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A Virtual Tribute to Quark Confinement and the Hadron Spectrum (vConf21)

News from the strong interactions program of NA61/SHINE

Wojciech Bryliński[1,*]
for the NA61/SHINE Collaboration

[1]Warsaw University of Technology

Abstract. NA61/SHINE (SPS Heavy Ion and Neutrino Experiment) is a fixed-target experiment operating at the CERN SPS accelerator. The main goal of the strong interactions program of NA61/SHINE is to study the properties of the phase transition between confined matter and quark-gluon plasma by performing a two-dimensional scan in beam momentum and size of collided nuclei. Within this program, collisions of different systems (p+p, p+Pb, Be+Be, Ar+Sc, Xe+La, Pb+Pb) over a wide range of beam momenta (13A-150(8)*A* GeV/*c*) have been recorded.
This contribution discusses the latest results of hadron production in p+p, Be+Be, Ar+Sc and Pb+Pb reactions measured by the NA61/SHINE. In particular, the results include charged kaons and pions spectra and higher-order moments of multiplicity and net charge distributions. The presented data are compared with the predictions of different theoretical models as well as the results from other experiments. Finally, the motivation and plans for future NA61/SHINE measurements are discussed.

1 Introduction

SPS Heavy Ion and Neutrino Experiment (SHINE) [1] is a fixed-target experiment operating at the Super Proton Synchrotron (SPS) at the European Organization for Nuclear Research (CERN). The main physics motivation of the NA61/SHINE experiment is to study the properties of the phase transition between hadronic matter and quark-gluon plasma. Within this program, NA61/SHINE performed a two-dimensional scan in collision energy (13*A*–150(8)*A* GeV/*c*) and system size (p+p, Be+Be, Ar+Sc, Xe+La, Pb+Pb). The phase diagram of strongly interacting matter as well as the overall summary of collected data is presented in Figure 1.

The NA61/SHINE detector is a multi-purpose spectrometer optimised to study hadron production in various types of collisions. The schematic picture of the detector is shown in Figure 2. The main subdetectors of the whole setup are the Time Projection Chambers. Two Vertex-TPCs (VTPCs), located in the magnetic field, together with two large volume Main-TPCs (MTPCs) are main tracking devices and are able to register a large number of particle tracks (up to 1500 in central Pb+Pb collisions). Four smaller TPCs: GAP-TPC and 3 Forward-TPCs (FTPCs) are located along the beam axis. Such a setup gives an excellent capabilities in charged particles momenta measurement and allows for the particle identification complemented by the information from the Time-of-Flight (ToF) detectors. The last

*e-mail: wojciech.brylinski@cern.ch

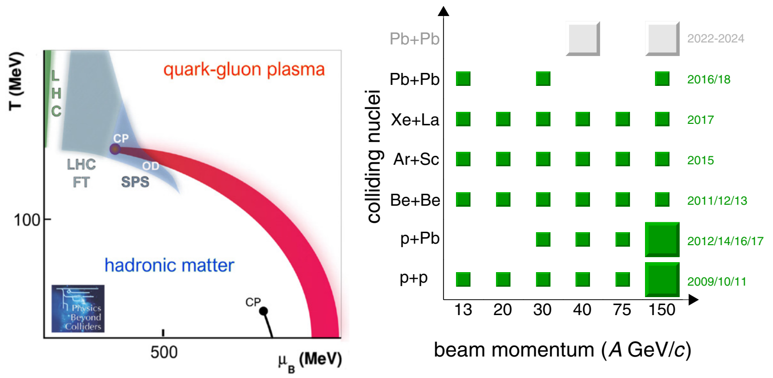

Figure 1. Phase diagram of strongly interacting matter (left). Schematic picture presenting the data collected within system size – beam momentum scan performed by NA61/SHINE (right).

detectors on the beamline are Projectile Spectator Detectors (MPSD and FPSD), which measure the energy of spectators. This information is used to determine the centrality in A+A collisions with very good accuracy. Beam particles are measured by an array of beam detectors. They are used for the beam trajectory measurement as well as the identification of beam particles.

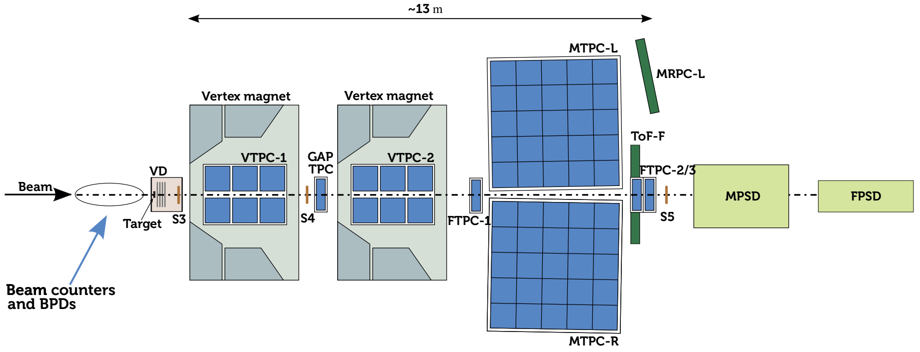

Figure 2. The schematic picture of the NA61/SHINE detector.

2 Study of the onset of deconfinement

The Statistical Model of the Early Stage (SMES) [2] predicts several signatures of the first order phase transition between the hadron gas and the quark-gluon plasma. In the transition region, constant temperature and pressure in the mixed-phase and an increase of the number of internal degrees of freedom are expected.

The energy and system-size dependence of K^+/π^+ ratio at mid-rapidity is presented in Figure 3. The results were obtained using data collected by NA61/SHINE: p+p [3], Be+Be

[4], Ar+Sc (preliminary) as well as NA49: Pb+Pb [5]. The visible structure for Pb+Pb and Au+Au data (so-called horn) in K^+/π^+ ratio was predicted by SMES as the signature of the onset of deconfinement. The presented results were compered with dynamical and statistical models (see right pannel of Figure 3). The dynamical models that do not include the phase transition (EPOS [6], UrQMD [7] and SMASH [8]) describe the data for small systems (p+p and Be+Be), but fail to describe the data for heavier systems (Ar+Sc and Pb+Pb). On the other hand, the PHSD [9] model which includes the phase transition agrees with the data for heavier systems and overestimates the data for smaller systems. Both statistical models which were taken into consideration – with (SMES [10]) and without (HRG [11]) phase transition included – overestimate the K^+/π^+ ratio especially for small systems.

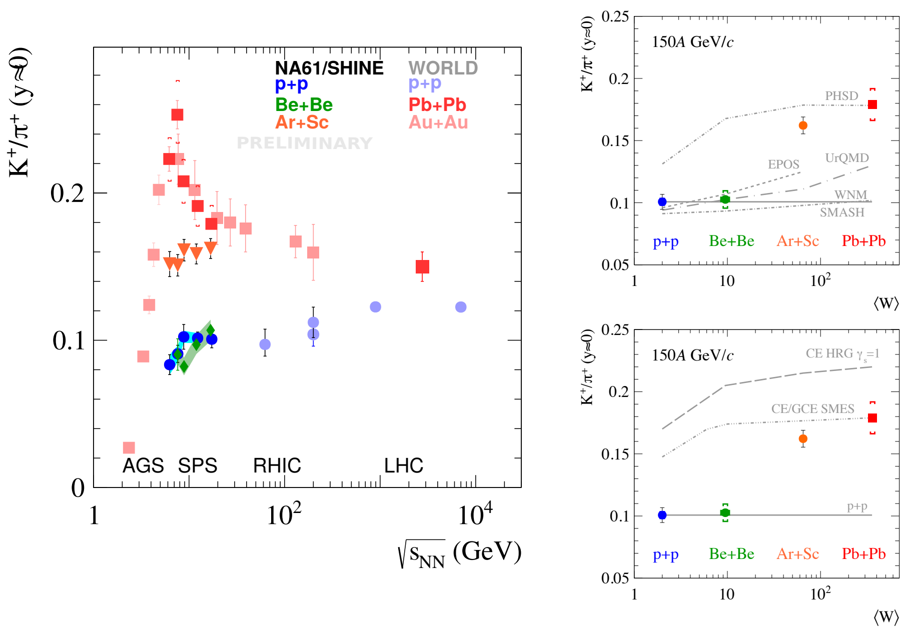

Figure 3. System-size and energy dependence of K^+/π^+ ratio compared with other experiments (left) as well as dynamical and statistical models (right).

The energy dependence of K^+/π^+ ratios as well as inverse slope parameter for p+p collisions are shown in Figure 4. The comparison to the corresponding results for heavier systems reveals similarities in the collision energy dependence – a rapid change of the hadron production properties in the same energy range. This phenomena for p+p collisions occurs very close the energy that corresponds to the phase transition in heavy systems (approximately 8 GeV).

3 Search for the critical point

The expected signature of the critical point (CP) is a non-monotonic dependence of various fluctuations measured in the NA61/SHINE system size – energy scan. A special interest is devoted to the fluctuations of conserved charges (electric, strangeness or baryon number) [12–14]. In order to compare the fluctuations in systems of different sizes, one should use the quantities which are insensitive to the size of the system. Such quantities are called intensive quantities and can be obtained by the division of cumulants κ_i of the measured distribution,

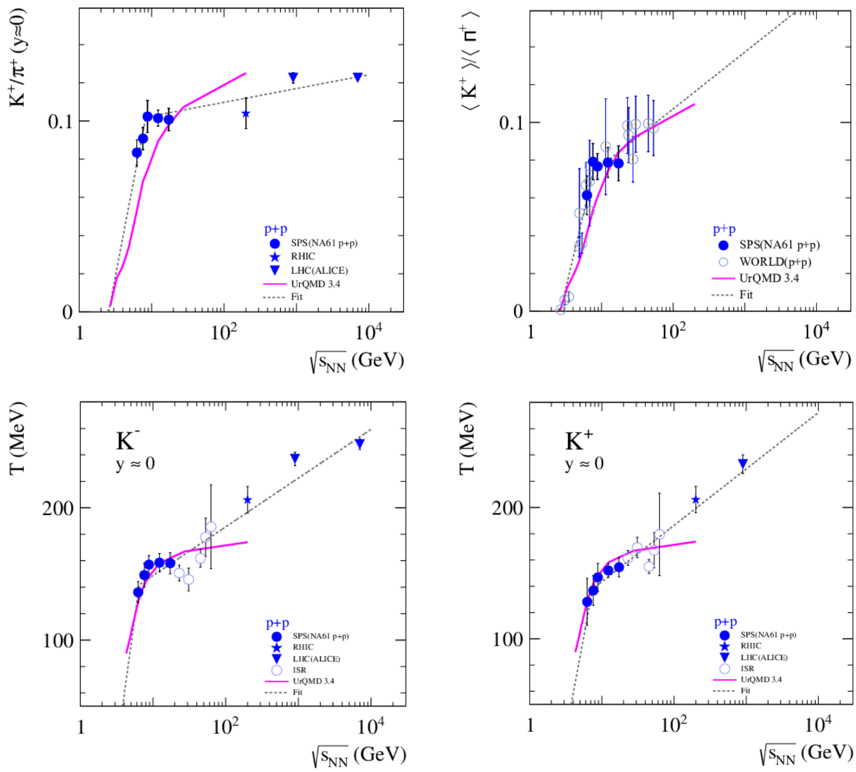

Figure 4. Energy dependence of the K^+/π^+ ratio in inelastic p+p interactions at mid-rapidity (top-left) and in the full phase-space (top-right) as well the inverse slope parameter T of transverse mass spectra at mid-rapidity for K^- (bottom-left) and K^+ (bottom-right) mesons.

where i is the order of the cumulant. For second, third and fourth order cumulants intensive quantities are defined as: κ_2/κ_1, κ_3/κ_2 and κ_4/κ_2. Figure 5 shows the system size and energy dependence of second, third and fourth order cumulant ratio of negatively charged hadrons in p+p, Be+Be and Ar+Sc collisions. So far, there is no clear evidence of the critical point, however more detailed studies are needed.

Proton intermittency is another possible tool that can be used to search for critical point. In the proximity of CP a local power-law fluctuation of the baryon density should be manifested. It can be searched for by studying the scaling behaviour of second factorial moments, $F_2(\delta) = \frac{\langle \frac{1}{M}\sum_{i=1}^{M} n_i(n_i-1)\rangle}{\langle \frac{1}{M}\sum_{i=1}^{M} n_i\rangle^2}$ with the cell size or, equivalently, with the number of cells M in (px, py) space of protons at mid-rapidity [15–17]. NA61/SHINE measures $F_2(M)$ using statistically independent points and cumulative variables. Preliminary results on $F_2(M)$ of mid-rapidity protons measured in 0-20% most central Ar+Sc collisions at 150A GeV/c and 0-10% most central Pb+Pb collisions at 30A GeV/c are presented in Figure 6. The intermittency index φ_2 for a system freezing out at the QCD critical endpoint is expected to be $\varphi_2 = 5/6$ assuming that the latter belongs to the 3-D Ising universality class. $F_2(M)$ of protons for Ar+Sc at 150A GeV/c and Pb+Pb at 30A GeV/c show no indication for power-law increase with a bin size.

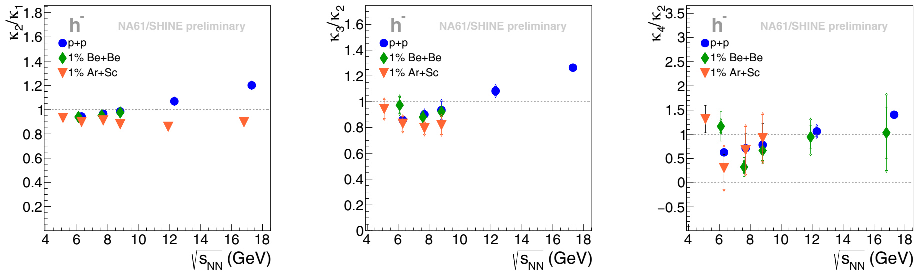

Figure 5. Preliminary results on the energy and system-size dependence of multiplicity fluctuations of negatively charged hadrons.

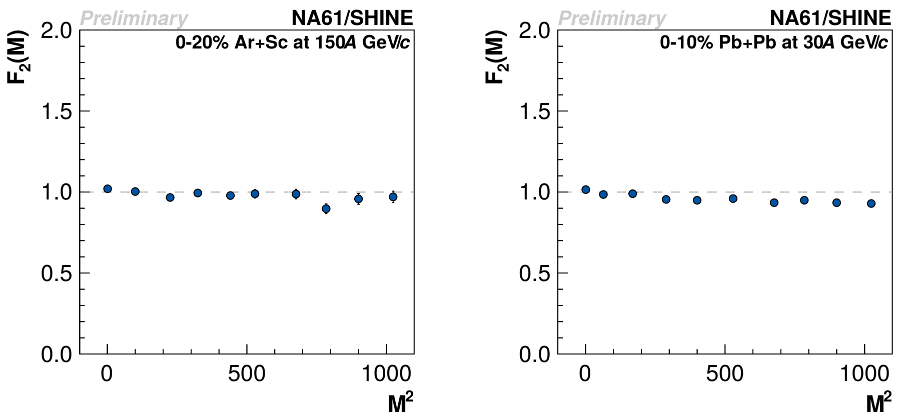

Figure 6. Preliminary results on $F_2(M)$ of mid-rapidity protons measured in 0-20% most central Ar+Sc collisions at 150*A* GeV/*c* (left) and 0-10% most central Pb+Pb collisions at 30*A* GeV/*c* (right).

4 Open charm measurements

The physics program of NA61/SHINE was extended by measurements of open charm production in A+A collisions which is the main goal of NA61/SHINE beyond 2021. It was motivated by three main questions:

- What is the mechanism of open charm production?
- How does the onset of deconfinement impact open charm production?
- How does the formation of quark-gluon plasma impact J/ψ production?

The mean multiplicity of charm quarks $\langle c\bar{c}\rangle$ produced in a full phase space in heavy-ion collisions is not yet known and has to be measured in order to answer these questions. The acceptance of the NA61/SHINE detector is large enough to extrapolate the measurements to the full phase space with relatively small uncertainties. This unique feature makes NA61/SHINE the only experiment which is able to perform such measurement in the near future.

To meet the challenges of the required spatial resolution of primary and secondary vertex reconstruction, the detector was upgraded by a micro vertex detector. A Small-Acceptance version of the Vertex Detector (SAVD) was successfully commissioned in December 2016 and first pilot data were collected for Pb+Pb collisions at a beam momentum of 150*A* GeV/*c*.

This data allowed to validate the measurement concept and to perform the first direct measurement of open charm hadron production in collisions of nuclei at the SPS energies. Figure 7 (left) shows the first indication of a D^0 and $\overline{D^0}$ peak. In October and November 2017, the large statistics datasets for Xe+La collisions at 75*A* and 150*A* GeV/*c* were registered. The distribution of the longitudinal coordinate of the primary vertex is shown in Figure 7 (right).

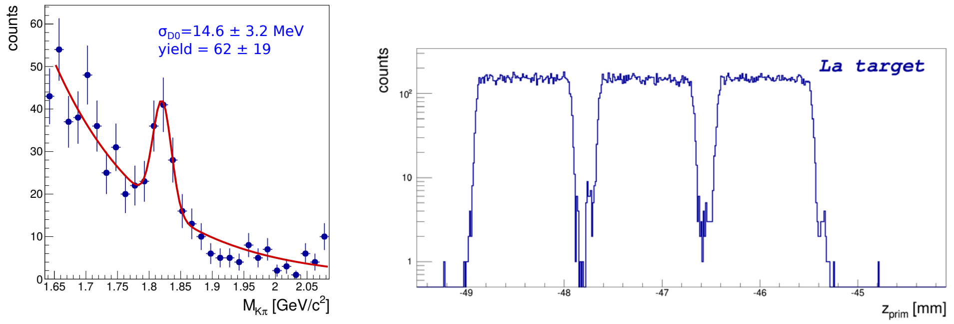

Figure 7. Invariant mass distribution of D^0 and $\overline{D^0}$ candidates in central Pb+Pb collisions at after the background suppression cuts (left). Distribution of longitudinal coordinate of the primary vertex for interactions in the La target, which was composed of three 1 mm plates (right).

5 NA61/SHINE detector upgrades

The NA61/SHINE spectrometer is undergoing a significant upgrade during the Long Shutdown 2 at CERN (2019-2021) [18]. Most of the upgrades are dedicated to open charm physics program which requires the increase of the phase space coverage of Vertex Detector and the tenfold increase of data taking rate to about 1 kHz. The most important points of the upgrade are summarized below:

- 10 fold increase of data taking rate up to 1kHz thanks to the replacement of the TPC read-out electronics,
- improvement of acceptance and efficiency of the Vertex Detector,
- improvement of radiation tolerance of the PSD hadron calorimeter,
- introduction of new TOF detector based on mRPC technology,
- replacement of old readout electronics based on CAMAC and FASTBUS standards,
- development of the new trigger and data acquisition system.

The first physics data taking with the upgraded setup is planned for 2022.

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References

[1] N. Abgrall *et al.* [NA61 Collaboration], JINST **9**, P06005 (2014) doi:10.1088/1748-0221/9/06/P06005 [arXiv:1401.4699 [physics.ins-det]].

[2] M. Gazdzicki and M. I. Gorenstein, Acta Phys. Polon. B **30**, 2705 (1999) [hep-ph/9803462].

[3] A. Aduszkiewicz *et al.* [NA61/SHINE], Eur. Phys. J. C **77** (2017) no.10, 671 doi:10.1140/epjc/s10052-017-5260-4 [arXiv:1705.02467 [nucl-ex]].

[4] A. Acharya *et al.* [NA61/SHINE], Eur. Phys. J. C **81** (2021) no.5, 397 doi:10.1140/epjc/s10052-021-09135-3 [arXiv:2101.08494 [hep-ex]].

[5] S. V. Afanasiev *et al.* [NA49], Phys. Rev. C **66** (2002), 054902 doi:10.1103/PhysRevC.66.054902 [arXiv:nucl-ex/0205002 [nucl-ex]].

[6] T. Pierog and K. Werner, Nucl. Phys. B Proc. Suppl. **196** (2009), 102-105 doi:10.1016/j.nuclphysbps.2009.09.017 [arXiv:0905.1198 [hep-ph]].

[7] A. Motornenko *et al.*, Phys. Rev. C99 (2019) 3, 034909 doi:10.1103/PhysRevC.99.034909

[8] J. Mohs, S. Ryu and H. Elfner, J. Phys. G **47** (2020) no.6, 065101 doi:10.1088/1361-6471/ab7bd1 [arXiv:1909.05586 [nucl-th]].

[9] V. Kireyeu, I. Grishmanovskii, V. Kolesnikov, V. Voronyuk and E. Bratkovskaya, Eur. Phys. J. A **56** (2020) no.9, 223 doi:10.1140/epja/s10050-020-00232-7 [arXiv:2006.14739 [hep-ph]].

[10] R. V. Poberezhnyuk, M. Gazdzicki and M. I. Gorenstein, Acta Phys. Polon. B **46** (2015) no.10, 1991 doi:10.5506/APhysPolB.46.1991 [arXiv:1502.05650 [nucl-th]].

[11] A. Motornenko, V. V. Begun, V. Vovchenko, M. I. Gorenstein and H. Stoecker, Phys. Rev. C **99** (2019) no.3, 034909 doi:10.1103/PhysRevC.99.034909 [arXiv:1811.10645 [nucl-th]].

[12] M. A. Stephanov, Phys. Rev. Lett. **102** (2009), 032301 doi:10.1103/PhysRevLett.102.032301 [arXiv:0809.3450 [hep-ph]].

[13] M. Asakawa and M. Kitazawa, Prog. Part. Nucl. Phys. **90** (2016), 299-342 doi:10.1016/j.ppnp.2016.04.002 [arXiv:1512.05038 [nucl-th]].

[14] M. A. Stephanov, K. Rajagopal and E. V. Shuryak, Phys. Rev. Lett. **81** (1998), 4816-4819 doi:10.1103/PhysRevLett.81.4816 [arXiv:hep-ph/9806219 [hep-ph]].

[15] A. Bialas and R. B. Peschanski, Nucl. Phys. B **273** (1986), 703-718 doi:10.1016/0550-3213(86)90386-X

[16] L. Turko, Phys. Lett. B **227** (1989), 149-152 doi:10.1016/0370-2693(89)91298-7

[17] F. K. Diakonos, N. G. Antoniou and G. Mavromanolakis, PoS **CPOD2006** (2006), 010 doi:10.22323/1.029.0010

[18] A. Aduszkiewicz *et al.* [NA61 Collaboration], CERN-SPSC-2018-008, SPSC-P-330-ADD-10