PHENIX results on $J/\psi$ polarization in p+p collisions.

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Abstract. One of the big questions in quarkonia production is how heavy-quark pairs are produced in the initial hard scattering and hadronize into final quarkonia states. This question also affects the estimation of quarkonia breakup cross-sections and color screening in heavy ion collisions. Many existing models describe well general features of quarkonia production like cross-section and transverse momentum distributions. In order to differentiate between various models one has to study quarkonia production in more details. One of such tools is a study of angular distributions of decay leptons, usually called polarization. The PHENIX experiment has measured inclusive $J/\psi$ polar and azimuthal angular decay coefficients in the mid ($|y| < 0.35$) and forward ($1.2 < |y| < 2.2$) rapidity regions in p+p collisions at 200 GeV and 510 GeV. This talk will present the analysis strategy as well as the results in different polarization frames.

1. Introduction

Measurements of quarkonium states in p+p collisions provide a unique tool for testing Quantum Chromodynamics (QCD). The $J/\psi$ is a colorless neutral meson with spin 1, decays with considerable branching ratio into lepton pairs, and is produced predominantly via gluon fusion at Relativistic Heavy Ion Collider (RHIC) energies. Various theoretical models have been developed to describe the general features of $J/\psi$ production such as transverse momentum ($p_T$) spectra, while consistent predictions of the spin alignment measurements for quarkonia remain a challenge.

The spin alignment of a positively charged lepton from a $J/\psi$ decay, commonly known as “polarization”, has been measured at the Tevatron [1], RHIC [2, 3], and the Large Hadron Collider [4, 5, 6]. Measuring spin alignment provides additional tests for the theory and understanding dominant quarkonium production mechanisms in different kinematic regimes. The $J/\psi$ polarization is measured by fitting the angular distribution of a positively charged lepton, shown in Eq. (1), to data and extracting decay angular coefficients.

\[
\frac{dN}{d\Omega} \sim 1 + \lambda_\theta \cos^2 \theta + \lambda_{\theta\phi} \sin^2 \theta \cos 2\phi + \lambda_\phi \sin 2\theta \cos \phi
\]  

where $\theta$ is the polar and $\phi$ is the azimuthal angles of a positive decay lepton in $J/\psi$ rest frame. The coefficients $\lambda_\theta$, $\lambda_{\theta\phi}$ and $\lambda_\phi$ are determined most commonly in the helicity (HX) frame [9], Collins-Soper (C-S) frame [10] and Gottfried-Jackson (G-J) frame [11] defined in the $J/\psi$ production plane.

Equation (2) shows the two frame-invariant variables defined to characterize the decay angular distribution.
\[ \tilde{\lambda} = \frac{\lambda_\theta + 3 \lambda_\phi}{1 - \lambda_\phi}, \quad F = \frac{1 + \lambda_\theta + 2 \lambda_\phi}{3 + \lambda_\theta} \]  

Previously a PHENIX $J/\psi$ measurement at $\sqrt{s} = 510$ GeV in p+p at forward rapidity showed largely longitudinal net polarization (negative angular coefficients) \[3\], while a prior midrapidity PHENIX measurement at $\sqrt{s} = 200$ GeV was consistent with no strong polarization \[2\]. The present analysis for midrapidity $J/\psi$ production in $\sqrt{s} = 510$ GeV collisions is complementary to both previous measurements.

2. Analysis Procedure

$J/\psi$'s were reconstructed via invariant mass distribution of opposite sign electron pairs. Combinatorial background was subtracted using same-sign pairs (for high $p_T$ pairs detected in the same PHENIX Central Arm) or mixed events method (for low $p_T$ pairs detected in opposite Arms). Signal and remaining correlated (physics) background were fit by a sum of a Crystal Ball function for signal and an exponential for the background. Number of $J/\psi$'s was then determined by adding up counts in 2.8-3.3 GeV/$c^2$ mass range (after all background subtraction). An example of such fit is shown in Fig. 1. $\cos \theta - \phi$ phase space was divided into 10 bins in $\phi$ and 5 bins in $\cos \theta$ and number of $J/\psi$'s were counted for each bin, as is shown in Fig. 2.

![Figure 1. Example of a dilepton invariant mass distribution fit.](image1)

![Figure 2. Invariant mass distributions for all $\cos \theta - \phi$ bins in Gottfried-Jackson frame.](image2)

The $\cos \theta - \phi$ histogram obtained in this way was then corrected for acceptance times efficiency calculated using full Geant 3 simulation and fit with Eq. 1 An example of such fit is shown in Fig. 3 for Gottfried Jackson frame at mid-rapidity. Color contours show one (red), two (blue) and three (black) sigma uncertainty of the fit. Red point indicates most probable value.

3. Results

The results of $J/\psi$ polarization measurement at mid-rapidity are shown in Fig. 4 for the $\lambda_\theta$, $\tilde{\lambda}$ and $F$ for the three polarization frames. The results are consistent with no polarization. At low $p_T$ PHENIX acceptance for Collins-Soper frame is very limited, and therefore the measurement was not performed.

The results of $J/\psi$ polarization measurement at forward rapidity are shown in Fig. 5 and Fig. 6 for the $\lambda_\theta$ and $\tilde{\lambda}$ correspondingly. These results were published by the PHENIX collaboration.
Figure 3. Example of a fit to $\cos \theta - \phi$ distribution.

Figure 4. $\lambda_\theta$ (left), $\tilde{\lambda}$ (center) and $F$ (right) as a function of transverse momentum.

Figure 5. $\lambda_\theta$ as a function of $p_T$ for forward rapidity [3].

Figure 6. $\tilde{\lambda}$ as a function of $p_T$ for forward rapidity [3].
previously in Ref. [3]. The results indicate negative (longitudinal) polarization, in contrast with two theory predictions by H.S.Chung et al. [12] and H.Shao et al. [13], also shown in Fig. 5.

\( \lambda_0 \) and \( \tilde{\lambda} \) dependence on rapidity is shown in Fig. 7 and Fig. 8 correspondingly. The \( p_T \) integration range for mid-rapidity measurement is 3-10 GeV/c, while for forward rapidity it is 4-10 GeV/c. \( \lambda_0 \) is consistent with no polarization in all frames, while \( \tilde{\lambda} \) seems to indicate a trend to negative (longitudinal) polarization at forward rapidity, although experimental uncertainties are rather large.

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**Figure 7.** \( \lambda_0 \) as a function of rapidity.

**Figure 8.** \( \tilde{\lambda} \) as a function of rapidity.

Theory comparisions are shown in Fig. 9, Fig. 10, and Fig. 11. Fig. 9 shows \( \lambda_0 \) as a function of \( x_T = 2p_T/\sqrt{s} \) in Helicity frame for mid-rapidity at \( \sqrt{s} = 200 \text{ GeV} \) and \( \sqrt{s} = 510 \text{ GeV} \). The data are are overlaid with CSM and NRQCD predictions in the Helicity frame from [7]. Both calculations are in desagreement with the data. Fig. 10 shows \( \lambda_0 \) as a function of \( p_T \) for Helicity and Collins-Soper frames. The predictions from [7] are also shown for Helicity (red band) and Collins-Soper (blue band) frames. While prediction for Helicity frame disagree with the data, calculations in Collins-Soper frame describe data reasonably well. Fig. 11 shows \( \tilde{\lambda} \) as a function of \( p_T \) for Heicity frame. along with theoretical predictions from the same two models. Just like for \( \lambda_0 \) in Fig. 9 theory disagrees with the data.

Fig. 12 shows cross-section times branchinh ratio of \( J/\psi \) as a function of transverse momentum. The distribution is fit with a Kaplan function. Fit parameters are \( A = 37.6 \pm 2.2 \text{ nb}/(\text{GeV}/c) \), \( b = 4.33 \pm 0.28 \text{ GeV}/c \), and \( n = 4.61 \pm 0.32 \). Green curve shows theory prediction based on full NRQCD at NLO with leading relativistic corrections that include CS and CO states, provided by Butenschön et al. [7] and is in reasonable agreement with the data above \( p_T > 2\text{ GeV}/c \).

It is interesting to note that the shape of the \( p_T \) dependence at \( \sqrt{s} = 510 \text{ GeV} \) is significantly different from that at \( \sqrt{s} = 200 \text{ GeV} \), measured by the PHENIX experiment previously [2].

The \( p_T \)-integrated cross section times branching ratio is shown in Fig. 13 along with the previous PHENIX results at \( \sqrt{s} = 200 \text{ GeV} \) [8] and the world results from the LHC and Tevatron. All systematic errors for CDF and ALICE experiments were added in quadrature. A simple logarithmic dependence on the collision energy is seen for \( J/\psi \) production at midrapidity, making estimates of \( J/\psi \) yield at any \( \sqrt{s} \) easy, and inviting the theory community to model the trend. The fit parameters are \( A = 70.4 \text{ nb} \), and \( b = 9.27 \text{ GeV}^{-1} \).
4. Conclusions
The PHENIX experiment has measured $J/\psi$ polarization in p+p collisions at 200 and 510 GeV both at mid- and forward rapidity. The results are consistent with no polarization at mid-rapidity, but there is an indication of negative polarization at forward rapidity with some $p_T$ dependence. Various NRQCD-based predictions cannot describe the full set of polarization data, while $J/\psi$ production cross-section as a function of $p_T$ is reasonably well described by NRQCD calculations.

The PHENIX experiment has measured $J/\psi$ $p_T$ distributions and production cross-section in p+p collisions. Cross-section’s $\sqrt{s}$ dependence follows a simple logarithmic law.
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