EPJ Web of Conferences **274**, 05007 (2022) https://doi.org/10.1051/epjconf/202227405007
XVth Quark Confinement and the Hadron Spectrum

Open and hidden heavy flavor measurements at RHIC

Leszek Kosarzewski[1,*]

[1]Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Břehová 78/7, 115 19 Staré Město, Prague, Czech Republic

Abstract. Quarks of heavy flavors are useful tool to study quark-gluon plasma created in heavy-ion collisions. Due to their high mass and early production time, heavy quarks experience the entire evolution of the system created in these collisions. Open heavy flavor meson measurements are sensitive to the energy loss in the QGP, while quarkonia are sensitive to the temperature of the QGP as they dissociate because of Debye-like screening of color charges.

This presentation is a summary of the latest heavy flavor studies performed at RHIC. Results from both STAR and PHENIX experiments are presented, compared to theoretical calculations and the implications discussed.

1 Introduction

Heavy quarks are a good probe of quark gluon plasma properties, which can be created in relativistic heavy ion collisions, thanks to their early production and treatment with pQCD calculations. The production mechanisms and in-medium interactions are however different for open heavy flavor mesons and quarkonia. The first group may be produced via fragmentation or coalescence, while interactions with the hot medium include energy loss due to induced gluon radiation [1] or elastic collisions [2]. The radiative energy loss is mass dependent and resulted in "‘dead cone"’ effect which was directly observed by ALICE [3]. Quarkonia, on the other hand, are produced through color singlet [4] or color octet [5] intermediate states which hadronize into a bound state of $q\bar{q}$. The color octet channel requires color neutralization by emission of additional gluons. In QGP, quarkonia are affected by screening of color charges, which causes the bound state to dissociate at high temperature [6]. Furthermore quarkonium states can also be supressed due to parton energy loss in the medium [7]. If the density of heavy quarks is sufficiently high, it is also possible for quarkonium to regenerate [8].

Measurements of heavy flavor spectra in $p + p$ collisions allow to test the production models. In order to study the suppression within the QGP, a nuclear modification factor R_{AA} has to be measured. Elliptic flow is studied with v_2 coefficient and provides information about the interactions with the medium and the degree of thermalization. Finally, studies of $p + A$ or $d + A$ collisions allow to test the influence of cold nuclear matter effects on the heavy quark production [9].

This paper focuses on recent heavy flavor measurements performed at RHIC by STAR and PHENIX experiments.

*e-mail: kosarles@fjfi.cvut.cz

2 Charm and bottom production

Production of charm and bottom in $p + p$ collisions was measured both by STAR [10] and PHENIX [11–13] experiments, which allowed the calculation of charm and bottom production cross sections. Especially interesting is a measurement of $b\bar{b}$ cross section via $B^0 \leftrightarrow \bar{B}^0$ meson oscillations [14]. This is done by selecting like-sign dimuons originating from the aforementioned oscillations. The measured spectrum favors $b\bar{b}$ production through flavor creation or excitation over gluon splitting. The overall trend of production cross section vs. collision energy is well described by NLO pQCD calculations [15] as shown in Fig. 1a (left).

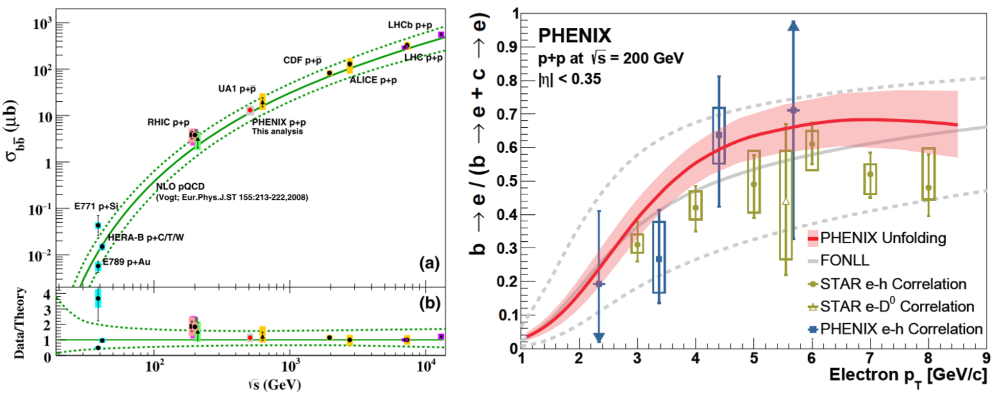

Figure 1: Left: Bottom production cross section vs. $\sqrt{s}$ [14] compared to NLO pQCD calculation [15]. Right: Fraction of semileptonic decays of b to the total $c + b$ semileptonic decays [11].

2.1 Charm hadrochemistry

Study of charm hadrochemistry in $Au + Au$ collisions allows to investigate the hadronization mechanisms of these quarks. STAR measured ratios of $(D_s^+ + D_s^-)/(D^0 + \bar{D}^0)$ [16], shown in Fig. 3a (left), and $(\Lambda_c^+ + \Lambda_c^-)/(D^0 + \bar{D}^0)$ at 200 GeV [17], presented in Fig. 3a (left) as a function of number of participant nucleons $< N_{part} >$. Both ratios indicate an enhancement with respect to PYTHIA and they are well described by coalescence models. This points to possible charm quark redistribution happening in $Au + Au$ collisions, which enhances these ratios. Furthermore, it is more likely to produce a strange open charm hadrons, due to strangeness enhancement [18].

2.2 Charm and bottom energy loss

The nuclear modification factor R_{AA} of $c \to e$ and $b \to e$ decays in $Au + Au$ collisions at 200 GeV was measured by STAR [19]. The p_T dependence of R_{AA} is shown in Fig. 2a (left), while the ratio of R_{CP} of b to c is presented in Fig. 2a (right). The data show a mass ordering of heavy quark energy loss, where charm quarks are more suppressed than bottom. This can be related to the observed "‘dead cone"’ effect [3]. A similar measurement was performed at PHENIX [20], yielding consistent results. The PHENIX and STAR data are well described by the energy loss models for $p_T > 4$GeV/c, which include both collisional and radiative energy loss.

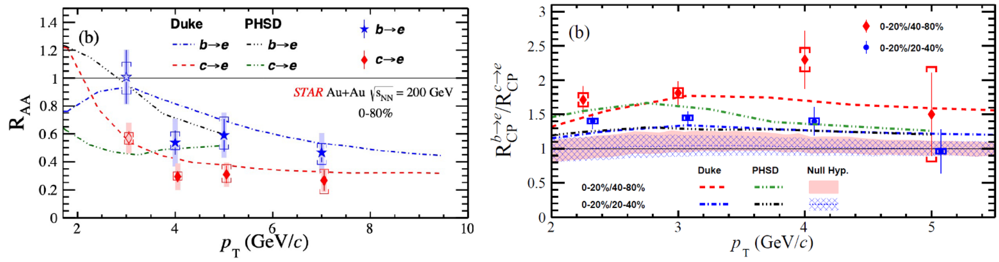

Figure 2: Left: Nuclear modification factor of $c \to e$ and $b \to e$ decays measured vs. p_T by STAR in $A + A$ collisions at 200 GeV [19]. Right: Ratio of R_{CP} of bottom to charm semileptonic decays vs. p_T. [19]

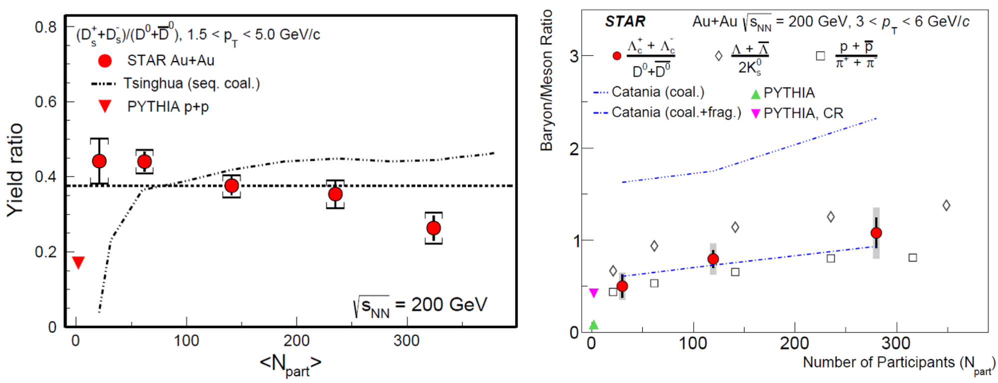

Figure 3: Left: Ratio of $(D_s^+ + D_s^-)/(D^0 + \bar{D}^0)$ [16] vs. $< N_{part} >$ measured by STAR at 200 GeV. Right: Ratio of $(\Lambda_c^+ + \Lambda_c^-)/(D^0 + \bar{D}^0)$ vs. $< N_{part} >$ [17].

2.3 Flow of open heavy flavor

Measurements of flow of open heavy flavor, especially elliptic flow v_2 provide insight into heavy quark thermalization and interactions. This was studied at PHENIX [13] and STAR [22] in $Au + Au$ collisions at 200 GeV. There is a significant v_2 for D^0 mesons, which has a similar magnitude to lighter hadrons and follows scaling with number of constituent quarks. This means that charm quarks interact strongly with the medium and that they may be thermalized at RHIC energy. Similar studies have been performed in the semileptonic decay channel [23] at 200, 62.4, 39 GeV and at 54.4, 27 GeV [21] by STAR. The measured v_2 vs. p_T is presented in Fig. 4 and compared to model calculations. Strong heavy flavor interactions with medium persist at these energies, however the data for $p_T < 1.4$ GeV/c are underestimated by the TAMU and PHSD calculations [24–26].

3 Quarkonium

3.1 Quarkonium production and polarization

Both J/ψ [27, 28] and Υ [29] spectra were measured by STAR and J/ψ at PHENIX [30] in $p + p$ collisions. The data are overall well described by model calculations [31–34, 34–36]

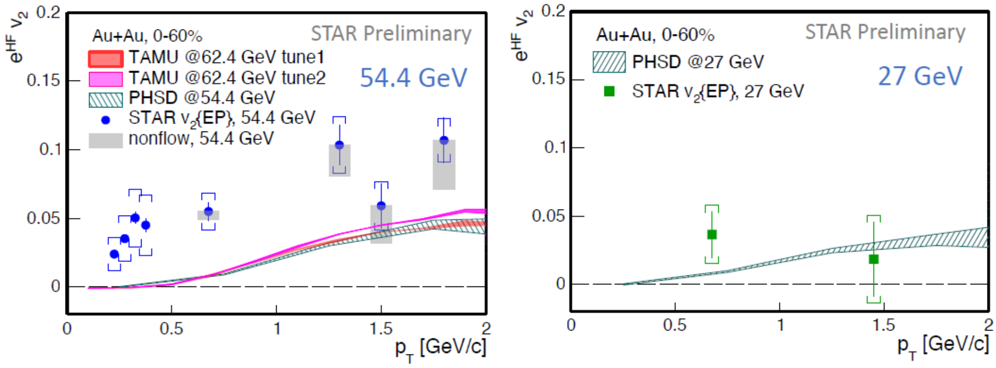

Figure 4: Left: Elliptic flow v_2 of heavy flavor decay electrons vs. p_T measured by STAR at 54.4 GeV [21]. Right: Similar measurement for 27 GeV [21].

with a contribution from $B \to J/\psi$ meson decays calculated with FONLL [37, 38]. The only exception is Υ p_T spectrum, which is overestimated by CGC+NRQCD calculation.

Another way to study quarkonium production mechanism is to measure it's polarization. The J/ψ polarization was measured by STAR and PHENIX in $p+p$ collisions at 200GeV [39] and 510 GeV [40] respectively in different reference frames. The results for polarization parameters are consistent with no polarization and the same results are obtained between the reference frames. The only exception is the value of λ_θ at high p_T and $|y| < 0.5$. The uncertainties are large, which means it's hard to rule out models, but the best description of the data is given by CGC+NRQCD calculation. PHENIX was able to measure polarization at forward rapidity $1.2 < y < 2.2$ and there is no difference compared to $|y| < 0.35$.

3.2 Quarkonium suppression

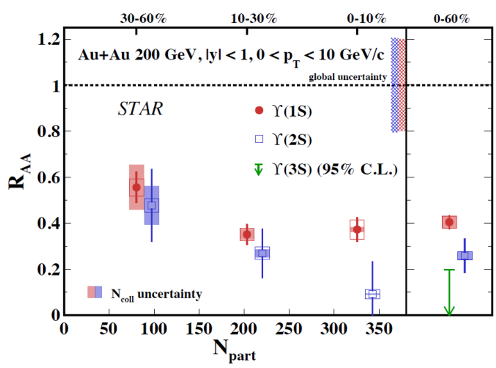

Figure 5: Nuclear modification factor of Υ states vs. N_{part} [41].

Suppression of J/ψ was measured using nuclear modification factor by STAR [42] and PHENIX [43] in $Au + Au$ collisions at 200 GeV. The R_{AA} of J/ψ was also measured at 62.4 GeV and 39 GeV by both experiments [44, 45]. The data show a trend of increasing R_{AA} with p_T and decreasing with centrality. In addition, no significant energy dependence is observed within uncertainties up to collision energy of 200 GeV. This behavior is reproduced by the suppression model calculations including regeneration of J/ψ [46].

STAR has also measured R_{AA} vs. $< N_{part} >$ and v_2 of J/ψ in $Ru + Ru$ and $Zr + Zr$ collisions [47]. The trend is similar across different systems, which may indicate an interplay of dissociation, regeneration and cold nuclear matter effects. The measured v_2 is consistent with no flow below $p_T < 4$ GeV/c.

Nuclear modification factor of Υ states was also measured by STAR [41, 48, 49] in Au+Au collisions at 200 GeV. This is shown vs. N_{part} in Fig. 5. It is a first observation of sequential suppression of Υ states at RHIC energy. Results also indicate increasing suppression with centrality. The R_{AA} of $\Upsilon(1S)$ and $\Upsilon(2S)$ in Fig. 6 is also compared to the model calculations, which include dissociation, regeneration and cold nuclear matter effects [50, 51]. The models are consistent with the data, but show larger separation between STAR and CMS. The R_{AA} of $\Upsilon(1S)$ is similar at RHIC and LHC, while $\Upsilon(2S)$ indicates a smaller suppression.

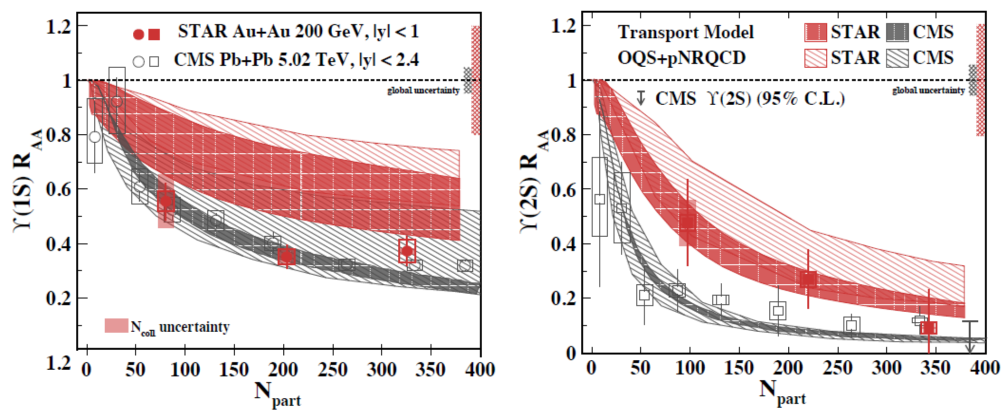

Figure 6: Nuclear modification factor R_{AA} vs. N_{part} for $\Upsilon(1S)$ (left) and $\Upsilon(2S)$ right measured by STAR and CMS [41].

4 Summary

So far, STAR and PHENIX performed a wide range of heavy flavor measurements. The charm R_{AA} indicate a similar level of suppression as for light hadrons and v_2 is also similar between heavy flavor and light hadrons. This means that there is strong interaction of charm quarks with medium down to 54.4 GeV. The R_{AA} of bottom is larger than charm, which suggests a mass dependence.

Quarkonium production at RHIC is well described by the production models with a few exceptions. The J/ψ R_{AA} has similar value when measured in different colliding systems, so there may be an interplay of suppression, regeneration and cold nuclear matter effects. Both J/ψ and Υ R_{AA} exhibit a similar trend of increasing suppression with centrality and decreasing with p_T. Interestingly, the $\Upsilon(1S)$ is similarly suppressed at RHIC and LHC, mostly due to dissociation of feed-down to $\Upsilon(1S)$ state. Furthermore a sequential suppression of Υ states was observed by STAR.

Acknowledgments

This work was supported by grant from The Czech Science Foundation, grant number: GJ20-16256Y

References

[1] M. Gyulassy, M. Plümer, Physics Letters B **243**, 432 (1990)
[2] M.H. Thoma, M. Gyulassy, Nuclear Physics B **351**, 491 (1991)
[3] and S. Acharya et al., Nature **605**, 440 (2022)
[4] C. Chao-Hsi, Nuclear Physics B **172**, 425 (1980)
[5] G.T. Bodwin, E. Braaten, T.C. Yuan, G.P. Lepage, Physical Review D **46**, R3703 (1992)
[6] T. Matsui, H. Satz, Physics Letters B **178**, 416 (1986)
[7] F. Arleo, S. Peigné, Journal of High Energy Physics **2013**, 122 (2013), `1212.0434`
[8] X. Du, M. He, R. Rapp, Physical Review C **96**, 054901 (2017), `1706.08670`
[9] R. Vogt, Physical Review C **71**, 054902 (2005), `0411378`
[10] L. Adamczyk et al., Physical Review D **86**, 072013 (2012), `1204.4244`
[11] C. Aidala et al. (PHENIX Collaboration), Phys. Rev. D **99**, 092003 (2019)
[12] A. Adare et al. (PHENIX Collaboration), Phys. Rev. C **96**, 024907 (2017)
[13] A. Adare et al. (PHENIX Collaboration), Phys. Rev. C **84**, 044905 (2011)
[14] U. Acharya et al. (PHENIX Collaboration), Phys. Rev. D **102**, 092002 (2020)
[15] R. Vogt, The European Physical Journal Special Topics **155**, 213 (2008)
[16] J. Adam et al. (STAR Collaboration), Phys. Rev. Lett. **127**, 092301 (2021)
[17] J. Adam et al. (STAR Collaboration), Phys. Rev. Lett. **124**, 172301 (2020)
[18] G. Agakishiev et al. (STAR Collaboration), Phys. Rev. Lett. **108**, 072301 (2012)
[19] STAR Collaboration, *Evidence of mass ordering of charm and bottom quark energy loss in au+au collisions at rhic* (2021), `https://arxiv.org/abs/2111.14615`
[20] U.A. Acharya et al., *Charm- and bottom-quark production in au+au collisions at* $\sqrt{s_{NN}}$ *= 200 gev* (2022), `https://arxiv.org/abs/2203.17058`
[21] Y.J. for the STAR Collaboration, *Recent open heavy flavor and quarkonia measurements from star*, `https://drupal.star.bnl.gov/STAR/files/AUM21_HF_v8.pdf`, rHIC & AGS Users meeting 2021
[22] L. Adamczyk et al. (STAR Collaboration), Phys. Rev. Lett. **118**, 212301 (2017)
[23] L. Adamczyk et al., Physical Review C **95**, 034907 (2017), `1405.6348v2`
[24] M. He, R.J. Fries, R. Rapp, Phys. Rev. C **91**, 024904 (2015)
[25] T. Song, H. Berrehrah, D. Cabrera, J.M. Torres-Rincon, L. Tolos, W. Cassing, E. Bratkovskaya, Phys. Rev. C **92**, 014910 (2015)
[26] T. Song, H. Berrehrah, J.M. Torres-Rincon, L. Tolos, D. Cabrera, W. Cassing, E. Bratkovskaya, Phys. Rev. C **96**, 014905 (2017)
[27] J. Adam et al., Physics Letters B **786**, 87 (2018), `1805.03745`
[28] J. Adam et al., Physical Review D **100**, 052009 (2019), `1905.06075`
[29] L. Kosarzewski, *Overview of Upsilon production studies performed with the STAR experiment*, in *Proceedings of 40th International Conference on High Energy physics — PoS(ICHEP2020)* (Sissa Medialab, Trieste, Italy, 2021), Vol. 390, p. 545, `https://pos.sissa.it/https://pos.sissa.it/390/545https://doi.org/10.22323/1.390.0545`
[30] U.A. Acharya et al. (PHENIX Collaboration), Phys. Rev. D **101**, 052006 (2020)

[31] A.D. Frawley, T. Ullrich, R. Vogt, Physics Reports **462**, 125 (2008), `0806.1013`
[32] M. Butenschoen, B.A. Kniehl, Physical Review D **84**, 051501 (2011), `1105.0820`
[33] M. Butenschoen, B.A. Kniehl, Physical Review Letters **108**, 172002 (2012), `1201.1872`
[34] Y.Q. Ma, R. Venugopalan, Physical Review Letters **113**, 192301 (2014), `1408.4075`
[35] Y.Q. Ma, K. Wang, K.T. Chao, Physical Review Letters **106**, 042002 (2011), `1009.3655`
[36] H. Han, Y.Q. Ma, C. Meng, H.S. Shao, Y.J. Zhang, K.T. Chao, Physical Review D **94**, 014028 (2016), `1410.8537`
[37] M. Cacciari, S. Frixione, N. Houdeau, M.L. Mangano, P. Nason, G. Ridolfi, Journal of High Energy Physics **2012**, 137 (2012), `1205.6344`
[38] M. Cacciari, M.L. Mangano, P. Nason, The European Physical Journal C **75**, 610 (2015), `1507.06197`
[39] J. Adam et al., Physical Review D **102**, 092009 (2020), `2007.04732`
[40] U. Acharya et al., Physical Review D **102**, 072008 (2020), `2005.14273`
[41] The STAR Collaboration, *Observation of sequential upsilon suppression in au+au collisions at* $\sqrt{s_{NN}}$ *= 200 gev with the star experiment* (2022), `https://arxiv.org/abs/2207.06568`
[42] L. Adamczyk et al., Physical Review C **90**, 024906 (2014), `1310.3563`
[43] A. Adare et al., Physical Review C **84**, 054912 (2011), `1103.6269`
[44] L. Adamczyk et al., Physics Letters B **771**, 13 (2017), `1607.07517`
[45] A. Adare et al., Physical Review C - Nuclear Physics **86**, 27 (2012), `1208.2251v1`
[46] X. Zhao, R. Rapp, Physical Review C **82**, 064905 (2010), `1008.5328`
[47] R.M. for the STAR Collaboration, *Recent hard probes results and prospects from the star experiment*, `https://drupal.star.bnl.gov/STAR/files/AUM21_HF_v8.pdf`, rIKEN BNL Research Center, 2022
[48] L. Adamczyk et al., Physics Letters B **735**, 127 (2014), `1312.3675`
[49] L. Adamczyk et al., Physics Letters B **743**, 537 (2015)
[50] X. Du, M. He, R. Rapp, Phys. Rev. C **96**, 054901 (2017)
[51] N. Brambilla, M.Á. Escobedo, A. Islam, M. Strickland, A. Tiwari, A. Vairo, P.V. Griend, Journal of High Energy Physics **2022** (2022)