NEWS FROM THE STRONG INTERACTIONS PROGRAM OF NA61/SHINE* **

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The NA61/SHINE experimental physics program focuses on searching for the critical point and studying the properties of the onset of deconfinement in the strongly interacting matter. A two-dimensional scan is performed by varying the beam momentum (from $13A$ to $150/158A$ GeV/c) and the system size (from $p+p$ to Pb+Pb) of the collided nuclei. This contribution presents the most recent results from the NA61/SHINE strong interactions program and includes future data-taking and analysis plans.

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1. Introduction

The NA61/SHINE is a large acceptance, fixed target experiment, which uses eight Time Projection Chambers and a Time-of-Flight detector to identify the produced particles and measure their momenta. The collision centrality is determined based on measurements from the high-resolution forward calorimeter, the Projectile Spectator Detector (PSD).

The large variety of beams and targets allowed to perform two-dimensional scan by varying the beam momentum (from $13A$ to $150/158A$ GeV/c) and the system size (from $p+p$ to Pb+Pb) of the collided nuclei. The main goals of the strong interactions program are searching for the critical point of strongly interacting matter and studying the properties of the onset of deconfinement.

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2. Study of the properties of the onset of deconfinement

The Statistical Model of the Early Stage [1] assumes a first-order phase transition from the hadronic matter to the Quark–Gluon Plasma (QGP) between top AGS ($\sqrt{s_{NN}} \approx 5$ GeV) and top SPS ($\sqrt{s_{NN}} \approx 17$ GeV) energies.

One of the predicted signatures of the deconfinement transition is horn, a non-monotonic change of K^+/π^+ ratio as a function of collision energy. The horn structure was observed by the NA49 experiment in central Pb+Pb collisions [2]. The NA61/SHINE extends the set of experimental data by p+p, Be+Be, and Ar+Sc collisions (Xe+La and Pb+Pb results are expected soon). The compilation of NA61/SHINE and world data is shown in Fig. 1. The plateau-like structures are visible in $p + p$ and Be+Be interactions at SPS energies. The K^+/π^+ ratio for Ar+Sc collisions is located between p+p and Pb+Pb data but no horn-like structure is visible.

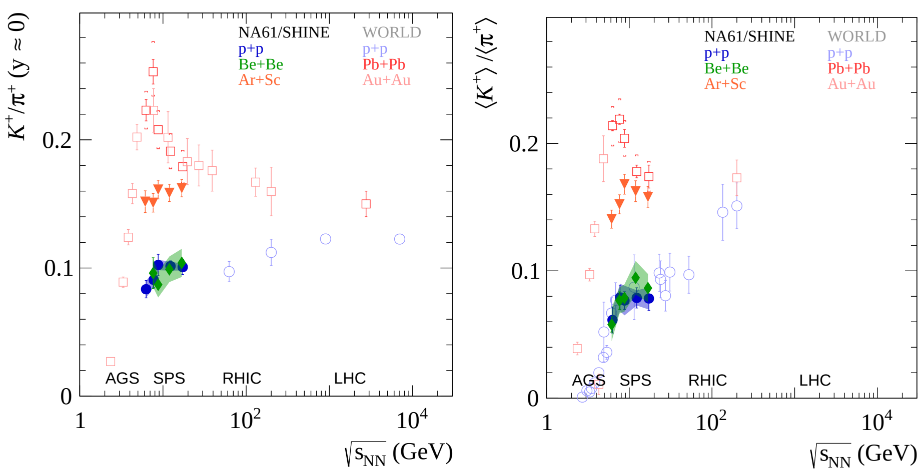

Fig. 1. The energy dependence of the K^+/π^+ particle yields ratio at mid-rapidity (left) and full acceptance (right) for the 20% most central Be+Be, central Pb+Pb, and Au+Au collisions, as well as inelastic $p + p$ interactions. The NA61/SHINE $p + p$ and Be+Be results are taken from Refs. [3, 4], whereas Ar+Sc points [5] are preliminary.

The K^+/π^+ ratio at mid-rapidity and inverse slope parameter T fitted to the transverse momentum spectra of K^+ mesons as a function of system size are shown in Fig. 2. All plots show similar, threshold-like behavior, which cannot be reproduced by any of the considered models. The observed rapid change of hadron production properties that starts when moving from Be+Be to Ar+Sc collisions at top SPS energies hints at the beginning of the creation of large clusters of strongly interacting matter called *the onset of fireball*.

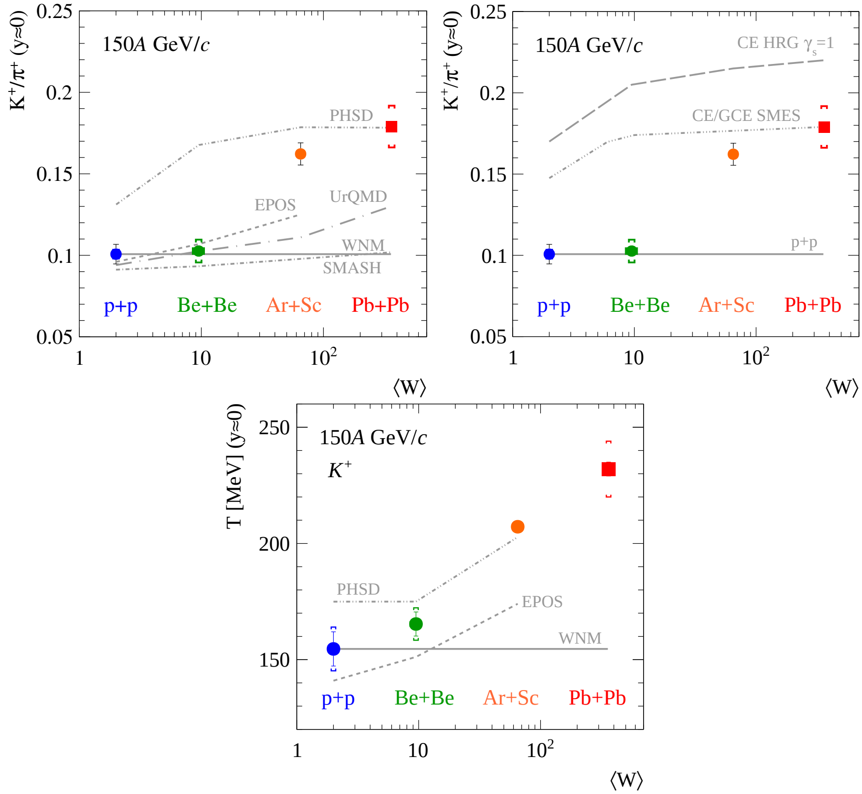

Fig. 2. Top: The system-size dependence of the K^+/π^+ ratio at mid-rapidity measured in NA61/SHINE $p+p$, Be+Be, Ar+Sc, and NA49 Pb+Pb collisions at $150A$ (Be+Be, Ar+Sc) or $158A$ ($p+p$, Pb+Pb) GeV$/c$ compared with dynamical (top left) and statistical (top right) models. Bottom: The inverse slope parameter T, fitted to K^+ transverse momentum spectra at the similar collision energy [5]. The NA61/SHINE $p+p$ and Be+Be results are taken from Refs. [3, 4], whereas Ar+Sc points [5] are preliminary.

3. Search for the critical point

The critical point (CP) signal should be visible as a non-monotonic dependence of various fluctuation/correlation measures. Figure 3 shows the energy dependence of fluctuations for negatively charged hadrons (h^-) and net-electric charge ($h^+ - h^-$), measured in $p+p$, Be+Be, and Ar+Sc collisions. The comparison of fluctuations in systems of different sizes is possible using intensive quantities. For h^-, one considers ratios of cumulants $\kappa_2/\kappa_1[h^-]$ (scaled variance), $\kappa_3/\kappa_2[h^-]$ (scaled skewness), and $\kappa_4/\kappa_2[h^-]$ (scaled kurtosis) (reference value of 1 is defined by the Poisson distribution). In the case of net-electric charge, the first two ratios are slightly modified to keep the reference value (1 for the Skellam distribution): $\kappa_2[h^+ - h^-]/(\kappa_1[h^+] + \kappa_1[h^-])$, $\kappa_3/\kappa_1[h^+ - h^-]$. Figure 3 shows that in the case of h^-, only the scaled variance presents significant differences between heavier and lighter systems. In the case of net-electric charge, the scaled skewness and scaled kurtosis suggest a non-monotonic behavior, within sizeable systematic uncertainties (current subject of analysis).

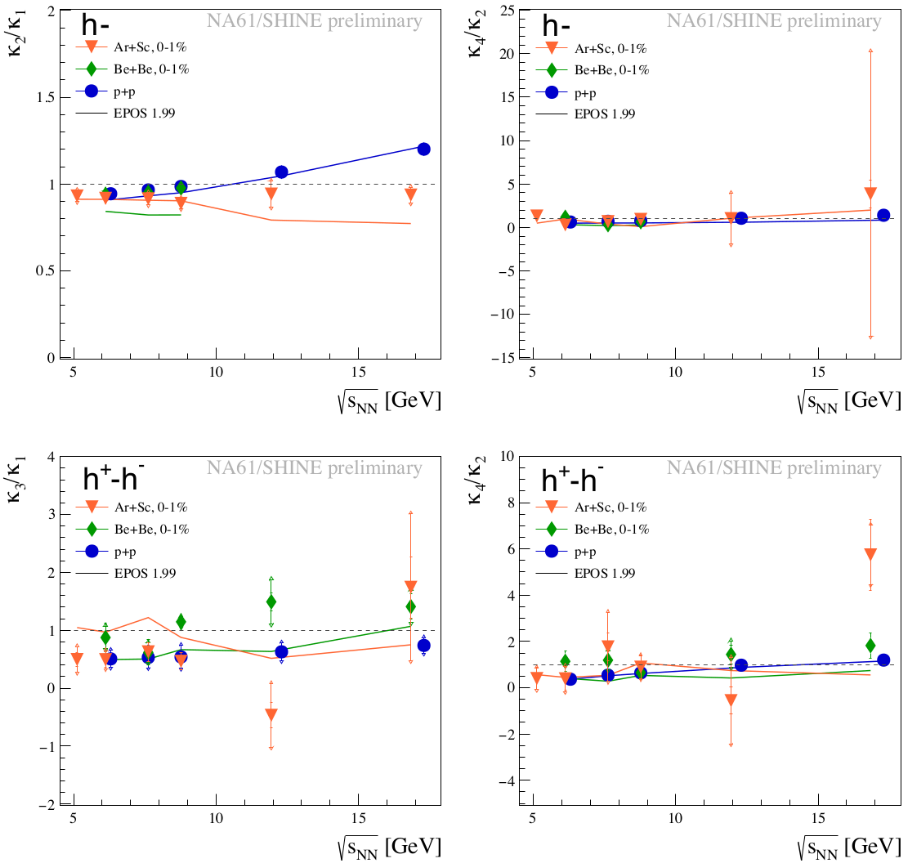

Fig. 3. Preliminary results on the energy dependence of fluctuations for negatively charged hadrons (top) and net-electric charge (bottom) in $p+p$, Be+Be, and Ar+Sc collisions.

Another possible tool for the search for CP is an intermittency analysis. Generally, the scaled factorial moments F_r are calculated based on the counted particles in cells in transverse momentum space [6]. If the system freezes out in the vicinity of the critical point, the scaled factorial moments should reveal a power-law dependence: $F_r(M) \sim M^{\phi_r}$, where M is the number of cells [7]. In this analysis, the statistically-independent points are used and instead of the $(p_x,\ p_y)$ cells, the cumulative variables are used to remove the dependence of the moments on the momentum distribution [8]. Preliminary results on $F_2(M)$ of mid-rapidity protons measured in the 0–20% most central Ar+Sc collisions at 150A GeV/c and 0–10% most central Pb+Pb collisions at 13A GeV/c are presented in Fig. 4 (top panels). The negatively charged hadron intermittency in 0–10% central Pb+Pb collisions at 30A GeV/c beam momentum up to the fourth scaled factorial moment is also shown in Fig. 4 (bottom panel). The measured $F_2(M)$ of protons for Ar+Sc at 150A GeV/c and Pb+Pb at 13A GeV/c, as well as $F_2(M)$, $F_3(M)$, and $F_4(M)$ of negatively charged hadrons in Pb+Pb at 30A GeV/c show no indication for power-law increase with a bin size which could indicate CP.

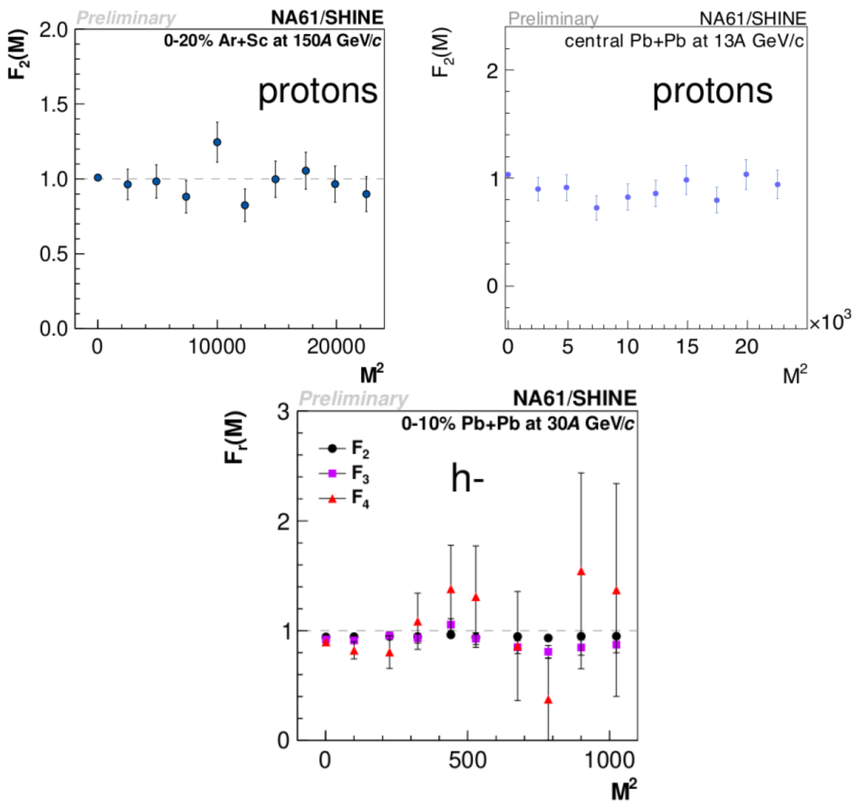

Fig. 4. Top: Preliminary results on intermittency analysis of mid-rapidity protons for the 0–20% most central Ar+Sc collisions at 150A GeV/c (top left) and 0–10% most central Pb+Pb collisions at 13A GeV/c (top right). Bottom: Preliminary results on intermittency analysis of mid-rapidity negatively charged hadrons for the 0–10% most central Pb+Pb collisions at 30A GeV/c.

The last topic connected with searching for CP are symmetric Lévy HBT correlations for the same-charge pion pairs in central Be+Be and Ar+Sc collisions at 150A GeV/c beam momentum. Usually, the correlation function assumes a Gaussian source but it can be generalized by the Lévy-shaped formula, $C(q) = 1 + \lambda\,\mathrm{e}^{-(qR)^{\alpha}}$, where the parameter α describes the shape of the source (for $\alpha = 2$, the source is Gaussian, for $\alpha = 1$, the source is described by the Cauchy distribution). For the critical system, the α parameter should be equal to 0.5 according to the prediction of the 3D Ising model [9]. The α parameter as a function of transverse mass is shown in Fig. 5. The results do not indicate the critical point in Be+Be and Ar+Sc collisions. The values of α parameters are between Gaussian and Cauchy shapes and might be a sign of anomalous diffusion. The R Lévy scale parameter is also presented in Fig. 5 and describes the length of homogeneity. The visible transverse mass dependence can be a sign of transverse flow.

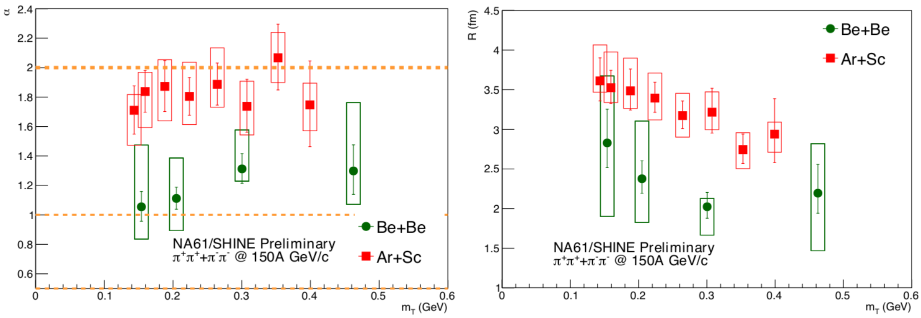

Fig. 5. Preliminary results on the symmetric Lévy HBT correlations for the same-charge pion pairs in central Be+Be and Ar+Sc collisions at 150A GeV/c beam momentum. The panels show the dependence of the α (left) and R (right) parameters on the transverse mass of the pair.

4. New data on hadron spectra in $p + p$ reactions

Finally, NA61/SHINE provides new and unique results on strangeness production in $p + p$ interactions. The spectra of strange mesons and multi-strange hyperons were measured with unprecedented precision at the SPS energy range. Figure 6 presents the rapidity distributions of $K^*(892)^0$ [10] and K^0_{S} mesons (Ref. [11] and preliminary results) produced in inelastic $p+p$ interactions at the SPS energies.

The high-statistics data of $p + p$ collisions at 158 GeV/c allowed the more challenging measurement of $\Xi(1530)^0$ and $\bar{\Xi}(1530)^0$ hyperon production [12], which are the only such results at the SPS energy. The first two-dimensional spectra of $\Xi(1530)^0$ and $\bar{\Xi}(1530)^0$ [12] in y and p_{T} bins are presented in Fig. 7.

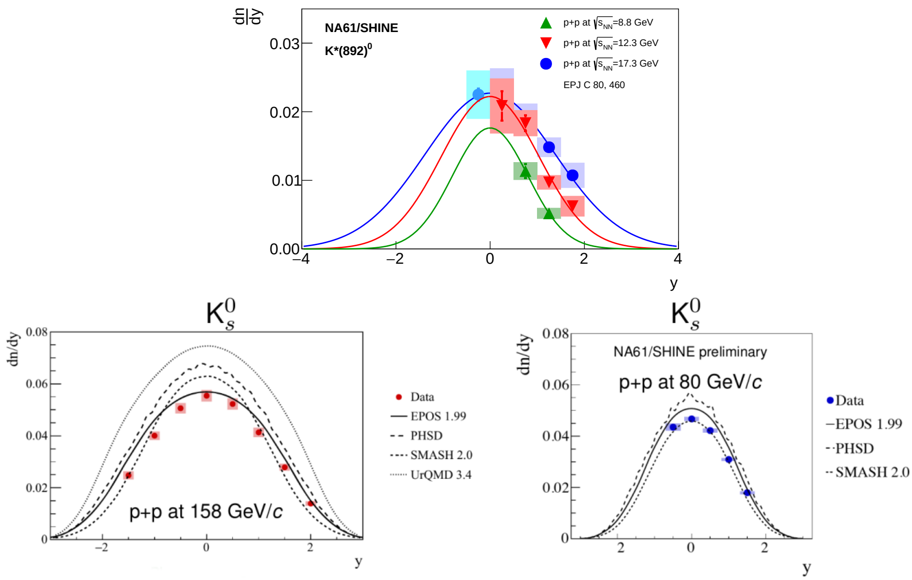

Fig. 6. Rapidity distributions of $K^*(892)^0$ (top) produced in inelastic $p+p$ interactions at 40–158 GeV/c [10] and K^0_S produced in inelastic $p+p$ collisions at 158 GeV/c [11] (bottom left) and 80 GeV/c (bottom right). K^0_S results at 80 GeV/c are preliminary.

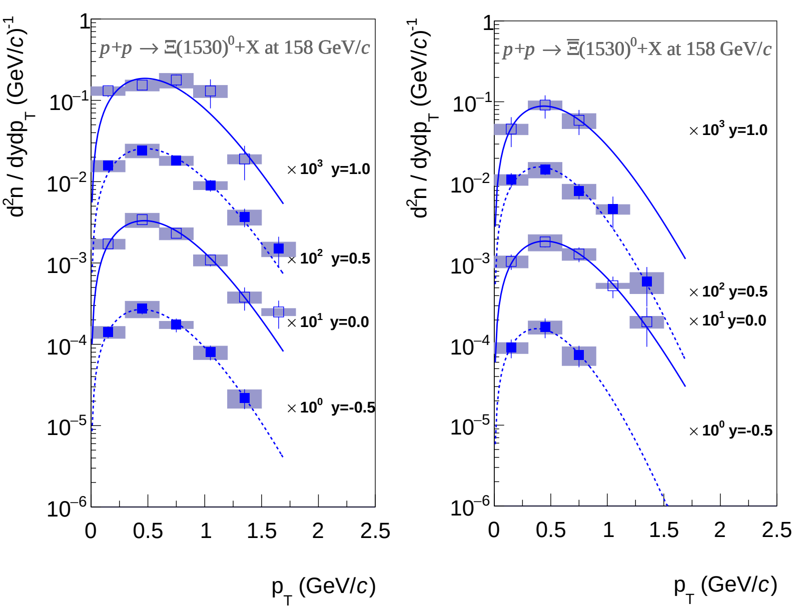

Fig. 7. Transverse momentum spectra in rapidity intervals of $\Xi(1530)^0$ and $\bar{\Xi}(1530)^0$ production in inelastic $p+p$ collisions at 158 GeV/c [12].

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