RECENT RESULTS FROM NA61/SHINE*

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The research programme of the NA61 Collaboration covers a wide range of hadronic physics in the CERN SPS energy range, encompassing measurements of hadron–hadron, hadron–nucleus as well as nucleus–nucleus collisions. The latter are analysed to better understand the properties of hot and dense nuclear matter. In this paper, recent results of particle production properties as well as event-by-event fluctuations in proton–proton, as signatures of the critical point of strongly interacting matter, in Be+Be and Ar+Sc interactions at beam energies of $19A/20A$, $30A$, $40A$, $75A/80A$ and $158A$ GeV/c are presented.

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1. The NA61/SHINE facility

The NA61/SHINE detector [1] is a large acceptance hadron spectrometer with excellent capabilities in charged particle momentum measurements and identification by a set of eight Time Projection Chambers as well as Time-of-Flight detectors. The high resolution forward calorimeter, the Projectile Spectator Detector (PSD), measures energy flow around the beam direction, which in nucleus–nucleus reactions is primarily a measure of the number of projectile spectator (non-interacted) nucleons and is thus related to the violence (centrality) of the collision. A set of beam detectors identifies beam particles and measures precisely their trajectories.

NA61/SHINE performed a two-dimensional scan in collision energy ($13A$–$150A$ GeV/c and a system size (p+p, Be+Be, Ar+Sc, Xe+La, Pb+Pb) to study the phase diagram of strongly interacting matter. The main goals of NA61/SHINE are the search for the critical point and a study of the onset of deconfinemnet.

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2. Study of the onset of deconfinement

2.1. Particle production properties

The Statistical Model of the Early Stage (SMES) [2] predicts a 1$^{\rm st}$ order phase transition from the quark–gluon plasma (QGP) to a hadron matter phase between top AGS and top SPS energies. In the transition region, constant temperature and pressure in the mixed phase and an increase of the number of internal degrees of freedom is expected.

A plateau ("step") in the energy dependence of the inverse slope parameter T was observed by the NA49 experiment in Pb+Pb collisions for $m_{\rm T}$ spectra of $K^{\pm}$. It was expected for the onset of deconfinement due to the presence of a mixed phase of hadron gas (HRG) and quark–gluon plasma. In $p+p$ interactions at SPS energies, the inverse slope parameter T of $m_{\rm T}$ spectra shows qualitatively similar energy dependence as in central Pb+Pb collisions ("step"), and such a behaviour seems to emerge also in Be+Be reactions, as is visible in Fig. 1. The values of the T parameter in Be+Be collisions are slightly above those in $p+p$ interactions. The T parameter in Ar+Sc reactions is found between those in $p+p$/Be+Be and Pb+Pb collisions.

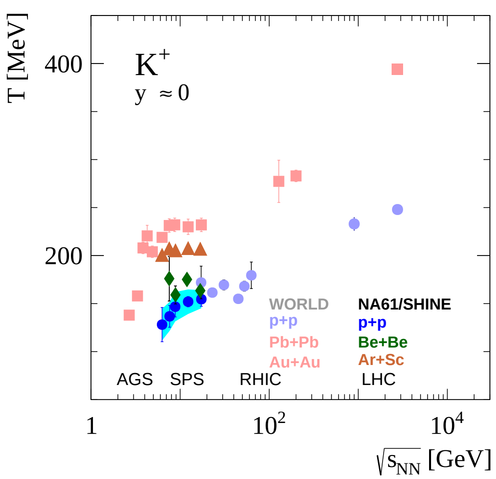

Fig. 1. (Colour on-line) Inverse slope parameter T of $m_{\rm T}$ spectra of K^- as a function of collision energy. Most results are shown with statistical uncertainties only. For the $p+p$ data, the grey/light blue band indicates systematic uncertainties.

Rapid changes of the ratios K^+/π^+ at mid-rapidity and $\langle K^+\rangle / \langle\pi^+\rangle$ as a function of collision energy ("horn") were observed in Pb+Pb collisions by the NA49 experiment. These were predicted by the SMES model as a signature of the onset of deconfinement. These two ratios together with new NA61/SHINE results from Be+Be and Ar+Sc collisions are shown in Fig. 2.

A plateau-like structure is visible in p+p interactions. The ratio K^+/π^+ at mid-rapidity as well as the ratio of total yields from Be+Be collisions is close to the p+p measurements. For the five analysed energies of Ar+Sc collisions, the ratio K^+/π^+ at mid-rapidity and $\langle K^+\rangle / \langle \pi^+\rangle$ is higher than in p+p collisions but shows a qualitatively similar energy dependence — no horn structure visible.

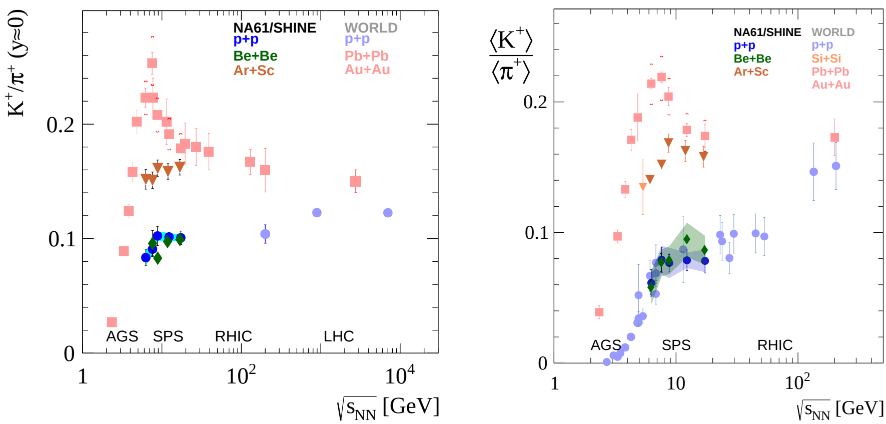

Fig. 2. Ratio of yields K^+/π^+ at mid-rapidity and the ratio of total yields $\langle K^+\rangle / \langle \pi^+\rangle$ produced in p+p, Be+Be and Pb+Pb collisions as a function of collision energy.

2.2. Flow

Directed flow v_1 was considered to be sensitive to the first order phase transition (strong softening of the Equation of State) [3–5]. The expected effect is a non-monotonic behaviour (change from positive to negative and again to positive values) of proton $\mathrm{d}v_1/\mathrm{d}y$ as a function of beam energy. This effect is usually referred to as collapse of proton flow. The NA49 experiment measured anti-flow of protons at mid-rapidity [6]. A negative value of $\mathrm{d}v_1/\mathrm{d}y$ was observed in peripheral Pb+Pb collisions at $40A$ GeV/c beam momentum ($\sqrt{s_{NN}} = 8.8$ GeV).

In 2018, the NA61/SHINE experiment reported the first results on anisotropic flow, measured in centrality-selected Pb+Pb collisions at $30A$ GeV/c beam momentum ($\sqrt{s_{NN}} = 7.6$ GeV). According to the *horn* structure in the energy dependence of the K^+/π^+ ratio in Pb+Pb collisions, this is the energy of the onset of deconfinement. Therefore, studying the centrality dependence of flow at this specific energy may allow to better understand the properties of the onset of deconfinement.

The NA61/SHINE fixed target setup allows tracking and particle identification over a wide rapidity range. Flow coefficients were measured relative to the spectator plane estimated with the Projectile Spectator Detector (PSD), which is unique for NA61. Preliminary results on the centrality dependence of $\mathrm{d}v_1/\mathrm{d}y$ at mid-rapidity, measured in Pb+Pb collisions at $30A$ GeV/c, are presented in Fig. 3 (left). One sees that the slope of pion v_1 is always negative. In contrast, the slope of proton v_1 changes sign for centrality of about 50%. Recently, preliminary results of directed flow for Pb+Pb collisions at $13A$ were released [7]. Proton directed flow as a function of rapidity is shown in Fig. 3 (right). The results do not show evidence for the collapse of proton directed flow in Pb+Pb interactions at $13A$ GeV/c.

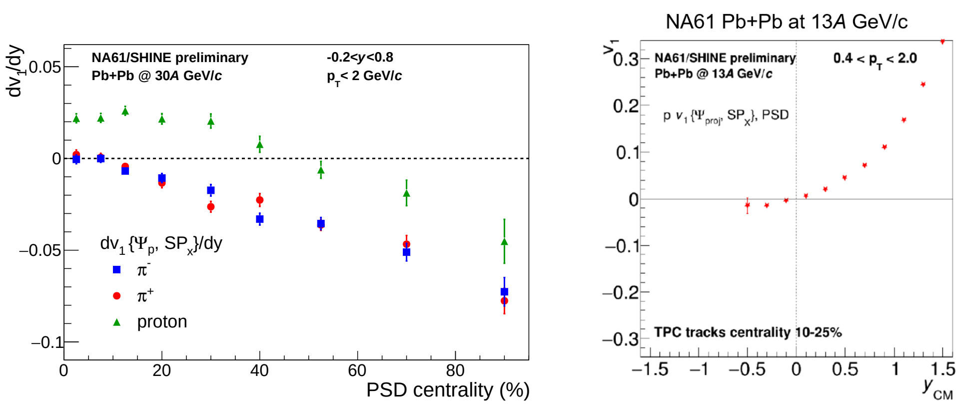

Fig. 3. Preliminary results on centrality dependence of $\mathrm{d}v_1/\mathrm{d}y$ at mid-rapidity measured in Pb+Pb collisions at $30A$ GeV/c (left) and v_1 as the function of rapidity measured in Pb+Pb at $13A$ GeV/c (right).

3. Search for the critical point

A critical point of strongly interacting matter is expected to lead to enhanced fluctuations of multiplicity and transverse momentum. For their study, NA61/SHINE uses the *strongly intensive* measures $\Delta[P_{\mathrm{T}}, N]$ and $\Sigma[P_{\mathrm{T}}, N]$, see Ref. [8]. In the Wounded Nucleon Model (WNM), they depend neither on the number of wounded nucleons (W) nor on fluctuations of W. In the Grand Canonical Ensemble, they do not depend on volume and volume fluctuations. Moreover, $\Delta[P_{\mathrm{T}}, N]$ and $\Sigma[P_{\mathrm{T}}, N]$ have two reference values, namely they are equal to zero in the case of no fluctuations and one in the case of independent particle production. The $\Sigma[P_{\mathrm{T}}, N]$ measure at $150A/158A$ GeV/c from the NA61/SHINE and NA49 experiments as a function of system size (wounded nucleons) is shown in Fig. 4 (left). The NA49 and NA61/SHINE measurements show consistent trends. Finally, NA61/SHINE results for the NA61/SHINE acceptance for p+p, Be+Be and Ar+Sc collisions are presented in Fig. 4 (right). So far, there are no prominent structures observed which could be related to a critical point.

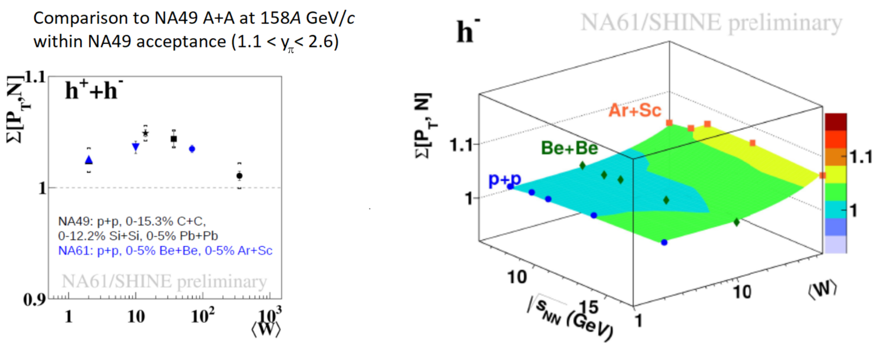

Fig. 4. (Colour on-line) $\Sigma[P_{\mathrm{T}}, N]$ for all charged hadrons ($h^+ + h^-$) from the NA61/SHINE and NA49 experiments as a function of the system size at $150A/158A$ GeV/c (left) and $\Sigma[P_{\mathrm{T}}, N]$ for negatively charged hadrons in inelastic $p+p$ (blue squares), 0–5% Be+Be (green diamonds), and 0–5% Ar+Sc (orange squares) collisions obtained by NA61/SHINE. For NA61/SHINE, only statistical uncertainties are shown. All the NA61/SHINE results are preliminary.

4. NA61/SHINE future physics programme

NA61/SHINE plans precise measurements of hadron and nuclear fragment production properties in reactions induced by hadron and ion beams after the Long Shutdown 2 [9, 10]. The measurements are requested by heavy ion, cosmic ray and neutrino communities and they will include:

— measurements of charm hadron production in Pb+Pb collisions for heavy-ion physics,

— measurements of nuclear fragmentation cross sections for cosmic ray physics,

— measurements of hadron production induced by proton and kaon beams for neutrino physics.

NA61/SHINE is the only experiment which will conduct such measurements in the near future in the CERN SPS beam momentum range.

The objective of charm hadron production measurements in Pb+Pb collisions is to obtain the first data on the mean number of $c\bar{c}$ pairs produced in the full phase space in heavy-ion collisions. Moreover, first results on the collision energy and system size dependence will be provided. This, in particular, should significantly help to answer the questions:

— What is the mechanism of open charm production?

— How does the onset of deconfinement impact open charm production?

— How does the formation of a quark–gluon plasma impact J/ψ production?

The objective of nuclear fragmentation cross-section measurements is to provide high-precision data needed for the interpretation of results from current-generation cosmic ray experiments.

The objectives of new hadron production measurements for neutrino physics are to further improve the precision of hadron production measurements for the currently used neutrino experiments replica targets.

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