Form of opening (renewal) for Project

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JINR DIRECTOR

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PROJECT PROPOSAL FORM

Opening/renewal of a research project/subproject of the large research infrastructure project within the Topical plan of JINR

1. General information on the research project of the theme/subproject of the large research infrastructure project (hereinafter LRIP subproject)

1.1 Theme code (for extended projects) - 02-1-1087-2009 Research on Relativistic Heavy and Light Ion Physics. Experiments at the Accelerator Complex Nuclotron-M/NICA at JINR and CERN SPS.

1.2 Project code (for extended projects)

1.3 Laboratory Veksler and Baldin Laboratory of High Energy Physics

1.4 Scientific field Particle physics and relativistic nuclear physics

1.5 Title of the project NA61/SHINE - SPS Heavy Ion and Neutrino Experiment

1.6 Project Malakhov A.I.

1.7 Project deputy leaders (scientific supervisor(s)) Dmitriev A.V., Zaitsev A.A.

2 Scientific case and project organization

2.1 Annotation

This project is a proposal to extend research the properties of hadron and nucleus fragmentation in interactions with hadron and nuclear beams within the NA61/SHINE experimental program at the SPS CERN. The experimental program includes the tasks of searching for a hypothetical critical point in the phase diagram of nuclear matter, studying the properties of the onset of deconfinement and open charm production. To solve these problems, scanning measurements of particle spectra and fluctuations of proton-proton, proton-nucleus and nucleus-nucleus interactions are carried out depending on the collision energy and system size. It provides unique opportunities to study the critical properties of dense and hot hadronic matter formed during the collision process.

The expected results from the NA61/SHINE experiment program are included in the JINR seven-year development plan for 2024-2030 (https://www.jinr.ru/wp-content/uploads/JINR_Docs/JINR_Seven-year_plan_2024-2030_rus.pdf p. 25 p. 4).

Data analysis continues in the following areas:

- production of light nuclei in nuclear interactions;
- generation of hyperons in the interactions Be + Be, Ar + Sc, Xe + La, Pb + Pb;
- production of antimatter in nucleus-nucleus interactions.
- production of charm particles in collisions of relativistic heavy ions.

Collaborative modeling work is underway for the NICA and NA61/SHINE projects, based on experimental data from the NA61/SHINE experiment.

Within the framework of the collaboration, members of the JINR group fulfill obligations both in physical data analysis and modeling, and in the implementation of the NA61/SHINE facility upgrade program, namely the development and installation of a new two-arm time-of-flight system. The installed left ToF arm was fully integrated into the facility and operated successfully during the 2023 data acquisition. The right arm of the ToF is expected to be installed in 2024, which will cover the full acceptance of the NA61 setup.

The unique experience of working in an international collaboration will allow its participants to apply the acquired skills in the implementation of NICA megaprojects at JINR.

It should be noted that the results of the work of the JINR group members in the collaboration are periodic publications of articles in major peer-reviewed journals, as well as defense of candidate and doctoral dissertations. Currently, preparations are underway for the defense of several candidate and doctoral dissertations.

2.2 Scientific case

2.2.1 Introduction

The NA61/SHINE experiment at CERN SPS got its name (SPS Heavy Ion and Neutrino Experiment) due to its dual experimental program. On the one hand, precise measurements of spectra are carried out, necessary for experiments with cosmic rays and neutrinos. On the other hand, the onset of deconfinement is being investigated (search for the “horn”, “kink”, “step” and “dale” structures in spectra), discovered by the previous NA49 experiment at CERN SPS [1] and a systematic search is being carried out for a hypothetical second-order critical point in the phase diagram QCD (search for the nonmonotonic dependence of various correlation and fluctuation observables on the collision energy and the size of colliding nuclei). The strong interaction program in the NA61/SHINE experiment is based on scanning beams of light and intermediate nuclei (p+p, p+Pb, Be+Be, Ar+Sc, Xe+La, Pb+Pb) with energies in the range 13A - 158A GeV. These studies are motivated by the rapid changes observed in the NA49 experiment in the properties of hadron production in central Pb+Pb collisions at energies of about 30A GeV/c [2, 3]. The results were interpreted as the onset of deconfinement; they were confirmed by the results of experiments at RHIC [4] and LHC (see [5]).

The goals of the NA61/SHINE strong interaction program are achieved experimentally by 2D scanning of the collision energy and size of colliding nuclei. This allows us to systematically study the phase diagram of strongly interacting matter [1]. In particular, analysis of existing data within the framework of statistical models suggests that due to an increase in collision energy, the temperature increases and the baryon chemical potential of a fireball of strongly interacting matter during kinetic freezing decreases [6], while due to an increase in the nuclear mass of colliding nuclei, the temperature decreases [6– 9] (Fig. 2).

As part of this NA61/SHINE program, the collaboration collected data p+p, Be+Be, Ar+Sc, Xe+La and Pb+Pb collisions during 2009-2018. Further measurements on high Pb+Pb collision statistics using the upgraded detector began in 2022 and 2023. [10].

It is worth highlighting the main areas of activity of JINR staff in the implementation of the NA61/SHINE project:

1. Study of the light nuclei production. This is important for several reasons:

First of all, the mechanism of cluster formation in nucleus-nucleus collisions has not been sufficiently studied and requires further research. On the other hand, for example, deuterons and tritons are not elementary hadron particles and, due to their low binding energy compared to the temperature of the system, it is very likely that they will not survive in secondary collisions. Thus, it is likely that the observed deuterons and tritons, as well as a significant part of the bound states of several nucleons detected near the mid rapidity region, are produced at a late stage of the reaction. Therefore, experimentally observed light nuclei produced at late stages of reaction evolution can provide information about the spatio-temporal structure of the late stage of the collision.

2. Study of hyperons and hypernuclei productions in the interactions of Ar + Sc, Xe + La, Pb + Pb. Relativistic collisions of heavy ions provide a unique opportunity to create and study hot and dense matter in laboratory conditions. At the initial stage of the reaction, QGP is formed, and at the final stage, the process of hadronization and cluster formation occurs. The capture of produced hyperons by clusters of nucleons leads to the production of hypernuclei, which is a very rare process at the threshold energy for the strangeness production. Hypernuclei are unique objects for deepening our knowledge of the interactions of strange particles with nuclei in a multiparticle environment and under controlled conditions. This, in turn, is necessary to obtain a more general and self-consistent description of baryon-baryon interactions.

3. Study of antimatter production in relativistic nuclear interactions.

4. Analysis of experimental data using the Dubna approach. The development of the approach to the study of relativistic nuclear interactions in the space of four-dimensional velocities, proposed by Academician A.M. Baldin.

5. Measurement of the average number of charm quark-antiquark pairs $\langle c\bar{c} \rangle$ produced in the full phase space of interacting heavy ions. The peculiarity of the charm particle production in collisions of heavy ions may be a sign of the formation of QGPs, in particular, the suppression of the yield of J/ψ mesons. Such data are not yet available, and such an analysis is planned as part of the NA61/SHINE experiment.

6. Development of a time-of-flight detector based on multi-gap resistive plate chambers (MRPC) with high time resolution. Joint development of detectors for NA61 and NICA is underway. The beams of nuclei at CERN are used to test and debug detectors.

7. The Laboratory of Nuclear Problems participates in the NA61 neutrino program. The NA61/SHINE collaboration has a hadron production measurement program for long-baseline neutrino oscillation experiments at FNAL and J-PARC. These measurements expand knowledge of the neutrino flux created by neutrino beams from accelerators.

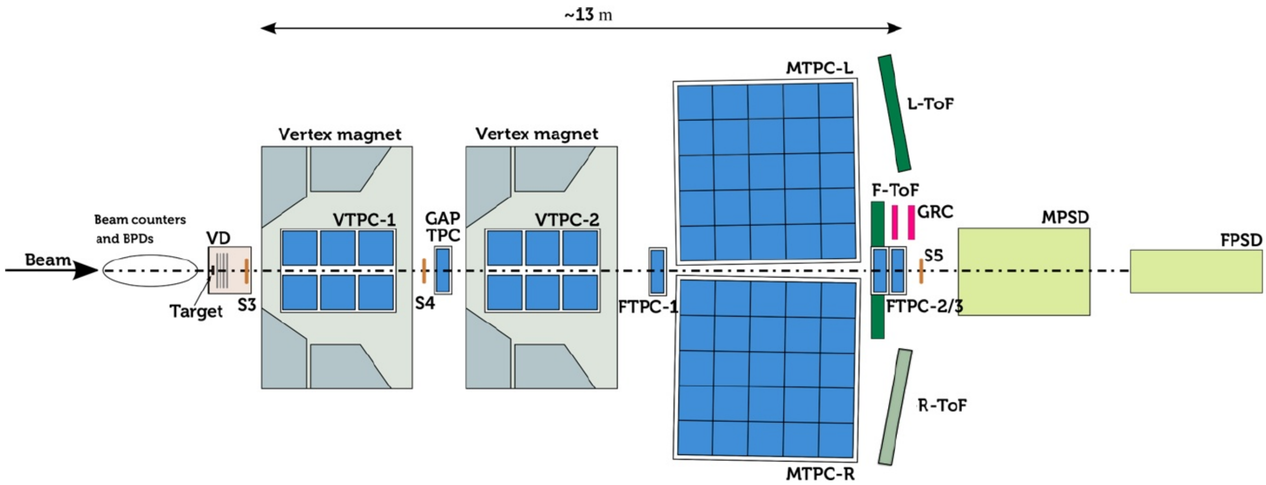

Fig. 1. Schematic layout of the NA61/SHINE setup after the upgrade was carried out during the shutdown of LS2. The light green sector (R-ToF) indicates the installation location of the right ToF arm of the MRPC detector.

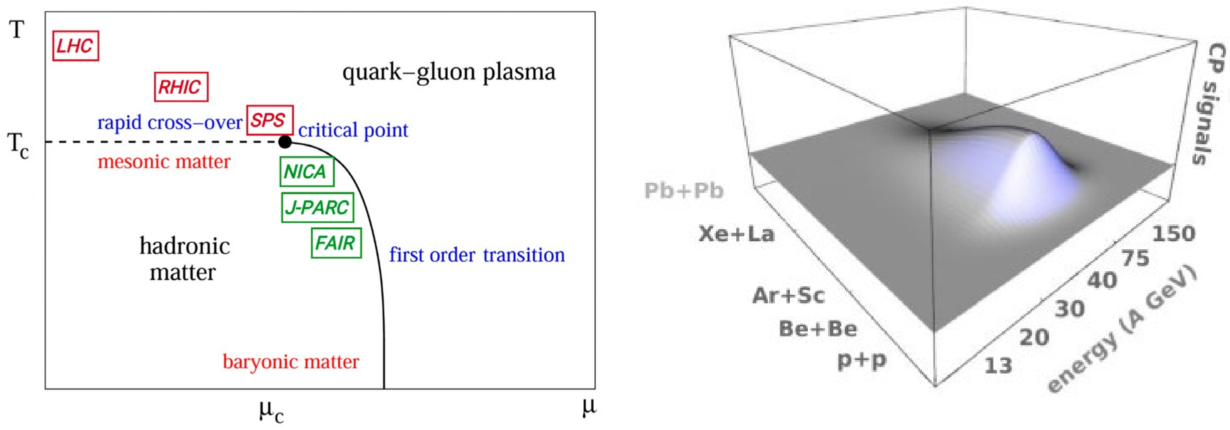

Fig. 2. Left: a hypothetical drawing of the phase diagram of a strongly interacting substance with a critical point, depicted as a function of the baryon chemical potential μ and temperature T. Right: a representation of the hill of fluctuations that could be observed in a beam momentum and system size scan, provided that the "freezeout" parameters "are close to the critical point.

2.2.2 Status of research.

In the period from 2022 to 2024, the NA61/SHINE collaboration accumulated record data statistics, largely due to the upgrading of the setup. Below are the main results in three areas of the experiment program for the period 2021-2024:

1. Study of the properties of the onset of deconfinement.

The early-stage statistical model [11] assumes a first-order phase transition from hadronic matter to quark-gluon plasma (QGP) in the energy range starting from AGS ($\sqrt{s_{NN}} \approx 5$ GeV) to SPS ($\sqrt{s_{NN}} \approx 17$ GeV). One of the predicted signs of the deconfinement transition is the “horn” structure, a non-monotonic change in the K^+/π^+ yield ratio as a function of collision energy, observed at $\sqrt{s_{NN}} \approx 8$ GeV. A similar structure was observed in data from the NA49 experiment in central Pb+Pb collisions [12]. NA61/SHINE expands the experimental data set with p+p, Be+Be and Ar+Sc collisions. In recent years, the experimental program has been expanded to include Pb+Pb collisions, where open charm production and collective effects are studied. Data on the interactions of Xe+La and Pb+Pb are currently being analyzed. One of the recent results of the collaboration is related to the obtaining of inclusive p_T spectra, distributions of rapidity and average multiplicities $\pi^\pm$, $K^\pm$, p and $\bar{p}$, produced in 0–10% central Ar+Sc collisions at 13A–150AGeV/c [13]. The energy dependence of the ratio of like-charged kaons to pions is presented, as well as the inverse slope parameter T in the entire phase region for the most central Ar+Sc collisions at different initial energies [13]. A compilation of NA61/SHINE and world data is presented in Fig. 3. As can be seen, for colliding systems up to A=45, the “horn” structure does not appear either in the central rapidity region (Fig. 3) or in the full phase space (Fig. 4). However, a clear difference is observed between the two sets of data: the results for p+p and Be+Be collisions show similar values and dependence on collision energy, while the data for Pb+Pb, Au+Au and Ar+Sc collisions show much higher ratios. K^+/π^+. Moreover, although the Ar+Sc data is clearly separated from small colliding systems, its energy dependence does not show the “horn” structure observed in the Pb+Pb and Au+Au reactions. The latest data on Xe+La interactions at 150 A GeV/c [14] are also shown in Fig. 3; the Xe+La points (preliminary) are close to the Pb+Pb/Au+Au results at similar energies.

Figures 3 and 4 show the energy dependence of the K^-/π^- ratio. Although the number of s and $\bar{s}$-quarks produced as a result of the collision is the same, their distribution among strange hadrons is strongly influenced by the large net baryon density characteristic of nuclear-nuclear collisions at SPS energies. Therefore, most of the s-quarks will be distributed in Λ-baryons, while in the case of $\bar{s}$ -quarks the production of $\bar{\Lambda}$ is strongly suppressed. Thus, the vast majority of s quarks are carried away in collisions by K^+ and K^0 mesons, which are expected to be produced in similar quantities. Therefore, K^+ yields are a more sensitive measure of strangeness content than K^- yields. Therefore, the K^-/π^- ratio is not expected to exhibit a characteristic maximum close to $\sqrt{s_{NN}} = 8$ GeV, “horn,” and all systems studied at SPS energies exhibit an approximately monotonic increase toward higher collision energies. It can be concluded that the data obtained for Ar+Sc interactions are very similar to the Pb+Pb data at high collision energies (75 A, 150 A GeV/c), and at low energies (<40 A GeV/c) they are more similar into small colliding systems.

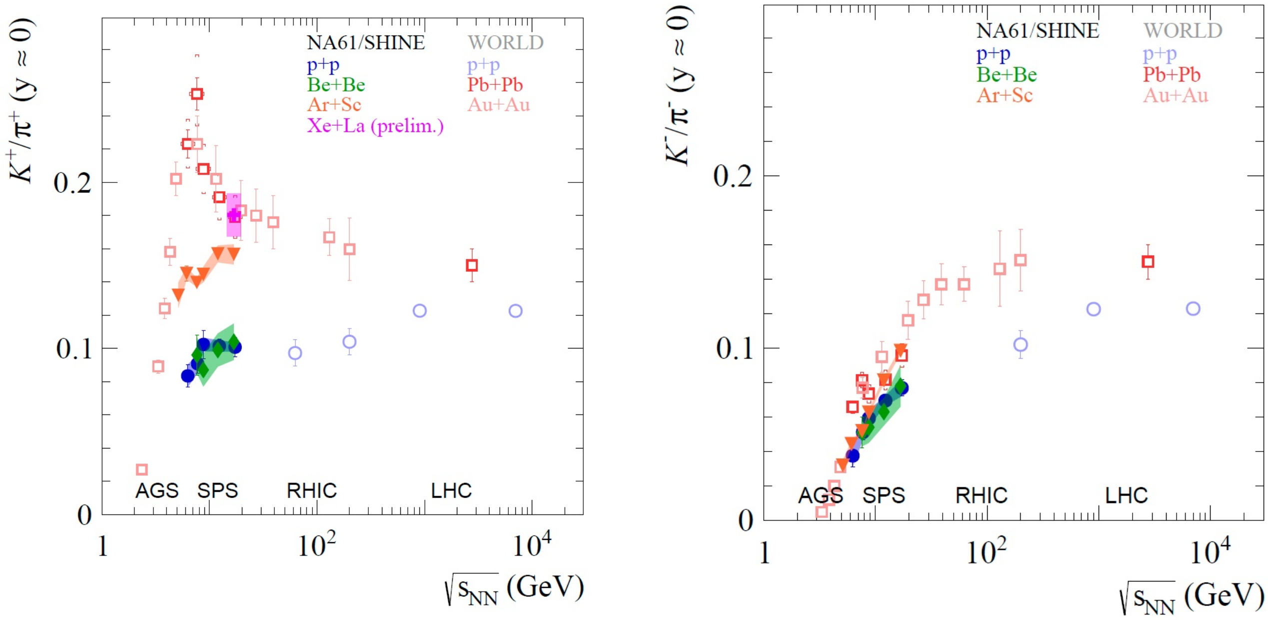

Fig. 3. Energy dependence of the ratio $K^{\pm}/\pi^{\pm}$ in the central rapidity region for positively (left) and negatively (right) charged particles for central Ar+Sc, Be+Be, Pb+Pb and Au+Au collisions, as well as inelastic p+ p interactions [13]. The point for Xe+La at 150 A GeV/c is preliminary.

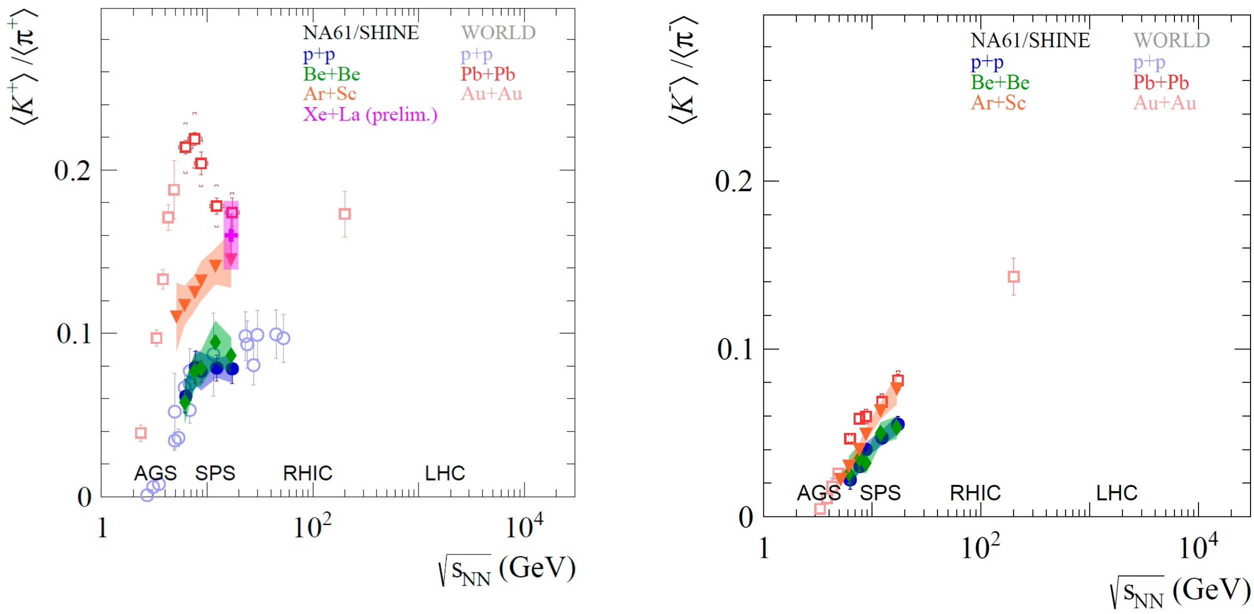

Fig. 4. Energy dependence of the average multiplicity ratio ⟨K⟩/⟨π⟩ of positively (left) and negatively (right) charged particles for central Ar+Sc, Be+Be, Pb+Pb and Au+Au collisions, as well as inelastic p+p interactions [13]. The point for Xe+La at 150 A GeV/c is preliminary.

In Fig. Figure 5 shows the spectrum of the K^+/π^+ ratio produced in the mid rapidity region and the spectrum of the inverse slope parameter T, extracted from fitting the transverse momentum spectra of the produced K^+ mesons depending on the size of the colliding system (in the figure <W> - the number of nucleons participating in the interaction). All graphs demonstrate similar threshold behavior, which cannot be explained by any of the presented models. The observed rapid change in the properties of hadron formation that start from the transition of Be+Be to Ar+Sc collisions at high SPS energies, indicates the beginning of the creation of large clusters of strongly interacting matter—fireballs.

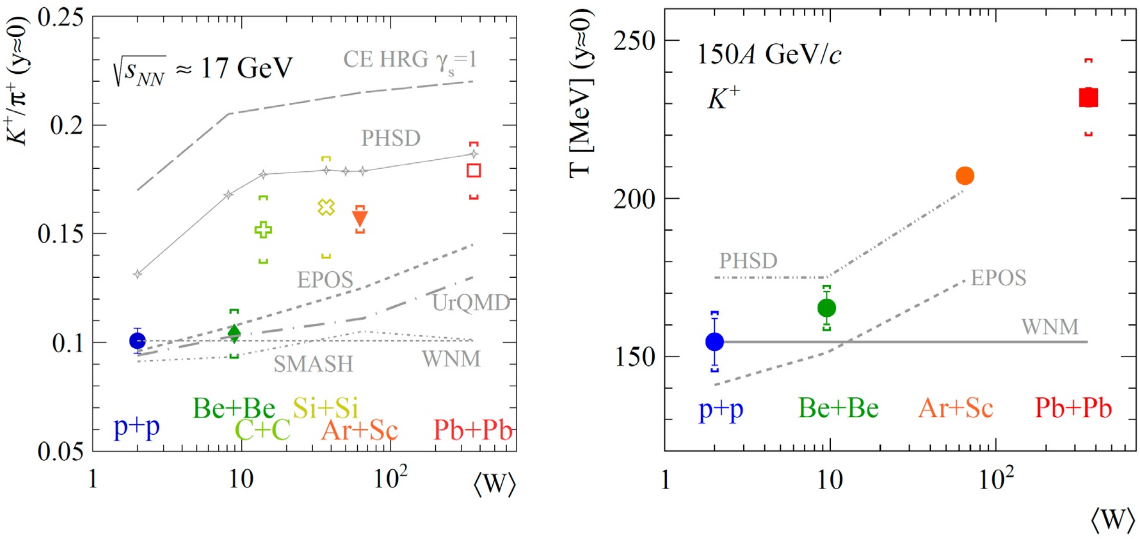

Fig. 5. Left: Dependence of the K^+/π^+ ratio on the size of the colliding system in the mid rapidity region, according to data from the NA61/SHINE collaborations in p+p, Be+Be, Ar+Sc and NA49 in Pb+Pb at 150 A (Be+ Be, Ar+Sc) or 158A (p+p, Pb+Pb) GeV/c compared to the dynamical and statistical models. Right: inverse slope parameter T extracted from p_T spectra of K^+-meson at similar collision energies [5].

2. Search for a hypothetical critical point on the QCD phase diagram.

The signal of the critical point can be the non-monotonicity of the dependence of various fluctuations and correlations in measurements. In Fig. Figure 6 shows the energy dependences of fluctuations of negatively charged hadrons (h^-) and the net electric charge ($h^+ - h^-$), measured in p+p, Be+Be and Ar+Sc collisions [15]. Comparison of fluctuations in systems of different sizes is possible using intensive quantities. For h^-, the cumulant ratios κ2/κ1[h^-] (scaled variance), κ3/κ2[h^-] (scaled skewness), and κ4/κ2[h−] (scaled kurtosis) are considered (reference value 1 is determined by the Poisson distribution). In the case of net electric charge, the first two ratios are slightly modified to maintain the existing significant differences between heavier and lighter systems. In the case of net electric charge, scaled skewness and scaled kurtosis suggest non-monotonic behavior within large systematic uncertainties.

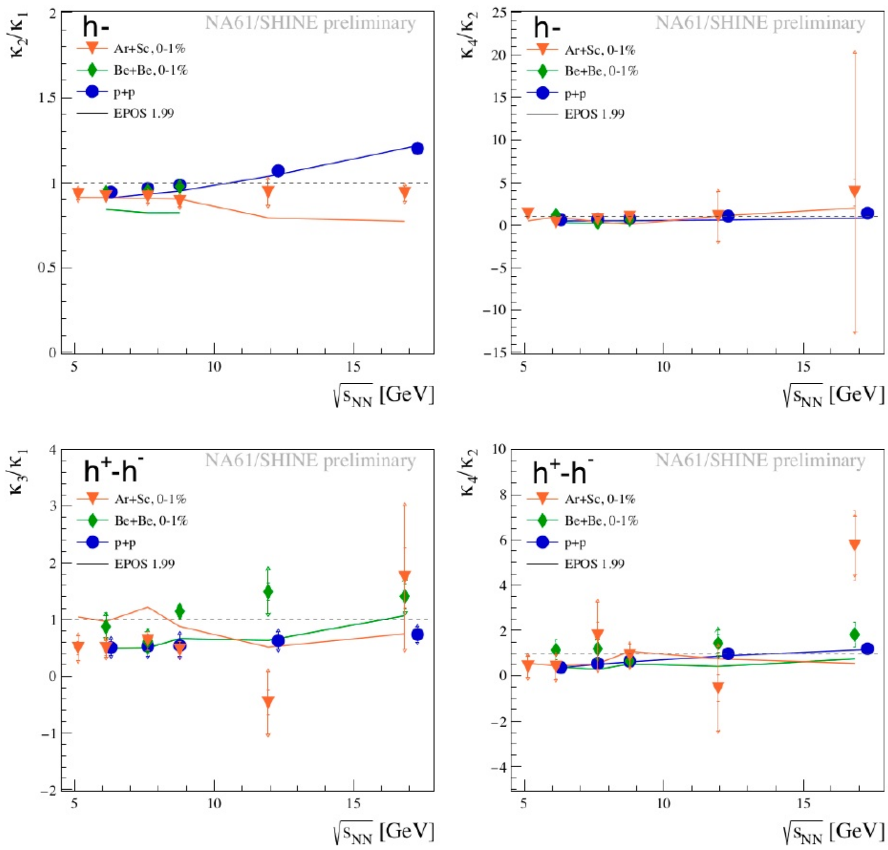

Fig. 6. Energy dependence of fluctuations of negatively charged hadrons (top 2 figures) and net electric charge (bottom two figures) in p+p, Be+Be and Ar+Sc collisions [15].

Another possible tool for finding the critical point is intermittency analysis. Typically, scaled factorial moments F_r are calculated from counted particles in transverse momentum space cells. Theory predicts [16] that if the system freezes near the critical point, then the scaled factorial moments should have a power-law dependence: $F_r(M) \sim M^{\varphi r}$, where M is the number of cells. Preliminary results on $F_2(M)$ of protons in the central region, measured in the 0–20% most central Ar+Sc collisions at 150 A GeV/c [17] and central Pb+Pb collisions at 13 A GeV/c, are presented in Fig. 7. Intermittency of negatively charged hadrons in central Pb+Pb collisions at a beam momentum of 30 A GeV/c up to the fourth scaled factorial moment is also shown in Fig. 7. Measured $F_2(M)$ of Ar+Sc protons at 150 A GeV/c and Pb+Pb at 13 A GeV/c, as well as $F_2(M)$, $F_3(M)$ and $F_4(M)$ of negatively charged hadrons in Pb+ Pb at 30 A GeV/c shows no evidence of a power-law increase with cell size that would indicate a critical point signal [18,19].

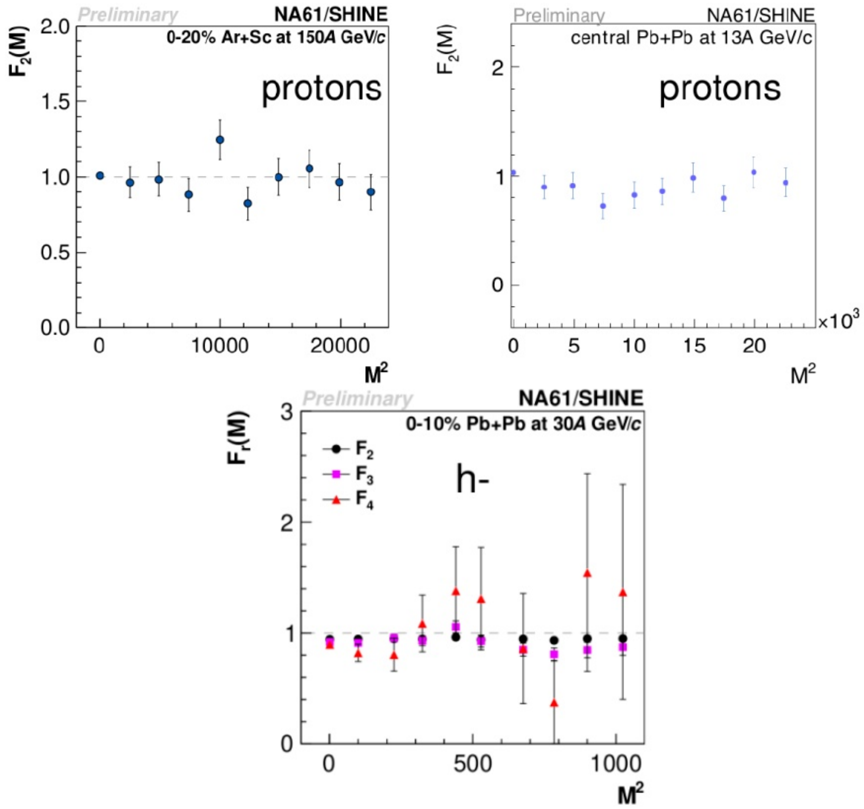

Fig. 7. Analysis of proton intermittency from the most central Ar + Sc collisions at 150 A GeV/c (top left) and the 0–10% most central Pb + Pb collisions at 13 A GeV/c (top right). Bottom: Preliminary results of the intermittency analysis of negatively charged hadrons from the most central Pb + Pb collisions at 30 A GeV/c.

The latest results related to the search for the critical point are the symmetric Lévy HBT correlations for pairs of pions with the same charge in central Ar + Sc collisions at a beam momentum of 150 A GeV/c, shown in Fig. 8 [20]. Here, instead of the usual Gaussian source shape, a more general Lévy-stable distribution is used. Its parameter α describes the shape of the source: for α = 2 the source is Gaussian, for α = 1 it is a Cauchy distribution, and the three-dimensional Ising model with a random external field predicts α = 0.5±0.05 for the critical system. It is clear from the figure that there is no indication of a critical point for central Ar+Sc collisions at maximum SPS energy.

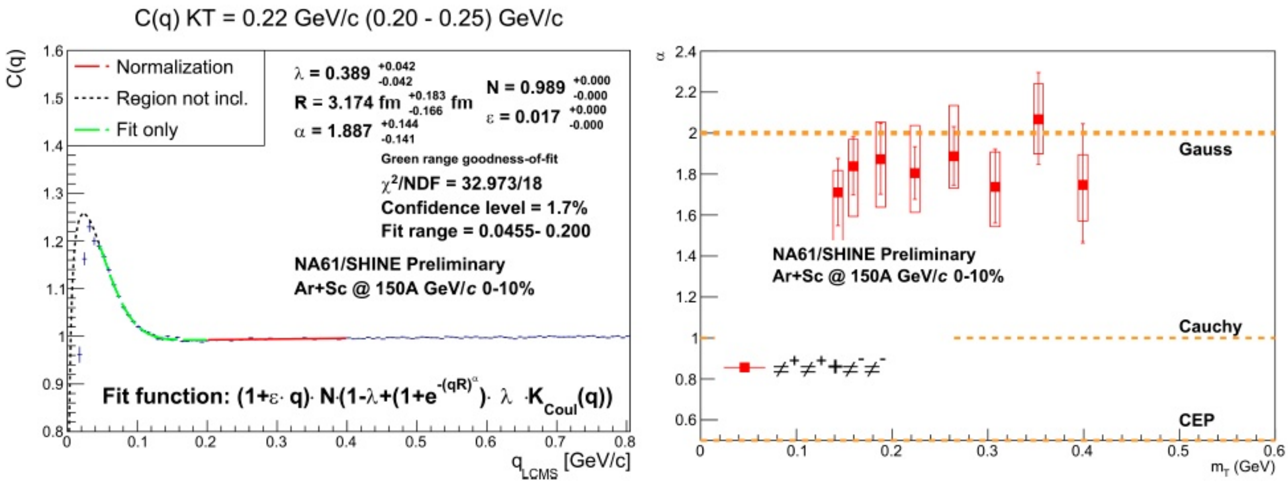

Fig. 8. Results from symmetric Lévy HBT correlations for pairs of pions with the same charge in central Ar+Sc collisions at a beam momentum of 150 A GeV/c. The left graph shows an example of a correlation function, and the right graph shows the dependence of the shape parameter of the selected source on the transverse mass of the pair.

Ongoing research to find the critical point using proton intermittency is summarized in a diagram of chemical freezeout temperature and chemical potential (Fig. 9) [21]. Intermittance analysis for other reactions obtained by the NA61/SHINE program for strong interactions has been completed in full, and new results should be expected soon.

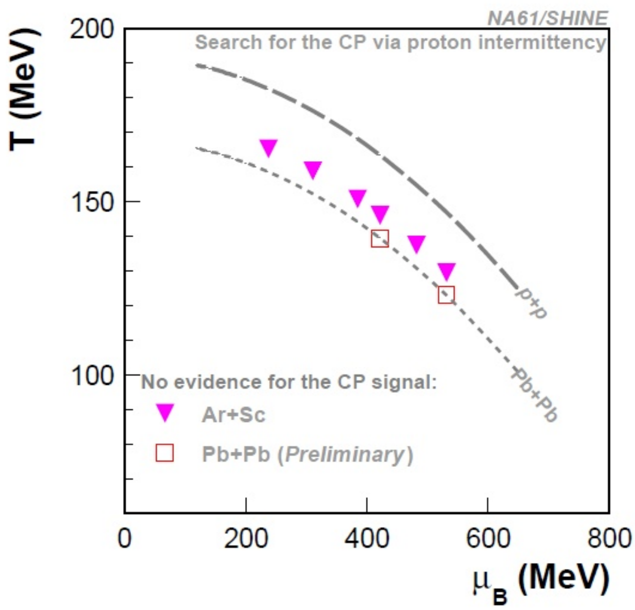

Fig. 9. Diagram of chemical freezeout temperature and baryon-chemical potential. The dotted line indicates the parameters in p+p interactions, the dotted line in central Pb+Pb collisions. Colored dots indicate reactions (Ar+Sc and Pb+Pb) on the T-μB phase diagram for which a search for a critical point was carried out, but no evidence of the existence of a critical point was found.

New data on hadron spectra in p+p reactions.

In Fig. Fig. 10 presents some of the latest results on the rapidity spectra of neutral kaons: $K^*(892)^0$ at beam momenta of 40 and 80 GeV/c [22] compared to 158 GeV/c [23] and K_S^0 at energies $\sqrt{s_{NN}}$ 17.3, 12.3, 8.8 and 7.7 GeV [24]. This data will, on the one hand, serve as a reference for future data from larger systems, and on the other hand, will serve as input to models that attempt to describe the production of strangeness at SPS energies. Statistically supported data from p+p collisions at an energy of 158 GeV/c allowed more complex measurements of the production of hyperons Ξ(1530)0 and $\bar{\Xi}(1530)^0$ [25], which are the only such results at the SPS energy. The first two-dimensional spectra Ξ(1530)0 and $\bar{\Xi}(1530)^0$ [25] are presented in Fig. 11.

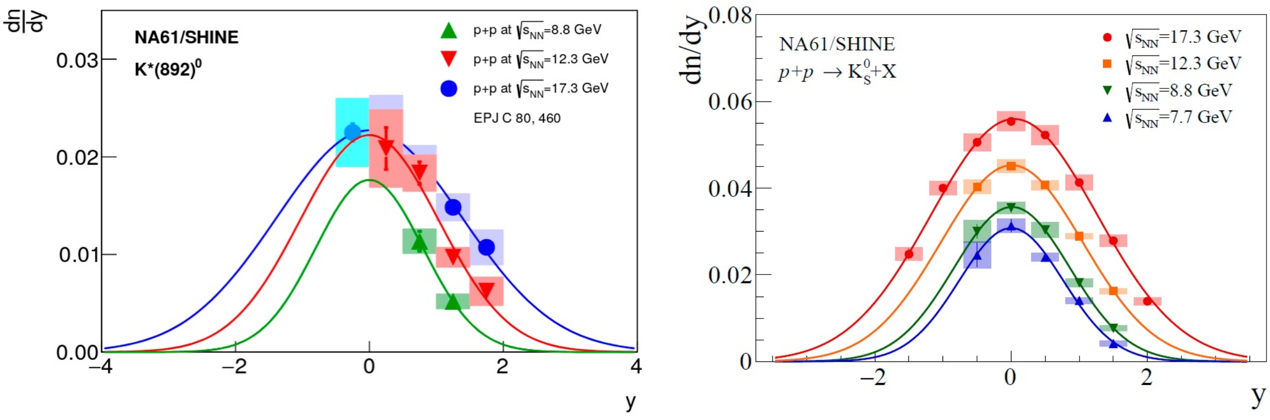

Fig. 10. Rapidity spectra of neutral kaons produced in p + p collisions: $K^*(892)^0$ at beam momenta of 40 and 80 GeV/c [22] in comparison with data for 158 GeV/c [23] (left), K_S^0 at initial energies $\sqrt{s_{NN}}$ 17.3, 12.3, 8.8 and 7.7 GeV (right).

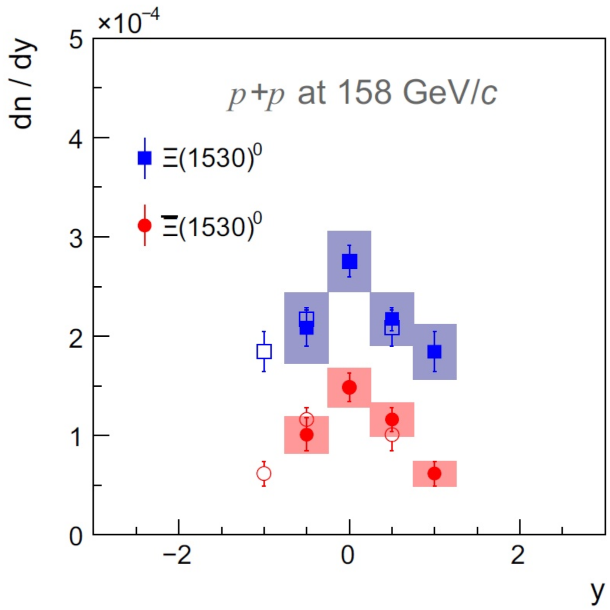

Fig. 11 Rapidity spectra $\Xi(1530)^0$ (blue squares) and $\bar{\Xi}(1530)^0$ (red circles) produced in inelastic p+p interactions at an energy of 158 GeV/c.

An unexpected excess of the production of charged $K^{\pm}$ mesons over neutral K^0 mesons in central Ar+Sc collisions at an energy of $\sqrt{s_{NN}}$=11.9 GeV was discovered [26]. Experimental data show the predominance of the production of K-mesons containing $(u,\bar{u})$ over mesons containing $(d,\bar{d})$ in the kinematic range available for measurement. In the mid rapidity region, the relative excess of charged mesons is (23.3±5.5)%. Earlier data from other experiments in the collision energy range $5 < \sqrt{s_{NN}} < 200$ GeV, although with large errors, are consistent with the present result (Fig. 12). The origin of this unexpected excess remains to be determined.

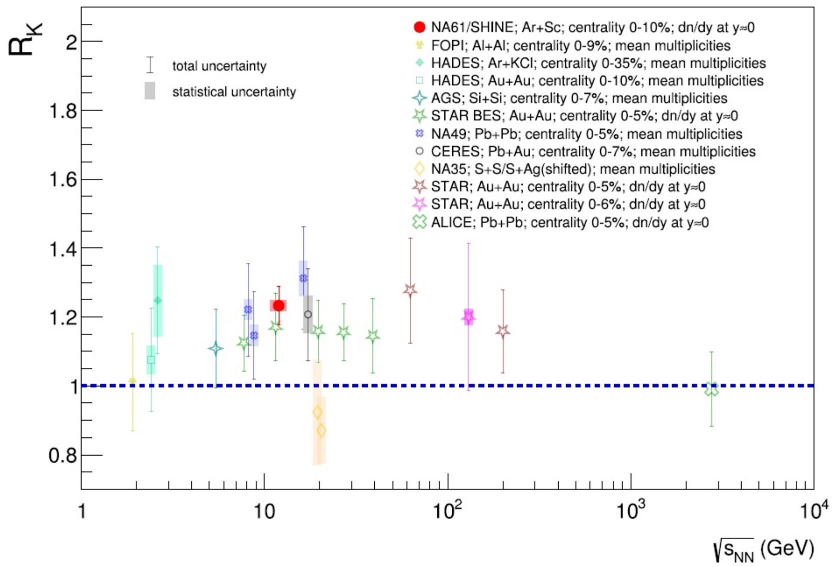

Fig. 12. The ratio of the yields of charged and neutral K-mesons in nuclear-nuclear collisions depending on the collision energy. The NA61/SHINE measurement is shown as a red dot [26].

Recently, the strong interaction program of the NA61/SHINE experiment was expanded by measurements of open charm production, mainly D mesons, in Pb+Pb interactions. The average multiplicity of charm quarks $\langle c\bar{c} \rangle$ produced in full phase space as a result of heavy ion collisions is not yet known and needs to be measured. The acceptance of the NA61/SHINE detector is large enough to extrapolate measurements to full phase space with relatively small errors. This unique feature makes

NA61/SHINE the only experiment that will be able to perform such measurements in the CERN SPS energy region. To address the challenges associated with the required spatial resolution of primary and secondary vertex reconstruction, the NA61/SHINE setup was upgraded with a pixel vertex detector. Using this detector, it will be possible to reconstruct the decays of D-mesons at a distance of ≈ 1 mm from the point of primary interaction. Between 2022 and 2023 statistics of about 180 million events of Pb+Pb interactions at an energy of 150 A GeV/s have been collected. In the medium-term experimental program, it is planned to increase statistics to 500 million trigger events over 7 weeks of beam time in the period from 2024 to 2025 [27].

3. Recent results from the neutrino program of the NA61/SHINE experiment

For many years, the NA61/SHINE collaboration has been implementing a hadron production measurement program for the long-baseline neutrino oscillation experiments at J-PARC and Fermilab (FNAL). These measurements improve knowledge of the neutrino flux produced in neutrino beams at accelerators. NA61/SHINE measures total cross sections and differential hadron yield spectra on thin targets and replicas of the T2K experiment target. NA61/SHINE also performs hadron production measurements needed to interpret extensive air shower (EAS) data at ultra-high energies, and measures production and fragmentation cross sections to understand galactic cosmic ray (GCR) data.

The interaction of 120 GeV/c protons with carbon is of particular interest to neutrino research teams because it represents the primary interaction that forms the neutrino beam at Fermilab to provide the neutrino physics of the MINERvA and NOvA experiments. This interest motivated the development of the Forward TPC (FTPC) system on the NA61/SHINE facility (see Figure 1).

The collaboration obtained data on the production of charged and neutral hadrons in p+C interactions with an energy of 120 GeV/c. The results are available for use in simulators and are included in Fermilab's neutrino flux prediction package PPFX [28].

An analysis of neutral hadrons was performed in 2022 and published in 2023. The results of [29] included the measured yields of K_S^0, Λ and $\bar{\Lambda}$, identified using invariant masses and selection of momentum asymmetry from reconstructed two-particle secondary vertices (Fig. 13). The results are the first measurements for this process at this energy. Recently, measurements of the production of charged hadrons in p+C interaction events with an energy of 120 GeV/c were carried out [30]. The data will also be used in the near future to improve estimates of neutrino fluxes in Fermilab experiments.

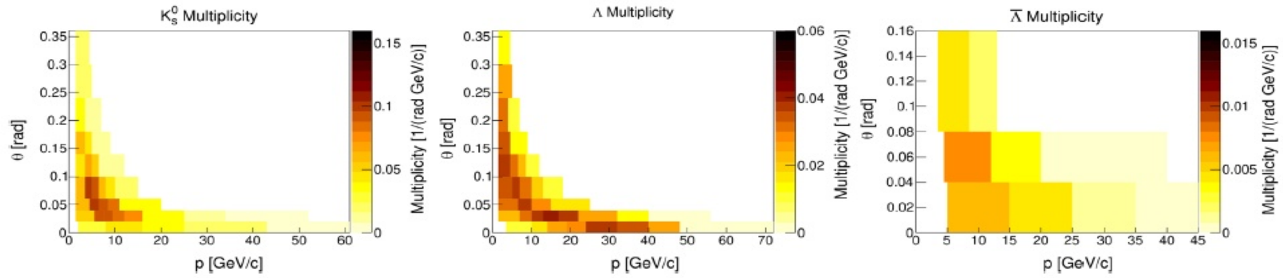

Fig. 13. Two-dimensional distributions according to the multiplicity of born K_S^0, Λ and $\bar{\Lambda}$.

The results of measurements of the spectra $\pi^{\pm}$, $K^{\pm}$, p, $\bar{p}$, Λ, $\bar{\Lambda}$ and K_S^0 produced in the interactions of negatively charged pions with carbon nuclei at beam momenta of 158 and 350 GeV/s were obtained [31]. Thus, together with recent results on the production of ρ_0, ω and K_0^* mesons in π^-+C interactions [32], studies of hadron production have been successfully completed to understand air showers induced by ultra-high-energy cosmic rays. The spectra measured by NA61/SHINE provide a unique reference data set with unprecedented precision and large phase space coverage for tuning models of particle production in extensive air showers. As an example, the spectra of produced antiprotons are shown in Fig. 14.

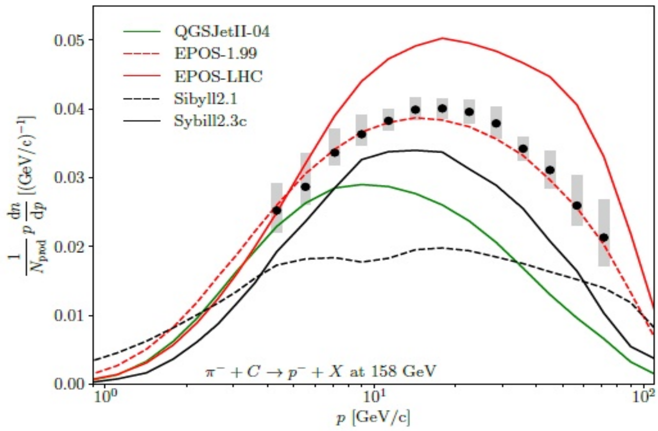

Fig. 14. Spectrum of transverse momenta of produced antiprotons in π^-+C interactions at an energy of 158 GeV/c in comparison with model predictions.

In 2018, the feasibility of fragmentation studies was demonstrated. The total cross section for the production of B [32] and ^{11}C [34] nuclei in the ^{12}C+p reactions at an energy of 13.5 A GeV/c was obtained using polyethylene and graphite targets. More recently, the production cross sections for boron isotopes (^{11}B and ^{10}B) were measured [35].

Physicists from the JINR group also carried out original research using the approach to studying relativistic nuclear interactions in four-dimensional velocity space, which was previously developed by Academician A.M. Baldin. The principles of similarity and self-similarity turned out to be very fruitful in the study of nuclear interactions at high energies [36, 37]. Previously [38], a modified approach was successfully applied to describe the inclusive spectra of produced pions and kaons at the mid rapidity region in p+p interactions. The essence of the modification of the self-similar approach is to include quark-gluon dynamics in the production of hadrons in nucleon-nucleon interaction in the rapidity region y = 0. The resulting calculations showed a fairly successful description of the ratios of the yields of kaons ($K^{\pm}$) and pions ($\pi^{\pm}$) in a wide range of initial energies, up to the LHC. It is worth noting that this approach is sensitive, especially in the energy region of 8 GeV, to the mass number of colliding nuclei (A-dependence). Recently, it was proposed to describe the NA61/SHINE collaboration spectra of produced charged pions and kaons in the mid rapidity region in the most central Be+Be collisions. A satisfactory description of both the inclusive p_T spectra $\pi^{\pm}$ and $K^{\pm}$ and the ratios of the total yield of kaons and pions as a function of the initial energy was obtained [39]. The results of the calculations are presented in Fig. 15 compared to other model predictions. The first results of applying the Dubna approach to describing new data from the collaboration on the production of charged kaons at mid rapidity in Ar+Sc collisions were obtained [40].

Calculations of the Dubna approach BMLZ (Baldin-Malakhov-Lykasov-Zaitsev model) gave satisfactory results in describing the experimental data on the ratios of antiproton yields to proton yields ($\bar{p}/p$), antideuterons to deuterons ($\bar{d}/d$) and antihelium-3 to helium -3 ($\overline{He^3}/He^3$). It was shown that, taking into account the stopping effect, the experimental data are well described with one constant C_2 = 0.146 for p+p, Be+Be, S+S, Cu+Cu, Au+Au, Pb+Pb collisions in a wide energy range from ISR to LHC [41].

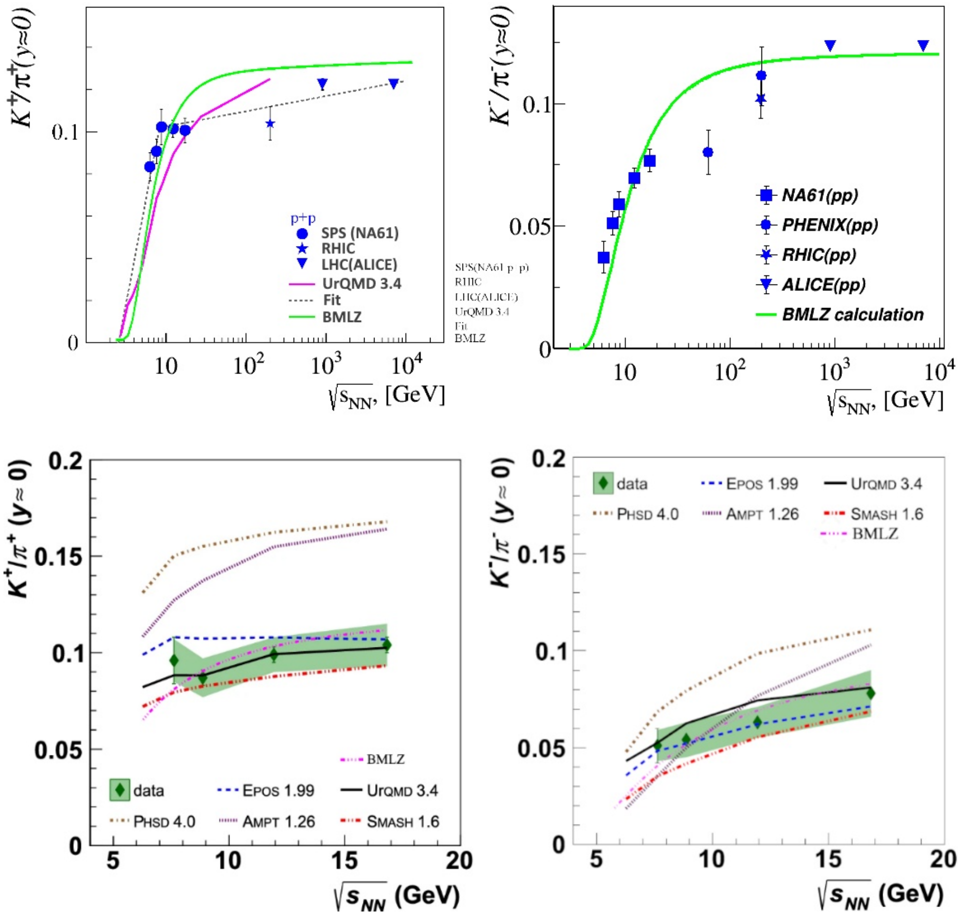

Fig. 15. $K^{\pm}/\pi^{\pm}$ ratios in inelastic pp interactions (top pictures) and the most central BeBe collisions (bottom pictures) in the mid rapidity region. Curved lines indicate model predictions, including the Dubna model - BMLZ (Baldin-Malakhov-Lykasov-Zaitsev model).

As part of one of the most advanced microscopic transport approaches, Parton-Hadron-Quantum-Molecular Dynamics (PHQMD), designed to describe complex processes of heavy ion collisions, developers, incl. physicists of the JINR group use a cluster search algorithm together with a "stabilization" program in the form of the so-called. "afterburner" due to QMD dynamics limitations. Recognizing the potential for improvement, the team decided to focus on replacing the existing stabilizing routine with a fully dynamic cluster search routine. This modification is necessary to improve the accuracy and realism of our simulations by tracking the dynamic evolution of clusters throughout the collision process. Conducting rigorous testing using simulated and experimental data on heavy ion collisions will confirm the effectiveness of the improved approach.

This evolution of the description of cluster formation within the PHQMD transport approach will not only establish the basis for more accurate and realistic simulations in the challenging domain of high-energy physics, but will also improve understanding of the dynamics of heavy ion collisions.

Currently, data from the NA49 experiment have made it possible to provide, within the framework of the PHQMD approach, the first indications of the mechanism of formation of light nuclei in a hot and dense environment. However, due to instrumental limitations and the wide extrapolation range of deuteron transverse momentum spectra, new, more accurate measurements from the NA61/SHINE experiment are required for reliable conclusions.

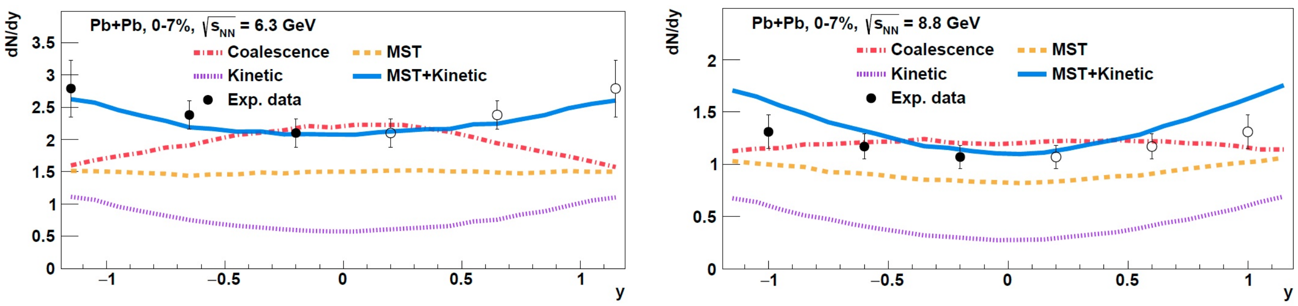

Fig. 16. Deuteron rapidity distribution for the most central Pb+Pb collisions according to the NA49 collaboration data at E_{lab} collision energies of 20 and 40 A GeV in comparison with PHQMD calculations for various scenarios [42].

2.2.3 Setup modification

The NA61/SHINE experimental facility is a multi-purpose spectrometer designed to study hadron production in various types of collisions. An important feature of the installation are four large-volume time projection chambers (TPCs). Two vertex champers (VTPC), located in a magnetic field, together with two main chambers (MTPC) are the main tracking devices and are capable of recording a large number of particle tracks (up to 1500 in central Pb+Pb collisions). Four smaller TPCs: GAP-TPC and 3 Forward-TPC (FTPC) are located along the beam line. This setup provides precise momentum measurements of charged particles and allows particle identification, complementing the information from time-of-flight (ToF) detectors. The farthest detectors on the beam line are hadron calorimeters (MPSD and FPSD). Information from these detectors is used to determine centrality in nucleus-nucleus collisions with very good accuracy. Beam particles are measured by a set of beam position detectors (BPDs). These are used to measure the beam trajectory as well as identification of beam particles.

During the long shutdown (LS2) at CERN, the NA61/SHINE facility was significantly modified. Upgrading of the NA61/SHINE detector included the following: replacement of the time-projection system readout electronics; creation of a new vertex detector (VD); development of a new time-of-flight system (ToF-L/R); production of new beam position detectors; creation of a reference chamber for drift velocity measurements in TPC (GRC); modernization of the hadron calorimeter; commissioning of the data acquisition system; introduction of a new trigger system; integration of a readout system based on the DRS4 chip. A schematic representation of the upgraded NA61/SHINE facility is shown in Fig. 1. The main goal of upgrading the installation was to significantly increase the data acquisition rate from 80 Hz to 1.6 kHz, which is important for the open charm measurement program. In 2022, the updated NA61/SHINE installation was successfully launched, which made it possible to collect record data statistics for all three experimental programs in a short period of beam time (180 million trigger events were recorded in the "target IN" mode in 6 weeks). The significant effort that the NA61/SHINE collaboration has invested in upgrading the detector is opening up new opportunities for physics research and will keep the NA61/SHINE experiment running for the next several years.

A group of JINR employees made a significant contribution to the modernization of the facility, namely, they were responsible for the development, creation and commissioning of a 1728-channel time-of-flight (ToF-L) system with high time resolution (~ 50 ps) [43]. The previous TOF system consisted of two walls, each of which had 891 scintillation detectors [44]. One of the walls was developed at JINR. The average time resolution was 75 ps, which ensured the separation of kaons from pions up to a momentum of 8 GeV/s. After 20 years of operation, most parts of the system would require significant reconstruction. In this regard, it was decided to replace the old system with a new ToF system based on multi-gap resistive plate chambers (MRPCs) of the BM@N type, which became possible thanks to a grant from the JINR Directorate. The design of the new NA61/SHINE time-of-flight system will consist of two symmetrical L/R-ToF modules (Fig. 17). The left arm of the ToF (L-ToF) system was brought into service during the long shutdown period (LS2) from 2019 to 2021. The left arm readout system is designed based on 32-channel DRS4 modules with analog electronics. In total, the L-ToF module consists of 1920 channels. The presence of a second arm (R-ToF) will completely cover the necessary acceptance of the NA61/SHINE facility. Production of all elements of the second arm of R-ToF (also based on mRPC technology) is largely completed and field installation is expected shortly. The main candidate for the role of a second-arm readout system is the picoTDC ASIC. In 2023, the mRPC detector was tested with picoTDC readout at an R-ToF system site to determine its performance [45].

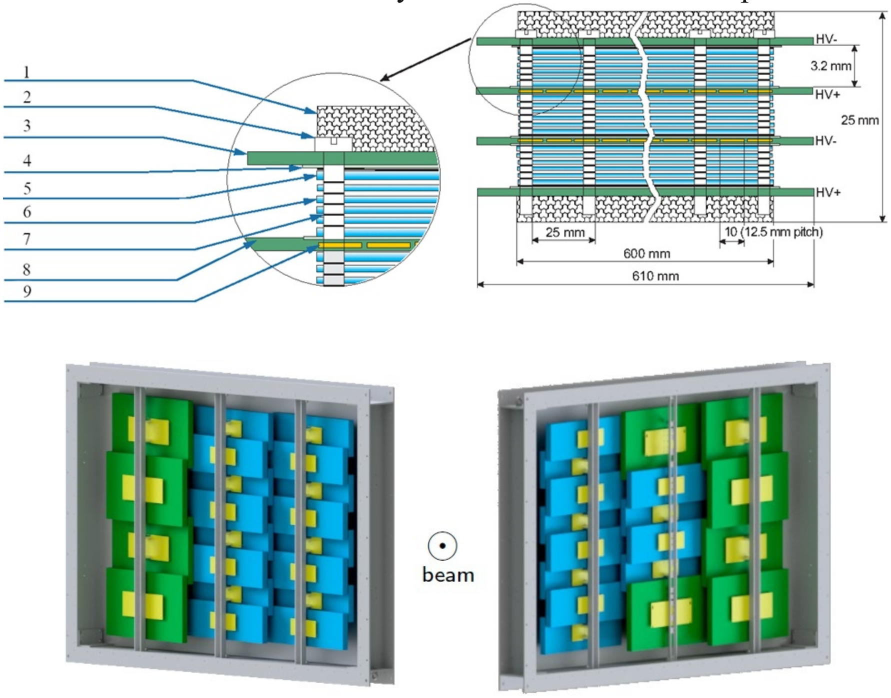

Fig. 17. Top picture: schematic diagram of the MRPC detector. 1 - honeycomb panel (5 mm), 2 - plastic screw, 3 - external printed circuit board (1 mm, 4 - mylar film (1 micron), 5 - external glass with conductive paint (420 microns), 6 - internal glass (280 μm), 7 - fishing line (200 μm), 8 - printed circuit board with strips (1.5 mm), 9 - strip. Bottom picture: schematic representation of two ToF modules.

2.2.4 Work plans

The extensive statistics already accumulated at various energies and the wide range of colliding nuclei allow us to obtain a large number of planned physical results. The Dubna group plans in the period from 2025 to 2029 take an active part in obtaining and analyzing data in all experimental programs of the NA61/SHINE project and in particular:

- production of light nuclei in nuclear interactions
- production of hyperons in interactions Be+Be, Ar+Sc, Xe+La, Pb+Pb (Identification and reconstruction of spectra of Λ-hyperons in Ar+Sc and Xe+La collisions at 30A and 150A·GeV as the first step towards studying the formation of hypernuclei);
- production of antimatter in nucleus-nuclear interactions;
- production of the open and hidden charm particles in the interaction of heavy ions;
- neutrino program (responsibility of a group from the Laboratory of Nuclear Problems);
- commissioning of a new time-of-flight system based on MRPC will be completed.

Presentations at international meetings, conferences and publication of scientific articles are planned. Based on the results of the NA61/SHINE experiment and the NICA project, it is planned to prepare candidate and doctoral dissertations.

Beam time plans for 2025:

The collaboration made a request for a lead beam for open charm measurements. Thus, the program for 2025 includes:

Physics with lead beam:

The measurements requested for 2025 are a continuation of the open charm measurements using a lead beam. Assuming successful ion data collection in 2024, it is expected that four weeks of Pb beam at 150 GeV/c will be required to complete the program of measurements of charm hadrons in Pb+Pb collisions [46,47].

Physics with hadron beams:

NA61/SHINE is considering requesting hadron beams in the summer of 2025. Two types of measurements are discussed: neutrinos, cosmic rays, and strong interaction physics. Measurements with low energy hadron beams, discussed in the appendix [48], and measurements with a proton beam at 300 GeV/c. The first requires the construction and commissioning of the low-energy branch of the H2 beamline, and the second requires the commissioning of the MRPC (right arm) time-of-flight detector.

2.2.5. Area of responsibility of the JINR group

JINR contributions/responsibilities:

- creation of a TOF system based on MRPC;
- ToF-L and overall facility maintenance during data taking ToF-R commisioning
- participation in trigger R&D
- service and further development of calibration software
- reconstruction chain in the SHINE framework
- data analysis.

2.2.6 Publications and dissertations

For the period 2020-2024. project participants defended two candidate dissertations:

1. Kireev V. “Study of the processes of hadron production, formation of nuclei and hypernuclei in collisions of heavy ions in the PHQMD model”, 2023, JINR Dubna.
2. Ilieva S. “Measurement of the production cross section of 31 GeV/c protons on carbon via beam attenuation in a 90-cm-long target” 2021

Preparations are underway for the defense of two candidate and one doctoral theses.

Publications:

1. NA61/SHINE Experiment. New Results and Future Plans, JINR news, No.1, (2023), pp.17-21
2. V. Babkin, V.A. Baskov, A. Burdyko, M. Buryakov, S. Buzin, A. Dmitriev, V.A. Dronov,P. Dulov, V. Golovatyuk, R. Kolesnikov, A.I. L’vov, A. Malakhov, V.V. Polyansky, M. Rumyantsev, Beam test results of the MRPC prototype for the new NA61/SHINE ToF system //Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 1034 (2022) 166735.
3. Time-of-Flight System for Particle Identification in NA61/SHINE experiment at CERN (2024), to be published
4. Signal classification algorithms for the MRPC with DRS4 readout (2024), to be published
5. Test of the mRPC with picoTDC readout for the new NA61/SHINE ToF system (2024), to be published
6. Kireyeu V. et al. Cluster formation near midrapidity--can the mechanism be identified experimentally? //arXiv preprint arXiv:2304.12019. – 2023, accepted for publication in Phys. Rev.C
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15. G.I. Lykasov, A.I. Malakhov and A.A. Zaitsev, Production of charged kaons in ArSc collisions arXiv:2402.03260, to be published

Collaboration papers:

16. NA61/SHINE Collaboration, Search for a critical point of strongly-interacting matter in central 40Ar +45Sc collisions at 13A-75A GeV/c beam momentum, arXiv:2401.03445 [nucl-ex]
17. NA61/SHINE Collaboration, Multiplicity and Net-Charge Fluctuations in Ion+Ion Collisions at the SPS Energies, Moscow University Physics Bulletin. 77 (2022) 2, 178-179
18. NA61/SHINE Collaboration, Measurement of hadron production in π--C interactions at 158 and 350 GeV/c with NA61/SHINE at the CERN SPS, Physical Review D 107.6 (2023): 062004.
19. NA61/SHINE Collaboration, Measurements of KS0, Λ, and Λ¯ production in 120 GeV/c p+C interactions, Physical Review D 107.7 (2023): 072004
20. NA61/SHINE Collaboration, Two-pion femtoscopic correlations in Be+Be collisions at sNN=16.84 GeV measured by the NA61/SHINE at CERN, EPJ C 83.10 (2023): 919.
21. NA61/SHINE Collaboration, Search for the critical point of strongly-interacting matter in 40Ar + 45Sc collisions at 150A GeV/c using scaled factorial moments of protons, EPJ C 83.9 (2023): 881.
22. NA61/SHINE Collaboration, Measurements of π+, π−, p, p¯, K+ and K− production in 120 GeV/c p + C interactions, arXiv:2306.02961 [hep-ex]
23. NA61/SHINE Collaboration, Femtoscopic Correlation Measurement with Symmetric Lévy-Type Source at NA61/SHINE, Universe 9.7 (2023): 298
24. NA61/SHINE Collaboration, Measurements of π±, K±, p and p¯spectra in 40Ar+45Sc collisions at 13A to 150A GeV/c, arXiv:2308.16683 [nucl-ex]
25. NA61/SHINE Collaboration, Excess of charged over neutral K meson production in high-energy collisions of atomic nuclei, arXiv:2312.06572 [nucl-ex]
26. NA61/SHINE Collaboration, Measurements of higher-order cumulants of multiplicity and net-electric charge distributions in inelastic proton-proton interactions by NA61/SHINE, arXiv:2312.13706 [hep-ex]

2.2.7. Authors' scientific experience

The authors of the project have extensive scientific experience. A. Malakhov, G. Melkumov and G. Lykasov have doctoral degrees and participate in the study of problems of relativistic nuclear physics. Six young employees also actively participated in the project. Four of them - M. Buryakov, A. Dmitriev, R. Kolesnikov and M. Rumyantsev - are developing a time-of-flight system for the NA61/SHINE project based on MRPC detectors. MRPC team members use knowledge gained from R&D and operation of ToF systems for the NICA project. The remaining two employees - V. Kireev, A. Zaitsev - actively participated in the analysis of experimental data and their theoretical interpretation. Everyone has publications and plans to prepare candidate and doctoral dissertations.

2.2.8 Strengths, weaknesses, opportunities, threats

Strengths of the project:

• completion of the creation of a high-resolution TOF wall;
• compliance with the particle physics program;
• the presence of a modern experimental setup with unique parameters;
• a large amount of experimental data has been collected on proton-nucleus and nuclear-nucleus interactions in a wide energy range (from 13 to 158A GeV)
• extensive experience in analyzing experimental data;
• a large number of young employees;
• opportunity to train young people for the NICA project.

It was hardly possible to find any weak points in the project. The project has the opportunity to attract more young physicists who will also study for the NICA megascience project.

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2.3 Estimated completion date
2025-2029

2.4 Participating JINR laboratories
Veksler and Baldin Laboratory of High Energy Physics (VBLHEP)
Dzhelepov Laboratory of Nuclear Problems (DLNP)

2.4.1 MICC resource requirements

Computing resources	Distribution by year				
	1st year	2nd year	3rd year	4th year	5th year
Data storage (TB) - EOS - Tapes					
Tier 1 (CPU core hours)					
Tier 2 (CPU core hours)					
SC Govorun (CPU core hours) - CPU - GPU					
Clouds (CPU cores)					

2.5. Participating countries, scientific and educational organizations

Organization	Country	City	Participants	Type of agreement
Institute of Physics and Technology of Mongolian Academy of Sciences	Mongolia	Ulaanbaatar	B.Baatar, Ts. Baatar, M.Sovd, N. Khishigbuyan, B. Otgongerel, M. Urangua	Agreement
Sofia University “St. Kliment Ohridski”	Bulgaria	Sofia	M. Bogomilov, D. Kolev, S. Ilieva, R. Tsenov	Agreement
The American College	India	Madurai	N. Marimuthu, S. Sanila	Agreement

2.6. Key partners *(those collaborators whose financial, infrastructural participation is substantial for the implementation of the research program. An example is JINR's participation in the LHC experiments at CERN).*

3. Manpower
3.1. Manpower needs in the first year of implementation

№№ n/a	Category of personnel	JINR staff, amount of FTE	JINR Associated Personnel, amount of FTE
1.	research scientists	5.2	
2.	engineers	1.0	

3.	specialists		
4.	office workers		
5.	technicians		
	Total:	**6.2**	

3.2. Available manpower
3.2.1. JINR staff

No.	Category of personnel	Full name	Division	Position	Amount of FTE
1.	research scientists	Golovatyuk V.M.	VBLHEP	Head of Dep.	0.1
		Dmitriev A.V.	VBLHEP	Researcher	0.8
		Zaitsev A.A.	VBLHEP	S. Researcher	0.6
		Kireyeu V.A.	VBLHEP	Researcher	0.4
		Krasnoperov A.V.	DLNP	S. Researcher	0.1
		Lykasov G.I.	DLNP	L. Researcher	0.3
		Lyubushkin V.V.	DLNP	S. Researcher	0.1
		Malakhov A.I.	VBLHEP	Head of Dep.	0.4
		Matveev V.A.	JINR management	Scientific director	0.1
		Melkumov G.L.	VBLHEP	L. Researcher	1.0
		Popov B.A.	DNLP	S. Researcher	0.9
		Rumyantsev M.M.	VBLHEP	Researcher	0.3
		Tereshchenko V.V.	DNLP	Head of Gr.	0.1
2.	engineers	Buryakov M.G.	VBLHEP	L. Engineer	0.3
		Kolesnikov R.Yu.	VBLHEP	L. Engineer	0.7
3.	specialists				
4.	technicians				
	Total:				**6.2**

3.2.2. JINR associated personnel

No.	Category of personnel	Partner organization	Amount of FTE
1.	research scientists		
2.	engineers		
3.	specialists		

4.	technicians		
	Total:		

4. Financing
4.1 Total estimated cost of the project 950 k$
The total cost estimate of the project (for the whole period, excluding salary).
The details are given in a separate table below.

4.2 Extra funding sources
Expected funding from partners/customers – a total estimate.

Project Leader __________/Malakhov A.I./

Date of submission of the project to the Chief Scientific Secretary: _________
Date of decision of the laboratory's STC: _________ document number: _________

Year of the project start: ________________

(for extended projects) – Project start year: _______

Proposed schedule and resource request for the Project NA61/SHINE

Expenditures, resources, funding sources			Cost (thousands of US dollars)/ Resource requirements	Cost/Resources, distribution by years				
				1st year	2nd year	3rd year	4th year	5th year
		International cooperation	400	80	80	80	80	80
		Materials	500	100	100	100	100	100
		Equipment, Third-party company services	50	10	10	10	10	10
		Commissioning						
		R&D contracts with other research organizations						
		Software purchasing						
		Design/construction						
		Service costs (*planned in case of direct project affiliation)*						
Resources required	**Standard hours**	Resources						
		– the amount of FTE,						
		– accelerator/installation,						
		– reactor,…						
Sources of funding	**JINR Budget**	JINR budget *(budget items)*	950	190	190	190	190	190
	Extra fudning (supplementary estimates)	Contributions by partners Funds under contracts with customers Other sources of funding						

Project Leader ______ /Малахов А.И./

Laboratory Economist ______ /Панкратова/

APPROVAL SHEET FOR PROJECT

Study of Hadron Production in Hadron-Nucleus and Nucleus- Nucleus Collisions at the CERN SPS (SHINE - SPS Heavy Ion and Neutrino Experiment)

SHORT DESIGNATION OF THE PROJECT **NA61/SHINE**

PROJECT CODE

THEME CODE 02-1-1087-2009

NAME OF THE PROJECT LEADER **Malakhov A.I.**

AGREED

JINR VICE-DIRECTOR	SIGNATURE	NAME	DATE
CHIEF SCIENTIFIC SECRETARY	SIGNATURE	NAME	DATE
CHIEF ENGINEER	SIGNATURE	NAME	DATE
LABORATORY DIRECTOR	SIGNATURE	NAME	DATE
CHIEF LABORATORY ENGINEER	SIGNATURE	NAME	DATE
LABORATORY SCIENTIFIC SECRETARY	SIGNATURE	NAME	DATE
THEME LEADER	SIGNATURE	NAME	DATE
PROJECT LEADER	SIGNATURE	NAME	DATE

APPROVED BY THE PAC	SIGNATURE	NAME	DATE

Referee report on extension of the project NA61/SHINE (JINR participation)

The experiment NA61/SHINE at the CERN SPS accelerator (**SPS Heavy Ion and Neutrino Experiment**) received its name due to the dual experimental program.

The research program devoted to strong interactions in NA61/SHINE is based on scanning with beams of light and intermediate nuclei (p+p, p+Pb, Be+Be, Ar+Sc, Xe+La, Pb+Pb) with energies in a range of 13A – 158A GeV.

Note that it is this energy range that corresponds to the transition energy region to be studied at the constructed JINR accelerator complex NICA.

Precise measurements of the processes necessary for experiments with cosmic rays and neutrinos are performed in the framework of this experiment. During many years, the NA61/SHINE collaboration has been pursuing the program of hadron production measurements for experiments with neutrino oscillations with long base at J-PARC and Fermilab. These measurements contribute to our knowledge of neutrino flux formed with accelerated particle beams. NA61/SHINE is also engaged in measurement of hadron production required for interpretation of data on extensive atmospheric showers at ultrahigh energies, as well as measurement of cross sections of production and fragmentation for understanding the data on galactic cosmic rays.

It should specially be noted that NA61/SHINE is the only world facility for investigations in the field of relativistic nuclear physics in the abovementioned energy range that possesses the set of detectors (TPC+TOF) ensuring precision measurement of angular and energy characteristics of secondary particles in the conditions of their identification.

The JINR research group has been actively participating in the creation of the detector base for NA61/SHINE for a long time. The NA61/SHINE collaboration performed an extensive work on the facility upgrade 2019-2022. The engineers and physicists of the Laboratory of High Energy Physics created a new time-of-flight registration system based on MRPC detectors, which is the key detector for charged particle identification. The system consists of two walls. The first wall has already been installed in the facility and demonstrated reliable operation in the accelerator runs during 2023. At present, the second wall of the detector is being installed and put in operation. The new system ensures a substantially better time resolution (50 ps) than the previous one based on scintillation counters (70 ps).

A large amount of experimental data on p+p, Be+Be, Ar+Sc, Xe+La, and Pb+Pb collisions was acquired by the NA61/SHINE collaboration in 2009-2018 in the framework of the accepted research program. After the upgrade the data acquisition rate increased substantially (by approximately a factor of 15).

Measurements of observable variables sensitive to the considered effects in nucleus-nucleus collisions should be performed upon scanning the phase diagram. Such observables are the multiplicity of charged particles, their transverse momenta, and spectral characteristics of secondary hadrons, including strange baryons and antibaryons.

Initially, the research program of the NA61/SHINE experiment included measurements of the yields of charged particles in p+p collisions and central collisions of ^{7}Be + ^{9}Be, Ar+ Sc,p+ Pb, and Xe + La nuclei at momenta of 13, 19, 30, 40, 75, 150/158 AGeV/c per nucleon. Then the research program of NA61/SHINE was extended. Now it includes the investigation of collective flows in nucleus-nucleus collisions in the same energy range, as well as investigation of hyperon and hyper-nuclei production. Hyper-nuclei are unique objects which can serve for enhancement of our knowledge on interaction of strange particles with nuclei in a multiparticle medium under the controllable conditions.

The program on investigation of charmed particle production in collisions of relativistic heavy ions is also very important. Some researchers assume that the specific feature of charmed particle production in collisions of heavy ions may serve as an indication of QGP formation, in particular, this is related to suppression of J/ψ-meson yield. Such data are lacking yet, and it is planned to perform such analysis in the framework of the NA61/SHINE experiment.

It should be underlined that the experimental results inspired certain theoretical studies, especially those on the proof of the beginning of deconfinement at SPS at a decreased energy. It is planned to continue these studies. Moreover, this activity stimulated the measurements at low energies in the experiments STAR and PHENIX at RHIC (Brookhaven National Laboratory, USA) and implementation of first-priority projects in the framework of the NICA/MPD scientific program at JINR and CBM at GSI.

The JINR researchers made a substantial contribution in the measurement and analysis of the processes of light nuclei production. This part of the experiment was completely carried out by the LHEP team, starting from data acquisition, to data analysis, and publication of obtained physical results. The collaboration in the framework of NA61/SHINE is extremely efficient and fruitful for both organizations: CERN and JINR. Several PhD and Dr.Sci. Theses were defended based on the results obtained in the NA49/NA61SHINE experiment.

The extension of this collaboration will contribute to deeper understanding of the properties of nuclear matter at relativistic energies. The analysis of experimental data acquired at NA61/SHINE is definitely extremely valuable for preparation of experiments at the JINR accelerator complex NICA. The participation of JINR in the NA61/SHINE experiment is also of great importance for training JINR young scientists for the upcoming research within the NICA project, the physical program of this project containing the tasks close to those addressed at NA61/SHINE. The experience of the JINR group in design, development, and maintenance of various detectors for SPS accelerated ion beams at CERN and their participation in processing and analysis of experimental data cannot be overestimated for further relativistic nuclear physics research at JINR.

It follows from the above said that the participation of the JINR group in the NA61 experiment is undoubtedly fruitful. The required finances are completely justified by the excellent physical results serving to the benefit of high scientific reputation of our institute. I believe that the anticipated results will certainly be considered a substantial contribution to the development of the long-term research programs in the field of relativistic heavy ion physics at JINR. I recommend to approve extension of the JINR participation in the experiment NA61 in 2025-2029 with the first priority in the framework of the requested funding.

Dr. Phys.-Matem. Sci.,
Head of department, LHEP JINR
15.03.2024

A.A. Baldin

Referee report
on the NA61/SHINE project (JINR participation)

The presented project is a continuation of the successful participation of a group of employees of the Veksler and Baldin Laboratory of High Energy Physics and the Dzhelepov Laboratory of Nuclear Problems of JINR in the NA61/SHINE experiment at the CERN Super Proton Synchrotron (SPS).

NA61/SHINE is a multi-purpose spectrometer to study the hadron-proton, hadron-nuclear and nuclear-nuclear collisions. The wide momentum range of the beam particles, from pions to lead nuclei, together with the high acceptance and high resolutions of the NA61/SHINE detector provides a unique opportunity to perform the necessary measurements. The experimental program includes the tasks of searching for a hypothetical critical point in the phase diagram of nuclear matter, studying the properties of the onset of deconfinement and the formation of the open charm. Precise measurements of the processes necessary for experiments with cosmic rays and neutrinos are also carried out.

The data analysis will continue in the following directions:
- formation of light nuclei during nuclear interactions;
- production of hyperons in Be+Be, Ar+Sc, Xe+La, Pb+Pb interactions;
- formation of antimatter in nuclear-nuclear interactions;
- open and hidden charm production in heavy ion interaction.

In addition, the joint modeling work is underway for the NICA and NA61/SHINE projects, based on experimental data obtained in the NA61/SHINE experiment.

The NA61/SHINE collaboration has done a lot of work to modernize the setup in 2019-2022. JINR group members, within the framework of the collaboration, have fulfilled obligations both for physical data analysis and simulation to implement the NA61/SHINE setup upgrade program, namely, to develop and install a new time-of-flight system based on MRPC detectors. The installed left arm of the ToF was fully integrated into the setup and successfully worked during the data runs in 2023. The right shoulder of the ToF is expected to be installed in 2024, which will cover the entire acceptance of the set-up.

The project provides an overview of the program of physical research on relativistic interactions of nuclei and describes the unique experimental results obtained over the past three years with the active participation of JINR staff in the NA61/SHINE project. The work plans for the experiment for the period of 2025-2029 are also given.

It is necessary to analyze a huge amount of collected data and ensure the operation of the upgraded setup on SPS beams.

The experiment provides a comprehensive and consistent study of hadron interactions, starting with elementary nucleon-nucleon processes and ending with collisions of heavy ions with different atomic numbers and beam energies (20AGeV-158AGeV).

The project participants are co-authors of numerous publications and presentations on this topic, which are widely cited in the world literature.

JINR physicists have also performed original research using the approach to study relativistic nuclear interactions in the four-dimensional velocity space, which was previously proposed by Academician A.M. Baldin. The introduction of the similarity parameter proved to be very fruitful in the study of nuclear interactions at high energies. The modified approach has been successfully applied to describe the inclusive spectra of generated pions and kaons in the central region of rapidity in pp and AA interactions. The essence of the modification of this approach is to include quark-gluon dynamics in the generation of hadrons in the nucleon-nucleon interaction in the central region of velocities ($y = 0$). The calculations have shown a fairly successful description of the ratio of the yields of kaons and pions in a wide range of initial energies, up to the LHC energies.

Further participation in the NA61/SHINE experiment will allow physicists to continue the systematic study of nuclear interactions from light nuclei till the heavy ones, including medium-sized nuclei. For this program, the research at the NA6/SHINE facility is extremely valuable and still out of competition due to the unique installation parameters and the presence of nuclear beams at the SPS at CERN. In particular, after the upgrade, the data taking run speed was increased by about 15 times.

It is important to emphasize that the beam momentum range provided by SPS for NA61/SHINE is very important for heavy ion, neutrino and cosmic ray communities. The efforts are being made worldwide to construct new installations providing ion and hadron beams in the momentum range of the CERN SPS beam. These are fixed-target setups at FAIR, Germany, as well as the NICA collider installation, Russia. They will start working after the main results of the project are received, which are extremely necessary for planning future experiments.

JINR group's participation in the NA61/SHINE experiment is necessary as part of training young specialists for the NICA project. Several doctoral dissertations have already been defended in physics close to the NICA program within the framework of the NA61/SHINE| project. In the near future, it is planned to prepare two PhD and doctoral dissertations using the results of the NA61/SHINE experiment and modeling for the NICA project. Experienced employees who have defended their doctoral and PhD theses based on the results of the NA61 experiment are currently successfully working on the NICA project.

Financial requests are fully justified in order to obtain significant physical results, which will become a significant contribution to the JINR research program. It should be emphasized that JINR's participation in the NA61/SHINE experiment is very important, since the research program of this experiment lies in the main stream of the long-term program in the field of relativistic nuclear physics at JINR. It is complements the research conducted at the Nuclotron (JINR), RHIC (BNL), and the experimental results obtained are necessary for planning research at the NICA accelerator complex. The unique experience of working in the international collaboration will allow its participants to apply their acquired skills in the implementation of the NICA megaproject at JINR.

Thus, the participation of the JINR group in the analysis of the experimental data of the NA61/SHINE project and in new measurements at this facility is fruitful and its extension for the next 5 years should be recommended with the first priority.

Candidate of Physical and
Mathematical Sciences,
Head of the Sector LTP of JINR S.G. Bondarenko

15.03.2024