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# Investigation of the high-$p_{\mathrm{T}}$ strange baryon anomalies at RHIC

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**Abstract.** Results from RHIC have shown that there is an enhanced baryon/meson ratio in the intermediate transverse momentum range ($2 < p_{\mathrm{T}} < 6\,\mathrm{GeV}/c$) in Au + Au collisions at both $\sqrt{s_{NN}} = 130$ and 200 GeV. This was initially demonstrated by measurements of the $\overline{p}/\pi^{-}$ ratio which was then extended in $p_{\mathrm{T}}$ by the $\Lambda/K^0_S$ ratio. The data were successfully described by models utilising different hadronization mechanisms: those having recombination of quarks and others having an interplay between flow, jet quenching and incorporating baryon junction loops. The strange particle data from the first Au + Au run at $\sqrt{s_{NN}} = 200$ GeV gave tantalising hints that the observed enhancement of baryons compared to mesons was diminished by a $p_{\mathrm{T}}$ of 6 GeV/$c$, but a lack of statistics in this range made a definitive statement impossible. Here we present an extended analysis of identified strange baryons and mesons in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV using data obtained by the STAR experiment from the 2004 running period. The increase in statistics extends the measurement of $\Lambda$ hyperons out to at least 7 GeV/$c$ and $K^0_S$ mesons out to 9 GeV/$c$. This data allows us to place limits on the range where in-vacuum fragmentation functions are applicable and the effect of baryon dominance is reduced. We also discuss the prospects for making these measurements using multiply-strange baryons and mesons ($\Omega$ and $\varphi$).

## 1 Introduction

One of the most interesting observations to arise from the first few weeks of running at RHIC (Au + Au collisions at $\sqrt{s_{NN}} = 130$ GeV) was that the yield of (anti)baryons approached that of mesons at higher $p_{\mathrm{T}}$ ($> 2$ GeV/$c$) [1, 2]. The larger data-sets obtained in 2002 and 2004, consisting of Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV have allowed the study of this phenomenon in greater detail. Using the large acceptance Time Projection Chamber, the STAR experiment is ideally suited to perform a high statistics measurement using strange baryons and mesons reconstructed through their charged daughters. The limit on $p_{\mathrm{T}}$ reach in this method is dominated by statistics only.

The data-sets used in the analyses reported in this paper correspond to $\sim 1.5 \times 10^6$ minimum bias events in the short Au + Au at $\sqrt{s_{NN}} = 200$ GeV running period (2002), and $\sim 2.0 \times 10^7$ events in the longer run (2004). Similar numbers of events were used for the most central bins due to the implementation of a dedicated online trigger. We will also make comparisons to the strange baryon/meson ratios measured at lower energies, both in STAR and at the SPS at CERN. Finally, we give an indication of future measurements using multiply-strange hadrons which will be performed on this topic.

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## 2 Baryon production anomalies at RHIC

### 2.1 The $p/\pi$ ratio

The $(\overline{p})p/\pi$ ratios were measured by both the STAR and PHENIX experiments in the 2002 data set at RHIC [3, 4]. Both experiments found that the ratio increased monotonically from low $p_{\mathrm{T}}$ up to approximately 3 GeV/$c$ where the statistics for the measurement (and applicability of the PID method) ran out. The value of these ratios approached unity, indicating that the production of matter in this region was close to being dominated by baryons. This value is a factor of 5 times higher than that observed in elementary collisions [5]. These have proved to be interesting measurements which have prompted a large amount of work from the theory community to try and explain the data. These range from simple hydrodynamical models [10], to more exotic models such as recombination [11–14] and the 'soft+quench' model [15]. Although the hydrodynamical models predict a monotonic rise in the baryon/meson ratio, both the recombination and 'soft+quench' models predict a turn-over in this ratio at the point where the data stop. These will be discussed later in the text.

### 2.2 Strange baryons and mesons

Although some hints of anomalous baryon production were present in the $\sqrt{s_{NN}} = 130$ GeV Au + Au data [2], the low statistics ($\sim 1.87 \times 10^5$ minimum bias events were recorded by STAR) meant that the reach in $p_T$ was limited. The first year of running Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV increased this number of usable events by an order of magnitude for both minimum bias and central triggers. With this data, $\Lambda$ and $K^0_S$ production could be measured up to 6 GeV/c in $p_T$ for the most central 5% of the cross-section. With the second long Au + Au running at full energy, STAR recorded more than an order of magnitude more events than in the shorter 200 GeV run referred to above.

Figure 1 shows the $\Lambda/K^0_S$ ratio from both the 2002 and 2004 data-sets. The Au + Au data to the left of the dashed vertical line are from 2002 and the data to the right are from 2004, all of the $p+p$ data are from 2002 only. The data is presented in this way to emphasise the benefit of the greater statistics. Although the 2002 data extend in the most central bin to 6 GeV/$c$, in the most peripheral bin they only reach 4.5 GeV/$c$. All the higher momentum bins have large statistical errors [3]. It is noticeable that the ratio in Au + Au collisions is strongly dependent on the centrality of the collision and in all cases is greater than that observed in minimum-bias $p+p$ collisions [6]. It has also been observed that the magnitude of the $\Lambda/K^0_S$ ratio is dependent on the multiplicity of the $p+p$ collision.

An interesting observation in Fig. 1 is that the ratio at lower $p_T$ is independent of centrality and continues to rise before saturating at different values for different centralities. It is also evident from Fig. 1 that at higher $p_T$, the ratios appear to drop back to the same value, independent of centrality. These values are consistent with the ratios measured in $p+p$ collisions, though that measurement has large statistical error bars. Due to the lower statistics, it was not possible to make this conclusion from the 2002 data alone.

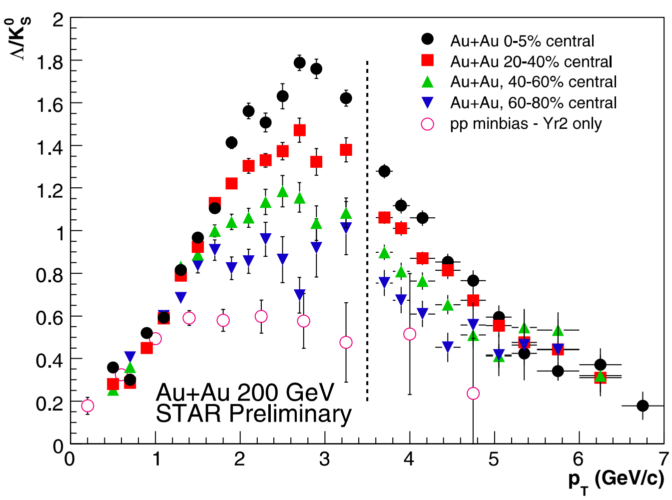


**Fig. 1.** The $\Lambda/K^0_S$ ratio as a function of $p_T$ for different centralities in Au + Au collisions, together with minimum-bias $p+p$ collisions. In the Au + Au case, the data to the *left* of the *dashed vertical line* represent the 2002 data-set and those to the *right* are from the 2004 run . All data from $p+p$ collisions are from 2002

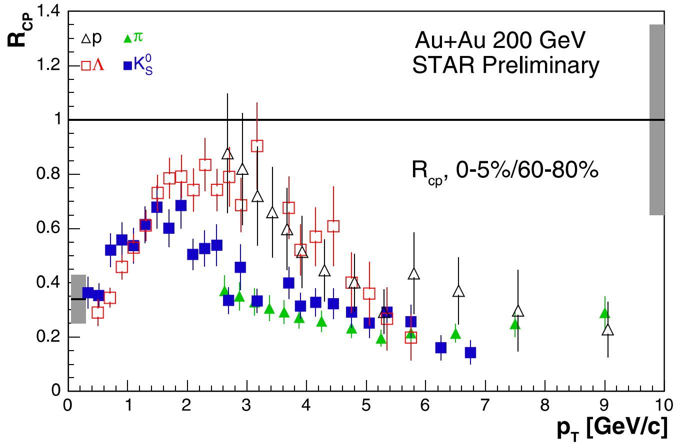


**Fig. 2.** The $R_{CP}$ ratio for $p$, $\pi$, $\Lambda$ and $K^0_S$ for the 0–5%/60–80% centrality bins. At intermediate $p_T$, there is a clear difference in the suppression of the baryons and mesons with respect to binary scaling. This is no longer apparent at higher $p_T$

The fact that in the $\Lambda/K^0_S$ ratio the values at 6 GeV/$c$ are similar for all centralities in Au + Au collisions, is also observed by forming the $R_{CP}$ ratios, as shown in Fig. 2. The $R_{CP}$ ratio represents the ratio of the yield in central collisions, divided by that in the peripheral collisions, appropriately scaled by the number of binary collisions in each system, as given in (1). Here, the value of $R_{CP}$ for the $\Lambda$ and $K^0_S$ is different at intermediate $p_T$ but then is the same for $p_T \sim 6$ GeV/$c$ [7].

$$R_{CP} = \frac{N^{\text{per.}}_{\text{bin}}\, \mathrm{d}N/\mathrm{d}\mathbf{y}^{\text{cen.}}}{N^{\text{cen.}}_{\text{bin}}\, \mathrm{d}N/\mathrm{d}\mathbf{y}^{\text{per.}}}\,. \tag{1}$$

If the production of particles is dominated by binary scaling, which might be expected in hard processes at high $p_T$ ($> 2$ GeV/$c$), then this ratio should be unity. The deviation from unity in Fig. 2 has been interpreted as the in-medium suppression of particle production through jet fragmentation [8].

It is interesting to note that the $R_{CP}$ for the $p$ and $\Lambda$ are consistent, despite the measured enhancement of strangeness in Au + Au collisions with respect to $p+p$ collisions. This is more strongly observed when comparing the enhancement and $R_{AA}$ of the $\Xi$, compared to the $\Lambda$ and $p$ [9].

### 2.2.1 Comparison to theoretical models

Figure 3 shows the comparison of the $\Lambda/K^0_S$ data to different models. The left panel represents the 'soft+quench' model and the right panel has a number of recombination models as described in the text below.

The 'soft+quench' model assumes soft particle production at low $p_T$ (i.e. the yields are proportional to $e^{-p_T/T}$, where $T$ is the inverse slope parameter) [15]. At higher $p_T$, particle production is described using a leading-order pQCD calculation incorporating gluonic baryon junctions to transport the baryon number from the initial colliding nuclei to mid-rapidity.

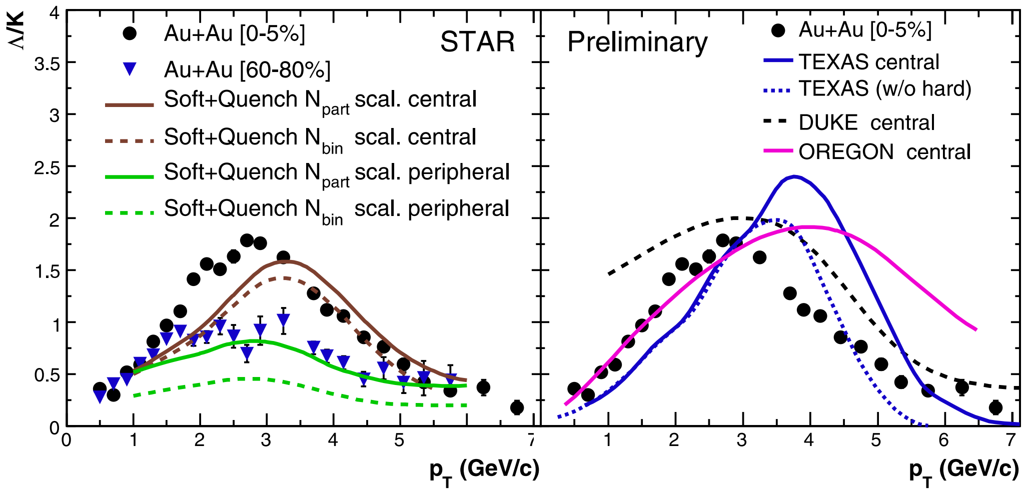


**Fig. 3.** *Left panel*: The $\Lambda/K^0_S$ ratio for two different centralities together with model predictions from the 'soft+quench' model. *Right panel*: The $\Lambda/K^0_S$ ratio for the most central data together with data from different recombination models. See text for explanations of the models

The 'DUKE' recombination model assumes that massive, thermal, quarks recombine and form the valence quarks of the produced hadron (two for a meson, three for a baryon respectively) in the intermediate $p_T$ region [11]. At higher $p_T$, the model uses medium modified jet fragmentation. The region in $p_T$ at which the latter place begins to dominate is governed by the parton distributions: when they are exponential, recombination is the dominant process and when they are power-law in shape, fragmentation is dominant.

The second recombination model presented in Fig. 3 is from the 'TEXAS' group [12,13]. It differs from the 'DUKE' model in that it also incorporates recombination between the soft, thermal partons and co-moving quarks coming from mini-jets. This has the effect of increasing the ratio above 3 GeV/$c$ in $p_T$, as shown by the full and dotted blue curves in the figure.

The final curve in Fig. 3 represents the recombination model from the 'OREGON' group [14]. This again allows for the recombination of thermal quarks, but then differs in its treatment of the higher $p_T$ regime as it doesn't use fragmentation functions, but instead mini-jets are allowed to form showers which then recombine.

Recombination models are, in essence, a very natural explanation of particle production and they work well for describing other phenomena in heavy-ion collisions (such as the particle-identified elliptic flow, $v_2$ [16]). However, there are still many open questions about this class of models which need addressing, such as the lack of energy conservation. Recombination models also do not work at low $p_T$ and the models described above use a couple of techniques to solve this, one is an attempt at an analytical solution and the other is a Monte Carlo technique.

Of all the models presented, the 'soft+quench' model appears to reproduce the data the best though it has to invoke exotic mechanisms of baryon production to do so. Of the recombination models, the implementations of the model which do not include the recombination between soft and hard partons agree better with the data, an effect which is noticeably apparent for $p_T > 3$ GeV/$c$. However, it should be noted that none of the models are in as good an agreement with the data as the 'soft+quench' model. The 'soft+quench' model also is in reasonable agreement with the peripheral data, which is a prediction which has often been requested but is consistently missing for all of the recombination models.

## 3 Comparisons to different energies

Comparing the $\Lambda/K^0_S$ ratio across energies is difficult because the value of the net-baryon density changes with energy and this has a significant effect on baryon (and anti-baryon) production. This is observed at the SPS, for example, where the $\Lambda/K^0_S$ ratio reaches a maximum value of 4, a factor of 2 higher than that observed in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV [17]. To solve this problem, Fig. 4 shows the double ratio, that of the $R_{CP}(\Lambda)$ divided by $R_{CP}(K^0_S)$. This is done for Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV and 62 GeV (0–5%/40–60%), together with Pb + Pb collisions at $\sqrt{s_{NN}} = 17.2$ GeV for a slightly different centrality class(0–5%/40–55%) [18].

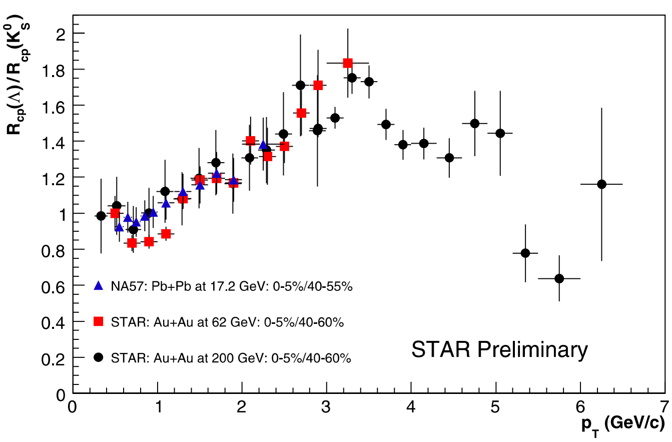


**Fig. 4.** The double $\Lambda/K^0_S$ ratio as a function of $p_T$ for a number of different energies. This ratio takes out the energy dependent net-baryon density contribution to the $\Lambda/K^0_S$ ratio

There is a remarkable agreement between all three energies where the data are present ($p_T < 3$ GeV/$c$). This can perhaps be interpreted as implying that the production mechanisms of $\Lambda$ and $K^0_S$ are similar in all systems, which makes it important for predictions to become available for the lower energies. A different way of showing this is to compare the ratio of the $\Lambda/K^0_S$ ratio between STAR and NA49 (Pb + Pb collisions at $\sqrt{s_{NN}} = 17.2$ GeV at the CERN SPS), which gives a constant value as a function of $p_T$ in the measured region [17].

## 4 Future measurements

One of the recent predictions from the 'OREGON' recombination model involves the mulitply-strange hadrons, the $\Omega$ and the $\varphi$. In this model, the production of the $\Omega$ and $\varphi$ is predominantly from thermal-parton recombination, the processes involving the recombination of shower partons are strongly suppressed by up to four orders of magnitude up to a $p_T$ of 8 GeV/$c$ [19]. The consequences of this are that the $\Omega/\varphi$ ratio should rise monotonically with $p_T$ and that no two-particle azimuthal correlations will be visible with $\Omega$- and $\varphi$-trigger particles.

The $\Omega/\varphi$ ratio is presented in Fig. 5 for the 12% most central collisions. Although it does have an increase with $p_T$, the degree of this is different to the model prediction and is approximately constant for $p_T > 2$ GeV/$c$, making direct conclusions difficult [20]. In the near future, it is envisioned that the $\Omega/\varphi$ ratio can be measured as a function of centrality up to intermediate $p_T$.

Due to the clean $\Omega$ signal (with a large signal to background ratio) which is available after applying geometric cuts to the data, coupled with the high-statistics 2004 data-set, it should be possible to perform two-particle azimuthal correlations for $\Omega$-triggers. However, it should be noted that the number of raw particles in the $p_T$ range of interest is statistically limited, which may make the interpretation of the data a challenge. Preliminary measurements of this variable will be available in the near future.

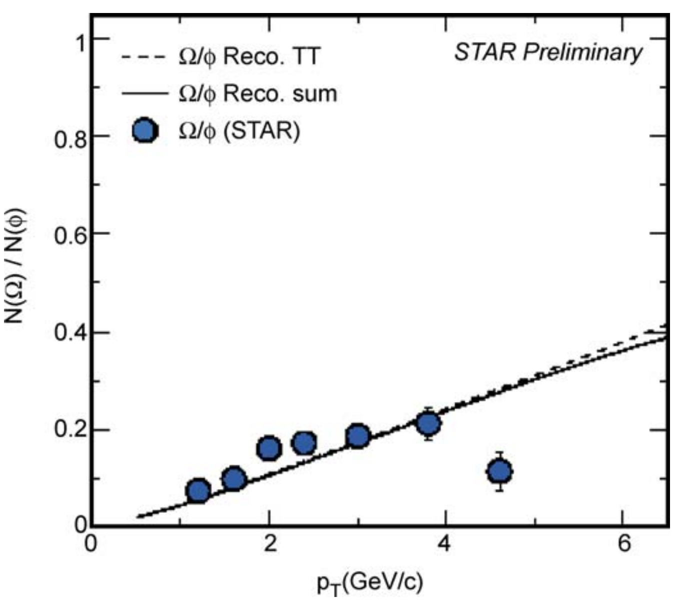


**Fig. 5.** The $\Omega/\varphi$ ratio as a function of $p_T$ for central Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV

## 5 Summary

In this paper we have presented strange baryon and meson ratios from the large statistics run at RHIC for Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The $\Lambda/K^0_S$ ratio from the limited 2002 data-set was the first measurement which showed that the baryon/meson ratio peaked at intermediate $p_T$ and decreased towards the value measured in $p + p$ collisions. The 2004 data extend out to 7 GeV/$c$ in the most central bin and 6 GeV/$c$ for the most peripheral bin, allowing for the first time to show that the ratio is the same in all centralities for $p_T > 6$ GeV/$c$. This observation is also manifested in the $R_{CP}$ ratio, where the suppression from binary scaling is the same for all measured baryons and mesons ($p$, $\Lambda$, $\pi$ and $K^0_S$) for $p_T > 6$ GeV/$c$.

To measure this effect for different energies, the double ratio, $R_{CP}(\Lambda)/R_{CP}(K^0_S)$, was formed in order to neglect the effect of the changing net-baryon density. This measurement showed that the production mechanism of strange particles appears to be the same at both the CERN-SPS and at RHIC.

In the near future, more detailed measurements will be able to be made with multiply-strange baryons and mesons in order to test recent predictions from the 'OREGON' recombination model on the $\Omega/\varphi$ ratio and on two-particle azimuthal correlations involving $\Omega$-trigger particles.

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