Recent results on strangeness from ALICE at LHC

Benjamin Döningus (for the ALICE Collaboration)
Institut für Kernphysik, Goethe-Universität Frankfurt, Max-von-Laue-Str. 1, 60438 Frankfurt, Germany
E-mail: b.doenigus@gsi.de

Abstract. Recent measurements performed in high-multiplicity proton-proton (pp) and proton-lead (p-Pb) collisions have shown features that are similar to those observed in lead-lead (Pb-Pb) collisions. These observations warrant a comprehensive measurement of the production of identified particles as a function of multiplicity in all systems. The production of different strange and multi-strange particle species at mid-rapidity measured as a function of multiplicity in pp collisions at $\sqrt{s} = 7$ TeV with the ALICE setup are conducted. Spectral shapes studied both for individual particles and via particle ratios such as ($\Lambda/K_S^0$) as a function of $p_T$ exhibit an evolution with event multiplicity and the production rates of hyperons are observed to increase more strongly than those of non-strange hadrons. These phenomena are qualitatively similar to the ones observed in p-Pb and Pb-Pb collisions. The values in high-multiplicity pp and p–Pb collisions approach the ones in Pb–Pb.

1. Introduction

Ultra-relativistic heavy-ion collisions at the LHC offer a unique way to study QCD matter at very high temperatures. Lattice QCD calculations [1,2] suggest that a transition from confined hadrons to a state of deconfined matter, the so-called quark-gluon plasma, is happening at temperatures above $T_c = (154\pm9)$ MeV and/or energy densities above $\epsilon_c = 0.34\pm0.16$ GeV/fm$^3$. These are clearly reached in these collisions as one can deduce for instance from the measurement of direct photon transverse momentum spectra. These lead to effective temperatures of $T_{\text{eff}} = (297\pm12(\text{stat})\pm41(\text{syst}))$ MeV averaged over the collision, extracted through the slope of the spectra [3]. Comparisons to models lead to initial temperatures of up to 740 MeV [4].

The evolution of the collisions themselves are imagined usually as a sequence of the following stages: two Lorentz contracted nuclei approach each other, they collide, and after a short time (less than 1fm/c) a quark-gluon plasma is formed which eventually expands, cools down and hadronizes. Finally the hadrons rescatter and freeze out. The temperature where the hadrons stop being produced is called chemical freeze-out temperature $T_{\text{ch}}$ and the temperature when the hadrons stop scattering is denoted as kinetic freeze-out temperature $T_{\text{fo}}$.

If one uses an analogy between a light source and a particle source one can extract also a temperature from the measured multiplicities of the different particle species. This is possible using an approach based on a grand canonical ensemble with the main ingredients: (chemical freeze-out) temperature $T_{\text{ch}}$, volume $V$ and baryo-chemical potential $\mu_B$. The latter is basically zero at the LHC, namely baryons and anti-baryons are produced with equal amounts [5]. This approach is called (statistical) thermal model and the measurement of the production yield of different particle species, such as $\pi$, K, p, etc. can be used to extract a temperature of about 156 MeV at the LHC [6]. If this is done for the different available energies at different
Figure 1. $p_T$-differential yields of $K^0_S$, $\Lambda + \bar{\Lambda}$, $\Xi^- + \bar{\Xi}^+$ and $\Omega^- + \bar{\Omega}^+$ measured in $|y| < 0.5$ for a selection of event classes, indicated by roman numbers in brackets, where I denotes the highest and X the lowest multiplicity. The data are scaled by different factors to improve the visibility. The dashed curves represent Tsallis-Lévy fits to each individual distribution to extract integrated yields. Figure taken from [15].

laboratories one sees that there is an increase up to energies reached at the SPS at CERN and then the temperature stays constant. This is another hint that the quark-gluon plasma is formed around a temperature of 159 MeV, which is the average of the extracted temperatures in the aforementioned plateau ($T_{lim}$). This leads to the assumption $T_{lim} \approx T_{ch} \approx T_c$ [7].

Before the observation of this interesting fact many signatures of the quark-gluon plasma have been proposed. One of the earliest ones was the possible enhancement of strangeness in ultra-relativistic heavy-ion collisions, relative to production in elementary collisions [8,9]. This was observed at the SPS [10] but is nowadays often interpreted in the opposite direction, as a lifting of the suppression when moving from elementary collisions such as pp to Pb–Pb for
instance [11,12]. This can be understood also as the necessity to treat strangeness canonically and not as introduced before in a grand canonical ensemble [13,14].

\[ \langle \frac{dN_{ch}}{d\eta} \rangle_{|\eta|<0.5} \]

\[ \text{Ratio of yields to (} \pi^+ + \pi^- \text{)} \]

Figure 2. \( p_T \)-integrated yield ratios of strange and multi-strange hadrons to (\( \pi^+ + \pi^- \)) as a function of \( \langle \frac{dN_{ch}}{d\eta} \rangle \) measured in the rapidity interval \( |\eta| < 0.5 \). The empty and dark-shaded boxes show the total systematic uncertainty and the contribution uncorrelated across multiplicity bins, respectively. The values are compared to calculations from MC models [17,18,19] and to results obtained in Pb–Pb and p–Pb collisions at the LHC. Figure from [16].

Measurement of strangeness production in heavy-ion collisions is nevertheless of high importance not only because the yields are needed for the determination of the chemical freeze-out temperature but also because they revealed some interesting points when the measurements were extended towards p–Pb collisions and in particular in multiplicity bins [15]. There it was observed that the ratios of hyperon production yields to those of charged pions increase as a function of multiplicity until the thermal model expectation is reached, namely the ratios in
high multiplicity p–Pb approaching those in Pb–Pb. As shown in [15], this trend is qualitatively reproduced within a thermal model with additional local conservation of strangeness. The high statistics and precision data taken by the ALICE Collaboration in pp collisions at $\sqrt{s} = 7$ TeV allows also the splitting in multiplicity classes and thus a comparison with the p–Pb and Pb–Pb measurements.

2. Results

The measured transverse momentum spectra for $K^0_S$, $\Lambda + \bar{\Lambda}$, $\Xi^- + \bar{\Xi}^+$, and $\Omega^- + \bar{\Omega}^+$ are depicted in Figure 1 for three different exemplary multiplicity classes. The multiplicity classes are numbered using roman figures from I to X, whereas I denotes the highest multiplicity and X the lowest (for details see [16]). One can already see here that the spectra become harder at higher multiplicities. A separate study shows in addition that the hardening is more pronounced for baryons than for mesons.

Figure 3. Particle production yield ratios $\Lambda/K^0_S = (\Lambda + \bar{\Lambda})/2K^0_S$ and $p/\pi = (p + \bar{p})/(\pi^+ + \pi^-)$ as a function of $\langle dN_{ch}/d\eta\rangle$ measured in the rapidity interval $|\eta| < 0.5$. The empty and dark-shaded boxes show the total systematic uncertainty and the contribution uncorrelated across multiplicity bins, respectively. The values are compared to calculations from MC models [17,18,19] in pp collisions at $\sqrt{s} = 7$ TeV and to results obtained in p–Pb collisions at the LHC. Figure taken from [16], where also more details can be found.

One can now extract the integrated production yield for a given multiplicity bin and build the ratio to the yield of charged pions to estimate the relative strangeness production. This is
shown as a function of the mean charged particle multiplicity \( \langle dN_{ch}/d\eta \rangle \) in Figure 2. Here a significant enhancement of strange and multi-strange particle production can be seen, where the rise depends strongly on the strangeness content. In addition one can see that no MC prediction describes the observed trend satisfactorily, whereas the pp data follows the trend observed in p–Pb nicely and this is not expected because both systems are expected to have different initial states. In particular it is visible that the particle ratios reach values that are similar to those observed in central Pb–Pb collisions.

To cancel the effect of strangeness the baryon to meson ratio is build as displayed for \( \Lambda/K^0_S \) and \( p/\pi \) in Figure 3. No increase for protons (non-strange) is observed, which is contrary to model predictions, e.g. DIPSY [18]. The ratios do not change significantly as a function of multiplicity, which shows that the observed enhanced production rates of strange hadrons with respect to pions is not due to the difference in the hadron masses but clearly connected to the strangeness content.

Figure 4. Particle production yield ratios of strange and multi-strange hadrons to pions normalised to the values measured in the inclusive INEL\(>0 \) pp sample, both in pp and in p–Pb collisions. The common systematic uncertainties cancel in the double-ratio. The empty boxes represent the remaining uncorrelated uncertainties. The lines represent a simultaneous fit of the results with the empirical scaling formula as discussed in [16] where also this figure is taken from.

The dynamical evolution is illustrated in Figure 4 as the ratio to pions for the previously shown data normalised by values measured in the inclusive INEL\(>0 \) pp sample, both for pp and
p–Pb results. INEL>0 denotes here the requirement that the analysed events contain at least one charged particle produced with \( p_T > 0 \) in the pseudorapidity interval \(|\eta| < 1\). The observed multiplicity-dependent enhancement with respect to the INEL>0 sample follows a hierarchy connected to the strangeness content of the hadrons. The observed increase is clearly more pronounced for baryons with higher strangeness content.

3. Conclusion
The presented multiplicity dependence of the production of primary strange (\( K_S^0, \Lambda, \bar{\Lambda} \)) and multi-strange (\( \Xi^-, \Xi^+, \Omega^- , \Omega^+ \)) hadrons in pp collisions at \( \sqrt{s} = 7 \) TeV shows clearly that the smaller systems as pp and p–Pb reveal interesting results and deserve more attention. The measured \( p_T \) spectra become harder as the multiplicity increases. The spectral shapes as well as the multiplicity and mass dependence are showing similar behaviour as observed in p–Pb and Pb–Pb collisions at the LHC, this can be interpreted as a collective expansion of the system in the final state. The \( p_T \)-integrated yields of strange and multi-strange particles relative to pions increase significantly with multiplicity. There is a remarkable consistency across systems of this observable as a function of multiplicity. The observed enhancement increases with strangeness content rather than with mass or baryon number of the hadron and this trend can not be reproduced by the investigated MC generators. Further studies extending to higher multiplicity in small systems are essential, as they would give inside to the question if strangeness production saturates at the thermal equilibrium values such as predicted by the grand canonical statistical model or if it continues increasing. In addition it will be interesting to see if in pp collisions at higher energy, i.e. \( \sqrt{s} = 13 \) TeV, the same trends will be observed.

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5. References
[1] Bazavov A et al. (hotQCD), 2014 Phys. Rev. D 90 094503
[2] Borsanyi S et al. (Budapest-Wuppertal group), JHEP 09 (2010) 073
[3] Adam J et al. (ALICE Collaboration), 2015 Phys. Lett. B 754 235
[4] Chatterjee R et al., 2013 Phys. Rev. C 88 034901
[5] Andronic A et al., 2011 J. Phys. G 38 124081
[6] Floris M, 2014 Nucl. Phys. A 931 103
[7] Andronic A et al., 2009 Phys. Lett. B 673 142, erratum ibid 2009 678 516
[8] Rafelski J and M"uller B, 1982 Phys. Rev. Lett. 48 1066, erratum ibid 1986 56 2334
[9] M"uller B, Koch P and Rafelski J, 1986 Phys. Rept. 142 167
[10] Antinori F et al., 2006 J. Phys. G 32 427
[11] Blume C and Markert C, 2011 Prog. Part. Nucl. Phys. 66 834
[12] Hamisch S, Redlich K and A. Tounsi, 2000 Phys. Lett. B 486 61
[13] Redlich K and Tounsi A, 2002 Eur. Phys. J. C 24 589
[14] Tounsi A, Mischke A and Redlich K, 2003 Nucl. Phys. A 715 565c
[15] Adam J et al. (ALICE Collaboration), 2016 Phys. Lett. B 758 389
[16] Adam J et al. (ALICE Collaboration), 2016 arXiv:1606.07424
[17] Sj"orstrand T et al., 2008 Comput. Phys. Commun. 178 852
[18] Flensburg C et al., 2011 JHEP 08 103
[19] Pierog T et al., 2015 Phys. Rev. C 92 034906