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Strangeness production and onset of deconfinement study in NA61/SHINE

Magdalena Kuich[a,*] **for the NA61/SHINE Collaboration**

[a] *Faculty of Physics, University of Warsaw, Pasteura 5, Warsaw, Poland*

E-mail: mkuich@cern.ch

This contribution summarises the recent results of the NA61/SHINE experiment on strangeness production in the system size dependence will be presented. Preliminary results on K^+ and K^- production in central Ar+Sc collisions will be discussed within the scope of the onset of deconfinement. Furthermore, final results on Ξ^- and $\overline{\Xi^+}$ hyperon production, as well as preliminary spectra of $\Xi^0(1530)$ and $\overline{\Xi^0}(1530)$ produced in p+p interactions at 158 GeV/c will be reported along with results on an experimental search for pentaquarks.

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*Speaker

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1. Introduction

NA61/SHINE is a multipurpose fixed-target facility at the CERN Super Proton Synchrotron. The main goals of the NA61/SHINE strong-interactions programme are to discover the critical point of strongly interacting matter as well as to study the properties of produced particles relevant for the search of the onset of deconfinement, more accurately the 1^{st} order phase transition between the state of hadronic matter and the QGP. In order to reach these goals, a study of hadron production properties is performed in nucleus-nucleus, proton-proton and proton-nucleus interactions as a function of collision energy and size of the colliding nuclei with a special emphasis on the strange-hadrons production properties.

NA61/SHINE research on strangeness production is in particular motivated by the Statistical Model of the Early Stage (SMES) [2], which predicts eminent indicators of the 1^{st} order phase transition in strangeness production due to different characteristics of its carriers in hadronic matter and QGP. Predicted observables for the heaviest colliding systems were witnessed by the NA49 experiment [3] at CERN SPS and afterwards confirmed by the STAR experiment [8] at RHIC. Only NA61/SHINE carried out a systematic scan also of lighter colliding systems to investigate possible other rapid transitions and to study the nature of the onset of deconfinement.

NA61/SHINE detection system [1] is a large acceptance hadron spectrometer based on a set of eight Time Projection Chambers complemented by Time-of-Flight detectors. This setup allows for precise momentum reconstruction and identification of charged particles. The high-resolution forward calorimeter, the Projectile Spectator Detector (PSD), measures energy flow around the beam direction, so-called Forward Energy (E_F), which in nucleus-nucleus reactions is primarily a measure of the number of the projectile spectators, i.e non-interacting projectile nucleons. Thus, the measurement of E_F can be related to the collision centrality. The incoming beam is monitored by a set of beam detectors, which allows to identify the beam particles and measure precisely their trajectories.

NA61/SHINE performed a two-dimensional scan in collision energy (13A-150A GeV/c) and system size (p+p, p+Pb, Be+Be, Ar+Sc, Xe+La, Pb+Pb) to study the phase diagram of strongly interacting matter.

2. Strangeness production in NA61/SHINE

NA61/SHINE studies the strangeness production in hadron-hadron and nucleus-nucleus collisions within the two-dimensional scan in collision energy and system size. Preliminary results on K^+ transverse momentum and rapidity spectra obtained in Ar+Sc collisions at five beam momenta are presented in Fig. 1. Transverse momentum spectra were parametrized and extrapolated with a function 1, which yields the inverse slope parameter T.

$$\frac{d^2n}{dp_t dy} = \frac{Sp_T}{T^2 + Tm_K} \exp\left(-\frac{\sqrt{p_T^2 + m + K^2} - m_K}{T}\right) \tag{1}$$

The rapidity spectra are described and extrapolated by a sum of symmetric Gaussian functions to obtain mesons' mean multiplicities.

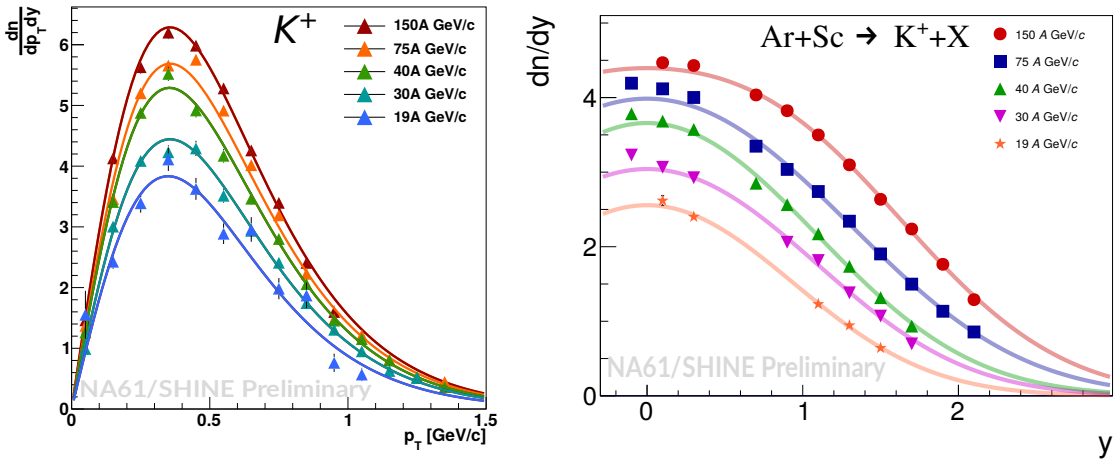

Figure 1: NA61/SHINE preliminary results on K^+ transverse momentum (*left*) and rapidity (*right*) spectra obtained from central Ar+Sc collisions in the SPS energy range. Only statistical uncertainties are shown.

Fig. 2 presents the energy dependence of the inverse slope parameter of m_T spectra of charged kaons. A plateau structure in the energy dependence of the inverse slope parameter observed in

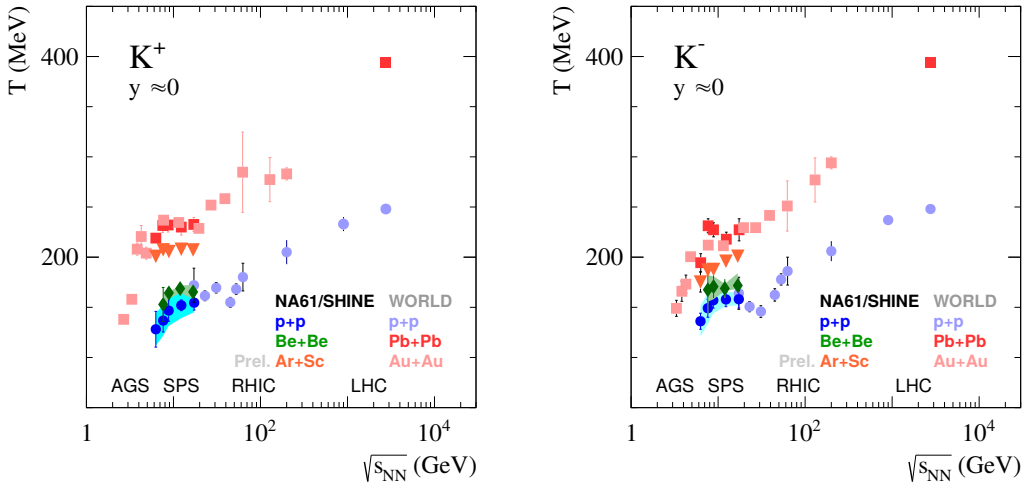

Figure 2: The energy dependence of the inverse slope parameter of K^+ (*left*) and K^- (*right*) m_T spectra for the central Ar+Sc collisions as well as p+p and central Be+Be, Au+Au and Pb+Pb collisions [3–13].

heavy-ion collisions was interpreted within the SMES due to the coexistence of the QGP and hadron gas. The NA61/SHINE results from Ar+Sc collisions as well as p+p and Be+Be interactions exhibit a qualitatively similar energy dependence (step) for the inverse slope parameter. Fig. 3 shows the multiplicity ratio of positively charged kaons to pions at mid-rapidity (*left*) and in 4π acceptance (*right*). In both cases results from central Ar+Sc collisions do not reveal a horn structure similar to the one observed in Au+Au/Pb+Pb collisions, which was attributed to the onset of deconfinement [3]. Surprisingly, K^+/π^+ and $\langle K^+\rangle/\langle\pi^+\rangle$ ratios measured in central Ar+Sc collisions at high SPS energies are close to the ones from Pb+Pb/Au+Au collisions. With a decrease of the collision energy the

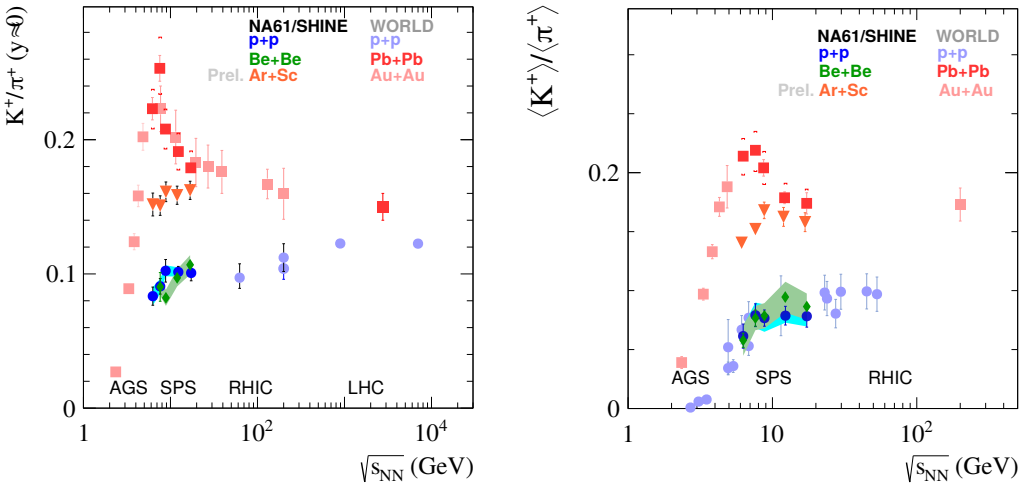

Figure 3: The energy dependence of the K^+/π^+ particle yields ratio at mid-rapidity (*left*) and full acceptance (*right*) for the central Ar+Sc collisions as well as p+p and central Be+Be, Au+Au and Pb+Pb collisions [3–13].

ratios are set between the results from Pb+Pb/Au+Au and Be+Be/p+p collisions. Such a behaviour stands in contradiction to the prediction of SMES [14] and statistical Hadron-Resonance Gas (HRG) model [15]. Moreover, these results in combination with the results on the energy dependance of the inverse slope parameter might be a hint for existence of some transition effects in this collision energy region of more complicated nature than the 1^{st} [2] order phase transition between hadronic matter and QGP. Detailed measurements in the region of light-nuclei would be useful to study the complexity of the transition region.

The high-statistics sample of the p+p interactions measured at beam momentum of 158 GeV/c resulted in a fruitful study of the multi-strange hadrons production. The left panel of Fig. 4 presents rapidity spectra of Ξ^- and $\overline{\Xi^+}$ hadrons [16]. A strong suppression of $\overline{\Xi^+}$ production was observed, as $\overline{\Xi^+}/\Xi^-$ yields ratio is $0.24 \pm 0.01 \pm 0.05$. The right panel of Fig. 4 presents rapidity spectra of $\Xi^0(1530)$ and $\overline{\Xi^0}(1530)$ hadrons [17]. The suppression of the $\overline{\Xi^0}$ production is slightly weaker, as the $\overline{\Xi^0}/\Xi^0$ yields ratio is $0.294 \pm 0.017 \pm 0.047$. Presented results are the only ones available for p+p interactions in the SPS energy range.

Charged Ξ hyperon mean multiplicities measured by NA61/SHINE in inelastic p+p interactions were used to calculate the enhancement factors, E_S, as a ratio of rapidity density for $\Xi^-(\overline{\Xi^+})$ production in mid-rapidity in nucleus-nucleus collisions per $\langle N_W \rangle$ divided by the corresponding value from p+p interactions [16] at a given collision energy:

$$E_S = \frac{2}{\langle N_W \rangle} \frac{dn/dy(A+A)}{dn/dy(p+p)}. \tag{2}$$

The enhancement factors are presented in Fig. 5 as a function of average number of wounded nucleons. The enhancement factors, based on A+A measurements by NA49 and p+p results from NA61/SHINE, increase approximately linearly from 3.5 in C+C to 9 in central Pb+Pb collisions [18]. This result is compared to data from the NA57 experiment at the SPS [19], the STAR experiment at the RHIC [20] and the ALICE experiment at the LHC [21]. The NA61/SHINE results on $\Xi^{\pm}$

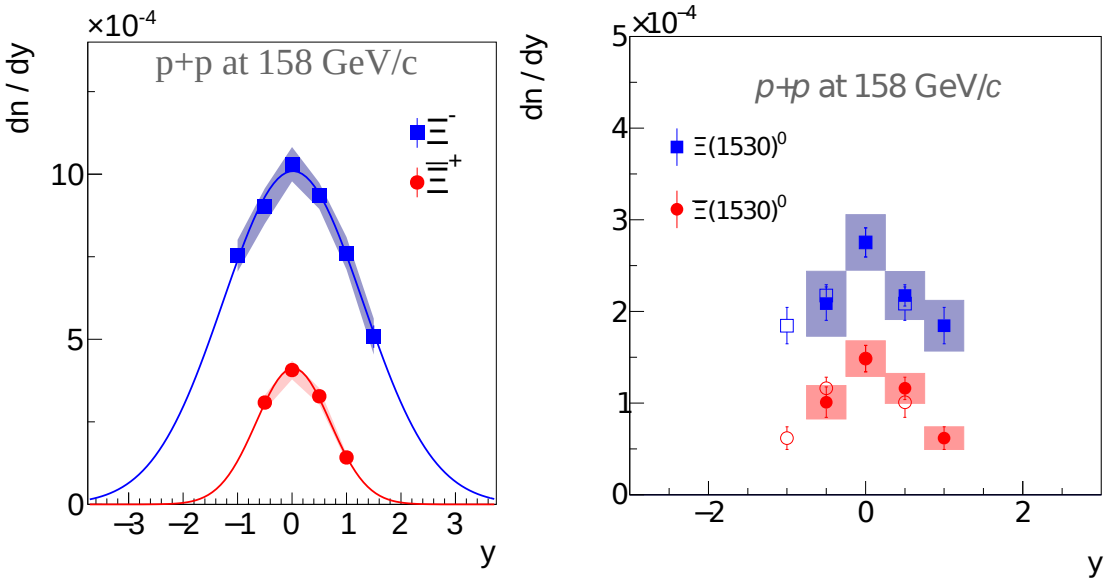

Figure 4: Rapidity spectra of Ξ^- and $\overline{\Xi^+}$ [16] (*left*) as well as $\Xi^0(1530)$ and $\overline{\Xi^0}(1530)$ [17] produced in inelastic p+p interactions at 158 GeV/c.

production in p+p interactions created a new reference for the recalculation of the strangeness enhancement observed in the NA57 p+Be and A+A data.

Pentaquark states have been extensively investigated theoretically in the context of the constituent quark model [22–25]. Previous possible evidence from the NA49 collaboration of the existence of a narrow $\Xi^-\pi^-$ baryon resonance in p+p interactions [27] is not confirmed with almost 10 times greater event statistics measured by NA61/SHINE. Fig. 6 presents the sum of the $\Xi^-\pi^-$, $\Xi^-\pi^+$, $\Xi^+\pi^-$, and $\Xi^+\pi^+$ invariant mass spectra [26]. The vertical dashed grey line shows the theoretically predicted $\Xi^{--}_{3/2}$ mass from the model [28]. The black rectangle indicates the mass window in which the NA49 collaboration observed an enhancement with a significance of 5.6 standard deviations [27]. Such signal was not observed in any of the derived invariant mass distributions ($\Xi^-\pi^-$, $\Xi^-\pi^+$, $\Xi^+\pi^-$, $\Xi^+\pi^+$) nor summarized one.

Moreover, presented results on the production of Ξ^-, $\overline{\Xi^+}$, $\Xi^0(1530)$ and $\overline{\Xi^0}(1530)$ multi-strange hadrons were compared with predictions of UrQMD 3.4, Epos 1.99, Ampt 1.26, Smash 1.6 and Phsd. The comparison exposed striking discrepancy between experimental results and model predictions on strangeness production in p+p interactions at top SPS energy. More details on these comparison can be found in [16] and [17].

3. Summary

This contribution focuses on recent results from the NA61/SHINE on strangeness production and the onset of deconfinement of the 1^{st} order phase transition. Preliminary results on charged K meson spectra were presented along with energy and system-size dependence of the onset of

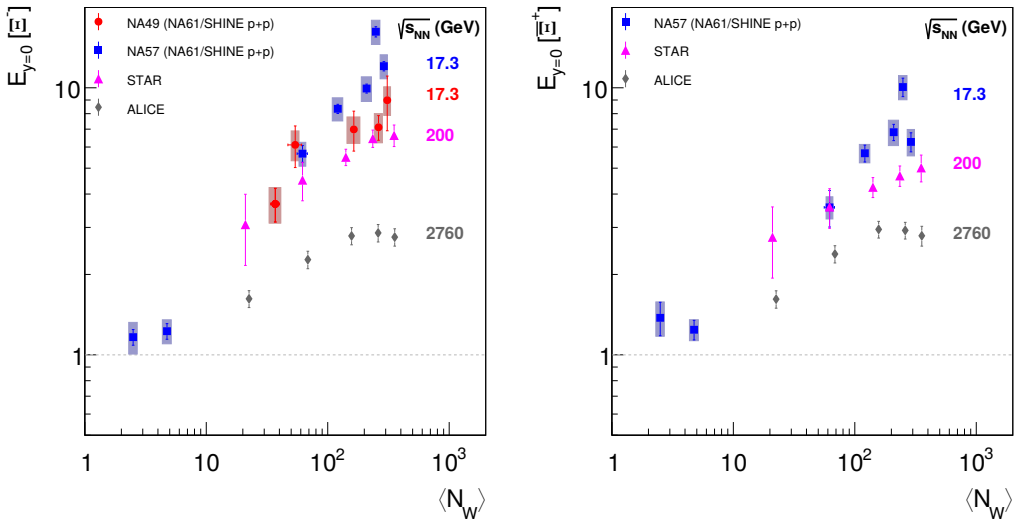

Figure 5: The strangeness enhancement factor E at the mid-rapidity as a function of average number of wounded nucleons $\langle N_W \rangle$ calculated as a ratio of rapidity density for Ξ^- (*left*) and $\overline{\Xi^+}$ production (*right*) in nucleus-nucleus interactions per $\langle N_W \rangle$ divided by the corresponding value for p+p interactions [16].

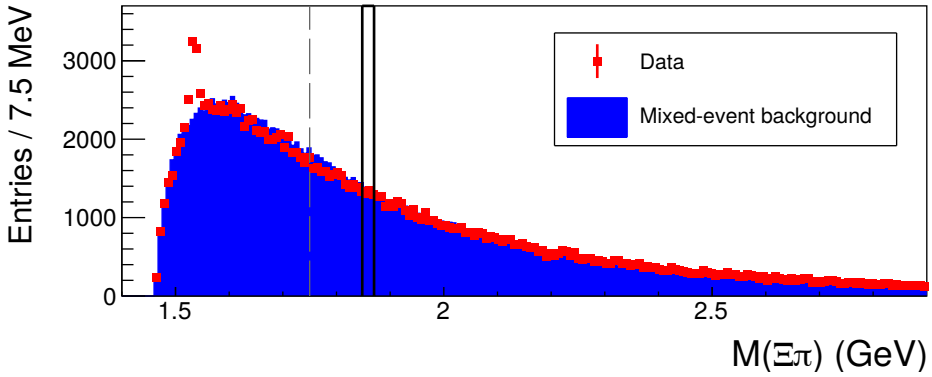

Figure 6: The sum of the $\Xi^-\pi^-$, $\Xi^-\pi^+$, $\Xi^+\pi^-$, and $\Xi^+\pi^+$ invariant mass spectra [26]. The vertical dashed grey line shows the theoretically predicted $\Xi^{--}_{3/2}$ mass from the model [28]. The black rectangle indicates the mass window in which the NA49 collaboration observed an enhancement with a significance of 5.6 standard deviations [27]. A narrow peak of the $\Xi^0(1530)$ state is observed.

deconfinement observables - K^+/π^+ ratio and inverse slope parameter of m_T spectra. No indication of the 1$^{\text{st}}$ order phase transition was observed in the Ar+Sc results. However, unexpected system-size dependences of K^+/π^+ and $\langle K^+ \rangle / \langle \pi^+ \rangle$, contradicting predictions of SMES and statistical HRG model were observed. Moreover, the unique results on Ξ^-, $\overline{\Xi^+}$, $\Xi^0(1530)$ and $\overline{\Xi^0}(1530)$ multi-strange hadrons production in p+p interactions at 158 GeV/c were discussed. The NA61/SHINE results on $\Xi^\pm$ production in p+p interactions created a new baseline reference for the recalculation of the strangeness enhancement observed in p+Be and A+A data at the top SPS energy. The NA61/SHINE results on p+p interactions at 158 GeV/c show no indication for theoretically predicted $\Xi^{--}_{3/2}$ pentaquark.

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