Charmonium Production in pp Collisions at PHENIX

Andrew S. Hoover

Dept. of Physics, New Mexico State University, Las Cruces, NM 88003
for the PHENIX Collaboration

Abstract: A preliminary measurement of the J/ψ production cross section in $\sqrt{s} = 200$ GeV pp collisions at PHENIX is presented. Using observations of the $J/\psi \rightarrow \mu^+\mu^-$ and $J/\psi \rightarrow e^+e^-$ decay channels, the total production cross section for J/ψ is found to be 3.8$\pm$0.6(stat.)$\pm$1.3(sys.)μb. The measurement agrees well with predictions given by the Color Evaporation Model and non-relativistic QCD. Our one available data point for the differential p_t cross section indicates that the color octet production mechanisms dominate J/ψ production at RHIC.

1. Introduction

There is now great interest in the study of J/ψ production in pp collisions following the observation that the Color Singlet Model significantly underpredicts the J/ψ and ψ' cross sections from the CDF data [1]. Models which include color octet production mechanisms are now favored. Previous measurements of the total J/ψ cross section have been limited to the low energy region below $\sim$60 GeV. Measurements at RHIC will significantly extend our reach to higher energies. The PHENIX experiment will collect J/ψ data from polarized pp collisions at $\sqrt{s} = 200$ and 500 GeV. This will allow us to test currently available production models like the Color Evaporation Model (CEM)[2], and non-relativistic QCD (NRQCD) [3]. NRQCD employs a factorization of the production amplitude into short distance perturbative coefficients, and long distance matrix elements which must be extracted from experimental data. These matrix elements should be universal, meaning that once they have been determined (from the CDF data, for example), they can be used to make predictions for other experiments like PHENIX, providing a test of the theory.

There is also interest in studying J/ψ production in heavy ion collisions in light of results from the NA50 experiment [4][5], which showed a suppression of J/ψ production in Pb-Pb collisions at $\sqrt{s_{NN}} = 17.3$ GeV, possibly due to creation of a Quark-Gluon Plasma (QGP). PHENIX has collected data for Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV, allowing for further study of J/ψ suppression as a possible signal of the QGP. PHENIX has also collected data for d-Au collisions, allowing for the study of nuclear absorption effects.

2. Experimental Data

During the 2001-02 RHIC running period, the PHENIX experiment collected data for Au-Au and pp collisions at $\sqrt{s_{NN}} = 200$ GeV. The pp results are discussed here. The J/ψ particle is observed via its decay to electrons in the PHENIX central arms, and via its decay to muons in the south muon arm (the north muon arm was added after this running period). The central arms cover the rapidity range -0.35 $< y <$ 0.35, and the south muon arm covers the rapidity range -2.2 $< y <$ -1.2.

J/ψ events are selected by requiring a coincidence of the minimum-bias trigger and a level-1 J/ψ trigger. The minimum-bias trigger requires a hit in each of the two Beam-Beam Counters (BBC). The J/ψ trigger for the central arms required that at least 700 MeV be deposited in the Electromagnetic Calorimeter (EMC). The J/ψ trigger for the muon arm required at least one shallow muon (reaching at least the first of five Muon Identifier (MuId) layers), and one deep muon

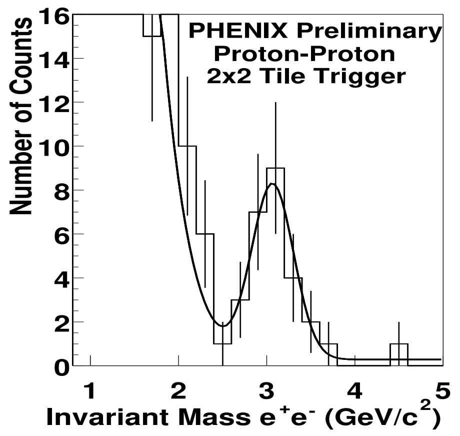

Figure 1: Invariant mass spectrum for unlike-sign dielectron pairs.

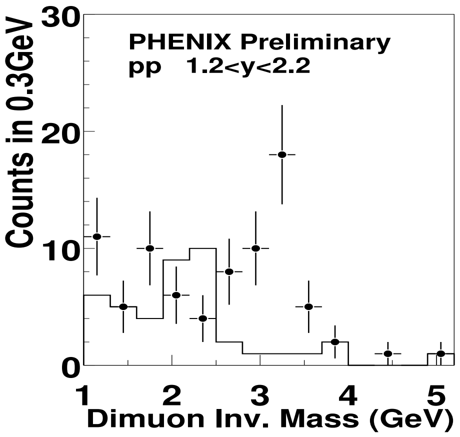

Figure 2: Invariant mass spectrum for like-sign dimuon pairs (histogram), and unlike-sign pairs (points).

(reaching at least the fourth MuId layer). Electron candidates in the central arms were charged tracks associated with a ring in the Ring Imaging Cherenkov (RICH) detector and an EMC hit. Muon candidates in the south muon arm were found by matching hits in the MuId with clusters of hits in the three Muon Tracker (MuTr) tracking stations and the vertex determined by the BBC. Invariant mass distributions for dielectron and dimuon candidates are created using all possible combinations of found tracks.

Figure 1 shows the invariant mass spectrum for unlike-sign dielectron pairs. The background shape is determined from the like-sign spectrum, then that functional form plus a gaussian is fitted to the unlike-sign data. Figure 2 shows the invariant mass spectrum for like-sign dimuon pairs (histogram), and unlike-sign pairs (points). The like-sign spectrum is subtracted from the unlike-sign spectrum to perform the background subtraction.

To compute the production cross section, the dimuon data is divided into two rapidity bins, $-2.2 < y < -1.7$ and $-1.7 < y < -1.2$, while the dielectron data fills one rapidity bin in the range $-0.35 < y < 0.35$. The number of observed J/ψ in the dimuon channel is found to be 26 ± 6(stat.)± 2.6(sys.) for the rapidity bin $-1.7 < y < -1.2$, and 10 ± 4(stat.)± 1.0(sys.) for the $-2.2 < y < -1.7$ bin. For the dielectron channel, the number of observed J/ψ in the rapidity bin $-0.35 < y < 0.35$ is 24 ± 6(stat.)± 4(sys.).

The J/ψ production cross section for each rapidity bin is computed using the formula

$$B_{ll}\frac{\mathrm{d}\sigma}{\mathrm{d}y} = \frac{1}{\Delta y}\frac{N_{J/\psi}}{\mathcal{L}(A\epsilon)_{J/\psi}} \ , \tag{1}$$

where $N_{J/\psi}$ is the number of observed J/ψ , B_{ll} is the branching ratio for J/ψ decaying to dileptons (5.9% from the PDG), $\mathcal{L}$ is the integrated luminosity, and $(A\epsilon)_{J/\psi}$ is the product of the detector acceptance and the triggering and reconstruction efficiencies. The PYTHIA event generator, a detector simulation, and the track reconstruction software were used to determine the detector acceptance and efficiency for single J/ψ particles in the south muon arm and the central arms. The data sample discussed here contains J/ψ in the p_t range 0-5 GeV. For the muon data, enough

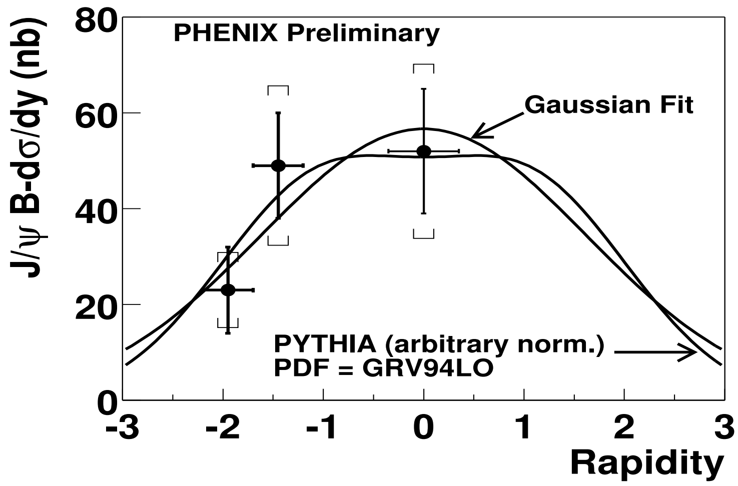

Figure 3: $\mathrm{d}\sigma/\mathrm{d}y$ times the branching ratio for J/ψ production in pp collisions.

events were collected to determine that the PYTHIA p_t distribution is a good match to the data. The PYTHIA p_t distribution was used to determine the $(A\epsilon)_{J/\psi}$ factor for each of the two rapidity bins. For the south muon arm, $(A\epsilon)_{J/\psi} = 0.0131$ for the rapidity range $-1.7 < y < -1.2$, and $(A\epsilon)_{J/\psi} = 0.0108$ for the rapidity range $-2.2 < y < -1.7$, with a systematic error of 18% for both values, to account for variations in the active detector regions. For the electron data, there were not enough events to determine the shape of the p_t distribution. Two models for the p_t distribution with different values of $\langle p_t \rangle$ were used as input to the simulation to determine the $(A\epsilon)_{J/\psi}$ for the central arms. The average value from the different models was taken, and a systematic error of 7% was assigned to account for the differences. An additional 22% systematic error is assigned to account for variations in the active detector area and the triggering efficiency. These systematic errors are then added in quadrature. For J/ψ decaying into the central arms, we find $(A\epsilon)_{J/\psi} = 0.0096$, with a systematic error of 23%. Finally, the integrated luminosity was found to be 81 nb^{-1} for the dimuon data, and 48 nb^{-1} for the dielectron data, with a 20% systematic error for both. The results of the calculations for the three rapidity bins using these input values are shown in Figure 3.

The total production cross section for J/ψ in full phase space is determined by fitting the rapidity distribution in Figure 3 with a function, integrating it, and dividing by the branching ratio. Fitting the rapidity distribution and integrating with either a gaussian function or the PYTHIA distribution shape give virtually the same result. The average of the two methods gives $\sigma_{J/\psi} = 3.8 \pm 0.6$ (stat.) $\pm$ 1.3 (sys.) μb.

The quantity $\mathrm{d}\sigma_{J/\psi}/\mathrm{d}p_t$ is also computed from the muon data in the range 2 GeV$< p_t <$3 GeV. Although the data extends down to $p_t = 0$ GeV, the theoretical prediction[8] is limited to $p_t > 2$ GeV. In this p_t bin, it is found that $(A\epsilon)_{J/\psi} = 0.011$ with an 18% systematic error. The number of J/ψ in this p_t bin is 8$\pm$3.2(stat.)$\pm$0.8(sys.). These values then give $\mathrm{d}\sigma_{J/\psi}/\mathrm{d}p_t = 146.01 \pm 68.6$ nb/GeV in the range 2 GeV$< p_t <$3 GeV, where the statistical and systematic errors have been added in quadrature.

3. Discussion

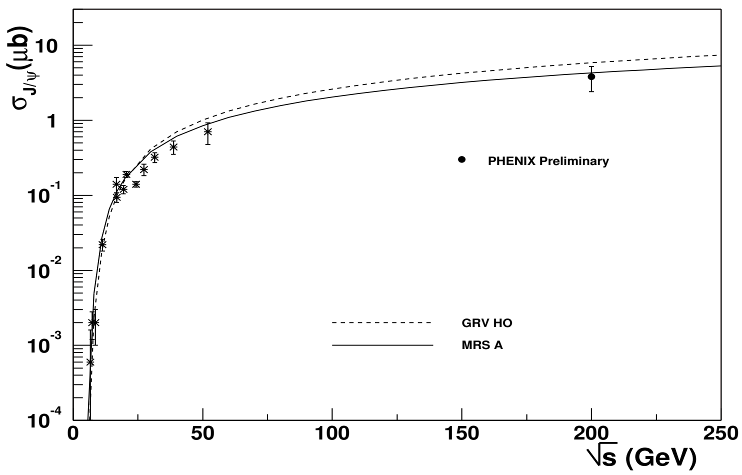

Figure 4: Color Evaporation Model predictions and experimental data points for the total production cross section of J/ψ in pp collisions.

The calculation for the total J/ψ production cross section discussed in [2] has been extended by the authors of that paper to higher center of mass energies to allow comparison with the PHENIX data point. Figure 4 shows the theoretical prediction, along with data points from lower energy experiments and the PHENIX data point at 200 GeV. There is good agreement between the CEM prediction and the measured data points.

A NRQCD prediction for the total J/ψ production cross section as a function of $\sqrt{s}$ has been performed in [7]. Matrix elements determined from the Tevatron data are used to perform the calculation. Figure 5 shows the theoretical predictions, along with data points from lower energy experiments and the PHENIX data point at 200 GeV. The charm quark mass is chosen as shown to provide the best agreement between theory and data, and the QCD scale is set to the charm mass. There is a fair amount of uncertainty between different parton distribution functions. The PHENIX data point is consistent with the NRQCD prediction.

A NRQCD calculation for the p_t dependence of the J/ψ cross section at RHIC has been performed in [8]. There is a large uncertainty in the calculation for p_t below 2 GeV due to the intrinsic motion of the partons inside the colliding protons. In the region $p_t > 2$ GeV, we currently have data for one bin covering the range 2-3 GeV. The NRQCD prediction and the PHENIX data point are shown in Figure 6. Similar to what was observed in the Tevatron data [1], the color singlet production mechanism is inadequate for describing the observed production cross section. In fact, the cross section is dominated by the color octet production mechanism. The single data point currently available indicates that color octet processes dominate J/ψ production at RHIC.

4. Summary and Outlook

The NRQCD factorization method is presently our best theory for charmonium production. The theory is able to predict the p_t differential cross section observed at the Tevatron [6]. Charmonium production measurements at RHIC will further test the theory. From current preliminary analysis of J/ψ production at PHENIX, the total production cross section appears to be well described by NRQCD and also by the CEM. A single data point for the p_t differential cross section is in agreement

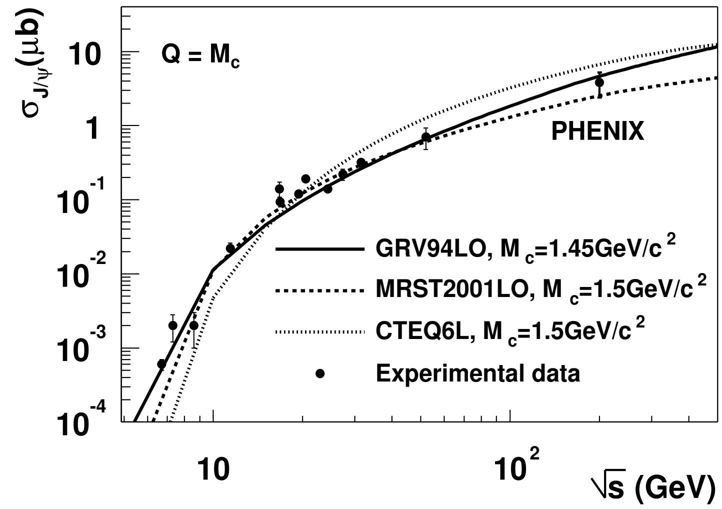

Figure 5: NRQCD predictions and experimental data points for the total production cross section of J/ψ in pp collisions.

with a NRQCD calculation, and indicates that the production of J/ψ at RHIC is dominated by color octet processes. These measurements will improve greatly with increased statistics in coming years. We also expect pp collisions at $\sqrt{s} = 500$ GeV, which will increase our range in p_t.

A critical measurement for the future is the J/ψ polarization. This is an excellent test for NRQCD theory, and is also able to distinguish between NRQCD and the CEM. In the CEM, any polarization is lost due to many gluon emissions, and so the model predicts the J/ψ will be produced unpolarized. NRQCD predicts that at large p_t, the production of charmonium will be dominated by color octet gluon fragmentation. This process produces J/ψ with a large transverse polarization [9]. It is expected that at large p_t, the J/ψ will become increasingly transversely polarized. The CDF experiment has made observations which are not in agreement with this prediction [10]. In fact, they observe a trend towards longitudinal polarization at high p_t. This clearly presents a serious problem for the application of the NRQCD factorization method to charmonium production. Measurements at RHIC will allow for additional study of the J/ψ polarization.

References

[1] F. Abe, *et al.*(CDF Collaboration), Phys. Rev. Lett. **79**, 572 (1997)

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

[3] G.T. Bodwin, E. Braaten, and G.P. Lepage, Phys. Rev. **D51**, 1125 (1997)

[4] M.C. Abreu *et al.*, Phys. Lett. **B410**, 337 (1997)

[5] M.C. Abreu *et al.*, Phys. Lett. **B477**, 28 (2000)

[6] M. Krämer, Prog. Part. Nucl. Phys., **47**, 141 (2001)

[7] H. Sato, Ph.D. thesis, "J/ψ Production in pp Collisions at $\sqrt{s} = 200$ GeV", Kyoto University, Japan (2003) http://www.phenix.bnl.gov/WWW/publish/satohiro/thesis/thesis.ps.gz

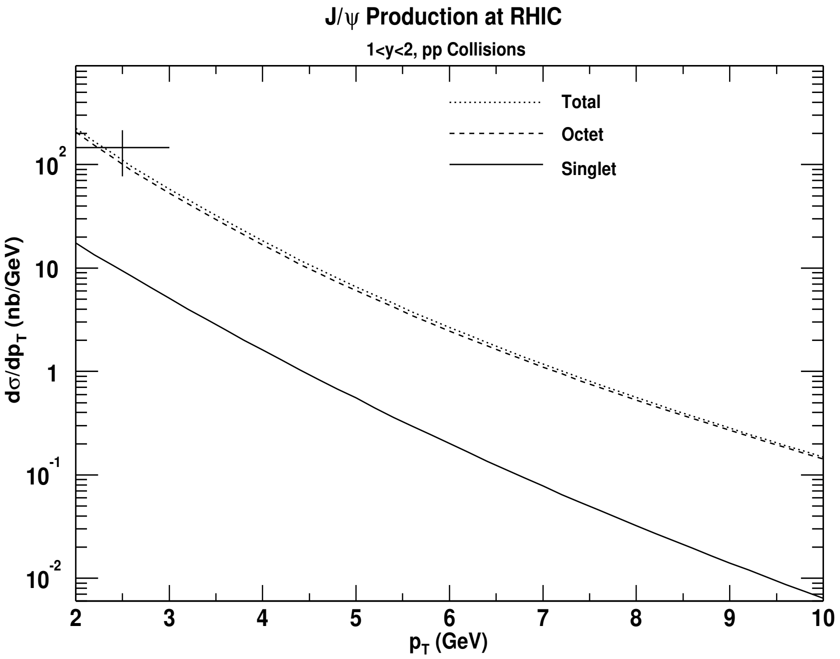

Figure 6: NRQCD predictions and PHENIX data point for the p_t differential cross section of J/ψ in pp collisions at $\sqrt{s} = 200$ GeV.

[8] G. Nayak, M. X. Liu, F. Cooper, hep-ph/0302095 (2003)

[9] E. Braaten, B. Kniehl, and J. Lee, Phys. Rev. **D62**, 94005 (2000)

[10] T. Affolder, *et al.*, Phys. Rev. Lett. **85**, 2886 (2000)