

# Strangeness production as a function of system size and energy at RHIC

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**Abstract.** In this paper we report on strangeness measurements in p+p, Au+Au and Cu+Cu collisions at different energies in the STAR detector at RHIC. We will focus on two momentum regions in particular: Firstly we look at strangeness enhancement in A+A collisions with respect to p+p. These yields are dominated by low transverse momentum. We compare the enhancements from Au+Au and Cu+Cu data at  $\sqrt{s_{NN}} = 200$  GeV with Pb+Pb data at  $\sqrt{s_{NN}} = 17.2$  GeV and find that the enhancement does not scale with  $N_{part}$  as expected, but rather scales with  $N_{part}^{1/3}$ , where  $N_{part}$  represents the number of participants; We then examine  $\Lambda/K_S^0$  ratios at intermediate transverse momentum in both Au+Au and Cu+Cu data where we find a greater enhancement in Cu+Cu compared to Au+Au data when we compare integrated ratios between  $1.5 < p_T < 3.5$  GeV/c.

## 1. Introduction

The production of strange hadrons in relativistic heavy-ion collisions has long been suggested as a tool for studying possible de-confinement scenarios as all strangeness is produced in the collision [1]. The production of strange hadrons in dense matter is believed to be dominated by gluon interactions and the lower threshold energy required for producing  $s\bar{s}$  pairs compared to strange hadrons from nucleon-nucleon interactions has led to the prediction of strangeness enhancement in a QGP relative to p+p collisions. In this scenario, the enhancement should scale with the number of strange valence quarks in the hadron. However, in order to study the onset of any de-confinement, it is necessary to study processes which show different behaviour in different medium densities.

In this paper we will present data on the production of strange baryons in p+p, Au+Au and Cu+Cu collisions measured in the STAR experiment at RHIC. The p+p data comes from  $\sim 1.4 \times 10^7$  events, the Au+Au data from  $\sim 3 \times 10^7$  events and the Cu+Cu data from  $\sim 5.5 \times 10^7$  events respectively. In all cases, the hyperons were reconstructed via their charged daughters which were measured in the Time Projection Chamber (TPC) [2] at mid-rapidity ( $|y| < 1$ ) through the following decay channels (and their charge conjugates):  $\Lambda \rightarrow p + \pi$ ,  $\Xi \rightarrow \Lambda + \pi$ ,  $\Omega \rightarrow \Lambda + K$ . The addition of the lighter-ion Cu+Cu data allows for a more detailed investigation of the data at lower values of  $N_{part}$  where the errors are larger in the more peripheral Au+Au data compared to the central Cu+Cu data where the Glauber centralities are better defined within the framework of a MC Glauber calculation [3]. The data presented in this paper is outlined in Table 1, which presents the centrality bin,  $N_{part}$ ,  $N_{bin}$  (the number of binary collisions) and  $dN_{ch}/dy$  respectively.

Au+Au				Cu+Cu		
Centrality (%)	$N_{part}$	$N_{bin}$	$dN_{ch}/dy$	Centrality (%)	$N_{part}$	$N_{bin}$
0-5	351±3	1039±79	691±49			
5-10	293±7	810±58	558±40			
10-20	231±3.2	574±42	421±30			
20-40	139±5	278±30	238±20	0-10	98.4±1.0	185.7±5.9
				10-20	74.8±2.5	126.7±6.7
40-60	59±5	82±12	98±10	20-30	54.4±2.8	81.5±6.0
				30-40	38.5±2.5	51.0±4.8
60-80	19±3.5	19 ±5	32±10	40-60	21.9±2.6	24.3±3.9

**Table 1.**  $N_{part}$  and  $N_{bin}$  definitions for Au+Au and Cu+Cu centrality classes.

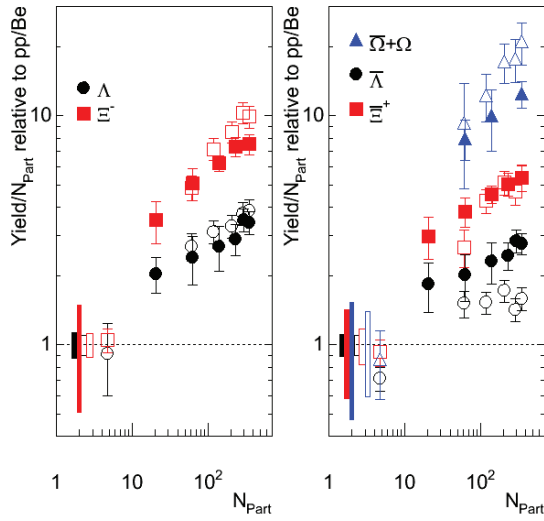
## 2. Low $p_T$ : Strangeness Enhancement

Figure 1 shows the enhancement of strange baryons in STAR for Au+Au collisions at  $\sqrt{s_{NN}} = 200$  GeV (solid symbols) compared to those measured in Pb+Pb collisions at  $\sqrt{s_{NN}} = 17$  GeV by the NA57 collaboration at CERN (open symbols) [4]. The left panel contains hyperons whose valence quarks include those which could come from the colliding nuclei, the valence quarks of the hyperons in the right panel all have to be created in the collision. Due to the lack of p+p reference data, the NA57 measurement shows enhancement relative to p+Be collisions. Intriguingly, the measured enhancement values are approximately the same in both cases, for all particle species, despite the order of magnitude difference in the two centre of mass energies. The small difference for the  $\bar{\Lambda}$  may be attributed to the difference in net-baryon densities between the collision energies. The interpretation of this effect is difficult as it involves the convolution of two different effects: if de-confinement is reached in A+A collisions, then strange quark production is enhanced with respect to a gas of hadrons and this enhancement is expected to be greater for higher energies; hyperon production is suppressed in the more elementary collisions due to a lack of available phase space, with the suppression being greater for the lower energies. Within the framework of a canonical model, where strangeness conservation is performed exactly, it was expected that the latter effect should dominate and that the overall enhancement should decrease with increasing energy [5]. However, another prediction from this model is that the enhancement should be flat with increasing  $N_{part}$ . This is clearly not the case in the data.

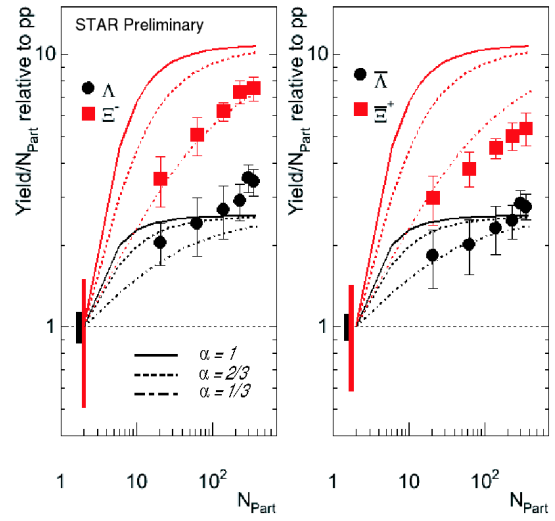
In order to understand this effect further, it is of interest to investigate the enhancement of strangeness in this theoretical model. Figure 2 shows the STAR data (Au+Au relative to p+p collisions at  $\sqrt{s_{NN}} = 200$  GeV) along with three different predictions from this canonical model. In this model, the volume for strangeness production is given by equation 1, where the default value of  $\alpha$  is 1, namely that strangeness production is deemed to be proportional to  $N_{part}$ , the number of participants in the collision. In equation 1,  $V_0 = 4/3\pi R^3$  and  $A = N_{part}/2$  [6].

$$V = A^\alpha V_0 \quad (1)$$

Each of the predictions presented in Figure 2 use a constant chemical freeze-out temperature of 165 MeV for all values of  $N_{part}$  and a baryon chemical potential,  $\mu_B$ , of 29 MeV. Changing the temperature parameter was found to only change the scale of the enhancement and not the shape evolution with  $N_{part}$ , where the higher the freeze-out temperature, the lower the enhancement. The three lines on the plot correspond to predictions for the evolution with different treatments of the volume parameter. The solid line is for the case where  $\alpha = 1$ , the dashed line is for  $\alpha$



**Figure 1.** (Colour online) Enhancement factors for hyperons: Au+Au relative to p+p collisions at  $\sqrt{s_{NN}}$  200 GeV (solid); Pb+Pb relative to p+Be collisions at  $\sqrt{s_{NN}} = 17.2$  GeV (open).



**Figure 2.** (Colour online) Expected evolution of enhancement factors within a canonical formalism for a chemical freeze-out temperature of 165 MeV and 3 different values of  $\alpha$  (see equation 1).

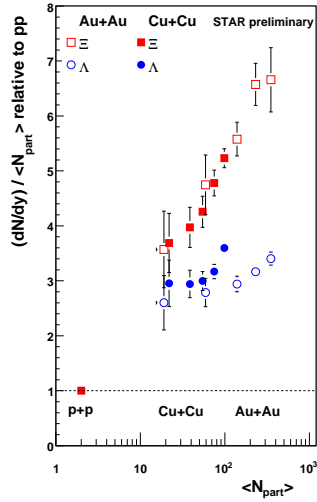
$= 2/3$  and the dashed-dotted line is for  $\alpha = 1/3$ . These values correspond to  $A \sim N_{part}$ ,  $N_{part}^{2/3}$  and  $N_{part}^{1/3}$ , which can in turn be thought of as being proportional to the volume, area and length of the fireball seen by the particles, respectively. Although naively one would think that  $N_{part}$  would have the best description, it is clear that the length dependence,  $N_{part}^{1/3}$ , describes the shape of the data better. It is interesting to note that this scaling also occurs in other variables such as femtoscopic radii [7].

The addition of the lighter species Cu+Cu data allows for a more detailed investigation of the enhancement at lower values of  $N_{part}$ , where the peripheral Au+Au bins have large errors and the Cu+Cu centralities are better defined in the Glauber calculation and are illustrated in Table 1. Figure 3 shows the relative enhancements for particles and Figure 4 that of anti-particles, for Au+Au and Cu+Cu data as a function of  $N_{part}$ .

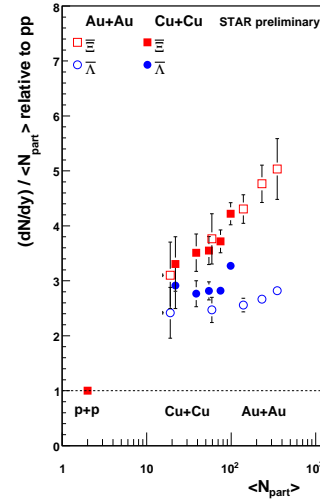
As can be seen in Figures 3 and 4, there is a clear difference between  $\Lambda$  and  $\bar{\Lambda}$  enhancements for Cu+Cu and Au+Au for the same  $N_{part}$  values, perhaps indicating that the geometry of the collision bears an important role (“spherical” central Cu+Cu collision versus “almond-like” peripheral Au+Au collision). However, for the multi-strange particles, this difference is not apparent though it is worth noting that the error bars are larger for the multi-strange particles.

### 3. Intermediate $p_T$ : Particle Ratios

One of the first indications of anomalous behaviour in the intermediate  $p_T$  region ( $2 < p_T < 6$  GeV/c) in relativistic heavy-ion collisions was the measurement of the  $\Lambda/K_S^0$  ratio as a function of  $p_T$  for different centralities [8]. This showed that at intermediate  $p_T$ , the  $\Lambda/K_S^0$  ratio increased with centrality until for the 0-5% most central Au+Au collisions, the ratio was a factor of 3 greater than that measured in the more elementary  $p + p$  data. This extended the earlier  $p/\pi$  measurement [9] in that it extended the reach for identified baryons and mesons to higher  $p_T$ . This was important because it showed that the baryon/meson ratio didn’t just increase and then plateau at  $p_T \sim 4$  GeV/c, but did in fact turn over and approach the values from



**Figure 3.** (Colour online) Enhancement factors for  $\Lambda$  and  $\Xi$  hyperons in Au+Au and Cu+Cu relative to p+p collisions at  $\sqrt{s_{NN}}$  200 GeV.

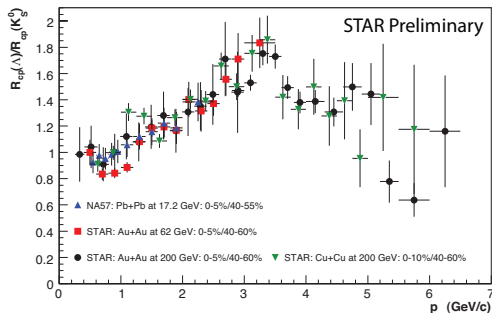


**Figure 4.** (Colour online) Enhancement factors for  $\bar{\Lambda}$  and  $\bar{\Xi}$  hyperons in Au+Au and Cu+Cu relative to p+p collisions at  $\sqrt{s_{NN}}$  200 GeV.

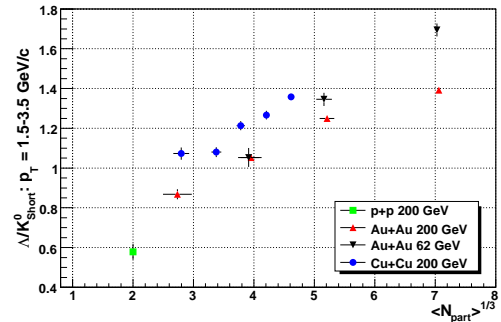
$p + p$  data at  $p_T \sim 6$  GeV/c. With the more recent high-statistics data-set, this point has been better elucidated [10]. This has led to the postulation that particle production in this intermediate  $p_T$  region is not dominated by fragmentation as had previously been thought, but is rather governed by more exotic mechanisms. Currently, the most probable mechanism for this is that of recombination/coalescence (ReCo) which states that two or three low  $p_T$  partons can recombine to form mesons and baryons at intermediate  $p_T$  respectively [11]. The ReCo mechanism is calculated to be more important for particle production than fragmentation when the parton spectrum is exponential and fragmentation is the dominant process when the parton spectrum behaves as a power law. A natural consequence of this mechanism is a baryon/meson ratio greater than unity in the intermediate  $p_T$  region and indeed, these models can qualitatively reproduce the data. As well as particle ratios, it has been shown that elliptic flow ( $v_2$ ) also shows a baryon/meson effect in that for  $p_T > 2$  GeV/c, the baryons and mesons show distinct groupings. When dividing the  $v_2$  value by the number of valence quarks and plotting this versus the  $p_T$  (again divided by the number of valence quarks), then the two groupings come together, suggestive that all quarks have the same  $v_2$  value for a given  $p_T$  and that the hadron  $v_2$  is simply determined by its valence quark content. Interestingly, in this scenario, the heavier *strange* quarks have the same  $v_2$  as the lighter *up* and *down* quarks [12].

By plotting the  $\Lambda/K_S^0$  ratio versus  $p_T$  in central/peripheral collisions, it has been possible to explore this effect as a function of energy as this nullifies any net-baryon density effects, under the assumption that the net-baryon density is relatively independent of collision centrality. This ratio has been previously shown to be independent of energy in the  $p_T$  range where data is present [10]. With the addition of the Cu+Cu data, it is possible to study this effect for a much smaller collision system. Figure 5 shows this ratio with the addition of the Cu+Cu data points. It is very striking how well the Cu+Cu data and Au+Au data match up considering that the  $N_{part}$  and  $N_{bin}$  values are very different for the centralities under consideration.

In order to further explore the  $\Lambda/K_S^0$  ratio in different systems, in Figure 6 we plot the  $\Lambda/K_S^0$  ratio integrated in the  $p_T$  region  $1.5 \rightarrow 3.5$  GeV/c for different collision systems and energies versus  $N_{part}^{1/3}$ . The difference between the Au+Au results at different energies may be ascribed



**Figure 5.** (Colour online)  $\Lambda/K_S^0$  ratio as for central/peripheral collisions for different collision systems and energies.



**Figure 6.** (Colour online) Integrated  $\Lambda/K_S^0$  ratio for  $1.5 < p_T < 3.5$  GeV/c for different collision systems and energies.

to the different net-baryon densities at the two different energies but the difference between the Cu+Cu and Au+Au data at  $\sqrt{s_{NN}} = 200$  GeV cannot be explained by this. For a given value of  $N_{part}^{1/3}$ , the  $\Lambda/K_S^0$  ratio in Cu+Cu is higher than that in Au+Au collisions. This indicates that the geometry of the collision plays an important role in these ratios, with the ratio higher in the more spherical collision. One would assume that this is a natural prediction from a coalescence model as the partons would be closer in space in the more central lighter-ion collision than a peripheral heavy-ion collision. To test this, we await calculations from theorists to appear in the literature.

#### 4. Summary

In this paper we have presented new data on strangeness production in Cu+Cu collisions at  $\sqrt{s_{NN}} = 200$  GeV measured in the STAR detector at RHIC. We showed that in the yield enhancement plot, which is dominated by the data at  $p_T < 2$  GeV/c, the enhancement for  $\Lambda$  and  $\bar{\Lambda}$  hyperons is greater at the same value of  $N_{part}$  than the values from Au+Au collisions at the same energy. However, the multi-strange hyperons do not show this effect outside of the error bars. At intermediate  $p_T$ , where the  $\Lambda/K_S^0$  ratio has shown to exhibit anomalous behaviour, we have found that the integrated value of the  $\Lambda/K_S^0$  ratio is enhanced in Cu+Cu collisions with respect to the value at a corresponding  $N_{part}$  value in Au+Au collisions. Both of these effects indicate that the geometry of the collision plays an important role in strangeness production, with the lighter-ion Cu+Cu central (spherical) collisions seemingly more conducive to strangeness production than the peripheral heavy-ion Au+Au (almond) collisions.

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