Abstract. In this article we report on the results of quarkonia production in p+p, d+Au, and Au+Au collisions at midrapidity via the dielectron decay channel at $\sqrt{s_{NN}} = 200$ GeV from STAR. Results from J/$\psi$ production in p+p collisions for $p_T < 14$ GeV/c are presented to provide a baseline for studying suppression in heavy ion collisions and are also used to understand the quarkonium production mechanism. The nuclear modification factor for J/$\psi$ in d+Au collisions for $p_T < 5$ GeV/c and Au+Au collisions for $p_T < 10$ GeV/c is reported, along with J/$\psi$ elliptic flow $v_2$ in Au+Au collisions. The results from $\Upsilon$(1S+2S+3S) production in p+p and Au+Au collisions are also provided, and the Upsilon nuclear modification factor in Au+Au collisions is presented.

1. Introduction
The production of heavy quarkonia has been extensively used to probe the hot and dense medium created in heavy ion collisions, as they are expected to be suppressed in a deconfined medium due to the Debye screening of the heavy quark potential [1]. Because of their large mass, heavy quarks are primarily created in the initial hard scattering of the collision and provide information about the early stages and the evolution of the system. There are however various modifications other than color-screening to quarkonium production in heavy ion collisions, such as the recombination of charm quarks [2] into bound-state charmonium, formation time effects where high transverse momentum ($p_T$) particles may escape from the suppression region [3], and modifications to feeddown and sequential melting of excited states [4]. There are further modifications to quarkonium production in heavy ion collisions from Cold Nuclear Matter effects (CNM) [5], such as modifications to parton distribution functions (PDFs) inside the nucleus (shadowing) [6], and nuclear absorption [7]. To disentangle all of these effects, a quantitative understanding of J/$\psi$ and $\Upsilon$ production in p+A, d+A, and A+A is required.

In this article, the results for J/$\psi$ production in p+p, d+Au, and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV from the STAR detector are reported. The J/$\psi$ $p_T$ spectrum and nuclear modification factor at midrapidity ($|y| < 1$) for $p_T < 10$ GeV/c in 0−60% centrality collisions are presented, along with the J/$\psi$ elliptic flow $v_2$ in 20−60% central Au+Au collisions. The $\Upsilon$ production in p+p and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV are presented, and the nuclear modification factor in Au+Au collisions is discussed. The following sections in this article will describe the experimental setup and data used in this analysis, as well as a description of the analysis methods. This is followed by a discussion of the results for J/$\psi$ and $\Upsilon$ production from STAR. Finally, a summary is provided.
2. Experiment and Analysis

The STAR experiment is a large acceptance multi-purpose detector which covers full azimuth and pseudorapidity of $|\eta| < 1$ [8]. The p+p, d+Au and Au+Au data were recorded in 2009, 2008, and 2010, respectively. The data were obtained using a minimum bias trigger by selecting on coincidences in the Vertex Position Detector (VPD) [9] located 5.7 m from the interaction point. The d+Au trigger also required a neutron to strike the East (gold facing) Zero Degree Calorimeter (ZDC) [10], which is located outside of the STAR magnet at 18 m from the interaction point. An additional trigger was also used in Au+Au collisions to identify central events by requiring a high occupancy in the detector. To improve statistics, the Upsilon analysis in p+p, d+Au, and Au+Au collisions, and the J/ψ analysis at high-\(p_T\) in p+p and Au+Au collisions used a high tower (HT) trigger, which required a minimum energy deposit in a single tower ($\Delta\eta \times \Delta\phi = 0.05 \times 0.05$) of the Barrel Electromagnetic Calorimeter (BEMC) [11]. A threshold energy of $E_T = 4.3$ GeV was used for the HT trigger in Au+Au collisions. Two HT triggers were used in p+p collisions with energy thresholds of $E_T = 2.6$ GeV and $E_T = 6.0$ GeV. Furthermore, the p+p dataset used for the Upsilon analysis was also required to satisfy a specific Upsilon trigger. This used the energy deposited in the calorimeter to reconstruct the candidate $\Upsilon$ particles assuming that any large energy deposits came from electrons, and events containing reconstructed particles with a mass near that of the $\Upsilon$ ($5 < \text{GeV}/c^2 < 20$) were recorded.

The reconstruction of J/ψ and $\Upsilon(1S+2S+3S)$ has been performed via the dielectron decay channel, $J/\psi \ (\Upsilon) \rightarrow e^+e^-\ (\Upsilon)$ with a branching ratio (B) of 5.9% (2.4%). The primary detectors used in this analysis are the Time Projection Chamber (TPC) [12], the Time of Flight (TOF) [13], and the BEMC. These detectors provide tracking and particle identification in $|\eta| < 1$ and $0 < \phi < 2\pi$. The TPC provides tracking and particle identification via the ionization energy loss per unit length ($dE/dx$) of charged particles. The TOF, which measures the flight time and velocity of particles, was used in the analysis of J/ψ in p+p and Au+Au data for low-\(p_T\) electron identification ($p_T \lesssim 1.5$ GeV/c) to improve electron-hadron discrimination provided by the TPC, especially where the electron and hadron $dE/dx$ overlap. The TOF was not available for the d+Au data recording, and was not used for the $\Upsilon$ and high-\(p_T\) J/ψ analyses as it is less effective at separating electrons from hadrons at higher \(p_T\). The BEMC is a lead-scintillator calorimeter and has been used to improve the particle identification at high \(p_T\), in addition to providing a trigger mechanism for the HT and Upsilon trigger. The energy obtained from the BEMC has been combined with the TPC momentum to obtain the energy-to-momentum ratio $\langle E/p \rangle$ which can be used to distinguish electrons from hadrons.

3. J/ψ production in p+p collisions

The invariant cross section for inclusive J/ψ production in p+p collisions is shown as a function of \(p_T\) in the left panel of Fig. 1. The low-\(p_T\) results ($p_T < 3$ GeV/c) are combined with the high-\(p_T\) data ($2 < p_T < 14$ GeV/c) [14] to extend the J/ψ coverage at STAR to $0 < p_T < 14$ GeV/c. Also shown are the PHENIX results for $|y| < 0.35$ [15]. The data are compared to the Color Evaporation Model (CEM) [16] for prompt J/ψ production in p+p collisions, which includes initial (direct) production and contributions from excited states. The CEM is able to describe the data well for the entire range of transverse momentum, however it does not include contributions from B decay. The data are also compared to the Non-Relativistic QCD (NRQCD), next-to-leading order (NLO) Color Singlet and Color Octet (CS+CO) [17] model for prompt and direct J/ψ production, which agrees with the data well at high \(p_T\), but does not provide a prediction at low \(p_T\). Also shown are the next-to-next-to-leading order (NNLO*) Color Singlet (CS) [18] model for direct J/ψ production in p+p collisions. These under-estimate the yield for \(p_T > 3\) GeV/c, however they do not include feeddown contributions from the decay of B meson or excited charmonium states. The fraction of inclusive J/ψ in p+p collisions from $B \rightarrow J/\psi$ decays is obtained by fitting the azimuthal angle correlation between high-\(p_T\) J/ψ and charged...
Figure 1. (Color online) (left) The invariant cross section versus transverse momentum for $J/\psi$ in $p+p$ collisions from STAR. The results are compared to theoretical predictions and other measurements. (right) The fraction of $B \rightarrow J/\psi$ for inclusive production in $p+p$ collisions from STAR, compared to the results from other experiments and FONLL+CEM model calculations [14].

hadrons at STAR with the simulated correlation functions for $J/\psi$ from prompt production and B feeddown. The results are shown in the right panel of Fig. 1, and the fraction of inclusive $J/\psi$ from B feeddown was found to be $10-25\%$, increasing with increasing $p_T$ [14]. The results are consistent to similar measurements at various experiments and with FONLL+CEM model predictions [19, 20].

4. $J/\psi$ production in d+Au collisions
The nuclear modification factor in d+Au collisions ($R_{dA}$) for $J/\psi$ with $p_T < 5$ GeV/c and $|y| < 1$ is shown in the left panel of Fig. 2 versus the number of nucleon-nucleon collisions ($N_{\text{coll}}$). The normalization uncertainty from the statistical and systematic uncertainty on the $J/\psi$ p+p cross section, the uncertainty on the inelastic cross section, and the uncertainty on $N_{\text{coll}}$ are indicated on the vertical axis. The $J/\psi$ nuclear modification factor is compared to model predictions for the cold nuclear matter effects on $J/\psi$ production in d+Au collisions. The CNM effects include the modification of nuclear parton distribution functions obtained from the EPS09 [21] parameterization. The shadowing from the nPDFs is with a $J/\psi$ nuclear absorption cross section ($\sigma_{\text{abs}}$) [22], which is determined from a fit to the STAR data, and a value of $\sigma_{\text{abs}} = 2.8^{+3.5}_{-2.6}$ (stat.) $^{+4.9}_{-2.8}$ (syst.) $^{+1.3}_{-1.1}$ (EPS09) mb was obtained. The $R_{dA}$ calculated using the EPS09 nPDFs combined with an absorption cross section of $\sigma_{\text{abs}} = 3$ mb is shown in Fig. 2, and the bands indicate the uncertainty of the EPS09 nPDFs. The model predictions are able to describe the data well.

The $p_T$ dependence of the $J/\psi$ nuclear modification factor in $|y| < 1$ for minimum bias d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV collisions is shown in the right panel of Fig. 2. The grey band represents the statistical uncertainty on the $J/\psi$ p+p cross section. The normalization uncertainties from the systematic uncertainty on the $J/\psi$ p+p cross section and the uncertainty on $N_{\text{coll}}$ are indicated on the vertical axis. The results are compared to PHENIX data in $|y| < 0.35$, and are in agreement within the uncertainties [23, 24].
5. J/ψ production in Au+Au collisions

The J/ψ invariant yield in Au+Au collisions at √s_{NN} = 200 GeV are shown in the left panel of Fig. 3 as a function of p_T and collision centrality [14]. The results are consistent with PHENIX measurements for p_T < 5 GeV/c and |y| < 0.35 [25]. The J/ψ invariant yield in Au+Au collisions is compared to a Tsallis Blast Wave (TBW) model assuming that the J/ψ flows like lighter hadrons (solid line) [26, 27]. The agreement with the data is good for p_T > 2 GeV/c, but underestimates the yield below this. The STAR data are also fitted with a TBW model in 0 < p_T < 10 GeV/c that assumes a zero radial flow, β = 0 (dashed line) [26]. This improves the agreement with the data at low-p_T, suggesting that the J/ψ has a small radial flow, or that there may be contributions from recombination at low-p_T.

The J/ψ yield in Au+Au collisions is shown on a linear scale in the right panel of Fig. 3 for various collision centralities. The results are compared to predictions from viscous hydrodynamics using a J/ψ decoupling temperature of T = 120 MeV (dotted line) and T = 165 MeV (solid line) [34]. The predictions assume a zero chemical potential for J/ψ at kinetic freeze-out, and the scale of the predictions is determined from a fit to the data in p_T < 5 GeV. The data favor the higher decoupling temperature and are well described for 2 < p_T < 5 GeV/c. However, the hydrodynamic calculations fail to describe the low p_T J/ψ yield (p_T < 2 GeV/c). The data are also compared to theoretical predictions based on the suppression of J/ψ due to color-screening and the statistical regeneration of charm quarks in Au+Au collisions, including B meson feeddown and formation time effects [28] (dashed line). The contribution from initial production dominates in peripheral events, with regeneration becoming more significant in central events and at low p_T. The predictions are able to describe the data across the measured transverse momentum range.

The J/ψ elliptic flow (v_2) in 20–60% centrality Au+Au collisions is shown in Fig. 4. The data are consistent with zero within the uncertainties, disfavoring the case where J/ψ is produced dominantly by coalescence from thermalized charm quarks for p_T > 2 GeV/c in mid-central collisions. The results are compared to various theoretical predictions [29] - [34]. The data are well described by models with J/ψ production from initial production only, or from a mixture between initial production and coalescence. This is consistent with the results shown in Fig. 3,
Figure 3. (Color online) (left) The $J/\psi$ invariant yield versus transverse momentum and collision centrality in Au+Au collisions. The results are compared to previous measurements and TBW model predictions [14, 25, 26, 27]. (right) The $J/\psi$ yield versus transverse momentum and collision centrality in Au+Au collisions. The results are compared to theoretical predictions [28, 34].

Figure 4. (Color online) The $J/\psi$ elliptic flow $v_2$ in 20 – 60% central Au+Au collisions. The data are compared to various model predictions.

which indicate that the contribution from coalescence is only significant at low $p_T$ in central collisions.

The transverse momentum dependence of the $J/\psi$ nuclear modification factor in Au+Au collisions ($R_{AA}$) is shown in the left panel of Fig. 5 for various collision centralities [14]. The uncertainty from $N_{\text{coll}}$ and the inelastic cross section in p+p collisions are indicated by the boxes on the vertical axis, and the shaded bands indicate the statistical uncertainty on the $J/\psi$ cross section in p+p collisions. The data are consistent with PHENIX results [25] in $|y| < 0.35$. The $J/\psi R_{AA}$ is compared to theoretical calculations including contributions from prompt production and statistical charm quark regeneration in Au+Au collisions (dashed line [28] and solid line [35]). The latter also includes B feeddown and formation time effects to $J/\psi$ production. Both models
are able to reproduce the trend of the data, and these cannot be distinguished given the current data. A significant suppression is observed for $p_T < 3 \text{ GeV/c}$ in Au+Au collisions. The data exhibit an increase in $R_{AA}$ for $p_T > 1 \text{ GeV/c}$ for all centralities, with $R_{AA}$ approaching unity for $p_T > 5 \text{ GeV/c}$ in peripheral collisions.

![Graph showing suppression in Au+Au collisions](image)

Figure 5. (Color online) (left) The $J/\psi$ nuclear modification factor versus transverse momentum and collision centrality in Au+Au collisions. (right) The $J/\psi$ nuclear modification factor versus $N_{\text{part}}$ for $J/\psi$ in Au+Au collisions [14, 36]. The data are compared to previous measurements and theoretical predictions (solid line [35] and dashed line [28]).

The centrality dependence of the $J/\psi$ nuclear modification factor in Au+Au collisions is shown in the right panel of Fig. 5 as a function of $N_{\text{part}}$ for $p_T < 5 \text{ GeV/c}$ (closed circles) and $p_T > 5 \text{ GeV/c}$ (open circles). The relative uncertainty on $N_{\text{coll}}$ in Au+Au collisions is indicated by the shaded band. The uncertainty on the $J/\psi$ cross section in p+p collisions and the uncertainty on the inelastic cross section in p+p collisions is indicated by the box on the vertical axis. The data are compared to the PHENIX results for $p_T < 5 \text{ GeV/c}$ in $|y| < 0.35$ [25] and are consistent within errors. The data exhibit a significant suppression in central collisions, decreasing in more peripheral collisions. There is less suppression observed at high $p_T$ across the collision centrality range, with $R_{AA}$ approaching unity in peripheral collisions. The results are compared to theoretical predictions for $J/\psi$ production in Au+Au collisions including the suppression of $J/\psi$ due to color-screening and the statistical regeneration of charm quarks [28, 35]. The predictions are able to describe the data reasonably well across the collision centrality range, and cannot be distinguished by the current low-$p_T$ data.

6. $\Upsilon$ production in p+p collisions

The $\Upsilon(1S+2S+3S)$ yield and cross section in p+p collisions for $|y| < 0.5$ are shown in the left panel of Fig. 6. The cross section is compared to NLO pQCD calculations for Upsilon production using the CEM (boxes) [16] and CS (dotted line) [37] models. The data favor the CEM calculations. The $\Upsilon$ cross section is compared to the world data trend as a function of $\sqrt{s}$ in the right panel of Fig. 6. The results are also compared to CEM calculations [16], which are able to describe the data well across a wide range of collision energy.

7. $\Upsilon$ production in Au+Au collisions

The $\Upsilon$ invariant mass spectrum after like-sign background subtraction in 0−60% central Au+Au collisions is shown in the left panel of Fig. 7. This is fitted with a function which includes
the $\Upsilon(1S+2S+3S)$ signal shape and contributions from Drell-Yan and $b\bar{b}$. The shape of the Drell-Yan and $b\bar{b}$ contributions are determined using PYTHIA and CEM calculations, and the normalization is determined in the combined fit to the signal and background. The Upsilon yield is determined from the counts after subtracting the background. The $\Upsilon$ nuclear modification factor in Au+Au collisions is shown as a function of $N_{\text{part}}$ in the right panel of Fig. 7. A significant suppression is observed in central events. The results are compared to lattice-based QCD calculations for the $\Upsilon$ melting, and are combined with a hydrodynamic model which is used to describe the expansion of the surrounding partonic medium [38]. The results favor the internal energy potential, which predicts an almost complete suppression of $\Upsilon(3S)$ in central collisions, with less suppression observed for $\Upsilon(2S)$ and $\Upsilon(1S)$.

Figure 6. (Color online) (left) The $\Upsilon(1S+2S+3S)$ counts and cross section in p+p collisions. The results are compared to theoretical calculations [16, 37]. (right) The $\Upsilon$ cross section as a function of collision energy compared to the world data trend and CEM predictions [16].

Figure 7. (Color online) (left) The $\Upsilon$ invariant mass spectrum in 0 – 60% central Au+Au collisions after like-sign background subtraction. (right) The $\Upsilon(1S+2S+3S)$ nuclear modification factor versus $N_{\text{part}}$ in Au+Au collisions. The results are compared to theoretical predictions [38].
8. Summary
The production of quarkonia at the STAR detector is described in this article. The $J/\psi$ invariant cross section is presented and compared to various theoretical calculations, and the fraction of inclusive $J/\psi$ production from B meson feeddown is calculated. The $J/\psi$ nuclear modification factor in $d+Au$ collisions is compared to the EPS09 calculations for shadowing and used to determine the $J/\psi$ nuclear absorption cross section. The $J/\psi$ invariant yield, elliptic flow, and nuclear modification factor in $Au+Au$ collisions are compared to various theoretical calculations. Predictions based on the suppression and regeneration of $J/\psi$ and nuclear modification factor in $Au+Au$ collisions are compared to various theoretical calculations, and the fraction of inclusive $J/\psi$ in $d+Au$ collisions is compared to the EPS09 calculations for shadowing and used to describe the data reasonably well, and predict that initial production dominates mid-central and peripheral collisions, while the contribution from coalescence may become significant at low $p_T$ in central collisions. The $\Upsilon(1S+2S+3S)$ invariant cross section in p+p collisions is compared to the world data trend and theoretical calculations, and can be described reasonably well by the color evaporation model. The $\Upsilon$ nuclear modification factor is presented, and exhibits a significant suppression in central collisions. The $\Upsilon(1S+2S+3S)$ invariant cross section in p+p collisions is compared to the world data trend and theoretical calculations, and can be described reasonably well by the color evaporation model. The $\Upsilon$ nuclear modification factor is presented, and exhibits a significant suppression in central collisions. The results are consistent with a model based on lattice QCD calculations of Upsilon melting in a hot medium and indicate an almost complete melting of the $\Upsilon(3S)$ state.

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