# Updates on Flavor Production from STAR

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**Abstract.** In these proceedings, some of the latest results from the STAR ex-4 periment on heavy, strange and light flavor hadron production and their flow are 5 summarized. Over the years STAR has collected heavy ion collision data over a 6 wide range of collision energies from  $\sqrt{s_{\rm NN}} = 200 \,{\rm GeV}$  down to  $\sqrt{s_{\rm NN}} = 3 \,{\rm GeV}$ . 7 In high energy heavy ion collisions, heavy flavor hadrons are a valuable probe to 8 study properties of the Quark Gluon Plasma (QGP) created in these collisions. 9 Measurements of strange and light flavor hadrons at lower collision energies 10 help understand the properties of the QCD matter at finite baryon densities and 11 the phase structure of the QCD matter. Furthermore, the high statistics data col-12 lected at  $\sqrt{s_{\rm NN}}$  = 3 GeV allows measurements of hypernuclei production and 13 flow, which can provide insights into the hyperon - nucleon interactions and 14 hyperon contribution to the nuclear equation of state. 15

# 16 1 Introduction

Measurements of elliptic flow  $(v_2)$  of D mesons and electrons from heavy flavor hadron de-17 cays (HFE) in heavy-ion collisions at top RHIC energy and LHC energies show comparable 18 values to those of light flavor hadrons, indicating that charm quarks interact strongly with 19 the Quark Gluon Plasma (QGP) at these energies [1, 2]. These measurements have helped 20 constrain the charm quark diffusion coefficient in the QGP [3]. Measurements of HFE  $v_2$  at 21 lower collision energies can help constrain the temperature dependence of charm quark trans-22 port in the QGP. The observed  $J/\psi$  nuclear modification factor (R<sub>AA</sub>) in heavy-ion collisions 23 at RHIC and LHC has contributions from a regeneration component, in addition to that from 24 in-medium dissociation [4]. Better precision measurements at lower collision energies can 25 also help constrain these different contributions. 26 The Beam Energy Scan Phase II (BES-II) program at STAR, following the BES-I, aims to 27

conduct high statistics measurements of various observables in the high baryon density region 28  $(200 < \mu_B < 720 \text{ MeV})$  to understand the phase structure of QCD matter. As part of BES-II, 29 STAR has collected a high statistics dataset of Au+Au collisions at  $\sqrt{s_{NN}} = 3$  GeV ( $\mu_B = 720$ 30 MeV), using a fixed-target setup. The detailed measurements of the collective flow of various 31 identified light and strange flavor hadrons with this dataset can improve our understanding of 32 the nature and Equation of State (EoS) of the QCD matter in the high  $\mu_B$  region. In addition, 33 the high statistics 3 GeV dataset allows the measurement of strange and multi-strange hadron 34 production, providing insights into the canonical suppression of strangeness production at low 35 collision energies [6]. The same dataset also enables measurements of the yields, lifetime and 36 flow of hypernuclei, owing to their enhanced cross-sections at these low energies, which can 37

help understand the hyperon - nucleon interactions and hyperon contribution to the nuclear
 EoS.

In these proceedings, measurements of HFE  $v_2$  in Au+Au collisions at  $\sqrt{s_{NN}} = 54.4$  and 27 GeV and R<sub>AA</sub> of J/ $\psi$  in Au+Au collisions at  $\sqrt{s_{NN}} = 54.4$  GeV are presented. Measurements of  $v_2$  of identified hadrons, yield ratios of strange and multi-strange hadrons, and yields, lifetime and directed flow ( $v_1$ ) of hypernuclei  ${}^{\Lambda}_{3}H$  and  ${}^{\Lambda}_{4}H$  in Au+Au collisions at  $\sqrt{s_{NN}} = 3$  GeV are also presented. The results are compared to model calculations and the physics implications are discussed.

### <sup>46</sup> 2 Heavy flavor measurements at $\sqrt{s_{\rm NN}}$ = 54.4 and 27 GeV

STAR had previously carried out measurements of  $v_2$  of HFE at  $\sqrt{s_{NN}} = 62.4$  and 39 GeV [2]. 47 The measured HFE  $v_2$  values were found to be smaller, although consistent within the large 48 uncertainties, than the values measured at 200 GeV. In 2017 and 2018 STAR collected 10 49 times more statistics at  $\sqrt{s_{NN}}$  = 54.4 GeV and 27 GeV compared to those used for previous 50 measurements at 62.4 and 39 GeV. The left panel of Fig. 1 shows the measured  $v_2$  of HFE at 51 54.4 and 27 GeV as a function of transverse momentum  $(p_T)$ , compared to the measurements 52 at 200 GeV. The measured  $v_2$  values at 54.4 GeV are non-zero and comparable to those at 53 200 GeV, indicating strong interactions of the charm quarks with the QGP medium. The 54 measurements at 27 GeV show a hint of lower values, albeit with large uncertainties. The 55 right panel of Fig. 1 shows the comparison of the measured HFE  $v_2$  values at 54.4 GeV to 56 different theoretical model calculations. The TAMU [7] and PHSD [8] model calculations, 57 which incorporate charm quark diffusion in the QGP, describe the data at high  $p_{\rm T}$ , but are 58

<sup>59</sup> lower than the measured values at low  $p_{\rm T}$ .



**Figure 1.** (Left) The  $v_2$  of HFE as a function of  $p_T$  in 0-60% Au+Au collisions compared between  $\sqrt{s_{NN}} = 54.4$ , 27 and 200 GeV. The error bars are statistical uncertainties and brackets indicate systematic uncertainties. The blue hatched area indicates the estimated non-flow contribution to the measured  $v_2$  values. (Right) The  $v_2$  of HFE as a function of  $p_T$  in 0-60% Au+Au collisions at  $\sqrt{s_{NN}} = 54.4$  GeV compared to different model calculations [7, 8].

The in-medium dissociation of  $J/\psi$ , due to Debye like color screening in the QGP 60 medium, has been proposed as an evidence of the formation of the QGP and a valuable tool to 61 study its properties, particularly the medium temperature [9]. Suppression of  $J/\psi$  production 62 has been observed at both RHIC and the LHC. However, the observed suppression also gets 63 contribution from regeneration of  $J/\psi$  from deconfined charm quarks in the medium [4, 10]. 64 Measurements of the J/ $\psi$  suppression at a lower collision energy of  $\sqrt{s_{\rm NN}} = 54.4$  GeV, where 65 the charm quark production cross-section and thus the regeneration contribution are lower, 66 can help better understand the in-medium  $J/\psi$  dissociation. The left panel of Fig. 2 shows the 67

nuclear modification factor  $R_{AA}$ , the ratio of yields in A+A collisions to that in p+p collisions 68 scaled by the number of binary nucleon-nucleon collisions  $N_{coll}$ , as a function of number of 69 participating nucleons in the collision  $(N_{\text{part}})$  for different collision energies. The right panel 70 shows the RAA in central collisions as a function of collision energy. The new measurements 71 at 54.4 GeV are shown in red markers, and have significantly improved precision compared 72 to previous low energy STAR measurements at 62.4 and 39 GeV [11]. The measured values 73 show no significant collision energy dependence from 17.2 to 200 GeV within uncertainties. 74 A model calculation [10] that takes into account both in-medium dissociation and regenera-75 tion, along with cold nuclear matter effects, can reproduce the measured values. 76



**Figure 2.** (Left) The R<sub>AA</sub> of  $J/\psi$  as a function of  $N_{\text{part}}$  for different collision energies. The error bars, boxes and shaded bands on the data points denote statistical, systematic and  $N_{\text{coll}}$  uncertainties respectively. The shaded bands at 1 indicate the uncertainties from the p+p baseline. (Right) The R<sub>AA</sub> of  $J/\psi$  in central collisions as a function of collision energy, including measurements at SPS and LHC [12]. The error bands indicate statistical uncertainties and boxes indicate the combined systematic,  $N_{\text{coll}}$  and p+p baseline uncertainties.

# **3** Strange and light flavor production

#### <sup>78</sup> 3.1 Disappearance of partonic collectivity at $\sqrt{s_{\rm NN}}$ = 3 GeV

The large positive values of  $v_2$  and its number of constituent quark (NCQ) scaling observed 79 for identified hadrons in high energy heavy-ion collisions have been argued as evidence for 80 the creation of a strongly interacting QGP [13]. At lower collision energies, below  $\sqrt{s_{\rm NN}}$  = 81 27 GeV, where the passage time of the colliding nuclei becomes comparable to or larger than 82 the time scale of parton production, a negative 'squeeze out' contribution from the shadow-83 ing by spectator nucleons is expected for the  $v_2$ , in addition to the contribution from partonic 84 collectivity [14]. At even lower collision energies,  $\sqrt{s_{NN}} \sim 5$  GeV, hadronic transport and 85 baryonic mean field interactions among the colliding nuclei also contribute to the observed 86 flow harmonics [15]. In 2018 STAR collected about  $2.6 \times 10^8$  minimum bias Au+Au colli-87 sions at  $\sqrt{s_{\rm NN}}$  = 3 GeV. The high statistics dataset allows to carry out detailed measurements 88 of the  $v_2$  of various identified hadrons at mid-rapidity in this interesting region of QCD phase 89 space. 90

Figure 3 shows the NCQ scaled  $v_2$  of identified hadrons as a function of the scaled transverse kinetic energy in Au+Au collisions at  $\sqrt{s_{NN}} = 3$  GeV. The figure also shows measurements at  $\sqrt{s_{NN}} = 4.5$  GeV [5] and from the new datasets at  $\sqrt{s_{NN}} = 54.4$  and 27 GeV. The  $v_2$ values at 54.4 and 27 show NCQ scaling. Positive values and scaling within uncertainties are also observed at  $\sqrt{s_{NN}} = 4.5$  GeV. At  $\sqrt{s_{NN}} = 3$  GeV, the measured  $v_2$  values turn negative and the NCQ scaling breaks down. Figure 4 shows the centrality dependence of the  $v_2$  values of different identified hadrons at  $\sqrt{s_{NN}} = 3$  GeV. Calculations from the UrQMD model [16]

at  $\sqrt{s_{\rm NN}}$  = 3 GeV in the cascade mode, that incorporates hadronic transport and spectator 98 shadowing, and in the meanfield mode, which includes additional baryonic meanfield inter-99 actions, are also shown. The UrQMD cascade mode cannot describe the measured  $v_2$  values 100 and are of opposite sign. The UrQMD meanfield mode calculations, with a value of the in-101 compressibility  $\kappa = 380$  MeV, can reproduce the trends in the data, except for  $K^+$ . These 102 measurements and comparisons show that a medium dominated by hadronic and baryonic 103 interactions, rather than partonic interactions, is produced in Au+Au collisions at  $\sqrt{s_{NN}} = 3$ 104 GeV. 105



**Figure 3.** The  $v_2$  scaled by the number of constituent quarks  $n_q$  as a function of the scaled transverse kinetic energy at different collision energies for negative (left) and positive particles (right). Statistical and systematic uncertainties are indicated by error bars and shaded bands on data points, respectively. The dashed lines denote the NCQ scaling curves at different energies.



**Figure 4.** The  $v_2$  of protons (left), pions (middle) and kaons (right) as a function of centrality for Au+Au collisions at  $\sqrt{s_{NN}} = 3$  GeV. Statistical and systematic uncertainties are indicated by error bars and shaded bands on data points, respectively. UrQMD calculations in cascade and meanfiled modes are shown as gray and golden bands respectively.

#### **3.2** Canonical suppression of strangeness production

Statistical thermal models have been successful in describing the hadron yields in heavy-ion collisions [17]. At low collision energies and in small collision systems, as the strangeness production is rare, it has been argued that the strangeness number needs to conserved locally and on an event by event basis. Therefore a Canonical Ensemble (CE) is more suitable to describe the statistical production of strange hadrons as opposed to a Grand Canonical Ensemble (GCE). This would cause progressive suppression of yields of strange hadrons with non-zero strangeness numbers [6, 18]. Figure 5 shows the yield ratios of  $\phi$  mesons to that of  $K^-$  on the

left and yield ratios of  $\phi$  relative to  $\Xi^-$  on the right as a function of collision energy. The new 114 measurements at 3 GeV are shown as colored markers. The GCE calculations are strongly 115 disfavored, being lower than the measured ratios at  $5\sigma$  and  $4\sigma$  significances respectively, in 116 the 0-10% most central collisions. The CE calculation with a strangeness correlation length 117  $(r_c) \sim 3.2$  fm can describe the  $\phi/K^-$  yield ratio. There is a hint of a centrality dependence of 118 the ratios at  $\sqrt{s_{\rm NN}} = 3$  GeV. Future higher precision measurements can provide better insights 119 into the centrality dependence. Transport model calculations from a modified UrQMD [19] 120 and SMASH [20] that take into account high mass resonances that decay into  $\phi$  and  $\Xi^-$  can 121 also describe the ratios at 3 GeV. 122



**Figure 5.** The yield ratios of  $\phi$  to that of  $K^-$  (left) and of  $\phi$  to that of  $\Xi^-$  (right) as a function of collision energy. The new measurements at 3 GeV are shown in colored markers and at other energies [21] in solid black and open gray markers. The error bars and brackets on the 3 GeV data points denote the statistical and systematic uncertainties respectively. The gray solid line indicates the GCE calculation while the dashed lines indicate CE calculations with different  $r_c$  values [6, 18, 22]. The default UrQMD [16] calculations are shown in solid black line, while the modified UrQMD [19] and SMASH [20] calculations are shown in the green and red bands respectively.

# <sup>123</sup> 4 Hypernuclei production at $\sqrt{s_{\rm NN}}$ = 3 GeV

Hypernuclei production cross-sections in heavy-ion collisions are large at colliding energies 124  $\sim$  3 GeV [23]. This provides an opportunity to measure the lifetime, yield and collective flow 125 of hypernuclei with the  $\sqrt{s_{\rm NN}} = 3 \text{ GeV Au} + \text{Au}$  collision dataset. The lifetimes of  ${}_3^{\Lambda}H$  and  ${}_4^{\Lambda}H$ 126 measured using the 3 GeV dataset are  $232 \pm 29$  (stat)  $\pm 37$  (sys) and  $218 \pm 8$  (stat)  $\pm 12$  (sys), 127 respectively. The  ${}^{\Lambda}_{4}H$  lifetime measurement obtained is the most precise to date. The two left 128 panels of Fig. 6 show the yields within rapidity |y| < 0.5 of the hypernuclei  ${}_3^{\Lambda}H$  and  ${}_4^{\Lambda}H$ , along 129 with model calculations, as a function of collision energy. Thermal model calculations [23] 130 can describe the measured  ${}_{3}^{\Lambda}H$  yield at 3 GeV and also at the LHC energy [24]. The thermal 131 model calculations are done with a CE for strangeness production. The model however under-132 predicts the yield of  ${}^{\Lambda}_{A}H$  at 3 GeV. Coalescence model calculations [25] overestimate the  ${}^{\Lambda}_{3}H$ 133 yield while under-predict the  ${}^{\Lambda}_{4}H$  yield at 3 GeV. A hybrid UrQMD calculation over-predicts 134 yields of both  ${}^{\Lambda}_{3}H$  and  ${}^{\Lambda}_{4}H$ . The right panel of Fig. 6 shows the slope of directed flow at 135 midrapidty,  $dv_1/dy|_{u=0}$ , of various light nuclei and hypernuclei as a function of their mass for 136 Au+Au collisions at  $\sqrt{s_{\rm NN}}$  = 3 GeV. A mass scaling of directed flow slope has been observed 137 for light nuclei which is attributed to the coalescence production of light nuclei [26]. The 138 hypernuclei also show a mass scaling of  $v_1$  slope, albeit with large uncertainties, suggesting 139 coalescence production also for hypernuclei. These measurements will help better constrain 140 the hypernucleus production models and also the hyperon contribution to nuclear EoS. 141



**Figure 6.** The yield in |y| < 0.5 of  ${}_{3}^{\Lambda}H$  (left) and  ${}_{4}^{\Lambda}H$  (middle), along with model comparisons, as a function of collision energy. The boxes indicate the total uncertainties. (Right) The measured slope,  $dv_1/dy|_{y=0}$ , in Au+Au collisions at  $\sqrt{s_{NN}} = 3$  of different light nuclei and hypernuclei as a function of mass. Error bars indicate total uncertainties. The yellow line shows a linear fit to the light nuclei measurements. Combined results from the 2-body and 3-body decay channels are used for the  ${}_{3}^{\Lambda}H$   $v_1$  measurements and for yield measurements of both the hypernuclei results from only 2-body decay channel are used.

#### 142 5 Summary

We have presented some of the newest measurements from STAR on heavy, strange and light 143 flavor hadron production and collective flow. Measurement of HFE  $v_2$  with a much improved 144 precision in Au+Au collisions at  $\sqrt{s_{NN}}$  = 54.4 GeV, compared to previous measurements at 145 62.4 and 39 GeV, shows non-zero values comparable to the  $v_2$  of HFE measured at 200 GeV. 146 This indicates that charm quarks interact strongly with the QGP medium produced in 54.4 147 GeV collisions. The R<sub>AA</sub> of J/ $\psi$  measured in Au+Au collisions at  $\sqrt{s_{\rm NN}} = 54.4$  GeV has 148 improved precision compared to previous measurements at 62.4 and 39 GeV. The measure-149 ments show no significant collision energy dependence of RAA within uncertainties compared 150 to that at 200 GeV and other lower energy measurements. Elliptic flows of identified hadrons 151 in Au+Au collisions at  $\sqrt{s_{\rm NN}} = 3$  GeV show negative values and a breakdown of the NCQ 152 scaling. Hadronic transport model calculations from UrQMD with baryonic meanfield in-153 teractions can describe the trends seen in data. These observations indicate the formation 154 of a medium dominated by hadronic interactions and a nuclear EoS in Au+Au collisions at 155 3 GeV. Strange and multi-strange hadron yield measurements in Au+Au collisions at  $\sqrt{s_{\rm NN}}$ 156 = 3 GeV strongly disfavor GCE calculations and show evidence of canonical suppression 157 in strangeness production. Thermal model calculations are consistent with the measured  $\frac{3}{3}H$ 158 yield, while under-predct the  ${}^{\Lambda}_{A}H$  yield. Coalescence model calculations fail to describe yields 159 of both the hypernuclei. Measurements of directed flow slope,  $dv_1/dy|_{u=0}$ , of light nuclei and 160 hypernuclei show mass scaling within uncertainties. The mass scaling is consistent with a 161 picture of coalescence production for the light nuclei and hypernuclei. 162

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