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Recent results from NA61/SHINE strong interaction program

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NA61/SHINE is a multipurpose fixed-target experiment located at the CERN SPS. One of its main goals is to study the phase diagram of strongly interacting matter. For this purpose, a unique two-dimensional scan in beam momentum $13A$–$150(8)A$ GeV/c and the system size, including p+p, p+Pb, Be+Be, Ar+Sc, Xe+La, and Pb+Pb collisions, was performed. The main goal of the strong interaction program is to understand the onset of deconfinement and locate the critical point of strongly interacting matter.

The paper reviews results from NA61/SHINE strong interaction program, focusing on hadron spectra and fluctuations in various collisions. The new results on strangeness production, particularly the ratio of positively charged kaons to pions, are also presented, including the first results for Xe+La collisions. It also reviews the recent NA61/SHINE results on proton and negatively charged hadron intermittency to search for the QCD critical point. The direct measurement of the open charm performed by NA61/SHINE is also presented. The NA61/SHINE data are compared with other experimental results and predictions from theoretical models and confronted with Power-law model predictions.

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1. Introduction

NA61/SHINE is a large acceptance hadron spectrometer located at the CERN SPS [1]. Eight large volume Time Projection Chambers (TPC), accompanied by the Time of Flight detectors (ToF), provide tracking and identification of produced particles. It also offers high momentum resolution down to p_T=0. The Projectile Spectator Detector (PSD), a precise zero-degree hadron calorimeter, measures the energy of projectile spectators, which can be related to the centrality of the collision. The Vertex Detector (VD) mounted close to the target provides the position of decay vertices located near the primary vertex. Such capability is crucial for measurements of D^0 and $\overline{D}^0$ particles.

The strong interaction program is mainly devoted to studying properties of the onset of deconfinement and the onset of fireball, as well as searching for the critical point of strongly interacting matter. Within the program, NA61/SHINE did a 2-dimensional scan in the beam momentum (13A–150(8)A GeV/c) and system size, collecting p+p, p+Pb, Be+Be, Ar+Sc, Xe+La, and Pb+Pb collisions.

N61/SHINE uses three methods for charged particle identification. The first one is the h^- method, which is based on the fact that the majority of negatively charged particles are π mesons. The contribution of other particles is subtracted by EPOS Monte-Carlo. The second method uses TPC energy loss (dE/dx) measurements for particle identification. The third method uses dE/dx values from TPCs and Time of Flight from TOF walls. The acceptance of charged particles depends on the method used.

2. Onset of deconfinement and onset of fireball

Using h^- and dE/dx methods, NA61/SHINE has obtained preliminary spectra of transverse momentum and rapidity for charged pions and kaons in central Xe+La collisions at four beam momenta [2]. The spectra provide the inverse slope parameter from the fit to p_T (m_T) distribution and also yields in full phase space. The ratio of positively charged kaons and pions was obtained using these yields. Such a ratio is a measure of strangeness to entropy ratio with different numbers of degrees of freedom in QGP and hadron phase. Thus, it's a good probe of the onset of deconfinement. Energy dependence of the ratio exhibits the non-monotonic "horn" structure in central Pb+Pb collisions collected by NA49 and Au+Au data from STAR, which was predicted by SMES model as a signature of the phase transition [3]. The NA61/SHINE Xe+La points lay below Pb+Pb and above points for lighter systems Ar+Sc, Be+Be, and p+p (Fig. 1 *Left*, *Center*). It is known that kaons are only weakly affected by rescattering and resonance decay during the post-hydro phase at SPS energies. Their inverse slope parameter reflects the thermal freeze-out temperature and radial flow velocity, and it may be sensitive to the phase transition. The inverse slope parameter for positively charged kaons as a function of energy shows a "step" structure with the plateau in the same energy range where the "horn" structure is observed. Similar energy dependence is seen in all systems from p+p to Pb+Pb, although the value of the inverse slope parameter is grooving with system size (Fig. 1 *Right*).

The same probes might be shown as a function of system size. They are shown for A+A collisions at beam momentum 150(8)A GeV/c together with several model predictions from dynamical models PHSD, EPOS. UrQMD, SMASH, and statistical model Fig. 2 (for details see Ref. [4] and

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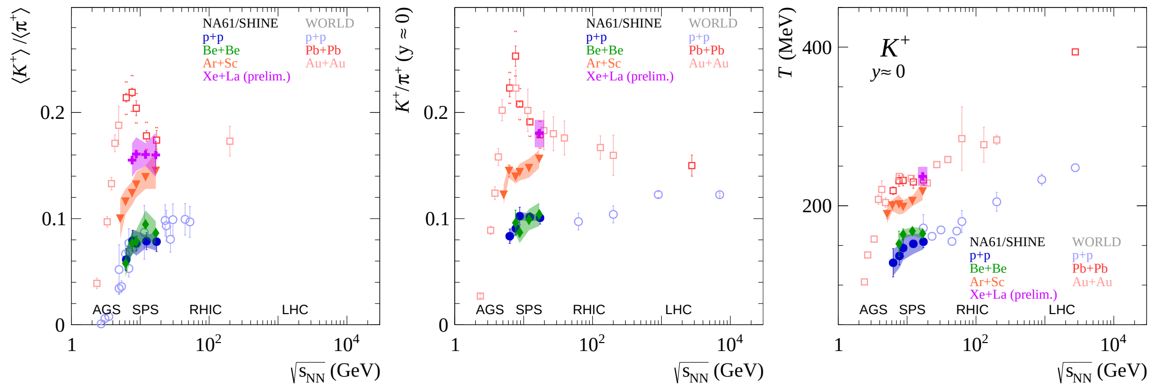

Figure 1: Energy dependence of the $\langle K^+\rangle/\langle\pi^+\rangle$ ratio measured in the full phase ("horn") (*Left*), the K^+/π^+ ratio at midrapidity ("horn") (*Center*), and the inverse slope parameter of the transverse mass distribution for K^+ ("step") (*Right*). NA61/SHINE and LHC data from central Pb+Pb and RHIC results from central Au+Au collisions are shown. See Ref. [5] for references to the NA61/SHINE and world data points. For NA61/SHINE data, color bands represent systematic uncertainties, while error bars correspond to statistical ones.

references therein). One can see that both probes in Ar+Sc collisions are larger than in p+p, Be+Be and lower than in Xe+La, Pb+Pb. The increase from small to intermediate and large systems might be a hint of the onset of fireball creation. None of the models used in the comparisons reproduces system size dependence in the whole range, although the best agreement with data is observed in the case of PHSD.

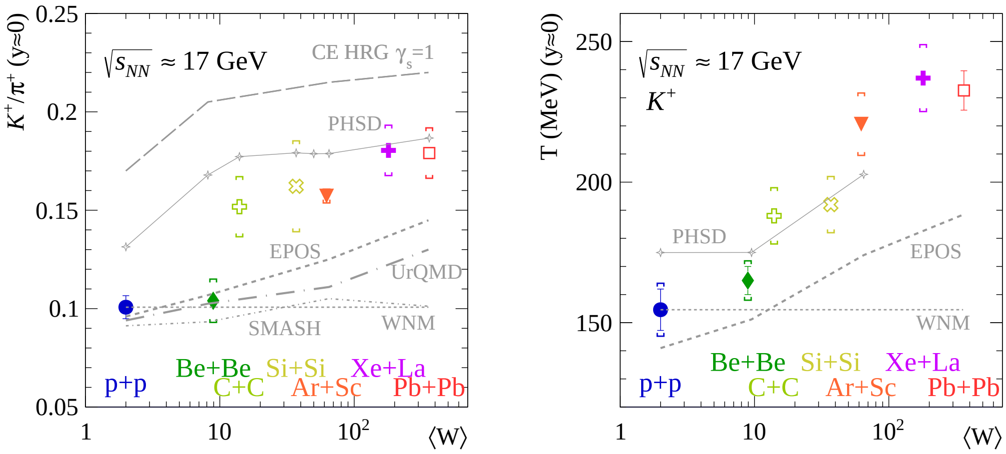

Figure 2: *Left*: System size dependence quantified by the mean number of wounded nucleons of the K^+/π^+ ratio at mid-rapidity measured at 150(8)A GeV/c compared with models. *Right*: System size dependence of the inverse slope parameter T of K^+ at the same collision energy [2, 4].

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3. Excess of charged over neutral kaon production

Recently NA61/SHINE has simultaneously measured the production of K^+,K^-, and K^0_S mesons in central Ar+Sc collisions at beam momentum 75A GeV/c ($\sqrt{s_{NN}}$=11.9 GeV). In this analysis charged kaons were identified by dE/dx and TOF-dE/dx methods. The yields were corrected for detector acceptance and reconstruction efficiency, as well as weak decays and secondary interactions [4]. K^0_S mesons were reconstructed based on the topology of decay into charged pions [6]. Assuming approximate isospin symmetry between u and d quarks in strong interactions and neglecting the small effect of the CP violation, one can expect the relation between productions $K^0_S = \frac{K^+ + K^-}{2}$ in the collisions of "charge-symmetric" nuclei (Z=N). The excess of charged over neutral K mesons is observed by NA61/SHINE in the whole rapidity range, and at midrapidity (Fig. 3 *Left*), it's equal to 18.4% with an uncertainty of about 6% [7]. Most of the world's data obtained by different experiments show the excess at a similar level although with higher uncertainty (Fig. 3 *Right*). The size of the effect is not reproduced by theoretical and statistical models, which predict more or less isospin symmetry with only a small excess of several percent.

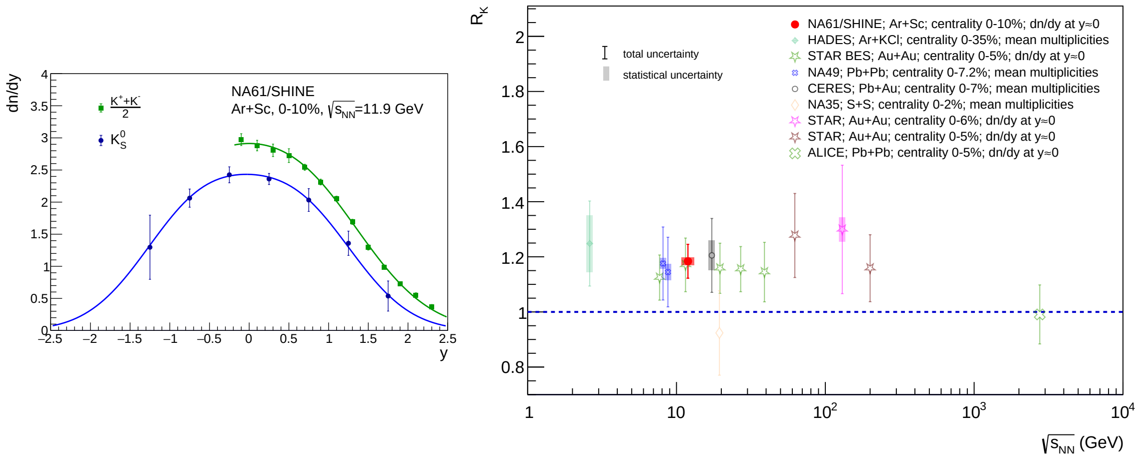

Figure 3: *Left*: Comparison of rapidity spectrum of neutral (K^0_S) with the average spectrum of charged (K^+ and K^-) mesons in 0–10% central Ar+Sc collisions at beam momentum 75A GeV/c ($\sqrt{s_{NN}}$=11.9 GeV). The total uncertainties are plotted and calculated as the square root of the sum of squared statistical and systematic uncertainties $\left(\sqrt{(\mathrm{stat})^2 + (\mathrm{sys})^2}\right)$. For charged kaons [4], the total uncertainties were calculated separately for positively charged and negatively charged kaons and then propagated. *Right*: Compilation of the available data on the ratio of charged to neutral kaons ($R_K = (K^+ + K^-)/(2K^0_S)$) as a function of $\sqrt{s_{NN}}$. The measurement from NA61/SHINE is shown as a red dot. The world data needed to obtain R_k values come from the references given in Ref. [8].

4. Search for the critical point - intermittency analysis

One of the tools for CP investigation is proton intermittency. In the proximity of the CP, local power-law fluctuations of the baryon density are expected. This can be explored by studying scaled factorial moments with the cell size or, equivalently, with the number of 2-D cells in the space of components of transverse momentum p_x-p_y for protons at mid-rapidity [9, 10]. NA61/SHINE measures scaled factorial moments of multiplicity distributions $F_r(M)$ using statistically independent points and cumulative variables. Results on $F_2(M)$ of mid-rapidity protons measured in central

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Ar+Sc collisions at 13*A*–150*A* GeV/*c* [11, 12] are presented in Fig. 4 *Left*. Additionally, results on $F_r(M)$ $(r = 2, 3, 4)$ of negatively charged hadrons in the 10% most central Pb+Pb collisions at 30*A* GeV/*c* [13] are shown in Fig. 4 . The power-law scaling exponent ($F_2(M) \sim M^{2\phi_2}$) intermittency index ϕ_2 for a system freezing out at the QCD critical endpoint is expected to be $\phi_2 = 5/6$, assuming it belongs to the 3-D Ising universality class. Measured $F_2(M)$ of protons for Ar+Sc at 13*A*–150*A* GeV/*c* shows no indication of a power-law increase with bin size, which could indicate CP. This holds for $F_2(M)$ of negatively charged hadrons for Pb+Pb at 30*A* GeV/*c* as well. The Fig. 4 *Right* shows the points in the $T - \mu_B$ phase diagram for reactions for which the critical point search was conducted and no evidence for the critical point was found.

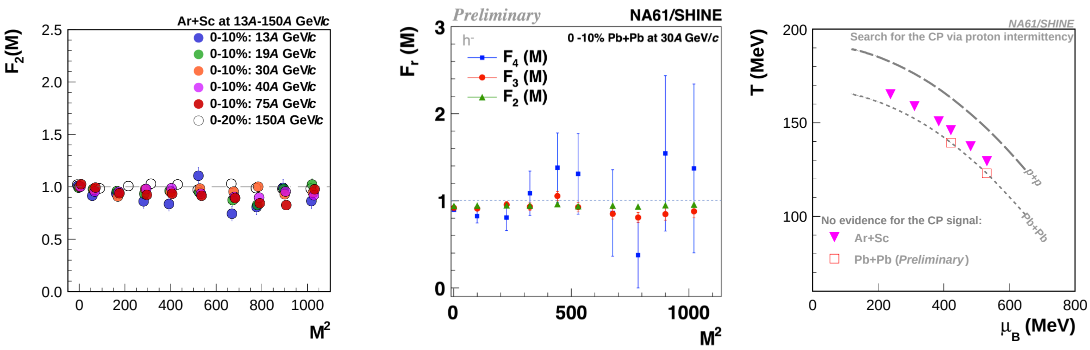

Figure 4: *Left*: Results on $F_2(M)$ of protons in central Ar+Sc collisions at 13*A*–150*A* GeV . *Center*: Scaled factorial moments of 2–4 order for negatively charged hadrons produced in the 10% most central Pb+Pb collisions at 30*A* GeV . *Right*: Diagram of chemical freeze-out temperature and baryon-chemical potential. The dashed line indicates parameters in p+p interactions and the dotted line in the central Pb+Pb collisions; points estimated and extrapolated (μ_B for p+p) based on Ref. [14]. The colored points mark reactions (Ar+Sc and Pb+Pb [13]) in the $T - \mu_B$ phase diagram for which the search for the critical point was conducted.

5. Direct measurement of open charm

The first-ever direct measurement of open charm production in nucleus-nucleus collisions at CERN SPS energies has recently been performed by NA61/SHINE using Small Acceptance Vertex Detector (SAVD) [15]. This result was obtained in Xe+La collisions at $\sqrt{s_{NN}}$=16.8 GeV (for details see Ref. [16]). The $D^0 + \overline{D}^0$ yield visible in acceptance was extrapolated to the total 4π yield using three different models (AMPT, PHSD, PYTHIA) to estimate the corresponding model-related uncertainty. As apparent in Fig. 5, the NA61/SHINE measurement offers sufficient discrimination power to bring a decisive improvement to existing models of open charm production, which in their present version differ by as much as three orders of magnitude at this collision energy. The statistically rich Pb+Pb data collected in 2022 and 2023 using the upgraded NA61/SHINE detector with upgraded Vertex Detector is currently under analysis.

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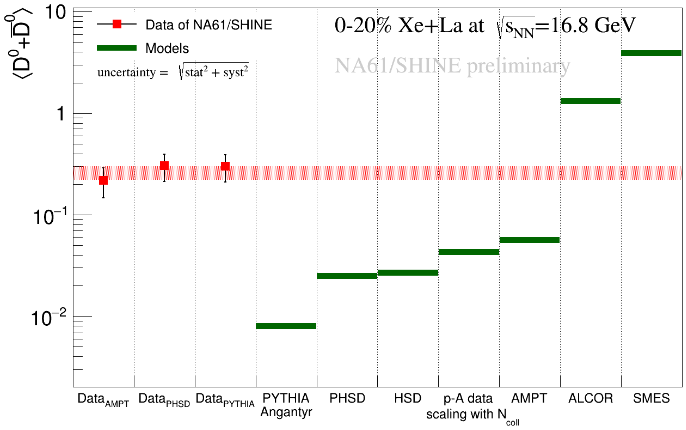

Figure 5: Comparison of the obtained NA61/SHINE preliminary results on 4π-yield $D^0 + \overline{D}^0$. to the theoretical model predictions. The red band indicates the theoretical uncertainty of the results due to the unknown phase space distribution of D^0, $\overline{D}^0$.

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