

# News on strangeness production from the NA61/SHINE experiment

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**Abstract.** Strangeness production in high-energy hadronic and nuclear collisions continues to be one of the central topics in the study of strongly interacting matter. The data collected by the NA61/SHINE experiment at the CERN SPS North Area allow for a comprehensive scan of the strangeness production across various collision energies and system sizes.

This article focuses on the new results of the strangeness production in central collisions of medium-sized nuclei, such as Ar+Sc, at the SPS energy range. In particular, the results for Lambda hyperons and charged and neutral  $K$  mesons are shown. The energy and system size dependencies of Lambda-to-pion and strangeness-to-pion ratios are also explored. Moreover, an unexpected excess of charged over neutral  $K$  meson production in Ar+Sc and  $\pi^-$ +C interactions is presented. The obtained results are compared with predictions from selected particle production models, as well as with existing world data from proton-proton and nucleus-nucleus collisions.

## 1 Introduction

The study of strongly interacting matter under extreme conditions provides valuable insights into the nature of the early Universe and the structure of compact astrophysical objects. In particular, high-energy heavy-ion collisions allow experimental access to the transition between hadronic matter and the quark-gluon plasma (QGP) and, thus, outline the phase diagram of strongly interacting matter.

One of the earliest proposed signatures of QGP formation is the enhancement of strangeness production relative to baseline proton-proton and proton-nucleus collisions [1]. Various experiments at the CERN Super Proton Synchrotron (SPS), including NA49, reported striking evidence of enhanced strangeness in heavy-ion collisions. In particular, NA49 experiment observed non-monotonic behaviour in the energy dependence of the  $K^+/\pi^+$  at intermediate SPS energies, collectively referred to as the “horn” structure [2].

Nevertheless, data for intermediate-size systems remains insufficient. Such studies serve as valuable tests for theoretical models of particle production and are crucial for disentangling collective effects associated with QGP formation from initial-state effects present in smaller systems. The NA61/SHINE experiment at the CERN SPS addresses this gap by systematically studying collisions across a wide range of system sizes and beam energies. It employs a fixed-target setup with large acceptance and excellent tracking and particle identification capabilities [3].

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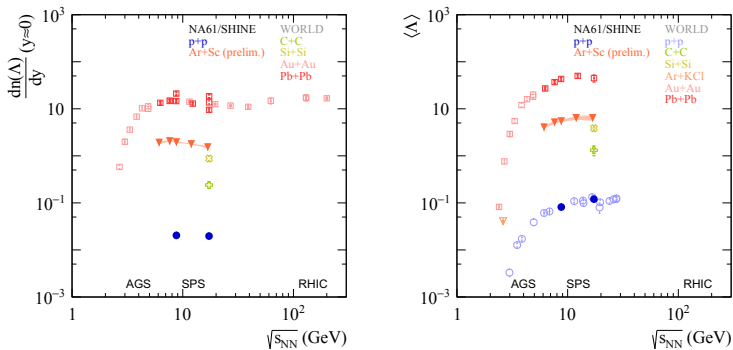
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## 2 Results

### 2.1 $\Lambda$ baryon production in Ar+Sc collisions

New preliminary results on  $\Lambda$  baryon production in the 10% most central Ar+Sc collisions at beam momenta of 19A and 30A GeV/c (corresponding to collision center-of-mass energy per nucleon pair  $\sqrt{s_{NN}} = 6.12, 7.62$  GeV) are presented along with earlier results at three higher energies (40A, 75A, and 150A GeV/c, which correspond to  $\sqrt{s_{NN}} = 8.77, 11.9,$  and  $16.8$  GeV, respectively) previously shown in Ref. [4].  $\Lambda$  baryons were reconstructed via their dominant weak decay channel  $\Lambda \rightarrow p + \pi^-$  with branching ratio  $BR = 63.9\%$ . The results discussed below refer to hadrons produced in strong interactions and electromagnetic decays. The raw yields, obtained by fitting the invariant mass spectra, are corrected for detector acceptance, reconstruction efficiency, selection cuts, branching ratio, and feed-down from heavier hyperons. For full details of the analysis procedure, see Ref. [5]. The obtained mean multiplicities of  $\Lambda$  baryons are  $4.073 \pm 0.052$  (stat)  $\pm 0.24$  (sys) for Ar+Sc at 19A GeV/c, and  $5.190 \pm 0.059$  (stat)  $\pm 0.36$  (sys) for Ar+Sc at 30A GeV/c.

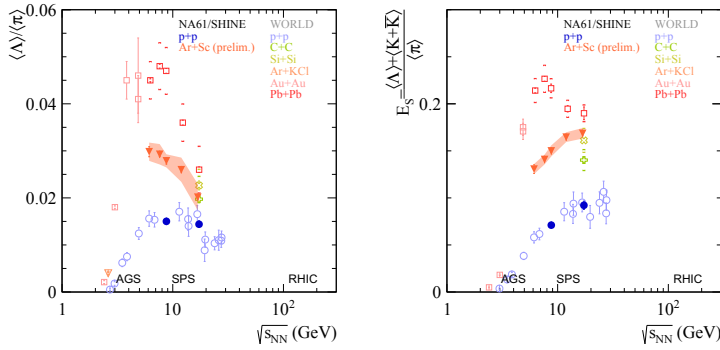
Figure 1 illustrates the energy dependence of the mid-rapidity yields and mean multiplicities of  $\Lambda$  baryons in Ar+Sc collisions, compared against existing measurements from a range of systems. Within the SPS energy range, both observables tend to flatten, indicating a saturation-like behaviour that appears to be independent of system size. Interestingly, the values obtained in Ar+Sc and Si+Si collisions are much closer to those measured in central Au+Au and Pb+Pb interactions than to those observed in  $p+p$  collisions.



**Figure 1.** The energy dependence of mid-rapidity yield (*left*) and the mean multiplicity (*right*) of  $\Lambda$  baryons. The systematic uncertainties of the Ar+Sc results are presented as shaded bands. Results for  $p+p$ , Ar+Sc, Ar+KCl, C+C, Si+Si, Au+Au, and Pb+Pb are shown (NA61/SHINE:  $p+p$ , Ar+Sc; NA49: C+C, Si+Si, Pb+Pb; NA57: Pb+Pb; STAR: Au+Au; PHENIX: Au+Au; E891: Au+Au; E895: Au+Au; E896: Au+Au; HADES: Ar+KCl, Au+Au; bubble chamber experiments:  $p+p$ ). For the references to the world data, see Ref. [6].

Figure 2 shows the energy dependence of the  $\langle \Lambda \rangle / \langle \pi \rangle$  ratio and the strangeness enhancement factor  $E_S$ , defined following Ref. [7] as  $E_S = \frac{\langle \Lambda \rangle + \langle K + \bar{K} \rangle}{\langle \pi \rangle}$ , where  $\langle \pi \rangle$  is equal to  $1.5 \cdot (\langle \pi^+ \rangle + \langle \pi^- \rangle)$ , and  $\langle \pi^+ \rangle$  and  $\langle \pi^- \rangle$  are mean multiplicities of positively and negatively charged pions, respectively. Since the  $\bar{\Lambda} / \Lambda$  ratio is below 0.15 in the SPS energy range [2], the contribution of  $\bar{\Lambda}$  to  $E_S$  is neglected. For  $p+p$  interactions,  $\langle K + \bar{K} \rangle$  is approximated as  $4 \cdot \langle K_S^0 \rangle$ , while for nucleus-nucleus collisions it is calculated as  $2 \cdot (\langle K^+ \rangle + \langle K^- \rangle)$  as suggested in Ref. [8]. In central Pb+Pb and Au+Au collisions, both  $\langle \Lambda \rangle / \langle \pi \rangle$  and  $E_S$  display

a pronounced maximum near mid-SPS energies. No such peak is observed for lighter systems, including Ar+Sc, though the overall trend in  $\langle\Lambda\rangle/\langle\pi\rangle$  in Ar+Sc is comparable to that in Pb+Pb collisions.



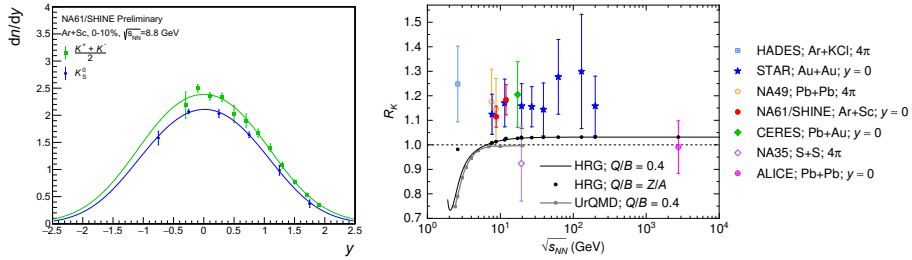
**Figure 2.** The energy dependence of  $\langle\Lambda\rangle/\langle\pi\rangle$  ratio (*left*) and strangeness enhancement  $E_S$  (*right*). The systematic uncertainties of the Ar+Sc results are presented as shaded bands. Results for  $p+p$ , Ar+Sc, Ar+KCl, C+C, Si+Si, Au+Au, and Pb+Pb are shown (NA61/SHINE:  $p+p$ , Ar+Sc; NA49: C+C, Si+Si, Pb+Pb; NA57: Pb+Pb; STAR: Au+Au; PHENIX: Au+Au; E891: Au+Au; E895: Au+Au; E896: Au+Au; HADES: Ar+KCl, Au+Au; bubble chamber experiments:  $p+p$ ). For the references to the world data, see Ref. [6].

## 2.2 Charged and neutral kaon productions in Ar+Sc collisions

NA61/SHINE has measured charged kaon production in the 10% most central Ar+Sc collisions at beam momenta of 13A, 19A, 30A, 40A, 75A, and 150A GeV/c (corresponding to  $\sqrt{s_{NN}} = 5.12, 6.12, 7.62, 8.77, 11.9$  and  $16.8$  GeV) [9]. Charged kaons were identified by using  $dE/dx$  method and combined  $tof$ - $dE/dx$  method. The yields of charged  $K$  mesons at mid-rapidity in the 10% most central Ar+Sc collisions at beam momenta of 40A and 75A GeV/c were determined in the interval of collision center-of-mass rapidity  $0.0 < y < 0.2$  and amount to  $(dn/dy)(K^+)_{y \approx 0} = 3.732 \pm 0.016$  (stat)  $\pm 0.148$  (sys) and  $(dn/dy)(K^-)_{y \approx 0} = 2.029 \pm 0.012$  (stat)  $\pm 0.069$  (sys) at 75A GeV/c and  $(dn/dy)(K^+)_{y \approx 0} = 3.283 \pm 0.041$  (stat)  $\pm 0.118$  (sys) and  $(dn/dy)(K^-)_{y \approx 0} = 1.417 \pm 0.024$  (stat)  $\pm 0.048$  (sys) at 40A GeV/c.

$K_S^0$  mesons were identified by the characteristic topology of their decay into charged pions ( $K_S^0 \rightarrow \pi^+ + \pi^-$ ) with a branching ratio  $BR = 69.2\%$ . Their production was measured in the 10% most central Ar+Sc collisions at beam momenta of 40A (preliminary) and 75A GeV/c [10]. Figure 3 (*left*) shows the rapidity distribution of  $K_S^0$  mesons at beam momentum of 40A GeV/c, together with the result of a double Gaussian fit. The yield of  $K_S^0$  meson at mid-rapidity, determined from the fit at  $y = 0$ , amounts to  $(dn/dy)_{y \approx 0} = 2.108 \pm 0.016$  (stat)  $\pm 0.052$  (sys) and  $(dn/dy)_{y \approx 0} = 2.433 \pm 0.027$  (stat)  $\pm 0.102$  (sys) at 40A and 75A GeV/c, respectively. At both momenta, an excess of charged over neutral kaons is observed, although an approximately equal abundance of charged and neutral kaons is expected since Ar and Sc nuclei are nearly isospin symmetric (valence quarks  $u = d$  within 6%), for details see Ref. [10]. At mid-rapidity, the charged-to-neutral kaon ratio, defined as  $R_K = (K^+ + K^-)/(2K_S^0)$ , was found to be  $1.115 \pm 0.043$  (tot) and  $1.184 \pm 0.061$  (tot) at 40A and 75A GeV/c, respectively.

In Fig. 3 (*right*), the charged-to-neutral kaon ratio is compared with a compilation of kaon production results from other experiments and predictions from the Ultrarelativistic Quantum



**Figure 3.** *Left:* The rapidity spectrum of  $K_S^0$  mesons (blue circles, preliminary) and the averaged spectrum of charged kaons (green squares, Ref. [9]) measured in 0–10% central Ar+Sc collisions at 40A GeV/c. Total uncertainties are drawn. Blue and green curves show the result of a double Gaussian fit to the  $K_S^0$  and averaged fit for charged kaons spectra, respectively. *Right:* Charged-to-neutral kaon ratio as a function of collision energy. Experimental data are shown by symbols with total uncertainties. HRG baseline for electric-to-baryon charge  $Q/B = 0.4$  is shown by a black line. HRG baseline for  $Q/B$  values specified accordingly to the given types of colliding nuclei is represented by black dots. UrQMD model results are shown by grey squares. Figure from Ref. [10] updated with the new NA61/SHINE data point.

Molecular Dynamics (UrQMD) [11] and Hadron Resonance Gas (HRG) [12] models. While data from other experiments are consistent with the NA61/SHINE results, both models fail to reproduce the observed charged-to-neutral kaon ratio. The deviation of the experimental results for the  $R_K$  factor from HRG model prediction reaches a significance of  $4.7\sigma$  when only the NA61/SHINE data at 75A GeV/c are included in the averaging (see Ref. [10] for details). This significance increases to  $5.3\sigma$  when the NA61/SHINE results at 40A GeV/c are also taken into account.

Ratios  $R_K > 1$  were also observed in  $\pi^- + C$  collisions at beam momenta of 158 and 350 GeV/c [13]. The models fail to reproduce the charged-to-neutral kaon ratio also for this small asymmetric system.

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