APPROVED

Director of Laboratory

Butenko A.V.

"02" 04 **2026**

REPORT ON 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. Scientific field

Elementary particle physics and relativistic nuclear physics

1.2. 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)

1.3. Project code

02-1-1087-1-2012/2026

1.4.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.

1.5. Actual duration of the Project

2025-2026 (2 years)

1.6. Project Leader(s)

A.I. Malakhov

1.7. Project Deputy Leader(s)

A.V. Dmitriev, A.A. Zaitsev

2. Scientific report

2.1. Annotation

NA61/SHINE is a multipurpose fixed-target hadron spectrometer at the SPS accelerator at CERN. The experiment's research program includes the study of strong interactions, as well as precision measurements in neutrino and cosmic ray physics, using accelerated beams of hadrons and nuclei (from p+p to Pb+Pb) in the energy range $5 < \sqrt{s_{NN}} < 16.8/17.3$ GeV. The project is aimed at searching for the second-order critical point in the phase diagram of quantum chromodynamics, including by identifying the nonmonotonic behavior of characteristic observables, such as transverse momentum and multiplicity fluctuations, and searching for nonmonotonic behavior of observables such as transverse momentum and multiplicity fluctuations, the intermittent signal, etc., when the system undergoes freeze-out near the critical point. Another important focus of the program is studying the properties of the onset of deconfinement, including searching for characteristic "horn," "kink," "step," and "dale" structures in collisions of light nuclei. In recent years, the experimental program has expanded to include studies of heavy Pb+Pb collisions, which explore the processes of open charm production and collective effects in hot, dense nuclear matter.

2.2. A detailed scientific report

2.2.1. Description of the mode of operation and functioning of the main systems and equipment

The NA61/SHINE experimental facility is a large-acceptance hadron spectrometer located in the CERN-SPS North Experimental Area (NA) at the H2 line. A schematic representation of the upgraded NA61/SHINE facility is shown in Fig. 1.

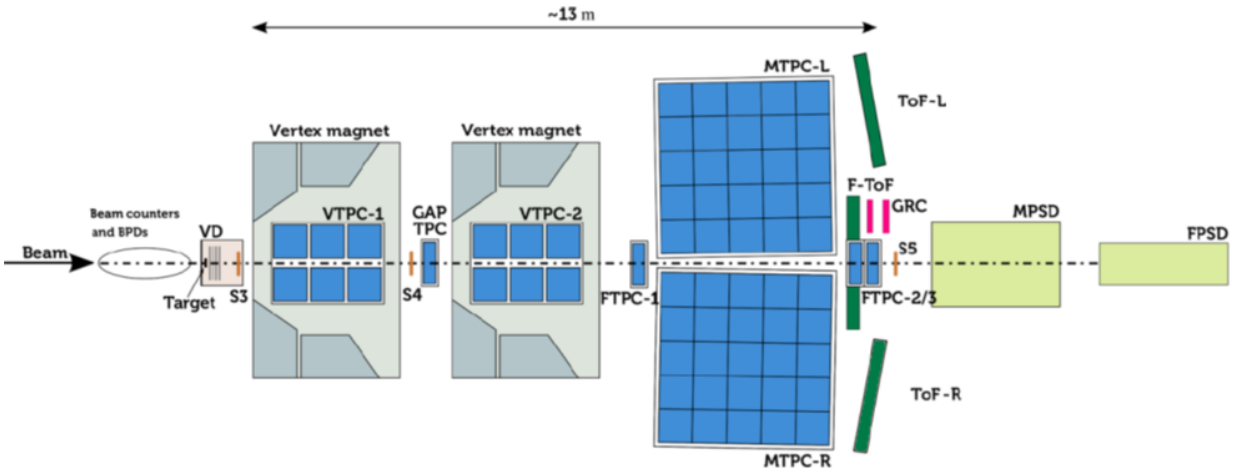

Fig. 1. Schematic representation of the NA61/SHINE experimental setup after modernization.

The NA61/SHINE experimental setup includes the following detector systems:

TPC. Four large-volume time-projection chambers (TPCs) are the core components of the charged particle detection system. Two of these, called vertex TPCs (VTPCs), are located behind the target within superconducting magnets, providing precise momentum measurements due to track curvature in the magnetic field. The magnets have a maximum total bending capacity of 9 Tesla. The magnetic field can be scaled proportionally to the beam momentum to maximize phase-space acquisition at all momenta. The main TPCs (MTPCs) are located symmetrically with respect to the beamline, behind the magnets, and serve to accurately reconstruct the trajectories of particles emitted at small angles. The small TPCs (GAP-TPC and FTPC-1, 2, 3) are located directly on the beamline. The TPCs are filled with Ar:CO_2 gas mixtures in a ratio of 90:10 for the VTPC and GAP-TPC and 95:5 for the MTPC.

ToF. During the 2019-2022 upgrade, a new ToF system was created: a dual-arm detector (ToF-L + ToF-R) based on the MRPC with high temporal resolution. It is worth noting that the development, construction, and commissioning of the 1728+1728-channel ToF system are being provided by the JINR team. A distinctive feature of the system's design is the use of an analog on-chamber amplifier and a data acquisition system based on the DRS4 module. This work led to the development of a 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 facility is planned for 2026. To enable the detector to be used in conjunction with the new tracker (LAST), a transition to a new type of readout electronics based on the picoTDC module is being considered.

PSD. The Forward Hadron Calorimeter (PSD) measures the energy flux near the beam direction, which in nucleus-nucleus collisions is primarily determined by the number of spectator (non-interacting) nucleons in the projectile and is thus related to the collision's degree of centrality.

VD. The NA61/SHINE vertex detector (VD) is designed for high-precision measurements of primary and secondary interaction vertices and is used to study the production of open charm particles in nucleus-nucleus collisions. The detector is located between the target and the first vertex time-projection chamber and operates in a weak magnetic field, recording the tracks of charged particles in the immediate vicinity of the interaction point. It consists of four stations of MIMOSA-26AHR silicon

pixel sensors placed at distances of 5, 10, 15, and 20 cm from the target, which allows for the precise reconstruction of particle trajectories. Each sensor has a high spatial resolution of approximately 4.5 μm due to a small pixel size (~18.4 μm), which ensures the precise determination of the coordinates of the decay vertices of short-lived particles. The high accuracy of vertex reconstruction allows for the efficient isolation of secondary vertices of D-meson decays and, thereby, the study of charm quark production processes in heavy-ion collisions.

Beam Counters. A set of beam detectors identifies beam particles and accurately measures their trajectories. The first detector, S1, is located in front of the target. It is equipped with four photomultipliers (PMs) that are directly connected to the scintillator. The second beam counter, S2, has only one PM. Two veto-scintillation detectors, V0 (round with a central hole) and V1 (square, also with a central hole), are installed. An additional veto detector, V0, is installed to eliminate beam halo interactions. The x-y position of the incident particle beam is measured using three beam position detectors (BPDs) mounted in front of the target along the beam line. The BPDs used in NA61/SHINE are proportional chambers filled with an Ar:CO2 85:15 gas mixture with an active area of 48 × 48 mm². Two orthogonal sensor planes, made of 15-μm-diameter tungsten wires with a 2-mm pitch, are located between three cathode planes consisting of 25-μm-thick aluminized Mylar. The outer cathode planes have stripes with a 2-mm pitch, connected to the readout electronics. Each BPD independently measures the position of a triggered beam particle in two orthogonal directions, using two planes of orthogonal stripes.

2.2.2. A description of the experiments carried out (for pilot projects).

Late 2024.

At the end of 2024, the NA61/SHINE collaboration collected data to study the nuclear spallation of cosmic rays in the Galaxy. For this purpose, the 208Pb beam from the SPS was fragmented on the T2 target of the H2 beamline, and secondary nuclei with rigidity of 25 GV were directed toward the experimental setup. A total of 46 million events were recorded for nuclei from Li to Si. This measurement covers a wide range of projectiles relevant to the study of galactic cosmic rays. Interactions were recorded with a graphite target, a polyethylene target, and an empty target. Based on this dataset, it will be possible to determine the nucleus-proton interaction cross sections relevant to cosmic ray interactions in the interstellar medium.

2025 year

In June 2025, three weeks of beamline operation were allocated to collect data using protons on a lower-density LBNF prototype target to study the dependence of the neutrino flux on target density. The beamline operation was shortened to two and a half weeks due to a scheduled shutdown of the EHN1 facility during the last three days. During the data collection period, all TPC chambers were operational, including the Long Target Tracker (LTT) and the Front-End Time-of-Flight (ToF-F) detector. These are critical detectors for neutrino physics measurements. For approximately two weeks, measurements of proton interactions on a segmented carbon target at 120 GeV/c with the LBNF target were conducted. Approximately 140 million proton interactions (the LBNF prototype target) were recorded.

The ^{16}O beamline operation was conducted for 10 days, from late June to early July 2025. The primary objective of this run was to obtain oxygen-oxygen (O+O) interaction data at a momentum of 150 AGeV/s. These measurements were conducted using a water target, with the interaction probability maintained at approximately 6%. Approximately 42 million O+O interactions were successfully recorded during the run. In addition, several hours were allocated to collecting oxygen-carbon (O+C) and oxygen-polyethylene (O+CH2) interaction data. These additional measurements, comprising a total of approximately 4 million events, will be used for fragmentation cross-section studies.

At the end of 2025, data collection was conducted on 300 GeV proton interactions on a liquid hydrogen target. The total event statistics for the pp event were approximately 360 million interactions.

2.2.3. A description of the scientific work undertaken and the results obtained.
In accordance with the thematic plan:

Isospin symmetry breaking in AA collisions.

During the period under review, the NA61/SHINE collaboration's most unexpected finding to date was published: the observation of a large isospin (flavor) symmetry breaking between u- and d-quarks during kaon production in Ar+Sc collisions. The paper [1] was published in Nature Communications in March 2025. Chronologically, this observation in the Ar+Sc data was preceded by the first finding from the NA61/SHINE cosmic ray program, which reported an unexpected excess of charged kaons compared to neutral ones produced in π^- + C reactions at $\sqrt{s}$ = 17.3 and 25.7 GeV. Although this result contradicts theoretical models, it is difficult to interpret in terms of isospin symmetry, since the projectile $\pi^-(\bar{u}d)$ has a non-zero third isospin component ($I_z = -1$). On the other hand, for colliding charge-symmetric nuclei (N = Z), exact isospin symmetry implies

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

for the average yields of produced charged and neutral kaons (the second equality does not take into account the small effect of CP symmetry violation). The central reaction Ar+Sc at $\sqrt{s_{NN}}$ = 11.9 GeV, studied within the framework of the strong interactions program, reveals an excess of charged kaons of 18.4 ± 6.1% in the average rapidity (Fig. 1). This excess corresponds to 4.2 ± 1.6 additional charged kaons produced per one central Ar+Sc event. A compilation of the results for the K^+, K^-, and K^0_S yields published in other experiments demonstrates agreement with the NA61/SHINE result over a wide energy range, but with significantly larger uncertainties. The observed effect remains unexplained by theoretical models. The JINR group proposed a description of this ratio within the BMLZ approach. Figure 2 shows preliminary calculations in comparison with experimental data [2].

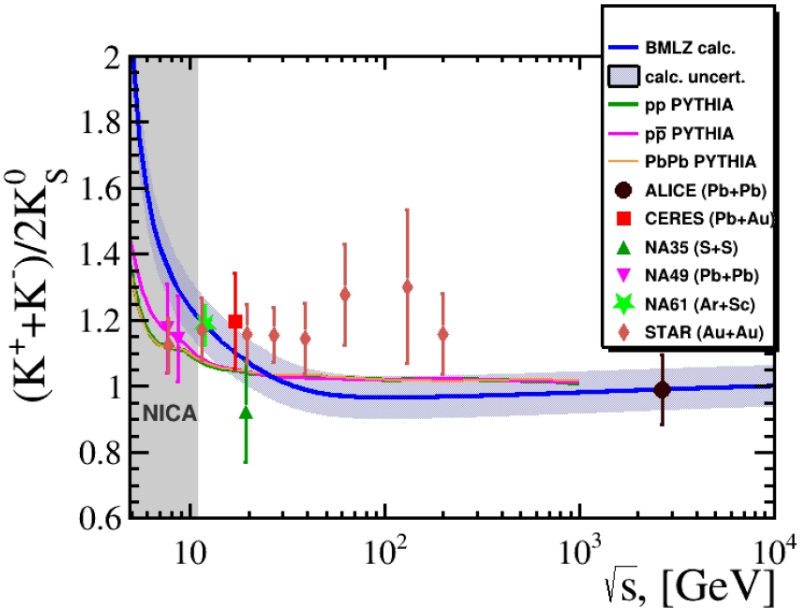

Fig. 2. The ratio $R_K = (\sigma_{K^+}+\sigma_{K^-})/2\sigma_{K0S}$, as a function of $\sqrt{s}$, calculated within the BMLZ approach (blue line) and the Lund model (green-pp, purple-$p\bar{p}$, yellow-$PbPb$).

The recently obtained XeLa data at $\sqrt{s}$ = 16.8 GeV yielded the first direct measurement of $D^0 + \overline{D^0}$ in A+A at SPS energies [10]. The data were measured with a small acceptance, a prototype vertex detector, and had relatively small statistics for this analysis. This allowed only non-differential

measurements in full phase space, making the acceptance and efficiency correction model-dependent. Three different models were used to estimate the correction, yielding three different results, shown in Fig. 3, right. As can be seen from the graph, even with relatively large uncertainties, these results impose strong constraints and distinguish existing hadron production models.

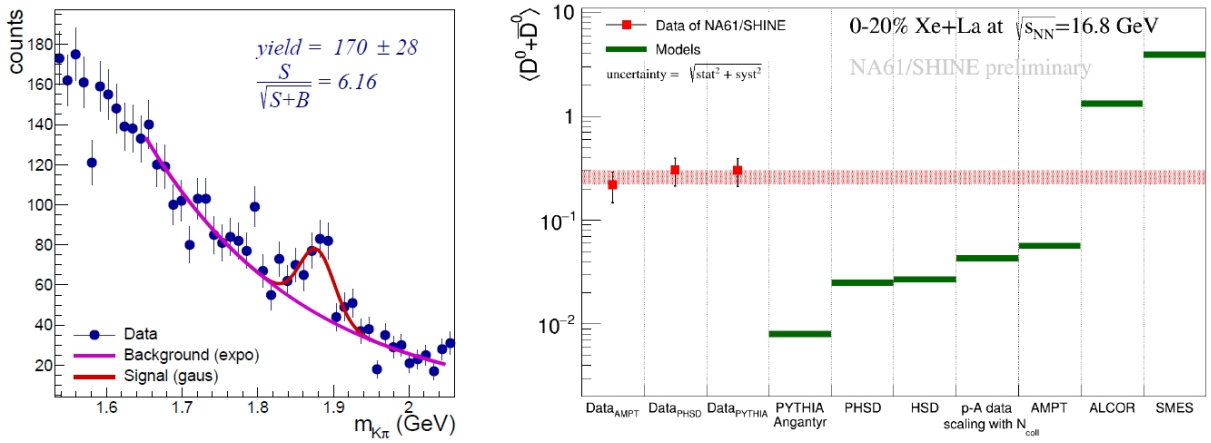

Fig. 3. Preliminary NA61/SHINE results for the $D^0 + \overline{D^0}$ yield measured in the most central Xe+La collisions at $\sqrt{s}$ = 16.8 GeV. Left: the invariant mass spectrum used to extract the initial yield value. Right: the yield corrected for acceptance and efficiency with three different models, compared with the model predictions. The red bar indicates uncertainty due to the model dependence of the correction.

In 2025, the second (right) arm of the high-resolution (50 ps) time-of-flight detector was commissioned at the NA61/SHINE facility. The detector was designed and developed at JINR. By the start of experimental data collection (November 2025) on the interaction of a 300 GeV proton beam with a liquid hydrogen target, the two-arm time-of-flight system based on MRPC detectors was fully operational, exceeding the acceptance of the NA61 facility (Fig. 4).

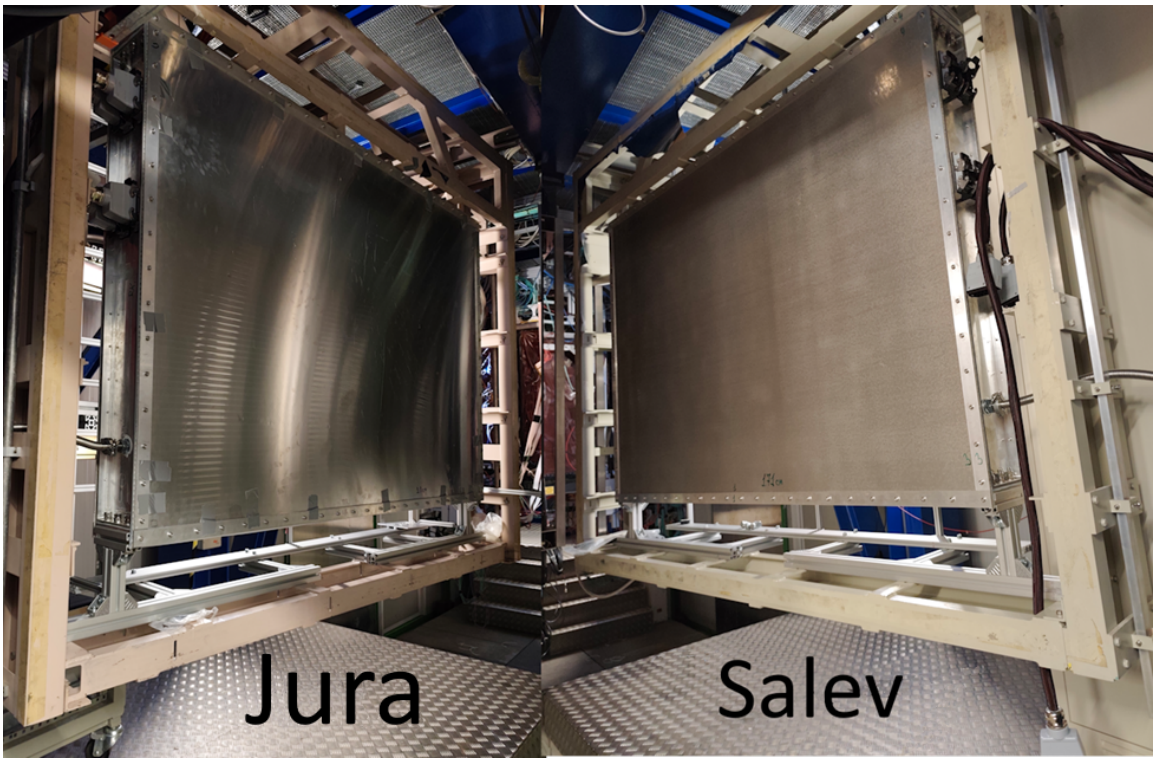

Fig. 4. Images of the right and left walls (Jura and Salev) of the MRPC-based time-of-flight system in the NA61/SHINE experimental area.

To conduct new measurements of proton-proton correlations and differential cross sections for the production of deuterons, antideuterons, and antiprotons in p+p interactions at 300 GeV/c, a new liquid hydrogen target (LHT) was developed and commissioned. A group of JINR staff members played a key role in the implementation of this project. The LHT is a closed-loop cryogenic system (Fig. 5). It is based on a cryostat with a phase separator, which liquefies hydrogen and delivers it to a Mylar target cell with a diameter of 4 cm and a length of 20 cm, located directly in the beam line. To minimize heat gain, the target and phase separator are housed in an insulating vacuum created by a two-stage pumping system. The system's operating parameters, including pressure, temperature, and liquid hydrogen level, are continuously monitored by sensors and a PLC-based automatic control system. The design of the target and the implemented operating procedures ensure both safe operation of the facility and the ability to quickly switch between liquid and gaseous target modes, which is important for assessing background contributions.

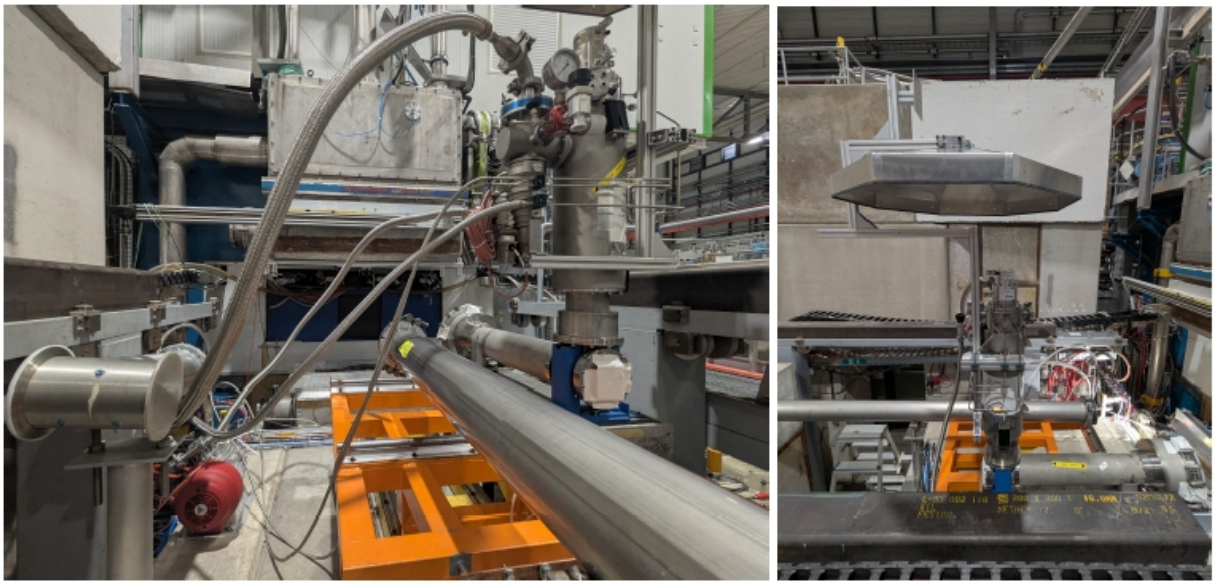

Fig. 5. Location of the LHT (left). The right image shows a photograph of the protective roof for collecting potential hydrogen leaks.

2.2.4. A list of the main publications of JINR authors, including associated personnel on the results of the project work (list of bibliographical references).

1. The NA61/SHINE Collaboration. Evidence of isospin-symmetry violation in high-energy collisions of atomic nuclei. Nat Commun. 2025. 16. P. 2849 https://doi.org/10.1038/s41467-025-57234-6
2. A.V. Guskov, G.I. Lykasov, A.I. Malakhov and A.A. Zaitsev. K-meson production and isospin-symmetry in $\boldsymbol{pp}$ and $\boldsymbol{AA}$collisions. PoS QCDEX2025 2025 p.18.
3. The NA61/SHINE Collaboration. Proposal from the NA61/SHINE Collaboration for update of European Strategy for Particle Physics arXiv:2507.08602 / EPJ Web Conf. 316 (2025)
4. The NA61/SHINE Collaboration., Giacosa, F., Gorenstein, M. et al. Evidence of isospin-symmetry violation in high-energy collisions of atomic nuclei. Nat Commun 16, 2849 (2025). https://doi.org/10.1038/s41467-025-57234-6
5. NA61/SHINE Collaboration. Multiplicity and net-electric charge fluctuations in central Ar+Sc interactions at 13A, 19A, 30A, 40A, 75A, and 150A beam momenta measured by NA61/SHINE at the CERN SPS. Eur. Phys. J. C 85, 918 (2025). https://doi.org/10.1140/epjc/s10052-025-14621-z
6. Lykasov G.I., Malakhov A.I., Zaitsev A.A. Production of charged kaons in $ArSc$ collisions // Eur. Phys. J. A. 2024. Vol. 60. P. 239. https://doi.org/10.1140/epja/s10050-024-01452-x

7. Malakhov A.I., Zaitsev A.A., Kolesnikova E.A., Lykasov G.I. Investigation of Relativistic Nuclear Collisions in the Four-Velocity Space // Physics of Particles and Nuclei. 2024. Vol. 55, No. 4. pp. 768–772. https://doi.org/10.1134/S1063779624700151
8. Malakhov A.I., Zaitsev A.A., Lykasov G.I. New Results of the Study of Relativistic Nuclear Interactions in the Space of Four-Dimensional Velocities // Physics of Particles and Nuclei. 2025. Vol. 56, No. 3. pp. 891–898. https://doi.org/10.1134/S1063779624702472
9. G. I. Lykasov, A. I. Malakhov, M. A. Malyshev, A. V. Lipatov and A. A. Zaitsev. Gluon Distribution in Nucleon and Its Application to Analysis of ep DIS, pp and AA Collisions at High Energies and Mid-Rapidity //Phys. Part. Nuclei. 2024. Vol. **55**. pp. 941-949. https://doi.org/10.1134/S1063779624700631
10. Merzlaya A. First D^0+ $\overline{D^0}$ measurement in nucleus-nucleus collisions at SPS energies with NA61/SHINE //EPJ Web of Conferences. – EDP Sciences, 2025. – T. 316. – C. 04004.

2.3. Status and stage (TDR, CDR, ongoing project) of the project (including percentage of implementation of the declared milestones of the project *(if applicable)*

An ongoing project, currently in the experimental data collection and analysis phase. Upgrade of an existing facility.

3. International scientific and technical cooperation.

Actually participating countries, institutions and 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

4. Plan/actual analysis of resources used: human (including associated personnel), financial, IT, infrastructure

4.1. Human resources (actual at the time of reporting, total number of participants)

(total number of participants)

№№ п/а	Category employee	Core staff Amount of FTE	Associated personnel Amount of FTE
1.	Scientific staff	3.8	
2.	engineers	1.4	
3.	professionals		
	Total:	**5.2**	

4.2. The actual estimated cost of the project

Names of costs, resources, funding sources			Cost (thousands of dollars) resource requirements	Proposal from the laboratory for allocation of funding and resources				
				2025	2nd year	3rd year	4th year	5th year
		International cooperation (IC)	91	91				
		Materials	39	39				
		Equipment and third-party services	169	169				
		Commissioning work						
		Services of research organisations	36	36				
		Acquisition of software						
		Design/construction						
		Service costs (*planned in case of direct project affiliation)*						
Resources required	**Normo-hours**	Resources						
		– The amount of FTE,						
		– accelerator/installation,						
		– reactor, ...						
Sources of funding	**Budgetary resources**	JINR budget*(budgetitems*	335	335				
	Extrabudgetary (supplementary estimates)	Contributions by co-contractors Funds under contracts with customers Other sources of funding						

4.3.Other resources

Computer resources consumed MICC	Distribution by year				
	1st year	2nd year	3rd year	4th year	5th year
Data storage (TB) - EOS - Ribbons					
Tier 1 (core-hour)					
Tier 2 (core-hour)					
SC Talker (core-hour) - CPU - GPU					
Clouds (CPU cores)					

5. Conclusion

Currently, the NA61/SHINE facility is operating stably and efficiently, regularly collecting experimental data in the planned modes, and actively analyzing the results, resulting in scientific papers published in leading international journals. The results obtained to date are of high quality, meet the current international standards in experimental nuclear physics, and confirm the competitiveness of the NA61/SHINE experiment. Overall, the scientific results achieved are commensurate with the resources expended and justify continued participation in the project.

6. Proposed reviewers

A.A. Baldin (LHEP JINR)

Theme Leader

_____ / Malakhov A.I.

"02" 04 2026

Project Leader

_____ / Malakhov A.I.

"02" 04 2026

Laboratory Economist

_____ / Pankratova E.D.

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