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Recent Results from the Strong Interaction Program of the NA61/SHINE Experiment and Physics Plans Beyond 2020

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The NA61/SHINE experiment at the CERN SPS studies hadron production properties in hadron-nucleus and nucleus-nucleus collisions. The experiment performs unique measurements for physics of strong interactions as well as important measurements for neutrino and cosmic-ray physics. Results from the strong interaction programme indicate a threshold for formation of large clusters interpreted as the onset of fireball. A scaled-factorial-moment analysis of the proton density fluctuations in Ar+Sc collisions at 150A GeV/c shows an intermittency signal, which may be a first trace of critical behavior. The main objective of the future NA61/SHINE program is to obtain high-precision data on charm hadron production. This new program is planed to start after 2020 and requires significant upgrades of the NA61/SHINE detector setup. Besides the construction of a large accectance vertex detector, a 10-fold increase of the event recording rate is foreseen.

KEYWORDS: QCD matter, phase transitions, critical point, open charm

1. Introduction

NA61/SHINE ("the SPS Heavy Ion and Neutrino Experiment") is an experiment at the CERN Super-Proton-Synchrotron (SPS) measuring the hadron production in hadron-nucleus and nucleus-nucleus collisions with a large acceptance detector system [1]. It has used a similar experimental fixed target setup as NA49 but with extended research programme. The measurements performed for a wide range of reactions provide valuable data for studying the properties of hadronic matter under extreme conditions. They also provide precise results on hadron production for determining the neutrino flux in long-baseline neutrino experiments and for more reliable simulations of cosmic-ray showers. The primary aim of the strong interaction programme is the investigation of the transition from hadron gas to quark-gluon plasma and the search for the predicted critical point. A scan of the phase diagram of strongly interacting matter was done by changing energy and size of the collision system (from p+p to Pb+Pb in the beam momentum range 13A ÷ 150A GeV/c). Various observables, e.g. quantities measuring event-to-event fluctuations of the particle multiplicity, which are expected to reveal the occurrence of a phase transition or of critical behavior are examined. The experimental program has recently been extended by measurements of charm hadron production in nucleus-nucleus collisions, which are expected to provide an additional insight into the phase transition behavior of hadronic matter. For this purpose, a vertex detector was constructed to meet the challenges of open charm measurements.

2. Recent results

2.1 Onset of deconfinement

The discovery of the onset of deconfinement was achieved by the NA49 Collaboration [2]. The observed maximum (horn) in the excitation function of the K^+/π^+ ratio measured at mid-rapidity in Pb+Pb reactions, located at the low CERN SPS energies, has been interpreted as an evidence of the onset of deconfinement. Such an interpretation is based on predictions of the Statistical Model of the Early Stage (SMES), which contains a first-order phase transition from the hadron gas to the quark-gluon plasma [3]. A collection of available data on K^+/π^+ supplemented by recent NA61/SHINE results from p+p and Be+Be collisions is presented in Fig. 1(a). New data suggest a somewhat similar bend-like structure also for the relatively small system produced in proton-proton reactions. The position of the heavy-ion "horn" and the p + p "bend" coincide in terms of the collision energy $\sqrt{s_{NN}}$. Additionally to above results, Fig. 1(b) displays the energy dependence of the inverse slope T, obtained from the fit to the produced negative kaon m_T distribution. In central heavy ion collisions this "apparent temperature " displays a characteristic step-like behavior which can be interpreted as a strong interaction analogy to the ice-water phase transition. A trace of the step structure is also observed in the light p+p and Be+Be systems. The origin of this effect and its possible relation to the deconfinement transition remains to be clarified.

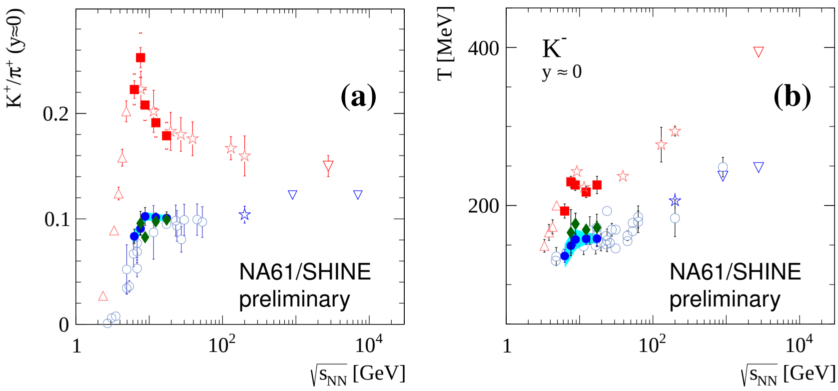

Fig. 1. (a) Compilation of experimental data on the K^+/π^+ ratio and (b) inverse slope parameter T for K^- in Pb+Pb, Au + Au (red), Be+Be (green) and p + p (blue) reactions. Closed symbols mark NA49 and NA61/SHINE data. Open symbols indicate all other "world" data (see Ref. [4] for a detailed reference list).

2.2 Onset of fireball

Figure 2 shows the system size dependence of the K^+/π^+ ratio for three different collision energies. The p+p and Be+Be results are on the same level independent of the collision energy. They can be described by particle production from incoherent superposition of nucleon-nucleon collisions, as predicted by the Wounded Nucleon Model [5]. When passing to heavier systems one observes a rapid increase towards the statistical model expectations. This effect can be interpreted as the onset of fireball, the begining of formation of a large thermalized cluster. The position of the onset of fireball seems to be energy independent in the SPS range.

2.3 Search for the critical point

The localization of the critical point in the phase diagram of strongly interacting matter is supposed to reveal itself in the measurement of the "hill of fluctuations" as a function of colliding system

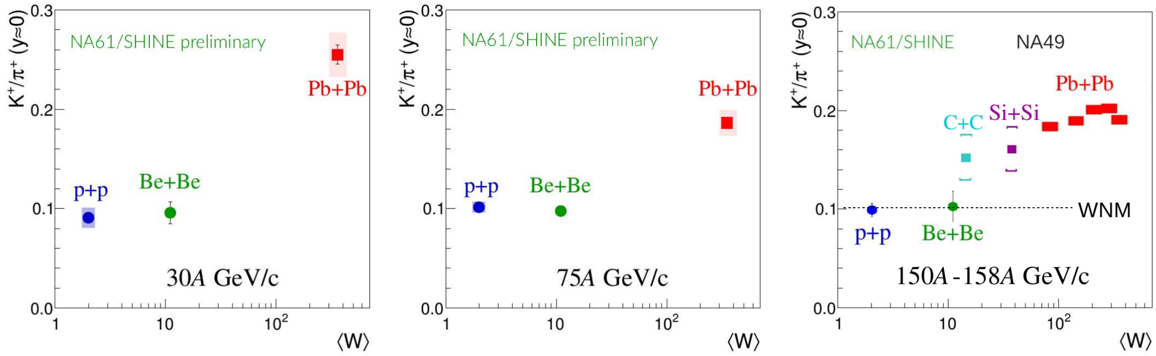

Fig. 2. Dependence of the mid-rapidity K^+/π^+ ratio on the mean number of participant nucleons (or wounded nucleons) $\langle W\rangle$, observed at 30*A*, 75*A* and 150-158*A* GeV/*c*. Square symbols mark NA49 data.

size and energy. So far, the main result from NA61/SHINE in its search for the critical point comes from an intermittency analysis of the proton density distribution in transverse momentum space at mid-rapidity. In this analysis, the transverse momentum space is partitioned into $M \times M$ equal-size bins, and the proton distribution is quantified by multiplicities in individual bins. If the system exhibits critical fluctuations, the second scaled factorial moment of the multiplicity distribution is expected to scale with M as a power-law: $F_2(M) \sim (M^2)^{\phi_2}$, where ϕ_2 is the intermittency index [6].

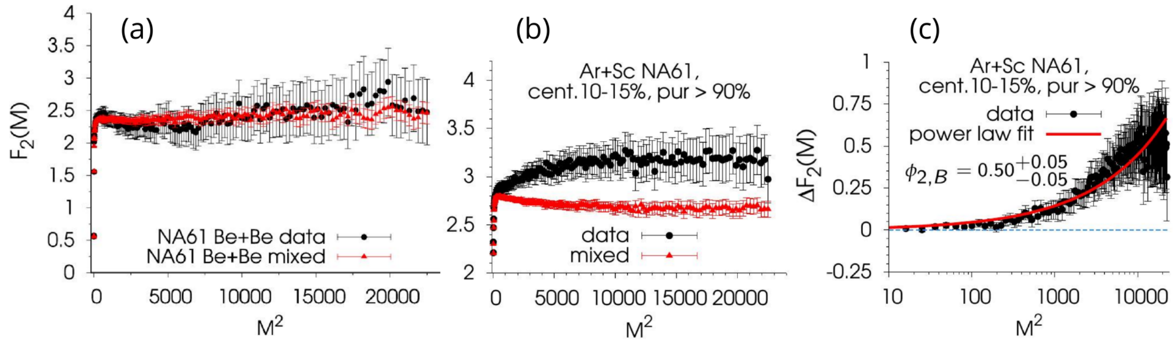

Fig. 3. (a) Factorial moments $F_2(M)$ for protons produced close to mid-rapidity measured in the 0-12% most central Be+Be collisions at 150*A* GeV/*c* (black points). The red points show results for mixed events. (b) As in (a) for 10-15% central Ar+Sc. (c) Power-law fit to the Ar+Sc background subtracted data (the differences between the black and red points in panel (b)).

Preliminary results on $F_2(M)$ for Be+Be and Ar+Sc systems at 150*A* GeV/*c* are shown in Fig. 3(a) and (b) by the black points. The experimental data require corrections for the presence of a background of uncorrelated and misidentified protons. The background was estimated by calculating $F_2(M)$ for mixed events and is shown in the figure by the red points. $F_2(M)$ values calculated for Be+Be data are at the background level, indicating no intermittency signal. In contrast, an intermittency effect is seen in mid-central Ar+Sc collisions at 150*A* GeV/*c*. The background subtracted $F_2(M)$ results with a power-law fit are shown in panel (c). This confirms a similar observation in Si + Si collisions located in a nearby position on the phase diagram from the NA49 experiment [7]. The analysis of new data for Xe+La at 150*A* GeV/*c* as well as Ar+Sc at 75*A* GeV/*c* collected recently might strengthen the evidence for the expected nonmonotonic system size and collision energy dependence of an intermittency signal from the critical point.

3. Open charm measurements

The aim of the open charm measurements is to obtain the first data on the mean number of $\langle c\bar{c}\rangle$ pairs produced in full phase space available to the heavy ion reactions at SPS enery range.

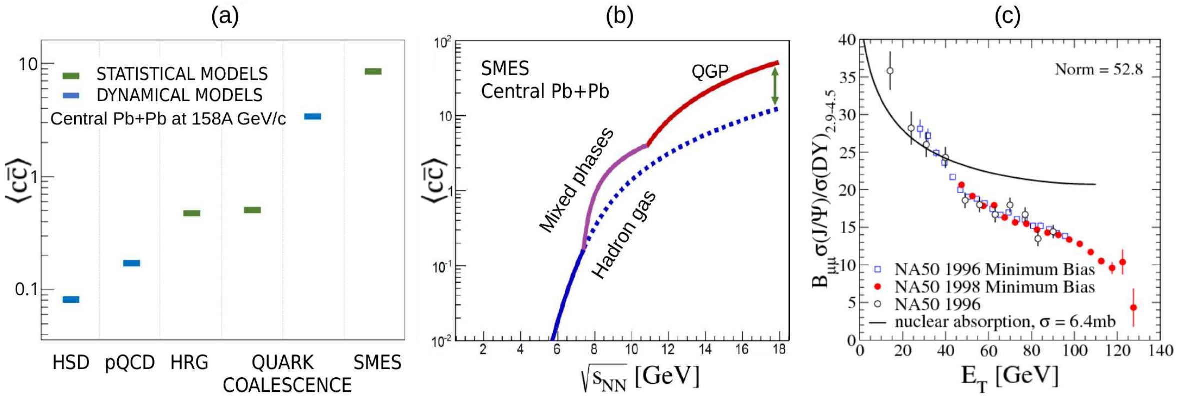

Fig. 4. (a) Mean multiplicity of charm quark-antiquark pairs produced in the full phase space in central Pb+Pb collisions at $158A$ GeV/c calculated with dynamical models (blue bars): HSD [10, 11], pQCD–inspired [12,13], and Dynamical Quark Coalescence [14], as well as statistical models (green bars): HRG [15], Statistical Quark Coalescence [15], and SMES [3]. (b) Energy dependence of $\langle c\bar{c}\rangle$ in central Pb+Pb collisions calculated within the SMES model [3]. The blue line corresponds to confined, the purple line to mixed phase, and the red line to deconfined matter. The dashed line presents the prediction without a phase transition. (c) The ratio of $\sigma_{J/\psi}/\sigma_{DY}$ as a function of the transverse energy (a measure of collision violence or centrality) in Pb+Pb collisions at $158A$ GeV measured by NA50. The curve represents the J/ψ suppression due to ordinary nuclear absorption [16].

The fundamental need for these new measurements originate from the following reasons: (i) the mechanism of open charm production is known with uncertainties reaching about two orders of magnitude as shown in Fig. 4(a) [3, 8]. Measurements of $\langle c\bar{c}\rangle$ will allow to discriminate between models, and thus to learn about the charm quark and hadron production mechanism. A good estimate of $\langle c\bar{c}\rangle$ can be obtained by measuring the yields of D^0, D^+ and their antiparticles because these mesons carry about 85% of the total produced charm [9]. (ii) deconfined matter is expected to differ from confined matter in terms of $c\bar{c}$ production. In confined matter the lightest charm carriers are D mesons, whereas in deconfined matter the carriers are charm quarks. The production of a $D\bar{D}$ pair ($2m_D$ = 3.7 GeV) requires more energy (about 1 GeV) than the production of a $c\bar{c}$ pair ($2m_c$ = 2.6 GeV). Since the effective numbers of degrees of freedom of charm hadrons and charm quarks are similar [17], more abundant charm production is expected in deconfined than in confined matter. Consequently, in analogy to strangeness production [3, 18], a change in the collision energy dependence of $\langle c\bar{c}\rangle$ may be a signal of the onset of deconfinement. Figure 4(b) presents the collision energy dependence of $\langle c\bar{c}\rangle$ in central Pb+Pb collisions predicted by the Statistical Model of the Early Stage [3]. According to this model, the phase transition from hadron gas to quark-gluon plasma can be indicated by a nonmonotonic enhancement of $\langle c\bar{c}\rangle$ production. (iii) The supression of $\langle J/\psi\rangle$ production in Pb +Pb collisions, an important argument for the discovery of a new state of matter announced by CERN in the year 2008 [19], was claimed on the basis of the assumption of the proportionality of mean $\langle c\bar{c}\rangle$ pair multiplicity to that of average multiplicity of Drell-Yan pairs, $\langle c\bar{c}\rangle \sim \langle DY\rangle$. This may be incorrect due to effects as shadowing or parton energy loss [20, 21]. The clarification of this important issue requires new experimental data on $c\bar{c}$ rather than Drell-Yan production. Figure 4(c) presents the original data on $\langle J/\psi\rangle$ production normalized to the mean multiplicity of Drell-Yan pairs $\langle DY\rangle$ in Pb+Pb collisions at the top SPS energy obtained by the NA50 collaboration. The solid line shows a model prediction for normal nuclear absorption of J/ψ in the medium [16].

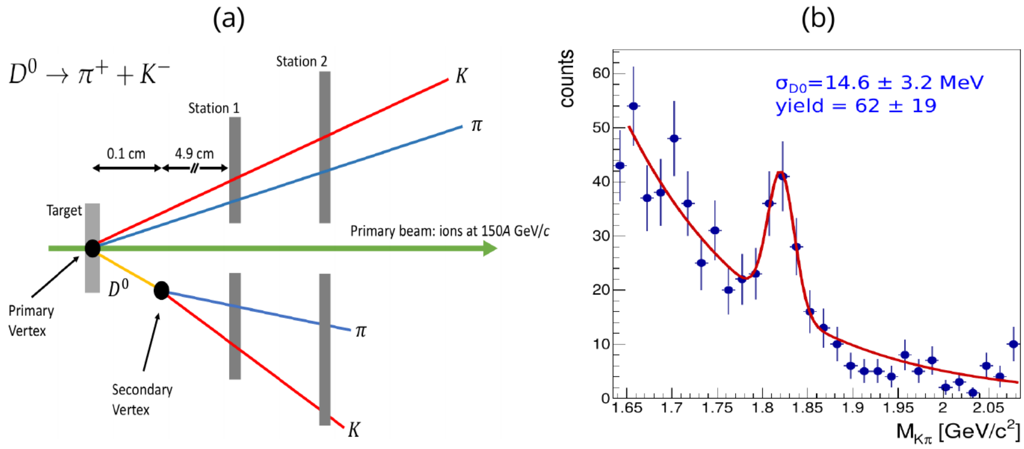

Fig. 5. (a) Schematics of reconstruction of a $D^0 \to \pi^+ + K^-$ decay with help of Vertex Detector. (b) Invariant mass spectrum of D^0 and $\overline{D^0}$ candidates in a test run on central Pb+Pb collisions at 150*A* GeV/*c*.

The first NA61/SHINE measurements of open charm production were performed in December 2016 during a Pb+Pb test run, using a new high-resolution vertex detector [22]. Its role in measurements of charm D^0 mesons via their hadronic decay channel is schematically shown in Fig. 5(a). Identification of the daughter particles of D^0 is based on measuring the separation between the primary and secondary decay vertices. Due to the Lorenz boost, the average separation is about 1 mm. Figure 5(b) shows the first indication of a D^0 or $\overline{D^0}$ peak in the invariant mass distribution obtained from these measurements.

Successful performance of this detector led to the decision to use it during the Xe+La data taking in 2017 and Pb+Pb run in 2018. The collected data are currently under analysis. Precise measurements of various open charm mesons produced in Pb+Pb collisions, which will allow determining $\langle c\bar{c} \rangle$ are planned for the years 2021-2024.

4. Plans for the period 2021-2024

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 of the CERN accelerators [8]. The measurements will include:
- 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.

The implementation of this program requires a significant modification of the NA61/SHINE spectrometer. The upgrade is primarily motivated by the charm program. In order to obtain a suficient statistics of rare events, in particular events containg charm hadrons, the data readout rate will be increased from the current 80 Hz to 1 kHz. Also the phase-space coverage of the Vertex Detector will be increased by a factor of about 2. This requires replacement of the TPC read-out electronics and construction of a new Vertex Detector. Additionally new trigger and data acquisition systems will be implemented, the Projectile Spectator Detector will be upgraded. Finally, new ToF detectors are planned to be constructed for particle identification at mid-rapidity. The detector upgrades are graph-

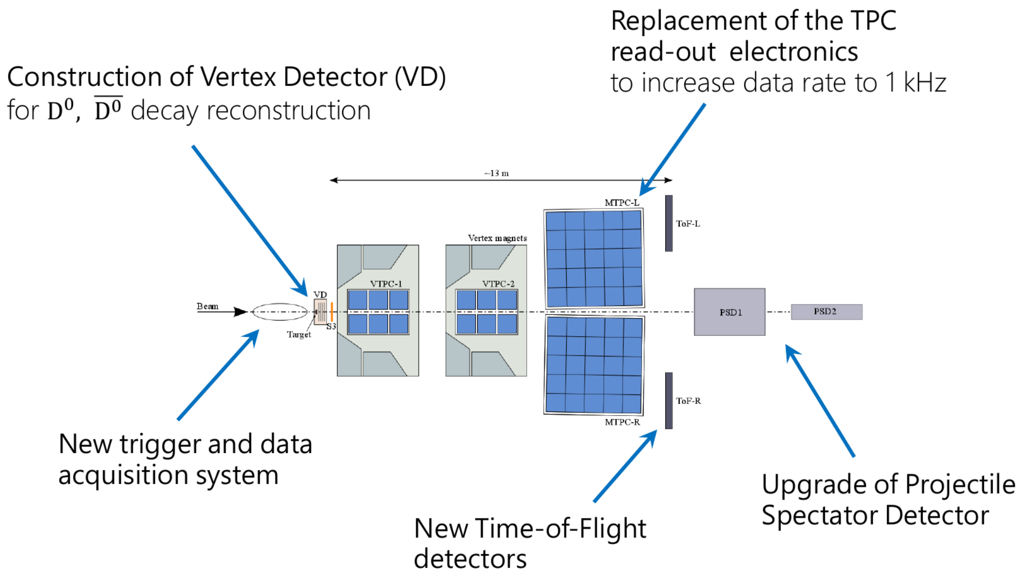

Fig. 6. Upgrades of the NA61/SHINE detectors planned to be completed during the Long Shutdown 2 period.

ically summarized in Fig. 6. With the upgraded NA61/SHINE spectrometer, one expects that during one day of data taking $6 \cdot 10^6$ Pb+Pb collisions at 150*A* GeV/*c* will be collected.

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