Charmonium Production at PHENIX

Current Status and Future Goals

Andrew S. Hoover
New Mexico State University
(for the PHENIX collaboration)

Outline:

- Theories of charmonium production
- The PHENIX experiment
- PHENIX preliminary results on J/ψ cross section in pp collisions
- Conclusions

Why Study Charmonium?

- Help us gain a better understanding of QCD. Verify validity of NRQCD factorization method.
- Test various production mechanisms: Color Evaporation Model, Color Singlet and Color Octet contributions to NRQCD.
- Resolve discrepancies between observations and theory (cross section and polarization).
- Search for J/ψ suppression or enhancement in heavy ion collisions. Compare with NA50 observations.
- Study charmonium production in pA collisions, can nuclear effects explain observed suppession?

Color Evaporation Model

Introduced ~1977:

F. Halzen, Phys. Lett. B69, 105 (1977)

J.F. Amundson, O.J.P. Eboli, E.M. Gregores, and F. Halzen,
Phys. Lett. B390, 323 (1997)

Color singlet property of ψ is not enforced over short distances, i.e. - color is ignored in the short distance perturbative diagrams.

Observable color singlet state is a result of many soft gluon emissions over large distances.

Cross section for ψ is given by $\sigma_\psi = \rho_\psi \sigma_{onium}$, σ_{onium} is the sum of all cross sections for onium states and is computed from pQCD. ρ_ψ is the fraction of onium states which materialize as ψ's and is determined empirically.

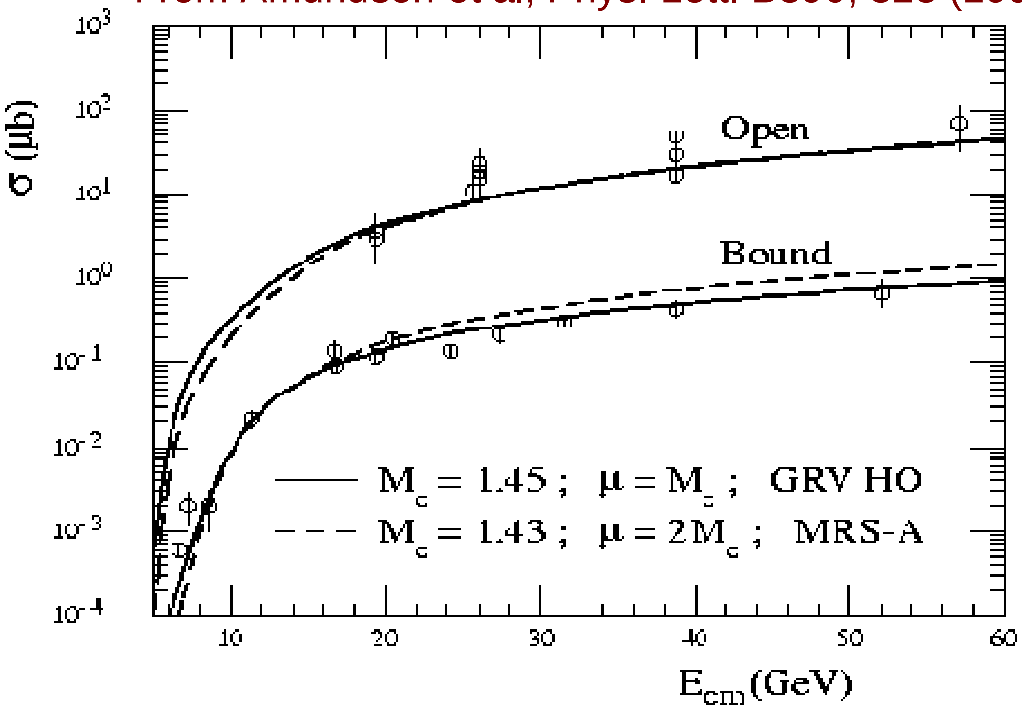
CEM Predictions for Hadroproduction of ψ

$\rho_\psi = 0.5$ is determined from photoproduction data (some theoretical uncertainty due to choice of scales and PDFs).

Higher order QCD corrections are determined by fitting the hadroproduction cross section of $D\bar{D}$ (open) pairs with a global K factor.

ρ_ψ and the K factor are then used to predict the cross section for J/ψ (bound)

From Amundson et al, Phys. Lett. B390, 323 (1997)



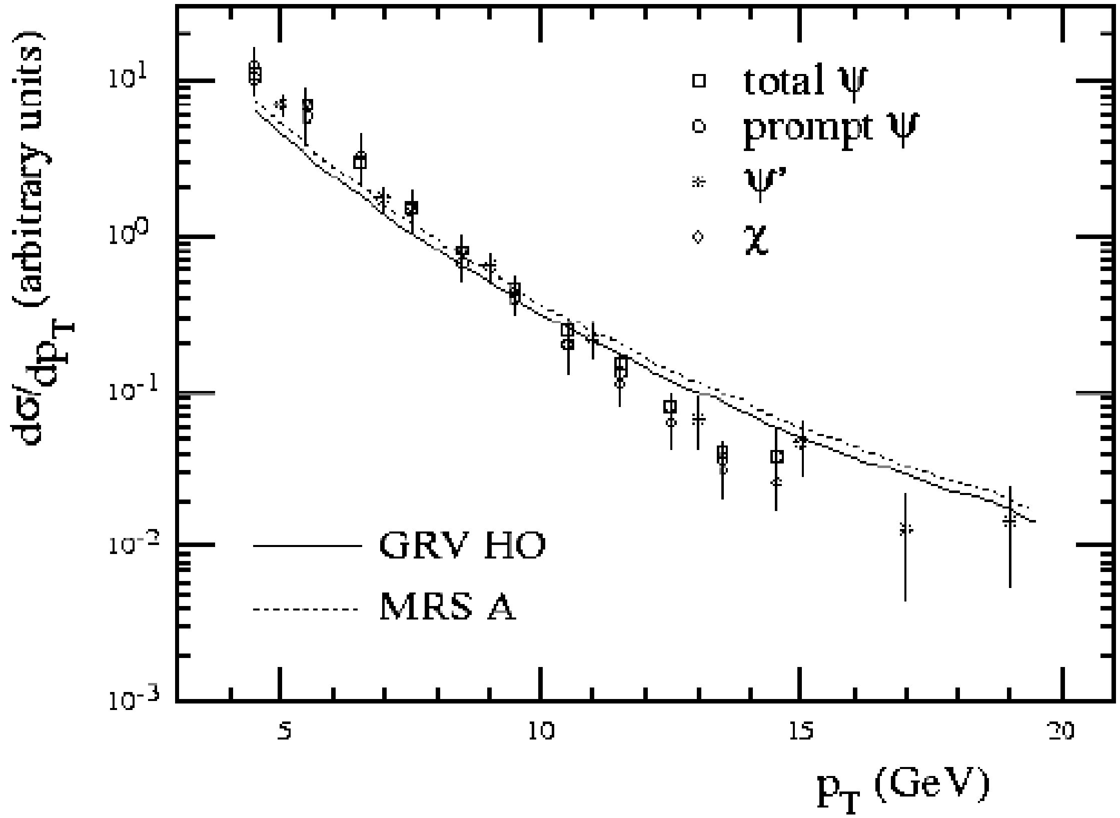
PHENIX at 200 GeV →

CEM and the Tevatron p_T Distribution

All charmonium states share the same production dynamics
==> p_T distributions are the same up to a constant.

K factor = 2.2

From Amundson et al, Phys. Lett. B390, 323 (1997)



NRQCD Factorization Method

NRQCD theory with color singlet and color octet contributions is a more recent proposal for charmonium production. Color is included. But first, an overview of NRQCD factorization and scaling:

$$p + p \longrightarrow \psi + X$$

$$\sigma_\psi = \sum_{i,j} \int_0^1 dx_1 dx_2\, f_{i/p}(x_1)\, f_{j/p}(x_2)\, \hat{\sigma}(pp \longrightarrow \psi)$$

$$\hat{\sigma}(pp \longrightarrow \psi) = \sum_n M_n \langle \mathcal{O}_n^\psi \rangle$$

Perturbative short distance coefficients. Calculable with pQCD and have expansions in α_s.

Non perturbative long distance matrix elements. Describe the hadronization process, have expansions in the heavy quark velocity v, and are determined by fits to data.

Separation of the amplitude into short distance coefficients and long distance matrix elements is the NRQCD " factorization method ".

Scaling of the Matrix Elements

The color singlet state $^3S_1^{(1)}$ is the dominant Fock state for charmonium. Other charmonium states can be reached by some number of electric and magnetic transitions. Electric transition: $\Delta L = \pm 1$, $\Delta S = 0$; Magnetic transition: $\Delta L = 0$, $\Delta S = \pm 1$.

For each electric transition, the matrix element scales like v^2.

For each magnetic transition, the matrix element scales like v^4.

In general, a matrix element scales like $v^{3+2L+2E+4M}$, where L is the angular momentum, E is the number of electric transitions, and M is the number of magnetic transitions.

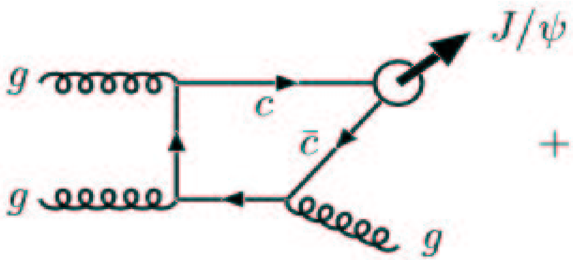
Usually the velocity scaling of the matrix elements is listed with respect to the base state $^3S_1^{(1)}$. That is, $^3S_1^{(1)} \sim v^3$, but will usually be listed as $^3S_1^{(1)} \sim v^0$.

The Color Singlet Contributions

Assumes only heavy quark pairs formed in the dominant Fock state $^3S_1^{(1)}$ will form observable charmonium.

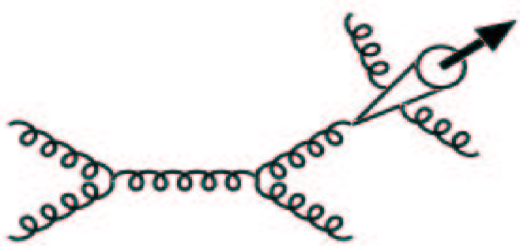
Diagrams from Kramer, Prog. Part. Nucl. Phys. **47**, 141 (2001)

leading-order colour-singlet: $g + g \rightarrow c\bar{c}[^3S_1^{(1)}] + g$



$$+ \ldots \qquad \sim \alpha_s^3 \frac{(2m_c)^4}{p_t^8}$$

colour-singlet fragmentation: $g + g \rightarrow [c\bar{c}[^3S_1^{(1)}] + gg] + g$

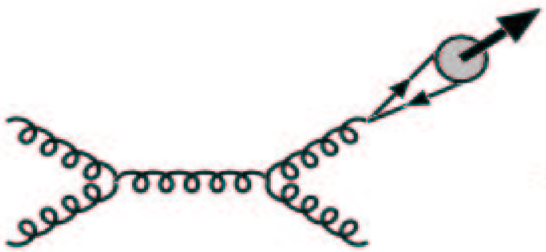


$$+ \ldots \qquad \sim \alpha_s^5 \frac{1}{p_t^4}$$

The Color Octet Contributions

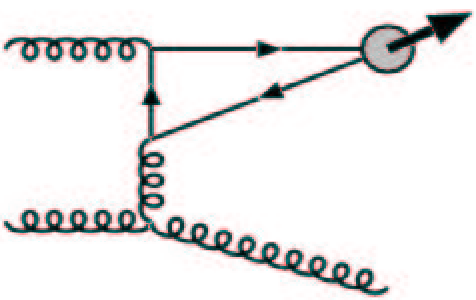
Charmonium in a color octet state can form observable charmonium via emission of soft gluons.

colour-octet fragmentation: $g + g \to c\bar{c}[^3S_1^{(8)}] + g$



$+ \ldots \qquad \sim \alpha_s^3 \frac{1}{p_t^4} v^4$

colour-octet t-channel gluon exchange: $g + g \to c\bar{c}[^1S_0^{(8)}, {}^3P_J^{(8)}] + g$

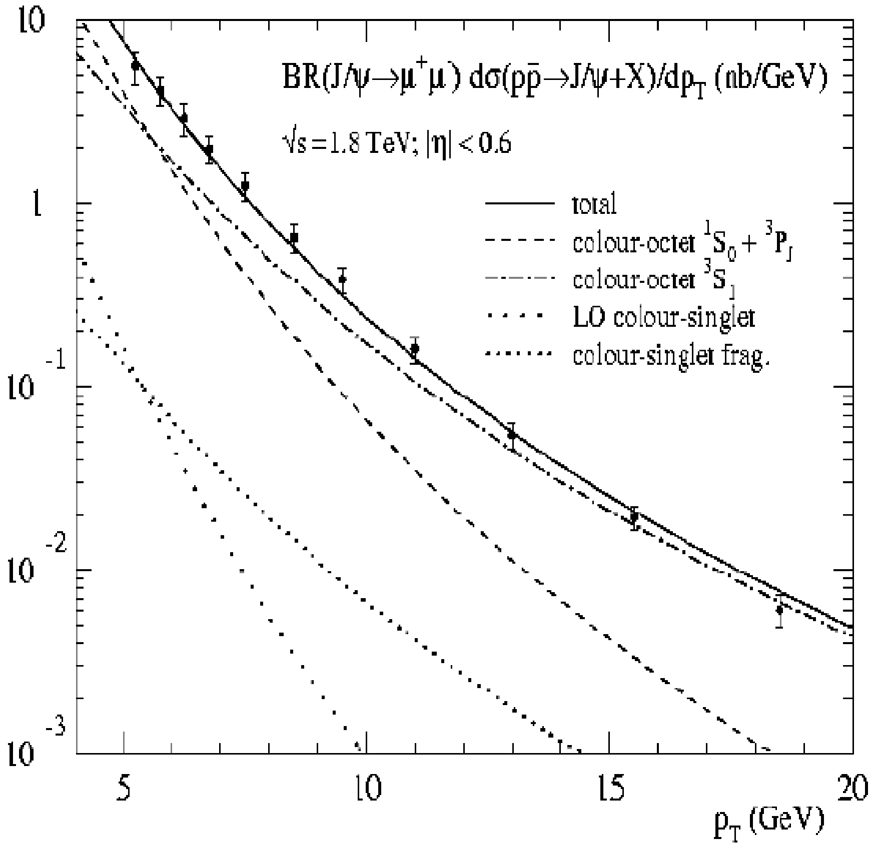


$+ \ldots \qquad \sim \alpha_s^3 \frac{(2m_c)^2}{p_t^6} v^4$

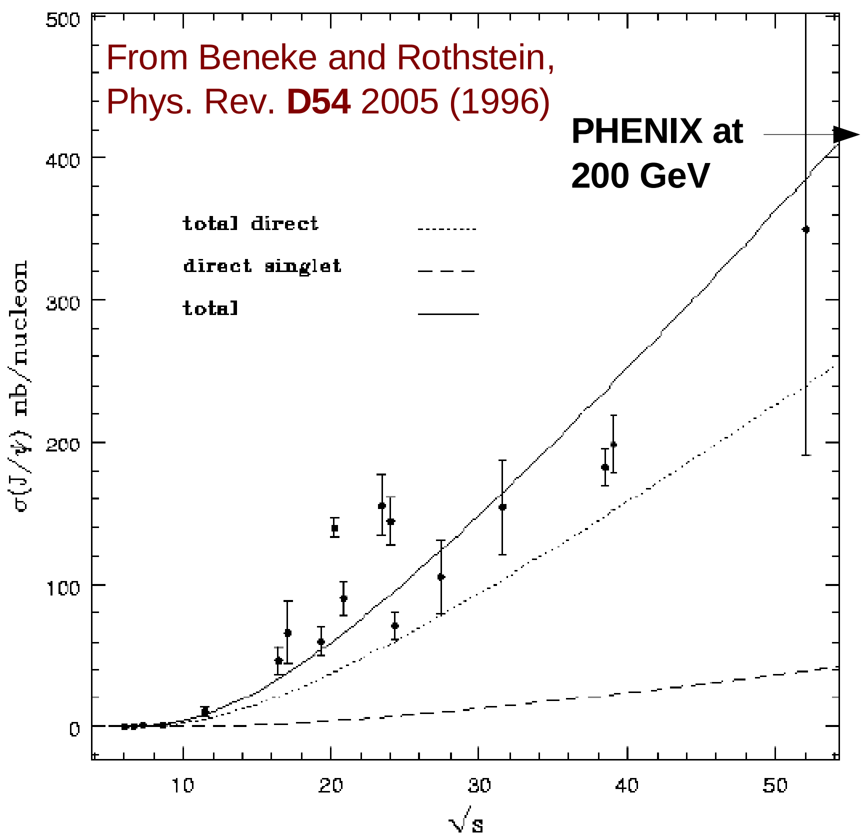
Experimental Verification of NRQCD

The four matrix elements ${}^3S_1^{(1)}$, ${}^3S_1^{(8)}$, ${}^1S_0^{(8)}$, and ${}^3P_J^{(8)}$ are fitted to the Tevatron p_T data. Those matrix elements can be used to predict total cross sections.

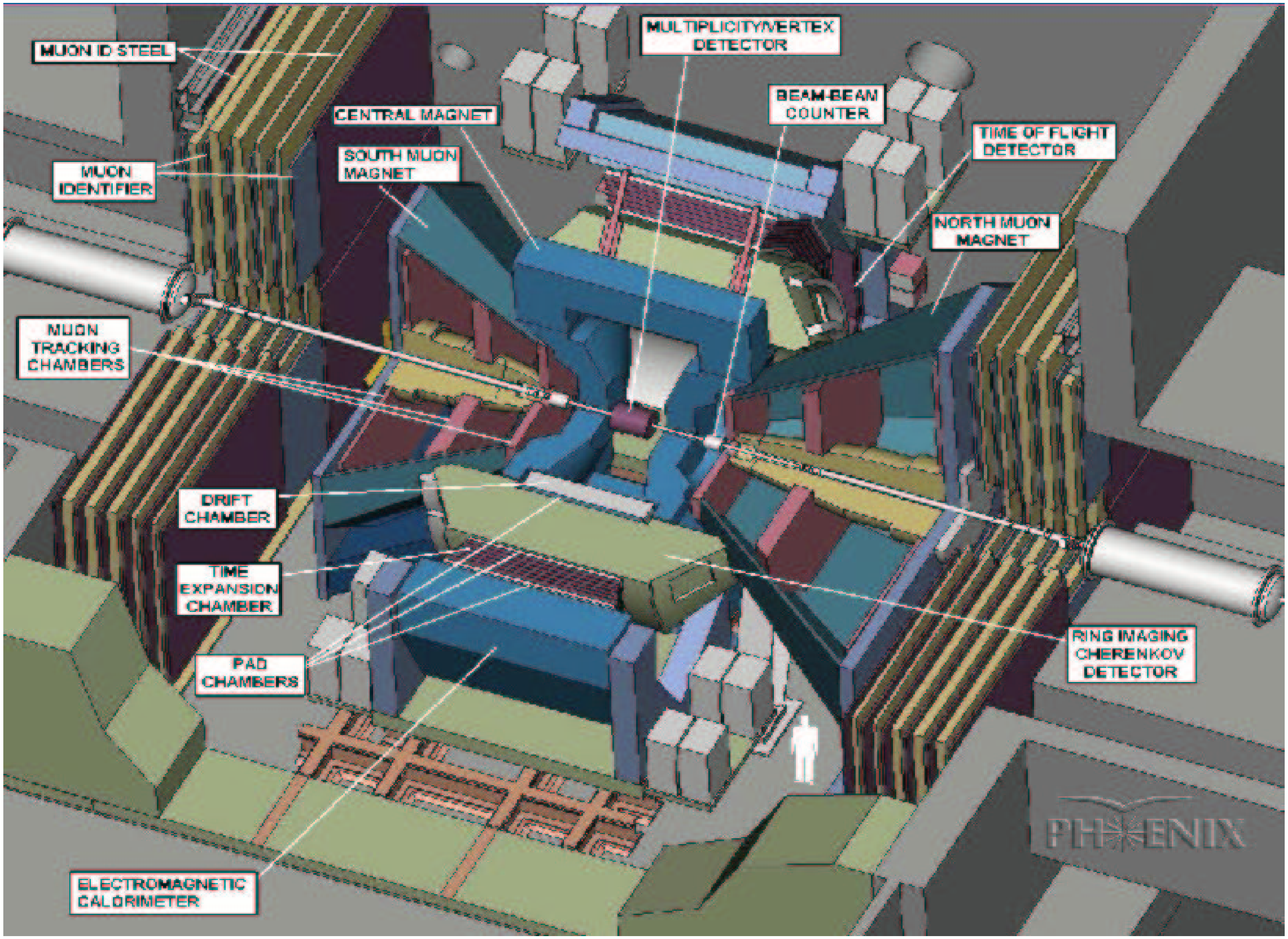
Tevatron p_T distribution



Total cross sections



The PHENIX Experiment



The PHENIX Experiment

Detects muons at forward rapidities

Two muon arms (north and south)
$-1.2 < y < -2.2$ in south arm, $1.2 < y < 2.4$ in north arm
Complete azimuthal coverage in each arm
Detects muons with 2 GeV < p < 50 GeV
π/μ rejection $\sim 10^{-4}$

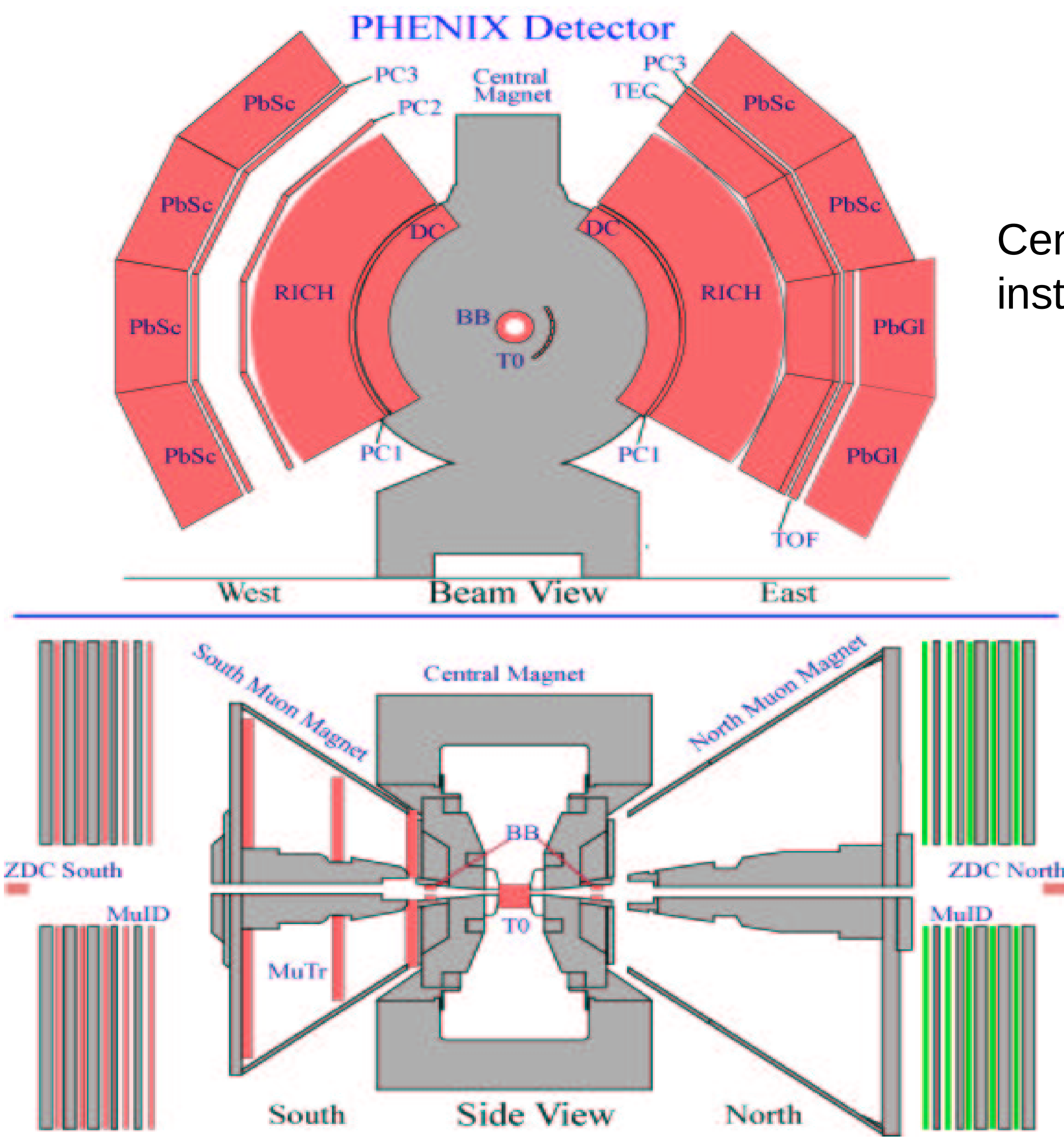
Detects electrons, hadrons, photons at mid-rapidities

Two central arms (east and west)
$-0.35 < y < 0.35$ for each arm
Azimuthal coverage $\pi/4$ for each arm
Electron identification in the range 0.2 GeV < p < 5 GeV
π/e rejection $\sim 10^{-4}$

PHENIX Expectations

Run 2 (complete): preliminary J/ψ cross section in pp collisions, attempt at J/ψ cross section in Au collisions.
Run 3 (in progress): d-Au collisions to study nuclear effects on J/ψ production, followed by pp run to give more statistics for cross section and polarization measurements.
Run 4: More Au collisions. J/ψ supression in Quark Gluon Plasma?

PHENIX Run 2 Setup



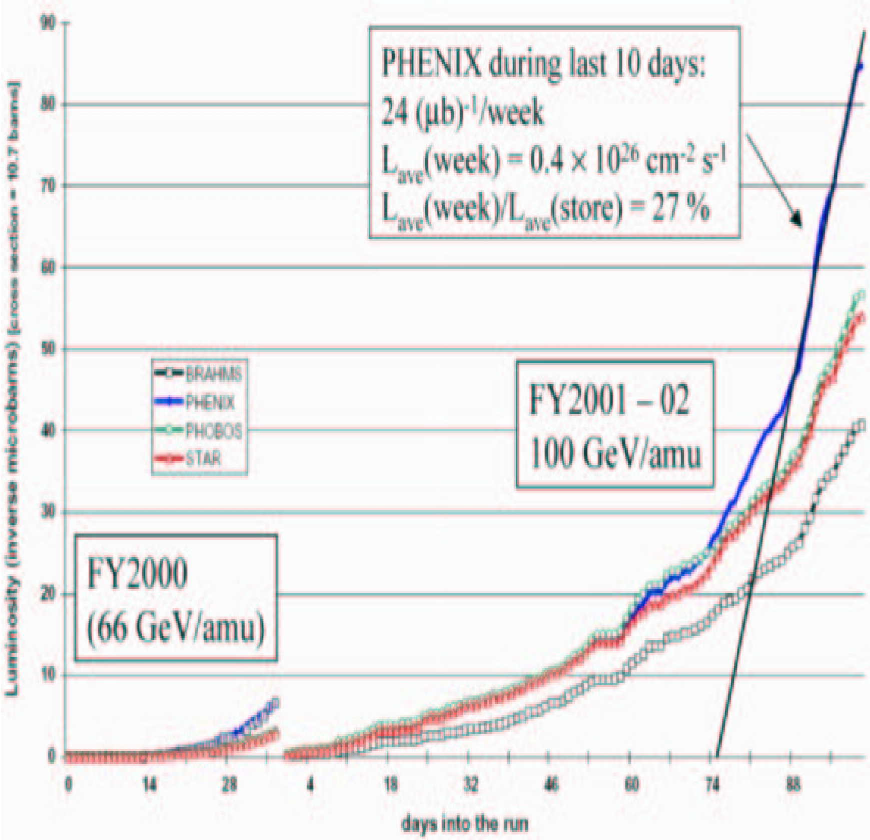
Central arms completely instrumented for Run 2

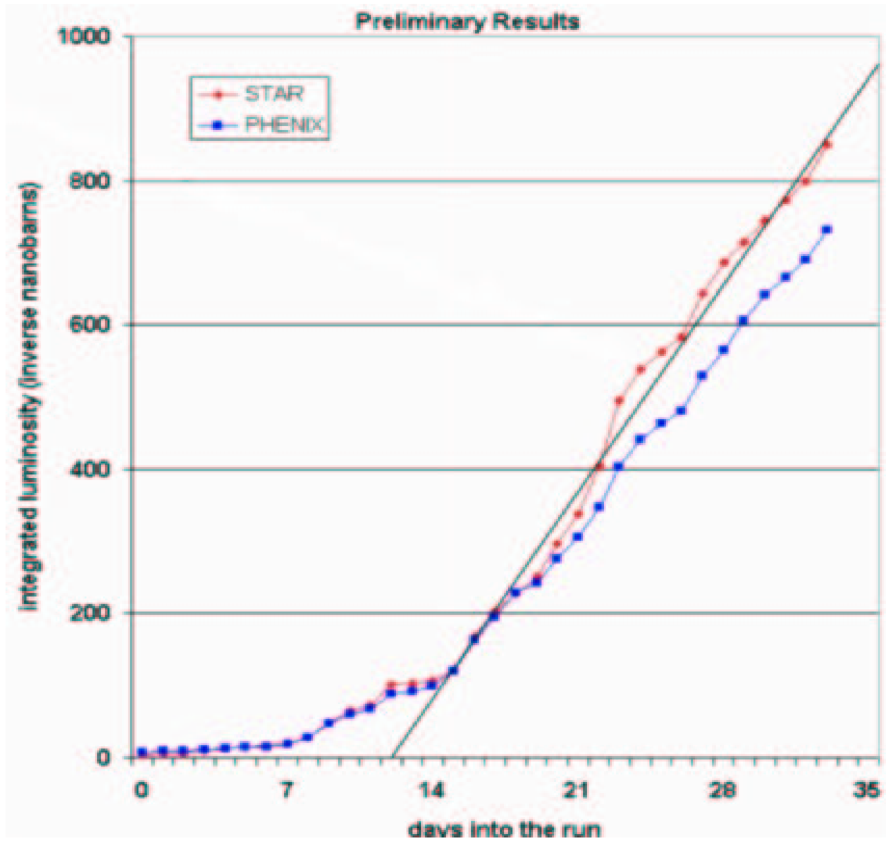
Only the south muon arm was installed for Run 2. The north arm is currently operational for Run 3.

RHIC Run 2 Luminosity

Au-Au running: After online vertex cuts and duty factor, PHENIX collected collision data for an integrated luminosity of 24 μb^{-1}.

pp running: PHENIX collected collision data for an integrated luminosity of 150 nb^{-1}



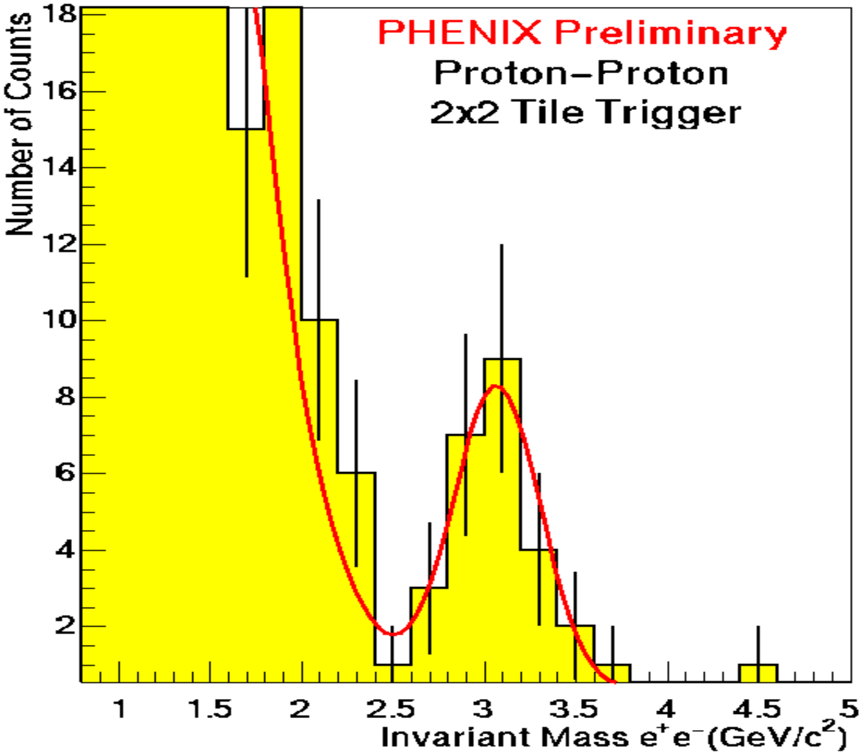


pp: $J/\psi \longrightarrow e^+ e^-$ Analysis

Trigger: at least one hit in each Beam-Beam Counter, EMCal deposited energy > 700 MeV.

After offline cuts, about 48 nb^{-1} (1.0 x 10^9 events) was used for a preliminary analysis.

Fit like sign spectrum, use that functional form + gaussian signal to fit unlike sign spectrum.



$N_{J/\psi} = 24 \pm 6$ (stat) ± 4 (sys)

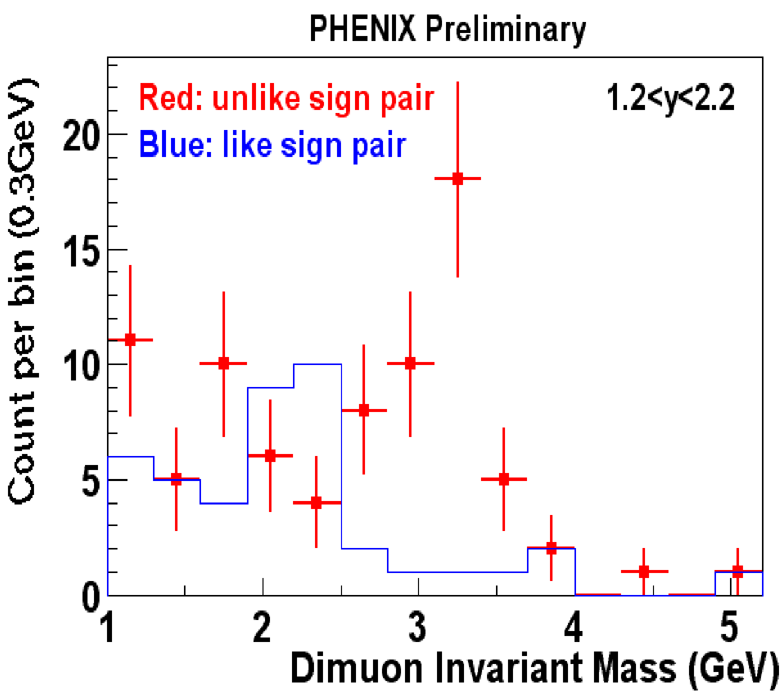
pp: J/ψ ⟶ $\mu^+ \mu^-$ Analysis

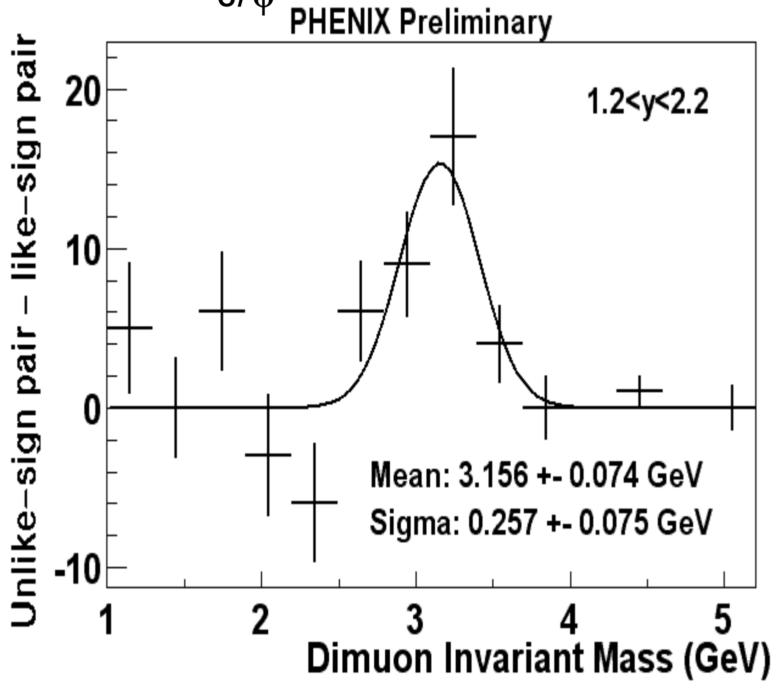
Trigger: at least one hit in each Beam-Beam Counter, at least one deep and one shallow road in the Muon Identifier.

After offline cuts, about 81 nb^{-1} (1.7 x 10^9 events) was used for a preliminary analysis.

Subtract like sign spectrum from unlike sign spectrum to get signal.

$N_{J/\psi}$ = 36 ± 7 (stat) ± 4 (sys)

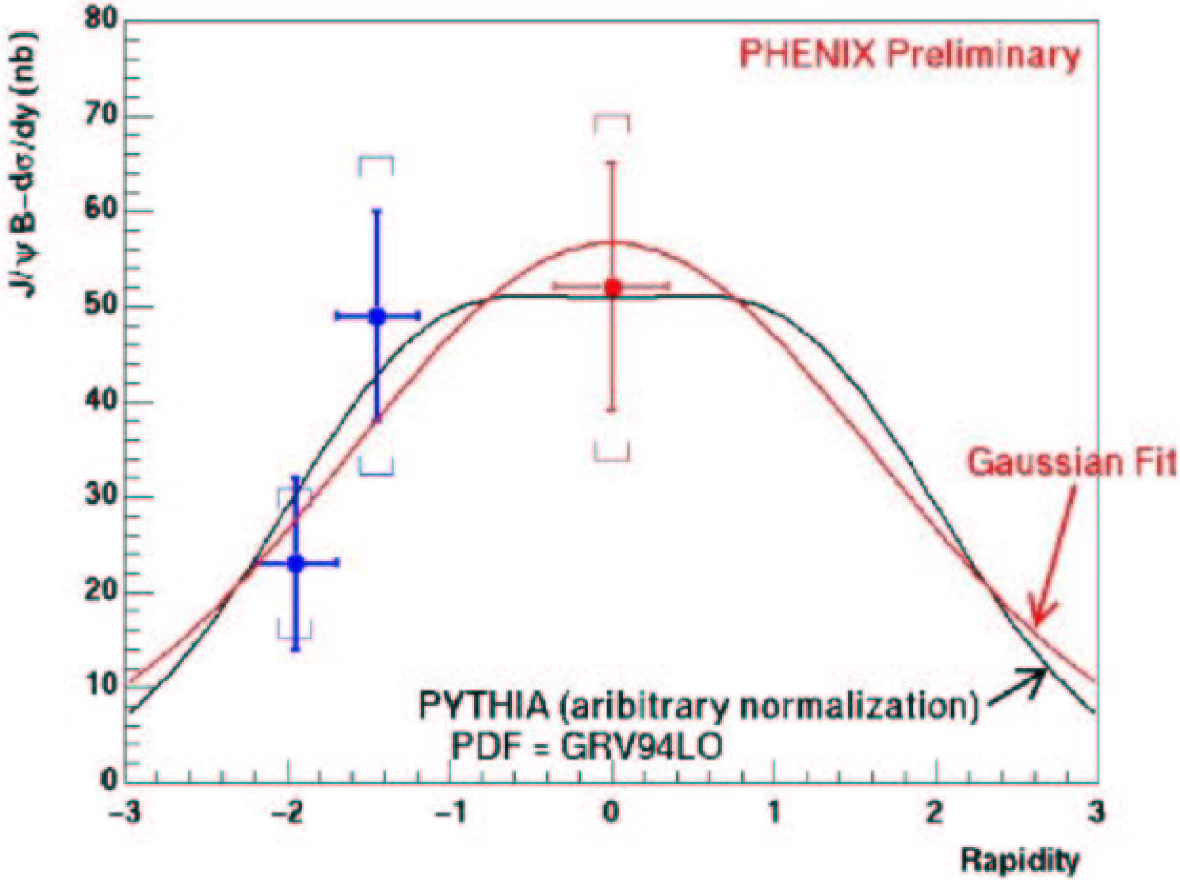




pp Cross Section and Rapidity Distribution

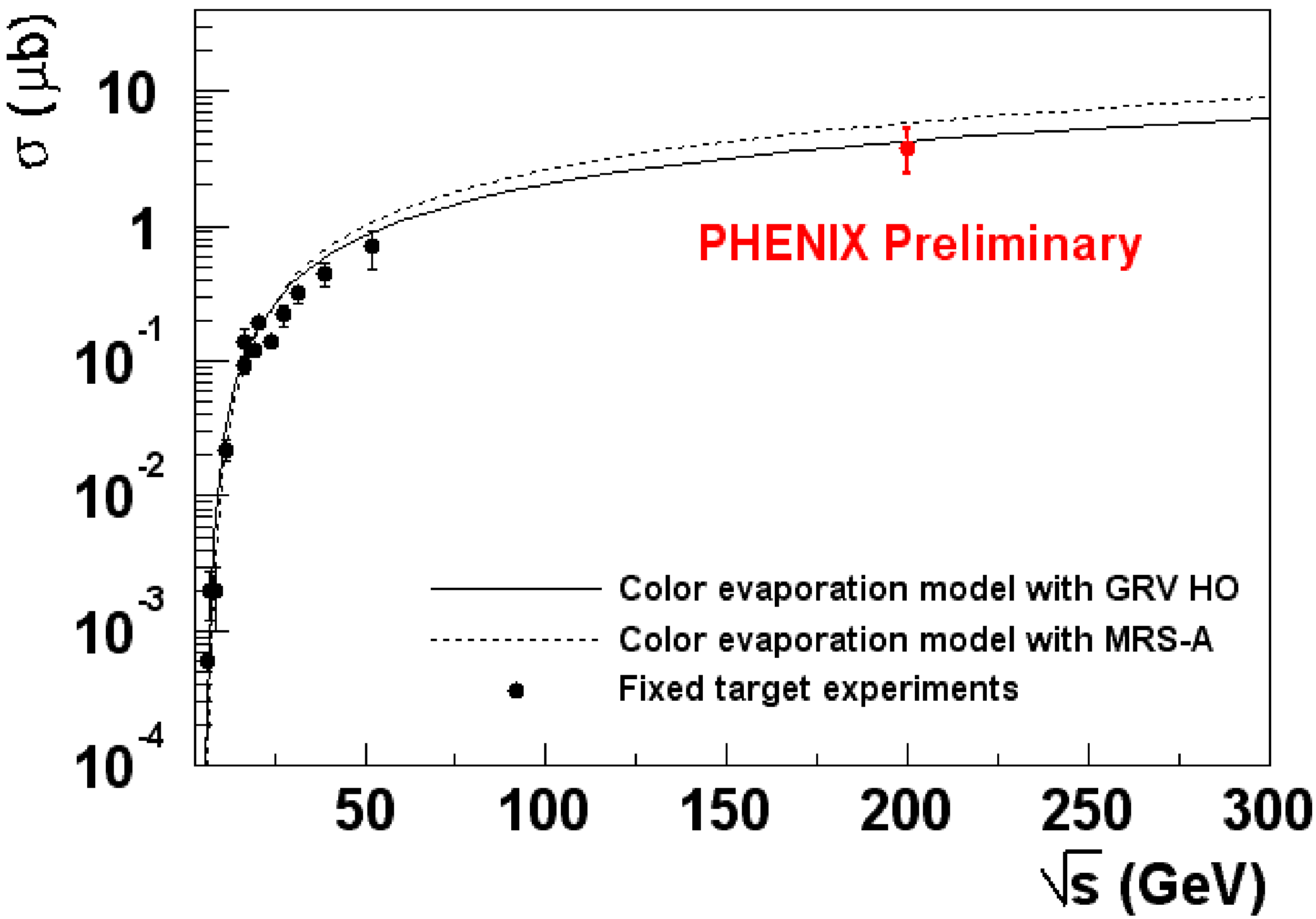
Muon data is divided into two rapidity bins. Gaussian and PYTHIA shapes are fit to the data and averaged, integrated to get the total cross section.

$$\sigma = 3.8 \pm 0.6(\text{stat}) \pm 1.3(\text{sys}) \;\; \mu b$$



Comparison with Color Evaporation Model

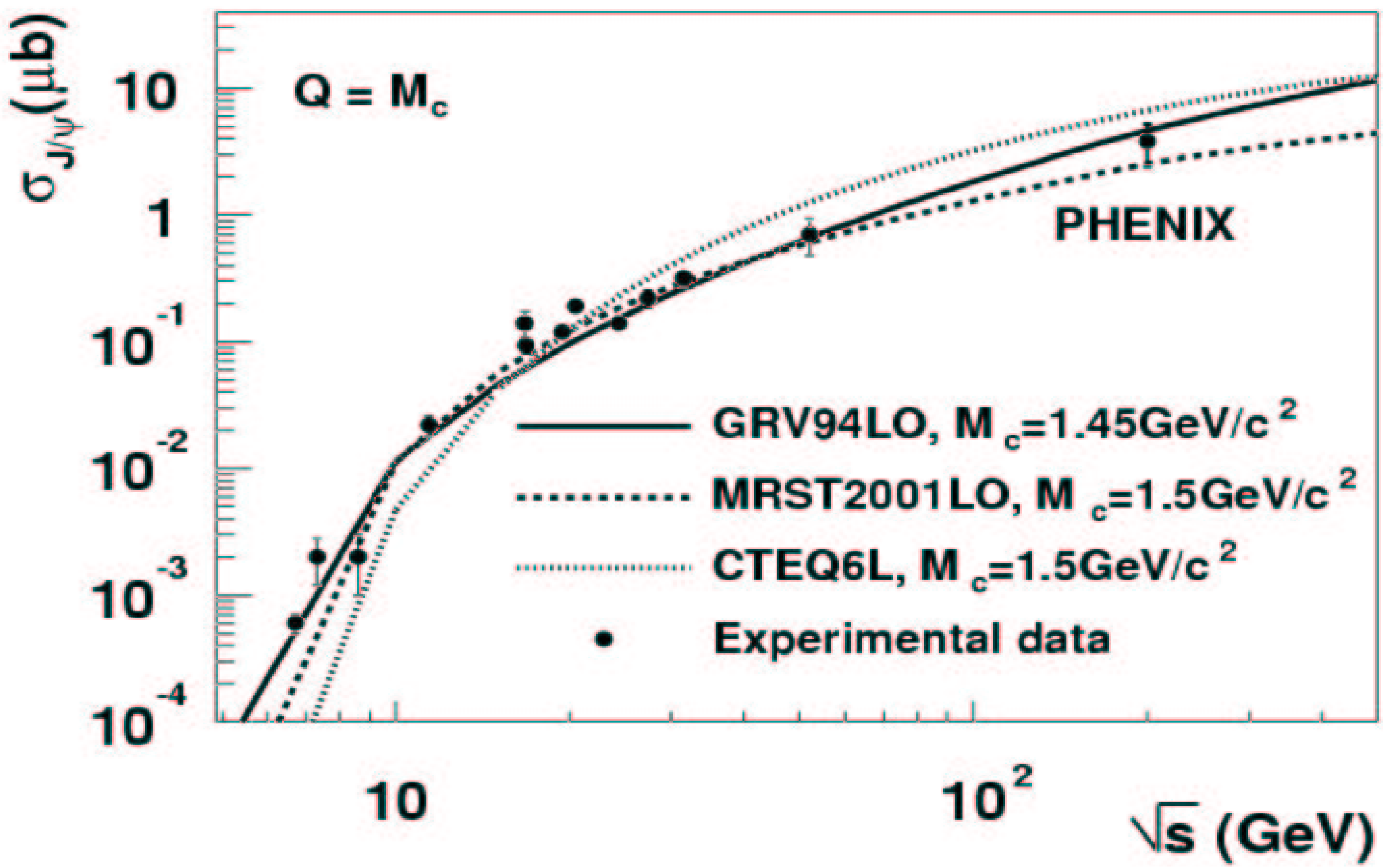
See J.F. Amundson, O.J.P. Eboli, E.M. Gregores, and F. Halzen, Phys. Lett. B390, 323 (1997)



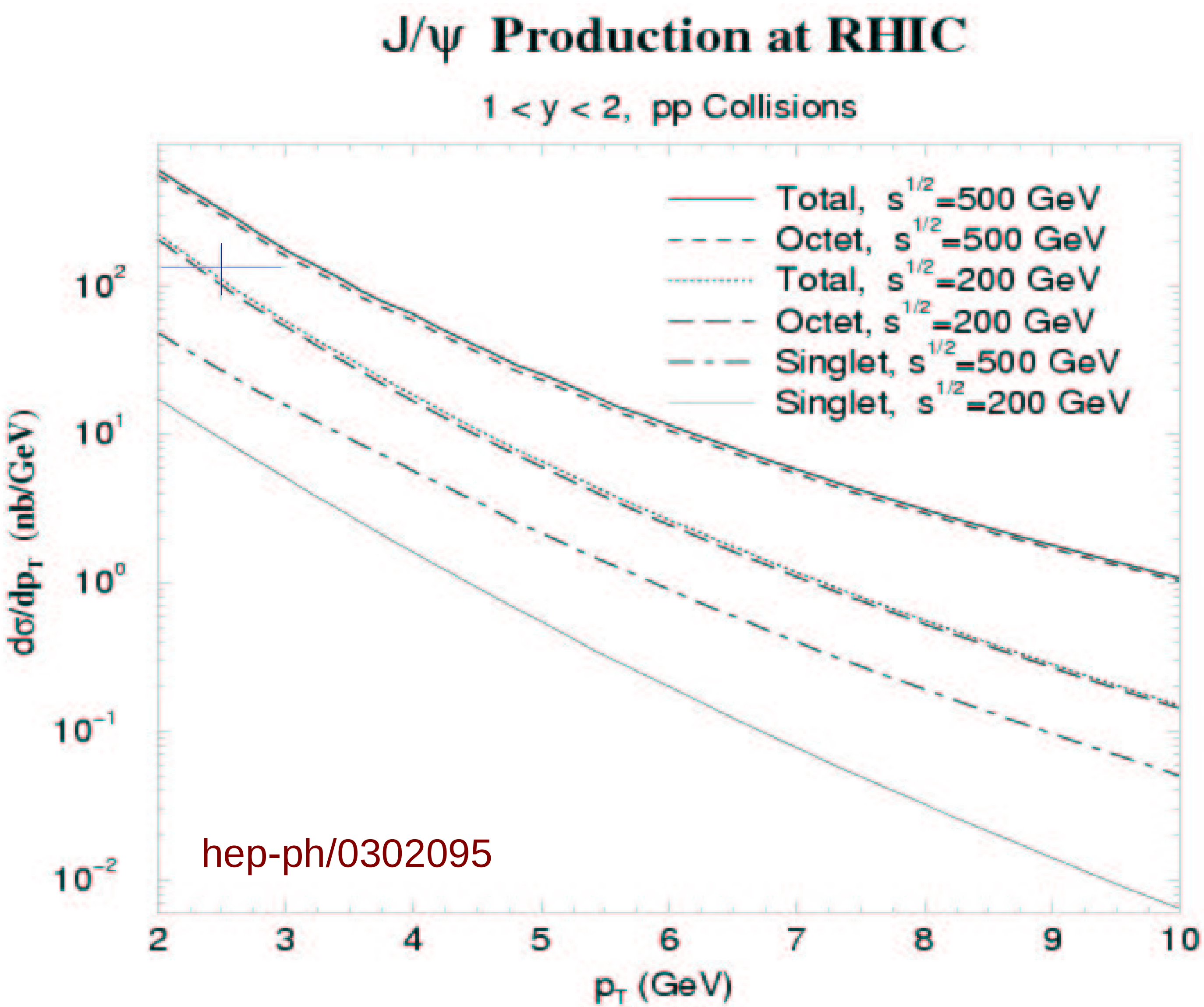
Comparison with NRQCD

NRQCD with color octet contributions. Calculations by PHENIX collaborators H. Sato and N. Saito.

Some uncertainty due to choice of scale, charm mass.



J/ψ p_T Spectrum at RHIC



Conclusions

- A charmonium production measurement is an important test of the production theories.
- A preliminary J/ψ cross section measurement in pp collisions at PHENIX is consistent with the Color Evaporation model and NRQCD theory. One data point at p_T = 2-3 GeV appears to confirm that the color octet contributions are the dominant ones.
- Statistics for J/ψ production in heavy ion collisions will not allow for conclusions about suppression/enhancement at this time. We expect more statistics in coming runs from addition of north muon arm and more integrated luminosity.
- A J/ψ polarization measurement was attempted, but statistics are too low for the result to be meaningful. Should get enough statistics from future runs to do it.