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# SCIENTIFIC AND TECHNICAL REASONING FOR THE RENEWAL OF THE PROJECT

## «Study of Hadron Production in Hadron-Nucleus and Nucleus-Nucleus Collisions at the CERN SPS (NA61/SHINE - SPS Heavy Ion and Neutrino Experiment)»

**1. General information on the project**

**1.1. Theme code 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** 02-1-1087-1-2012/2031

**1.3. Laboratory**

VBLHEP

**1.4. Scientific field**

Elementary particle physics and relativistic nuclear physics

**1.5. The name of the Project** Study of Hadron Production in Hadron-Nucleus and Nucleus-Nucleus Collisions at the CERN SPS (**NA61/SHINE** - SPS Heavy Ion and Neutrino Experiment)

**1.6. Project Leader(s)**

A.I. Malakhov

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**1.8. Scientific supervisor of the project**

**2. Scientific Justification and Organizational Structure**

**2.1. Abstract**

The proposed project continues a research program focused on hadronic and nuclear fragmentation in hadron–nucleus and nucleus–nucleus interactions. The research is conducted within the NA61/SHINE collaboration at the SPS accelerator complex at CERN. Key areas of the experiment include searching for the putative critical point in the phase diagram of nuclear matter, studying threshold effects of deconfinement, and mechanisms of open charm production. The work involves systematically measuring particle yields and fluctuations in hadron-proton, hadron-nucleus, and nucleus-nucleus collisions with varying energies and mass numbers of the interacting systems. This enables detailed studies of critical phenomena in the dense and hot hadronic medium formed at high energies.

**2.2. Scientific Rationale**

**2.2.1 Introduction**

The NA61/SHINE experiment is a multipurpose fixed-target hadron spectrometer at the SPS accelerator at CERN (Fig. 1, sketch of the setup). Its research program includes the study of strong interactions, as well as precision measurements in neutrino and cosmic ray physics. A significant advantage of NA61/SHINE over collider experiments is its extended coverage of the phase space available for particle production. This includes the entire hemisphere of the incident nucleus at the

collision site, without the restriction of low pT values. As the only detector of this type operating at the SPS, NA61/SHINE has the unique capability of performing measurements on a diverse set of beams and targets in the center-of-mass collision energy range of $5 < \sqrt{s_{NN}} < 17$ GeV. The experimental data set also includes large samples obtained using replicas of the T2K, NuMI, and LBNF/DUNE neutrino experiments' targets. Since 2022, following the completion of the experimental setup upgrade, the data acquisition rate has been increased to 1 kHz; an increase to 10 kHz is under discussion.

The goals of the NA61/SHINE strong interaction program are being achieved experimentally by two-dimensional scanning of the collision energy and the size of colliding nuclei. This allows for a systematic investigation of the phase diagram of strongly interacting matter [1]. In particular, analysis of existing data within the framework of statistical models suggests that increasing the collision energy increases the temperature and decreases the baryon chemical potential of the strongly interacting matter fireball during kinetic freeze-out [2], while increasing the nuclear mass of the colliding nuclei decreases the temperature [2–5] (Fig. 2).

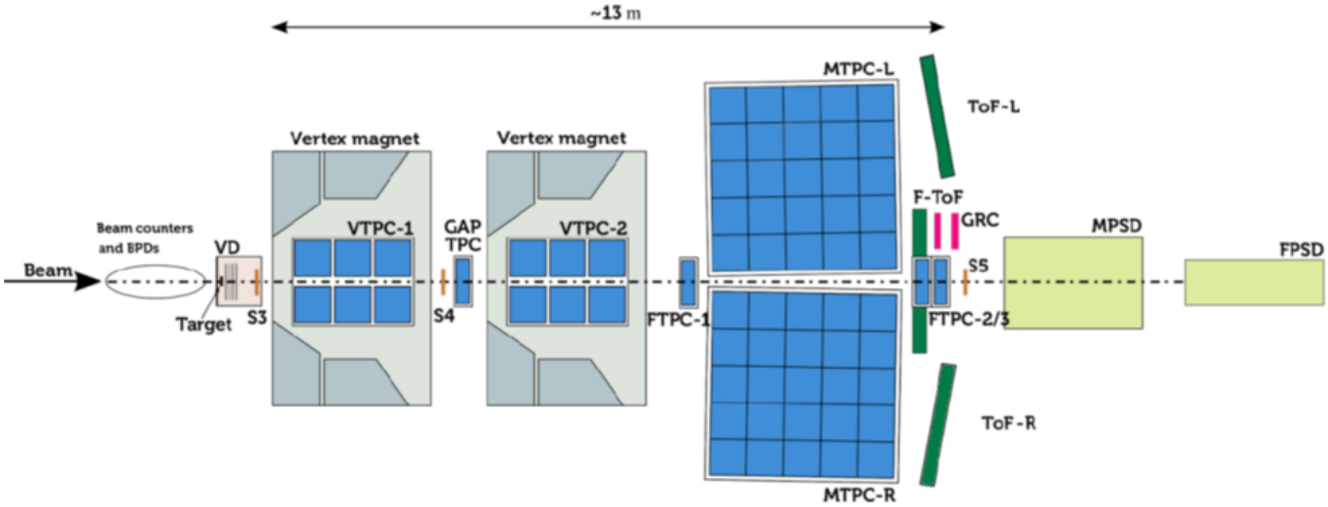



Fig. 1. Schematic representation of the NA61/SHINE experimental setup.

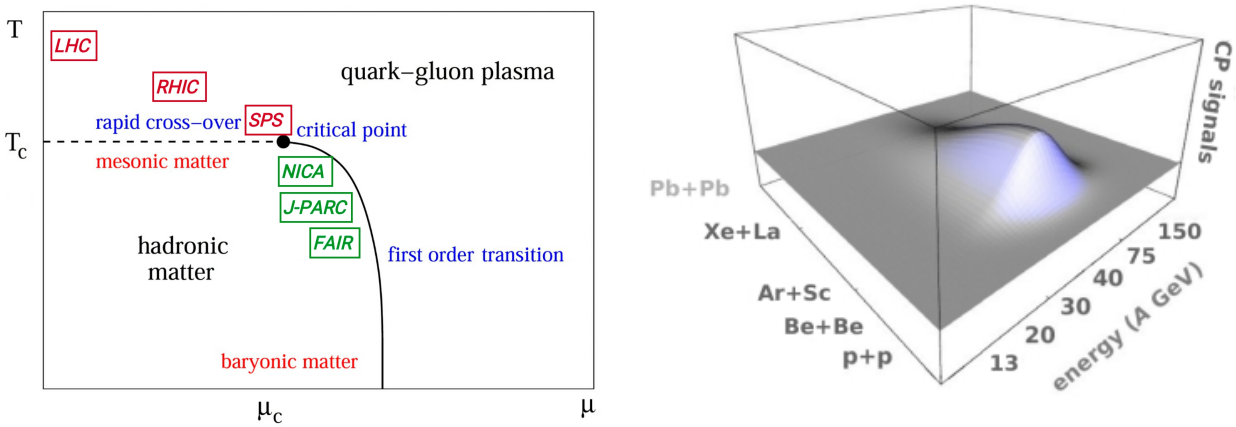



Fig. 2. Left: A hypothetical plot of the phase diagram of strongly interacting matter with a critical point, plotted as a function of the baryon chemical potential μ and temperature T. Right: An image of the fluctuation hill that can be observed in a beam momentum and system size scan, provided that the freeze-out parameters are close to the critical point [6].

The main areas of activity of the JINR team in the NA61/SHINE project are:

1. Study of the formation of light nuclei. This area is of interest for several reasons. Firstly, clustering processes in nucleus–nucleus collisions remain poorly understood and require further theoretical and experimental analysis. Secondly, objects such as deuterons and tritons are not elementary hadrons; due to their low binding energy compared to the ambient temperature in a

highenergy collision system, the probability of their preservation in subsequent interactions appears low. This suggests that the observed deuterons, tritons, and a significant fraction of other multinucleon bound states detected in the central rapidity region are formed predominantly in the late stages of reaction evolution. Thus, experimentally measured light nuclei arising in the final stages of collisions can serve as an informative tool for studying the spatiotemporal structure of the system at a late stage of its development.

2. Relativistic heavy-ion collisions offer unique opportunities for the creation and study of hot, dense matter in the laboratory. In the early stages of the reaction, quark-gluon plasma is formed, while in the final stage, hadronization and clustering of matter occur. The capture of the resulting hyperons into nucleon clusters can lead to the formation of hypernuclei—an extremely rare process, especially near the threshold for strangeness production. Hypernuclei represent a unique tool for in-depth studies of the interactions of strange particles with nuclear matter in a multiparticle medium under controlled experimental conditions. The data obtained are fundamental for constructing a more general and self-consistent description of baryon–baryon interactions.

3. Study of antimatter production in relativistic nuclear interactions. The results of such studies are important because they can be used to interpret antinuclei fluxes in cosmic rays and to search for dark matter signals in astrophysical experiments, where precise knowledge of the background processes of antinuclei production in hadron collisions is critical.

4. Description of experimental data using the self-similarity approach. A development of the approach to studying relativistic nuclear interactions in four-dimensional velocity space proposed by Academician A.M. Baldin is being used.

5. Measurement of the average number of charmed quark-antiquark pairs produced in the full phase space of interacting heavy ions. Heavy quark correlations are expected to provide insight into the physics of strongly interacting matter and significant potential for discovery. It has recently been suggested that in the case of charmed-anticharmed hadron pairs, the collective matter flow generated in heavy ion collisions allows for verification of the locality of heavy quark production and their transport properties.

6. Commissioning, technical support, and data analysis of a two-arm time-of-flight detector based on the MRPC with a total number of channels of approximately 3500.

7. The Laboratory of Nuclear Problems is participating in the NA61 neutrino program. The NA61/SHINE collaboration has a program of hadron production measurements for the long-baseline neutrino oscillation experiments at T2K, NuMI, and LBNF/DUNE. These measurements expand our understanding of the neutrino flux produced by accelerator neutrino beams.

8. Commissioning and technical support of liquid hydrogen and liquid nitrogen targets.

**2.2.2 Research Status.**

As part of the NA61/SHINE program, the collaboration collected data on p+p to Pb+Pb collisions from 2009 to 2026, with the latest measurements performed on a significantly larger sample of events.

Currently, the collaboration has accumulated data on:

• for the heavy ion program –$p$+$p$, $\pi^+$+C, $\pi^-$+C, $p$+Pb, Be+Be, O+O, Ar+Sc, Xe+La, and Pb+Pb, with different momenta for each reaction;

• for the neutrino program –with thin targets $p$+C, $p$+Al, $p$+Be, $p$+Ti, as well as large samples obtained using replicas of the targets of the T2K, NuMI, and LBNF/DUNE neutrino experiments;

• for the cosmic ray program – reactions involving the fragmentation of Li-Si+C nuclei.

Measurements are planned to continue after the third long-term shutdown (LS3) at CERN during the fourth phase of operation of the SPS accelerator complex. The main objectives are to study transitions to quark–gluon plasma (QGP) in light ion systems through comprehensive measurements of produced hadrons with a large angular coverage, as well as to study hadron production related to neutrino and cosmic ray physics in the SPS energy range.

1. **Strong Interaction Research Program.**

Assuming a statistical description of strongly interacting matter, its phase diagram can be described by the dominance of different phases. A hadronic phase can be distinguished at low temperature T and a quark–gluon plasma (QGP) phase at high temperature T. At higher values of the barychemical potential (μB), other exotic forms of matter may be present. At sufficiently high temperatures and energy densities, the system undergoes a phase transition from the hadronic phase to the QGP phase. One of the signatures of such a transition, predicted by the statistical model of the early stage (SMES) [7], is the ratio of positively charged kaons to positively charged pions ($K^+/\pi^+$), which is related to the strangeness-to-entropy ratio. This ratio should increase with energy in the hadronic phase, reach a maximum at the phase transition, and then decrease and approach saturation. This was indeed first observed (see Fig. 3a) in the NA49 experiment in Pb+Pb collisions compared to *p*+*p* interactions, where no such structure was observed. The NA61/SHINE size and energy scans were aimed at further studying the hadron production mechanism at intermediate colliding system sizes. The results obtained in the *p*+*p*, Be+Be, Ar+Sc, and Xe+La scans indicate a transition in the hadron production mechanism between light systems (*p*+*p* and Be+Be) and heavy systems (Ar+Sc, Xe+La, and Pb+Pb).

The most popular models describing the hadron production process are the creation and decay of resonances or strings, and the formation and hadronization of quark-gluon plasma. Measurements show that the applicability ranges of existing models in the space of parameters controllable in the laboratory (collision energy and collision mass number) have not yet been well studied [8].

When quark masses are equal and no other interactions occur, QCD assumes that the interactions are independent of the quark type (flavor). This property is called flavor symmetry. It reduces to isospin symmetry when only up and down quarks are considered. During hadron-nucleus collisions, many of the new particles are the lightest mesons—pions and kaons—made up of up (*u*), down (*d*), and strange (*s*) quarks. The effective masses of the up and down quarks are mu = 2.16(7) MeV and md = 4.70(7) MeV. They are not equal, but are significantly smaller than the QCD scale, LQCD. Therefore, the isospin symmetry breaking is small, as confirmed by the pion or kaon mass ratio, $(m_{\pi^+}-m_{\pi^0})/(m_{\pi^+}+m_{\pi^0}) \backsimeq 0.017$. For $K^+$ and $K^0$, this ratio is 0.004. The elastic cross sections for pion–pion, pion–nucleon, and nucleon–nucleon scattering confirm isospin symmetry. One specific isospin transformation is the inversion of the third isospin component. It is equivalent to the permutation $u \leftrightarrow d$ and, in the case of hadrons, leads to the following particle exchange: $p \leftrightarrow n$, $\pi^+ \leftrightarrow \pi^-$, $K^+ \leftrightarrow K^0$, $K^0 \leftrightarrow K^-$, etc. In the case of nuclear collisions, where the nuclei have equal numbers of protons and neutrons, the strong interactions are expected to be invariant under the charge symmetry transformation for each nucleus and hadron in the initial and final states. Invariance implies that the average number of hadrons associated with a charge transformation, such as $K^+$ and $K^0$, as well as $K^0$ and $K^-$, is the same. It should be emphasized that the models only predict the properties of ensembles, so average values must be taken into account. Thus, the ratio of charged to neutral kaons in ion interactions at $N_n = N_p$ should be as follows:

$$R_K = \frac{\langle K^+ \rangle + \langle K^- \rangle}{2\,\langle K_S^0 \rangle} = 1\,.$$

The NA61/SHINE collaboration obtained an unexpectedly large value of $R_K = 1.184(61)$ in the most central Ar+Sc collisions at $\sqrt{s_{NN}} = 11.9$ GeV [9]. The measurements, as well as a comparison with other experimental results and a new NA61/SHINE preliminary point at $\sqrt{s_{NN}} = 8.8$ GeV [10], are shown in Fig. 3c. The ratio $R_K$ is systematically greater than unity in the entire accessible energy range except for LHC energies. The results were compared with the predictions of models calculated for reactions matching the experimental data, which typically have Q/B < 1/2, where Q and B are the total net charge and net baryon number in the system. The models take into account this and other known isospin symmetry breaking effects. They cannot describe the experimental data. To unravel the nature of the transition from light to heavy systems and study the unexpectedly large isospin violation, the NA61/SHINE collaboration proposed a new set of measurements with light ions (A < 40) at three beam momenta:

• at the highest SPS momentum of 150 A GeV/*c*, to identify the region of the sharp transition between string formation and QGP;

• at an intermediate momentum of 30 A GeV/*c*, to establish the dependence on the mass number of the nucleus near the region in which all three mechanisms can simultaneously contribute: resonant states, strings, and QGP;

• at the lowest momentum of 13 A GeV/*c*, to establish a continuous dependence on the mass number of the nucleus (the absence of an abrupt transition) in the region dominated by resonant processes.

For this purpose, three variants of colliding systems were proposed to be considered: $^{16}O+^{16}O$, $^{24}Mg+^{24}Mg$, and $^{10}B+^{10}B$. All of them use the optimal configuration of the NA61/SHINE detector [11].

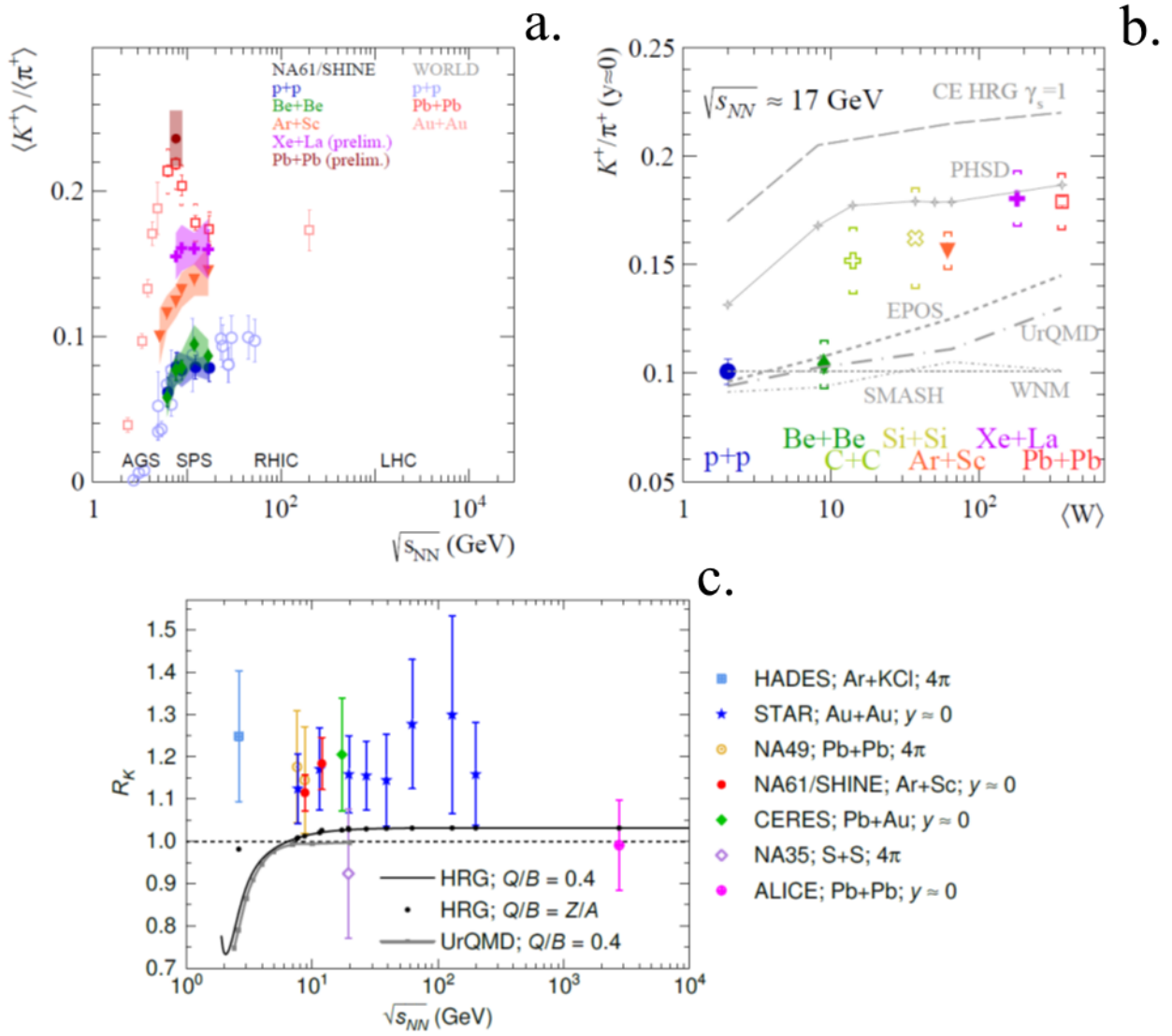



Fig. 3. a: Energy dependence of the mean multiplicity ratio $\langle K^+\rangle/\langle\pi^+\rangle$. b: Dependence of the mean rapidity ratio $K^+/\pi^+$ on the system size at $\sqrt{s_{NN}}$ = 16.8 (17.3) GeV. c: Energy dependence of $R_K$

### $c-\bar{c}$ Quark Correlations

Heavy, rarely formed charm and bottom quarks play a special role [12, 13] in studies of the quark–gluon plasma (QGP), whose properties are predominantly determined by light quarks and gluons. In particular, heavy quark correlations have a high probability of providing insights into the physics of strongly interacting matter and significant potential for discoveries.

Previously, momentum correlations of hadrons containing c and b quarks were considered as a tool for testing the degree of thermalization of heavy quarks in the hot and dense medium formed as a result of collisions. In this context, two main effects were analyzed: the weakening of the initial

backto-back correlations [14, 15] and the strengthening of correlations due to the interaction of heavy quarks with the collectively flowing medium [16].

It has recently been proposed [17, 18] that, in the case of charm-anticharm hadron pair production, the collective matter flow created in heavy-ion collisions allows one to test the locality of heavy quark production and their transport properties. The first results on D-meson production in central Xe+La collisions at 150 AGeV/*c* [19] show that the average multiplicity of $c-\bar{c}$ quark pairs is less than unity. Using collision number scaling, one can expect about one $c-\bar{c}$ pair in central Pb+Pb collisions at this beam momentum. This expectation will soon be confirmed by ongoing NA61/SHINE measurements [20]. This makes charm-anticharm quark correlation measurements at CERN SPS very promising.

The azimuthal correlations of charm and anticharm hadrons are expected to be particularly sensitive to their spatial correlations at freeze-out [17, 18]. Figure 4 shows the distribution of $c-\bar{c}$ hadron pairs by the azimuthal angle difference $\Delta\phi$ for local, independent, and correlated emission from the hypersurface during freezing (see [17, 18] for details).

Thus, measurements of the correlation between charmed and anticharmed hadrons in central Pb+Pb collisions at the maximum energy of CERN SPS should provide unique information for testing assumptions about the locality of $c-\bar{c}$ pair production and their subsequent subthreshold transport in dense media. Upgrades to the NA61/SHINE detector using existing experimental technologies and beam intensities at the CERN SPS H2 line should enable corresponding measurements to be performed after LS3.

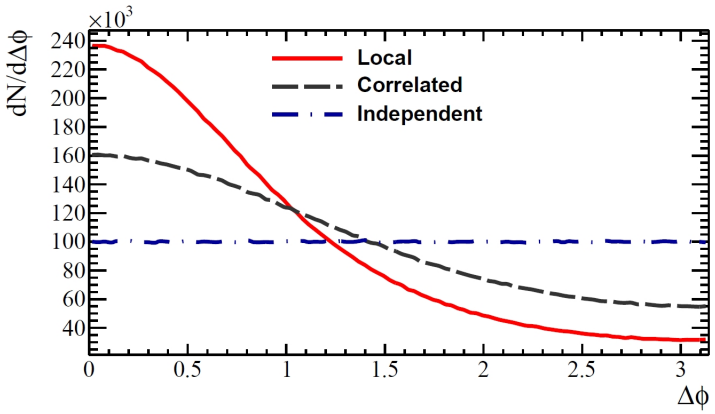



Fig. 4. Distribution of $c-\bar{c}$ hadron pairs by the difference in azimuthal angles $\Delta\phi$, modeled for central Pb+Pb collisions at 150 AGeV/c for local, independent and correlated ($\sigma$ = 2 fm) radiation models (see [17, 18]).

**Cosmic Rays**

Cosmic ray physics in the GeV to TeV energy range has entered an era of precision thanks to recent data from cosmic-ray experiments. However, limited knowledge of nuclear reactions, particularly regarding the production of antimatter and secondary nuclei, limits the information that can be extracted from these data, such as source properties, galactic transport, and indirect searches for dark matter particles. A recent review [21] offers a detailed roadmap for addressing the most pressing gaps in cross-section data, thereby effectively addressing many open physics questions. NA61/SHINE has the potential to make significant contributions to the interpretation of existing cosmic ray data.

Recently, the AMS-02 collaboration reported the detection of several cosmic antideuteron candidate events in the energy range of several GeV per nucleon [22]. It remains an open question whether the explanation of these events requires new physical principles, such as the annihilation or decay of dark matter, or whether they can be explained by known astrophysical processes. The astrophysical background flux of antideuterons is formed predominantly through interactions of protons with interstellar hydrogen and helium. The cross section for antideuteron production increases, while the cosmic proton flux decreases with energy. Consequently, the peak of cosmic antideuteron production occurs at a momentum of approximately 300 GeV/*c* in *p*+*p* interactions. Currently,

uncertainties in the astrophysical background of antideuterons are on the order of a factor of ten, that is, they range from approximately one-tenth to ten times greater than predicted values.

In 2025, NA61/SHINE collected high-statistic p+p data (~$3\times10^8$ events) at 300 GeV/*c* to build a modern model with significantly reduced uncertainties, definitively determining whether the usual astrophysical background can explain these events. This dataset allows for the construction of a new, modern antideuteron model based on the source sizes of *p*+*p* interactions and differential cross sections for antiproton production. This model will also be confirmed by direct measurements of deuteron and antideuteron production cross sections. Significantly improved measurements with NA61/SHINE are crucial for assessing the hypothetical origin of the antideuteron candidates from AMS-02 within the dark matter framework.

In the post-LS3 period, more *p*+*p* data at lower and higher energies will be available to build a complete model. The focus will be on understanding antideuteron production in the SPS energy range with a 10% uncertainty level, as well as the corresponding deuteron-particle correlation results, which will enable the development of a next-generation model for the production of light (anti)deuterons. These data will also allow for the first measurement of antihelium-3 production at SPS energies, complementing the high-energy ALICE measurements.

**Neutrino Program**

NA61/SHINE carried out a large-scale program of hadron production measurements to understand the precise neutrino beam flux. Run3 obtained high-event data using replicas of the T2K and LBNF/DUNE targets, as well as hadron interactions on thin solid targets. Simultaneously, physical analyses of Run2 data were completed and published: interactions of 120 GeV/*c* protons on carbon, with the new TPC direct scanning system providing full phase-space coverage [23, 24]. In 2026, NA61/SHINE plans to begin atmospheric neutrino flux studies using a series of experiments with 20 GeV/*c* protons on a liquid nitrogen target to model the dominant cosmic ray interactions in the atmosphere. These datasets are currently being analyzed, and the analysis is expected to be completed during Run 3.

In Run 4, NA61/SHINE plans to conduct hadron production studies on nuclear targets using a new very low-energy H2 beamline. These measurements will include both proton and meson interactions with nitrogen at momenta lower than the current H2 beamline, down to 2 GeV/*c*, and with solid materials, to improve predictions of neutrino fluxes from atmospheric sources, accelerator beamlines, and spallation sources. The NA61/SHINE low-energy beamline project was supported by the leadership of eleven neutrino and muon physics collaborations in a letter to CERN management in November 2024. CERN prepared a technical study [25].

Up until LS3, the NA61/SHINE collaboration continues to conduct high-statistic data collection on replica targets for T2K and LBNF/DUNE. However, the LBNF/DUNE and Hyper-Kamiokande neutrino beamlines are expected to evolve with the advent of new target designs and materials over their expected long lifetimes.

Measurements. Current data sets on replica targets may be insufficient to estimate the neutrino flux from these future target configurations. Therefore, NA61/SHINE will retain the ability to collect new data sets on replica targets as new neutrino beam target designs are developed. Detailed plans for specific measurements are not currently possible, but they will be proposed as needed in the future.

### 2.2.3. Development of Theoretical Models by the JINR Group

There is still no consensus in the scientific community on the mechanism of light nucleus formation: a) more than half a century has passed since the coalescence approach was first proposed to describe deuteron production in emulsions and then modified to describe the formation of light nuclei in relativistic heavy-ion reactions; b) decades ago, transport approaches were proposed to solve the problem of describing the dynamics of heavy-ion collisions, along with the so-called "minimum spanning tree" (MST) procedure as a cluster search algorithm. Both methods have shown good descriptions of experimental data over the years, but were applied to different approaches within different codebases.

Now, the "Common Clustering Library" (CCL) has been developed with the goal of combining the available algorithms in a single codebase to allow their application to various theoretical approaches and thus eliminate implementation-related uncertainties. Particular attention was paid to validating the CCL library results at the energies of the future NICA complex. Since NA49/61 data are available only at these energies, they were used for comparison. Figure 5 shows the rapidity density distribution of 3He. In addition to the experimental data, three cluster formation mechanisms are also considered:

1) coalescence with the spin-isospin coupling criterion;

2) the "MST" (or "potential" mechanism;

3) coalescence with the additional condition of negative binding energy.

The following are the first results obtained:

1. The coalescence results do not describe the shape of the experimental data and overestimate the data by more than a factor of 2 in the intermediate rapidity region.

2. The "MST" results are in excellent agreement with the data.

3. The suppression of the "$E_{bind} < 0$" constraint for coalescent nuclei is too strong.

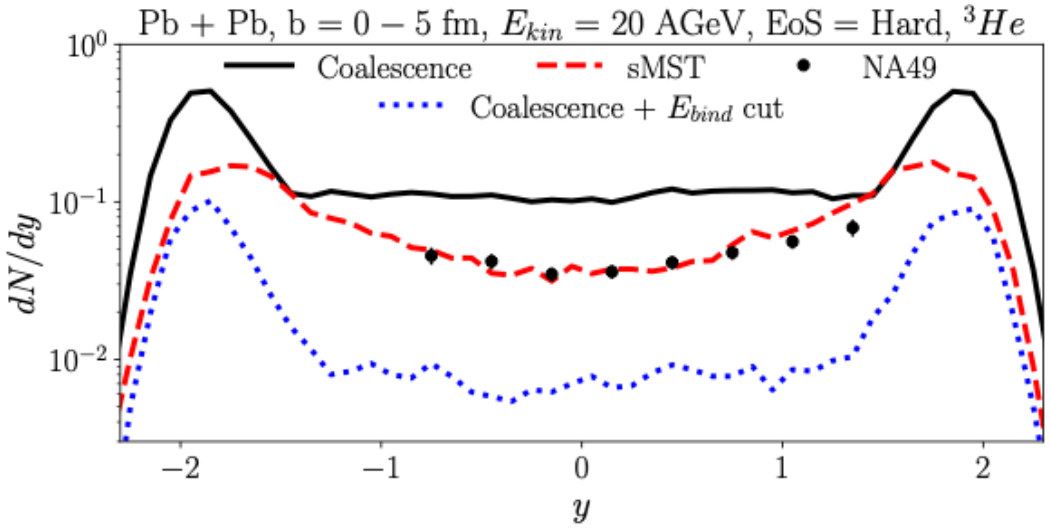



Fig. 5. Rapidity density distribution for $^3$He. Black solid lines show fusion taking into account the spin-isospin interaction. Red dashed lines show the results of the MST [26].

It should be emphasized that the NA49 data are crucial for understanding the areas of priority interest for NICA experiments. The expected NA61 data, which will be available in the coming years, will not compete with the NICA/MPD data but rather complement them and serve as a confirmation of the initial results.

A group of JINR staff members proposed a further development of the approach (BMLZ – Baldin-Malakhov-Lykasov-Zaitsev) for studying relativistic nuclear interactions in four-dimensional velocity space using the similarity principle proposed by Academician A.M. Baldin. A key development of the initial approach was the inclusion of the quark-gluon dynamics of soft hadron production in NN interactions. This step allowed us to relate soft hadron production in pp collisions to deep inelastic ep scattering (HERA) data at small $x$ and $Q^2$, where gluon density saturation effects are evident. This approach yielded satisfactory results in describing experimental data, including those from the NA61/SHINE collaboration:

**1. Inclusive pt spectra of produced π- and K-mesons.** The presented approach provides a satisfactory description of the inclusive $p_T$ spectra measured by the NA61/SHINE collaboration:

- for pp collisions in the energy range $\sqrt{s_{NN}} \approx 6$–17 GeV [27].
- for collisions of light nuclei Be+Be and Ar+Sc at $\sqrt{s_{NN}} \approx 5$–17 GeV [28, 29].
- RHIC (STAR) and LHC (ALICE) data

- for heavy ions (Au+Au, Pb+Pb) at $\sqrt{s_{NN}}$ =200 GeV and 2.76 TeV, respectively, are also described. The calculations correctly reproduce both the shape of the spectra at low $p_T$ (< 1.5 GeV/*c*) and their energy dependence.

2. **K/π yield ratios.** The approach successfully explains the different behavior of the K/π ratios in light and heavy colliding systems. In *pp* and BeBe collisions, a monotonic increase in the $K^+/\pi^+$ and $K^-/\pi^-$ ratios from the production threshold to $\sqrt{s_{NN}}$ ~ 20–30 GeV, with a subsequent monotonic increase up to LHC energies [27–30], is predicted and confirmed by NA61/SHINE data.

3. **Antiparticle and particle yield ratios.** The approach was extended to calculate the ratios of antibaryon to baryon yields ($\bar{p}$ / $p$, $\bar{d}$ / $d$, ${}^3\overline{He}$ / ${}^3He$). Using a single parameter C2 = 0.146 and taking into account the baryon "stopping" effect in the central region, an excellent description of experimental data was achieved for a wide range of systems (*pp*, BeBe, SS, CuCu, AuAu, PbPb) in the energy range from the SPS to the LHC [31].

4. **Observation of isospin symmetry breaking in AA collisions**. The NA61/SHINE collaboration [9] detected a significant isospin symmetry breaking, expressed as an anomalous ratio of the yields of charged and neutral kaons. A description of this ratio is proposed within the BMLZ approach. Figure 6 shows preliminary calculations in comparison with experimental data [33]:

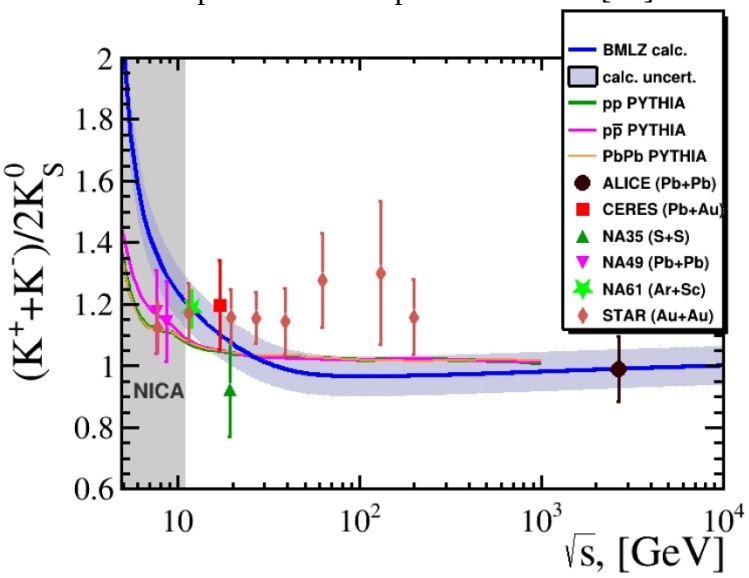



Fig. 6. The ratio $R_K = (\sigma_{K^+}+\sigma_{K^-})/2\sigma_{K0S}$, as a function of $\sqrt{s}$, calculated within the BMLZ approach [5] (blue line) and the Lund model (green-$pp$, purple-$p\bar{p}$ , yellow-$PbPb$) [33].

The results thus obtained demonstrate the high efficiency of the BMLZ approach for the universal description of a wide range of phenomena in relativistic nuclear physics. The developed approach is of particular value for future research at the NICA collider. At NICA's energy range, this formalism is an ideal tool for identifying universal patterns in the production of strange hadrons and antimatter, quantitatively analyzing baryon density and nucleon "stopping" in the central rapidity region, and interpreting MPD and SPD data within a unified theoretical framework already tested on SPS and RHIC data.

### 2.2.4. Plans for Strong Interaction Physics

Measurements are planned for three main ions—oxygen, magnesium, and boron—at three beam momenta: 13, 30, and 150 AGeV/*c*. Each ion species will be sampled for 21 days of beam operation, allowing for seven days of data collection at each momentum value. (Oxygen data at 150 AGeV/*c* were collected in 2025.)

The goals of these measurements are to investigate the dependence of the transition from hadronic to partonic matter on the system size and energy. Specifically, the program aims to:

- determine the onset of quark-gluon plasma formation at the highest energy (150 AGeV/c),

- study the interaction of hadronic and partonic mechanisms at intermediate energies (30 AGeV/c),
- investigate resonance-dominated dynamics at the lowest energy (13 AGeV/*c*).

NA61/SHINE also plans to undergo a major upgrade, which will enable data collection in two different modes. As part of the upgrade, the first time projection chamber (VTPC-1) will be replaced with a fast tracking system capable of data collection rates of up to 10 kHz. This system will include high-precision silicon pixel detectors located close to the target and larger-area gas detectors located downstream. In the first mode, the new tracker will operate in conjunction with the existing detectors (TPC and ToF), recording data at a rate of 1–2 kHz. In the second mode, the tracker will operate independently at a rate of 10 kHz. This high-speed processing capability will enable precise measurements of charmed hadron production in central Pb+Pb collisions, including studies of charmed-anticharmed particle correlations, which is crucial for constraining charmed particle diffusion and understanding their formation mechanisms. The upgraded detector will also facilitate measurements using light ions and support future programs in neutrino and cosmic ray physics. A key aspect of the design will be the compatibility of the new tracking system with all physics objectives of the experiment. Additional studies of strong interactions will focus on the production of strange particles during the transition to quark-gluon plasma to improve our understanding of the evolution of the early Universe and the formation of neutron stars.

### 2.2.5 Modification of the Facility

The NA61/SHINE detector configuration with a dual-arm time-of-flight detector is sufficient to continue measurements of hadron production in medium-sized nuclei and to study strange particle production. However, the proposed neutrino and $c - \bar{c}$ correlation measurements require significant upgrades to the detector and beamline, respectively. The current event acquisition rate of the NA61/SHINE detector does not exceed 2 kHz due to the equipment's limitations, while the new measurements require increasing the rate to 10 kHz. To achieve this, the following upgrades are necessary:

• Creation of a new silicon tracking detector (LAST);
• Development of a new low-energy beamline for neutrino and cosmic ray physics.
• Completion of work on commissioning the second arm of the time-of-flight system.

**Development of a Silicon Tracking Detector (LAST)**

Studies of $c - \bar{c}$ correlations require data acquisition rates of 10 kHz or higher. While such rates are readily achievable with current detector technologies, they exceed the capabilities of the existing NA61/SHINE facility, which includes large TPCs. To overcome this limitation, a new magnetic spectrometer is planned, equipped with a fast silicon tracker for reconstructing primary and decaying vertices, complemented by large-scale microstructure gas detectors (MPGDs) for further tracking to improve momentum resolution. According to preliminary Monte Carlo simulations, this facility will enable particle momentum reconstruction with a resolution of 0.7% and a coverage of nearly 40%. The silicon tracker will be similar to the existing vertex detector based on ALPIDE sensors, while the technology for the large-scale MPGDs has not yet been determined. Monte Carlo simulations predict 10 tracks per cm² per central Pb+Pb collision and up to $5\times10^4$ MIP/cm²/s of total charged particle flux in the inner region of the detector, and significantly less in the outer regions.

Low-energy beamline. The existing H2 beamline can provide hadron beams in the 13–400 GeV/*c* range. The goal of the low-energy beamline design is to provide hadron beams below this range, down to 2 GeV/*c*. The low-energy beamline configuration should not interfere with standard high-energy operation even after the construction of a new low-energy beamline branch. Low-energy beamline configurations can coexist with the "standard" high-energy configuration, and the H2 beamline will be able to provide hadron beams in the 2–400 GeV/*c* range. Furthermore, to collect sufficient statistical data for spectral measurements within a reasonable beamline lifetime, e.g., two to three weeks per data set, the particle count must exceed at least 50 Hz (~250 particles per burst). To fully utilize the physics capabilities offered by nuclear beamlines, it would be extremely beneficial to

provide a wider range of ion species for various experiments. The proposed addition of a second heavy ion source and the modernization of the heavy ion complex will significantly enhance the scientific potential not only for NA61/SHINE but for all heavy ion experiments at CERN.

**Second Arm of the MRPC-Based Time-of-Flight System**

The JINR team made a significant contribution to the modernization of the facility: they were responsible for the development, construction, and commissioning of the 1728+1728-channel time-of-flight system (ToF-L + ToF-R) with high temporal resolution (Fig. 7). A key feature of the system design is the use of an analog on-chamber amplifier and a data acquisition system based on the DRS4 module. This work resulted in the development of a fundamentally new concept for the MRPC time-of-flight detector, combining particle detection efficiency at intensities up to 2 kHz/cm², a temporal resolution better than 52 ps, and a coordinate resolution in the detector plane better than 5 mm. Completion of the second arm (ToF-R) of the setup is planned for 2026. To enable the combined use of the detector with the new tracker (LAST), a transition to a new type of readout electronics based on the picoTDC module is being considered.

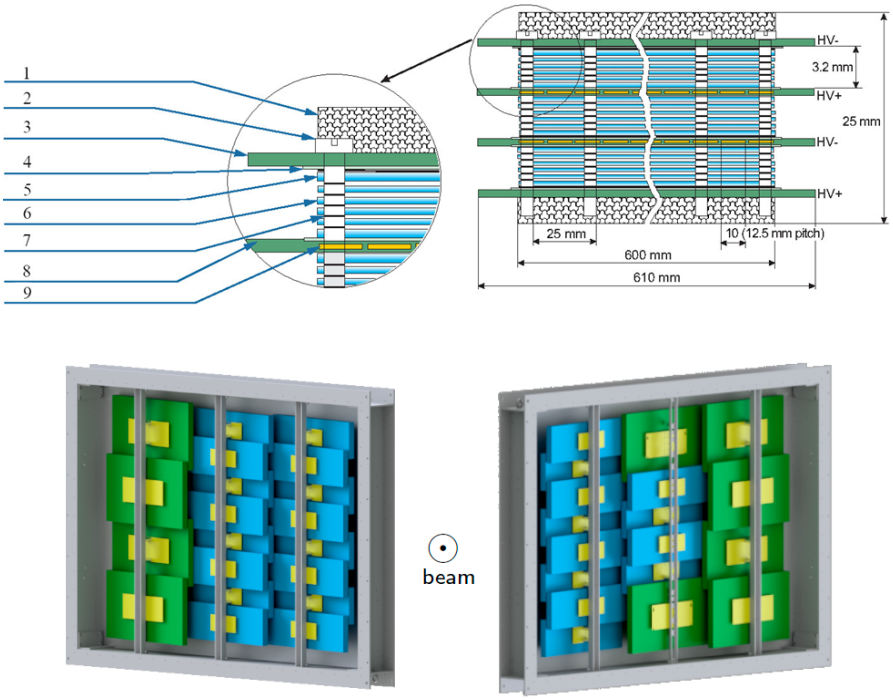



Fig. 7. Top figure: schematic of the MRPC detector device. 1 - honeycomb panel (5 mm), 2 - plastic screw, 3 - outer printed circuit board (1 mm, 4 - mylar film (1 μm), 5 - outer glass with conductive paint (420 μm), 6 - inner glass (280 μm), 7 - fishing line (200 μm), 8 - printed circuit board with strips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

**2.2.6 2026 + LS3 Work Plans**

Beam Time Plans for 2026:

Four weeks of beam time are requested for proton-nitrogen interaction studies using the liquid nitrogen target currently under construction in Japan and CERN. These interactions, which will be conducted at the lowest beam energy currently available, will serve as a starting point for studying atmospheric interactions. To obtain interaction data near the Fermilab booster's beam-neutrino (BNB) energy, an additional week of proton-beryllium interaction observations is required. BNB modeling currently utilizes momentum scaling from the NA61/SHINE proton dataset at 31 GeV/c to the BNB beam at 8.9 GeV/c. An additional dataset at 15-20 GeV/*c* will reduce the uncertainty associated with scaling. This dataset will be useful in the interim, pending the availability of low-energy beamline results.

Post-LS3 Plans

NA61/SHINE has prepared a plan for a new physics program for the post-LS3 period (2027–2029). It was submitted as input to the European Particle Physics Strategy Update [67]. Key topics include a new low-energy neutrino production measurement program, a series of light ion collision studies, a study of correlated charmed particles, which will require a major upgrade of the detector's tracking systems, and further cosmic ray physics measurements.

Future plans therefore include:

• **2026**:

– Continuation of the heavy ion (lead beam) program to complete the open charmed ion dataset and request a hadron beam for proton-nitrogen and proton-beryllium interaction studies. Final commissioning work on the second arm of the time-of-flight system.

• **2027–2029 (LS3): Major facility upgrade**:

– Installation of a high-speed silicon tracker to significantly increase data collection throughput.

– Expansion to use lighter ion beams for broader coverage of physics phenomena.

– Construction of a low-energy beamline.

• **After 2029**:

– High-precision charm ion measurements using upgraded detectors.

– Program expansion to support neutrino and cosmic ray research.

### 2.2.7. JINR Group Responsibilities

JINR Contributions/Responsibilities:

- Development and maintenance of the MRPC-based TOF system;
- Development and maintenance of liquid hydrogen and liquid nitrogen targets;
- Software development and library maintenance;
- Reconstruction of initial data and DST production;
- Data analysis.
- Development of theoretical models for interpreting physical results.

### 2.2.9. Scientific Experience of the Authors

The project authors have extensive scientific experience. A. Malakhov, G. Melkumov, and G. Lykasov hold doctoral degrees and are involved in research into relativistic nuclear physics. Six young researchers also actively participated in the project. Five of them—S. Buzin, 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. The MRPC team members are using the knowledge gained during R&D and operation of ToF systems for the NICA project. The remaining two employees, V. Kireev and A. Zaitsev, are actively involved in the analysis of experimental data and their theoretical interpretation. All have published papers and are planning to complete their PhD and doctoral dissertations.

Strengths, Weaknesses, Opportunities, and Threats

**Project Strengths:**

- High-resolution time-of-flight wall has been completed;
- Compliance with the particle physics program;
- Availability of a modern experimental setup with unique parameters;
- A large volume of experimental data has been collected on proton-nucleus and nucleus-nucleus interactions over a wide energy range (from 13 to 158 A GeV)
- Extensive experience in experimental data analysis;
- A large number of young employees;
- Opportunities to train young people for the NICA project.

**Weakness:**

- uncertainties in global political conditions;
- limited resources for data analysis, to be addressed through the involvement of students and postdoctoral researchers in the new sector of the Laboratory.

**Opportunities:**

- Synergy with future projects**.** Strong complementarity with FAIR, RHIC BES, and NICA programs. NA61/SHINE provides essential reference data.
- High-quality experimental data**.** Large existing data sets with different system sizes and energies enable precision measurements and advanced theoretical interpretations.

**Threats**: Increasing competition for SPS beam time.

The project has the potential to attract more young physicists, who will also be trained for the NICA megascience project.

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**2.3. Estimated completion date**
**2027-2031**

**2.4. Participating JINR laboratories**
V.I. Veksler and A.M. Baldin Laboratory of High Energy Physics (LHEP),
V.P. 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)<br>- EOS<br>- Ribbons | | | | | |
| Tier 1 (core-hour) | | | | | |
| Tier 2 (core-hour) | | | | | |
| SC Talker (core-hour)<br>- CPU<br>- GPU | | | | | |
| Clouds (CPU cores) | | | | | |

### 2.5. Participating countries, scientific and educational organisations

| Organisation | 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. Co-executing organisations***(those collaborating organisations/partners without whose financial, infrastructural participation the implementation of the research programme is impossible. An example is JINR's participation in the LHC experiments at CERN).*

**3. Staffing**

**3.1. Staffing needs in the first year of implementation**(total number of participants)

| №№ n/a | Category employee | Core staff Amount of FTE | Associated Personnel Amount of FTE |
|---|---|---|---|
| 1. | Scientific staff | 4.5 | |
| 2. | engineers | 1.7 | |
| 3. | professionals | | |
| 4. | employees | | |
| 5. | workers | | |
| **Total:** | | **6.2** | |

### 3.2. Human resources available

**3.2.1. JINR core staff**(total number of participants)

| №№ п/а | Category of employees | Full name | Division | Position | Amount of FTE |
|---|---|---|---|---|---|
| 1. | Scientific staff | Golovatyuk V.M. | VBLHEP | Head of Dep. | 0.1 |
| | | Dmitriev A.V. | VBLHEP | Researcher | 0.9 |
| | | Zaitsev A.A. | VBLHEP | Senior R. | 0.3 |
| | | Kireev V.A. | VBLHEP | Senior R. | 0.3 |
| | | Krasnoperov A.V. | DLNP | Senior R. | 0.1 |
| | | Lykasov G.I. | DLNP | Chief R. | 0.3 |
| | | Lyubushkin V.V. | DLNP | Senior R. | 0.1 |
| | | Malakhov A.I. | VBLHEP | Head of Dep. | 0.3 |
| | | Matveev V.A. | JINR Directorate | Scient. Director | 0.1 |
| | | Melkumov G.L. | VBLHEP | Chief R. | 0.8 |
| | | Popov B.A. | DLNP | Senior R. | 0.9 |
| | | Rumyantsev M.M. | VBLHEP | Researcher | 0.2 |
| | | Tereshchenko V.V. | DLNP | Head of Group | 0.1 |
| 2. | engineers | Buryakov M.G. | VBLHEP | Lead Engineer | 0.3 |
| | | Buzin S.G. | VBLHEP | Senior Engineer | 0.3 |
| | | Kolesnikov R.Yu. | VBLHEP | Assist. Metrol. | 0.5 |
| | | Morozov S.V. | VBLHEP | Engineer | 0.3 |
| | | Karpushkin N.M. | VBLHEP | Engineer | 0.3 |
| 3. | professionals | | | | |
| 4. | workers | | | | |
| **Total:** | | | | | **6.2** |

**3.2.2. JINR associated personnel**(total number of participants)

| №№ п/а | Category of employees | Partner organisation | Amount of FTE |
|---|---|---|---|
| 1. | Scientific employees | | |
| 2. | engineers | | |
| 3. | professionals | | |

| | | | |
|---|---|---|---|
| 4. | workers | | |
| **Total:** | | | |

**4. Financial support**

**4.1. Total estimated cost of the project/subproject 950 kUSD**

Forecast of the total estimated cost (specify cumulatively for the whole period, excluding FPC). The details are given in a separate form.

**4.2. Extrabudgetary funding sources**

Estimated funding from co-executors/customers - total.

**Project Leader** /A.I. Malakhov/

Date of submission of the project to DSOA: _____

Date of decision of the laboratory's STC: 3.03.26 document number: _____

Year of the project opening: _____

(for renewable projects) -- Project start year: _____

**Schedule proposal and resources required for the implementation of the Project**

| Names of costs, resources, sources of funding | | | Cost (thousands of dollars) resource requirements | Cost, Distribution by year | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | 2027 | 2028 | 2029 | 2030 | 2031 |
| | | International cooperation (IC) | 400 | 80 | 80 | 80 | 80 | 80 |
| | | Materials | 500 | 100 | 100 | 100 | 100 | 100 |
| | | Equipment and third-party services (commissioning) | 50 | 10 | 10 | 10 | 10 | 10 |
| | | Commissioning work | | | | | | |
| | | Services of research organisations | | | | | | |
| | | Acquisition of software | | | | | | |
| | | Design/construction | | | | | | |
| | | Service costs (*planned in case of direct project affiliation)* | | | | | | |
| **Resources required** | **Normo-hours** | Resources | | | | | | |
| | | – theamountofFTE, | | | | | | |
| | | – accelerator/installation, | | | | | | |
| | | – reactor,…. | | | | | | |
| **Sources of funding** | **Budgetary resources** | JINR budget*(budgetitems)* | 950 | 190 | 190 | 190 | 190 | 190 |
| | **Extra budgetary (supplementarye stimates)** | Contributions by co-contractors<br>Funds under contracts with customers<br>Other sources of funding | | | | | | |

Project Leader _____ / Malakhov A.I. /

Laboratory Economist _____ / _____ /

**APPROVAL SHEET FOR PROJECT**

NAME OF THE PROJECT Study of Hadron Production in Hadron-Nucleus and Nucleus-Nucleus Collisions at the CERN SPS (NA61/SHINE - SPS Heavy Ion and Neutrino Experiment)

SHORT NAME OF THE PROJECT NA61/SHINE

PROJECT CODE: 02-1-1087-1-2012/2031

THEME CODE: 02-1-1087-2009

PROJECT LEADER (s) Malakhov A.I.

AGREED

| | SIGNATURE | NAME | DATE |
|---|---|---|---|
| JINR VICE-DIRECTOR | | | |
| CHIEF SCIENTIFIC SECRETARY | | | |
| CHIEF ENGINEER | | | |
| LABORATORY DIRECTOR | | Butenko A.V. | 02.04.26 |
| CHIEF LABORATORY ENGINEER | | Agapov N.N. | 02.04.26 |
| LABORATORY SCIENTIFIC SECRETARY | | Cheplakov A.P. | 02.04.26 |
| THEME LEADER | | Malakhov A.I. | 02.04.26 |
| PROJECT LEADER | | Malakhov A.I. | 02.04.26 |
| PROJECT LEADER | | | |

| | SIGNATURE | NAME | DATE |
|---|---|---|---|
| APPROVED BY THE PAC | | | |