J/ψ Production in p+p Collisions at $\sqrt{s}$ = 200 GeV

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- Introduction
- Experimental Setup
- Data Analysis
- Results and Discussions
- Conclusion

J/ψ Measurements at RHIC-PHENIX

- Better understanding of Quantum Chromo-dynamics (QCD)
  - charmonium production includes
    - ✓ perturbative QCD aspects
    - ✓ non-perturbative QCD aspects

Cross sections
Polarization
Relative yields (χ/ψ etc)

In wide energy range

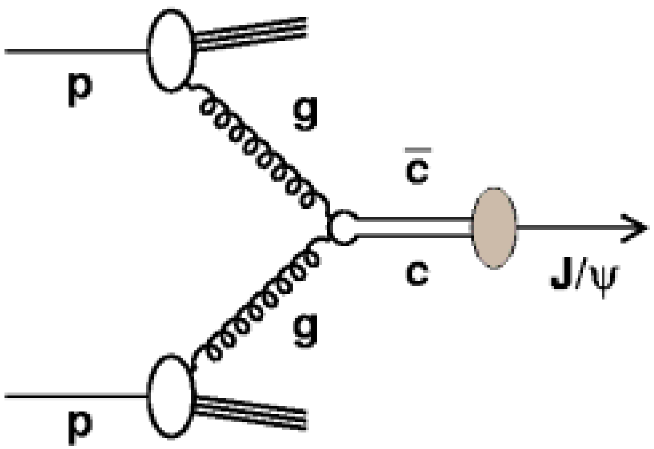
- Probe for new physics at RHIC
  - QGP physics with heavy-ion collisions at highest energy ($(\sqrt{s_{NN}})_{max}$ = 200 GeV for Au+Au)
  - Spin physics with polarized p+p collisions at highest energy ($\sqrt{s}_{max}$ = 500 GeV)

(Un-polarized) p+p data are important as reference

Charmonium production in hadron-hadron collisions

- Charmonium production in a hadron-hadron collision includes
  - Production of a $c\bar{c}$ pair (perturbative QCD calculation is applied)
  - Hadronization of the pair into a charmonium (non-perturbative QCD phenomenon) $\rightarrow$ not clearly understood yet
    - Color-evaporation model
    - Color-singlet model
    - Color-octet model

Gluon fusion is dominant



$$\sigma(pp \rightarrow \psi X) = \iint dx_1 dx_2 g(x_1, Q) g(x_2, Q) \sigma(gg \rightarrow \psi)$$

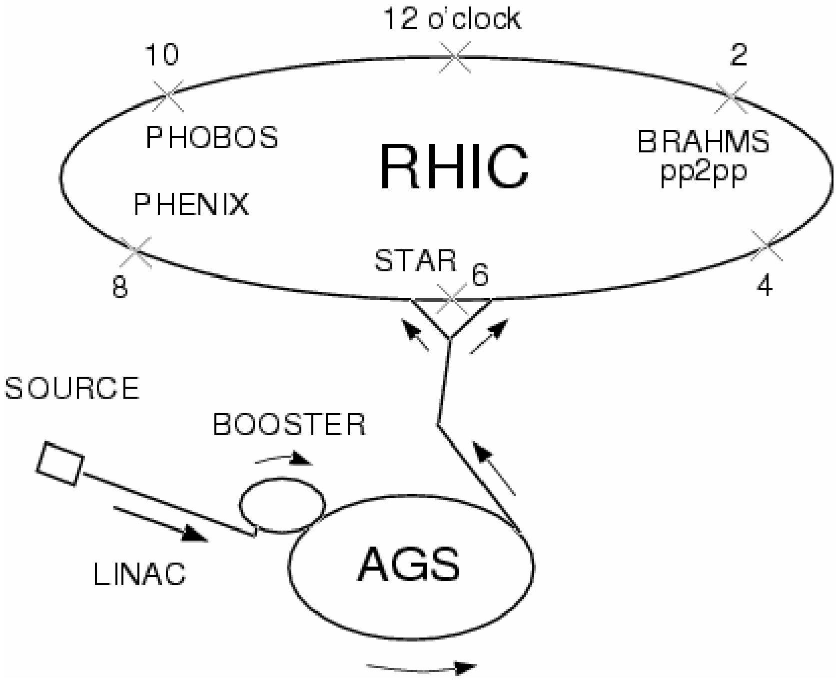
$$\sigma(gg \rightarrow \psi) = \sigma(gg \rightarrow c\bar{c}) P(c\bar{c} \rightarrow \psi)$$

J/ψ as a probe for new physics at RHIC

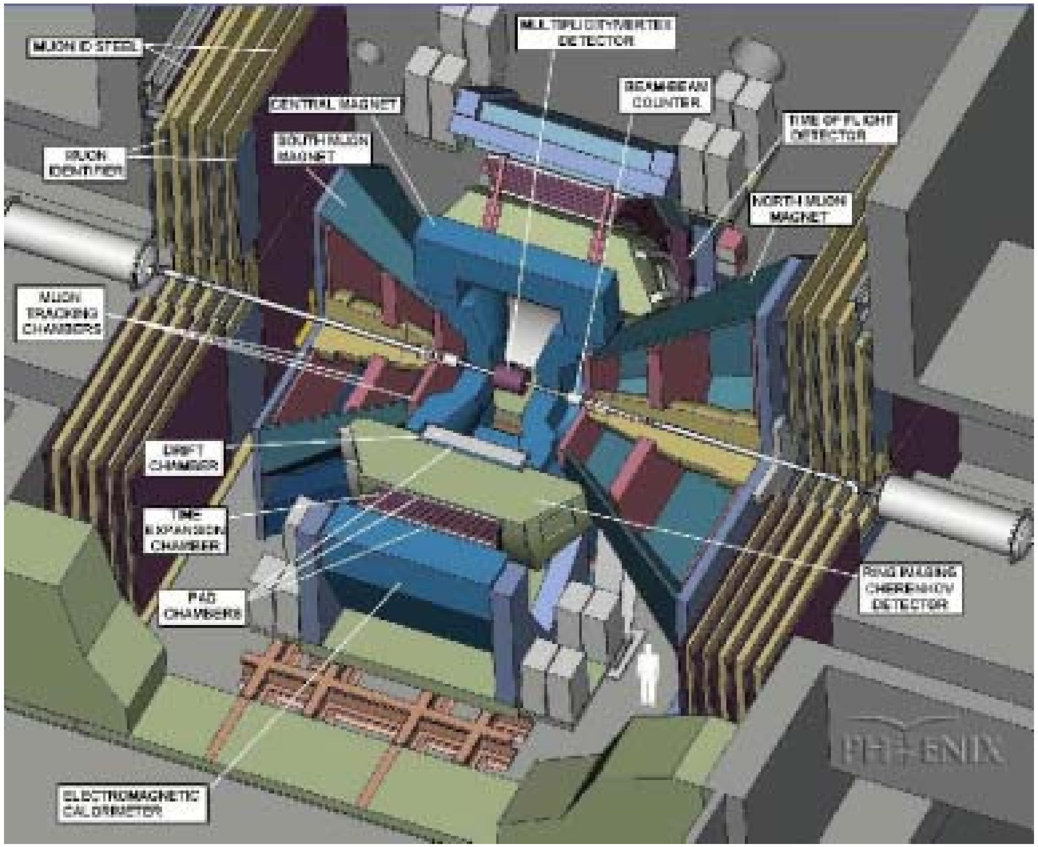
- Heavy Ion Physics
  - Search for the signature of the **Quark-Gluon Plasma** J/ψ yield in heavy ion collisions can be
    Suppressed due to **Debye color screening**
    OR
    Enhanced due to **Recombination**
  - Important to compare J/ψ yields in **Au+Au**, **p+p** (Run 2~) and **d+Au** (Run-3~) collisions to separate the normal nuclear effects
- Spin Physics
  - First direct measurement of the **polarized gluon distribution, ΔG(x),** in the proton using double-longitudinal spin asymmetries for the J/ψ production in **polarized p+p** collisions (Run-3~)
  - Understanding of the *production mechanism* is a key issue → unpolarized p+p data is useful (Run-2~)

The RHIC accelerator complex

- Two independent rings which can accelerate various kinds of ions (proton to Au nucleus) and polarized protons
- 6 interaction points and 5 experiments
- $\sqrt{s}_{max}$ = 500 GeV for p+p (200 GeV for Run-2)
- $L_{max} = 2 \times 10^{31}$ cm^{-2}sec^{-1} for p+p



The PHENIX Detector



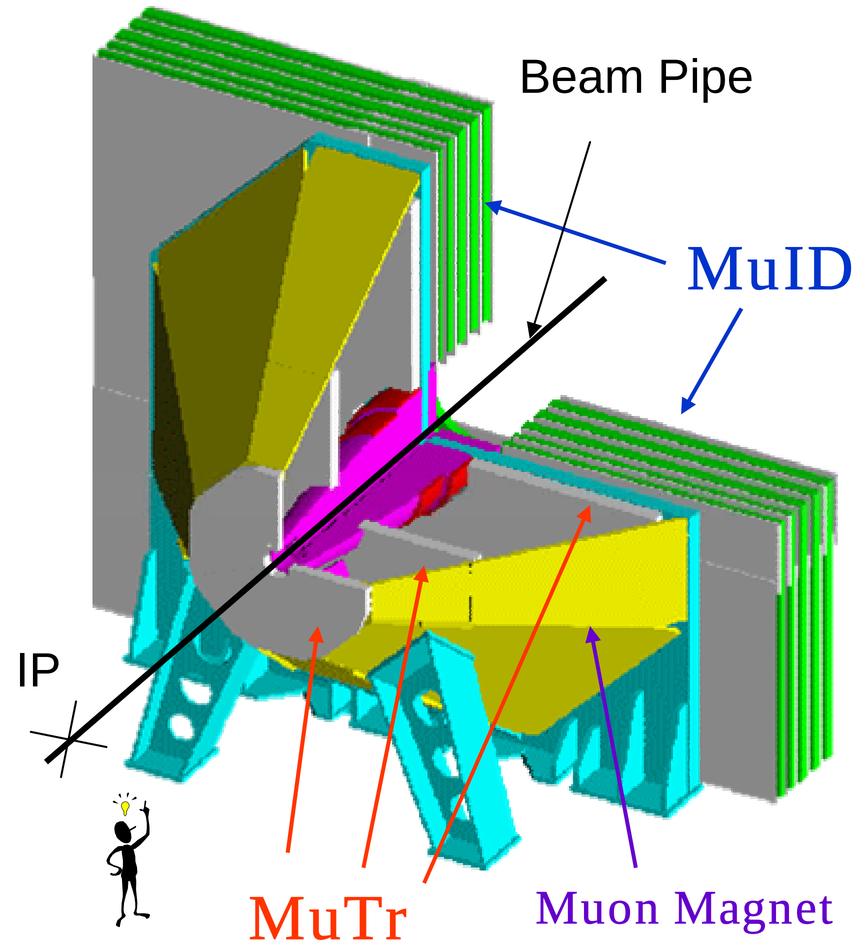
- e, γ, h (Central Arms)
  - $|\eta| < 0.35$, $\Delta\varphi = \pi$
  - $p_T > 0.2$ GeV/c (charged particles)
- μ (Muon Arms)
  - $1.2 < |\eta| < 2.4$, $\Delta\varphi = 2\pi$
  - $p_{tot} > 2$ GeV/c
- Interaction-trigger and vertex Detectors
  - Beam-Beam Counters ($3.0 < |\eta| < 3.9$)
  - Zero-Degree Calorimeters ($|\eta| > 6.2$)
  - Normalization Trigger Counters ($1.1 < |\eta| < 2.8$)

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

Low momentum (p_T) cut and wide rapidity coverage $\rightarrow$ enables the extraction of the total production cross-section at the highest energy

The PHENIX Muon Arms

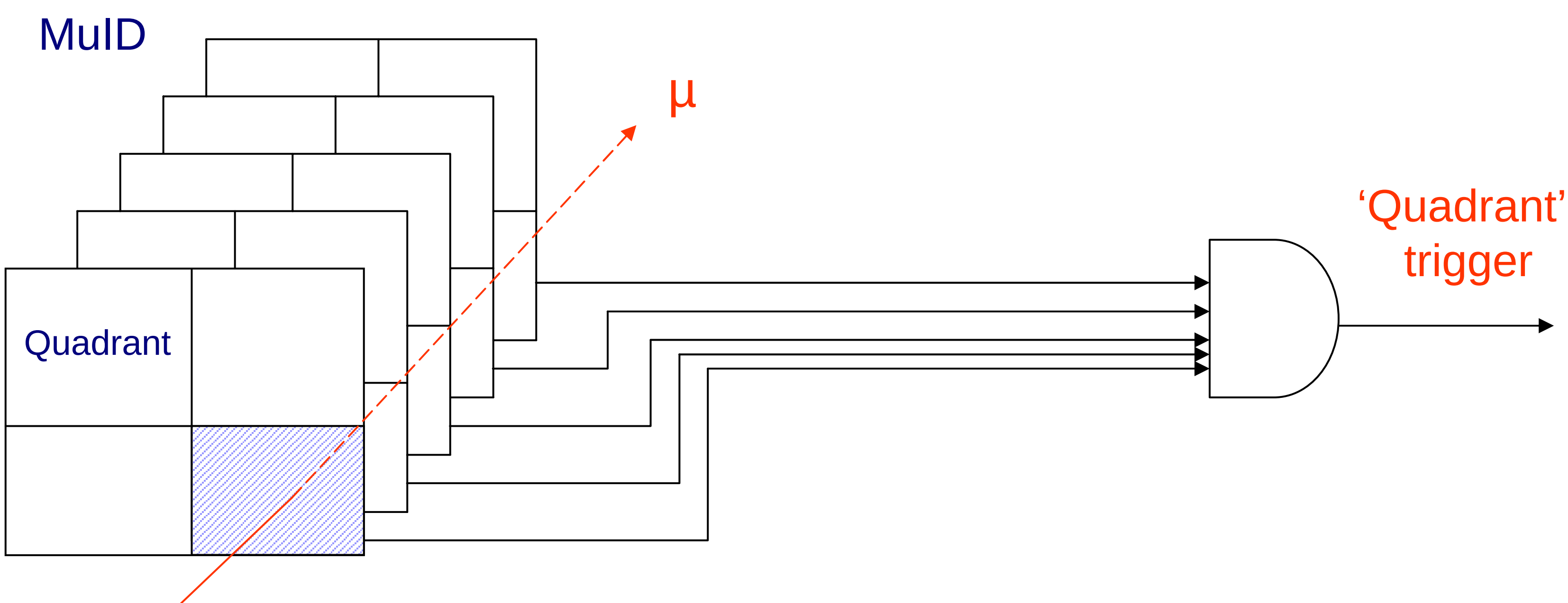
- Detect muons with
  - p_{tot} > 2 GeV/c
  - -1.2 > η > -2.2 (South Arm) or 1.2 < η < 2.4 (North Arm)
- Muon Tracker (MuTr)
  - Measure momentum of muons with cathode-readout strip chambers at 3 stations inside Muon Magnet
- Muon Identifier (MuID)
  - π/μ separation with 5-layer sandwich of chambers (Iarocci tubes) and steel
  - Trigger muons



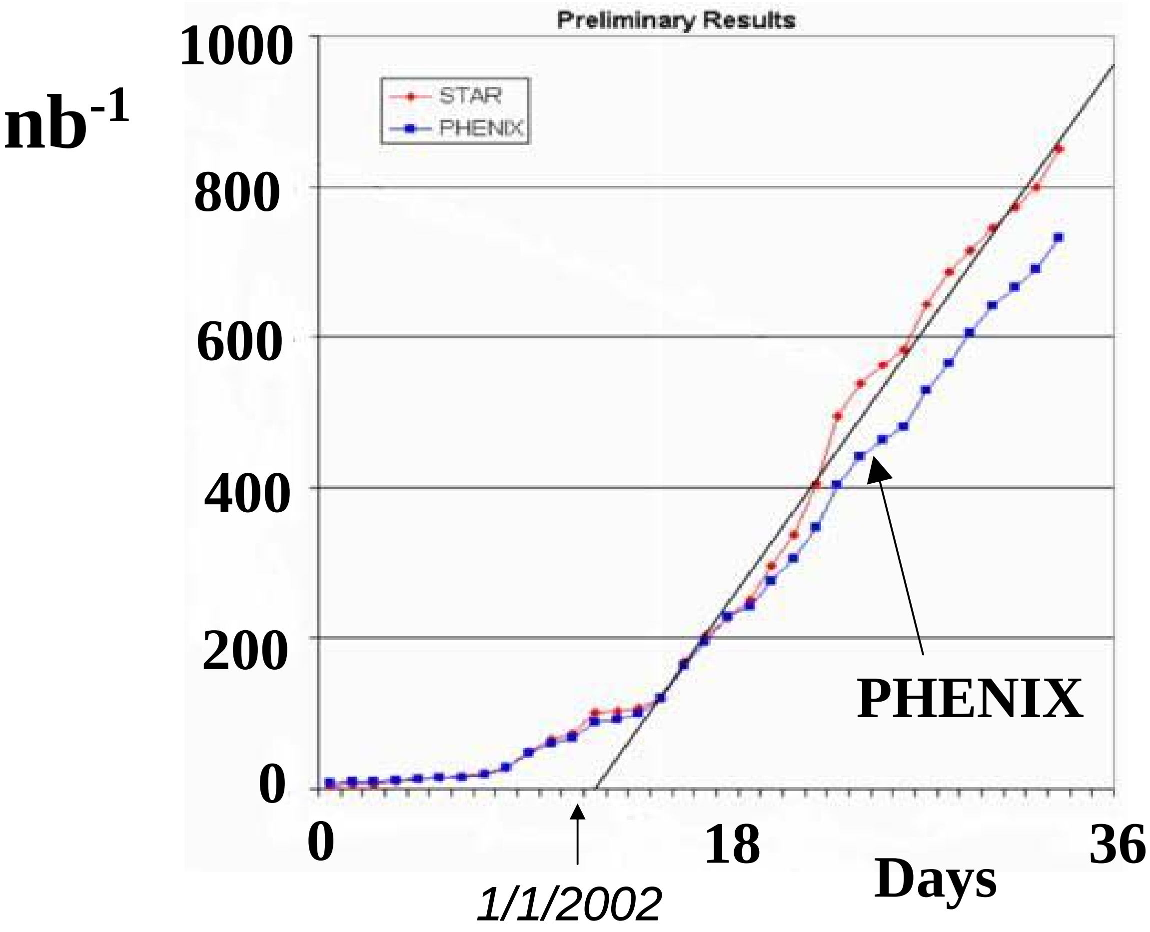
South Muon Arm was successfully operated first time during Run-2

Muon Trigger in Run-2 p+p

- Coincidence of fired planes of each quadrant gives a "quadrant trigger"
- Minimum bias (BBC) AND one quadrant for the "single-muon trigger" and more than one quadrant for the "dimuon trigger"
- Inefficiencies from hardware dead time is 1~2%
- Trigger rate was dominated by non-collision beam related background $\rightarrow$ survived with Run-2 luminosity (~100 Hz for the single-muon trigger and ~10 Hz for the dimuon trigger)



Run-2 p+p Integrated Luminosity



RHIC delivered 700 nb^{-1} to PHENIX

After online vertex cuts (75 cm), PHENIX recorded 150 nb^{-1}

For J/ψ analyses,
81 nb^{-1} for $\mu^+\mu^-$ and
48 nb^{-1} for e^+e^- are used

p+p Muon Event sample

150nb^{-1}

Number of p+p minimum-bias triggered events	196M
Number of single-muon triggered events	34M
Number of dimuon triggered events	4.8M

- Minimum-bias triggered events and single-muon triggered events are used to evaluate detector performance
- Dimuon triggered events are used to obtain the number of J/ψ $\rightarrow$ Contains most (>90%) of J/ψ statistics

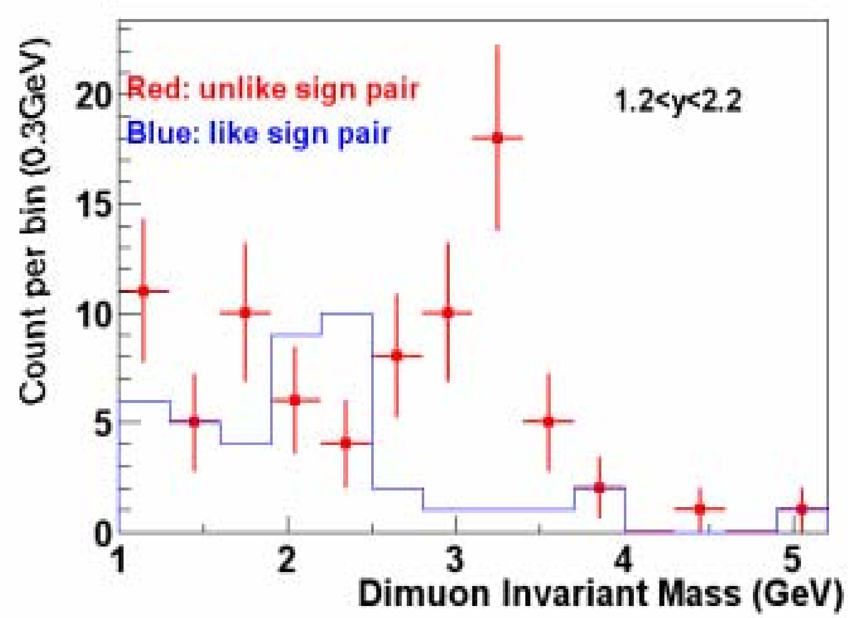
Analysis procedure

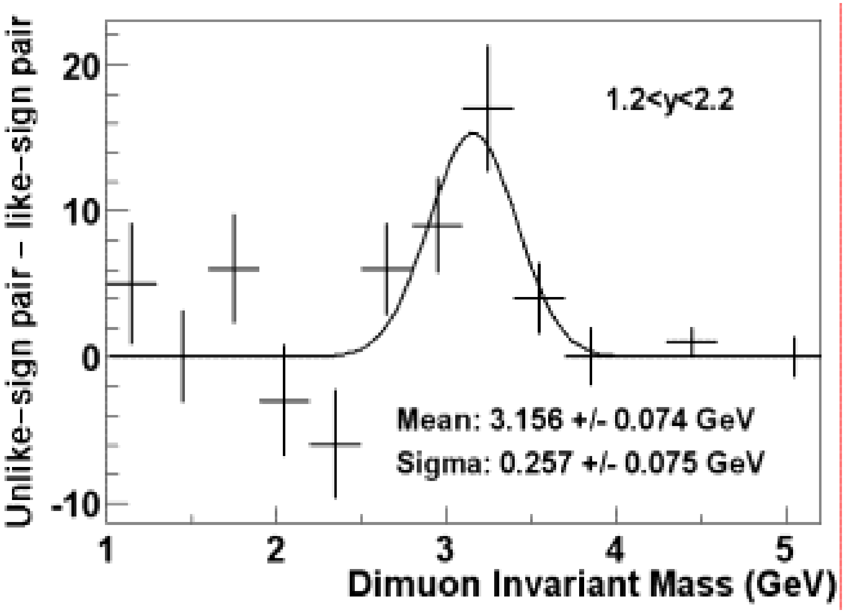
$$B_r(J/\psi \to \mu^+\mu^-)\frac{d\sigma_{J/\psi}}{dy} = \frac{N_{J/\psi}}{\eta_{acc}\varepsilon_{MuID}^{J/\psi}\varepsilon_{MuTr}^{J/\psi}\varepsilon_{BBC}^{J/\psi} L \Delta y}$$

- $N_{J/\psi}$: Number of observed J/ψ's in 1.2<y<2.2
- η_{acc}: South Muon Arm Acceptance times reconstruction efficiency for J/ψ (1.2<y<2.2) → $\mu^+\mu^-$ with100% chamber efficiencies
- $\varepsilon_{MuID}^{J/.\psi}$: Efficiency correction due to real chamber efficiencies of MuID
- $\varepsilon_{MuTr}^{J/.\psi}$: Efficiency correction due to real chamber efficiencies of MuTr
- $\varepsilon_{BBC}^{J/\psi}$: BBC trigger efficiency for p+p → J/ψ*X* events
- *L*: Luminosity with good vertex cut (|z-vertex|<38cm)

Dimuon mass

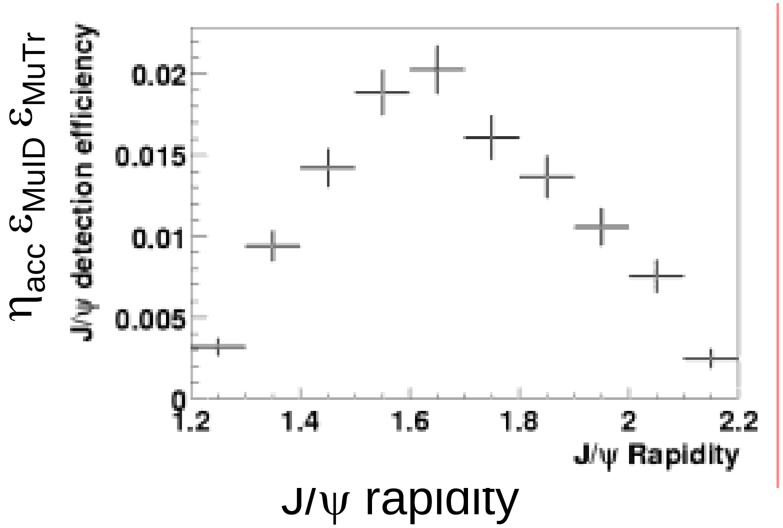
|Collision z-vertex| < 38cm
Track z-vertex matching < 30cm

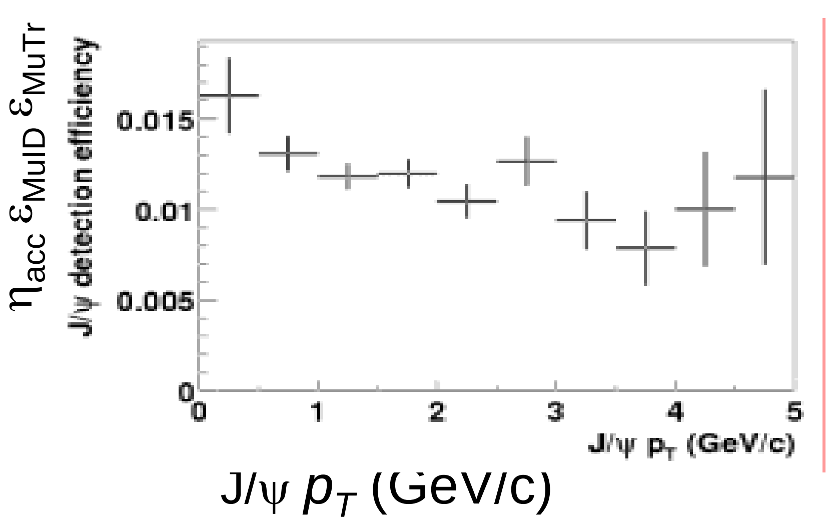




- Significant enhancement of unlike-sign pair in the J/ψ mass region
  - ✓ Peak (3156 ± 74 MeV/c^2) is consistent with the J/ψ mass
  - ✓ Mass width (257 ± 75 MeV/c^2) is consistent with expectation
- 36 counts in 2.5<mass<3.7GeV/c^2 assuming the same count of unlike and like-sign pairs from background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

J/ψ Acceptance × reconstruction efficiency with real chamber efficiencies





$$<\eta_{acc}\ \varepsilon_{MuID}{}^{J/\psi}\ \varepsilon_{MuTr}{}^{J/\psi}>_{1.2<y<2.2} = 0.0163$$

- Dead HV and electronics maps and chamber efficiencies obtained from real data are used
- $d\sigma/dy$ in $1.2<y<2.2$ can be measured with the South Muon Arm
- p_T dependence is small
- Uncertainty from unknown J/ψ polarization ~ 10% assuming $|\lambda|<0.3$

BBC efficiencies and luminosity

$$\varepsilon_{BBC}^{J/\psi} L = \frac{\varepsilon_{BBC}^{J/\psi}}{\varepsilon_{BBC}^{inela}} \frac{N_{BBC}}{\sigma_{inela}} = \frac{0.74}{0.51} \frac{1.72\times 10^{9}}{42mb} = 59 nb^{-1}$$

- $\varepsilon_{BBC}^{J/\psi}$: BBC efficiency for p+p → J/ψ X → $\mu^+\mu^-$ events
  p_T and rapidity dependences are small
- $\varepsilon_{BBC}^{inela}$: BBC efficiency for p+p inelastic events
- N_{BBC}: Number of BBC triggers with a vertex cut (|z|<38cm)
- σ_{inela}: p+p inelastic cross section = 42mb (√s fit → 3% error)

(first two items) ← simulation

(N_{BBC}) ← Real data

- Systematic error of $\varepsilon_{BBC}^{inela}$ from the uncertainty of initial particle distribution is estimated to be 15% comparing PYTHIA with the UA1 (p_T) and UA5 (rapidity) data
- Consistency check with the real data for $\varepsilon_{BBC}^{inela}$
  - ✓ Relative trigger efficiency $\varepsilon_{NTC}^{inela}/\varepsilon_{BBC}^{inela}$ is consistent with the relative trigger rate measured
  - ✓ $\varepsilon_{BBC}^{inela}\sigma_{inela}$ is consistent with the machine value (18.5mb) within their uncertainties

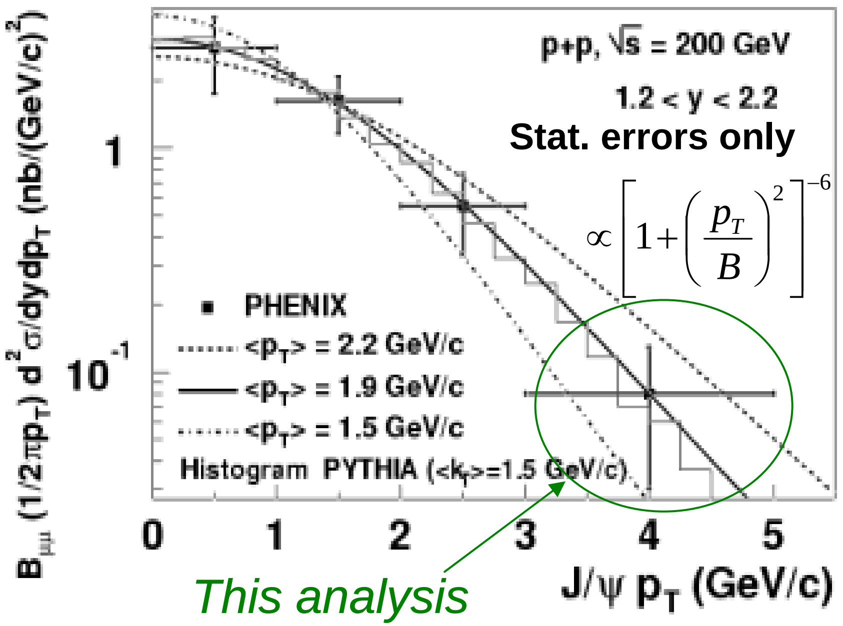
Summary of systematic uncertainties

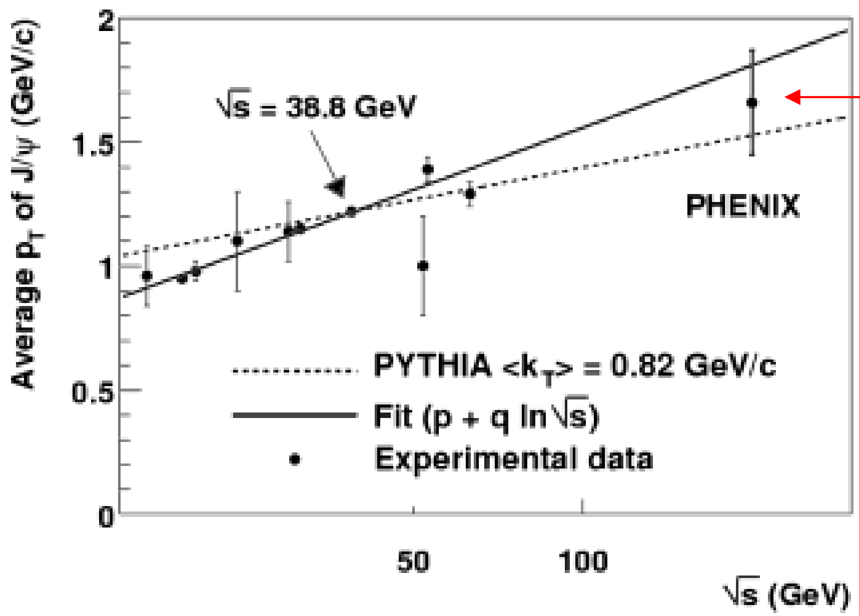
	Systematic Uncertainty
$N_{J/\psi}$	10% (cut dep.)
η_{acc}	10% (J/ψ pol. dep., $\lvert\lambda\rvert<0.3$)
$\varepsilon_{MuID}^{J/.\psi}$	11% (run dep.)
$\varepsilon_{MuTr}^{J/.\psi}$	10% (consistency with the real data)
$\varepsilon_{BBC}^{J/\psi}$	10% (initial particle-multiplicity)
L $(N_{BBC}/\varepsilon_{BBC}^{inela}\sigma_{inela})$	15% (initial particle-multiplicity)
Total	27%

Results and discussions

- p_T distribution and $<p_T>$
- Rapidity distribution
- Total cross section ($\sigma_{J/\psi}$)
  - $\sqrt{s}$ dependence
  - Absolute value

J/ψ p_T distribution and <p_T>

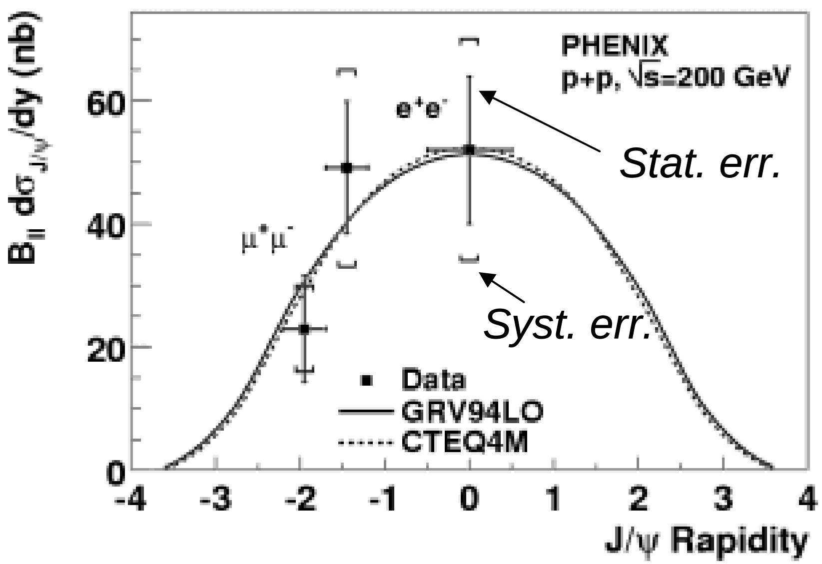


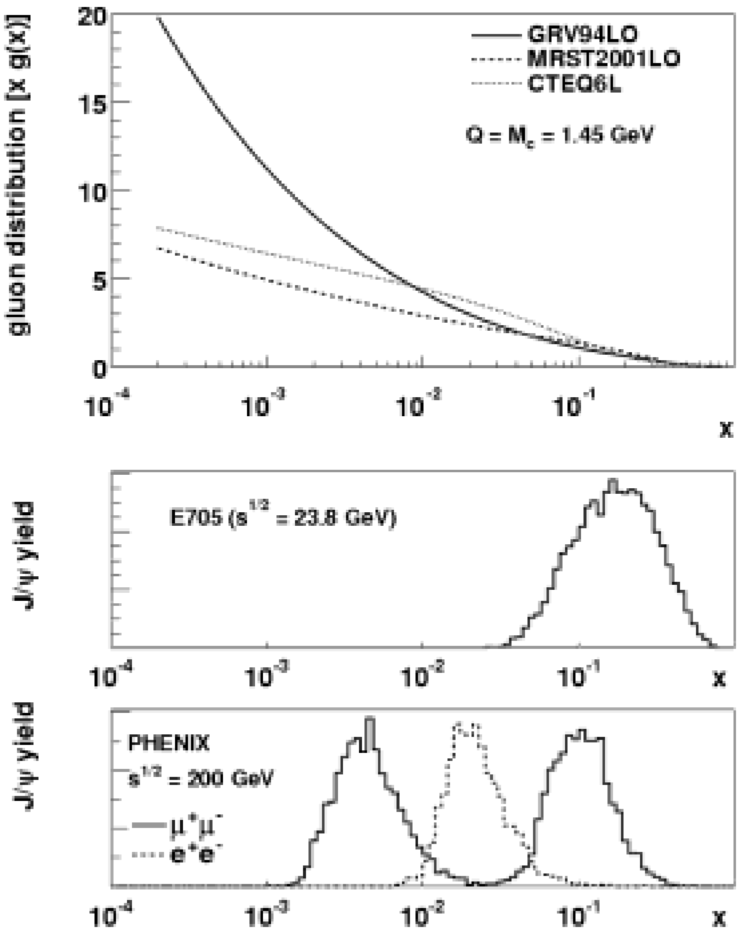


$\langle p_T \rangle_{y=1.7}$ = 1.66 ± 0.18 (stat.) ± 0.09 (syst.) GeV/*c*

- p_T-differential cross section (at low p_T) and $\langle p_T \rangle$ are mainly sensitive to $\langle k_T \rangle$ → consistent with PYTHIA (color-singlet model) prediction with a reasonable value of $\langle k_T \rangle$

J/ψ rapidity distribution and $\sigma_{J/\psi}$

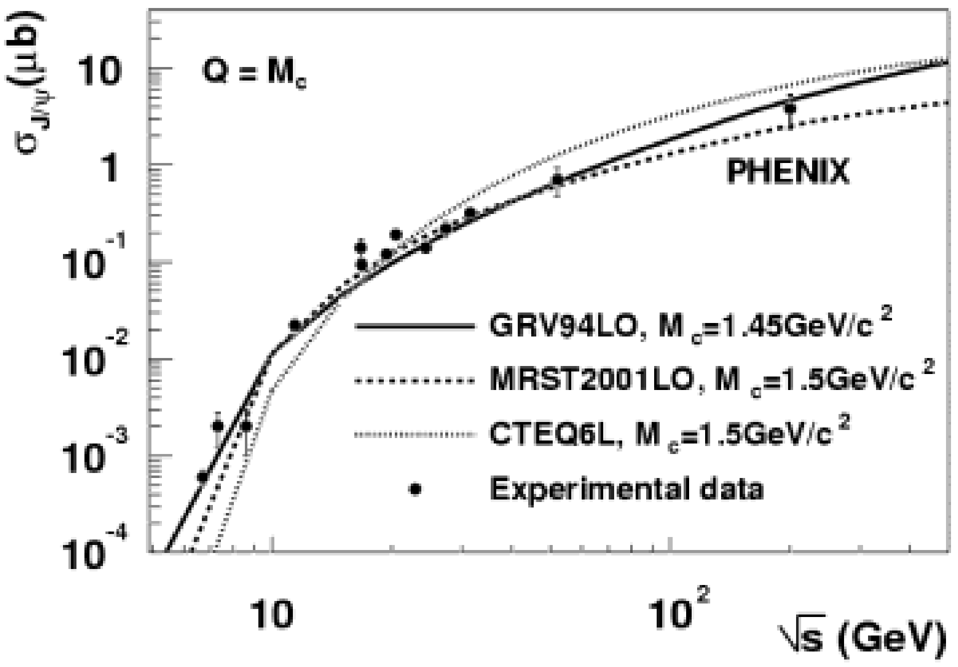




- Rapidity-differential cross section is mainly sensitive to gluon distribution function g(x,Q) in the proton and consistent with some typical PDF sets
- Global fit including $J/\psi \to e^+e^-$ (y=0) data gives total cross section

Br ($J/\psi \to l^+l^-$) σ ($p+p \to J/\psi X$) = 226 ± 36 (stat.) ± 79 (syst.) nb
σ ($p+p \to J/\psi X$) = 3.8 ± 0.6 (stat.) ± 1.3 (syst.) μb

$\sigma_{J/\psi}$ ($\sqrt{s}$ dependence)



$$\sigma_{J/\psi}(\sqrt{s}) \propto \int_{\sqrt{\tau}}^{1} \frac{dx}{x} g(x) g(\tau / x)$$

$$\sqrt{\tau} = 2m_c / \sqrt{s}$$

- Our new result and lower-energy results are consistent with typical gluon distribution functions → confirms the gluon fusion picture of J/ψ production in hadron-hadron collisions in a wide energy range

$\sigma_{J/\psi}$ (absolute value)

- **Absolute normalization for $\sigma_{J/\psi}$ is sensitive to production model**
  - Color-evaporation model (CEM)
    can explain $\sigma_{J/\psi}$ using $\rho_{J/\psi}$ (fraction of J/ψ to all produced $c\bar{c}$ pairs) ~ 0.06 determined by photo-production data
  - Color-singlet model (CSM)
    disagrees by a large (~20) factor
  - Color-octet model (COM)
    consistent but has large uncertainties from
    - Extraction of color-octet matrix element
    - Charm quark mass
    - Scales

Near future measurements

- Polarization of J/ψ
  Critical to separate production models
  - CEM - zero polarization
  - CSM and COM – sizable positive (transverse) polarization
- Double-longitudinal spin asymmetry (A_{LL}) for J/ψ production in longitudinally polarized p+p collisions
  - Polarized gluon density ($\Delta G(x)$)
  - Large difference in a_{LL} according to production model
    - ~+1 (CEM)
    - ~ -1 (CSM)
    - -0.3 ~ +0.7 (COM)

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

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

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

Conclusion

- With the South Muon Arm in the PHENIX detector covering $1.2 < y < 2.2$, J/ψ particles have been clearly identified with a small background via $\mu^+\mu^-$ decays in the first **p+p** Run at RHIC (Run-2) at **$\sqrt{s}$ = 200 GeV**.

pQCD

- p_T distribution and $\langle p_T \rangle_{y=1.7} = 1.66 \pm 0.18 \pm 0.09$ GeV/c are consistent with **PYTHIA prediction with a reasonable value of $\langle k_T \rangle$**.
- Rapidity distribution including the e^+e^- decay channel is consistent with **gluon distribution function** as well as $\sqrt{s}$ scaling of the total cross sections $\sigma_{J/\psi}(\sqrt{s} = 200\text{ GeV}) = 3.8 \pm 0.6\text{ (stat.)} \pm 1.3\text{ (syst.)}\ \mu b$ and lower energy results.
- The absolute normalization for $\sigma_{J/\psi}$ can be reproduced well by both the **color-evaporation model** and the **color-octet model**.
- *These results are also important as reference for Au+Au and polarized p+p data.*
- Further critical measurements to separate production models are planned in the near future at RHIC.
  - J/ψ polarization
  - A_{LL} for J/ψ production in longitudinally polarized p+p collisions

Non-pQCD