$J/$ and (2$S$) measurements in $p+p$ collisions at $\sqrt{s} = 500$ GeV in the STAR experiment

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Abstract. In this paper, we present the first measurement of $J/\psi$ production in $p+p$ collisions at $\sqrt{s} = 500$ GeV by the STAR experiment at RHIC in the rapidity range of $-1 < y < 1$ and transverse momentum range of $4 < p_T < 20$ GeV/c. We also report the ratio of the integrated yield of $\psi(2S)$ to that of $J/\psi$ over the $p_T$ range of $4 < p_T < 12$ GeV/c.

1. Introduction

$J/\psi$ production in heavy-ion collisions is an important tool for studying the properties of Quark-Gluon Plasma (QGP) [1]. Suppression of $J/\psi$ production in heavy-ion collisions, due to color screening of quark and anti-quark potential, has been proposed as a signature of QGP formation [2]. Various measurements of $J/\psi$ have been performed in different collision systems and at different energies, and indeed a suppression of $J/\psi$ production has been observed [3,4,5,6]. Interpretation of the observed suppression requires a good understanding of the production mechanisms in elementary $p+p$ collisions, which are however still largely unknown. Decay contributions from excited $c\bar{c}$ states and from B mesons could also complicate the picture [7]. $J/\psi$ measurement at a new beam energy provides new insights on $J/\psi$ production mechanisms and constrains theoretical model calculations. Furthermore, it is essential to push the measurement to high transverse momentum as model predictions differ the most at high $p_T$ and many calculations are only applicable at high $p_T$.

2. Experiment and Analysis

The STAR detector is a large-acceptance multi-purpose detector which covers full azimuth and pseudo-rapidity of $|\eta| < 1$ [8]. A high tower trigger, utilizing Barrel Electromagnetic Calorimeter (BEMC) as the trigger detector, was used to select $p+p$ collisions that potentially contained $J/\psi$. The data sample used for this analysis corresponds to an integrated luminosity of $22 \text{ pb}^{-1}$. The $J/\psi \rightarrow e^+e^-$ channel with a branching ratio of $B_{e^+e^-} = 5.9\%$ was utilized to reconstruct the $J/\psi$ signals. Electrons were identified using the Time Projection Chamber (TPC) through ionization energy loss (dE/dx) measurement. At high $p_T$, BEMC can further reject hadrons via the E/p cut, in which E is the energy deposited in the BEMC, and p is the momentum of the track matched to the BEMC signal.

We obtained the $J/\psi$ signal by subtracting the combinatorial and residual backgrounds from the unlike-sign $e^+e^-$ invariant mass spectrum. Figure 1 shows the invariant mass distribution...
for di-electron pairs within $|y| < 1$. The unlike-sign pairs are represented by black histogram. The combinatorial background was reconstructed by the like-sign method, in which electrons (positrons) were paired with every other electrons (positrons) in the same event, shown as the filled histogram in Figure 1. After combinatorial background subtraction, the $J/\psi$ candidates with residual background are shown as solid red circles. The residual background consists of contributions from Drell-Yan, $c\bar{c}$ pairs and $b\bar{b}$ pair decays. A Crystall Ball function plus an exponential function was used to simultaneously fit the $J/\psi$ signal and the residual background. $J/\psi$ yield was obtained by counting the bin contents after subtracting the residual background as well as the integral of the fitted Crystal Ball function in the mass range of $2.7 < M_{ee}^{inv} < 3.3$ GeV/c$^2$. The yields were corrected for the $\sim 10\%$ effect of $J/\psi \to e^+e^-\gamma$ decay that causes some of the $J/\psi$ to be reconstructed outside the above mass range. Similar analysis procedures and criteria were used to extract $\psi(2S)$ signals. Figure 1 also shows the invariant mass distribution for $\psi(2S)$ in the insert. The $\psi(2S)$ raw yields were obtained in the mass range of $3.5 < M_{ee}^{inv} < 3.8$ GeV/c$^2$. Acceptance and efficiency corrections were studied using Monte Carlo (MC) embedding technique [11], in which simulated $J/\psi \to e^+e^-$ were mixed into real events at the raw data level. The systematic uncertainty in the procedure is estimated by varying kinematic and electron identification (eID) cuts in both data analysis and MC simulations coherently. We have also varied the invariant mass window and fitting method for signal counting to evaluate the systematic uncertainty in the yield extraction procedure, including the contributions from electron bremsstrahlung energy loss and correlated background. The systematic uncertainties are summarized in Tab. 1.

Figure 1. (Color online) Invariant mass distribution of unlike-sign (black histogram) and like-sign (filled histogram) electron/positron pairs, for $4 < p_T < 20$ GeV/c and $|y| < 1$. An exponential function plus a Crystall-ball function are used to fit the $J/\psi$ signal and the residual background. The error bars depict the statistical error. $\psi(2S)$ signal is shown in the insert as well.
Table 1. Summary of systematic uncertainties of $J/\psi$ and $\psi(2S)$ for different sources.

<table>
<thead>
<tr>
<th>Description</th>
<th>$J/\psi$</th>
<th>$\psi(2S)/J/\psi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinematic and eID cuts</td>
<td>6.1%</td>
<td>7.6%</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>1.0%</td>
<td>3.0%</td>
</tr>
<tr>
<td>Yield extraction</td>
<td>1.3%</td>
<td>15%</td>
</tr>
<tr>
<td>Total</td>
<td>6.3%</td>
<td>17%</td>
</tr>
</tbody>
</table>

3. Results
Figure 2 shows the invariant cross section of $J/\psi$ multiplied by the branching ratio at mid-rapidity ($|y| < 1$) as a function of $p_T$ for $p+p$ collisions at $\sqrt{s} = 500$ GeV. Other experimental results are also shown [12,13,14]. It has already been found that high $p_T J/\psi$ follows the $x_T$ scaling [12]: $E d^2\sigma/dp_T^2 = g(x_T)/s^n$, where $x_T = 2p_T/\sqrt{s}$ and $n = 5.6 \pm 0.2$, which represents the number of constituents taking an active role in the production. We tested the $x_T$ hypothesis with our measurement in Fig. 3, and we found that $J/\psi$ follows $x_T$ scaling at $p_T > 4$ GeV/c. While low $p_T J/\psi$ production also originates from hard processes due to the mass scale, subsequent soft processes could cause a violation of $x_T$ scaling.

![Figure 2](image1.png)
![Figure 3](image2.png)

The inclusive $J/\psi$ production includes both prompt and non-prompt $J/\psi$. The prompt $J/\psi$ production consists of the direct production ($\sim 60\%$) and feed-down contribution from excited states $\psi(2S)$ ($\sim 10\%$) and $\chi_C$ ($\sim 30\%$), while non-prompt $J/\psi$ originate from B-meson decays. STAR has estimated the contribution from B-meson decays, within $10 \sim 25\%$ in the range of $4 < p_T < 12$ GeV/c, using azimuthal correlations between high $p_T J/\psi$ and charged hadrons.
We have measured the $\psi(2S)$ to $J/\psi$ ratio in $p+p$ collisions and the results are compared to other measurements at different colliding energies [15,16,17] in $p+p$ or $p+A$ collisions in Fig. 4. The STAR data point is consistent with the observed trend, with no collision energy dependence of the $\psi(2S)$ to $J/\psi$ ratio seen within the current precision.

**Figure 4.** $\psi(2S)$ to $J/\psi$ ratio, for $4 < p_T < 12$ GeV/c and $|y| < 1$. The error bars represent the statistical errors. The boxes represent the systematic uncertainties.

4. Summary

In summary, we report recent STAR measurements of the inclusive $J/\psi$ cross section in $p+p$ collisions at $\sqrt{s} = 500$ GeV, which extends $p_T$ to 20 GeV/c. The first measurement of $\psi(2S)$ to $J/\psi$ ratio is reported and compared with results from other experiments, with no collision energy dependence observed.

5. References