Υ Production in p+p $\sqrt{S_{NN}}$ = 200 GeV at STAR
A baseline process to study hot nuclear matter effects in relativistic heavy ion collisions

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Abstract
The Υ meson family consists of $b\bar{b}$. The 1S, 2S and 3S states can be studied at STAR through their dielectron decay channel. As the heaviest quarkonium meson measured at STAR, it is an important probe of the Quark Gluon Plasma (QGP) medium because the spectral properties of heavy mesons are modified by the QGP such that their production is suppressed. In order to make an accurate measurement of the quarkonium suppression due to the QGP, p+p measurements are necessary to establish the production cross section in collisions where no QGP is formed. Suppression is studied by examining the ratio of the invariant yield in A+A divided by the yield in p+p scaled by the number of binary collisions. If the QGP has no effect, this ratio should be one. This paper will discuss the analysis of the 2006 p+p Υ data set from STAR in preparation for a comparison with A+A and to establish an analysis method for the higher luminosity 2009 p+p run.

Introduction

Quarkonia are mesons consisting of a heavy quark and its anti quark. It is an important tool for studying strongly interacting matter as the heavy mesons are produced early in collisions. The absence of particular quarkonia states is thought to be an indication of deconfinement, where Debyre color screening dissolves the bounds of the $q\bar{q}$ pair [1]. By examining the total yield and the ratios of the Υ family, the temperature of the QGP can be calculated. Information about the quark gluon plasma can be found by examining the ratio of the yield of a particular quarkonium state over the yield of that state in p+p collisions, scaled by the number of collisions. The number of collisions is calculated using the Glauber model. This scaling factor is done to take the larger system size of A+A collisions compared to p+p collisions.

At RHIC, both the ψ and Υ families are produced. The STAR detector was not designed to detect the Υ, and to date no one has published a heavy ion Υ measurement. In 2006 the STAR detector was able to measure the Υ for the first time, though the detector was not able to distinguish between the various Υ states since the resolution at FWHM was 0.5 GeV. The 2009 p+p run will have both a higher luminosity and less material in the inner part of the detector, which will make measuring the separation in the states possible. The decay channel used at STAR is $\Upsilon \rightarrow e^+e^-$ due both to the large electron acceptance, and the efficiency of triggering on electrons in p+p and A+A events. The barrel electromagnetic-calorimeter (BEMC) and the Time Projection Chamber (TPC) are the two key detectors for quarkonia analyses. They measure the momentum and energy of the daughter particles, and allow for particle identification. Both the BEMC and the TPC have a coverage of $|\eta| < 1$ and $0 < \phi < 2\pi$. The BEMC is divided into 4800 towers, where each contain an area of $\Delta\phi = 0.05$ and $\Delta\eta = 0.05$ [2],[3].

Quarkonia Trigger

STAR has a specific two-stage trigger for Quarkonia measurements. The first part is a fast L0 trigger, with a decision time of ~1 μs, which triggers on a high tower of ~4 GeV in the BEMC. The second part is a slower L2 trigger scheme, with a decision time of ~400 μs, which requires a second tower cluster with the proper energy and topology. The dominant background source is photons coming from π^0 decays. Electrons coming from other sources, such as pion decays, generally have too low a p_T to cause a problem.

The high mass of the ϒ meson allows it to have the same trigger conditions in both p+p and A+A events. The L0 trigger requires a high tower of ~4 GeV, depending on the specific trigger being used. The efficiency of the L0 trigger, as calculated below, is ~99%. The L2 trigger consists of several parts. First the cluster energy threshold must be at least 2.5 GeV, where a cluster contains the 3 towers with the highest energy in a 3x3 section. The invariant mass of the L2 triggered tower cluster and the L0 triggered tower must be between 6 and 15 GeV/c^2. This is calculated directly from the energy left in the barrel calorimeter with the formula $m = \sqrt{(2E_1E_2(1-\cos(\theta)))}$ where E_1 is the energy left in the BEMC by the first daughter, E_2 is the energy left in the BEMC by the second daughter and θ is the opening angle between the two high towers in the BEMC. This allows a fast estimate of the invariant mass of the parent particle. The resolution of the invariant mass is ~1 GeV/c^2. The mass is reduced by ~0.5 GeV/c^2 by only using three towers. This algorithm was optimized for use in A+A collisions. The maximum value of the cosine of the opening angle between the L0 triggered tower and the L2 triggered tower is 0.5, which would eliminate ϒs with p_T > 14 GeV/c. In order to determine the L2 efficiency as well as the other efficiencies that are required for an accurate calculation, STAR uses embedded data.

Embedding at STAR

The efficiency of finding an ϒ is needed in order to accurately determine cross section. This is calculated by using a generated ϒ forced to decay to e^+e^-, which is then embedded into a background event. The generated ϒs are required to have a flat distribution in pT space from 0 to 10 GeV and a flat distribution in rapidity space from -2 to 2. This distribution, while unphysical, allows the statistical error bars to be even through out the phase space of interest.

For p+p collisions, part of the background event is a min-bias p+p event generated by PYTHIA and run through GEANT, which simulates the detector response. The generated event is then embedded into a real data zero-bias event so that detector noise and other effects can be accounted for. A zero-bias event is an event where the only trigger requirement is a blue-yellow coincidence, i.e. the two counter circulating beams are crossing in the detector. These events have a ~10% chance of having a collision at the 2006 p+p luminosity. This allows realistic noise and pile-up effects to be included in the embedded data set, which allows for a more accurate efficiency calculation. The embedded data contains both the Monte Carlo information as well as the information that would be available for a real event so that comparisons can be made.

In order to determine the efficiency of finding an ϒ, the geometric acceptance needs to be determined. If either of the ϒ daughters misses the barrel calorimeter, the ϒ can not be triggered on.

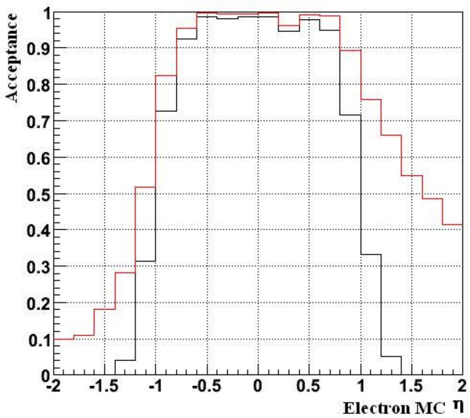

Figure 1. η distribution of the acceptance for Monte Carlo generated electrons. The red curve represents those with a single hit in the BEMC, the black curve represents those that left at least 0.25 GeV in the BEMC.

Even with a perfect detector, these events will be lost. Calculating the acceptance strictly based on geometry would not account for the cracks in the BEMC. We therefore use STAR's GEANT model and study the MC hits and tracks in the detector simulator. Insisting on a requirement of a single Monte Carlo hit within the BEMC caused an asymmetric distribution, as seen in Figure 1, because daughters with high positive η could shower off the end cap and leave hits in the BEMC. In the calculation, the geometric acceptance was determined by insisting that both Monte Carlo daughters leave at least 0.25 GeV of energy in the barrel calorimeter.

Once the acceptance is determined, we proceed to study the efficiencies. The L2 algorithm is run over the embedded data and returns the tower IDs of any tower pairs where one satisfies the L0 requirement and the other satisfies the L2 requirement. It is possible for events to have multiple combinations that satisfy these requirements. If either of the ϒ daughters point to a tower that satisfies the L0 requirement, the ϒ is considered found for the purposes of determining the L0 efficiency. This efficiency was calculated to be >99%. If both of the ϒ daughters point to a pair of towers that satisfies the L2 and L0 requirements, the ϒ is considered to be found for the purpose of determining the L2 efficiency. The efficiency is calculated as the number of events where the ϒ was found over the total number of events analyzed. The efficiency as a function of rapidity or transverse momentum is shown in Figures 2 and 3.

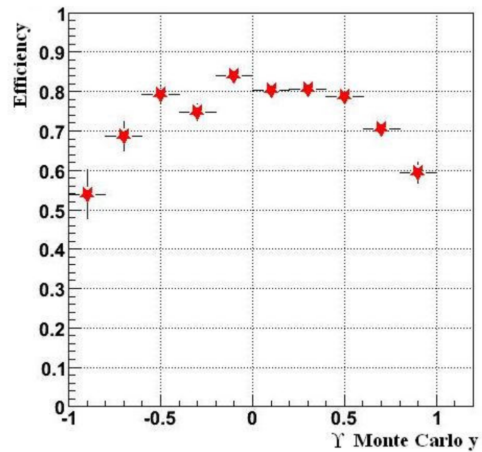

Figure 2. Embedded L2 Efficiency calculation versus the Monte Carlo ϒ rapidity for the 2005 STAR geometry. In 2005 the complete STAR BEMC was not available. The negative η and negative ϕ quadrant was missing.

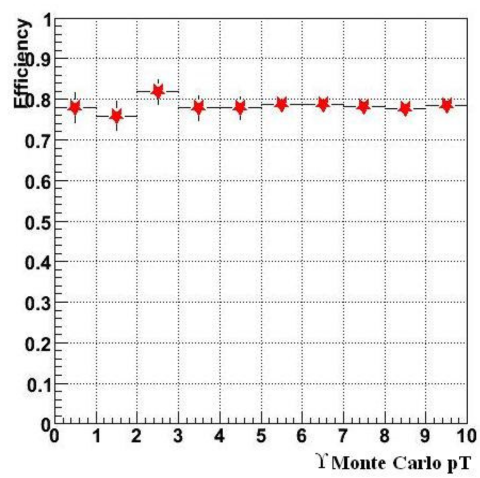

Figure 3. Embedded L2 Efficiency calculation versus Monte Carlo ϒ p_T for the 2005 STAR geometry.

The last piece of the efficiency calculation that can be acquired from embedded data is the tracking efficiency of the TPC. The Monte Carlo tracks are associated with reconstructed tracks that contain the TPC information. A number of cuts on track quality are used, and if the associated tracks to the ϒ daughter tracks pass the track quality cuts then the ϒ has been found. The track quality requirements used in this analsis were to require at least 20 fit points (out of a possible 45) in the TPC. The fraction of hit points over possible fit points had to exceed 0.52 to avoid including split tracks. The p_T had to be greater than 0.2 GeV/c. The efficiency of finding the parent ϒ due to track quality cuts, versus rapidity and transverse momentum is shown in Figures 4 and 5.

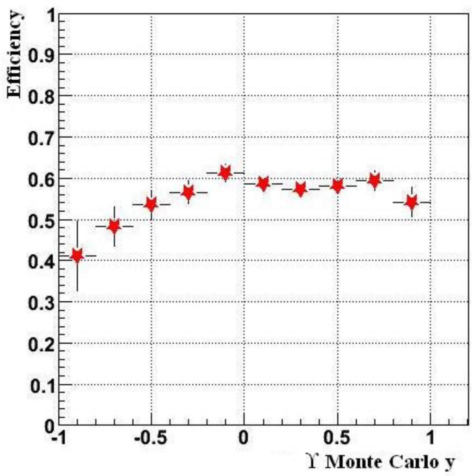

Figure 4. Embedded TPC tracking efficiency versus Monte Carlo ϒ rapidity.

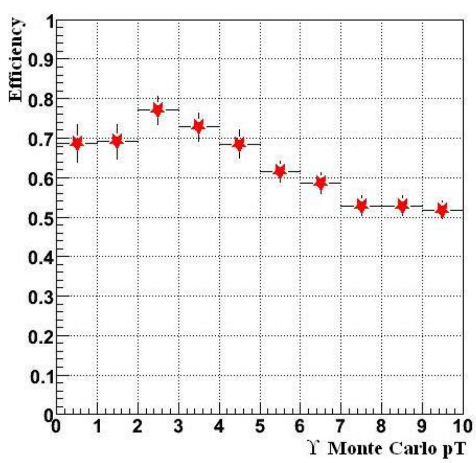

Figure 5. Embedded TPC tracking efficiency versus Monte Carlo ϒ pT. Tracks quality requirements were the same as for Figure 4.

2006 p+p Analysis

Analysis of the L2 triggered 2006 p+p data found that 97.5% of the events had an ϒ candidate when run with the offline L2 code as a sanity check. If the trigger were to work perfectly, the number of offline candidates would be 100%. STAR's offline code will ignore towers that were labeled as masked because they had been firing consistently at a rate much higher than what would be expected. If one of these towers fulfilled the online trigger, it would be ignored in the offline analysis, causing us to have an event with no ϒ candidate. Of the events analyzed, 13.8% of events having more than one candidate as shown in Figure 6.

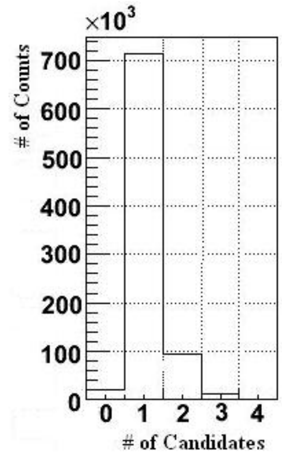

Figure 6. Number of ϒ candidates per L2 triggered event, where an ϒ candidate is a pair consisting of an L0 and an L2 Trigger. The mean is 1.15 candidates per event.

Once ϒ candidates are identified, the candidate daughters need to be analyzed to determine if they are electrons. We use information from both the TPC and the BEMC to do this. To determine the identity of the particles that created the tracks both the ionization energy loss, dE/dx, and the ratio of the energy in the BEMC divided by the momentum measured in the TPC, E/p, were used. The dE/dx cut was optimized by fitting Gaussian curves to the counts versus ln(dE/dx) for different momentum slices. A characteristic distribution for this method is shown in Figure 7.

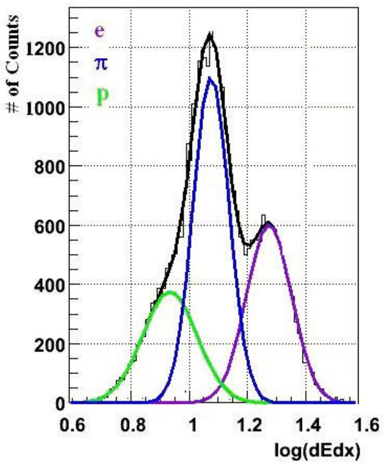

Figure 7. Gaussian fit for the momentum range 4 < p < 6 GeV/c. The χ^2/dof is 205.3/111 for this particular range. The fit is improved when smaller momentum slices are used.

In order to optimize the electron ID cut we used the effective signal defined as $S_{eff} = S/(2B/S + 1)$ where S is the signal and B is the background. S_{eff} is the background free signal equivalent such that the error is simply the square root of S_{eff}. This distribution for three different momentum cuts is shown in Figure 8. In this case, the signal was the number of electrons available and the background was the number of hadrons within the cut. This was determined by integrating the Gaussian curves shown in Figure 7. The efficiency and purity versus the cuts can also be calculated. The efficiency versus the momentum for a particular cut was extrapolated to momentum values where the overlap of the Bethe-Bloch curves made it impossible to do a Gaussian fit. For this analysis, dE/dx > 3.3 keV/cm was chosen, which gave an efficiency of 82.5% for the high energy daughter and an efficiency of 85.4% for the low energy daughter.

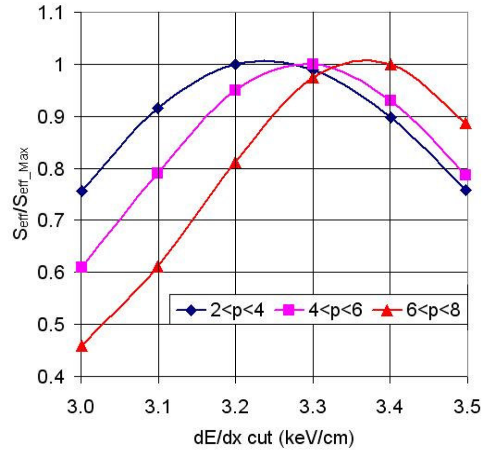

Figure 8. S_{eff} versus dE/dx cut for three momentum slices.

The dE/dx cut removed a large percentage of the low energy pions, but was not sufficient for a clean ϒ signal. Using the information from the BEMC by making a E/p cut improves the S/B ratio. Electrons should deposit all of their energy into the barrel calorimeter, so that their value of E/p should be 1. Since the distribution of E and 1/p are both Gaussian, the distribution of E/p for a single species should also be Gaussian. To get the mean and the sigma of the E/p Gaussian for electrons, a sample of hadrons was picked by requiring a dE/dx less than 2.5 keV/cm. This was then scaled so that it matched the distribution of potential ϒ daughters in the tail from E/p of 2 to 3 and then subtracted. The E/p curve for electrons and hadrons with a matched hadron curve is shown in Figure 9. The distribution that remains after the hadrons are subtracted is fit with a Gaussian as shown in the insert for figure 9. Particles with an E/p that fall outside of two sigmas of the centroid of the Gaussian are cut.

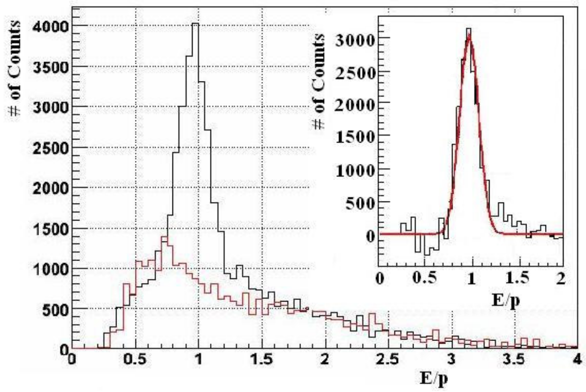

Figure 9. E/p for particles with dE/dx > 3.5 keV/cm, which contains both electrons and hadrons, is in black and particles with dE/dx < 2.5, which contains only hadrons, in red. The insert contains the red distribution subtracted from the black distribution and fit with a Gaussian.

The invariant mass of all particles that passed the PID and track quality cuts was calculated. The background was calculated using the formula $B = \sqrt{(2N_{++}*N_{--})}$ where N_{++} (N_{--}) is the invariant mass spectrum of particle pairs where both are positive (negative).[3] The invariant mass spectrum is calculated as N_{+-} - B, where N_{+-} is the invariant mass spectrum of pairs with opposite signs. The resulting curve was fit with a Gaussian to give the total number of ϒ found in the run.

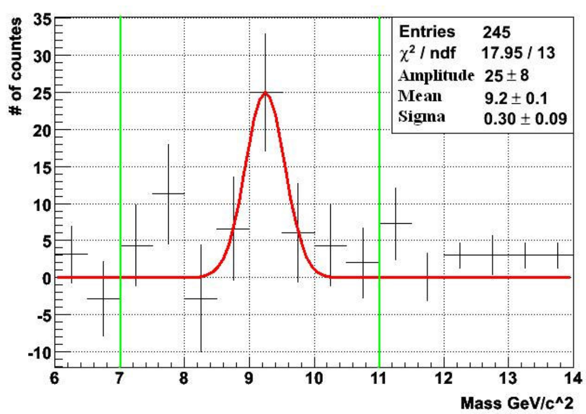

Figure 10. Invariant mass the ϒ with a |y| < 0.5. The green window represents the counting range used for the QM2006 analysis. The red curve is a Gaussian fit to the data.

After applying the efficiency corrections calculated both from embedding and from the particle identification, the ϒ cross section can be determined by the formula $d\sigma/dy|_{y=0} = N_{\Upsilon}/(dy*\varepsilon_{\Upsilon}*\int Ldt)$ where the integrated luminosity for this trigger during the 2006 run was determined to be 5.6 +/- 0.8 pb^{-1}. The yield should be calculated by fitting a line shape from embedded ϒ to the data. At this time this has not been done, so the yield was calculated totalling the counts from 7 GeV/c^2 to 11 GeV/c^2 for a total of 62 +/- 8. The mid-rapidity efficiency, including the acceptance, was calculated to be 15.1% +/- 0.9%. This gives a cross section of 73 +/- 11 (statistical) +/-22 (systematic) pb for ϒ (1S,2S,3S) -> e^+e^- [5]. This compares well with the NLO cross-section of ~90 pb calculated by Ramona Vogt.[6]

Outlook

The previous analysis of this data for Quark Matter 2006 did not take into account the extra candidates in events with more than one candidate. The offline algorithm needs to be improved in order to optimize the cuts. Once this has been optimized, the algorithm will need to be rerun over the embedded data in order to calculate the new efficiencies. At this point the systematic errors will be reanalyzed. This method needs to be applied to the other 2006 STAR ϒ trigger so that the full luminosity of ~9 pb^{-1} is utilized. This will allow us to calculate the invariant yield, which in turn will be used to calculate the p_T and y integrated R_{AA} after a similar analysis is completed for the 2007 Au+Au ϒ data set. This analysis was done as a proof of concept in order to prepare for the STAR 2009 p+p high luminosity run. The 2009 run will have five times the statistics based on its higher luminosity. The STAR detector has had silicon material removed from between the beam pipe and the TPC, which reduces the effect of Bremsstrahlung and will allow for a much cleaner ϒ signal. Simulations indicate that it may be possible to measure the ratio of the 2S to the 1S states. The reduction of this ratio from p+p to A+A is hypothesized to be an indicator of QGP.

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[2] M. Beddo et al., The STAR barrel electromagnetic calorimeter. Nucl. Instr. and Meth. A 499 (2003), p. 721.
[3] M. Anderson et al., The STAR time projection chamber: a unique tool for studying high multiplicity events at RHIC. Nucl. Instr. and Meth. A 499 (2003), p. 659.
[4] arXiv:nucl-ex/0203004
[5] D. Pibero, Quark Matter 2006 Proceedings
[6] A.D. Frawley, T. Ullrich, R. Vogt, Heavy flavor in heavy-ion collisions at RHIC and RHIC II. arXiv:0806.1013v2