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Is Strangeness Still Strange at the LHC?

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Abstract. Strangeness production is calculated in a pQCD-based model (including nuclear effects) in the high transverse momentum sector, where pQCD is expected to work well. We investigate pion, kaon, proton and lambda production in pp and heavy-ion collisions. Parton energy loss in AA collisions is taken into account. We compare strange-to-non-strange meson and baryon ratios to data at RHIC, and make predictions for the LHC. We find that these ratios significantly deviate from unity not only at RHIC but also at the LHC, indicating the special role of strangeness at both energies.

1. Introduction

Strange particles have played a major role in high-energy physics since the early 1950s. Originally, "strange" meant 'created in pairs, with a new quantum number, $s = \pm 1$, respectively'. It should also be understood that the meaning of "high-energy physics" continued to change in step with the construction of more and more powerful accelerators. In the collider era, the title question attracts renewed interest in connection with the extended volumes of high energy-density matter created in nucleus-nucleus (AA) collisions as the high-energy frontier moves from the Relativistic Heavy Ion Collider (RHIC) to the Large Hadron Collider (LHC). RHIC collides gold nuclei at 200 AGeV center-of-mass energy. The LHC will operate at more than an order of magnitude higher energies.

The historical roots stretch back to the 1940s: curious V-shaped tracks were found in emulsion, primarily in $\pi \to \mu$ decays. The mysterious '*V-particles*' were the first observed examples of matter with strangeness content. Later the Λ particle was identified and described by the additive quark model and the name "strangeness" was suggested by M. Gell-Mann in the middle of the '50s [1].

Another period of excitement was ushered in by the discovery of the J/Ψ in the famous "November Revolution" of 1974 [2]. This opened a new era of high-energy physics: strange quarks no longer represented the heaviest flavor, not present as valence contributions in everyday baryons. It was expected that at high energies the new ("charm") quarks will play a role similar to that of the strange quarks at lower energies as the small mass difference of the up, down, and strange quarks becomes negligible. As a consequence, it is natural to expect that in the high energy-density phase (quark-gluon plasma, QGP) up, down, and strange quarks have similar populations and play equivalent roles. This expectation is not completely borne out at RHIC; does it become a good approximation at LHC energies?

The non-Abelian quark-gluon matter can not be observed directly, but the abundances of final-state hadrons should be sensitive to the strangeness content. This is the basis of the so-called "strangeness signature" of the QGP, specifically the expected enhancement of strange anti-baryon production, as proposed by Müller and Rafelski [3] and independently by Bíró and Zimányi [4].

What can we expect from the $\sqrt{s} = 5.5$ ATeV $PbPb$ collisions, where more final-state strange particles are produced with larger transverse momenta ("hard probes"), and perturbative quantum chromo-dynamics (pQCD) is to provide more precise predictions? It is interesting to ask whether the role of strangeness will finally change at these energies, where we are going to have a more precise "microscope" in the form of the LHC experiments. Do the s quarks behave as light quarks (u and d) and does charm appear as the "first massive" flavor?

In this paper we present calculations for K/π and Λ/p ratios from AA collisions at RHIC and LHC energies. We include the effect of nuclear modifications on the produced particles. We present the results in terms of double ratios of nuclear modification factors.

2. Theoretical Model

The particle ratios were calculated using hadron spectra as provided by our perturbative QCD improved parton model [5]. The model is based on the factorization theorem and generates the invariant cross section as a convolution of (nuclear) parton distribution functions $f_{a/A}$, perturbative QCD cross sections $\mathrm{d}\sigma^{ab\to cd}/\mathrm{d}\hat{t}$, fragmentation functions $D_{\pi/c}$, and nuclear thickness functions t_A. We perform the calculation following Refs. [5, 6, 7, 8, 9, 10]:

$$E_h \frac{\mathrm{d}\sigma_h^{AA'}}{\mathrm{d}^3 p_h} \sim t_A(r)\; t_{A'}(|\mathbf{b}-\mathbf{r}|) \otimes f_{a/A}(x_a, Q^2; \mathbf{k}_{Ta}) \otimes f_{b/A'}(x_b, Q^2; \mathbf{k}_{Tb}) \otimes \\ \otimes \frac{\mathrm{d}\sigma^{ab\to cd}}{\mathrm{d}\hat{t}} \otimes \frac{D_{h/c}(z_c, \widehat{Q}^2)}{\pi z_c^2}\;, \qquad (1)$$

where Q^2 and $\widehat{Q}^2$ represent the factorization and fragmentation scales, respectively, x_a, x_b, and z_c are momentum fractions, and $\mathbf{k}_T$-s stand for two-dimensional transverse momentum vectors. The initial state effects of shadowing and multiscattering are included following the ideas in Refs. [5, 6, 7]. The collision geometry is described by the impact parameter (b) dependent Glauber nuclear thickness functions, $t_A(b)$.

For the nuclear parton distributions (PDFs) we have applied the MRST central gluon (cg) set [11] with the updated HIJING shadowing [12, 13]. Intrinsic transverse momentum and multiple scattering are treated according to Ref. [5]. For the fragmentation functions (FFs), we used a recent set by Albino, Kniehl, and Kramer [14] to calculate the K, π, p and Λ spectra. All calculated hadron spectra are charge averaged, thus pions, kaons, protons, and lambdas are $\pi = (\pi^+ + \pi^-)/2$, $K = (K^+ + K^-)/2$, $p = (p^+ + p^-)/2$, and $\Lambda = (\Lambda + \bar{\Lambda})/2$, respectively.

In the model the energy loss of partons propagating through the high energy-density matter was taken into account along the lines of the GLV treatment [15]. In this picture the amount of jet energy loss is parameterized in terms of the nuclear opacity L/λ, where L is the average distance traveled by the parton in the medium and λ stands for the mean free path. Opacity $L/\lambda = 0$ signifies no jet quenching, high values correspond to central collisions of heavy nuclei.

We are interested in the nuclear modification for strange species relative to hadrons not containing strange quarks, i.e. pions and protons. For this purpose we introduce the double ratio of different hadron's nuclear modification factors,

$$R_{AA}^{s\bar{s}}(p_T) = \frac{R_{AA}^{h^s}(p_T)}{R_{AA}^{h}(p_T)} = \frac{E_{h^s}\mathrm{d}\sigma_{h^s}^{AA}/\mathrm{d}^3p_{h^s}}{E_{h^s}\mathrm{d}\sigma_{h^s}^{pp}/\mathrm{d}^3p_{h^s}} \bigg/ \frac{E_h\mathrm{d}\sigma_h^{AA}/\mathrm{d}^3p_h}{E_h\mathrm{d}\sigma_h^{pp}/\mathrm{d}^3p_h} = \left[\frac{h^s}{h}\right]_{AA} \bigg/ \left[\frac{h^s}{h}\right]_{pp}, \tag{2}$$

where we used the notation h^s for charged-averaged strange hadrons and h for non-strange hadrons. The nuclear modification factor is defined as

$$R_{AA}^{h}(p_T) = \frac{1}{\langle N_{bin}\rangle} \cdot \frac{E_h\mathrm{d}\sigma_h^{AA}/\mathrm{d}^3p_h}{E_h\mathrm{d}\sigma_h^{pp}/\mathrm{d}^3p_h}\ . \tag{3}$$

Here $\langle N_{bin}\rangle$ is the average number of binary collisions in the various impact-parameter bins, which is determined by the geometry of the collisions and cancels from the double ratio (2).

The last equation of (2) indicates that the double ratio of nuclear modification factors can be obtained as the double ratio of strange-to-non-strange ratios in AA to pp collisions.

3. Strange Particle Ratios at RHIC Energies

On the *left side* of Fig. 1, in the bottom panel, K/π ratios are plotted as measured by the PHENIX collaboration in pp collisions [16] and by the STAR collaboration in $AuAu$ collisions [17, 18] at $\sqrt{s} = 200$ AGeV RHIC energy, together with calculated K/π ratios in pp collisions (*dotted line*) and $AuAu$ collisions without jet energy loss ($L/\lambda = 0$, *dashed*) and with opacity $L/\lambda = 4$ (*solid line*) for the most central ($0-10\%$) $AuAu$ collisions. In the top panel we show the calculated double ratios (2) relative to pp collisions without (*dashed*) and with (*solid line*) jet energy loss, compared to those obtained from the data. (Note that the experimental double ratios naturally have large uncertainties.)

The experimental K/π ratios are very similar to each other at low p_T, although a slight hint of 'strangness enhancement' is indicated by the ≈ 20 % increase in nucleus-nucleus collision relative to proton-proton collisions. However, this region can not be

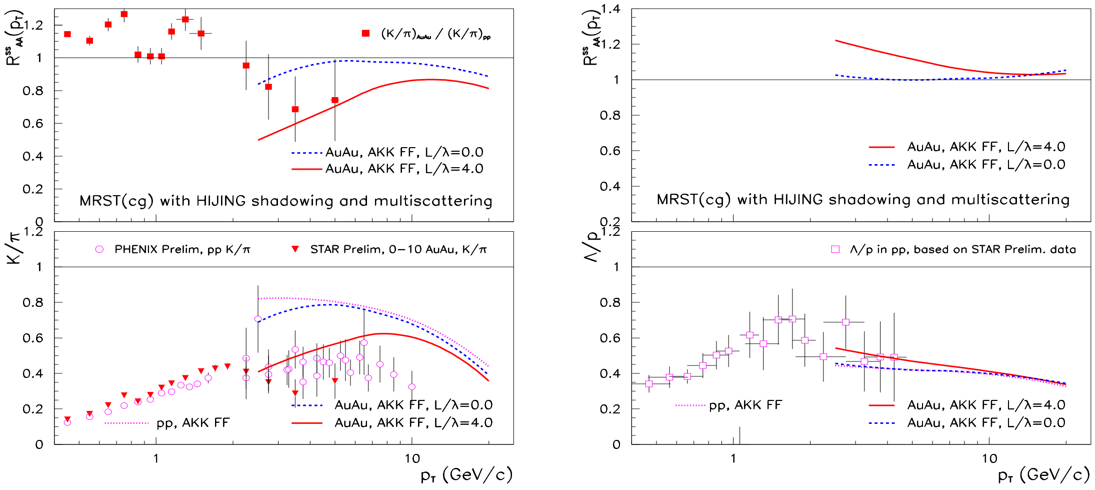

Figure 1. Calculated K/π ratios in $AuAu$ and pp collisions compared to PHENIX pp [16] STAR $AuAu$ [17, 18] data (*left side*) and Λ/p ratios with pp collision data from STAR [19, 20] (*right side*). The bottom panels display the strange-to-non-strange ratios, while the top panels show the double ratios defined by eq. (2).

investigated by pQCD calculations. At high p_T, forgeting the large error bars for a moment, the data in the top left panel show some suppression of kaons in $AuAu$ collisions. Do the theoretical calculations indicate a similar tendency? The answer is yes, as displayed by Fig. 1. Introducing stronger jet quenching with larger opacity in $AuAu$ collisions, the K/π ratio is decreasing. At very high p_T the data appear to fall faster than the theoretical curves. More data are needed with higher precision for a final answer. One needs to also keep in mind that data from PHENIX [16] and STAR [17, 18] were combined to obtain the experimental points in the top panel.

Considering the strange-to-non-starnge ratio, while the proton-proton calculations overestimate the data by up to a factor 2, there is a hint of potential agreement between the data and the calculations with an opacity of $L/\lambda = 4$ in the bottom panel. Unfortunately, as mentioned above, the calculations can not be extended to lower momenta, where pQCD is no longer reliable (technically due to PDF and FF limitations).

On the *right side* of Fig. 1 we show similar information for Λ/p ratios. Here, the calculated curves run very close to each other in the bottom panel. The data are for pp collisions from Refs. [19, 20]. (We are not aware of measured $AuAu$ Λ/p ratios, and we encourage such analysis.) In summary, the mesonic K/π ratio is more sensitive to jet energy loss in heavy-ion collisions than the Λ/p baryonic ratio. The reason is very simple: at lower p_T meson production is dominated by gluon fragmentation, which slowly turns into the dominance of quark fragmentation with increasing p_T. On the other hand, baryon production is dominated by leading quark fragmentation in a wide p_T region. In this sense the investigation of $\overline{\Lambda}/\overline{p}$ may be more interesting because the

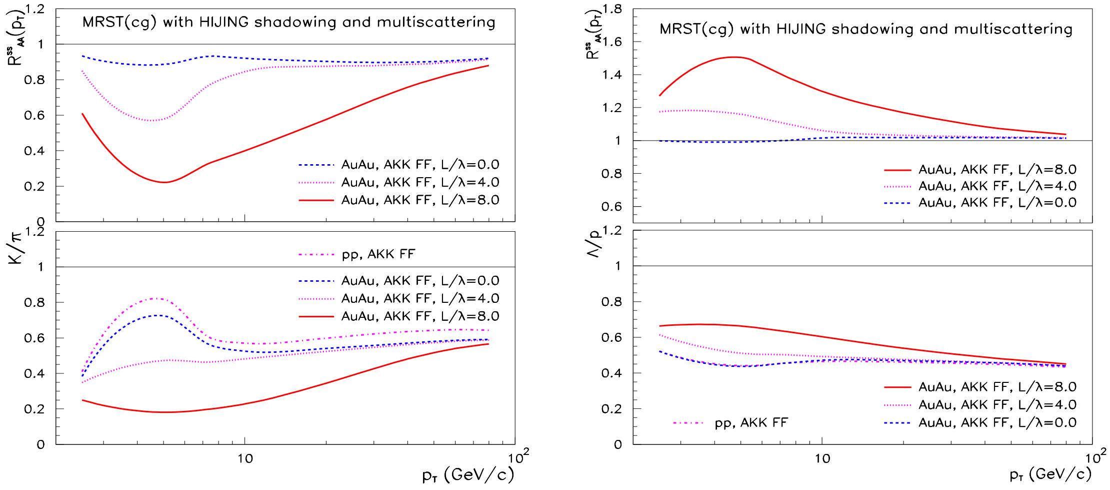

Figure 2. Calculated K/π (*left side*) and Λ/p (*right side*) ratios (bottom) and double ratios (top) in $PbPb$ collisions at $\sqrt{s} = 5.5$ ATeV with different opacities.

gluons have a larger contribution to this ratio.

4. Is Strangeness Still Strange at LHC Energies?

We repeat our calculations for $PbPb$ collisions for $\sqrt{s} = 5.5$ ATeV LHC energy. The results are displayed on Fig. 2. The opacity is expected to be higher at LHC due to the higher available energy. Using a simple $\mathrm{d}N/\mathrm{d}y \sim 1500 - 3000$ estimate, we obtain $L/\lambda \approx 8$ in the most central $0 - 10\%$ $PbPb$ collisions. For comparison, we also plot the results with $L/\lambda = 0$ and 4. On the bottom panel in the *left side* we show the K/π ratios with the double ratios on top, up to high transverse momenta. The *right side* contains the prediction for the Λ/p ratios.

Results at LHC energies are somewhat similar to those at RHIC energies. The lower- and intermediate-p_T variation of the hadron ratios arises from the different strengths of the jet quenching for quark and gluon contributions [21, 22]. Due to the quark dominated fragmentation, the difference disappears at high-p_T in the ratios.

5. Conclusions

We find that strangeness still behaves differently from the up and down quark contributions at LHC energies in that the K/π and Λ/p ratios are still below unity at $\sqrt{s} = 5.5$ ATeV. The strange-to-non-strange ratios are similar for mesons and baryons, and are expected to be similar at LHC to what was seen at RHIC. On the other hand, mesonic ratios show more structure in the intermediate momentum region, because gluonic contributions have a bigger role in this momentum window.

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References

[1] M. Gell-Mann, *Phys. Rev.* **92**, 833 (1953).
[2] J.J. Aubert *et al.*, *Phys. Rev. Lett.* **33**, 1404 (1974). J. E. Augustin *et al.*, *Phys. Rev. Lett.* **33**, 1406 (1974).
[3] B. Müller and J. Refelski, *Phys. Rev. Lett.* **48**, 1066 (1982).
[4] T.S. Bíró and J. Zimányi, *Nucl. Phys.* **A395**, 525 (1983); T.S. Bíró, B. Lukács, J. Zimányi, and H.W. Barz, *Nucl. Phys.* **A386**, 617 (1982).
[5] Y. Zhang *et al.*, *Phys. Rev.* **C65**, 034903 (2002).
[6] P. Lévai, G.G. Barnaföldi, G. Fai, and G. Papp, *arXiv:nucl-th/0306019.*
[7] P. Lévai, G.G. Barnaföldi, G. Fai, and G. Papp, *Nucl. Phys.* **A783**, 101c (2007).
[8] G.G. Barnaföldi, P. Lévai, G. Fai, and G. Papp, *J. Phys.* **G30**, s1125 (2004).
[9] G.G. Barnaföldi, P. Lévai, G. Fai, and G. Papp, *Nucl. Phys.* **A774**, 801 (2006).
[10] G.G. Barnaföldi, P. Lévai, G. Fai, and G. Papp, *Heavy Ion Phys.* **18**, 79 (2003).
[11] A.D. Martin *et al.*, *Eur. Phys. Jour.* **C23**, 73 (2003).
[12] S.J. Li and X.N. Wang, *Phys. Lett.* **B527**, 85 (2002).
[13] X.-N. Wang and M. Gyulassy, *Phys. Rev.* **D44**, 3501 (1991); *Comput. Phys. Comm.* **83**, 307 (1994).
[14] S. Albino, B.A. Kniehl and G. Kramer, *Nucl. Phys.* **B725** 181 (2005); *ibid.* **B734** 50 (2006).
[15] M. Gyulassy, P. Lévai, I. Vitev, *Phys. Rev. Lett.* **85**, 5535 (2000); *Nucl. Phys.* **B571**, 197 (2000); *ibid.* **B594**, 371 (2001) .
[16] V. Riabov, *arXiv:nucl-ex/0702046.*
[17] Ming Yao [STAR], *J. Phys.* **G**, *in this volume*, (2007).
[18] B.I. Adelev *et al.* [STAR], *Phys. Rev. Lett.* **97** 152301 (2006).
[19] M. Heinz [STAR], *J. Phys.* **G31**, s1011 (2005); *Eur.Phys.J.* **C49**, 129 (2007).
[20] J. Adams *et al.* [STAR], *Phys. Lett.* **B637**, 161 (2006).
[21] P. Lévai, G. Papp, G. Fai and M. Gyulassy, *Acta. Phys. Hung.* **A27** 459 (2006).
[22] G.G. Barnaföldi, P. Lévai, B.A. Cole, G. Fai, and G. Papp, *arXiv:0706.4387* (2007).