Measurements of Υ Production and Nuclear Modification Factor at STAR

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Abstract. Thermal suppression of quarkonium production in heavy-ion collisions, due to Debye screening of the quark-antiquark potential, has been proposed as a clear signature of quark-gluon plasma (QGP) formation. At RHIC energies, the Υ meson is a clean probe of the early system thanks to negligible levels of enhancement from b\bar{b} recombination and non-thermal suppression from co-mover absorption. We report on our measurement of the Υ \to e^+e^- cross section in Au+Au collisions at \sqrt{s_{NN}}=200 GeV. We compute the Nuclear Modification Factor by comparing these results to p+p collisions. In order to have a complete assessment of both hot and cold nuclear matter effects on Upsilon production we also report on results from d+Au collisions.

1. Introduction
The key goal of the RHIC program for the past decade has been to characterize the Quark-Gluon Plasma. By measuring its properties and evolution, we have a unique tool to study the underlying process governing it all: the strong nuclear force. Heavy quarkonia are unique probes into the dynamics of QGP evolution. Being massive, heavy quarkonia are produced almost exclusively via initial hard scatterings. They thereby allow us to extract information about the initial conditions of the QGP as well as observe effects due to evolution and cooling. Lattice-based calculations predict that the formation of a QGP will screen the inter-quark potential, thereby decreasing the meson’s binding energy and allowing thermal excitation to dissociate the quark-antiquark pair. By measuring the extent of this suppression and its dependence on system size, we can extract information about the initial temperature of the produced plasma [1, 2].

2. Analysis Techniques
The analyses shown in this paper were done using three different datasets: p+p from 2009, d+Au from 2008, and Au+Au from 2010. All systems were at end energy of \sqrt{s_{NN}} = 200 GeV. In all cases, for an event to be recorded, it first had to satisfy a High Tower trigger (\ET \gtrsim 4.3 GeV). Thanks to increased bandwidth in 2010 due to our DAQ1000 upgrade, we were able to record this trigger without any prescaling, so there were no additional requirements in the Au+Au system.

However, for the p+p and d+Au systems, we had an additional Upsilon trigger that ran on all events which fired the High Tower trigger. This trigger looks for a second energetic tower no closer than 90° to the tower which fired the first trigger. It then calculates an invariant mass
Figure 1. Left: Invariant mass spectrum of identified electrons. The red curve is the like-sign spectrum. The blue curve is the unlike-sign spectrum. The peak in the background is due to kinematic constraints imposed on our candidates by the Upsilon trigger. Right: To remove combinatorial pairs, we subtract the like-sign spectrum from the unlike-sign. The red curve represents our Υ signal. The dotted black curve is the combination of Drell-Yan and b¯b recombination.

assuming the energy in the towers came from electrons. If that energy is near the Υ mass, we record the event.

We relied on two main detectors in these analyses: the Time Projection Chamber (TPC) and the Barrel Electromagnetic Calorimeter (BEMC). The TPC is a gas-ionization chamber used to track charged particles. By looking at track curvature, we can measure the momentum and charge of produced particles. Also, by looking at the energy lost to ionization, we can identify particles based on their characteristic energy loss as a function of momentum. The BEMC is a lead-scintillator sandwich-style calorimeter used to measure energy carried by electromagnetic particles. By matching tracks from the TPC to deposited energy in the BEMC, we can reject BEMC signals from photons. Furthermore, we can identify electrons by comparing the energy deposited in the BEMC to the momentum measured in the TPC. Finally, the BEMC is a fast detector and serves as the basis for both triggers used in these analyses.

To reconstruct Upsilon candidates, we look at the invariant mass spectrum of unlike-sign (oppositely charged) identified electrons. For mass reconstruction, the momentum as measured by the TPC is used. In order to remove and contributions from random, combinatorial pairs, we subtract the like-sign spectrum from the unlike-sign spectrum. The resulting subtracted spectrum contains three signals: Drell-Yan production, b¯b recombination, and the desired Υ(1S+2S+3S) → e⁺e⁻ signal. The shape of the Drell-Yan signal is obtained from PYTHIA simulations. The b¯b background is obtained from pQCD calculation by R. Vogt. The shape of our Upsilon signal comes mainly from detector effects such as bremsstrahlung radiation and momentum resolution. It is obtained via embedding PYTHIA simulations into our detector model and real data.

3. Upsilon Production in p+p Collisions
In the left plot of Fig. 1, we show the invariant mass spectrum for both like-sign (red) and unlike-sign (blue) identified electron pairs. The peak in both signals around 9 GeV is a kinematic
constraint imposed by the condition of the Upsilon trigger. We use the shape of the like-sign spectrum to measure the kinematic conditions imposed by the trigger for use in our later fits. Furthermore, we subtract the like-sign spectrum from the unlike-sign to account for the combinatorial background. The results are show in the right plot of Fig. 1. We fit the subtracted spectrum to the integral of three signals: Drell-Yan, $b\bar{b}$ recombination, and the Upsilon signal. The Drell-Yan and $b\bar{b}$ signals are shown as a black dotted line. To obtain our yield of $\Upsilon$ mesons, we subtract the fit to Drell-Yan and $b\bar{b}$ from the subtracted spectrum. This helps remove any dependence we have on our choice of line-shape. We measure a cross section at $|y| < 0.5$ of $114 \pm 38^{+23}_{-24} \text{ pb}$.

The left plot of Fig. 2 shows the comparison between our measurement and the world data trend. The blue curve comes from a pQCD calculation by R. Vogt using the Color Evaporation Model. The right plot of Fig. 2 compares our measurement to two NLO pQCD calculations. The Color Singlet Model is shown as a blue dotted line [4]. The Color Evaporation Model is down as blue boxes [3]. Our measurement is much more consistent with the CEM calculation.

### 4. Upsilon Production in d+Au Collisions

The d+Au dataset was collected using the Upsilon trigger, imposing the same kinematic peak in the signal as was seen in the p+p analysis. We used the same technique as in p+p to isolate the signal. We report a combined Upsilon, Drell-Yan and $b\bar{b}$ cross section for $|y| < 0.5$ in the mass window 7 GeV < m < 11 GeV of 35 ± 4 ± 5 nb.

### 5. Upsilon Production in Au+Au Collisions

As a result of the installation of DAQ1000, which allows us to record Au+Au events at a rate of 1 KHz, we no longer needed the Upsilon trigger. As a result, we no longer had a kinematic peak imposed on the background (see Fig. 4, left). Furthermore, once we subtract the like-sign spectrum from the unlike-sign spectrum, our Drell-Yan and $b\bar{b}$ signal also do not have a kinematic peak (Fig. 4, center).

Since we do not know a priori what the ratio between the 1S, 2S, and 3S states should be, we
Figure 3. Invariant mass spectrum of unlike-sign minus like-sign pairs of identified electrons. This contains the Upsilon signal, Drell-Yan production, and $b\bar{b}$ recombination. We see an $8\sigma$ signal in the mass window of 7-11 GeV.

We fit our signal to lineshapes representing different scenarios (such as the excited states existing in the proportion to the ground state as in p+p, no excited states, half of p+p, etc.). We also still subtract the fit to the Drell-Yan and $b\bar{b}$ background from the subtracted spectrum to reduce further any dependence on our lineshapes.

By selecting on the number of charged tracks produced, we can separate our measurement into three centrality bins: 0% to 10%, 10% to 30%, and 30% to 60%. Using our p+p collisions as a baseline, we compute a nuclear modification factor, $R_{AA}$, as a function of the average number of participants (obtained via Glauber simulations). The results are shown in the right plot of Fig. 4. We compare our results to calculations done using lattice-based QCD results with a hydrodynamical model incorporating expansion, cooling, and temperature gradients [2]. The model is run using two different inter-quark potentials: one based on the internal energy of the quark-antiquark pair, the other on the free energy. Our results are more consistent with the internal energy model. However, more statistics are needed to reach any definitive conclusions.

6. Conclusions
Thanks to the large acceptance of the STAR detector and our dedicated Upsilon trigger, we were able to measure Υ mesons in p+p, d+Au, and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Measured p+p production is consistent with NLO calculations. Our results show increasing suppression with the number of participants. Furthermore, the results are consistent with hydrodynamical suppression models for the QGP.

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Figure 4. Left: Invariant mass spectrum of identified electrons in Au+Au system in the 0% to 60% centrality range. Like-sign pairs are in blue; unlike-sign in black. Note that the spectrum no longer has a kinematic peak imposed by the Upsilon trigger. Center: Unlike-sign signal subtracted from like-sign signal, 0%-60% centrality. The blue curve is the combination of Drell-Yan and $b\bar{b}$ . The black curve includes the Upsilon signal also. Right: $R_{AA}$ for 2010 Au+Au compared to 2009 p+p. The magenta and orange curves are theoretical predictions using a combination of lattice-based QCD and hydrodynamical expansion and cooling [2].