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J/ψ POLARIZATION IN $p+p$ COLLISIONS AT $\sqrt{s}=200$ GeV IN STAR*

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In this paper, J/ψ polarization at mid-rapidity in $p+p$ collisions at $\sqrt{s}=200$ GeV measured in the STAR experiment at RHIC is reported. J/ψ production is analyzed via the dielectron decay channel. J/ψ polarization is extracted from the decay angular distribution in the helicity frame. The J/ψ polarization is measured at transverse momentum range (2–6) GeV/c and is found to be consistent with NLO$^+$ Color Singlet Model (NLO$^+$ CSM), Color Octet Model (COM) predictions and with no polarization within current uncertainties.

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1. Introduction

A number of models with different J/ψ production mechanisms are able to describe the measured J/ψ production cross section reasonably well. It suggests that other observables are needed to discriminate between different J/ψ production models. J/ψ spin alignment, commonly named as J/ψ polarization, can be used as such an observable since various models have different p_{T} dependent predictions on the J/ψ polarization.

The Color Evaporation Model (CEM) describes J/ψ cross sections measured in many experiments reasonably well but has no prediction power regarding the J/ψ polarization. The NLO$^+$ Color Singlet Model (CSM) [1] predicts longitudinal J/ψ polarization in the helicity frame at low and mid p_{T} at mid-rapidity. These recent calculations of the CSM for the yield differential in p_{T} show better agreement with RHIC data at low and mid p_{T} than earlier CSM calculations and the result for J/ψ polarization is in good agreement with the PHENIX data. Non-relativistic quantum chromodynamics (NRQCD) effective theory, also known as Color Octet Model (COM)

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predicts transverse polarization at high J/ψ p_{T}, $p_{\mathrm{T}} > 5$ GeV/c which is in disagreement with the polarization measurement from the CDF experiment at FermiLab [2]. On the other hand, a tuned NRQCD predicts longitudinal J/ψ polarization at $1.5 < p_{\mathrm{T}} < 5$ GeV/c at mid-rapidity and is able to qualitatively describe the PHENIX J/ψ polarization measurements as well as the cross section measurements [3].

The measurement of J/ψ polarization at $p_{\mathrm{T}} > 5$ GeV/c is expected to have discrimination power against different models of J/ψ production since, *e.g.*, NLO^{+} CSM and COM predict different polarization in that J/ψ p_{T} region.

1.1. Decay angular distribution

In this study, J/ψ polarization is analyzed via the angular distribution of the electron decay from charmonium in the helicity frame [4]. The angular distribution is derived from the density matrix elements of the production amplitude using parity conservation rules. Polar angle θ is the angle between the positron momentum vector in the J/ψ rest frame and J/ψ momentum vector in the laboratory frame.

The angular distribution integrated over the azimuthal angle is parametrized

$$\frac{dN}{d\cos\theta} \propto 1 + \lambda\cos^2\theta\,, \tag{1}$$

where λ is the polarization parameter that contains both the longitudinal and transverse components of the J/ψ cross section. When $\lambda = 0$ there is no polarization, $\lambda = -1$ means full longitudinal polarization and $\lambda = 1$ corresponds to full transverse polarization.

2. Data analysis

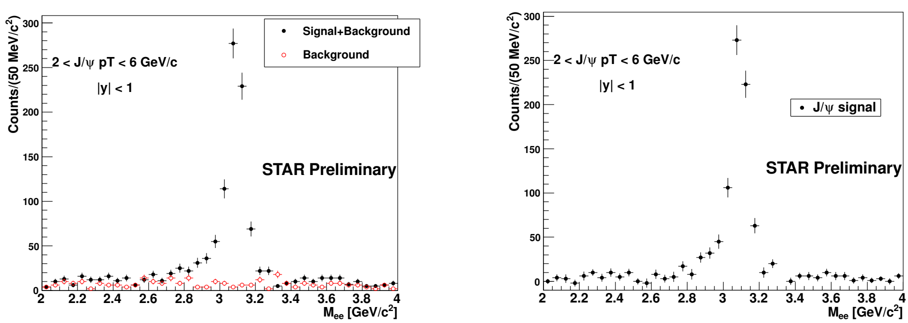
In this analysis, data recorded in 200 GeV $p+p$ collisions in the STAR experiment in year 2009 is used. The analyzed data was sampled from an integrated luminosity of ~ 1.5 pb^{-1} and was triggered by the STAR Barrel Electromagnetic Calorimeter (BEMC). The trigger required transverse energy deposited in a single BEMC tower ($\Delta\eta \times \Delta\phi = 0.05 \times 0.05$) to be within $2.6 < E_{\mathrm{T}} \leq 4.3$ GeV.

J/ψ is reconstructed via its dielectron decay channel $J/\psi \to e^{+}e^{-}$ with branching ratio BR $= 5.9\%$, and is required that at least one of electrons from J/ψ decay satisfies the trigger conditions. The Time Projection Chamber (TPC), Time-of-Flight (TOF) and BEMC detectors are used to reconstruct and identify electrons. The TPC provides information about dE/dx. Information from the TOF is very useful for electron identification and hadron rejection at lower momenta, where electron and hadron dE/dx bands overlap, $|1/\beta - 1| < 0.03$ ($\beta = \mathrm{v}/c$) cut was applied at $p < 1.4$ GeV/c.

In 2009, 72% of the TOF detector was installed. At higher momenta the BEMC can reject hadrons very efficiently. For momenta above 1.4 GeV/c a cut of $E/p > 0.5$ was used, where E is energy deposited in a single BEMC tower (for electrons E/p ratio is expected to be ≈ 1).

2.1. J/ψ signal

The cuts mentioned above allowed us to obtain a very clear J/ψ signal with a signal to background ratio of 15 and very high significance of 26σ. Fig. 1 (a) shows the invariant mass distribution of all combinations of e^+e^- pairs in black (closed circles) and combinatorial background in grey/red (open circles). The combinatorial background is calculated using like-sign technique, from a sum of e^+e^+ and e^-e^- pairs. The J/ψ signal is obtained by subtracting the (red) histogram (background) from the black histogram (signal + background), see Fig. 1 (b). The number of J/ψs calculated by counting bin entries in the invariant mass range (2.9–3.3) GeV/c^2 is 772 ± 29 in the J/ψ $p_{\rm T}$ range (2–6) GeV/c and $|y| < 1$. The same mass window is used for the polarization analysis for which the signal is split into 3 statistically comparable $p_{\rm T}$ bins.

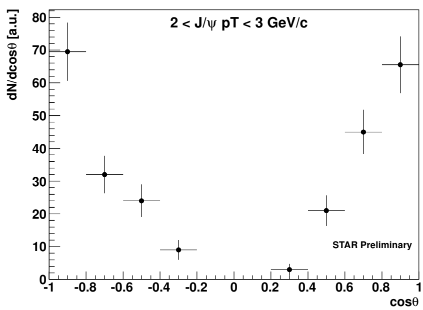


(a) (b)

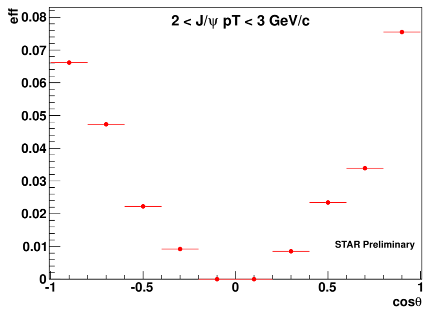
Fig. 1. Invariant mass distributions in J/ψ mass window (2.9–3.3) GeV/c^2, J/ψ $p_{\rm T}$ range (2–6) GeV/c and $|y| < 1$. (a) shows signal + background in black (full circles) and like-sign background in grey/red (open circles). (b) shows J/ψ signal after the combinatorial background subtraction.

3. J/ψ polarization

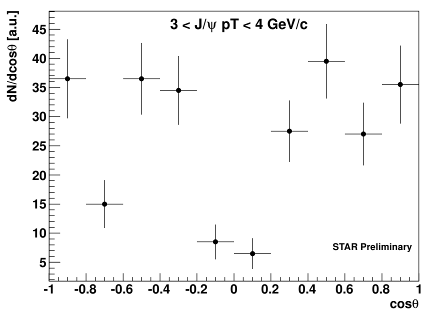
The uncorrected $\cos\theta$ distribution is obtained using the same electron identification cuts as J/ψ signal, in the J/ψ $p_{\rm T}$ range of (2–6) GeV/c and $|y| < 1$. The $\cos\theta$ distribution is divided into $3 J/\psi$ $p_{\rm T}$ bins: $2 < p_{\rm T} < 3$ GeV/c, $3 < p_{\rm T} < 4$ GeV/c and $4 < p_{\rm T} < 6$ GeV/c. The $\cos\theta$ distributions for the $3 p_{\rm T}$ bins, with combinatorial background subtracted are presented in Fig. 2 (a), 2 (c), 2 (e) respectively.



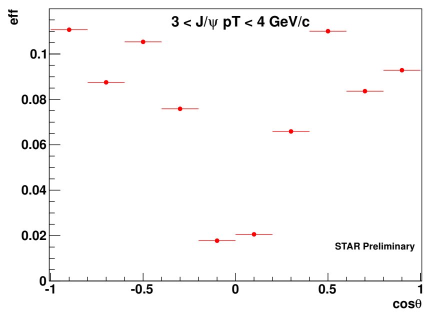
(a) J/ψ p_{T} range $2 < p_{\mathrm{T}} < 3$ GeV/c



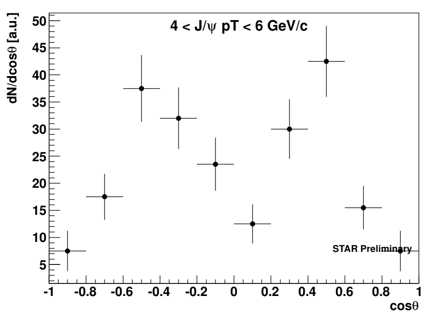
(b) J/ψ p_{T} range $2 < p_{\mathrm{T}} < 3$ GeV/c



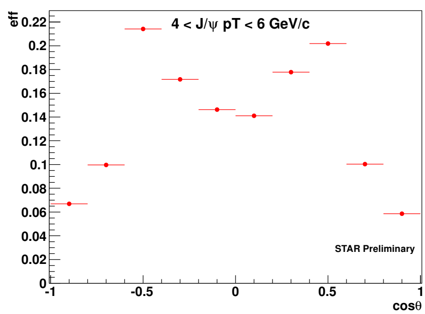
(c) J/ψ p_{T} range $3 < p_{\mathrm{T}} < 4$ GeV/c



(d) J/ψ p_{T} range $3 < p_{\mathrm{T}} < 4$ GeV/c



(e) J/ψ p_{T} range $4 < p_{\mathrm{T}} < 6$ GeV/c



(f) J/ψ p_{T} range $4 < p_{\mathrm{T}} < 6$ GeV/c

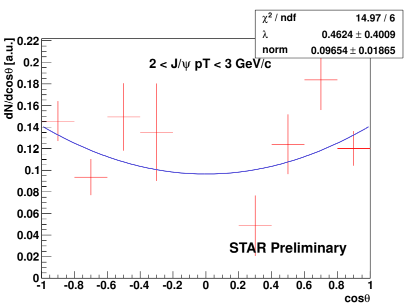
Fig. 2. Left plots — uncorrected $\cos\theta$ distribution with combinatorial background subtracted. Right plots — $\cos\theta$ efficiency.

3.1. Corrections

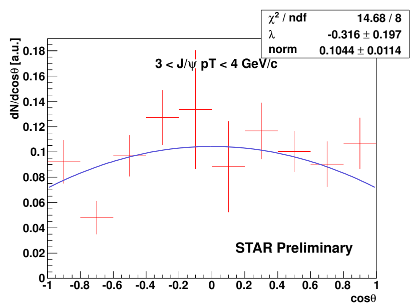
In order to get the $\cos\theta$ corrections, unpolarized Monte Carlo J/ψs with uniform p_{T} and rapidity distributions are embedded into real events and the detector response is simulated. All cuts used in the analysis were applied and the $\cos\theta$ efficiency as a function of J/ψ transverse momentum was obtained. $\cos\theta$ distributions were also re-weighted according to the real J/ψ p_{T} and y shapes. Obtained in that way, corrections were applied to uncorrected $\cos\theta$ distributions from data in 1 GeV/c wide J/ψ p_{T} bins. Corrections include acceptance correction, tracking efficiency, electron identification efficiency and trigger efficiency. The total J/ψ efficiency is shown *versus* J/ψ transverse momentum in Fig. 2 (b), 2 (d), 2 (f). The most critical factor is trigger efficiency. At least one of electrons from J/ψ decay must have p_{T} above 2.6 GeV/c since it is required to satisfy the trigger conditions. It causes significant loss in number of observed J/ψ at lower J/ψ p_{T} and the efficiency decrease with decreasing $|\cos\theta|$. It is well visible in Fig. 2 (b), where we lose all entries at $\cos\theta \sim 0$. With increasing J/ψ p_{T} the trigger efficiency increase but because the trigger has also the upper threshold ($E_{\mathrm{T}} \leq 4.3$ GeV) and due to the acceptance effect (single electron $p_{\mathrm{T}} > 0.4$ GeV/c and $|\eta| < 1$) we see drop of total efficiency at $|\cos\theta| \sim 1$, see Fig. 2 (f).

3.2. J/ψ polarization result

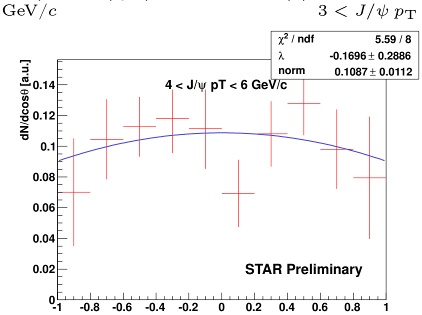
The corrected $\cos\theta$ distributions are fitted with: $\mathrm{norm}(1 + \lambda\cos^2\theta)$ (see Eq. 1) with no constraints on the fit parameters, see Fig. 3 (a), 3 (b), 3 (c), where 'norm' is a normalization factor, λ is the polarization parameter. Lines represent the most likely fits. Obtained results of the polarization parameter are: $\lambda = 0.46 \pm 0.40(\mathrm{stat.}) \pm 0.34(\mathrm{sys.})$, $\lambda = -0.32 \pm 0.20(\mathrm{stat.}) \pm 0.16(\mathrm{sys.})$, $\lambda = -0.17 \pm 0.29(\mathrm{stat.}) \pm 0.11(\mathrm{sys.})$ for J/ψ p_{T} ranges:



(a) $\lambda = 0.46 \pm 0.40(\mathrm{stat.}) \pm 0.34(\mathrm{sys.})$, $2 < J/\psi\ p_{\mathrm{T}} < 3$ GeV/c



(b) $\lambda = -0.32 \pm 0.20(\mathrm{stat.}) \pm 0.16(\mathrm{sys.})$, $3 < J/\psi\ p_{\mathrm{T}} < 4$ GeV/c



(c) $\lambda = -0.17 \pm 0.29(\mathrm{stat.}) \pm 0.11(\mathrm{sys.})$, $4 < J/\psi\ p_{\mathrm{T}} < 6$ GeV/c

Fig. 3. Corrected $\cos\theta$ distributions with the fit: $\mathrm{norm}(1 + \lambda\cos^2\theta)$, errors are statistical.

(2–3) GeV/c, (3–4) GeV/c, (4–6) GeV/c, respectively. Dominant sources of systematic uncertainties are: $\cos\theta$ binning and acceptance, J/ψ mass range, electron identification cut, trigger efficiency. Detailed work on systematic error estimation is in progress.

Polarization parameters as a function of J/ψ p_{T} are shown in Fig. 4. The STAR result (red star symbols) is compared with NLO$^+$ CSM [1] (light grey/blue shaded area) and COM [3] (dark gray hatched area) model predictions and with the PHENIX result for J/ψ polarization at mid-rapidity (black symbols) [5]. The STAR result is consistent with the COM and CSM predictions within current experimental and theoretical uncertainties. The measurement is also consistent with the PHENIX data and extends the p_{T} reach to ~ 6 GeV/c.

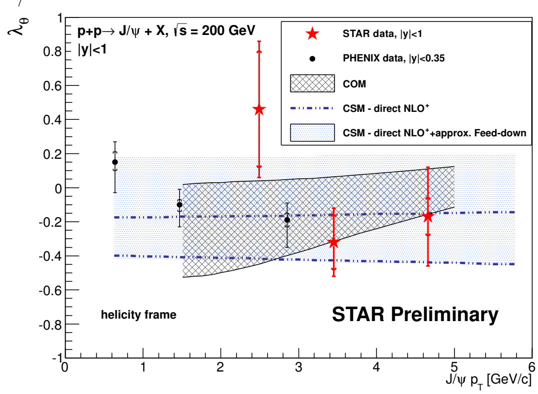


Fig. 4. STAR polarization parameter λ *versus* J/ψ p_{T} (red star symbols) compared with PHENIX result (black symbols) [5], NLO$^+$ CSM (light grey/blue shaded area) [1] and COM [3] (dark gray hatched area) predictions.

4. Summary

In this report, the J/ψ polarization measurement from the STAR experiment at mid-rapidity is presented. The polarization parameter λ is extracted in the helicity frame in 3 J/ψ p_{T} bins. Within current uncertainties the obtained transverse momentum dependent λ parameter is consistent with NLO$^+$ CSM and COM model predictions, and with no polarization.

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