J/\psi \text{ and } \psi(2S) \text{ measurement in } p+p \text{ collisions at } \sqrt{s} = 200 \text{ and } 500 \text{ GeV in the STAR experiment}

Barbara Trzeciak\textsuperscript{1} for the STAR Collaboration

\textsuperscript{1}Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Brehova 7, 115 19 Praha 1, Czech Republic

E-mail: trzecbar@fjfi.cvut.cz

Abstract. In this paper, results on the J/\psi cross section and polarization measured via the dielectron decay channel at mid-rapidity in p+p collisions at \( \sqrt{s} = 200 \) and 500 GeV in the STAR experiment are discussed. The first measurement of \( \psi(2S) \) to J/\psi ratio at \( \sqrt{s} = 500 \) GeV is also reported.

1. Introduction

J/\psi \text{ and } \psi(2S) \text{ are bound states of charm (c) and anti-charm (\bar{c}) quarks. Charmonium physical states have to be colorless, however they can be formed via a color-singlet (CS) or color-octet (CO) intermediate } c\bar{c} \text{ state. One of the first models of the charmonium production, the Color Singlet Model (CSM) [1], assumed that J/\psi is created through the color-singlet state only. This early prediction failed to describe the measured charmonium cross section which has led to the development of new models. For example, Non-Relativistic QCD (NRQCD) [1] calculations were proposed in which a } c\bar{c} \text{ color-octet intermediate states, in addition to a color-singlet states, can bind to form charmonia. }

However, the charmonium production mechanism in elementary particle collisions is not yet exactly known. For many years measurements of the J/\psi cross section have been used to test different J/\psi production models. While many models can describe relatively well the experimental data on the J/\psi cross section in p+p collisions [2–9], they have different predictions for the J/\psi polarization. Therefore, measurements of the J/\psi polarization may allow to discriminate among different models and provide new insight into the J/\psi production mechanism.

2. Charmonium measurements in STAR

In STAR, charmonia have been measured so far via the dielectron decay channel. The STAR detector [10] is a multi-purpose detector that has large acceptance at mid-rapidity, \(|\eta| < 1\) with a full azimuthal coverage. Electrons can be identified using the Time Projection Chamber (TPC) [11] through ionization energy loss (dE/dx) measurement. The Time Of Flight (TOF) detector [12] greatly enhances the electron identification capability at low momenta where the dE/dx bands for electrons and hadrons cross each other. At high p_T, electron identification can be improved by the Barrel Electromagnetic Calorimeter (BEMC) [13] which measures electron energy and shower shape. The BEMC is also used to trigger on high-p_T electrons (HT trigger). Minimum Bias (MB) events are triggered by the Vertex Position Detectors (VPD) [14].
3. \( J/\psi \) measurements in \( p+p \) at \( \sqrt{s} = 200 \text{ GeV} \)

STAR has measured inclusive \( J/\psi \) \( p_T \) spectra and polarization in \( p+p \) collisions at \( \sqrt{s} = 200 \text{ GeV} \) via the dielectron decay channel (\( B_{ee} = 5.9\% \)) at mid-rapidity (\(|y| < 1\)). These results are compared to different model predictions to understand \( J/\psi \) production mechanism in elementary collisions.

Left panel of Fig. 1 shows STAR low and high-\( p_T \) measurements of \( J/\psi \) \( p_T \) spectra [3,15] compared to model predictions. The Color Evaporation Model (CEM) [16] for prompt \( J/\psi \) can describe the \( p_T \) spectrum reasonably well, except the region around \( p_T \approx 3 \text{ GeV/c} \) where it over-predicts the data. NLO NRQCD calculations with color-singlet and color-octet transitions [17] for prompt \( J/\psi \) match the data for \( p_T > 4 \text{ GeV/c} \). NNLO* CS model [18] for direct \( J/\psi \) production under-predicts the STAR data, but the prediction does not include contributions from \( \psi(2S) \), \( \chi_C \) and \( B \)-meson decays to \( J/\psi \).

![Figure 1.](image-url)

**Figure 1.** Left: \( J/\psi \) invariant cross section vs \( p_T \) in \( p+p \) collisions at \( \sqrt{s} = 200 \text{ GeV} \) at mid-rapidity and \( 2 < p_T < 6 \text{ GeV/c} \) [19]. \( J/\psi \) polarization is analyzed via the angular distribution of the decay electrons that is described by:

\[
\frac{d^2N}{d(cos\theta)d\phi} \propto 1 + \lambda_0 \cos^2 \theta + \lambda_0 \sin^2 \theta \cos 2\phi + \lambda_0 \sin \theta \cos \phi, \]

where \( \theta \) and \( \phi \) are polar and azimuthal angles, respectively; \( \lambda_0 \), \( \lambda_0 \) and \( \lambda_{\phi0} \) are the angular decay coefficients. The \( p_T \) dependence of \( \lambda_0 \) is shown on the right panel of Fig. 1 with low-\( p_T \) PHENIX results [20] and compared to NRQCD calculations [21] and the NLO+ CSM prediction [22]. A trend observed in the RHIC data is towards longitudinal polarization as \( p_T \) increases and, within experimental and theoretical uncertainties, the result is consistent with the NLO+ CSM model.

The inclusive \( J/\psi \) production is a combination of prompt and non-prompt \( J/\psi \). The prompt \( J/\psi \) production consists of the direct one (\( \sim 60\% \)) and feed-down from excited states \( \psi(2S) \) (\( \sim 10\% \)) and \( \chi_C \) (\( \sim 30\% \)), while non-prompt \( J/\psi \) originate from \( B \)-hadron decays. STAR has estimated the contribution from \( B \)-meson decays using a measurement of azimuthal angular correlation between high-\( p_T \) \( J/\psi \) and charged hadrons [2,3]. The relative contribution of \( B \)-hadron decays to inclusive \( J/\psi \) yield is strongly \( p_T \) dependent and it is 10-25\% for \( 4 < p_T < 12 \text{ GeV/c} \), as it is shown on the left panel of Fig. 2. The measurement is consistent with the FONLL+CEM prediction [23,24].
Figure 2. Left: relative contribution from B-meson decays to inclusive J/ψ production in p+p at \( \sqrt{s} = 200 \text{ GeV} \) [3] compared to FONLL+CEM calculations [23,24]. Right: ratio of ψ(2S) to J/ψ in p + p collisions at \( \sqrt{s} = 500 \text{ GeV} \) from STAR (red circle) compared to results from other experiments at different energies.

4. J/ψ and ψ(2S) measurements in p+p at \( \sqrt{s} = 500 \text{ GeV} \)
In order to further test the charmonium production mechanism and constrain the feed-down contribution from the excited states to the inclusive J/ψ production, the J/ψ and ψ(2S) signals were extracted in p + p collisions at \( \sqrt{s} = 500 \text{ GeV} \) at mid-rapidity. The J/ψ \( p_T \) spectrum is shown on the left panel of Fig. 3. The STAR results at \( \sqrt{s} = 500 \text{ GeV} \) (full circles) are compared to those at \( \sqrt{s} = 200 \text{ GeV} \) (open circles) and with measurements of other experiments in p+\( \bar{p} \) collisions at different energies. The STAR measurements cover \( p_T \) range of 4 - 20 GeV/c with a good precision. It was also observed that J/ψ cross section follows the \( x_T \) scaling: 
\[ \frac{d^3 \sigma}{dp_T^3 dp_T d\theta} = g(x_T)/(\sqrt{s})^n, \]
where \( x_T = 2p_T/\sqrt{s} \), with \( n = 5.6 \pm 0.2 \) at mid-rapidity and \( p_T > 5 \text{ GeV/c} \) for a wide range of colliding energies [2]. At \( \sqrt{s} = 500 \text{ GeV} \) the same \( x_T \) scaling of high-\( p_T \) J/ψ production is seen, as shown on the right panel of Fig. 3.

Right panel of Fig. 2 shows ψ(2S)/J/ψ ratio from STAR (red full circle) compared to measurements of other experiments at different colliding energies, in \( p + p \) and \( p + A \) collisions. The STAR data point is consistent with the observed trend, and no collision energy dependence of the ψ(2S) to J/ψ ratio is seen with the current precision.

The statistics available at \( \sqrt{s} = 500 \text{ GeV} \) will allow us to extract the frame invariant polarization parameter, also in different reference frames, providing model independent information about the J/ψ polarization [25]. It will be possible to measure the azimuthal polarization parameter, \( \lambda_\phi \), and improve precision of the \( \lambda_\phi \) measurement. Analysis of J/ψ polarization at \( \sqrt{s} = 500 \text{ GeV} \) is ongoing.

5. Summary
In summary, STAR has measured the inclusive J/ψ cross section and polarization in p+p collisions at \( \sqrt{s} = 200 \text{ GeV} \) as a function of \( p_T \). The measurements are compared to different model predictions of the J/ψ production. The \( p_T \) spectrum is described well by the NRQCD calculations while the measured polarization parameter \( \lambda_\theta \) is consistent with the NLO+ CSM prediction. STAR new result for J/ψ at \( \sqrt{s} = 500 \text{ GeV} \) extends \( p_T \) reach up to 20 GeV/c. The first measurement of ψ(2S)/J/ψ ratio in p+p collisions at \( \sqrt{s} = 500 \text{ GeV} \) is reported and compared with results from other experiments. No collision energy dependence is observed.
Figure 3. $J/\psi$ invariant cross section vs $p_T$, left panel, and invariant cross section multiplied by $\sqrt{s}$ vs $x_T$, right panel, in $p+p$ collisions at $\sqrt{s} = 500$ GeV at mid-rapidity shown as full circles compared to measurements at different energies.

Acknowledgements
This publication was supported by the European social fund within the framework of realizing the project „Support of inter-sectoral mobility and quality enhancement of research teams at Czech Technical University in Prague”, CZ.1.07/2.3.00/30.0034.

References
1. Braaten E, Fleming S and Yuan T C 1996 *Ann. Rev. Nucl. Part. Sci.* **46** 197–235 (Preprint hep-ph/9602374)
2. Abelev B *et al.* (STAR Collaboration) 2009 *Phys. Rev.* C **80** 041902 (Preprint 0904.0439)
3. Adamczyk L *et al.* (STAR Collaboration) 2013 *Phys. Lett.* B **722** 55–62 (Preprint 1208.2736)
4. Adare A *et al.* (PHENIX Collaboration) 2012 *Phys.Rev.* D **85** 092004 (Preprint 1105.1966)
5. Abe F *et al.* (CDF Collaboration) 1997 *Phys. Rev. Lett.* **79**(4) 572–577
6. Acosta D *et al.* (CDF Collaboration) 2005 *Phys.Rev.* D **71** 032001 (Preprint hep-ex/0412071)
7. Aal J *et al.* (ATLAS Collaboration) 2011 *Nucl.Phys.* B **850** 387–444 (Preprint 1104.3038)
8. Khachatryan V *et al.* (CMS Collaboration) 2011 *Eur.Phys.J.* C **71** 1575 (Preprint 1011.4193)
9. Aaij R *et al.* (LHCb Collaboration) 2011 *Eur.Phys.J.* C **71** 1645 (Preprint 1103.0423)
10. Ackermann K *et al.* (STAR Collaboration) 2003 *Nucl. Instrum. Meth.* A **499** 624–632
11. Anderson M *et al.* 2003 *Nucl. Instrum. Meth.* A **499** 659–678 (Preprint nucl-ex/0301015)
12. Llope W J *et al.* 2012 *Nucl. Instrum. Meth.* A **661** 110–113
13. Bedde M *et al.* (STAR Collaboration) 2003 *Nucl. Instrum. Meth.* A **499** 725–739
14. Llope W J *et al.* 2004 *Nucl. Instrum. Meth.* A **522** 252–273 (Preprint nucl-ex/0308022)
15. Kosarzewski L (STAR Collaboration) 2012 Acta Phys.Polon.Suppl. 5 543–548
16. Frawley A D, Ullrich T and Vogt R 2008 *Phys.Rept.* **462** 125–175 (Preprint 0806.1013)
17. Ma Y Q, Wang K and Chao K T 2011 *Phys.Rev.* D **84** 114001 (Preprint 1012.1030)
18. Artseniet P *et al.* 2008 *Phys.Rev.Lett.* **101** 152001 (Preprint 0806.3282)
19. Adamczyk L *et al.* (STAR Collaboration) 2013 *Phys.Lett.* B **739** 180 (Preprint 1311.1621)
20. Adare A *et al.* (PHENIX Collaboration) 2010 *Phys. Rev. D* **82**(1) 012001
21. Chung H S, Yu C, Kim S and Lee J 2010 *Phys. Rev. D* **81**(1) 014020
22. Lansberg J 2011 *Phys. Lett.* B **695** 149–156 (Preprint 1003.4319)
23. Bedjidian M, Blaschke D, Bodwin G T, Carrer N, Cole B *et al.* 2004 (Preprint hep-ph/0311048)
24. Cacciari M, Nason P and Vogt R 2005 *Phys.Rev.Lett.* **95** 122001 (Preprint hep-ph/0502203)
25. Faccioli P, Lourenco C, Seixas J and Wohri H K 2010 *Eur. Phys. J.* C **69** 657–673 (Preprint 1006.2738)