Upsilon measurements in the STAR experiment

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The main focus of the heavy flavor program at RHIC is to investigate the properties of the quark-gluon plasma (QGP) by studying its effect on open heavy flavor and quarkonia production. Suppression of the J/ψ induced by Debye screening of the static quantum chromodynamics (QCD) potential between charm-anti-charm pairs was original hailed as an unambiguous signature of QGP formation [1]. However, this simple picture is complicated by competing effects that either reduce the yield, such as co-mover absorption [2-3], or enhance it, such as in recombination models [4-6]. Recently, a growing interest in studying the Upsilon meson (Υ) and its excited states has been kindled as it is expected that color screening will be the dominant effect contributing to any observed suppression of bottomonium production in heavy-ion collisions. A full spectroscopy of quarkonia states is now clearly recognized as one of the key measurements needed to understand the matter produced in high-energy heavy-ion collisions [7]. In particular, it has been recognized that data on the particle spectra of bottomonia can provide valuable information to constrain QGP models [8]. Due to the low production cross section of bottom-anti-bottom at RHIC (1.9 μb [9]), recombination effects in A+A collisions are negligible [10]. At the same time, the interaction cross section of bottomonium with the abundantly produced hadrons in these collisions is small [11], so suppression due to absorption by hadronic co-movers is expected by these models to be relatively unimportant. However, it will still be important to study production in d+Au collisions since available measurements by E772 [12] of cold nuclear matter effects on production at lower energy show some suppression. Nevertheless, the amount of suppression seen for the family is measured to be smaller than for charmonia. Therefore, bottomonium is expected to be a cleaner probe of high-temperature color screening effects. In addition to its important role in establishing deconfinement, a measurement of the Upsilon 1S, 2S, and 3S states in p+p and heavy-ion collisions can help to set limits on the medium temperature. The quarkonium measurements help in reaching these key goals because (*i*) an observation of suppression of Υ production in heavy-ion relative to p+p collisions would strongly imply Debye screening and therefore deconfinement [10, 13], and (*ii*) the sequential suppression pattern of the excited states is sensitive to the temperature reached in the medium [7]. In this regard, lattice QCD studies have seen a burst of activity in recent years. Studies of quarkonia spectral functions and potential models based on lattice QCD indicate that while the Upsilon(3S) melts even before the deconfinement transition and the Upsilon(2S) is likely to melt at RHIC $\sqrt{s}$=200 GeV), the Upsilon(1S) is expected to survive [7, 14, 15] beyond the parton-hadron phase transition. Recent results [13, 16] indicate further that almost all quarkonia states (J/ψ, ψ’, χ_c, χ_b, Upsilon(2S)) melt below 1.357 T_c and the only one to survive to higher temperature is Upsilon(1S), which melts at $2T_c$, where $T_c \approx 175$ MeV is the critical temperature for the phase transition. Therefore, a systematic study of all quarkonia states in p+p, d+Au, and Au+Au collisions will provide a clearer understanding of the properties of the QGP. Suppression of the Upsilon(2S) and Upsilon(3S) should be measurable at RHIC energies with increased integrated luminosity. In the near future, the larger luminosities proposed by the RHIC II program [17] will allow for a statistically significant measurement of all 3 states. In the context of this objective, one of the first steps is to establish a baseline cross section measurement of the bottomonia states in p+p collisions. There are no previous measurements of Upsilon production in p+p at the top RHIC energy for heavy ions (an upper limit was estimated in the 2004 data with only half of the calorimeter [18]). The luminosities available at RHIC in the 2006 run provided the first opportunity to measure bottomonium at the previously unexplored center-of-mass energy of $\sqrt{s}$=200 GeV. A dedicated trigger algorithm exploiting the capabilities of the STAR electromagnetic calorimeter is essential for this measurement, and its development in STAR allows the Upsilon family to be studied in the e^+e^- decay channel.

I. Upsilon cross section in p+p collisions at $\sqrt{s}$=200 GeV

The Cyclotron Institute was involved as primary author on a paper submitted by the STAR Collaboration to the journal publication Physical Review D which reports the Upsilon(1S+2S+3S) cross section at mid-rapidity, obtained with the STAR detector in p+p collisions at $\sqrt{s}$=200 GeV via the e^+e^- decay channel. This measurement uses an integrated luminosity of 7.9 pb^{-1} collected during RHIC Run VI (2006). The STAR data is compared to perturbative QCD calculations done at next-to-leading order (NLO) in the Color Evaporation Model (CEM) [17] and in the Color Singlet Model (CSM) [19].

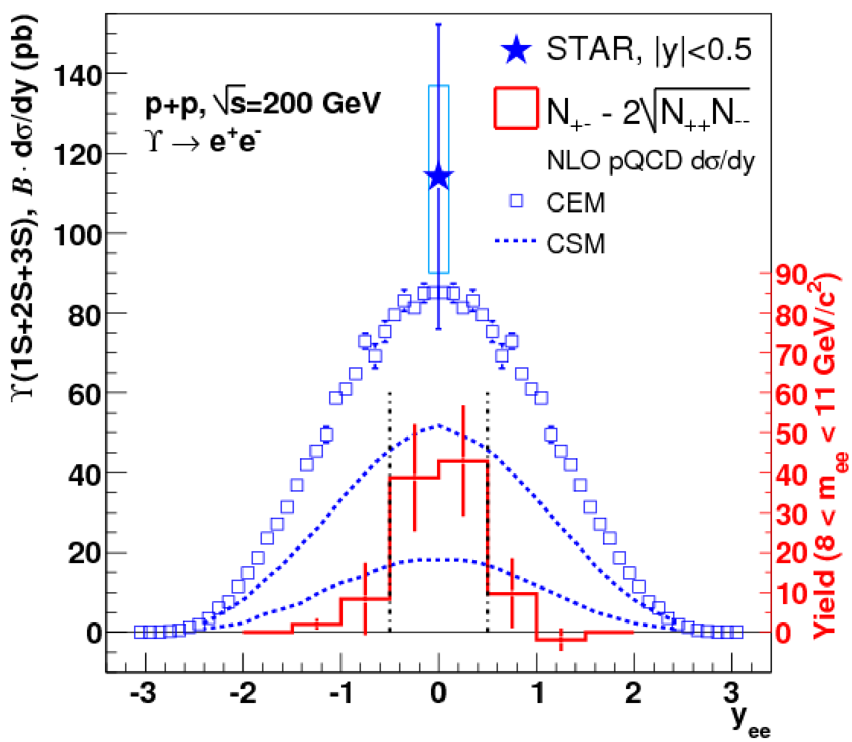

FIG. 1. The STAR measurement of the midrapidity Y(1S+2S+3S) cross section times branching ratio into electrons, compared to model calculations (COM and CSM).

We found the cross section to be 114±38 (stat.)$^{+23}_{-24}$ (syst.) pb. Perturbative QCD calculations at NLO in the CEM are in agreement with our measurement, while calculations in the CSM underestimate it. Our result is consistent with the trend seen in the world data as a function of the center-of-mass energy of the collision and extends the availability of Upsilon data to RHIC energies. The di-electron continuum in the invariant mass range near the Upsilon is also studied to obtain a combined cross section of Drell-Yan plus b-bbar $\rightarrow e^+e^-$.

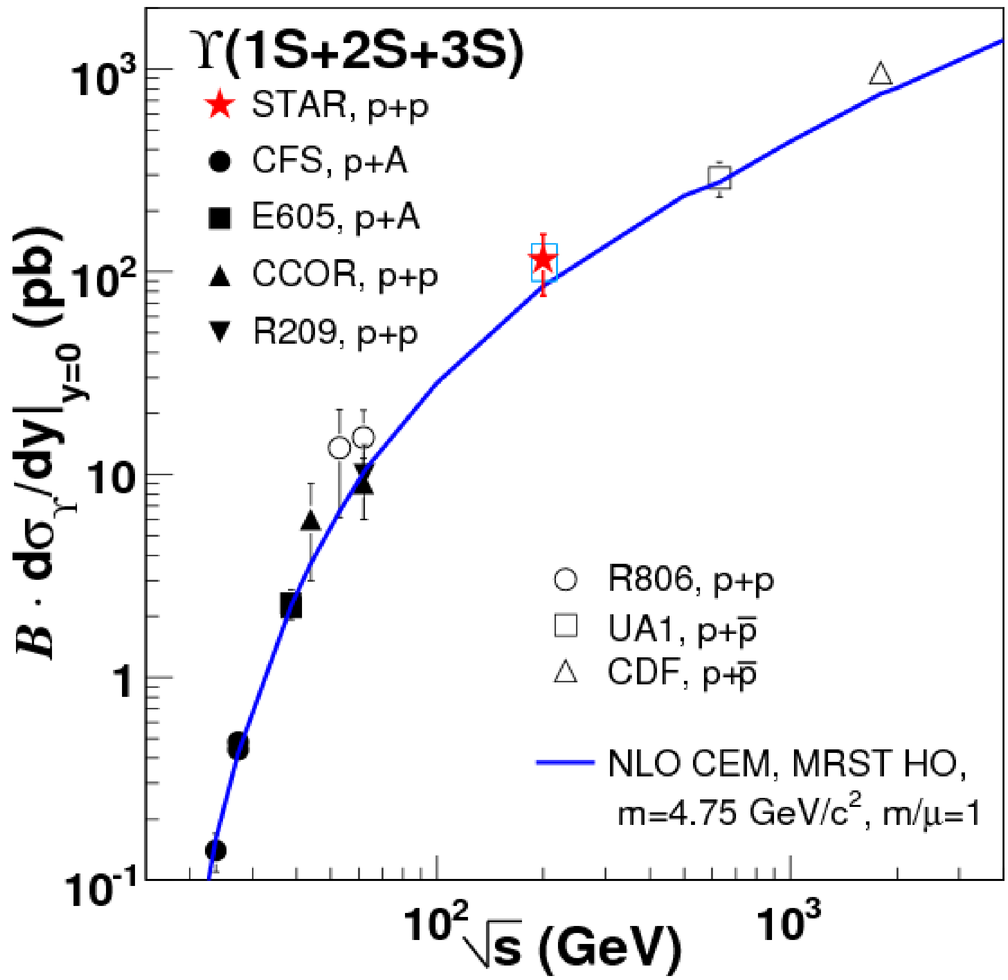

FIG. 2. Evolution of the Υ(1S+2S+3S) cross section with center-of-mass energy for the world data and an NLO CEM calculation.

II. Upsilon + Hadron correlations in d+Au and p+p collisions at √s=200 GeV

In order to further study the systematics of prompt production of heavy quarkonium, e.g. via the Color Singlet Model (CSM) vs. the Color Octet Model (COM), we have explored additional experimental observables. Hadronic activity directly around the Upsilon has been proposed [20] as an experimental observable to measure the radiation emitted off the colored heavy quark pair during production. Since the COM results in the radiation of a gluon off the produced quarkonium state, additional hadronic activity correlated with the Upsilon is expected for production through the color-octet channel vs. through a color singlet. Thus, possible insight into the prompt production mechanism of heavy quarkonium can be obtained from a correlation measurement. The high signal to background S/B ratio found in Upsilon reconstruction, even in d+Au collisions [21], enables us to perform an analysis of Upsilon + Hadron correlations. We performed the Upsilon + Hadron correlation analysis on the Run-8 d+Au and Run-9 p+p data, both at $\sqrt{(s_{NN})}$ = 200 GeV.

Fig. 3 shows the reconstructed mass from e+e- pairs (black) and like-sign pairs (red) in p+p data. There is very little background observed even without background subtraction. The next steps in this analysis include the embedding Upsilon particles into real events in order to evaluate the efficiency corrections and the line shapes of the Upsilon(1S), Upsilon(2S) and Upsilon(2S) states.

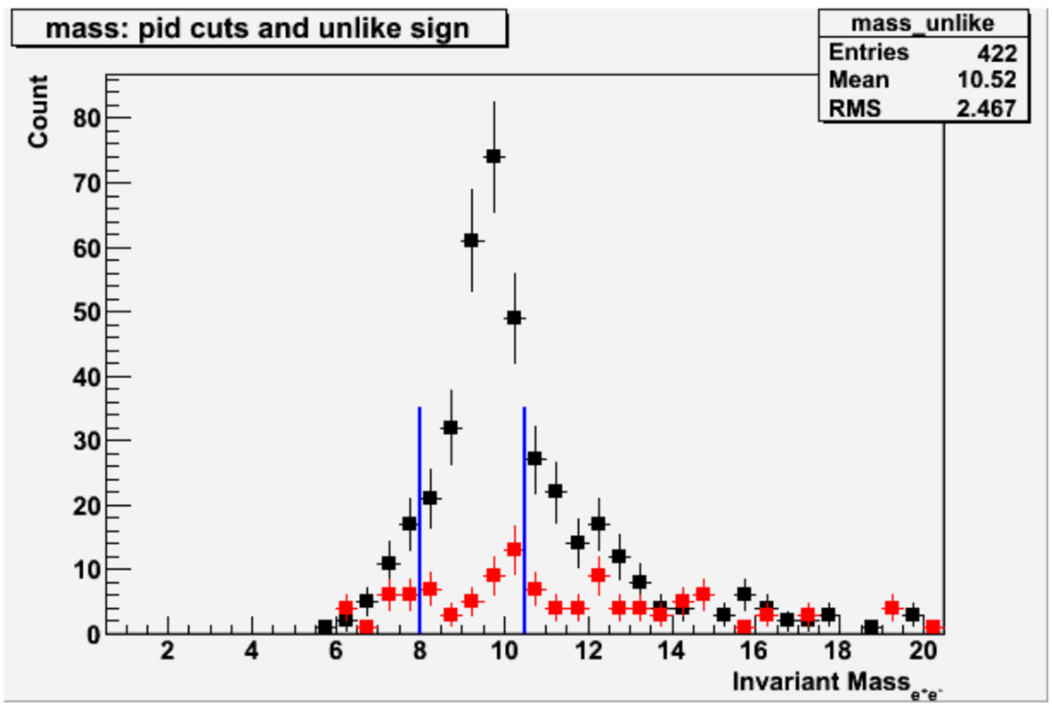

FIG. 3. Invariant mass distribution of e+e- pairs (black) and like-sign pairs (red) calculated in p+p events.

Fig. 3 also denotes the optimization for purity of the Upsilon's signal to background ratio (blue vertical lines) before the Upsilon + Hadron correlation is made. Fig. 4 shows the ΔΦ - correlation measurement in p+p data (black), which is then corrected for background contributions (red). The results are compared to Monte Carlo (PYTHIA) [22] simulations (blue). Interpretation of the ΔΦ – correlation shape is still in progress.

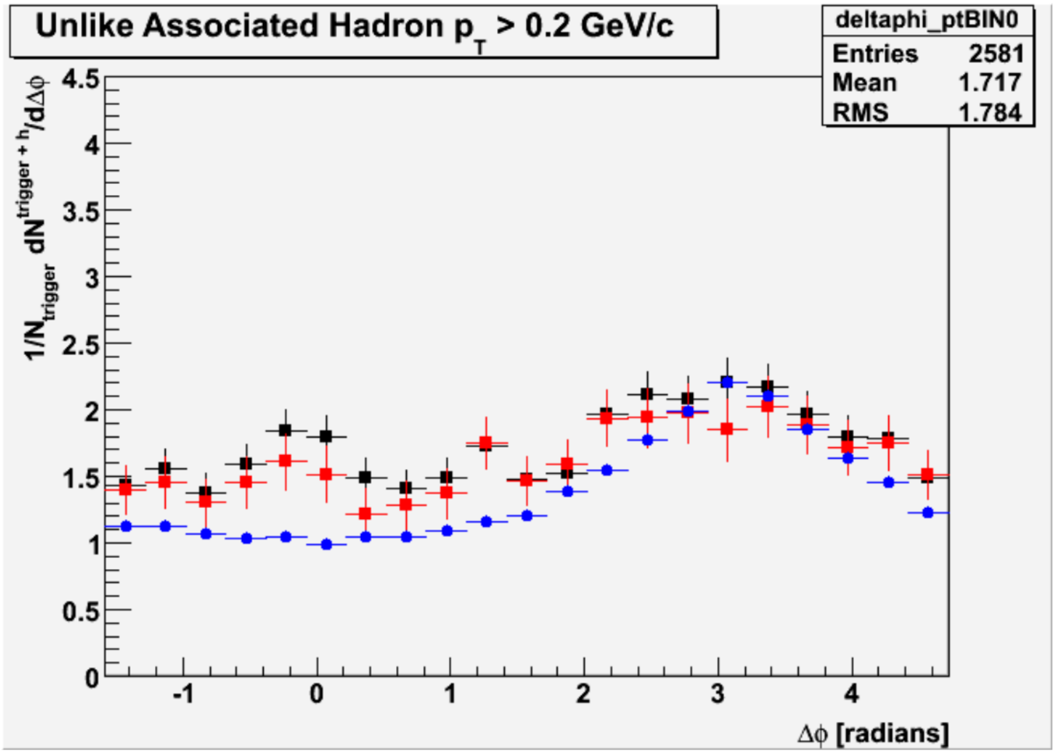

FIG. 4. Δϕ - correlation: raw (black), corrected for background (red), and compared to Monte Carlo (blue) in p+p events.

[1] T. Matsui and H. Satz, Phys. Lett. B **178**, 416 (1986).

[2] S. Gavin, M. Gyulassy, and A. Jackson, Phys. Lett. B **207**, 257 (1988).

[3] J.-P. Blaizot and J.-Y. Ollitrault, Phys. Rev. D **39**, 232 (1989).

[4] L. Grandchamp *et al.*, Phys. Rev. Lett. **92**, 212301 (2004).

[5] R.L. Thews *et al.*, Eur. Phys. J. C **43**, 97 (2005).

[6] A. Andronic *et al.*, nucl-th/0611023.

[7] S. Digal, P. Petreczky, and H. Satz, Phys. Rev. D **64**, 56 094015 (2001); [arXiv:hep-ph/0106017].

[8] J.F. Gunion and R. Vogt, Nucl. Phys. **B492**, 301 (1997); [arXiv:hep-ph/9610420].

[9] M. Cacciari, P. Nason and R. Vogt, Phys. Rev. Lett. **95**, 60 122001 (2005); [arXiv:hep-ph/0502203].

[10] L. Grandchamp *et al.*, Phys. Rev. C **73**, 064906 (2006).

[11] Z.w. Lin and C. M. Ko, Phys. Lett. B **503**, 104 (2001); [arXiv:nucl-th/0007027].

[12] D.M. Alde *et al.*, Phys. Rev. Lett. **66**, 2285 (1991).

[13] A. Mocsy and P. Petreczky, Phys. Rev. Lett. **99**, 211602 65 (2007); [arXiv:0706.2183 [hep-ph]].

[14] S. Digal, P. Petreczky and H. Satz, Phys. Lett. B **514**, 57 (2001); [arXiv:hep-ph/0105234].

[15] C.-Y. Wong, Phys. Rev. C **72**, 034906 (2005).

[16] A. Mocsy and P. Petreczky, Phys. Rev. D **77**, 014501 (2008); [arXiv:0705.2559 [hep-ph]].

[17] A.D. Frawley, T. Ullrich and R. Vogt, Phys. Rep. **462**, 72 125 (2008).

[18] T. Kollegger, Ph.D. thesis, Johann Wolfgang Goethe-Universitat Frankfurt am Main, 2005.

[19] S.J. Brodsky and J. P. Lansberg, arXiv:0908.0754 [hep-ph].
[20] A.C. Kraan, arXiv:0807.3123.
[21] H. Liu (STAR Collaboration), arXiv:0907.4538.
[22] T. Sjöstrand, S. Mrenna, and P. Skands, Comput. Phys. Commun. **178**, 852 (2008).