Open Questions in the Understanding of Strangeness Production in HIC – Experiment Perspective

Christoph Blume[1],⋆

[1] *Institut für Kernphysik, Goethe-Universität Frankfurt am Main,*
Max-von-Laue-Str. 1, 60438 Frankfurt am Main, Germany

Abstract. Open questions concerning strangeness production in heavy-ion collisions are discussed with a focus on the experimental aspects. The open points are presented in the context of recent measurements.

1 Introduction

The following is an attempt to compile a list of the most important open topics concerning strangeness production in heavy-ion physics. This list is seen from an experimentalist point-of-view (the theory perspective is discussed in [1]) and is also naturally incomplete and biased. In order to not get lost in the many facets of strangeness physics, the questions will be limited to those belonging to four main subjects: energy dependence of strangeness enhancement in nucleus-nucleus collisions, understanding of small systems, strangeness production at low energies and hyperon-interaction & hypernuclei.

2 Energy dependence of strangeness enhancement

It has been established already quite a while ago that the production of strange particles is significantly enhanced in heavy-ion reactions relative to elementary proton-proton collisions (for a review see [2]). Usually, the enhancement factor E is defined as:

$$E = \frac{2}{N_{\mathrm{part}}} \left(\left. \frac{dN(\mathrm{AA})}{dy} \right|_{y=0} \right) \Bigg/ \left(\left. \frac{dN(\mathrm{pp})}{dy} \right|_{y=0} \right) \tag{1}$$

It is a remarkable fact that E decreases significantly when going from SPS energies to the very high energies available at the LHC. E.g. for the Ω^- E is found to be around 20 at $\sqrt{s_{\mathrm{NN}}}$ = 17.3 GeV [3], $\sim$ 12 at $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV [4] and only $\sim$ 6 at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV [5], as illustrated in Fig. 1. While the enhancement factor has been measured for essentially all multi-strange (anti-)particles at these energies, data are still quite scarce for these rare particles at energies below $\sqrt{s_{\mathrm{NN}}}$ = 17.3 GeV. An interesting exception is the measurement of Ξ^- production in Ar+KCl collisions at 1.76A GeV beam energy by the HADES collaboration (left panel of Fig. 2) [6]. HADES also has studied the production of ϕ mesons at these sub-threshold energies (right panel of Fig. 2) [7]. The data are in so far remarkable as also here an enhancement of the rare strange particles is observed. The $\Xi^-/(\Lambda + \Sigma^0)$-ratio is found to be much larger than the statistical model expectation and the ϕ/K^--ratio rises dramatically towards very low energies.

⋆e-mail: blume@ikf.uni-frankfurt.de

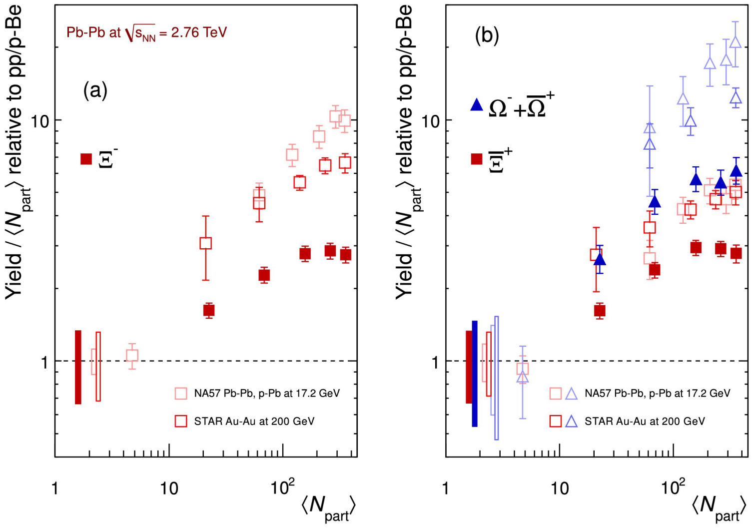

Figure 1. The enhancement factors for multi-strange (anti-)particles as a function of the number of participants $\langle N_{\text{part}} \rangle$ as measured at the SPS [3], RHIC [4] and LHC [5].

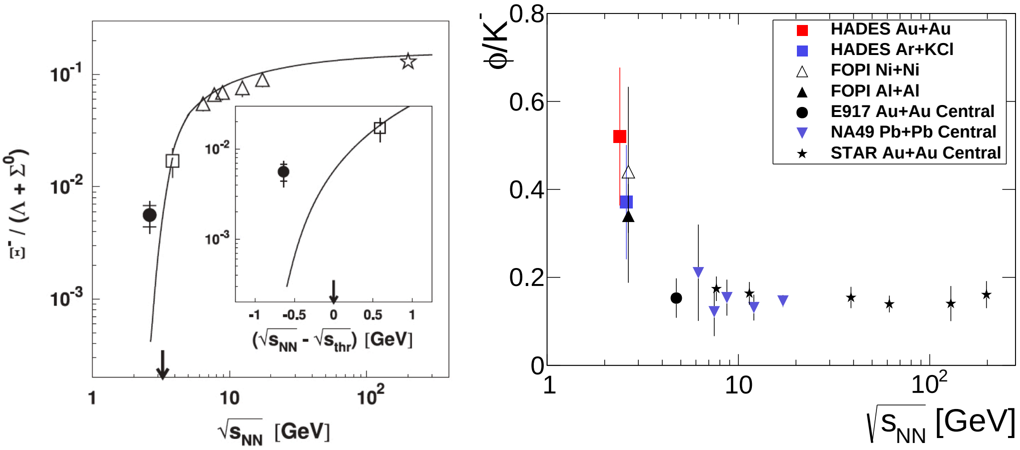

Figure 2. The $\Xi^-/(\Lambda + \Sigma^0)$-ratio (left panel, [6]) and the ϕ/K^--ratio (right panel, [7]) as a function of the centre-of-mass energy as measured in central heavy-ion collisions.

Taking these observations together, one finds that the strangeness enhancement, in particular for rare multi-strange (anti-)particles, exhibits a quite complicated energy dependence. As sketched in Fig. 3 there is evidence for a strong increase at sub-threshold energies and it has been established that there is a strong enhancement at intermediate (i.e. SPS energies) energies, which slowly decreases again towards high energies (i.e. RHIC and LHC). It remains an open question if there is any evidence for an onset of strangeness enhancement between low and intermediate energies. This should happen in a region where sub-threshold phenomena (dashed line) do not play a role any more and the partonic

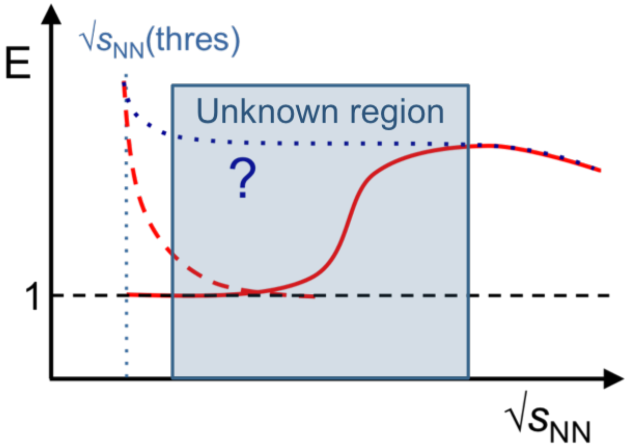

Figure 3. Sketch of the energy dependence of the enhancement factor of rare multi-strange (anti-)particles.

degrees of freedom (solid line) are becoming more and more effective. It might also very well be that there is no discernible onset visible, due to additional hadronic medium effects (dotted line) (e.g. multi-step hadronic reactions, resonances, multi-meson fusion processes, etc.). However, it is obvious that high quality data of rare particles in the energy range below $\sqrt{s_{\mathrm{NN}}} \sim 10$ GeV would be highly relevant (see also [8]) in order to answer the following questions:

- What is the energy dependence of strangeness enhancement over the whole energy region, in particular for multi-strange (anti-)particles?
- Could there be an onset somewhere?
- To what extend can hadronic effects cause a strangeness enhancement at intermediate energies (SPS and below)?
- Do we understand the dramatic effects at sub-threshold energies?
- Or, in other words, can finally a direct connection between strangeness enhancement and QGP formation be established?

3 Understanding of small systems

Small systems play a key role for the understanding of strangeness production in heavy-ion collisions. The decrease of the strangeness enhancement factor between SPS and LHC energies, as discussed in the previous section, is actually not caused by a decrease of the yields in heavy-ion collisions. In fact, they are already close to the statistical model expectation at top SPS-energies and increase only slightly towards higher energies. However, the yields of multi-strange particles increases much stronger in pp collisions than in AA (see left panel of Fig. 4). For instance, one finds that the Ξ/π ratios are almost the same at RHIC and LHC in central AA collisions, while this ratios increase significantly in pp collisions. Thus, the decrease of the strangeness enhancement is due to a release of the strangeness suppression in pp with increasing energies.

This phenomena can also be investigated by comparing pp collisions of different reaction violence at high energies. This is done by selecting pp event classes of different charged particle multiplicity

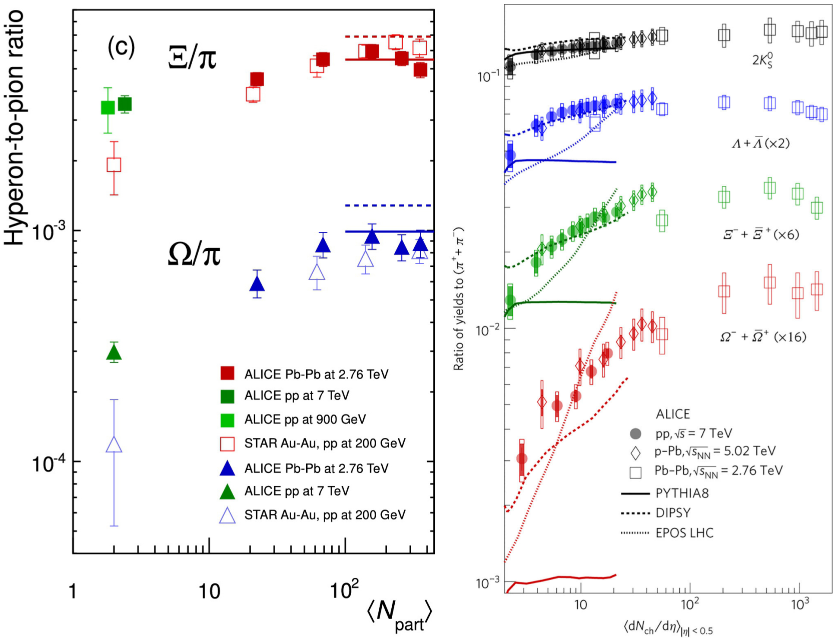

Figure 4. Left: the Ξ^-/π and Ω/π ratios in pp and AA collisions as a function of $\langle N_{\mathrm{part}}\rangle$ [5]. The lines correspond to statistical model predictions (solid line [9], dashed line [10]). Right: the yield ratios of strange particles and pions measured in pp, pA and AA collisions at the LHC as a function of $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ [11].

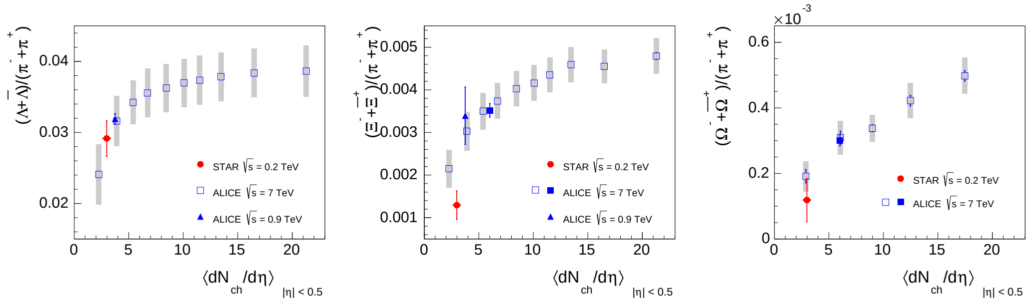

Figure 5. The yield ratios of strange particles to pions measured in multiplicity selected pp collisions at $\sqrt{s}$ = 7 TeV [11] and in minimum bias pp collisions measured at various energies by ALICE [12, 13] and STAR [14, 15] as a function of $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$.

$\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$. Such a study has recently be performed by the ALICE collaboration [11] (see right panel of Fig. 5). Here it was found that the yield ratios of strange particles to pions observed in very high multiplicity pp collisions are on the same level as the ones measured in peripheral heavy-ion reactions. Also, the multiplicity dependence of these ratios turns out to be very similar in pp and pA collisions. This is not at all trivial since the physics in a high multiplicity pp collision is quite different from the one in pA at the same multiplicity. While in the first case a very rare and violent pp interaction has to be involved, in the latter case the same multiplicity can be achieved by the much more likely superposition of several soft pp collisions.

In the statistical model approach strangeness enhancement is described by the transition from a canonical to a grand-canonical ensemble, which depends on the volume V_0 of the system. In this picture a strangeness hierarchy is expected [16], i.e. the volume dependence gets stronger with increasing strangeness content. Since such a hierarchy was observed in the multiplicity dependence [11], it is natural to interpret the pp data in this way by assuming a relation $V_0 \propto \langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \rangle$. In fact, as reasonable description of all particle ratios, with the notable exception of the ϕ/π-ratio (other peculiarities related to the ϕ-meson are discussed in Sect. 4), can be achieved within this model [17].

If this interpretation holds, the particle ratios should saturate for pp collisions at very high multiplicities when the grand-canonical limit is reached. As shown in Fig. 5, this might indeed already be the case for the Λ/π and Ξ/π ratios, while for the Ω/π it is rather still a continuous increase. Also, it would be interesting to establish whether $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ does provide an universal scaling variable for all energies. Fig. 5 shows a comparison of the multiplicity selected pp collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV to minimum bias pp reactions at lower energies. The minimum bias data points roughly follow the trend, however, it would be worthwhile to examine the multiplicity dependence also at low energies with good accuracy, in order to test whether really an universal scaling holds. In summary, the following questions would require further investigations:

- Does $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ provide an universal scaling for system size dependencies (pp $\rightarrow$ pA $\rightarrow$ AA)?
- Is the relation of $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ to the reaction volume the only relevant factor (look at other observables)?
- Does the multiplicity dependence match the transition from a canonical to a grand-canonical ensemble at all energies?
- Is a saturation of particle ratios observed in very high multiplicity pp collisions?

4 Low energies and the ϕ-meson

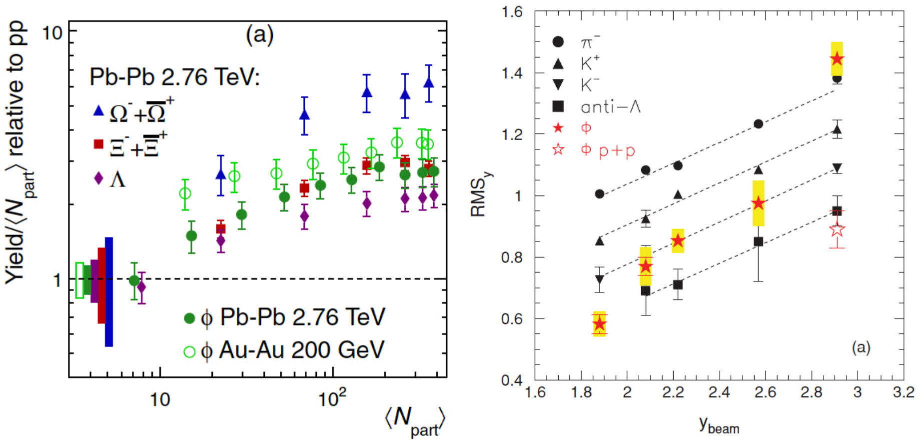

Figure 6. Left: the yield ratios of strange particles to pions measured in pp and AA collisions at different centre-of-mass energies as a function of $\langle N_{\mathrm{part}} \rangle$ [18]. Right: the widths of the rapidity distributions of the ϕ-meson measured at the SPS as a function of the beam rapidity y_{beam} [19].

Also at the lower end of the energy spectrum many unresolved questions are remaining. These are particularly important, since they are concerned with the behaviour of strange particles in a hadronic medium, which need to be understood before any conclusions about the partonic phases of heavy-ion collisions can be made.

A topic discussed since quite a while is the propagation of kaons in the medium. In low energy AA collisions a significant difference between the inverse slope parameters of the p_t spectra of K^- and K^+ has been observed ($T(K^+) > T(K^-)$). Since the cross section of reactions with nucleons are different ($\sigma(K^-) > \sigma(K^+)$) due to strangeness exchange reactions of the K^-, the rescattering with the hadronic medium should cause different freeze-out conditions for the two kaon species and thus can explain the different slope parameters [20]. Also, the kaon-nucleon potential, which is expected to be attractive for K^- and repulsive for K^+, can modify the inverse slope parameters. On the other side, the unexpectedly high ϕ/K^--ratio at low energies (see right panel of Fig. 2) can also provide a natural explanation for this observation. Since the feed-down from ϕ-decays at these energies is a substantial contribution to the kaon spectra, it will also modify their shape. This affects more strongly the rarer K^- than K^+ and thus will result in the different spectral shapes [21].

With its $s\bar{s}$ valence quark structure the ϕ-meson is effectively a strangeness neutral particle ($S = 0$). Nevertheless, it behaves in many ways as if it would have a non-zero strangeness. The enhancement factor for the ϕ is found to be between the ones for the Λ and Ξ (see left panel of Fig. 6), thus rather behaving as a particle with an effective strangeness in the range $1-2$ [18, 22]. Another so far unexplained observation related to the ϕ is the energy dependence of the widths of its rapidity distributions (right panel of Fig. 6). In heavy-ion collisions, it broadens much stronger than for π, K^- and K^+, which is difficult to reconcile with kaon-coalescence being the main production mechanism for ϕ-mesons [19]. Some important points to be clarified concerning heavy-ion collisions at low energies and the ϕ-mesons are therefore:

- Do we understand the production and propagation of strangeness at low energies?
- Is there any evidence for a sequential freeze-out due to different cross sections?
- Does the medium also at low energy behave macroscopically and can fully be described by the statistical model?
- Why does a non-strange particle behave so strange?

5 Hyperon interaction and hypernuclei

The investigation of hyperon-interactions is a crucial ingredient for the theoretical description of neutron stars. It may in particular be relevant for the understanding of high mass neutron stars with $M > 2\ M_\odot$. One way to obtain informations is via two-particle correlations. The STAR collaboration recently managed to extract a $\Lambda\Lambda$-correlation function in heavy-ion collisions [23] (see left panel of Fig. 8). As the strong interaction between the Λ-pairs causes a deviation of the correlation function from the quantum-statistical expectation of $C_{\Lambda\Lambda}(Q = 0) = 0.5$, one can infer information on the scattering lengths and effective interaction ranges by comparing it to corresponding models. Using the one by Lednický and Lyuboshitz [24], a weak repulsive interaction was inferred by the STAR collaboration [23]. However, an alternative analysis [25] rather favours a weak attractive interaction.

Another important source of information on this subject are hypernuclei and more and more data is becoming available. For instance, with the measurement of anti-hypertritons the STAR collaboration achieved the first observation of an anti-hypernucleus [26]. Generally, it is found that the (anti-)hypertriton yields agree very well with statistical model expectations [27]. Since their binding energy is very small, it is surprising that their yields are fixed in a chemical freeze-out environment

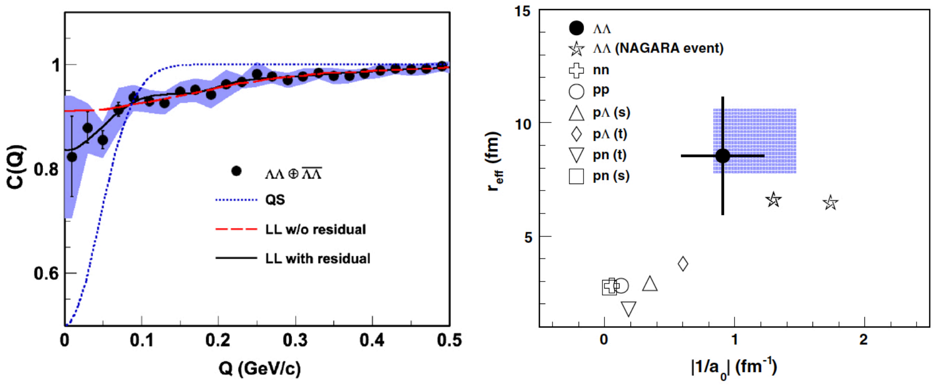

Figure 7. Left: the ΛΛ-correlation function measured in Au+Au collisions at RHIC [23]. Right: the S-wave scattering length a_0 and effective interaction range r_{eff}, as extracted from this correlation function with the model by Lednický and Lyuboshitz [24].

with a temperature higher by about two orders of magnitude. Current measurements of the Λ-lifetime from the decay of ${}^{3}_{\Lambda}$H seem to indicate that it is slightly lower than the one of a free Λ [28], which would be an indication for a modification of hyperon properties inside a nuclear medium.

The study of hyperon-interactions and their properties in nuclei has regained quite some momentum recently with the measurements at RHIC and LHC. High statistics data, in particular on double-hypernuclei, which will become available in the near future with facilities such as FAIR, will allow to address the questions listed below with much more precise information:

- What do we really know about hyperon-hyperon interactions?
- What is the possible contribution to the understanding of large-mass neutron stars?
- Why are the yields of very weakly bound objects (e.g. ${}^{3}_{\Lambda}$H) so well described by the statistical model (“snowball in hell”)?
- Are the properties of hyperons modified inside nuclei?

6 Acknowledgements

The author would like to acknowledge many helpful discussions with B. Dönigus, D. Cebra, C.-M. Ko, M. Lorenz, H. Ströbele and many others.

References

[1] C.M. Ko, *Open Questions in the Understanding of Strangeness Production in HIC – Theory Perspective*, these proceedings
[2] C. Blume, C. Markert, Prog. Part. Nucl. Phys. **66**, 834 (2011), `1105.2798`
[3] F. Antinori et al. (NA57), J. Phys. **G32**, 427 (2006), `nucl-ex/0601021`
[4] B.I. Abelev et al. (STAR), Phys. Rev. **C77**, 044908 (2008), `0705.2511`
[5] B.B. Abelev et al. (ALICE), Phys. Lett. **B728**, 216 (2014), [Erratum: Phys. Lett.B734,409(2014)], `1307.5543`

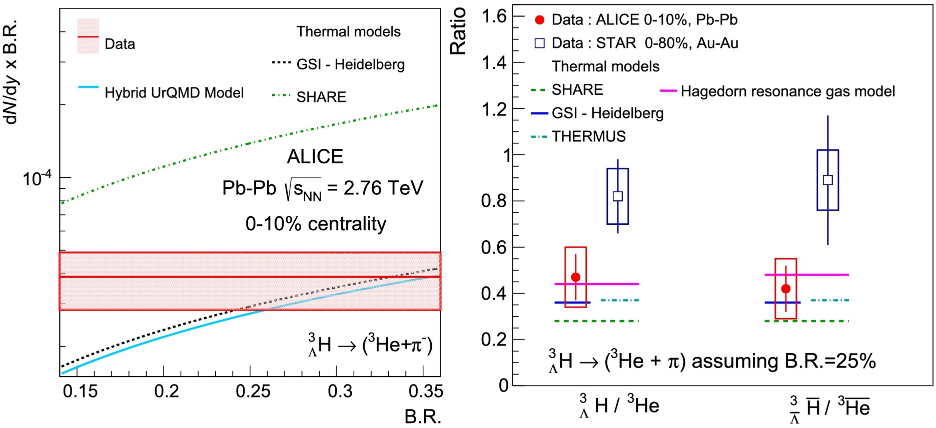

Figure 8. Left: the $^{3}_{\Lambda}$H yield as measured at the LHC in comparison to several model predictions [27]. Right: the $^{3}_{\Lambda}$H/^{3}He and $^{3}_{\bar{\Lambda}}\overline{\mathrm{H}}/^{3}\overline{\mathrm{He}}$ ratios measured at RHIC and LHC in comparison to statistical model predictions [27].

[6] G. Agakishiev et al. (HADES), Phys. Rev. Lett. **103**, 132301 (2009), `0907.3582`

[7] J. Adamczewski-Musch et al. (HADES) (2017), `1703.08418`

[8] D. Cebra, *Open Questions in the Understanding of Strangeness Production in HIC – Future Directions*, these proceedings

[9] A. Andronic, P. Braun-Munzinger, J. Stachel, Phys. Lett. **B673**, 142 (2009), [Erratum: Phys. Lett.B678,516(2009)], `0812.1186`

[10] J. Cleymans, I. Kraus, H. Oeschler, K. Redlich, S. Wheaton, Phys. Rev. **C74**, 034903 (2006), `hep-ph/0604237`

[11] J. Adam et al. (ALICE), Nature Phys. **13**, 535 (2017), `1606.07424`

[12] B. Abelev et al. (ALICE), Phys. Lett. **B712**, 309 (2012), `1204.0282`

[13] K. Aamodt et al. (ALICE), Eur. Phys. J. **C71**, 1594 (2011), `1012.3257`

[14] B.I. Abelev et al. (STAR), Phys. Rev. **C75**, 064901 (2007), `nucl-ex/0607033`

[15] B.I. Abelev et al. (STAR), Phys. Rev. **C79**, 034909 (2009), `0808.2041`

[16] S. Hamieh, K. Redlich, A. Tounsi, Phys. Lett. **B486**, 61 (2000), `hep-ph/0006024`

[17] V. Vislavicius, A. Kalweit (2016), `1610.03001`

[18] B.B. Abelev et al. (ALICE), Phys. Rev. **C91**, 024609 (2015), `1404.0495`

[19] C. Alt et al. (NA49), Phys. Rev. **C78**, 044907 (2008), `0806.1937`

[20] C. Hartnack, H. Oeschler, Y. Leifels, E.L. Bratkovskaya, J. Aichelin, Phys. Rept. **510**, 119 (2012), `1106.2083`

[21] H. Schuldes, *Recent results from HADES*, these proceedings

[22] B.I. Abelev et al. (STAR), Phys. Lett. **B673**, 183 (2009), `0810.4979`

[23] L. Adamczyk et al. (STAR), Phys. Rev. Lett. **114**, 022301 (2015), `1408.4360`

[24] R. Lednicky, V.L. Lyuboshits, Sov. J. Nucl. Phys. **35**, 770 (1982), [Yad. Fiz.35,1316(1981)]

[25] K. Morita, T. Furumoto, A. Ohnishi, Phys. Rev. **C91**, 024916 (2015), `1408.6682`

[26] B.I. Abelev et al. (STAR), Science **328**, 58 (2010), `1003.2030`

[27] J. Adam et al. (ALICE), Phys. Lett. **B754**, 360 (2016), `1506.08453`

[28] L. Adamczyk et al. (STAR) (2017), `1710.00436`