Upsilon Production and Upsilon + Hadron Correlations at STAR

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Abstract. The cross-section for the Υ(1S+2S+3S) di-electron decay channel is measured at mid-rapidity in the STAR detector, and the preliminary results for azimuthal correlations between Υ(1S+2S+3S) and hadrons are presented, using p+p and d+Au collisions at the RHIC center-of-mass energy √s = 200 GeV from Runs 6, 8 and 9. The STAR measurements establish a baseline for future Υ measurements in Au+Au collision systems and provide additional opportunities to study the Υ production mechanism.

1. Introduction
The use of heavy quarkonia as a tool for probing the medium formed at the Relativistic Heavy Ion Collider (RHIC). In particular, searches for the 'suppression' of the J/ψ meson, induced by Debye screening of the QCD potential between the charm anti-charm bound states, was initially suggested as being an unambiguous signature of QGP formation [1]. Theoretical scrutiny found that competing effects in the QGP can suppress [2-3] or enhance [4-6] the yield of J/ψ particles; it is also possible that these competing effects counterbalance their respective contributions to the final measured J/ψ yield.

Given the inescapable complexity that arises with the use of J/ψ as a QGP probe, increasing interests in the Υ meson and its excited states (2S,3S) for the studying of the QGP has come into focus. The combination of RHIC’s low bb̄ production cross-section (1.9 µb [7]) and the smallness of the interaction cross-section of bottomonium with hadrons in RHIC collisions [8] predicts that suppression due to absorption by hadronic co-movers is relatively negligible in these models. Further, theoretical calculations suggest that the Υ appears to be less susceptible to the competing effects inherent with J/ψ measurements - of the two competing in-medium mechanisms, Υ suppression is expected to be the dominant effect observed, not enhancement (recombination) [9]. As noted, a primary objective of the heavy-ion collision experiment at RHIC is to produce and study the QGP. The use of primordial J/ψ and Υ mesons created during these heavy-ion collisions, as probes of the QGP, is one of the many analysis-techniques used to study the QGP. The use of heavy quarkonia leads to the question - what is the mechanism(s) by which heavy quarkonia production proceeds? The significance of the production mechanism of heavy quarkonium, before being affected by the QGP cannot be overstated and remains an open issue, apart from the QGP-driven use of J/ψ and Υ in the STAR heavy flavor program.

The systematics of the prompt production of heavy quarkonium is not fully described by current models, e.g. the Color Singlet Model (CSM) and the Color Octet Model (COM). Historically, CSM calculations have grossly under-predicted production cross-sections, but recent
development with higher-order corrections can describe data better [10]. The COM has had success in explaining the $p_T$-spectra of heavy quarkonia, but the spin-alignment (polarization) prediction disagrees with experimental data [11]. Quarkonium production in hadronic collisions at RHIC energy is dominated by direct production via gluon fusion followed by CSM and/or COM transitions [12]. In Cu+Cu collisions, STAR observes a lack of expected suppression in high-$p_T$ $J/\psi$ $R_{AA}$ - the only hadron exhibiting this behavior in RHIC heavy-ion collisions. Figure 1 shows the high-$p_T$ $J/\psi$ $R_{AA}$ compared with various model predictions. The lack of $J/\psi$ suppression at high-$p_T$ suggests that $J/\psi$ cannot exist in a colored state on a long enough timescale to be affected by the medium, leading to an interpretation that the production is possibly not dominated via a color channel [13].

![Graph showing $J/\psi$ suppression in Cu+Cu data at $\sqrt{s} = 200$ GeV](image)

**Figure 1.** $J/\psi$ suppression in Cu+Cu data at $\sqrt{s} = 200$ GeV [13].

The STAR collaboration has contributed to the world data on bottomonium production and toward the understanding of the production mechanism. Here we review $\Upsilon$ results from Run-6 and Run-8 measurements. We also preview the Run-9 $\Upsilon$ invariant mass spectrum and present an additional technique for looking into the production mechanism of heavy quarkonia. Finally, we highlight future STAR capabilities for $\Upsilon$ reconstruction via the di-muon channel.

2. **STAR at RHIC**

RHIC is a two-ring, quasi-circular particle accelerator measuring 3.8 km in circumference, that accelerates and guides particle beams at collision-energies up to $\sqrt{s_{NN}} = 200$ GeV for Au+Au collisions and $\sqrt{s_{NN}} = 500$ GeV for p+p collisions.

The STAR experiment is home to the STAR (Solenoid Tracker At RHIC) detector. STAR is a multi-component detector, with each component designed to provide the specialized capabilities necessary for data collection in the high-energy, high luminosity-driven collision environment at RHIC. Two of the largest sub-detector components in STAR are the Time Projection Chamber (TPC), used for charged-particle tracking, and the Barrel Electro-Magnetic Calorimeter (BEMC), used for energy deposition related measurements. These two core-detector components enclose a significant geometrical volume, increasing the ability to study heavier (larger opening-angle) vector mesons such as $\Upsilon \rightarrow e^+e^-$: each detector has full-azimuthal ($0 \leq \phi \leq 2\pi$) coverage, and each detector has substantial rapidity acceptance ($|\eta_{TPC}| < 1.4$ and $|\eta_{BEMC}| < 1.0$).
3. Data and Analysis
The data recorded was selected using both Level-0 (L0) and Level-2 (L2) triggers. The L0 and L2 triggers at STAR for $\Upsilon$ reconstruction are detailed below.

The L0 trigger is a fast hardware-level decision, designed to make an acceptance decision for every RHIC bunch crossing. The L0 is a high-tower trigger, checking the condition for at least one BEMC tower with energy above a pre-defined threshold.

The L2 trigger is a software-level decision, acting as a topological trigger which checks for the condition of another BEMC energy deposit, indicative of a two-body decay. It is designed to find towers with an energy similar to the L0 threshold, and then use these energy-similar towers as the 'seeds' to form L2 clusters. The L2 algorithm takes these pairs of clusters and calculates the invariant mass, under the approximation

$$M \approx \sqrt{2E_1 E_2 (1 - \cos(\theta_{12}))},$$

where $E_i$ ($i = 1, 2$) is the cluster energy and $\theta_{12}$ is defined as the angle formed by the two approximately straight lines, extending from the vertex to the positions of the cluster. The straight-line approximation is valid under the known masses of the electron/positron and $\Upsilon$, the decay kinematics of the $\Upsilon$ daughters, and the known STAR magnetic field strength.

In STAR 2006 (Run-6) p+p data, the total $\Upsilon$(1S+2S+3S) total yield is $N = 67 \pm 22$ (stat). Integrated from 7 to 11 GeV, the background-subtracted $m_{ee}$ distribution results in $3\sigma$ significance [14]. Figure 2 shows the invariant mass spectrum for unlike-sign (blue) and like-sign (red).

![Figure 2. $\Upsilon$ invariant mass in Run-6 p+p data at $\sqrt{s} = 200$ GeV: Unlike-sign raw yield at $y_{ee} \leq |0.5|$ and like-sign combinatorial background (left panel). The $e^+e^-$ signal on the Upsilon mass-region after subtraction of like-sign combinatorial background (right panel).](image)

The STAR cross-section data point is consistent with the world data trend as a function of $\sqrt{s}$. The results of Next-to-Leading-Order perturbative Quantum Chromodynamics (NLO pQCD) calculations agree with the STAR data point within $1\sigma$ [15] in the Color Evaporation Model (CEM), while the Color Singlet Model (CSM) prediction underestimates the STAR data point by $2\sigma$ [16]. Figure 3 shows the STAR data point relative to the world data trend.

The Run-6 p+p data set is subject to a high rate of material conversion pairs, reducing the $\Upsilon$ mass peak signal to background (S/B). The reduced material in STAR Run-8 d+Au (and Run-9 p+p) data sets was the removal of the inner silicon detector systems (SVT + SSD). The final integrated luminosity for Run-8 was $32 \text{ nb}^{-1} \approx 12.5 \text{ pb}^{-1}$ (p+p equivalent).

In d+Au collisions, the signal + background pairings of unlike-sign electron pairs and background pairings of like-sign electron pairs results in a signal of $8\sigma$ significance [17]. Figure 4
Figure 3. Run-6 p+p data at $\sqrt{s} = 200$ GeV: $\Upsilon$ cross-section times branching ratio into electrons, with statistical error bars and a systematic uncertainty represented as a box (left panel). STAR cross-section data point relative to the world trend as a function of $\sqrt{s}$ (right panel).

shows the STAR $\Upsilon$(1S+2S+3S) unlike-sign (blue) and like-sign (black) mass spectrum (left panel), and the invariant mass peak after background subtraction (center panel) with an integrated (7 - 11 GeV/c$^2$) raw yield: 172 ± 20 (stat.).

Figure 4. $\Upsilon$ invariant mass (left and center panels) and the p$_T$-spectrum (right panel) in Run-8 d+Au data at $\sqrt{s} = 200$ GeV.

Figure 5 shows the cross-section results for Run-8 d+Au (left) and Run-6 p+p (right). The STAR cross-section data point for d+Au was found to be $B_{ee} (d\sigma/dy)_{\Upsilon^{1S}+\Upsilon^{2S}+\Upsilon^{3S}} = 35 \pm 4$ (stat) $\pm 5$ (syst) nb, and is consistent with the CEM prediction with anti-shadowing effects $+$ no absorption [18]. The measurement of the nuclear modification factor indicates that $\Upsilon$(1S+2S+3S) production is described by binary-collision scaling, within the current uncertainties, and that cold nuclear matter effects are not large. The most recent measured values for $R_{dAu} = 0.78 \pm 0.28$ (stat) $\pm 0.20$ (syst).
Figure 5. $R_{dAu}$ using $\Upsilon$ cross-sections at $\sqrt{s} = 200$ GeV: Run-6 p+p (left) and Run-8 d+Au (right) data.

The reduced material budget and improved statistics in Run-9 p+p data (integrated luminosity $\approx 3$ times greater than Run-6 p+p integrated luminosity) will help reduce the statistical uncertainty in $R_{dAu}$. Figure 6 shows the reconstructed mass from unlike-sign ($e^+e^-$) pairs (black) and like-sign ($e^+e^+ + e^-e^-$) pairs (red) in p+p data. There is very little background observed, even without the combinatorial background subtraction using like-sign pairs. The combinatorial background is normalized by the geometrical mean, following the prescription:

$$N = N_{++} - 2\sqrt{N_{++}N_{--}}$$

where the yield is extracted by integration of the invariant mass distribution of $\Upsilon(1S+2S+3S)$ after the subtraction of the normalized like-sign pair distribution. The $\Upsilon(1S+2S+3S)$ mass-analysis intends to separate the 'line shape' of the mass spectrum into the $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ states from the Drell-Yan and $b\bar{b} \rightarrow e^+e^-$ continuum contributions.

It is clear that the S/B region is higher in the Run-9 p+p measurement than the Run-6 p+p measurement. The high S/B ratio found in the reconstruction of $\Upsilon$ in the Run-9 p+p data enables us to attempt an analysis of Upsilon + Hadron azimuthal correlations. Prior to calculating the Upsilon + Hadron azimuthal correlation we cut tightly on the invariant mass-window from 8.0 to 11.5 GeV/$c^2$, for the purpose of optimizing our purity in the Upsilon’s S/B ratio (blue vertical lines). Increased hadronic activity (measured in space coordinates around the $\Upsilon$) directly around the quarkonium has been proposed as an experimental observable to measure the radiation emitted off the colored quark pair during production [19]. This measured activity may provide insight into the production mechanism of heavy quarkonium. Figure 7 shows an $\Upsilon$ produced with the single hard-gluon emission expected in CSM production vs. the multiple soft-gluon emissions expected in COM production.

In d+Au data, we see that the correlation is not significant relative to the underlying-event. Figure 8 shows the $\Delta\Phi$ - correlation shape in d+Au data corrected for background contributions (red). The results in data are then compared to PYTHIA [20] simulations (blue).

In p+p data, it is notable that PYTHIA does have a similar underlying-event. However, the correlation has not yet been corrected for acceptance and track efficiencies. Figure 9 shows the $\Delta\Phi$ - correlation shape in p+p data, corrected for background contributions (red). The results in data are then compared to PYTHIA (blue). We will attempt to decompose the observed correlation shape found in data, into the predicted contributions from gluon activity in both COM and CSM. Interpretation of the $\Delta\Phi$ - correlation shape is still in progress.
4. Future Measurements

The STAR program is expanding its lepton detection capability to include muons. Large mid-rapidity coverage of the muon telescope detector (MTD) allows for single muon detection from semi-leptonic decay of heavy flavor hadrons, as well as di-muon pairs from QGP thermal radiation and quarkonia decay. Muon detection expands the ability to study Drell-Yan production, light vector mesons, and constructing correlations of quarks and gluons as key signatures of resonances in the QGP.

The use of muons for analyses sidesteps the issue of $\gamma$-conversion pairs, minimizes the contributions from Dalitz decay, suffers less from the radiative losses in detector materials, and retains the ability to design muon-triggers in Au+Au collisions. The MTD triggering scenarios
extend from low to high-$p_T$ J/$\psi$ in central Au+Au collisions, provide excellent mass resolution for attempts at separating the different Υ states, and they open the door for analyses of electron-muon correlations, which aim to differentiate heavy flavor production from initial lepton pair production. The prototype of the MTD at STAR is operational from Run-7 to Run-10 [21-22].
5. Conclusions

STAR has measured the total \( \Upsilon(1S+2S+3S) \) yield to a 3\( \sigma \) level of significance in Run-6. The cross-section data point is consistent with the world data trend as a function of \( \sqrt{s} \) and is within 1\( \sigma \) of the NLO pQCD CEM calculations, but is underestimated by 2\( \sigma \) in NLO pQCD CSM calculations. In STAR Run-8 \( d+Au \) data, the results from a reduction in material budget and improved statistics leads to a measured total \( \Upsilon(1S+2S+3S) \) yield at an 8\( \sigma \) level of significance. The cross-section data point was found to be consistent with the CEM prediction with anti-shadowing effects, and the nuclear modification factor indicates the \( \Upsilon(1S+2S+3S) \) production as being described by binary-collision scaling, within the current uncertainties, leading to the conclusion that the effect from cold nuclear matter is not large. Run-9 \( p+p \) data saw a final integrated luminosity \( \approx 3 \) times greater than Run-6 \( p+p \) integrated luminosity. This will help reduce the statistical uncertainty in \( R_{dAu} \). There is very little background observed in Run-9 \( \Upsilon \) reconstruction, even without the combinatorial background subtraction using like-sign pairs. This reduction and increased luminosity makes it a real possibility for separating the \( \Upsilon(1S+2S+3S) \) mass states. These STAR measurements not only establish a baseline for future \( \Upsilon \) measurements in \( Au+Au \) collision systems, but they also provide insight into the \( \Upsilon \) production mechanism. In fact, the high Upsilon S/B ratio in Run-9 \( p+p \) data leads to an Upsilon + Hadron correlation in data with an underlying-event which is similar to that seen in PYTHIA simulations. The \( \Delta\Phi \) - correlation analysis is not yet corrected for acceptance and track efficiencies and awaits an attempt to decompose the observed \( \Delta\Phi \) - correlation shape from Run-9 \( p+p \) into possible contributions from the CSM and COM gluon activity. The STAR program is also expanding its event reconstruction capability to include processes involving muons. The MTD prototype at STAR is operational from Run-7 to Run-10, allowing for muon detection and the opportunity to minimize well-known issues that detract from electron-based analyses.

6. References

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