Abstract. In this paper, results on the J/ψ cross section and polarization measured via the dielectron decay channel at mid-rapidity in p+p collisions at √s = 200 and 500 GeV in the STAR experiment are discussed. Also, first measurements of the J/ψ production as a function of the charged-particle multiplicity density and of ψ(2S) to J/ψ ratio at √s = 500 GeV are reported.

1. Introduction
J/ψ and ψ(2S) are bound states of charm (c) and anti-charm (c̄) quarks. Final color-singlet charmonium physical state can be produced via either color-singlet (CS) or color-octet (CO) intermediate c̄c state. Based on this, there are different models that try to describe c̄c pair production and its hadronization to the physical charmonium state, such as Color Singlet Model (CSM), Color Evaporation Model (CEM), or more sophisticated Non-Relativistic QCD (NRQCD) calculations. However, the charmonium production mechanism in elementary particle collisions is not yet exactly known. For many years measurements of the charmonium cross sections have been used to test different production models. While many models can describe relatively well the experimental data on the J/ψ cross section in p+p collisions [1–8], they have different predictions for the J/ψ polarization. Therefore, measurements of the J/ψ polarization may allow to discriminate among different models and provide new insight into the J/ψ production mechanism. Further constraints for models can be obtained by looking at the J/ψ production vs relative charged-particle event multiplicity.

2. J/ψ cross-section measurements at √s = 200 and 500 GeV
STAR has measured inclusive J/ψ pT spectra in p+p collisions at √s = 200 and 500 GeV via the dielectron decay channel (Bee = 5.9%) at mid-rapidity (|y| < 1). These results are compared to different model predictions in order to understand the J/ψ production mechanism in elementary collisions. The left panel of Fig. 1 shows STAR low and high-pT measurements of J/ψ pT spectra [2,9] at √s = 200 GeV compared to different model predictions: CEM [10], NNLO* CS [12] and NLO NRQCD calculations with both color-singlet and color-octet contributions (NLO CS+CO) [11]. The NNLO* CS model prediction is for the direct J/ψ production only, so it does not include contributions from ψ(2S), χc and B-meson decays to J/ψ, which may account for as much as 40% of the inclusive J/ψ production. The right panel of Fig. 1 shows high-pT results at √s = 500 GeV compared to NLO NRQCD prediction for the prompt J/ψ production.
production \[11, 13, 14\]. In both cases NLO NRQCD calculations describe the data well at a higher \( p_T \) range, \( p_T \gtrsim 4 \text{ GeV/c} \). The result at \( \sqrt{s} = 200 \text{ GeV} \) is also in a good agreement with the CEM prediction.

Also, \( x_T \) scaling of \( J/\psi \) cross section is observed:

\[
\frac{d^2 \sigma}{2\pi p_T dp_T dy} = g(x_T) / (\sqrt{s})^n, \text{ where } x_T = 2p_T / \sqrt{s}, \text{ with } n = 5.6 \pm 0.2 \text{ at mid-rapidity and } p_T > 5 \text{ GeV/c} \text{ for a wide range of colliding energies} \[1\]. At \( \sqrt{s} = 500 \text{ GeV} \) the same \( x_T \) scaling of high-\( p_T \) \( J/\psi \) production is seen \[15\].

Figure 1. \( J/\psi \) invariant cross section vs \( p_T \) in \( p+p \) collisions at mid-rapidity, left: at \( \sqrt{s} = 200 \text{ GeV} \), low \[9\] and high \( p_T \) \[2\] results are shown as blue squares and red circles, respectively, and are compared to different model predictions \[10–12\], right: at \( \sqrt{s} = 500 \text{ GeV} \), compared to NRQCD calculations \[11,13,14\].

3. \( J/\psi \) and \( \psi(2S) \) measurements at \( \sqrt{s} = 500 \text{ GeV} \)

The left panel of Fig. 2 shows \( \psi(2S)/J/\psi \) 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 \( \psi(2S) \) to \( J/\psi \) ratio is seen with the current precision.

STAR has also measured \( J/\psi \) production vs event activity. The right panel of Fig. 2 shows relative \( J/\psi \) yield as a function of relative charged particle event multiplicity. The measurement is done for integrated \( p_T \) range in the dimuon decay channel and for \( p_T > 4 \text{ GeV/c} \) in the dielectron decay channel, shown as red and blue points, respectively. We observe a strong correlation between the \( J/\psi \) yield and event activity, and for \( p_T > 4 \text{ GeV/c} \) there is a stronger than linear growth for higher multiplicities. The same behaviour has been observed for \( J/\psi \) and open charm by the LHC experiments. There is also a hint of \( p_T \) dependence of the correlation, but further analysis, especially in the dimuon decay channel for higher event activity bins is required in order to draw strong conclusions. Results are also compared to the default PYTHIA 8 tune that includes multiple parton-parton interactions, for both analysed \( p_T \) ranges, and to the percolation model \[16\] which is based on a string screening assumption. Both models can describe the observed increase of the \( J/\psi \) relative yield.

4. \( J/\psi \) polarization measurements at \( \sqrt{s} = 200 \text{ and } 500 \text{ GeV} \)

\( J/\psi \) polarization is analyzed via the angular distribution of the decay electrons that is described by:

\[
\frac{d^2 N}{d(\cos \theta)d\phi} \propto 1 + \lambda_\theta \cos^2 \theta + \lambda_\phi \sin^2 \theta \cos 2\phi + \lambda_{\theta\phi} \sin 2\theta \cos \phi, \text{ where } \theta \text{ and } \phi \text{ are polar and azimuthal angles, respectively; } \lambda_\theta, \lambda_\phi \text{ and } \lambda_{\theta\phi} \text{ are the angular decay coefficients.} \]

The first STAR
measurement of the $J/\psi$ polarization was performed at $\sqrt{s} = 200$ GeV at mid-rapidity and $2 < p_T < 6$ GeV/$c$, in the helicity frame (HX) [17]. Due to limited statistics only $\lambda_\theta$ polarization parameter, related to the polar anisotropy was extracted as a function of $p_T$. The result was compared to NRQCD calculations [18] and the NLO$^+$ CSM prediction [19]. 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 prediction.

The $J/\psi$ polarization measurements have been extended to a wider $p_T$ range of 5-16 GeV/$c$ using $p+p$ dataset at $\sqrt{s} = 500$ GeV. Both $\lambda_\theta$ and $\lambda_\phi$ parameters have been extracted in the HX and the Collins-Soper (CS) frames. This has also allowed to obtain the frame invariant parameter $\lambda_{inv} = (\lambda_\theta + 3\lambda_\phi)/(1 - \lambda_\phi)$ in both frames which is a good cross-check between measurements since any arbitrary choice of a reference frame should give the same value of the $\lambda_{inv}$ [23]. The left panel of Fig. 3 shows $\lambda_\theta$ in the HX frame as a function of $p_T$ at $\sqrt{s} = 500$ GeV compared to results at $\sqrt{s} = 200$ GeV and to a prediction of the NLO NRQCD [14,20–22]. We observe similar trend of $\lambda_\theta$ going towards negative values with increasing $p_T$ in both analysed colliding energies. And at $\sqrt{s} = 500$ GeV we have also checked that the $\lambda_\phi$ parameter related to

**Figure 2.** Left: ratio of $\psi(2S)$ to $J/\psi$ in $p+p$ collisions at $\sqrt{s} = 500$ GeV from STAR (red circle) compared to results from other experiments at different energies. Right: Relative $J/\psi$ yield vs event activity compared to the default PYTHIA 8 tune and to the percolation model [16].
the azimuthal anisotropy is consistent with 0. Since the lower limit in the NRQCD calculations is unconstrained we do not draw conclusions from the comparison to data, and the new data points should help to constrain color-octet Long-Distance Matrix Elements for the model. The right panel of Fig. 3 shows $\lambda_{inv}$ parameters as a function of $p_T$ extracted in the HX and CS frames, shown as full and open symbols, respectively. $\lambda_{inv}$ has negative values and the results are in agreement between the frames.

5. Summary
In summary, STAR has measured the inclusive $J/\psi$ cross section and polarization in $p+p$ collisions at $\sqrt{s} = 200$ and 500 GeV as a function of $p_T$. The measurements are compared to different model predictions of the $J/\psi$ production. The $p_T$ spectra are described well by the NRQCD calculations. The polarization parameter $\lambda_0$ at $\sqrt{s} = 200$ GeV is consistent with the NLO$^+$ CSM. At both colliding energies $\lambda_0$ has a trend towards negative values with increasing $p_T$ in the HX frame. And at $\sqrt{s} = 500$ GeV in the HX frame the $\lambda_0$ parameter is consistent with 0. Also, frame invariant parameters, $\lambda_{inv}$, agree in the HX and CS frames. The first measurement of $\psi(2S)/J/\psi$ ratio in $p+p$ collisions at $\sqrt{s} = 500$ GeV is reported and compared with results from other experiments. No collision energy dependence is observed. A strong correlation is observed between relative $J/\psi$ yield and the event activity which is stronger than linear at higher multiplicities at $p_T > 4$ GeV/c.

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References
[1] Abelev B I et al. (STAR) 2009 Phys. Rev. C80 041902 (Preprint 0904.0439)
[2] Adamczyk L et al. (STAR) 2013 Phys. Lett. B722 55-62 (Preprint 1208.2736)
[3] Adare A et al. (PHENIX) 2012 Phys. Rev. D85 092004 (Preprint 1105.1966)
[4] Abe F et al. (CDF) 1997 Phys. Rev. Lett. 79 572-577
[5] Acosta D et al. (CDF) 2005 Phys. Rev. D71 032001 (Preprint hep-ex/0412071)
[6] Aad G et al. (ATLAS) 2011 Nucl. Phys. B850 387-444 (Preprint 1104.3038)
[7] Khachatryan V et al. (CMS) 2011 Eur. Phys. J. C71 1575 (Preprint 1011.4193)
[8] Aaij R et al. (LHCb) 2011 Eur. Phys. J. C71 1645 (Preprint 1103.0423)
[9] Kosarzewski L (STAR) 2012 Acta Phys. Polon. Supp. 5 543-548
[10] Frawley A D, Ullrich T and Vogt R 2008 Phys. Rept. 462 125-175 (Preprint 0806.1013)
[11] Ma Y Q, Wang K and Chao K T 2011 Phys. Rev. D84 114001 (Preprint 1012.1030)
[12] Artoisenet P, Campbell J M, Lansberg J P, Maltoni F and Tramontano F 2008 Phys. Rev. Lett. 101 152001 (Preprint 0806.3282)
[13] Ma Y Q, Wang K and Chao K T 2011 Phys. Rev. Lett. 106 042002 (Preprint 1009.3655)
[14] Shao H S, Han H, Ma Y Q, Meng C, Zhang Y J and Chao K T 2015 JHEP 05 103, and private communication (Preprint 1411.3300)
[15] Trzeciak B (STAR) 2015 J. Phys. Conf. Ser. 612 012038 (Preprint 1412.7341)
[16] Ferreiro E G and Pajares C 2012 Phys. Rev. C86 034903, and private communication (Preprint 1203.5936)
[17] Adamczyk L et al. (STAR) 2014 Phys. Lett. B739 180–188 (Preprint 1311.1621)
[18] Chung H S, Yu C, Kim S and Lee J 2010 Phys. Rev. D81 014020 (Preprint 0911.2113)
[19] Lansberg J P 2011 Phys. Lett. B695 149–156 (Preprint 1003.4319)
[20] Chao K T, Ma Y Q, Shao H S, Wang K and Zhang Y J 2012 Phys. Rev. Lett. 108 242004 (Preprint 1201.2675)
[21] Shao H S and Chao K T 2014 Phys. Rev. D90 014002 (Preprint 1209.4610)
[22] Shao H S, Ma Y Q, Wang K and Chao K T 2014 Phys. Rev. Lett. 112 182003, and private communication (Preprint 1402.2913)
[23] Faccioli P, Lourenco C, Seixas J and Wohri H K 2010 Eur. Phys. J. C69 657–673 (Preprint 1006.2738)