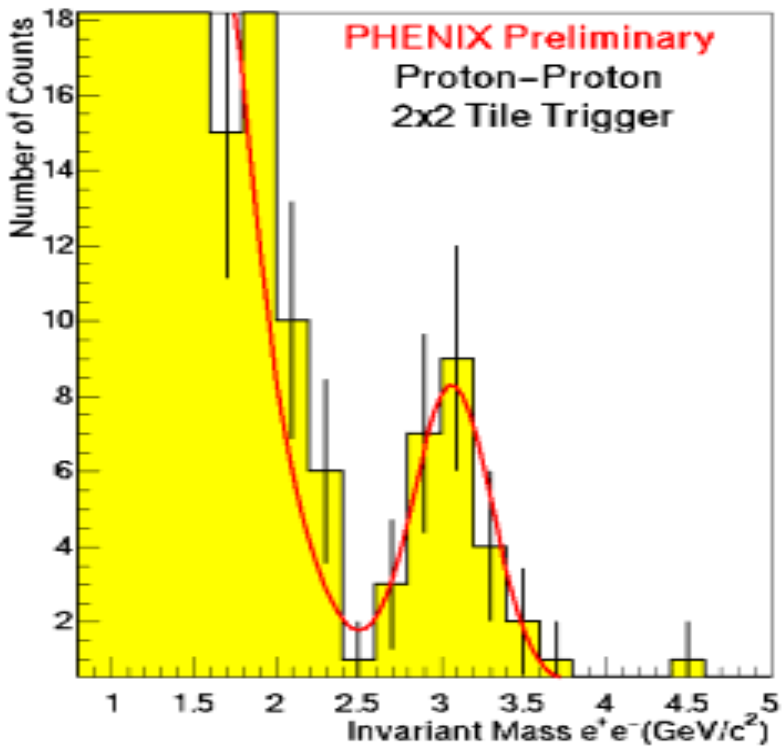
- Charged tracks are identified with Drift Chambers (DC) and Pad Chambers (PC1/2/3)
- Ring Imaging CHerenkov detector (RICH) and Electro-Magnetic Calorimeter (EMCal, i.e. PbSc/PbGl) are used to identify electrons
- EMCal is also used for electron/photon Trigger

# Electron LVL-1 Trigger and its Efficiency

- At least one energy sum of EMCal 2x2 towers exceeds the threshold (0.8GeV) → single electron/photon trigger
- Trigger efficiency for J/ψ→e+e- is estimated to be 0.90 + 0.06 - 0.07
  - Use Monte-Carlo tuned to describe single-photon efficiencies with real data well



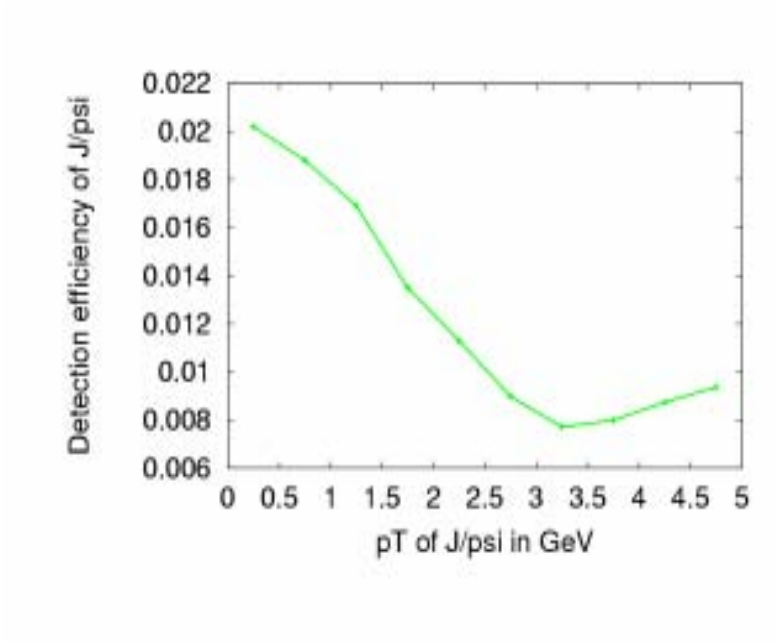
# $J/\psi \rightarrow e^+e^-$ signal




$N_{J/\psi} = 24 \pm 6\ (\text{stat.}) \pm 4\ (\text{syst.})$

# $J/\psi \rightarrow e^+e^-$ Acceptance and Reconstruction efficiency

- $\langle A_{cc}\, \varepsilon_{reco} \rangle_{|y|<0.5} = 0.0163 \pm 0.0020$
- Flat rapidity distribution in |y|<0.5 is assumed
- Uncertainties from unknown $p_T$ distribution is estimated to be 7%



# $Br\, d\sigma/dy\,|_{y=0}$ result

$$Br\left.\frac{d\sigma}{dy}\right|_{y=0} = \frac{N_{J/\psi}}{A_{cc}\varepsilon_{reco}\varepsilon_{run-run}\varepsilon_{trig}\varepsilon_{BBC}^{J/\psi}L\Delta y}$$

$N_{J/y} = 24 \pm 6(\text{stat.}) \pm 4(\text{syst.})$
$A_{cc}\ \varepsilon_{reco} = 0.0163 \pm 0.0020$
$\varepsilon_{run\text{-}run} = 0.87 \pm 0.09$ → additional Run-by-Run correction factor
$\varepsilon_{trig} = 0.90 + 0.06 - 0.07$
$\varepsilon_{BBC}^{J/\psi} = 0.75 \pm 0.11$
$L = 48 \pm 10\ \text{nb}^{-1}$
$\Delta y = 1.0$

→ Br $(J/\psi \rightarrow e^+e^-)\ d\sigma/dy|_{y=0} = 52 \pm 13\ (\text{stat.}) \pm 18\ (\text{syst.})$ nb

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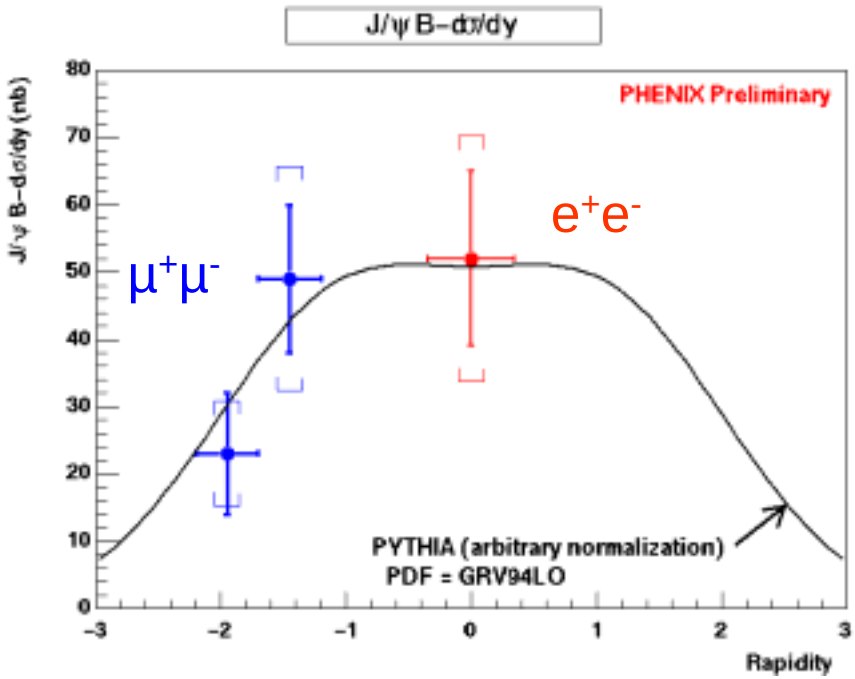
# $J/\psi$ Rapidity distribution and integrated cross section




- Rapidity distribution is consistent with PYTHIA
- A global fit gives

$$Br\,(J/\psi \rightarrow l^+l^-)\;\sigma\,(p+p \rightarrow J/\psi X)$$
$$= 226 \pm 36\ (stat.) \pm 79\ (syst.)\ nb$$
$$\sigma\,(p+p \rightarrow J/\psi X)$$
$$= 3.8 \pm 0.6\ (stat.) \pm 1.3\ (syst.)\ \mu b$$

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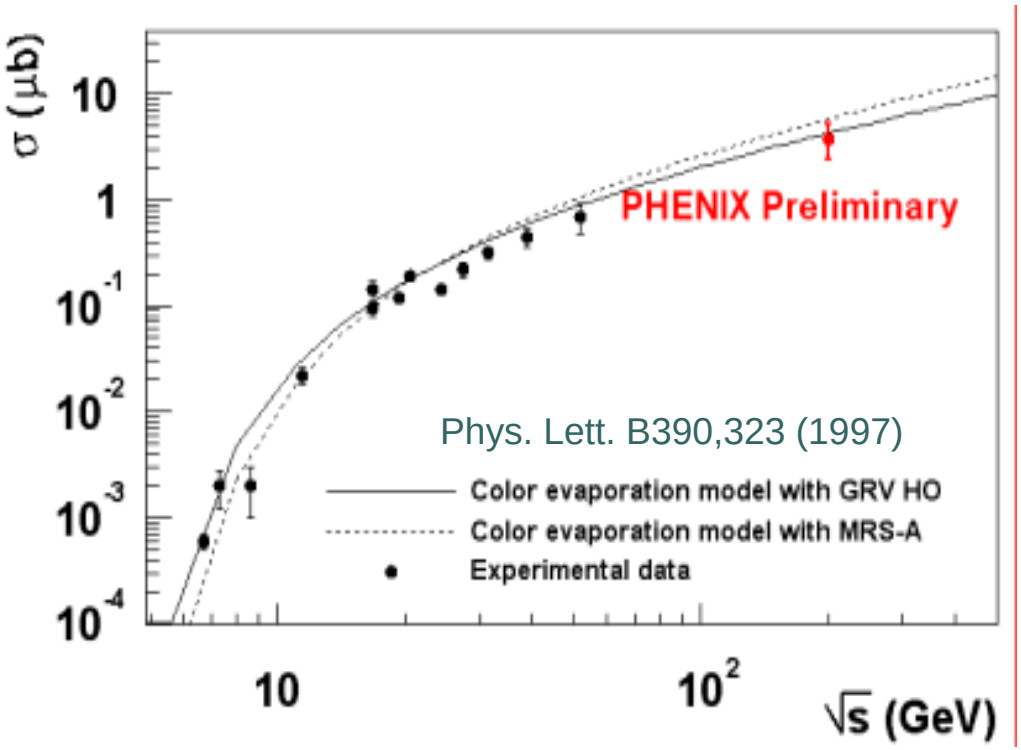
# Total Cross section compared with the Color-Evaporation Model prediction




- CEM Parameters are fixed by fitting low energy data
- Our result agrees with the CEM prediction at $\sqrt{s}$=200 GeV

# In Run-3 and later

- Much higher statistics (>10 times) leads to
  - Measurement of the J/ψ polarization (spin alignment) → critical test to discriminate theoretical models
  - More precise measurement of the $p_T$ slope
- Spin physics in longitudinally polarized p+p collisions
  - Double-longitudinal spin asymmetry ($A_{LL}$) of the J/ψ production → polarized gluon density

$$A_{LL}^{p+p\to J/\psi+X} \equiv \frac{\sigma^{++}-\sigma^{+-}}{\sigma^{++}+\sigma^{+-}} = \frac{\Delta G(x_1)}{G(x_1)}\frac{\Delta G(x_2)}{G(x_2)} a_{LL}^{g+g\to J/\psi+X}$$

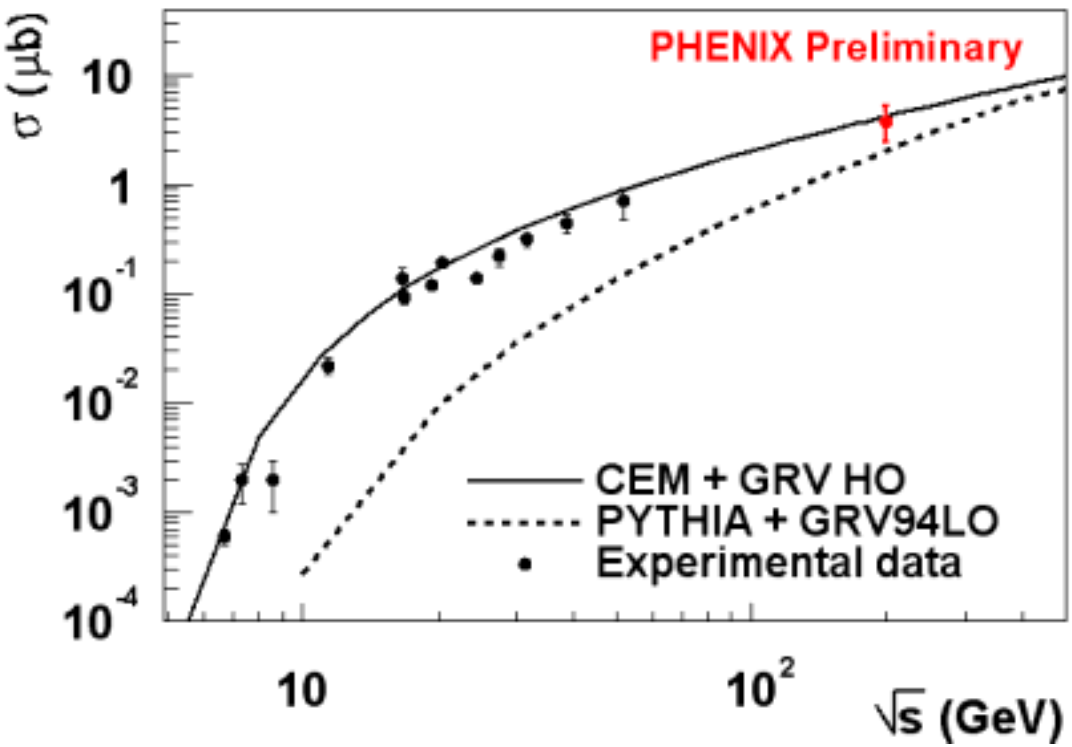
$\Delta G(x)$: polarized gluon density

$a_{LL}^{g+g\to J/\psi+X}$ : partonic subprocess asymmetry

# Summary

- Cross section of inclusive J/ψ production was measured with PHENIX using both $e^+e^-$ decay channel ($|y|<0.35$) and $\mu^+\mu^-$ decay channel ($1.2<y<2.2$) in Run-2 p+p collisions at $\sqrt{s}$ = 200 GeV.
- $Br(J/\psi\rightarrow\mu^+\mu^-)\, d\sigma_{J/\psi}/dy|_{y=1.7} = 37 \pm 7(stat.) \pm 11(syst.)$ nb
- $Br(J/\psi\rightarrow e^+e^-)\, d\sigma_{J/\psi}/dy|_{y=0} = 52 \pm 13(stat.) \pm 18(syst.)$ nb
- $p_T$ distribution and $\langle p_T \rangle_{y=1.7} = 1.66 \pm 0.18 \pm 0.09$ GeV/$c$ ($1.2<y<2.2$, $p_T<5$GeV/$c$) are obtained which are consistent with PYTHIA (Color-Singlet model).
- Rapidity fit including both results gives
  $\sigma_{J/\psi} = 3.8 \pm 0.6(stat.) \pm 1.3(syst.)$ μb
  which agrees with the Color-Evaporation model prediction.
- In Run-3, measurement of the J/ψ polarization and $A_{LL}$ is expected.

# Comparison with the Color-Singlet Model prediction using PYTHIA




- Assuming direct J/ψ (not from decays of $\chi_c$, ψ', nor *b*-quark) is dominant
- Tune PYTHIA parameters to reproduce Tevatron (fixed target experiments) $p_T$ spectra and open-charm cross-section measurement with PHENIX (single electron channel) at √s = 130 GeV