Annex 3.

Form of opening (renewal) for Project /
Sub-project of LRIP

APPROVED

JINR DIRECTOR

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SCIENTIFIC AND TECHNICAL REASONING FOR THE OPENING / RENEWAL OF PROJECT/SUB-PROJECT OF LARGE RESEARCH INFRASTRUCTURE PROJECT IN RESEARCH AREA WITHIN THE TOPICAL PLAN FOR JINR RESEARCH

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

1.1 Theme code / LRIP (for renewable themes) - *the theme code includes the opening date, the closing date is not given, as it is determined by the completion dates of the projects in the topic.*
02-2-1099-2010/2023 Study of Neutrino Oscillations (Project NOvA/DUNE)

1.2 Project/sub-project of a MIP code (for renewed themes)

1.3 Laboratory of Nuclear Problems and Laboratory of High Energy Physics

1.4 Scientific field Physics of elementary particles and relativistic nuclear physics

1.5 The name of the Project/subproject of the LRIP NOvA/DUNE

1.6 Project/ sub-project of the LRIP Leader(s) A. Olshevskiy

1.7 Project/sub-project of the LRIP Deputy Leader(s) (scientific supervisor of the project/sub-project of the LRIP) O.Samoylov, N.Anfimov

2 Scientific rationale and organizational structure

2.1 Annotation

Neutrino physics is a rapidly growing field in high-energy physics, which has experienced an additional boost over the last 25 years due to the discovery of the neutrino oscillation phenomenon by the Super-Kamiokande and SNO experiments. The leaders of these experiments were jointly awarded the Nobel Prize in 2015. In the two decades since this discovery, extensive studies of this phenomenon have been carried out using a plethora of unique experiments, which have provided remarkable and precise measurements of the parameters that define this process.

Neutrino oscillations refer to periodic transitions between different flavors of neutrino beams. This process was first suggested in the 1950s by the world-renowned JINR scientist Bruno Pontecorvo. Oscillations are possible because neutrinos are massive particles that can mix with one another. The neutrino oscillation parameters in the three-flavor paradigma are the two mass-squared differences and three mixing angles. The behavior of neutrino oscillations depends on these parameters, as well as the matter density, traveling distance of the particles, and their energy. Additionally, the phase of CP violation in the lepton sector is another parameter that enters the oscillation probability formula.

Currently, the goal of oscillation experiments is to measure the order of neutrino masses and the CP violation phase. Meanwhile, an additional goal is to enhance the precision of the already known parameters. All of these parameters are fundamental characteristics of the neutrino as a Standard Model particle, with numerous applications in both theory and other neutrino experiments.

There are several types of experiments that are designed to study neutrino oscillations. Traditionally these experiments are divided into four categories based on the type of neutrino source: solar, atmospheric, reactor, and accelerator. Three of these types use free particle sources, but accelerator neutrino experiments have the advantage of allowing for precise control of the parameters of the beams. Because of differences in experimental setups, each type of experiment is sensitive to different oscillation parameters. However, both the neutrino mass ordering and CP violation phase can be measured using accelerator neutrino beams, which also have the ability to switch between neutrino and antineutrino modes, a crucial capability for measuring deltaCP and resolving degeneracies.

Currently, there are two running accelerator neutrino experiments in the world that aim to study three-flavor oscillations. One of them is NOvA, a long-baseline neutrino experiment based at the Fermi National Accelerator Laboratory in the USA. NOvA utilizes two functionally-identical tracking calorimeters placed 809 km apart to observe the appearance of electron (anti)neutrinos and the disappearance of muon (anti)neutrinos in the muon (anti)neutrino-dominated 850kW NuMI beam. By observing these neutrino oscillations along with their antineutrino counterparts, NOvA is probing the outstanding aforementioned questions in neutrino physics, including the neutrino mass ordering, the leptonic CP violation parameterized by the phase δ_{CP}, the larger neutrino mass splitting Δm^2_{32}, and the mixing angle θ_{23}.

The NOvA experiment is expected to continue running until 2026. It is projected to have up to about 4-sigma sensitivity to the neutrino mass ordering and less than 2-sigma sensitivity to CP violation. These parameters will be the goal of the next generation of experiments, such as DUNE. DUNE, which is the mega-science project and the next flagship experiment of Fermilab in neutrino physics, has a very ambitious program that will be made possible due to the highest ever neutrino beam power, huge precise liquid argon TPC detectors, and a very long baseline of 1300 km. Despite the competitive nature of neutrino oscillation physics, DUNE's design characteristics are expected to provide it with a significant advantage over other projects. The goal of DUNE is to finalize the measurement of the neutrino mass ordering and CP violation phase.

The JINR group has been participating in the NOvA experiment since 2014, with a wide range of contributions that include experimental methods, computing, DDT and DAQ software, exotic physics searches, and oscillation analysis (the fits performed by JINR scientists became official NOvA results in 2018-2020). Additionally, a NOvA Remote Operation Center (ROC) for data-taking control was built in Dubna. The JINR group joined DUNE in 2020 with a contribution in building near detectors of this experiment and analysis preparations. JINR is responsible for design, production and operations of the Light readout system in the liquid argon calorimeter of DUNE Near Detector (ND-LAr)..

Another proposed JINR contribution is the straw-tracker of DUNE ND. This option was from the very beginning based on the JINR (VBLHEP) group expertise gained during previous straw tube production. It is expected that JINR will extend this expertise and maintain the leading scientific position in the straw project. Some R&D was already carried out by the JINR group and it is proposed to have an extensive design study and prototype testing during coming years as well as special R&D devoted to the straw-tracker production technology.

JINR scientists are involved in the management of NOvA and DUNE, occupying various positions such as DUNE's light readout NDLAr (L3 manager), NOvA's exotic physics group convener, production group convener, DAQ, DDT, and ROC experts.

In spite of very high competition in oscillation physics the common agreement is that all current and on-going experiments perfectly complement each other. Thus ongoing NOvA and T2K acknowledge strength of each other and carry on fully shared joint analysis with JINR involved from the NOvA side. Future IceCube, JUNO, ORCA, Hyper-Kamiokande and DUNE for sure will provide not only the cross check of each other, but being properly combined, introduce new features than a single result.

The work of NOvA/DUNE at JINR attracts a lot of attention from students and young staff. This provides a very good potential for growing and extending the JINR participation in this excellent physics with a good visibility.

2.2 Scientific justification (purpose, relevance and scientific novelty, methods and approaches, methodologies, expected results, risks)

Purpose:

The primary objective of the NOvA/DUNE project is to measure the yet unobserved neutrino oscillation parameters, namely the neutrino mass ordering and the CP violation phase. Additionally, the project aims to improve the precision of other known parameters in this field of study. The currently running NOvA experiment[1] is expected to provide a valuable contribution to the global understanding of these parameters. Combining NOvA results with those from other ongoing and soon upcoming experiments can provide important insights into the values of these unknown parameters. But the final answer will be obtained by the next generation experiments, such as DUNE[2]. The expertise gained by the JINR group in the NOvA experiment is also an important preparation for future measurements in DUNE.

In addition to the primary objective, the NOvA/DUNE projects have a wide variety of scientific goals. These include Beyond Standard Model searches and the study of free particle sources, such as supernova neutrinos, atmospheric muons, and the detection of magnetic monopoles if they exist. DUNE's future planning includes the consideration of different FD module methods[3] that will allow for a broader scientific goal while maintaining the oscillation potential. If accepted, DUNE will also be able to conduct searches for neutrinoless double-beta decay and proton decay.

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[1] Ayres D et al. (NOvA Collab), hep-ex/0503053 (2004)

[2] Abi B et al. (DUNE Collab) JINST 15 08 T08008 (2020)

[3] Askins M et al. (Theia Collab) Eur. Phys. J. C 80 5 416 (2020)

Relevance and scientific novelty

The scientific reasons for performing studies on neutrino oscillations are manifold. One of the reasons is the significant role that the order of masses plays in modeling neutrino fluxes during supernova explosions[4]. Furthermore, this parameter is crucial for evaluating the prospects of a whole class of experiments in neutrino physics that aim to search for neutrinoless double beta decay[5] and is an input parameter for experiments on direct measurement of neutrino masses[6] and search for relic neutrinos[7]. The phase of CP violation in the lepton sector, δ_{CP}, also has one main application that cannot be overestimated - it is associated with checking the origin of the asymmetry between matter and antimatter in the Universe[8].

All the parameters of neutrino oscillations are fundamental characteristics of this particle and are essential for understanding the process of neutrino propagation, which influences any possible practical applications of these particles that involve their movement. Some of the applications of neutrino beams include monitoring the operation of nuclear reactors, tomography of the Earth, and space exploration using ultrahigh-energy neutrinos.

In the past two decades, significant progress has been made in neutrino oscillation physics. The SNO[9] and KamLAND[10] experiments have measured the neutrino parameters Δm^2_{21} and θ_{12} very precisely using solar neutrinos. However, there is currently an interesting tension[11] between Super-Kamiokande[12] measurements and KamLAND+SNO, although in recent years, Super-Kamiokande has shown a tendency to reduce the significance of this discrepancy. The atmospheric parameter Δm^2_{32} is also well-known thanks to experiments like Super-Kamiokande, MINOS[13], T2K[14], NOvA and Daya Bay[15], but the mixing angle θ_{23} is still uncertain, and it is unclear which octant it belongs to. The Daya Bay experiment first measured[16] the non-zero mixing angle θ_{13} in 2012, which opened up the possibility of studying lepton CP violation through neutrino oscillations.

Thus accelerator neutrino experiments such as T2K and NOvA have made one of their primary goals to study δ_{CP}. However, due to statistical uncertainties, the current potential of these experiments is not enough to provide a firm measurement, even though they have the ability to switch between neutrino and antineutrino beams. While NOvA's long baseline also allows for a measurement of neutrino mass ordering, the presence of big degeneracies with other oscillation parameters makes a clean measurement challenging. Another type of neutrino experiment that can measure both δ_{CP} and neutrino mass ordering is atmospheric neutrino experiments, which uses naturally produced neutrinos and antineutrinos via colliding cosmic rays with the atmosphere. Currently, the main player in this field is the running Super-Kamiokande experiment. However, measuring δ_{CP} with atmospheric

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[4] Scholberg K J. Phys. G 45 1 014002 (2018)

[5] Dolinski M J et al. Ann. Rev. Nucl. Part. Sci. 69 219 (2019)

[6] Qian X et al. Prog.Part.Nucl.Phys. 83 1 (2015)

[7] De Salas P F et al. Front. Astron. Space Sci. 5 36 (2018)

[8] Pascoli S et al. Phys. Rev. D 75 083511 (2007), Branco G et al. Phys. Lett. B 645 432 (2007)

[9] Ahmad Q et al. (SNO Collab) Phys. Rev. Lett. 89 011301 (2002)

[10] Eguchi K et al. (KamLAND Collab) Phys. Rev. Lett. 90 021802 (2003)

[11] Nakajima Y .Recent results and future prospects from Super-Kamiokande., NEUTRINO-2020 conference (2020)

[12] Fukuda Y et al. (Super-Kamiokande Collab) Phys. Rev. Lett. 81 1562 (1998)

[13] Adamson P et al. (MINOS Collab)Phys.Rev.Lett. 125 (2020) 13, 131802

[14] Abe K et al. (T2K Collab) Phys.Rev.D 103 (2021) 11, 112008

[15] Adey D et al. (Daya Bay Collab) Phys.Rev.Lett. 121 (2018) 24, 241805

[16] An F et al. (Daya Bay Collab) Phys. Rev. Lett. 108 171803 (2012)

neutrinos is complicated due to the difficulty in separating neutrino/antineutrino events. Nevertheless, NOvA, Super-Kamiokande, and T2K are the only current oscillation experiments reporting measurements of δ_{CP} and mass ordering. In recent years, an interesting tension has been reported between these experiments, with both Super-Kamiokande[17] and T2K[18] preferring values of δ_{CP} closer to maximal CP violation ($3\pi/2$), while NOvA does not see any asymmetry between neutrinos and antineutrinos[19]. However, it should be noted that the significance of this tension is rather small, $< 2\sigma$. In spite of the fact that T2K, Super-Kamiokande and NOvA will run a few more years it's clear from current estimations that they wouldn't be able to finalize mass ordering and δ_{CP} measurement. There are some expectations about joint analysis of these experiment's data. Joint sensitivity is not publicly available but for sure it will be higher than individual ones.

Several experiments in preparation have the goal of finalizing δ_{CP} and mass ordering measurement. Mass ordering sensitivity of current and future projects is shown in Figure 1. IceCube's DeepCore[20] is under modernisation that should provide this experiment opportunity not only measuring Δm^2_{32} and θ_{23} but also mass ordering with modest sensitivity not higher than 4σ after 5 years of running. In about a year the JUNO[21] experiment should start taking data. This reactor experiment will have an ability to provide a clean measurement of mass ordering without any degeneracies with other oscillation parameters. That is very valuable for cross-check purposes. Experiment sensitivity is about 3σ after 6 years of running. KM3NeT's ARCA neutrino telescope in the Mediterranean sea will have a twin cluster ORCA[22] with dense strings deployed for oscillation study purposes with atmospheric neutrinos. This experiment will have very decent sensitivity to neutrino mass ordering that can allow it to make this measurement for all cases of oscillation parameters after about 10 years of data taking. Long baseline accelerator experiments Hyper-Kamiokande[23] and DUNE have a very similar setup. In case of DUNE sensitivity to neutrino mass ordering is $>5\sigma$ after a couple of years of data taking for all possible values of oscillation parameters. Both experiments have similar resolution on δ_{CP} (Figure 2).

On the current landscape there are also several future projects with unclear status: PINGU[24], ICAL@INO[25], ESSνSB[26], Protvino-to-ORCA[27], SuperCHOOZ[28], second Far Detector tank in

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[17] Linyan Wan. (2022, June 23 at Neutrino-2022) "New Results with Atmospheric Neutrinos at Super-Kamiokande" https://doi.org/10.5281/zenodo.6694761

[18] Abe K et al. (T2K Collab) e-Print: 2303.03222 [hep-ex]

[19] Acero M A et al. (NOvA Collab) Phys.Rev.D 106 (2022) 3, 032004

[20] Ishihara A (IceCube Collab) PoS ICRC2019 1031 (2020)

[21] Adam T et al., 1508.07166 [physics.ins-det] (2015)

[22] Adrian-Martinez S et al. (KM3Net Collab) J. Phys. G 43 8 084001 (2016)

[23] Abe K et al. (Hyper-Kamiokande Collab), 1805.04163 [physics.ins-det] (2018)

[24] Aartsen M et al. (IceCube Collab) J. Phys. G 44 5 054006 (2017)

[25] Ahmed S et al. (ICAL Collab) Pramana 88 5 79 (2017)

[26] Blennow M et al. Eur. Phys. J. C 80 3 190 (2020)

[27] Akindinov A V et al. Eur. Phys. J. C 79 9 758 (2019)

[28] A. Cabrera (29 Nov 2022, seminar at CERN) "The SuperChooz Experiment: Unveiling the Opportunity" https://indico.cern.ch/event/1215214/

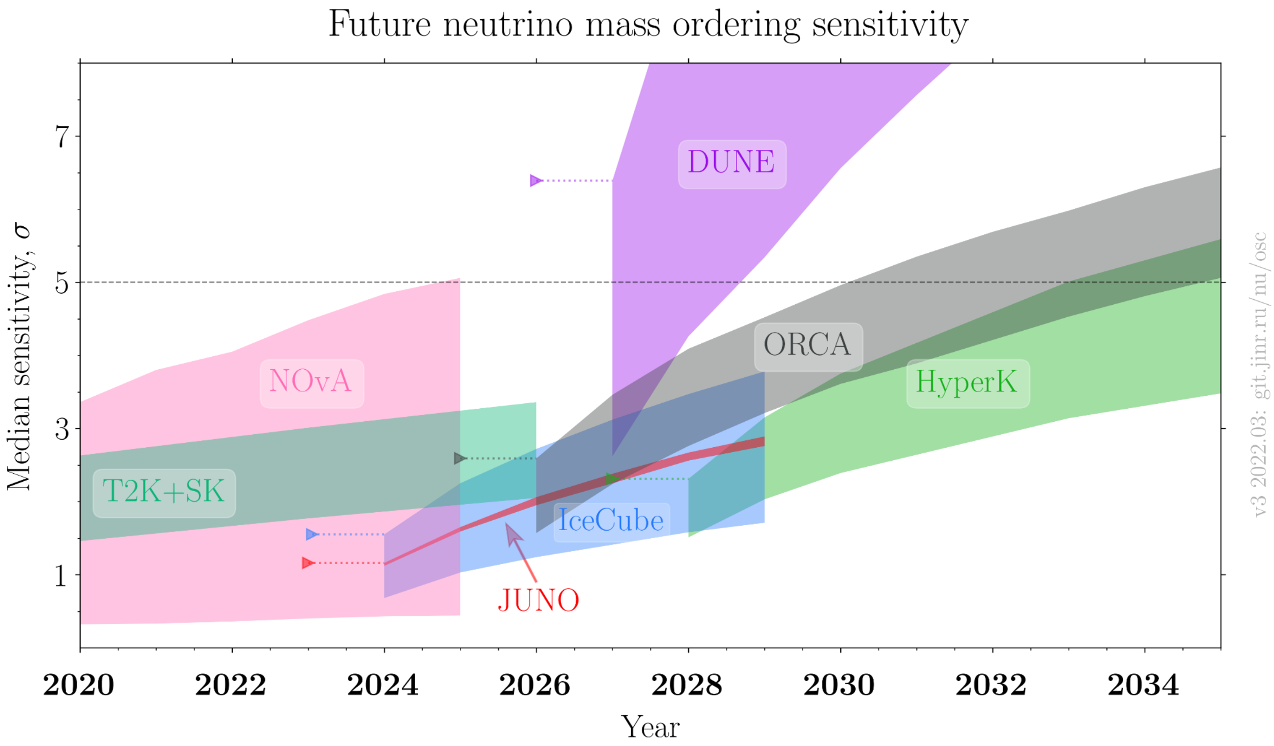

Figure 1. Expected sensitivity of current and future experiments to the neutrino mass hierarchy by years. The figures represent the areas of possible measurement, limited by combinations of oscillation parameters, leading to extreme sensitivity values for each experiment. The triangular markers mark the beginning of the data set.

Korea[29] for Hyper-Kamiokande. In case of their approval most likely they'll start producing results in late 2030s.

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[29] Abe K et al. (Hyper-Kamiokande Collab) PTEP 2018 6 063C01 (2018)

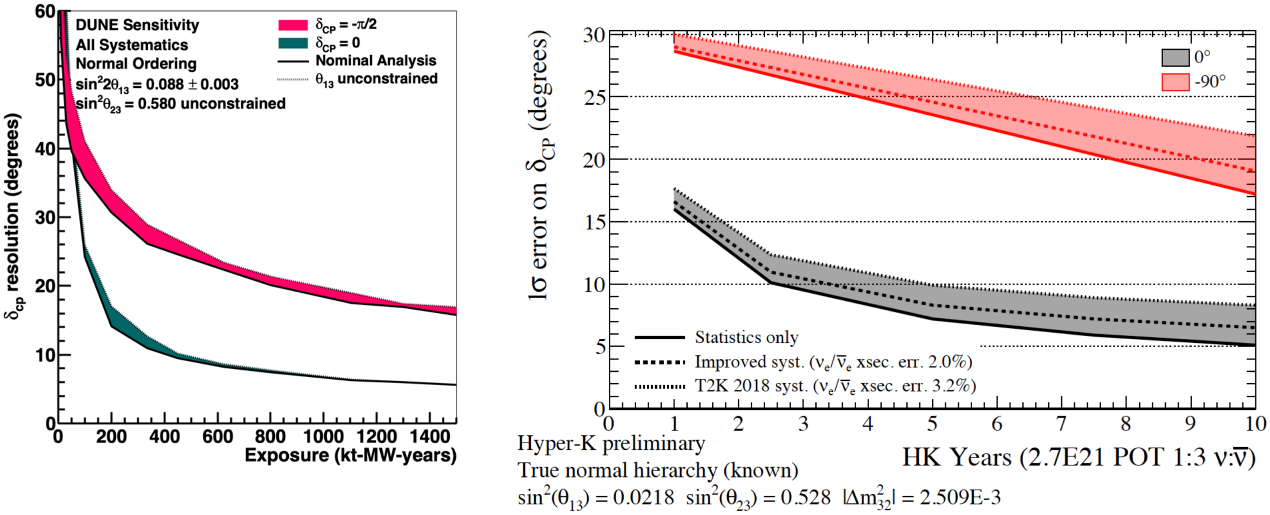

Figure 2. Expected sensitivity of DUNE (left) and Hyper-Kamiokande (right) experiments to CP resolution for CP = 0 and CP = 3/2 cases.

Methods and approaches

Both NOvA and DUNE are long baseline accelerator neutrino experiments. In the case of NOvA, the accelerator complex at Fermilab, inherited from Tevatron, is used to produce 120 GeV protons that are delivered to the carbon target. The neutrino beamline facility is inherited from NOvA's predecessor (the MINOS experiment). Magnetic horns, placed after the target, focus either positively or negatively charged mesons depending on the mode in which the experiment works (neutrino or antineutrino). Switching the horn current allows for changing the electric charge sign of the focusing beam. These pions and kaons then produce neutrinos while traveling through the decay pipe. In the case of the neutrino mode (antineutrino mode), the beam has the following composition — 95% ν_μ, 4% $\underline{\nu_\mu}$, 1% $\nu_e + \underline{\nu_e}$ (93% $\underline{\nu_\mu}$, 6% ν_μ, 1% $\nu_e + \underline{\nu_e}$). The addition of wrong sign background and nue component mostly appears due to muon decays. The accelerator complex at Fermilab is constantly being upgraded to produce more neutrinos. Thus, the designed power of the proton beam for NOvA was 700 kW, and recently, a 900 kW cable target and horns were installed. Currently the experiment works at 850kW beam power. Accelerator neutrino experiments measure exposure in terms of protons delivered to the target (POT). NOvA's most up-to-date analysis was performed with 13.6 x 10^{20} POT (neutrino beam) and 12.5 x 10^{20} POT (antineutrino beam). NOvA is expected to roughly double this exposure by the end of datataking.

Neutrinos travel through the Earth's crust to reach the Near Detector, which is located 1 km after the target to measure the initial neutrino flux. This is an important tool for controlling the initial beam composition, especially existing backgrounds and systematics. The Far Detector is placed 810 km away from the target and measures the neutrino flux after oscillations. Both NOvA detectors are placed off the beam axis at 14 mrad, which allows for obtaining a narrow energy peak at 2 GeV and suppressing high-energy tail backgrounds. The NOvA detectors are identical tracking calorimeters made of PVC cells filled with a liquid organic scintillator based on mineral oil with 5% pseudocumene. These cells are composed into planes, and planes with horizontal and vertical orientations alternate each other. The Far Detector (Near Detector) has dimensions of 15.4 m x 15.4 m x 60 m (4 m x 4 m x 16 m). Experiment setup is shown in Figure 3.

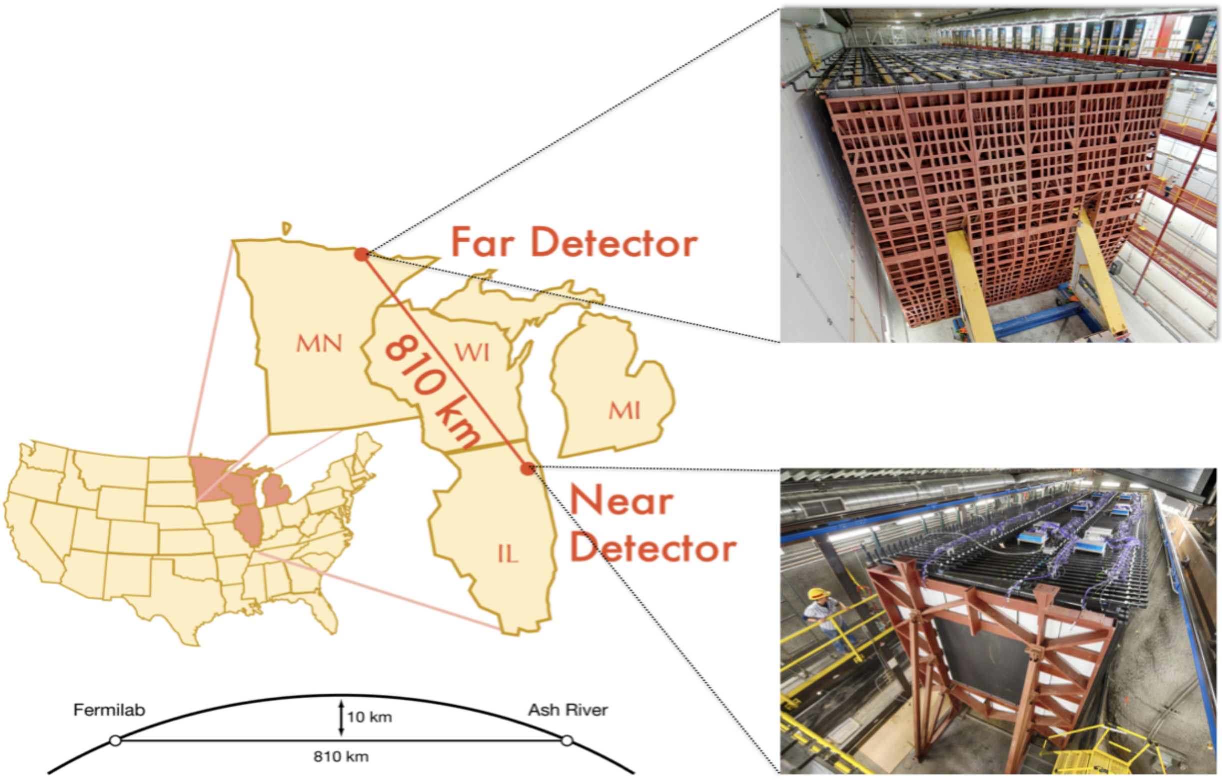

Figure 3. The NOvA experiment setup and detectors.

The detectors are optimal for measuring $\nu_e(\underline{\nu_e})$ and $\nu_\mu(\underline{\nu_\mu})$ via charged current interactions. Due to the identical detectors, systematic uncertainties connected with neutrino interaction cross-sections and flux partially cancel each other. Data-driven predictions based on the extrapolation of the measured event rate in the Near Detector are used for fitting Far Detector data. NOvA developed two fitting approaches based on Frequentist and Bayesian hypothesis, and both showed similar performance. JINR collaborators are working in the three-flavor oscillation analysis group in NOvA with different activities depending on the group needs. These days they're working on neutrino energy estimation, fitting and sensitivities in preparation for 2024 analysis release.

Another interesting application of NOvA's data is joint analysis with other experiments. Currently NOvA and T2K collaborations are developing joint three-flavor analysis of these experiment's data which is expected to be released in 2023. JINR scientists are involved in development of this analysis as members of NOvA's three-flavor group.

NOvA has various analyses with free natural sources of neutrino and other particles. One interesting measurement from the oscillation parameter's determination point of view is analysis of atmospheric neutrino oscillations. NOvA detects thousands of such neutrinos per year and these oscillations have sensitivity to the main goal of NOvA. This is also a good test of the Non Standard Interaction (NSI) hypothesis and a background for several physics analyses in Far detector. At present, the JINR group has started developing this analysis.

NOvA is the largest carbon-based supernova detector currently operating. In the event of a Galactic supernova, it will provide invaluable data which, in combination with detectors using different target materials, will constrain the flavor content of the supernova burst. The ND and FD have roughly equivalent supernova capabilities, with the ND's small mass being balanced by its low background. NOvA can both self-trigger on a supernova burst, if it is within 7 kpc (13 kpc) for a 9.6 (27) solar mass star, and be triggered by alerts from SNEWS. Given the estimated Galactic supernova rate of 3 per century, there is a 15% probability that NOvA observes a supernova burst through 2025(6), with the probability increasing linearly with each additional year. Dubna group developed a combined supernova detection system for both near and far detectors and monitor it.

The NOvA far detector, located on the Earth's surface, has a unique capability to detect low-mass (less 10^{10} GeV) monopoles, that would not reach underground detectors, and can match and surpass the MACRO and SLIM limits, covering a wider range of monopole masses. NOvA construction, hardware and setup allows to record tracks as slow as $\beta > 10^{-4}$, and we split the monopole searches into slow and fast options, where the ideas to catch signals follow the track speed and extra high ionization, respectively. Both searches are almost background free. Dubna group is performing the monopole search in NOvA.

Due to the surface location of the NOvA far detector, it can be used as a telescope for cosmic and atmospheric particles. An excellent opportunity for a detailed study of atmospheric muon fluxes: seasonal variations, correlation with solar and weather events, geomagnetic effects, high-energy muons and showers, etc. The Dubna group analyzes geomagnetic effects in the east-west asymmetry of muon spectra and tests the technique for measuring the spectrum of high-energy muons proposed by R.P. Kokoulin et al.

Compared to NOvA, the DUNE experiment will have several major differences. This experiment is expected to start data-taking in the late 2020s. The accelerator complex at Fermilab is currently being upgraded to provide a proton beam of ~1.2 MW for DUNE (Phase-I of experiment), with plans to upgrade the beam power to 2.4 MW after several years of running by replacing some subparts of the detector complex (Phase-II). Additionally, all components of the neutrino beamline (target, horns, decay pipe) will be different for DUNE, and neutrinos will travel 1300 km to the Far Detector complex (Figure 4). Both detector complexes will be placed on the beam axis, and a wide energy peak will cover two oscillation maxima, enhancing sensitivity to δ_{CP}. Due to the good energy resolution, all drawbacks of on-axis positioning will be eliminated.

The DUNE Far Detector will consist of four modules, with two TPC modules with dimensions of 19 m x 18 m x 66 m and a total of 17 kt of liquid argon (LArTPC) each being installed during Phase-I. Two other modules are under consideration for Phase-II of the experiment, with different technologies being discussed for adding for example neutrinoless double beta-decay searches to the scientific goals. The Near Detector complex[30] will consist of three detectors (Figure 5): NDLAr, which will also be a liquid argon TPC with 35 modules to maintain similarity with DUNE Far Detector modules with smaller size, another detector NDGAr that will measure signs of muons leaving NDLAr after neutrino interactions, consisting of a magnet and a gas argon TPC. These two detectors will be placed on a movable platform that will allow them to provide beam measurements at different off axis positions (DUNE-Prism). The third detector System for on-Axis Neutrino Detection (SAND), which will be placed on the beam axis and will consist of a straw-tube tracker (STT) placed inside a magnet. The primary goal of this detector is to provide beam monitoring, especially when the other detectors are making measurements off the beam axis. The DUNE-Prism

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[30] Abed Abud A et al. (DUNE Collab) Instruments 5 4 31 (2021)

predictions for the Far Detector differ significantly from NOvA's extrapolation. The key idea is to make a precise measurement of the neutrino flux and make a weighted sum of all these spectra to suppress dependence on flux and neutrino integration systematic uncertainties. JINR collaborators are working in DUNE-Prism group developing predictions for Far Detector's oscillation analysis.

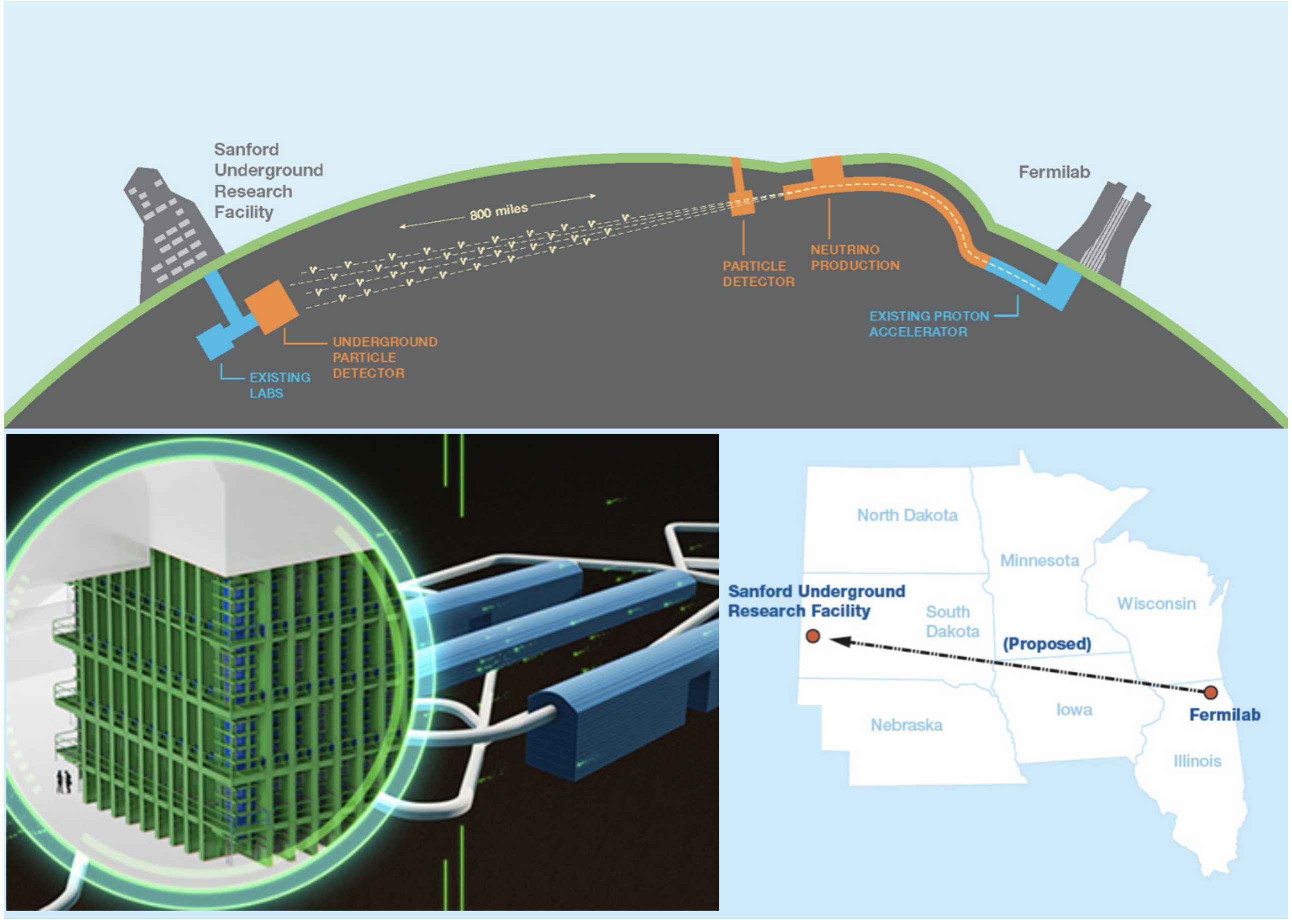

Figure 4. The DUNE experiment facilities.

Due to the different detectors used in DUNE, it will allow for various interesting measurements in particle physics and neutrino physics, particularly in the study of neutrino interactions. For the STT system in SAND it is considered placing layers of polypropylene and carbon between its modules, which will enable the identification of neutrino interactions with hydrogen using the CH2-C subtraction method. For a long time, the only available measurements of neutrino interaction cross-sections with hydrogen were limited by the results of low-statistics experiments with bubble chambers. SAND will provide valuable input for oscillation analysis due to an additional thin liquid argon target placed inside the detector. By comparing the cross-sections with hydrogen and argon, it is expected to reduce uncertainties in the calculations of neutrino interactions associated with nuclear effects. SAND will allow for the study of spin physics (polarization of Lambda-hyperons, spin asymmetry of vector mesons), particle multiplicity and production yields, neutrino interaction cross-sections on different targets that can be placed inside the detector, Weinberg angle, quasi-elastic and resonance interactions. JINR group is involved in development of reconstruction in STT, software for beam monitoring, resonance neutrino interactions and strange particle production analysis.

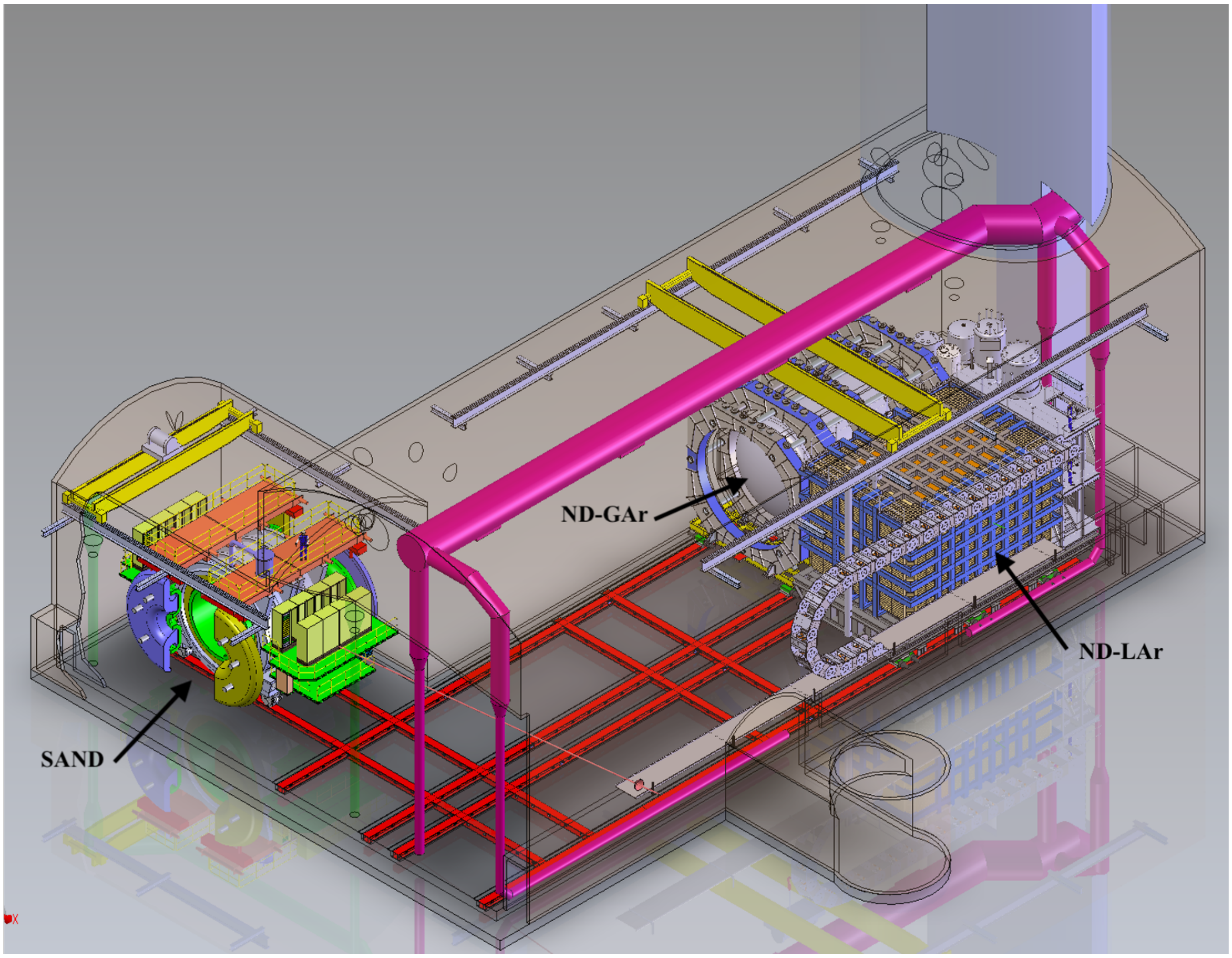

Figure 5. DUNE Near Detector complex at Fermilab. NDLAr and NDGAr are placed on movable platform to perform measurements of neutrino flux at different positions from beam axis.

For many years JINR is part of the NOvA data and Monte-Carlo prediction production network. During this period a computing infrastructure was deployed at JINR, including computational resources and data storages with different kinds of access mechanisms to fulfill the collaboration needs as well as the needs of the local group of researchers. This computing infrastructure consequently evolved into a Neutrino platform - a set of computing services and resources shared by all the neutrino experiments at JINR.

Recently our Institute also joined computing efforts of the DUNE experiment. While the overall data volumes are smaller than those routinely handled by the large LHC experiments, DUNE will still use substantial computing resources. A considerable proportion of disk and CPU capacity is expected from outside of the US (~ 50%) and national contributions of at least 5-20% are requested, depending upon the circumstance and capability of each compute-active-nation. JINR already provides both the CPU and disk capacity as our national contribution of the computing capacities for the experiment via a Grid-site at JINR, that was originally deployed for the NOvA experiment. Since DUNE plans on extending its computing requirements up to ~20k CPU cores and ~40 PB of disk space by 2025 (compared to 14k and ~25 PB of disk in 2023), JINR computing capacities will need to be increased accordingly.

Unlike DUNE, NOvA doesn't impose any strict requirements on collaborating institutes in terms of computing capacities. Therefore, the shared use of the existing neutrino platform computing infrastructure (together with other neutrino experiments JINR participates in) is expected to cover the needs of the experiment.

Methodologies

NOvA Scintillator studies

A challenge in simulating the NOvA detector response is the scintillator light output to different particles. In particular, the light from a scintillator is known to be saturated for particles with a high density of ionization losses (so-called, Birks law[31]). Another effect happens when a high-speed electron (or other charged particle) will pass through a dielectric medium faster than the speed of light inside the medium, the emitted waves add up constructively leading to coherent radiation known as Cherenkov radiation.

Two test stands have been built at JINR to measure the Birks constant for protons of a liquid scintillator[32] and the Cherenkov light contribution to its output. Birks constant was precisely measured for the NOvA scintillator, but Cherenkov light contribution is still a puzzle. Now we focus on the development of Cherenkov studies.

The bench consists of a few components:

- The Black Box, which is the light-tight metal box with equipment with connectors feedthrough. The Black Box is attached to a rotation platform.
- The PMT is 3''' Hamamatsu R12772 with cylindrical cuvette made of optical glass (it's diameter is 1 inch), that are located inside the Black Box in a vertical position.
- The cuvette with a liquid scintillator inside is used like the first detector. 2" NaI with PMT is used like the second detector.

The general idea of the measurement is to use Compton gamma-scattering to "prepare" electrons of various energies, and hence different speeds, in a liquid scintillator.

We use a monochromatic source 137Cs with E = 661.7 keV. By rotating the Black Box we change scattering angle and hence the energy of recoil electrons. Then we apply Birks's correction to the light output. Fitting below and above the Cherenkov threshold and extract the Slope difference.

Now we prepared the stand for Cherenkov light measurements and expect to finish scintillator studies in 2024.

DUNE ND-LAr Light Readout

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[31] J.B. Birks, "The theory and practice of scintillation counting", Pergamon Press, U.K. (1964).

[32] N. Anfimov, A. Antoshkin, A. Aurisano, O. Samoylov and A. Sotnikov "JINR stand measurements for improvements in the NOvA detector simulation chain" (2020) JINST 15 C06066.

Charge readout in LArTPCs has traditionally been accomplished via a set of projective wire planes, as successfully demonstrated e.g. in the ICARUS[33], ArgoNeuT[34], MicroBooNE[35] and ProtoDUNE-SP[36] experiments, and as planned for the first large detector module of the DUNE[37] experiment currently in preparation at the Sanford Underground Research Facility (SURF) underground laboratory in South Dakota. However, this approach leads to inherent ambiguities in the 3D reconstruction of charge information that present serious challenges for LArTPC-based near detectors, where a high rate of neutrino interactions and an associated high-intensity muon flux cannot be avoided. In particular, 3D reconstruction becomes limited by overlap of charge clusters in one or more projections, and the unique association of deposited charge to single interactions becomes intractable.

To overcome event pile-up, a novel approach has been proposed and is being developed for the LArTPC of the Near Detector (ND) complex of the DUNE experiment, dubbed ND-LAr[38], close to the neutrino source at Fermilab. This technology implements three main innovations compared to traditional wire-based LArTPCs: a pixelated charge readout enabling true 3D reconstruction, a high-performance light readout system providing fast and efficient detection of scintillation light, and segmentation into optically isolated regions. By achieving a low signal occupancy in both readout systems, the segmentation enables efficient reconstruction and unambiguous matching of charge and light signals.

The ND-LAr system will be a 5x7 array of the TPC modules with a size of 1.0 x 1.0 x 3.5 of cubic meters. To confirm the modular operation a 2x2 demonstrator is being constructed for tests at the Fermilab NuMI beam. The demonstrator contains 4 prototypes of smaller TPC modules with dimensions of 0.67 x 0.67 x 1.81 m^3. It is planned to manufacture a full-size near-detector module, the so-called Full-Scale Demonstrator (FSD), and to test it in 2024−2025

The ND-LAr offers true 3D tracking information using a pixelated charge readout[39]. The charge readout window (drift time) of 137μs is long compared to the 10μs beam spills at NuMI and LBNF beams. Neutrino interactions overlap and individual energy deposits cannot be easily associated with a specific neutrino vertex. This problem can be solved by incorporating fast timing information from the prompt scintillation light emitted by the charged particles in LAr at ~127 nm wavelengths along with ionization. The module's opaque cathode and walls contain scintillation light within each TPC (half module), improving the detection efficiency of the prompt component of the scintillation light. The solution developed by the JINR effort is a Light Collection Module (LCM) (or

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[33] Amerio, S.; et al. Design, construction and tests of the ICARUS T600 detector. Nucl. Instrum.Meth. A 2004,527, 329–410. doi:10.1016/j.nima.2004.02.044.

[34] Anderson, C.; et al. The ArgoNeuT Detector in the NuMI Low-Energy beam line at Fermilab. JINST 2012, 7, P10019, [arXiv:physics.ins-det/1205.6747] doi:10.1088/1748-0221/7/10/P10019.

[35] Acciarri, R.; et al. Design and Construction of the MicroBooNE Detector. JINST 2017,12, P02017, [arXiv:physics.ins-det/1612.05824]. doi:10.1088/1748-0221/12/02/P02017.

[36] Abi, B.; et al. First results on ProtoDUNE-SP liquid argon time projection chamber performance from a beam test at the CERN Neutrino Platform.JINST 2020, 15, P12004, [arXiv:physics.ins-det/2007.06722]. doi:10.1088/1748-0221/15/12/P12004.

[37] Abi, B.; et al. Deep Underground Neutrino Experiment (DUNE), Far Detector Technical Design Report, Volume I Introduction to DUNE. JINST 2020, 15, T08008, [arXiv:physics.ins-det/2002.02967]. doi:10.1088/1748-0221/15/08/T08008.

[38] DUNE Collaboration. Deep Underground Neutrino Experiment (DUNE) Near Detector Conceptual Design Report. *Instruments* **2021**, *5*. doi:10.3390/instruments5040031.

[39] Dwyer, D.; et al. LArPix: demonstration of low-power 3D pixelated charge readout for 755 liquid argon time projection chambers. *Journal of Instrumentation* **2018**, *13*, P10007–P10007.doi:10.1088/1748-0221/13/10/p10007.

another option: ArcLight), which is a compact dielectric light trap allowing for light collection from a large area and inside high electric fields.

The light detection[40] is based on the two-stage wavelength shifting: 127 nm (VUV) to 425 nm (blue) that increase the light penetration and then trap the blue light by shifting it to the green region (~510 nm). Finally, the green light is read out by means of Silicon Photomultipliers.

In the ND-LAr consortium, JINR took responsibility to provide and produce the complete light readout system. This includes: LCM/ArcLight modules, Front-End electronics (preamplifiers), ADC, power supply system, signal/power lines, DAQ and Slow Control. Our joint effort is also to implement light readout with charge readout by using time and data synchronization between the two systems.

The general scope of the Light Readout System within the NDLAr-TPC is presented in Figure 6. The LCM prototype is a frame cantilevered by a PVC plate that holds WLS fibers which are bent into two bundles and optically coupled to two SiPM light sensors. Fibers are grouped and held by spacer bars with holes fixed on the PVC plate by means of polycarbonate screws to provide matching of thermal contraction. The PVC plate with the WLS fibers is coated with TPB, which re-emits the absorbed VUV light to the blue. This light is then shifted inside multi-cladding 1.2 mm Kuraray Y-11 fibers to green and hence is trapped by total internal reflection guiding it to the SiPM readout at the fiber end. The LCM has dimensions are 100 mm x 300 mm x 10 mm (FSD - 100 mm x 500 mm x 10 mm) and grouped by three modules.

The ArCLight module has been developed by Bern University. The general concept is that blue light enters a bulk WLS volume and is re-emitted as green light, and the volume has a coating reflective to green light on all sides except on the SiPM photosensor window. A dichroic filter transparent to the blue light and reflective for the green is used on the TPB side. The overall module dimensions are 300 mm x 300 mm x 10 mm (FSD - 300 mm x 500 mm x 10 mm).

The readout chain is as follows (Figure 7). The group of 3 LCMs or 1 ArcLight is read out by means of 6 SiPMs sitting on 3 PCB attached to E-PCB with amplifiers. FSD design - 1 cold-PCB with 6 SiPMs and cold electronics (amplifiers). The electronics operate at cryogenic temperature of the Liquid Argon. The E-PCB has 6 preamplifiers that drive signal to long signal lines outside the TPC cryostat. Then signals (see Figure 7) are adjusted and transformed to differential signal lines by Variable-Gain Amplifiers and sent thereafter to the ADCs. The ADCs[41] are 62.5 MHz sampling converters, 14-bit amplitude resolution and 64-channel (differential signals) designed at JINR (VBLHEP) for NICA/MPD ECAL readout and adapted for our needs.

Since 2021, 4 prototypes of the TPC modules have been manufactured and successfully tested with cosmic rays. An important stage of approving the design and operation of the ND-LAr, Preliminary Design Review[42], has been passed. The assembly of the 2x2 module array and neutrino beam tests at Fermilab in 2023−2024 are being prepared. The manufacturing of the Full-Scale Demonstrator is planned for 2024, and it's characterization in 2024-2025. Then, the final approval of the detector, Final Design Review, is expected.

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[40] Anfimov, N.; et al. Development of the Light Collection Module for the Liquid Argon 762 Time Projection Chamber (LArTPC). *Journal of Instrumentation* **2020**, *15*, C07022–C07022. 763 doi:10.1088/1748-0221/15/07/c07022.

[41] A. Baskakov, S. Bazylev et al. MPD Data Acquisition System. Technical Design Report. Version 2018.8.27. https://nica.jinr.ru/documents/Rep_NICA_2019_eng_OK.pdf

[42] DUNE Preliminary Design Report. ND-LAr chapter. To be released in 2023.

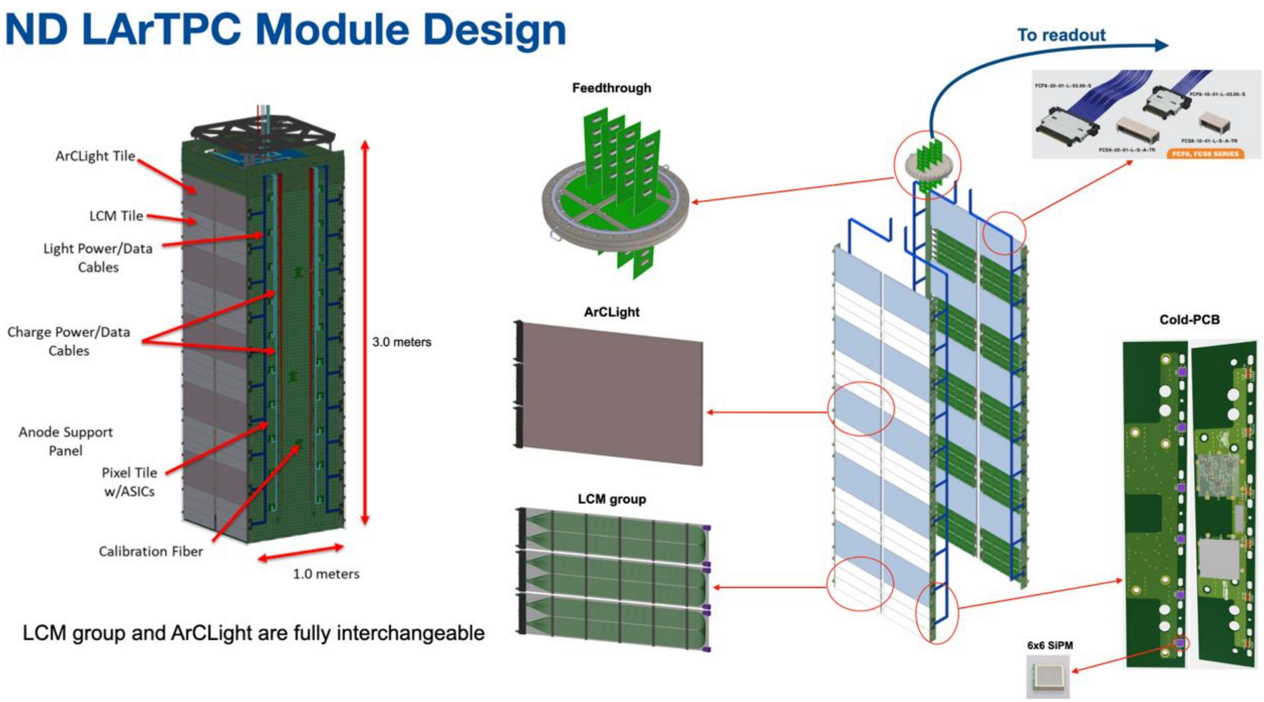

Figure 6. The Scope of the ND-LAr Light Readout System.

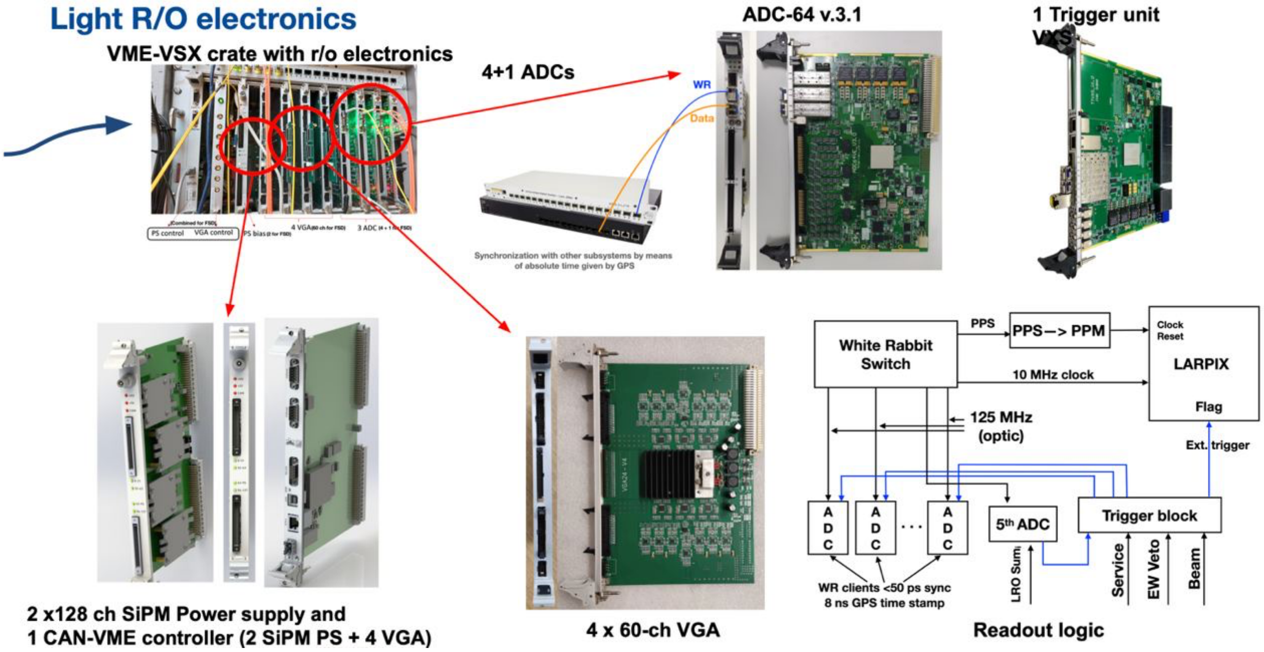

Figure 7. Light Readout Electronics

As a part of R&D we have constructed at JINR (DLNP) a cryogenic stand, which allowed numerous tests of the light readout system: light detection efficiency of different light collection modules, electronics, mechanical stresses, etc. This stand is important to provide R&D on the production of fibers with implanted TPB into a cladding.

System for on-Axis Neutrino Detection in DUNE

The DUNE "Phase 1" Near Detector (ND) complex includes a System for on-Axis Neutrino Detection (SAND) permanently located on-axis. The SAND detector (Figure 8) is based on a solenoidal superconducting magnet providing a 0.6 T magnetic field and supporting a 4π electromagnetic calorimeter (ECAL). Both the magnet and the ECAL are repurposed from the KLOE experiment. The inner magnetic volume (~43 m^3) will be instrumented with a novel integrated tracking and target system based on a Straw Tube Tracker (STT). This technology was chosen by the DUNE collaboration in September 2021 over alternative options. The inner tracker is complemented by a GRanular Argon for Interaction of Neutrinos (GRAIN), providing a thin liquid argon (LAr) active target (~ 1 ton) located upstream of the STT.

The primary goal of SAND is to perform in-situ measurements to constrain the leading systematic uncertainties affecting the long-baseline (LBL) oscillation analyses including the following:

- continuous monitoring of the event rates, beam profiles and spectra;
- precision in-situ flux measurements of ν_μ, $\underline{\nu}_\mu$, ν_e , $\underline{\nu}_e$ initially present in the beam as a function of energy;
- direct measurements of nuclear effects and constraints on the related nuclear smearing.

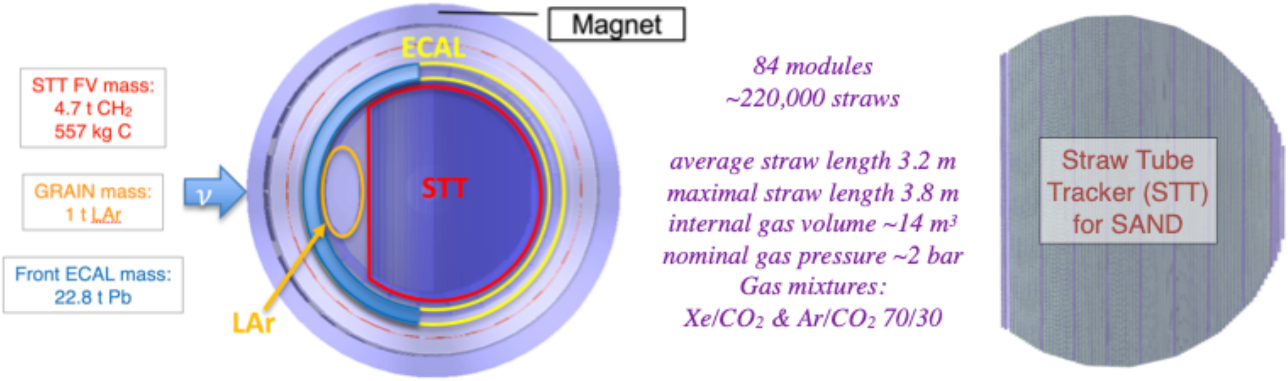

Figure 8. Left picture: side view of the SAND detector showing the main elements located inside the solenoidal superconducting magnet. Right picture: summary of the geometry (side view) and of the main STT parameters.

To this end, SAND must accurately reconstruct the four-momenta of visible final state particles produced in (anti)neutrino interactions, as well as the overall event kinematics and the corresponding momentum balance in a plane transverse to the beam direction. Furthermore, it must have excellent $\mu\pm$ and $e\pm$ identification capabilities and an accurate calibration of the momentum/energy scales. The same requirements, combined with the unprecedented intensity of the (anti)neutrino beams at the Long-Baseline Neutrino Facility (LBNF), will enable a broad program of physics measurements of fundamental interactions and of the properties of nucleons and nuclei synergistic with other fields.

Straw Tube Tracker (STT) for SAND

The STT represents a novel detector concept for neutrino physics, addressing the main limitations of past neutrino experiments. The STT is designed to offer an accurate control of the configuration, chemical composition and mass of the neutrino targets similar to electron scattering experiments, by physically separating the neutrino targets from the actual tracking system. A large number of thin planes – each typically 1-2% of radiation length X_0 – of various passive materials with comparable thickness are alternated and dispersed throughout active layers – made of four straw planes – of negligible mass in order to guarantee the same acceptance to final state particles produced in (anti)neutrino interactions (Figure 9). The STT allows to minimize the thickness of individual active layers and to approximate the ideal case of a pure target detector – the targets constitute about 97% of the mass – while keeping the total thickness of the stack comparable to one radiation length. Each target plane can be removed or replaced with different materials during data taking, providing a flexible target configuration. The average momentum resolution expected for muons is δp/p ~ 3.5% and the average angular resolution is better than 2 mrad. The momentum scale can be calibrated to about 0.2% using reconstructed $K_0 \rightarrow \pi^+\pi^-$ decays.

The STT offers unique detector capabilities which can enhance the LBL physics potential of DUNE. A key feature is the concept of "solid" hydrogen target, obtained by subtracting measurements on dedicated graphite (pure carbon) targets from those on polypropylene (CH2) targets (Figure 9).

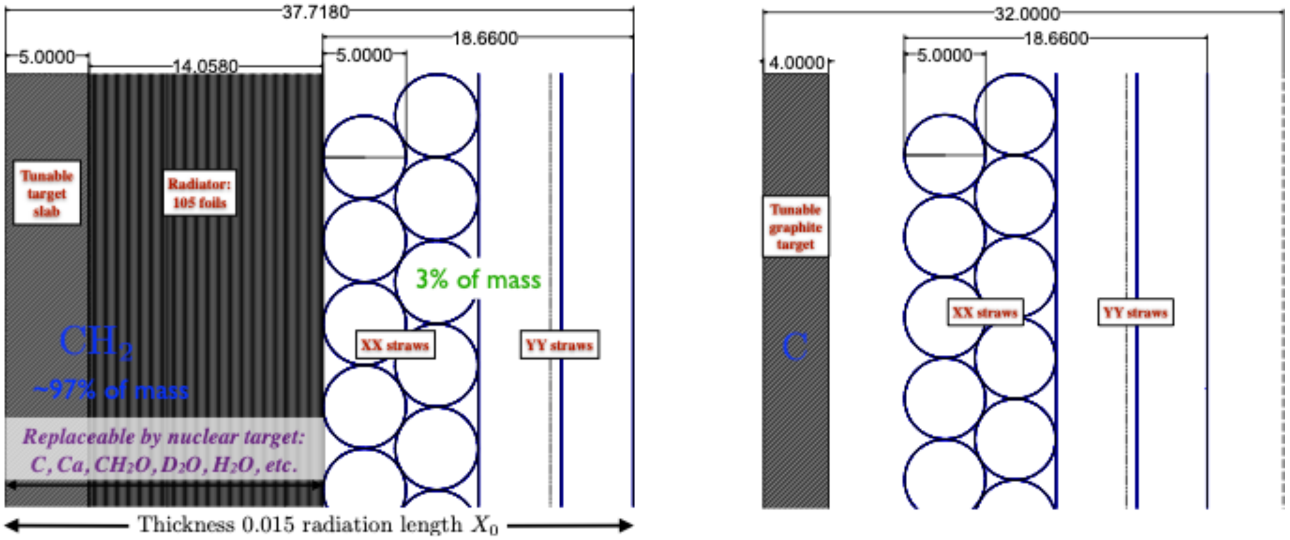

Figure 9. Drawing of a default STT module (left picture) including three main elements (left to right): (a) a tunable polypropylene CH2 target; (b) a radiator with 105 polypropylene foils for e± ID; (b) four straw layers XXYY. The radiator and plastic target are removed for modules to be equipped with nuclear targets, like the main graphite ones in the right picture.

This technique is conceived to be model-independent, as the data from the graphite targets automatically include all types of processes, as well as detector effects, relevant for the selection of interactions on H. For CC interactions the dilution factor with respect to a pure H2 target can be reduced by a factor 5-7 with a kinematic analysis based on energy-momentum conservation. The "solid" hydrogen target in STT provides a powerful tool to reduce the systematic uncertainties on various measurements in the DUNE ND. In particular, it allows a determination of (anti)neutrino flux with an accuracy not achievable with other known techniques. Furthermore, a direct comparison of interactions on H – free from nuclear effects – with the corresponding ones obtained from the nuclear targets – including the thin LAr one – allows to directly constrain the nuclear smearing resulting in an accurate calibration of the neutrino energy scale in (anti)neutrino interactions on nuclei.

The reduction of systematic uncertainties provided by the STT would also make it possible to exploit the unique properties of the neutrino probe for precision studies of fundamental interactions and of the structure of nucleons and nuclei. The ND site could then become a general purpose neutrino and antineutrino physics facility with a broad program of physics measurements complementary to the ongoing efforts in the fixed-target (12 GeV program at Thomas Jefferson laboratory), collider (Electron-Ion Collider), and nuclear physics communities. The level of precision achievable can provide insights on various fields generating hundreds of diverse physics studies including some traditional measurements and others which could probe new physics or address existing discrepancies. Precision tests of electroweak physics can be performed using various complementary physics processes in neutrino and antineutrino interactions. The unique combination of nuclear and "solid" hydrogen targets within STT allows precision studies of structure functions and parton distributions, QCD, sum rules, higher twists and non-perturbative effects, strangeness content of the nucleon, charm production, isospin physics, tests of charge symmetry, structure of the weak current, etc. This diverse program of precision measurements would concurrently be sensitive to new physics beyond the Standard Model, in a way complementary to direct searches. These latter can also be performed over a broad range of topics like sterile neutrinos, non-standard interactions, dark sector physics, etc.

From a technological standpoint, the STT project for SAND will allow the development of a next-generation optimized straw tracker with a tight integration with the front-end electronic readout. The resulting detector can represent a valuable solution for a number of other applications in various modern high energy physics experiments.

A complete review of the preliminary design of SAND will take place in November 2023. The Technical Design Report (TDR) of the entire ND complex will be prepared by the end of 2024. The completion of the final design and the corresponding review is expected in 2025. The actual production of the required STT modules is planned to start in 2026 and will last until the end of 2029, with the installation at the Fermilab ND site proceeding partially in parallel. The first LBNF beam is expected to be delivered to DUNE in the late 2020s. The SAND readiness from Day-1 is critical to guarantee that the data collected by the DUNE far detector can be correctly analyzed.

The following activities are envisaged at JINR during the period 2023-2026:

- Assembly and test of 1.2 m × 0.8 m prototype with C-composite frame and four XXYY straw layers in 2024.
- Assembly and test of full size prototype with one dimension of 4 m, C-composite frame and XXYY straws in 2025.
- Development of front-end (FE) readout electronics for the STT including ASIC revision in 2023-2026.
- Testbeam exposure of small 0.35 m × 0.35 m prototypes at CERN to evaluate the performance of different FE readout options/prototypes in 2023-2026
- Preparation of a JINR straw production center for the STT fabrication in 2024-2026 including (a) refurbishing of laboratory with clean room; (b) straw production line equipped with ultrasonic welding technology and related quality controls; (c) assembly and testing facility for the complete STT modules.

JINR straw tracker group

Track detectors based on straw drift tubes have a wide range of applicability in particle physics due to their good spatial and momentum resolution, relatively low costs and well- established production. JINR group has strong involvement in development, construction and installation for various straw detectors (ATLAS, COMPASS, NA62, NA64, SHiP, COMET). In 2014, JINR registered two patents for the manufacture of cylindrical tubes for gas-filled drift detectors and for measuring the location of wires in them. An example of a working straw spectrometer in the NA62 experiment is shown in Figure 10.

Figure 10. Installation process for one of four straw chambers in the NA62 experiment.

During the last several years 2021-2023 JINR group demonstrated the following aspects of the STT design. The JINR line (Figure 11) produced 5 m long straws with ultrasonic welding technology with required quality and maximal length. The straws passed measurements of maximal internal pressure, radial and longitudinal deformations vs. pressure, relaxation vs. time and humidity, gas tightness, etc. a 1m x 1m XXYY prototype was created to make gluing and pressure tests. A mockup prototype with plexiglass frame was assembled and tested with 20 um wire at STT operating conditions. JINR group in collaboration with PNPI (Gatchina, Russia) tested straw prototypes and electronic setups (VMM3/3a, TIGER) for the future projects NA64, SPD NICA and DUNE. The latest test stand at CERN is shown on Figure 12. Data analysis is in progress and expected in 2023.

Figure 11. 5m long straws for STT prototyping produced at JINR.

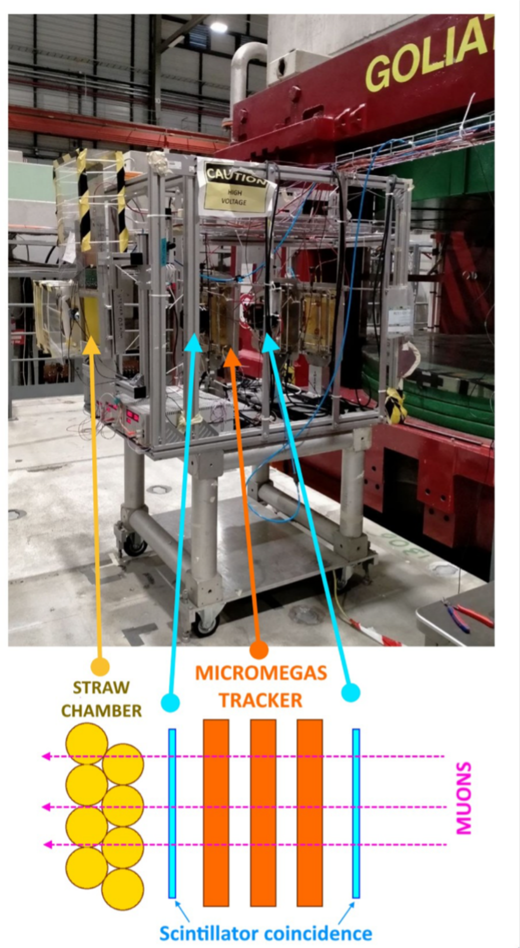

Figure 12. Test stand at CERN in 2022 setup: XX+YY STT prototype, scintillator planes for trigger, micromega trackers and electronics.

VBLHEP has unique technologies that have made it possible to create reliable straw detectors for the current experiments NA-62, NA-64. Ultrasonic welding made it possible to produce 17 km of vacuum-tight seam for NA-62, which has been successfully operated for 10 years (only one tube broke during this time). For the assembly process of the NA-62, NA-64 detectors, a lot of tools were created without which it is impossible to create full detectors.

Currently JINR has a prototype of a straw tubes production line, where the straws can be made with the following parameters: production - 1m/min, length up to 5.5 m, diameters - 5,10,20 mm, thickness - 15,20,36,50 µm, which basically corresponds to the STT characteristics: straw outer diameter: 5 mm, wall thickness: 20 µm or lower, double film metallization: 70 nm (inner) + 70 nm (outer), wire 20 µm diameter, 4 straw layer XXYY glued assembly, operated at internal overpressure of about 1 bar (2 bar absolute), thin modules with light C-composite frames, compact low-power frontend readout integrated into frames.

In total, for SAND STT it is necessary to manufacture about 220 '000 straws (up to 4m long). This amount is expected to be jointly produced by the consortium of several production centers, where the JINR is expected to play a leading scientific role due to recognized competence.

Expected results

The following results are expected with participation of the JINR team.

The NOvA experiment:

- measurement of neutrino mass hierarchy and reject CP conservation with $\leq 4\sigma$ and $\leq 2\sigma$ significance correspondingly;
- joint analyses with other experiments that will improve this sensitivity, namely NOvA+T2K analysis;
- a new restrictions on magnetic monopole existence with high gain data, higher statistics and updated trigger and analysis;
- trigger monitoring and analysis preparations for supernova neutrino signal detection;
- measurements of atmospheric muon spectra for different conditions;
- first NOvA's oscillation analysis made with atmospheric neutrinos;
- scintillator properties characterization, namely contribution of the Cerenkov light;
- ROC-Dubna and computing system operation.

The DUNE experiment:

- Light Readout System development for NDLAr;
- 2x2, FSD tests and measurements at NuMI neutrino beam;
- straw-tube prototyping, STT and electronics tests, preparations for production;
- developing computing infrastructure and setup;
- analysis preparations.

SWOT-Analysis

	Helpful	Harmful
Internal	**STRENGTHS** • Already fully operational NOvA experiment • Approved NOvA running until 2026 and changeover to DUNE • Tested and confirmed DUNE ND-LAr modules approach (approved at PDR level) • JINR responsibility for two major subsystems in DUNE ND (Light detection, Straw-tracker) • Rich non-oscillation program	**WEAKNESSES** • Systematic error sources depending on unknown cross-sections and detector features • Late DUNE start ~ 2032 • Restrictions for Russian fellows to enter DOE laboratories • Export/Import restrictions in the Russian Federation.
External	**OPPORTUNITIES** • Supernova burst, new physics existence	**THREATS** • Major accident with detectors or beam hardware

	- Systematic errors reduction due to new measurements or theory improvement - Development of new methods and technologies - World's best management standards	- Unexpected change of Fermilab plans due to significant budget cuts - Major changes in the world situation

2.3 Estimated completion date: 2040

2.4 Participating JINR laboratories: Dzhelepov Laboratory of Nuclear Problems (DLNP), Veksler and Baldin Laboratory of High Energy Physics (VBLHEP), Bogolyubov Laboratory of Theoretical Physics (BLTP), Mesheryakov Laboratory of Information Technologies (MLIT).

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	1 PB (Cloud)	1.3 PB (Cloud)	1.5 PB (Cloud)		
Tier 1 (core-hour)	0	0	0		
Tier 2 (core-hour)	0	0	0		
SC “Govorun” (cores-hours) - CPU - GPU	0	0	0		
Clouds (CPU cores)	1000	1250	1500		

2.5. Participating countries, scientific and educational organizations

The NOvA collaboration has about 40 participating organizations, while DUNE has about 200. We’re filling the table with actual partners of JINR group activities.

Organisation	**Country**	**City**	**Participants**	**Type of agreement**
FNAL	USA	Batavia, IL	Alex Himmel + 3 Jenifer Raaf + 4	JINR-FNAL agreement extension
University of Bern	Switzerland	Bern	Michele Weber + 2	Consortium agreement
CERN	Switzerland		Francesco Lanni,	Neutrino

			Filippo Resnati	Platform Agreement
LBNL	USA	Berkeley, CA	Daniel Dwyer + 1	DUNE Collaboration
SLAC	USA	Stanford, CA	Hirohisa Tanaka + 1	DUNE Collaboration
University of California, Irvine	USA	Irvine, CA	Juan Pedro Ochoa Ricoux Jianming Bian	DUNE Collaboration NOvA Collaboration
University of Minnesota	USA	Minneapolis, MN	Matt Strait	NOvA Collaboration
University of Minnesota Duluth	USA	Duluth, MN	Alec Habig	NOvA Collaboration
University of South Alabama	USA	Mobile, AL	Martin Frank	NOvA Collaboration
University of South Carolina	USA	Columbia, SC	Roberto Petti + 2	DUNE Collaboration
INFN	Italy	Pisa	Stefano di Falco + 1	DUNE Collaboration
INFN	Italy	Bologna	Gabriele Sirri	DUNE Collaboration
INFN	Italy	Padova	Matteo Tenti	DUNE Collaboration
Institute of Nuclear Physics	Kazakhstan	Almaty	Sayabek Sakhiyev + 6	DUNE Collaboration
The Institute for Nuclear Research of the Russian Academy of Sciences	Russia	Moscow	Anatoly Butkevich + 1	DUNE Collaboration
Queen Mary University of London	UK	London	Alexander Booth	NOvA Collaboration
University of Florida	USA	Gainesville	Mayly Sanchez + 2	NOvA Collaboration

Caltech	USA	Pasadena	Ryan Patterson, Zoya Vallary + 2	NOvA Collaboration
The College of William & Mary	USA	Williamsburg	Patricia Vahle, Erika Catano-Mur	NOvA Collaboration
Stony Brook University	USA	*Stony Brook, NY*	Michael Wilking	DUNE Collaboration
University of Mississippi	USA	*Oxford*	Gavin Davis, Jeffrey Kleykamp	NOvA Collaboration

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).*

Fermi National Accelerator Laboratory (FNAL), The University of Bern (UniBe).

3. Staffing

3.1. Staffing needs in the first year of implementation

№ № n/a	Category employee	Core staff, Amount of FTE	Associated Personnel Amount of FTE
1.	scientific staff	7+3	3
2.	engineers	4+5	3
3.	professionals		
	Total:	**19**	**6**

3.2. Human resources available

3.2.1. JINR core staff

№ № п/a	Category of employees	NAME	Division	Position	Amount of FTE
1.	scientific staff	Alexander Olshevsky	DLNP	Head of Department,Project leader	0.6
2.	scientific staff	Nikolay Anfimov	DLNP	Head of sector	0.5

				(deputy)	
3.	scientific staff	Oleg Samoylov	DLNP	Head of sector (deputy)	0.8
4.	scientific staff	Temur Enik	VBLHEP	Head of group	0.3
5.	scientific staff	Sergey Movchan	VBLHEP	Head of sector	0.3
6.	scientific staff	Georgy Kekelidze	VBLHEP	Head of sector	0.2
7.	scientific staff	Artem Chukanov	DLNP	Senior researcher, PhD	0.5
8.	scientific staff	Vyacheslav Tchalyshev	DLNP	Senior Researcher, PhD	0.5
9.	scientific staff	Anastasia Bolshakova	DLNP	Researcher, PhD	0.5
10.	scientific staff	Liudmila Kolupaeva	DLNP	Researcher, PhD	1.0
11.	scientific staff	Alexander Antoshkin	DLNP	Researcher	0.9
12.	scientific staff	Oleg Klimov	DLNP	Researcher	1.0
13.	scientific staff	Olga Petrova	DLNP	Researcher	1.0
14.	scientific staff	Arseniy Rybnikov	DLNP	Researcher	0.3
15.	scientific staff	Alexander Selyunin	DLNP	Researcher	0.7
16.	scientific staff	Vladislav Sharov	DLNP	Researcher	0.4
17.	scientific staff	Andrey Sheshukov	DLNP	Researcher	0.8
18.	scientific staff	Dmitry Shkirmanov	DLNP	Researcher	1.0
19.	scientific staff	Svetlana	DLNP	Researcher	0.5

		Vasina			
20.	engineers	Vasily Gromov	DLNP	Leading engineer	0.5
21.	engineers	Sergei Sokolov	DLNP	Senior engineer	0.6
22.	engineers	Vladimir Kozhukalov	DLNP	Engineer	1.0
23.	engineers	Ksenia Kuznetsova	DLNP	Engineer	0.5
24.	engineers	Dmitry Fedoseev	DLNP	Electronics engineer (1st class)	0.5
25.	engineers	Alexey Chetverikov	DLNP	Electronics engineer (2nd class)	0.5
26.	engineers	Albert Sotnikov	DLNP	Electronics engineer (1st class)	0.2
27.	PhD students	Anastasia Kalitkina	DLNP	PhD student	1.0
28.	PhD students	Anna Morozova	DLNP	PhD student	1.0
29.	students	Yuriy Ivaneev	DLNP	Master student	1.0
30.	students	Alexandra Ivanova	DLNP	Master student	1.0
31.	students	Anna Stepanova	DLNP	Master student	1.0
32.	students	Petr Lensky	DLNP	Bachelor student	1.0
33.	scientific staff	Aleksander Kolesnikov	VBLHEP	Researcher	0.2
34.	scientific staff	Aliaksei Paulau	VBLHEP	Researcher	0.1
35.	scientific staff	Dosbol	VBLHEP	Researcher	0.2

		Baygarashev			
36.	scientific staff	Kirill Salamatin	VBLHEP	Researcher	0.2
37.	scientific staff	Yerzan Mukhamedzhanov	VBLHEP	Researcher	0.2
38.	scientific staff	Yury Kovalev	VBLHEP	Researcher	0.4
39.	engineers	Evgenya Vasilieva	VBLHEP	Engineer	0.2
40.	engineers	Nikolay Azorsky	VBLHEP	Engineer	0.2
41.	engineers	Vitaly Bautin	VBLHEP	Electronics engineer	0.2
42.	PhD students	Kambar Ismail	VBLHEP	PhD student	0.2
43.	scientific staff	Igor Kakorin	BLTP	Researcher, PhD	1.0
44.	scientific staff	Konstantin Kuzmin	BLTP	Researcher, PhD	0.5
45.	scientific staff	Victor Matveev	BLTP	Scientific Leader of JINR, Academician of RAS	0.1
46.	scientific staff	Vadim Naumov	BLTP	Researcher, PhD	0.5
47.	engineers	Nikita Balashov	MLIT	Senior engineer	0.2
	Total:				**26.0**

3.2.2. JINR associated personnel

№№ п/а	**Category of employees**	**Partner organisation**	**Amount of FTE**
1.	students	Moscow State University	3.0

2.	students	Moscow Institute of Physics and Technology	1.0
	Total:		**4.0**

4. Financial support

4.1 Total estimated cost of the project/sub-project of the LRIP

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

1.22 M$ during three years

4.2 Extrabudgetary funding sources

Estimated funding from co-executors/customers - total.

—

Project (sub-project of the LRIP) Leader __________/___________/

Date of submission of the project (sub-project of the LRIP) to DSOA: _________

Date of decision of the laboratory's STC: _________ document number: _________

Year of the project (subproject of the LRIP) opening: ________________

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

Schedule proposal and resources required for the implementation of the Project / Sub-project of the LRIP

Names of costs, resources, sources of funding		**Cost (thousands of dollars) resource requirements**	**Cost, distribution by year**				
			1st year	2nd year	3rd year	4th year	5th year
	International cooperation (IC)	540	150 +30	150 +30	150 +30		
	Materials	350	100 +30	80+ 30	80+ 30		
	Equipment and third-party services (commissioning)	140	50+ 10	30+ 10	30+ 10		
	Commissioning work	30	10	10	10		
	Services of research organisations	70	20	30	20		
	Acquisition of software	60	20	20	20		

		Design/construction	15	5	5	5		
		Service costs (*planned in case of direct project affiliation)*	15	5	5	5		
Resources required	**Normo-hours**	Resources						
		– the amount of FTE,	150	50	50	50		
		– accelerator/installation,						
		– reactor,….						
Sources of funding	**Budgetary resources**	JINR budget *(budget items)*	1220	430	400	390		
	Extrabudgetary (supplementary estimates)	Contributions by co-contractors Funds under contracts with customers Other sources of funding						

Project (sub-project of the LRIP) Leader_________/________________/

Laboratory Economist _________/________________/

APPROVAL SHEET FOR PROJECT / SUBPROJECT OF THE LRIP

NAME OF THE PROJECT/SUBPROJECT OF THE LRIP

DESIGNATION OF THE PROJECT / SUBPROJECT OF THE LRIP

PROJECT/SUBPROJECT OF THE LRIP CODE

THEME / LRIP CODE

NAME OF THE PROJECT/ SUBPROJECT OF THE MIP LEADER

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 THEME / MIP LEADER	__________ SIGNATURE	__________ NAME	__________ DATE
PROJECT / SUBPROJECT OF THE LRIP LEADER	___________ SIGNATURE	__________ NAME	__________ DATE

APPROVED BY THE PAC

______________	____________	____________
SIGNATURE	NAME	DATE

Annex 4.

Project (sub-project of the LRIP) report form

1. General information on the project / subproject of the LRIP

1.1. Scientific field

Physics of elementary particles and relativistic nuclear physics

1.2. Name of the project / subproject of the LRIP

NOvA/DUNE

1.3. Project (subproject of the LRIP) code

Example (04-4-1140-1-2024/2027) 02-2-1099-1(2?)-2015(2021?)/2023 ?

1.4. Theme / LRIP code

theme 02-2-1099-2010/2023

1.5. Actual duration of the project/ subproject of the LRIP

2015-ongoing

1.6. Project / subproject of the LRIP Leader(s)

A.Olshevskiy

2. Scientific report

2.1. Annotation

The NOvA project at JINR was opened in 2015 and was modified to the joint NOvA/DUNE project in 2020. The JINR group has made significant progress in various areas in both NOvA and DUNE during these years.

NOvA is already an ongoing experiment that is producing scientific results. It is a long-baseline neutrino experiment based at Fermilab that aims to measure oscillation parameters. The most recent result, announced in 2020 with 13.6 x 10^{20} POT in neutrino mode and 12.6 x 10^{20} POT in antineutrino mode, showed no asymmetry in neutrino/antineutrino and obtained a mild preference for normal neutrino mass ordering. JINR group is involved in the NOvA three-flavor analysis, and several official analysis fits, including the 2020 result, were performed by JINR personnel. These results were official for NOvA and were published in several collaboration papers. Although NOvA's main goal is to measure oscillation parameters, there is a wide range of non-oscillation physics activities in which the JINR group has made a valuable contribution. Collaborators from Dubna developed a supernova neutrino detection trigger, several analyses with atmospheric muons, and searches for exotic signals like magnetic monopoles are ongoing. Methodological research conducted by the JINR group has made a highly regarded contribution to detector knowledge and simulation. A remote operation center was built in Dubna for Russian collaborators to take shifts. Large computer resources were deployed in MLIT that run collaboration production jobs, analysis jobs of JINR participants, and have a local storage of NOvA data.

DUNE is an experiment under preparation that will also be based at Fermilab and will be its next flagship after NOvA. These experiments have similar goals, but the main expectations in three-flavor neutrino oscillations are connected with DUNE. This experiment's capability to fulfill these expectations is directly related to detector performance. JINR participants were invited to join DUNE due to their large expertise in light collection systems. JINR group's responsibility is DUNE's full Liquid Argon Near Detector light readout. After choosing the detector design for another DUNE's Near Detector (SAND), another JINR group from VBLHEP was invited to join DUNE due to their very wide expertise in straw-tube production for various HEP experiments. Despite the fact that DUNE will start taking data in several years, various analyses are in preparation. JINR's computer resources for NOvA were also shared with DUNE.

2.2. A detailed scientific report

2.2.1. Description of the mode of operation and functioning of the main systems and equipment (for the LRIP subproject).

NOvA Operation. ROC-Dubna

The NOvA experiment at both the ND and FD sites have storages and file transfer systems to accumulate detector data. While this is safely done at the FD and ND locally, it is more efficient to monitor the operation of both systems from one location simultaneously, which can be accomplished from a Remote Operation Center (ROC).

Currently twenty five ROCs are operating for the NOvA experiment at different locations. The first non-US Remote Operation Center, ROC-Dubna, was developed at JINR and started operation in October 2015. It has all of the necessary features and allows for full monitoring and control of FD and ND operation, as well as communication with FNAL services and other ROCs.

NOvA data storage and transfer software based on Linux-nodes collect information from NOvA DAQ system. ROCs connect to control and operation nodes on both FD/ND sites via VNC-tunneling under secure protocols. Basic idea is that a VNC server transfers a VNC session to many VNC viewers at ROCs with control. In total there are 5 active Scientific Linux based VNC-sessions are connected directly to Near/Far Detectors' nodes at FNAL and through GateWays to another World. System includes 1 Linux node for Web-monitoring of the operated systems (Beam, ND/FD Cameras, Data transfer control, Ganglia, Nearline) and 1 Windows node for communication (NOvA electronic logbook, latest version of expert contact and Bulletin board, Polycom via Vidyo, Slack-chat, Skype, Zoom).

ROC-Dubna at JINR has developed infrastructure for 8 hours (a shift period) continuous work (stable internet, international land-lines, kitchen, ROC is also a public JINR area). Computing monitoring system on Zabbix controls local Linux-nodes, internet connection, server conditions and notifies JINR experts in case of troubles.

ROC-Dubna is also a very popular public place for the excursion visits by Scholars, Teachers, Students, Journalists and other JINR guests. Its presence at JINR has significantly increased the interest in the NOvA experiment by young people.

Computing Infrastructure

NOvA and DUNE are large-scale neutrino experiments which require a huge amount of computing resources to process all of its data. While the major amount of computing resources both experiments get from the local infrastructure at Fermilab - Fermigrid - they also rely on contributions from other participating organizations via the global distributed computing infrastructure Open

Science Grid (OSG). DUNE, being an international collaboration, planned on gathering ~5000 CPU cores and 24 PB of data storage as a general collaboration contribution by 2022. JINR already has an established Multifunctional Information and Computing Complex (MICC) at the Laboratory of Information Technology (LIT), two components (Tier-2 cluster and JINR Cloud) of which were set up and extended to provide computing support to the NOvA, Mu2e and DUNE experiments through the OSG.

Especially for the NOvA experiment 24 new servers were purchased and added to the JINR Cloud extending its resources by 540 CPU cores and ~3 TB RAM. These servers were used to host VMs of the new batch cluster and the OSG-site, allowing it to process jobs from both local JINR NOvA team and the NOvA jobs coming from the OSG, contributing directly to the NOvA collaboration. In this system every component of a Grid-site is virtualized, which is a first-time experience for the JINR Grid-sites and is an important step for further development of computing models at JINR.

With the growth of the virtual computing cluster development of the local data storage for storing a copy of the most requested experimental data becomes the most urgent task. Creation of such a storage system is crucial for the efficiency of local data analysis performance. To form the storage backend 4 storage servers were purchased, added to the cloud's Ceph storage system. The already existing dCache storage at JINR was registered in the Sequential Access via Metadata (SAM) data handling system and a dedicated cloud virtual machine with a large Ceph block-device was created and configured to join the NOvA dCache pool extending its 3 TB NOvA quota by 50 TB. Grid jobs use the GridFTP door to transfer data via the GridFTP protocol.

Participation of JINR as a Tier-2 Grid site in the DUNE computing infrastructure posed more strict requirements on capacities of both computing and storage hardware at JINR, therefore, overall capacity of the JINR computing infrastructure had to be increased.

The DUNE experiment plans to build a tiered distributed computing infrastructure (similar to CERN) to strengthen international cooperation. The estimate for the past period was to have ~5000 CPU cores and 24 PB disk storage by 2022 (split 25/75 % between Fermilab and the rest of Collaboration) and a serious contribution is considered to be 5-10 %.

In terms of CPU it was already possible for JINR to fulfill the DUNE "Tier-2" requirements by the joint use of existing NOvA (and other neutrino experiments) shared resources till 2022, and the subsequent increase of the number of CPUs to up to 1000, that were purchased and commissioned, allows to cover CPU requirements for the 2023.

Since the existing storage can't be shared similar to CPUs, the DUNE dedicated disk storage had to be purchased. Additional disk servers were used to create a Ceph-based cloud storage with 2 PB of raw disk space capacity and will be used as a storage backend for the Grid-storage to fulfill the DUNE Tier-2 datacenter requirements.

The current overall capacity of the NOvA/DUNE segment of the Grid-cluster is 38 computing servers with 1000 CPU cores and 12 storage servers with ~2 PB in total raw disk capacity.

NOvA Scintillator Studies

The scintillation response, S, depends on nature and energy, E, of the incident ionizing particle, of residual range r. The specific fluorescence, dS/dr , is not, in general, proportional to the specific energy loss dE/dr

$$\frac{ds}{dr} = \frac{A \cdot dE/dr}{1+kB \cdot dE/dr}$$

where A and k_B are constants which have been evaluated for the scintillator from observations of S and E, and the range-energy data. The k_B is known as the Birks constant. In the case of NOvA, it was necessary to measure the Birks constant for protons at the MeV energy scale.

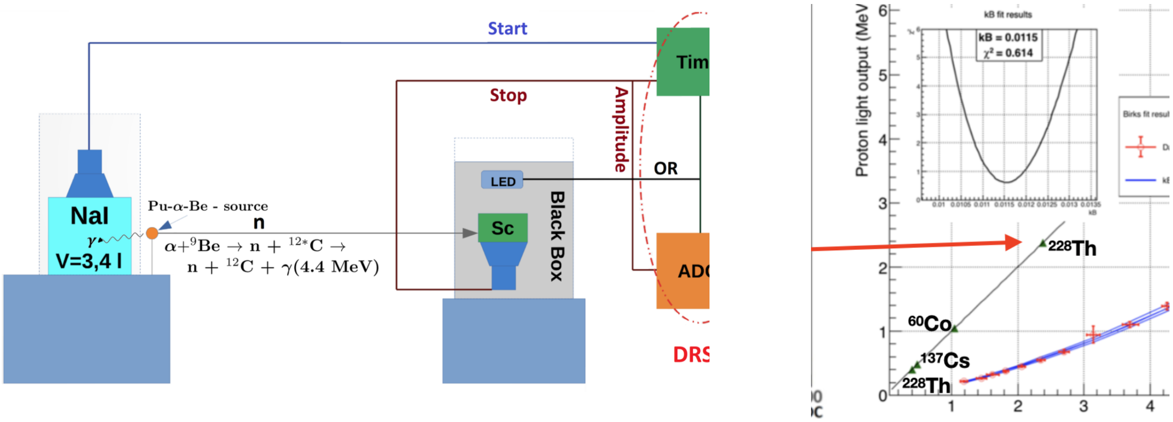

Figure 1. Left - block-scheme of the stand, Right - Calibration curve: linear fit is the black solid line and points are 405 kev(228Th), 477 keV(137Cs), 1041 keV(average energy of two lines 60Co), 2381keV(228Th); scintillator response on recoil protons: red point - experimental data, blue solid lines - MC fit with 1σ confidence intervals.

The scheme of the setup is presented in Figure 1, left. A neutron is produced by an isotope PuBe-source simultaneously with a gamma-quantum (~4.4 MeV), which triggers the start counter (NaI-crystal + PMT). The protons from the NOvA scintillator are hit by the neutrons in the cuvette read out by a PMT which generates the stop signal. As the DAQ we used a DRS4 board which allows coincidence between its channels. For the PMT calibration, we employed an LED pulsing with very low light intensity flashes. The cuvette, PMT and LED were put inside the black box. The cuvette was wrapped with white PTFE-tape in order to increase the light yield. At the PMT side, the cuvette is coupled with an optical grease.

The response from protons was calibrated with respect to gamma-sources 137Cs, 60Co, 228Th assuming negligible quenching effect for fast electrons (Cherenkov light contribution was not taken into account.) To extract Birks constant we used numerical integration by varying k_B to obtain S as a scintillation response on a proton. The constant A was assumed as the primary proton's kinetic energy. We perform numerical integration from 0 to Ep with step 1 keV using dE/dr values from NIST PSTAR tables.The NOvA scintillator is a solution based on mineral oil with mass indexes for Carbon ~85.5%, Hydrogen ~14.5 % and negligible for all other contributions.

Finally, data were analyzed by using NOvA simulation software which deposits energies based on GEANT and a custom simulation for light output (see Figure 1, right blue solid lines). And eventually the Birks constant was found as k_B=1.15±0.07 g/(MeV $\cdot cm^2$).

Now we prepared the stand for Cherenkov light measurements to improve Birks measurements and expect to finish scintillator studies in 2024.

2x2 modules testing for DUNE’s NDLAr

Module prototypes provide a large-scale, fully integrated test of the light readout system, enabling a detailed performance characterization of the ArCLight and LCM modules, readout, DAQ, triggering, and timing with a large event sample. Using cosmic ray data and dedicated diagnostic runs under a variety of detector configurations, a suite of tests was performed to assess the charge spectrum, inter- and intra-event timing accuracy, and photon detection efficiency.

Before collecting cosmic data, a SiPM gain calibration was performed using an LED source, where the bias voltage for each SiPM channel was adjusted to obtain a uniform gain distribution across the channels.

LCMs were used to provide an external trigger to the charge readout system, with an effective threshold of about 15 photoelectrons (p.e.). The trigger message, written into the continuous self-triggered data stream of the charge readout system, provides a precise timestamped flag for identifying coincidences between charge and light readout.

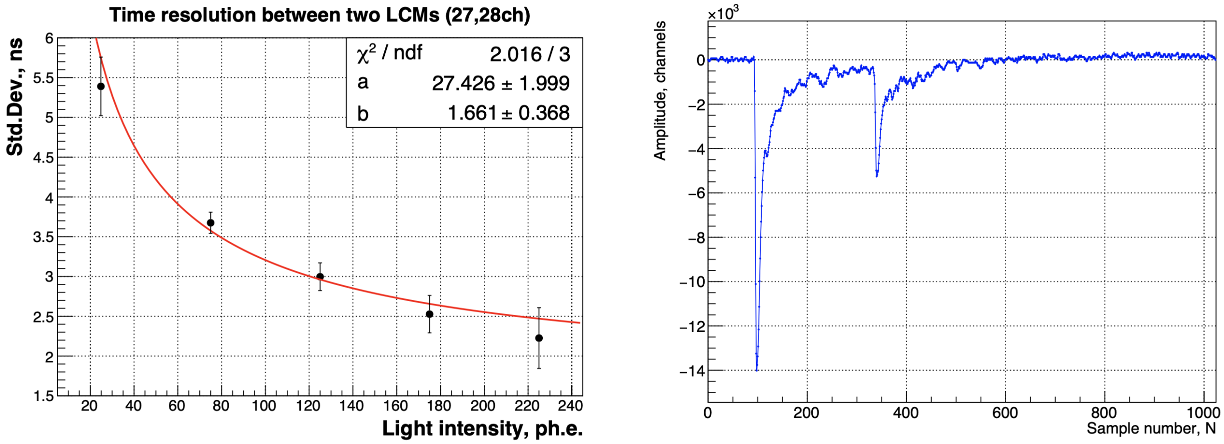

Figure 2. Module-0: The time resolution between two LCMs as a function of the signal response (left). Signals of the stopping muon and delayed Michel electron detected by the LCM (right).

Events induced by cosmic muons traversing the TPC volume were used to extract the time resolution of the light detectors (see Figure2 left and Figigure 4 left). The time measurement proceeds as follows: each waveform is oversampled through a Fourier transform to increase the number of points on the rising edge, enabling a good linear fit of it. Then, a linear fit to the baseline is performed, and the crossing point of the rising edge of the signal with the baseline is calculated, hence providing a robust single-channel event time.

An example application of the excellent timing resolution for the LCMs is the identification of Michel electrons (see Figure 2 right) from stopping muon decays, where the relative timing between the muon and electron signals is dominated by the mean lifetime of the muon, $\boldsymbol{\tau}\sim 2\mu s$.

Two examples of signals from a stopping muon and a delayed Michel electron detected by the LCM are shown in Figure 2. Since the muon decay time is variable but follows a well-understood exponential distribution, such events may be used, for example, to study event pile-up in neutrino interactions.

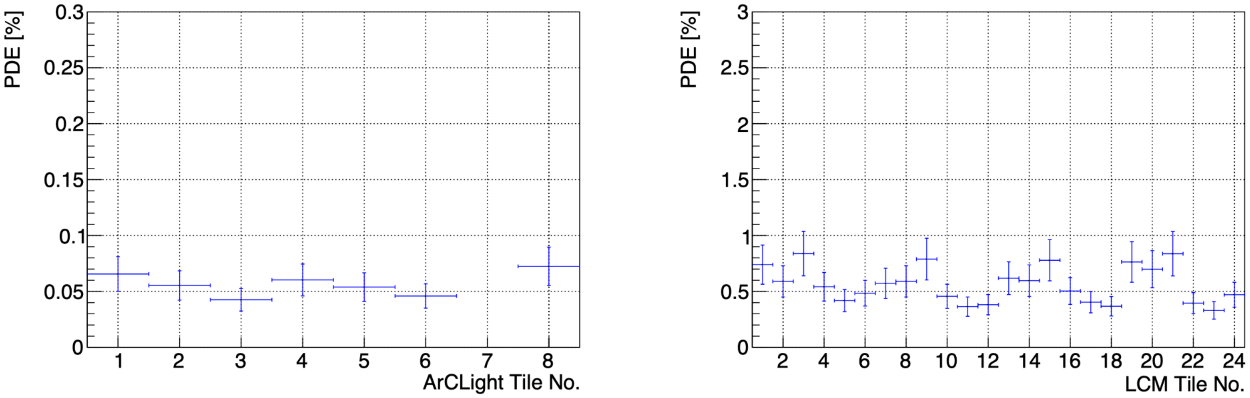

Figure 3. Absolute PDE for each ArCLight (left) and LCM (right) tile (arbitrary numbering). ArCLight tile 7 was disabled during Module-0 data taking. The LCM tiles are placed in sets of 3 to cover the same area as one ArCLight tile.

To assess the efficiency of the LRS, the scintillation light induced by tracks reconstructed from the TPC charge readout data is used. In particular, cosmic muon tracks crossing the entire detector vertically are considered.

In a 3D simulation, the charge of a track is discretized to single points with a mm-resolution along the track, assuming an infinitely thin true trajectory.

For each point in this voxelized event, the solid angle to the light detector in the detector module is then calculated. Next, assuming isotropic scintillation light emission, the solid angle can be used to compute the geometrical acceptance of the light for each detector tile.

The number of photons hitting the detector surface is estimated by multiplying the geometrical acceptance by the number of emitted photons per unit track length and integrating over the full track length. Here, the number of emitted photons per unit track length has been calculated for the nominal electric field intensity of 0.5 kV/cm.

Rayleigh scattering, a small effect over the relevant distance scales, is neglected in this calculation.

The photon detection efficiency (PDE) of the light detection system can be estimated by comparing the measured number of p.e. and the estimated number of photons hitting the detector surface, as obtained from the simulation described above.

Since the waveforms obtained with the light detectors have been integrated using a limited gate length, the actual scintillation light might be underestimated.

This was corrected by multiplying the number of reconstructed photons by an integration gate acceptance factor, which is calculated based on the detector response and the scintillation timing characteristics. Figure 3 shows the measured PDE for all ArCLight and LCM modules used in the Module-0 detector.

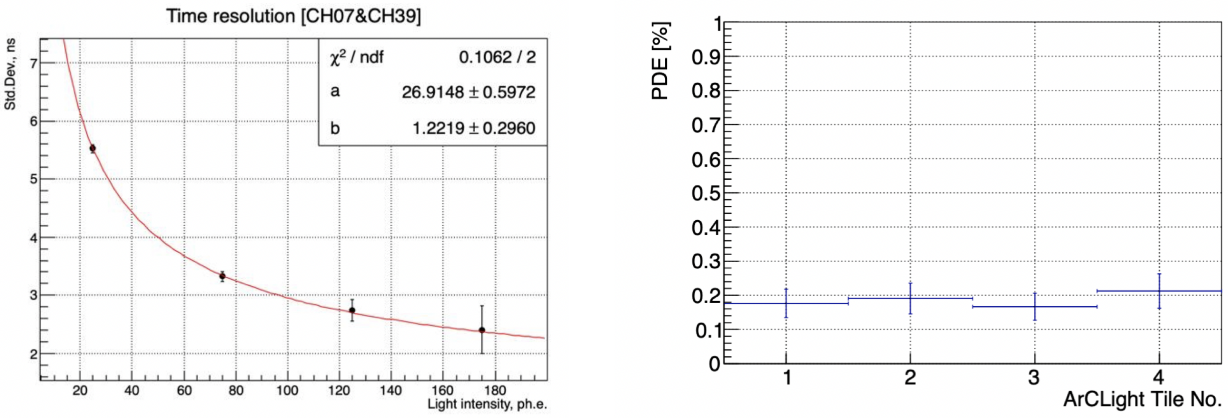

Figure 4. Module-1: The time resolution between two LCMs as a function of the signal response (left). Absolute PDE for each LCM (right) tile (arbitrary numbering).

Since 2021, 4 prototypes of the TPC modules have been manufactured and successfully tested with cosmic rays. Inmodules-1,2,3 we changed the sampling frequency of the DC to 62.5 Mhz (compared to 100 MHz) with 14-bit amplitude resolution (compared to 10-bit) which doesn't affect the timing resolution (figure 4 left) but significantly improved the dynamic range. We also screen cold Light readout electronics from digital noise pick-up from charge readout that slightly improve timing resolution compared to module-0.

Modules-1,2,3 have used SiPM with improved efficiency, PDE=35% compared to PDE=25% (mod-0), used to read out the light detectors. The ArcLight technology was significantly improved by applying new mirroring techniques. Fig. 5. Shows PDE for all ArCLight modules used in the Module-1 detector (right).

All four modules have been assembled, tested, and shipped to Fermilab for 2x2 testing.

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

2.2.3. A description of the scientific work undertaken and the results obtained.

The most recent three-flavor oscillation results from NOvA were obtained in 2020, with additional reanalysis of the data performed in 2022. The experiment has accumulated 13.6 x 10^{20} POT (ν) + 12.5 x 10^{20} POT ($\underline{\nu}$) in statistics. NOvA aims to study $\nu_\mu \to \nu_\mu$, $\nu_\mu \to \nu_e$, $\underline{\nu}_\mu \to \underline{\nu}_\mu$ and $\underline{\nu}_\mu \to \underline{\nu}_e$ oscillations by detecting the final state neutrinos via charged current interaction and comparing the results with the initial neutrino flux measured by the Near Detector. Selected in the Far Detector events are shown in Figures 5 and 6.

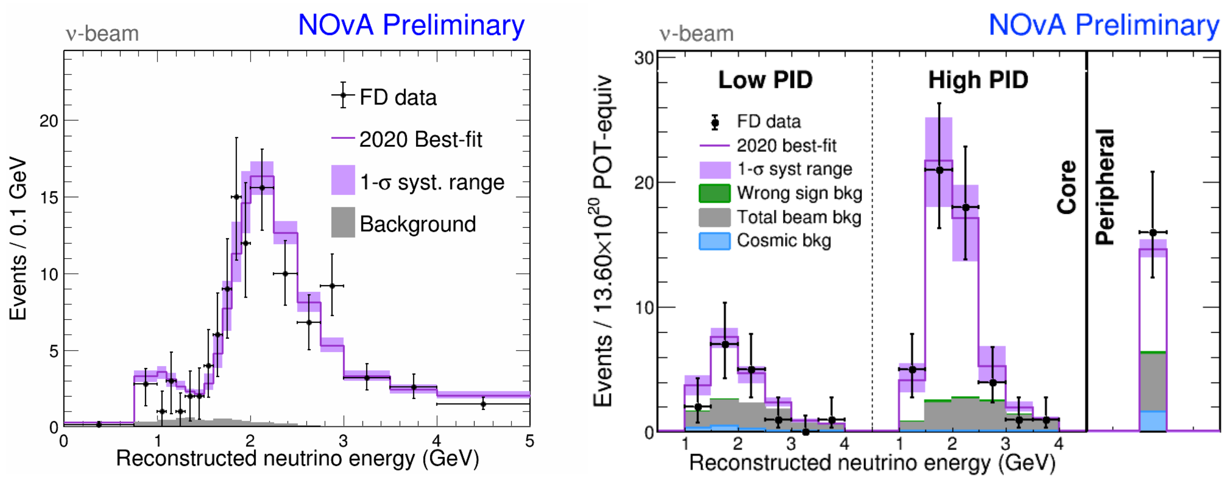

Figure 5. Muon and electron neutrino spectra of events selected in the NOvA Far Detector during neutrino mode operation. These spectra were used for data fits.

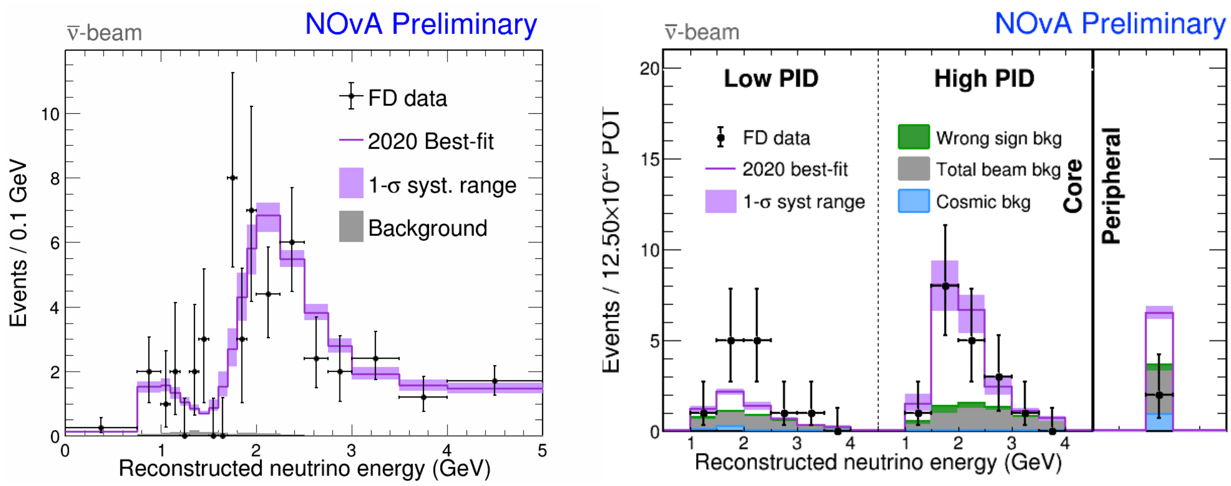

Figure 6. Muon and electron antineutrino spectra of events selected in the NOvA Far Detector during antineutrino mode operation. These spectra were used for data fits.

Spectra of selected events are combined in a joint fit to extract the neutrino oscillation parameters.The result obtained in 2020 was done within the framework of the Frequentist paradigm. Due to the lack of statistics, the fit was corrected using the Feldman-Cousins approach. The results obtained are shown in Figure 7. The 2022 reanalysis first time for NOvA utilized a different paradigm for obtaining the results - a Bayesian approach via Markov Chain Monte-Carlo (MCMC), as shown in Figure 8. Both results show similar conclusions in terms of physics.

NOvA's best fit value is in the point δ_{CP} = 0.82π, sin^2 θ_{23}= $0.57^{+0.03}_{-0.04}$, Δm^2_{32}= +(2.41 ±0.07)×10^{-3} eV^2. The Normal neutrino mass ordering and the upper octant of the angle θ_{23} ($\theta_{23} > \pi/4$) are weakly preferred at the 1σ and 1.2σ levels, respectively. The region $\delta_{CP} = \pi/2$ in the Inverted ordering was excluded at the level >3σ. The value $\delta_{CP} = 3\pi/2$ in the Normal ordering and the upper octant θ_{23} is excluded at the level ~2σ.

Thus NOvA sees no asymmetry in neutrino/antineutrino appearance.

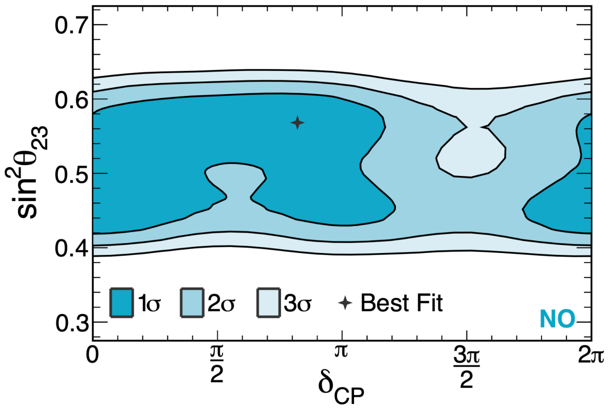

Figure 7. Confidence contours obtained by the NOvA experiment with 2020 data fit with the hypothesis of the normal order of neutrino masses (left) and the inverted order (right). Frequentist approach used.

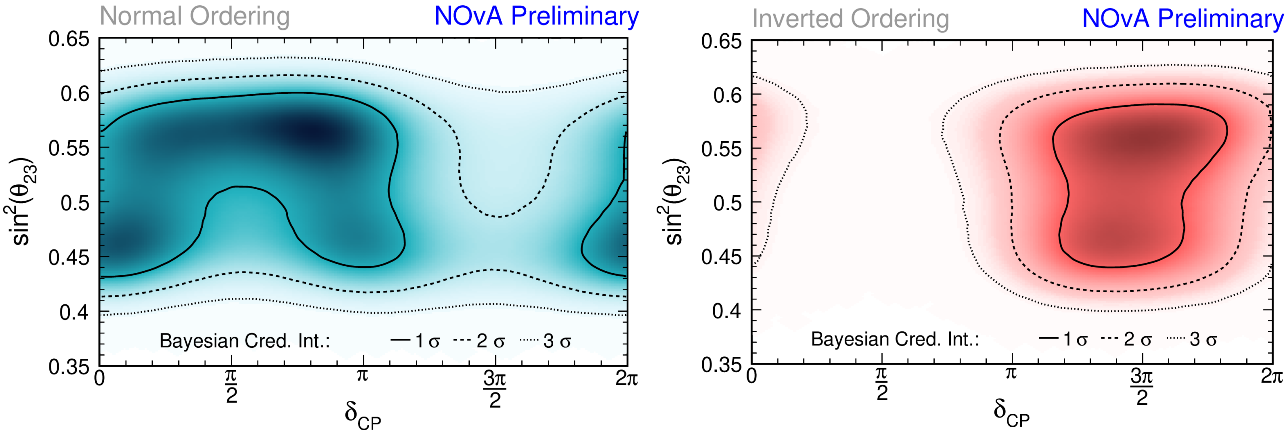

Figure 8. Credible intervals obtained by the NOvA experiment with 2020 data reanalysis in 2022 with the hypothesis of the normal order of neutrino masses (left) and the inverted order (right). Bayesian approach used.

JINR group is involved in NOvA three-flavor analysis group activities. The 2020 analysis fits with the Frequentist approach were obtained by JINR group members. These results became official and were published in collaboration paper Phys.Rev.D 106 (2022) 3, 032004. In 2021 - 2023 JINR group members had the following activities in three-flavor group: energy estimation of neutrino events, decomposition, experiment sensitivities, CP asymmetry and oscillation probabilities measurement from real detected data, analysis framework code review.

NOvA' results have good agreement with other oscillation experiments (Figure 9) although there is a tension with T2K experiment in δ_{CP} measurement that caused some excitement in the community. But we should note that statistical significance of this tension is quite low ($< 2\sigma$). Suggested by theoreticians hypotheses for resolving this tension mainly involve new physics. Another possible solution is just statistical fluctuation or unknown systematic uncertainty.

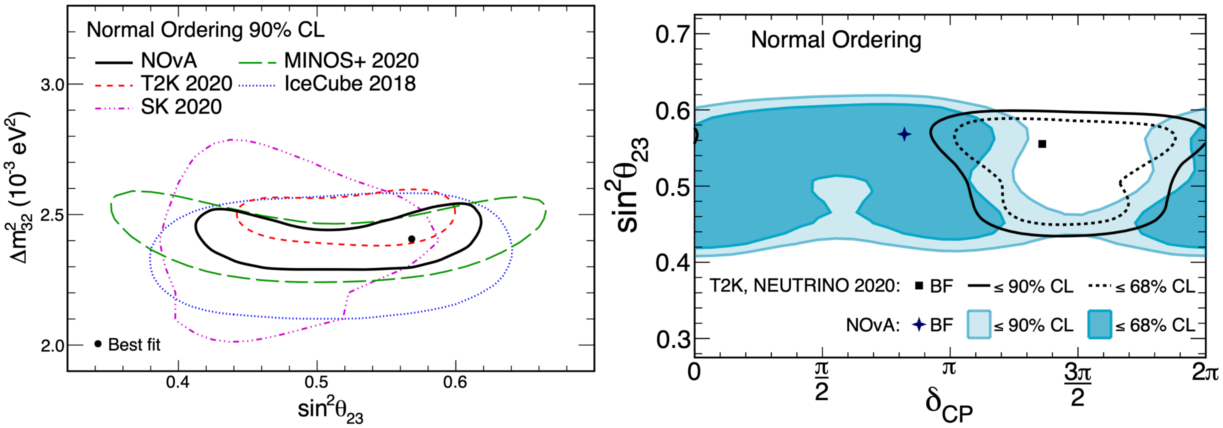

Figure 9. NOvA results compared with other oscillation experiment measurements. On the left plot atmospheric neutrino parameters' comparison is shown. On the right plot NOvA and T2K tension is shown for CP violation phase measurement.

Currently both NOvA and T2K are preparing joint analysis of collected data. JINR group members are involved in this analysis on the NOvA experiment side.

The search for slow magnetic monopole based on 95-days exposure in 2015 is published in Phys. Rev. D 103 (2021) 1, 012007. No events consistent with monopoles were observed, setting an upper limit on the flux of $2\times10^{-14}\ cm^{-2}s^{-1}\,sr^{-1}$ at 90% C.L. for monopole speed $6\times10^{-4}<\beta<5\times10^{-3}$ and mass greater than 5×10^{8} GeV. Because of NOvA's small overburden of 3 meters-water equivalent, this constraint covers a previously unexplored low-mass region. In addition we wish to note that the Dubna group made measurements for slow signals on performed test stand in JINR to verify monopole simulation. Setup imitated the signature of monopole signals by exposing APDs read out by NOvA electronics to light pulses generated by LEDs. The pulses had lengths that corresponded to the cell-crossing time of monopoles of various speeds and intensities corresponding to the expected monopole dE/dx.

The analysis of combining neutrino signals from Supernova in various experiments have been performed (JCAP12(2021)053). Supernova neutrino detection in neutrino and dark matter experiments is usually implemented as a real-time trigger system based on counting neutrino interactions within a moving time window. The sensitivity reach of such experiments can be improved by taking into account the time profile of the expected signal. JINR group members proposed a shape analysis of the incoming experimental data based on a log likelihood ratio variable containing the assumed signal shape. This approach also allows a combination of potential supernova signals in different detectors for a further sensitivity boost. The method is tested on the NOvA detectors to study their combined sensitivity to the core-collapse supernova signal, and also on KamLAND, Borexino and SK-Gd as potential detectors of presupernova neutrinos. Using the shape analysis enhances the signal significance for supernova detection and prediction, as well as the sensitivity reach of the experiment. It also extends the supernova prediction time when applied to the presupernova neutrino signal detection. Enhancements achieved with the shape analysis persist even in the case when the actual signal doesn't match the expected signal model. An article on the search for SN-like signals in coincidence with detected gravitational LIGO/VIRGO waves has been published (Phys. Rev.D 104 (2021) 6, 063024).

A few analyses on atmospheric muons are on-going. The Dubna group analyzes geomagnetic effects in the east-west asymmetry of muon spectra and tests the technique for measuring the spectrum of high-energy muons proposed by R.P. Kokoulin et al.

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).
2.2.5. A complete list of publications (electronic annex, for journal publications with journal impact factor).

List of publications with principal contribution from JINR group members in 2020-2023. Total number of NOvA publications with JINR authors included during this period is 12, total number of DUNE publications is 26.

2020:

1. M. Acero et al (NOvA Collaboration)"Supernova neutrino detection in NOvA" JCAP 10 (2020), 014
2. N. Anfimov, A. Antoshkin, A. Aurisano, O. Samoylov and A. Sotnikov "JINR stand measurements for improvements in the NOvA detector simulation chain" (2020) *JINST* **15** C06066.
3. N. Anfimov, R. Berner, I. Butorov, A. Chetverikov, D. Fedoseev, B. Gromov, D. Korablev, I. Kreslo, K. Kuznetsova, A. Olshevskiy, A. Rybnikov, A. Selyunin, V. Sharov, J. Sinclair, S. Sokolov, "Development of the Light Collection Module for the Liquid Argon Time Projection Chamber (LArTPC)", (2020) *JINST* **15** C07022
4. I.D. Kakorin, K.S. Kuzmin, V.A. Naumov "A Unified Empirical Model for Quasielastic Interactions of Neutrino and Antineutrino with Nuclei", Phys.Part.Nucl.Lett. 17 (2020) 3, 265-288

2021:

1. L. Kolupaeva, O. Samoylov "Study of Neutrino Oscillations in the NOvA Experiment", Yad.Fiz. 84 (2021) 1, 48-52
2. A. Sheshukov, A. Vishneva, A. Habig "Combined detection of supernova neutrino signals" *JCAP* 12 (2021) 12, 053
3. M. A. Acero et al. (NOvA Collaboration) "Search for Slow Magnetic Monopoles with the NOvA Detector on the Surface", Phys. Rev. D 103, 012007
4. A. D. Morozova, A. A. Kochanov, T. S. Sinegovskaya, S. I. Sinegovsky "High-energy spectra of the atmospheric neutrinos: predictions and measurements" e-Print:2109.13000
5. N.A. Balashov, I.S. Kuprikov, N.A. Kutovskiy, A.N. Makhalkin, Ye. Mazhitova, R.N. Semenov "Quantitative and qualitative changes in the JINR cloud infrastructure", Proceedings of the 9th International Conference "Distributed Computing and Grid Technologies in Science and Education" (GRID`2021)
6. N. Balashov, N. Kutovskiy, N. Tsegelnik "Resource management in private multi-service cloud environments" Proceedings of the 9th International Conference "Distributed Computing and Grid Technologies in Science and Education" (GRID'2021), Dubna, Russia (2021)

7. M.A.Acero et al (NOvA Collaboration) “Extended search for supernovalike neutrinos in NOvA coincident with LIGO/Virgo detections” Phys.Rev.D 104 (2021) 6, 063024
8. V Hewes at el (Dune Collaboration) “Deep Underground Neutrino Experiment (DUNE) Near Detector Conceptual Design Report” Instruments 5 (2021) 4, 31
9. Luis Alvarez-Ruso et al (GENIE Collaboration) “Recent highlights from GENIE v3” Eur.Phys.J.ST 230 (2021) 24, 4449-4467
10. I.Kakorin, K.Kuzmin ”Resonance axial-vector mass from experiments on neutrino-hydrogen and neutrino-deuterium scattering” Phys.Rev.D 104 (2021) 9, 9
11. I.Kakorin, K.Kuzmin, V.Naumov “Running axial mass of the nucleon as a phenomenological tool for calculating quasielastic neutrino–nucleus cross sections” Eur.Phys.J.C 81 (2021) 12, 1142
12. L.D. Kolupaeva, A.G. Olshevskiy, O.B. Samoylov “Status and Research Prospects of Three-Flavor Neutrino Oscillations”, Phys.Part.Nucl. 52 (2021) 3, 357-373
13. N. Balashov, N. Kutovskiy, N. Tsegelnik “Resource management in private multi-service cloud environments” Proceedings of the 9th International Conference “Distributed Computing and Grid Technologies in Science and Education” (GRID’2021), Dubna, Russia (2021)
14. S.Al Kharusi et al. (SNEWS Collaboration) “SNEWS 2.0: a next-generation supernova early warning system for multi-messenger astronomy” New J.Phys. 23 (2021) 3, 031201

2022:

1. M. Acero et al (NOvA Collaboration) “Improved measurement of neutrino oscillation parameters by the NOvA experiment” Phys.Rev.D 106 (2022) 3, 032004
2. I. Ruiz Simo, I.D. Kakorin,, V.A. Naumov,, K.S. Kuzmin,, J.E. Amaro “Analysis of the kinematic boundaries of the quasielastic neutrino-nucleus cross section in the superscaling model with a relativistic effective mass” Phys.Rev.D 105 (2022) 1, 013001
3. Julia Tena-Vidal et al (GENIE Collaboration) “Neutrino-nucleus CCπ_0 cross-section tuning in GENIE v3”, Phys.Rev.D 106 (2022) 11, 112001
4. A. Stepanova, L.Kolupaeva «Development of a shell for calculating the sensitivity of accelerator experiments in GNA based on the DUNE experiment» Scientific notes of the Faculty of Physics of Moscow State University (2022) № 4. 2240304
5. A. Stepanova, M. Gonchar, L. Kolupaeva, K. Treskov «Deep underground neutrino experiment DUNE – calculation of sensitivity to the measurement of oscillation parameters». PEPAN letters (2022) 19 5

2023:

1. L.D. Kolupaeva, M.O. Gonchar, A.G. Olshevskiy, O.B. Samoylov “Neutrino oscillations: status and research prospects for measurement of neutrino mass ordering and CP-violation phase” accepted for publication in Uspekhi Fizicheskih Nauk (2023)
2. A.Olshevskiy “Results of Neutrino Oscillations and the Search for Sterile Neutrino States” accepted to be published in PEPAN letters (2023)
3. A. Stepanova, L. Kolupaeva «Joint fit of long-baseline accelerator neutrino experiments in GNA software», sent to PEPAN Letters (2023)

Internal collaboration technotes written by JINR group members in 2020-2023:
2020:

1. A. Antoshkin, A. Habig, M. Strait, H. Britt, M. Frank, M. Greene, E. Milliner, J. Robbins, P. White, C. Dukes, R. Ehrlich, E. Song "NOvA Slow Monopole Analysis", 30 Jun 2020, DocDB 22610
2. L.Kolupaeva, T. Warburton "2020 Sensitivity and Fitting Technote", 6 Mar 2020, DocDB 44043

2021:

1. L. Kolupaeva "Technote on appearance oscillation probability and Acp measurement", DocDB 50477, 26 May 2021

2022:

1. A. Antoshkin, N. Anfimov, A. Chetverikov "Test bench for measurements of scintillators (NOvA, LAB-based etc.) properties. Cherenkov light.", Technical note # 57219, NOvA Collaboration document database, 22 Dec 2022
2. A. Antoshkin, M. Frank "Slow monopole Pre-selection", December 27, 2022, Technical note # 57246
3. O. Petrova "East-West asymmetry Technote", DocDB 56425, 28 Sep 2022
4. Light System ADC64ve_v3.2, technote, DUNE-doc-26097, 2 June, 2022
5. Light System VGA board**,** technote., DUNE-doc-24868-v3, 1 June, 2022
6. Light Readout System SiPM PS control board ORC**,** technote., DUNE-doc-25650-v1, 8 June, 2022
7. Light Readout System SiPM PS PCB ORC**,** technote, DUNE-doc-25655-v1, 8 June, 2022
8. Light Readout System Adapter card ORC**,** technote., DUNE-doc-25653-v2, 8 June, 2022
9. Light Readout System VGA control module ORC**,** technote., DUNE-doc-25657-v2, 9 June, 2022

2.2.6 List of talks presented at international conferences and meetings (electronic annex).

List of talks given at different conferences and public meetings by JINR group members in 2020-2023:

2020:

1. Andrey Sheshukov, "Real-time detection of supernova neutrino signal", 127th session of the JINR Scientific Council, Dubna.
2. Andrey Sheshukov, "Detecting neutrinos from the next galactic supernova in the NOvA detectors", CNNP-2020, Cape Town, South Africa, Feb 2020.
3. Nikolay Anfimov, "Improvements in the NOvA Detector Simulation based on JINR stand measurements", Instrumentation for Colliding Beam Physics (INSTR-20), February 24-28 2020, Budker Institute, Novosibirsk, Russia.
4. O. Samoilov, "Study of neutrino oscillations in the NOvA experiment", Session-conference of the Nuclear Physics Section of the Physical Sciences Department of the Russian Academy of Sciences, Novosibirsk, March 10-12, 2020.

5. L. D. Kolupaeva, “Oscillation analysis in the NOvA accelerator neutrino experiment”, seminar at DLNP JINR, April 3, 2020.
6. N. Balashov, “JINR Computing Infrastructure for the NOvA Experiment”, seminar at DLNP JINR, April 7, 2020.
7. Andrey Sheshukov, “Non-oscillation analyses of the NOvA experiment”, seminar at DLNP JINR, April 10, 2020.
8. Liudmila Kolupaeva, Thomas Warburton, “Long-baseline neutrino oscillation results from NOvA in neutrino and antineutrino modes”, Neutrino 2020, Chicago (USA), online poster session, June 2020.
9. Liudmila Kolupaeva, Anna Hall, “Data-Driven Cross Checks for nue selection efficiency in NOvA”, Neutrino 2020, Chicago (USA), online pooster seesion, June 2020.
10. Alec Habig, Andrey Sheshukov, Justin Vasel, “Galactic Supernova Neutrino Detection with the NOvA Detectors”, Neutrino 2020, Neutrino 2020, Chicago (USA), online poster session, June 2020.
11. Matthew Strait, Oleg Samoylov, “The Astrophysics Program of NOvA”, Neutrino 2020, Chicago (USA), online pooster seesion, June 2020.
12. Andrey Sheshukov, “NOvA in 10 minutes”, New Perspectives 2020, FNAL (USA), July 2020.
13. Liudmila Kolupaeva, “Recent three-flavor neutrino oscillation results from the NOvA experiment”, ICPPA-2020, oral talk, October 2020.
14. A.G. Olshevsky, “Investigation of neutrino oscillations in reactor and accelerator experiments”, invited talk at the INR RAS conference, December 4, 2020

2021:

1. L. Kolupaeva, “Current status and future prospects of three flavor neutrino oscillations”, AYSS-2021, 11-15 Oct, Almaty, Kazakhstan (Hybrid Event). (invited plenary talk)
2. O. Petrova, “East-West asymmetry in atmospheric muon fluxes in the Far Detector of NOvA”, AYSS-2021, 11-15 October, Almaty, Kazakhstan (Hybrid Event). (oral talk)
3. O. Samoylov, “The Astrophysics program of the NOvA experiment”, TeV Particle Astrophysics conference (TeVPA 2021), 25-29 October 2021, Chengdu, China (Hybrid Event) (oral talk)
4. N.V. Anfimov, "Liquid-argon TPC of the near detector of the DUNE experiment", DLNP JINR seminar, May 20, 2021
5. N.A. Balashov, I.S. Kuprikov, N.A. Kutovskiy, A.N. Makhalkin, Ye. Mazhitova, R.N. Semenov “Quantitative and qualitative changes in the JINR cloud infrastructure”, 9th International Conference "Distributed Computing and Grid Technologies in Science and Education" (GRID`2021), 5-9 July 2021, Dubna, Russia. (устное выступление)
6. N. Balashov, N. Kutovskiy, N. Tsegelnik “Resource management in private multi-service cloud environments” 9th International Conference “Distributed Computing and Grid Technologies in Science and Education” (GRID’2021), 5-9 July 2021, Dubna, Russia
7. V.Sharov ”Development of a multi-channel power supply for the TAO and DUNE experiments”, AYSS-2021, 13.10.2021 (oral talk)
8. S. Sokolov “Light detection system prototype for DUNE Near Detector TPC”, AYSS-2021, 13.10.2021 (oral talk)
9. A. V. Stepanova "Underground accelerator neutrino experiment (DUNE) - calculation of sensitivity to measuring oscillation parameters" XXVIII International scientific conference of

students, postgraduate students and young scientists "Lomonosov-2021", 12.04.2021 – 23.04.2021, Moscow, Russia

10. A. Stepanova, M. Gonchar, L. Kolupaeva, K. Treskov «Deep underground neutrino experiment DUNE – calculation of sensitivity to the measurement of oscillation parameters» AYSS- 2021, 11.10.2021 – 15.10.2021

2022:

1. L. Kolupaeva, A.Sutton on behalf of the NOvA Collaboration "Latest Long-baseline 3-flavor Neutrino Oscillation Results from the NOvA Experiment", Neutrino 2022, 30.05-4.06.2022 (poster talk)
2. A.G. Olshevsky "Results of neutrino oscillations and the search for sterile states of neutrinos", International Conference on Quantum Field Theory, High-Energy Physics, and Cosmology, 18-21 July 2022, Dubna (invited plenary talk)
3. O. Samoylov, "Astrophysics and beyond the Standard Model of particle physics in the NOvA experiment", ICPPA-2022, 29.11-02.12.2022, Moscow, Russia. (oral talk)
4. A. Sheshukov, "Neutrino signals of the next galactic supernova" 06 June 2022, JINR AYSS Conference "Alushta-2022" (oral talk)
5. A. Sheshukov, "SuperNova Early Warning System", ICPPA-2022, 29.11-02.12.2022, Moscow, Russia (poster talk)
6. N. Anfimov. "Methodical activities at DLNP JINR for international neutrino experiments JUNO and DUNE" Conference "Kruger 2022: Discovery Physics at the LHC", South Africa, December 4-9, 2022.
7. A. V. Stepanova, L. D. Kolupaeva "Development of a shell for calculating the sensitivity of accelerator experiments in GNA based on the DUNE experiment", International Conference of Students, Postgraduates and Young Scientists "Lomonosov-2022", , 04/11/2022 - 04/22/2022, Moscow, Russia
8. A.Stepanova, L.Kolupaeva, «The DUNE experiment PRISM method for data-driven predictions» Young Scientist Forum at Moscow International School of Physics 2022, 24.07.2022 - 02.08.2022, Dubna
9. A. Stepanova «Joint fit of long-baseline accelerator neutrino experiments in GNA software» The XXVI International Scientific Conference of Young Scientists and Specialists (AYSS-2022), 24.10.2022 — 28.10.2022

2023:

1. A.S. Selyunin "Light Detection System of the DUNE Near Detector LAr TPC", poster, 56th session of the JINR Program Advisory Committee for Particle Physics at JINR, January 24, 2023
2. A.S. Selyunin, DLNP JINR Scientific and Methodological Seminar, "Light reading system in liquid argon of the modular TPC near detector of the DUNE experiment", March 9, 2023
3. O. Samoylov "Study of neutrino oscillations in NOvA/DUNE accelerator experiments" DLNP Seminar March 16, 2023
4. A.Antoshkin "Slow magnetic monopoles search in NOvA", poster, 56th session of the JINR Program Advisory Committee for Particle Physics at JINR, January 24, 2023
5. V. Sharov, "Light readout system for liquid argon TPC of the DUNE ND", poster, 56th session of the JINR Program Advisory Committee for Particle Physics at JINR, January 24, 2023

6. A. Stepanova "Calculation of the accuracy of determining the parameters of neutrino oscillations in accelerator neutrino experiments with a long baseline", International Scientific Conference of Students, Postgraduates and Young Scientists "Lomonosov", 10.04.2023 - 21.04.2023, Moscow, Russia
7. A. Stepanova "The accuracy of determining the oscillation parameters in the DUNE experiment in comparison with other long-baseline accelerator neutrino experiments" Kurchatov Youth Scientific School, 03/20/2023 - 03/23/2023. Moscow, Russia

List of selected reports presented by JINR group members at the NOvA and DUNE collaboration meetings in 2020-2023:

2020:

1. Nikolay Anfimov, “NOvA benchmarking at Dubna”, NOvA Collaboration Meeting at the University of California, Irvine, 13-16 February 2020.
2. Alex Antoshkin, Martin Frank et. al., “Slow monopole analysis”, NOvA Collaboration Meeting, 13-16 February 2020.
3. N. Balashov, “JINR Computing Infrastructure Status”, NOvA Collaboration Meeting, 13-16 февраля 2020.
4. Jeremy Hewes, Oleg Samoylov, “Detector Simulation Summary”, Plenary talk, NOvA Collaboration Meeting at the University of California, Irvine, 13-16 February 2020.
5. Alex Antoshkin, Martin Frank et. al., “Slow monopole Paper Update”, NOvA Collaboration Meeting, 11-14 мая 2020.
6. Olga Petrova, “East-West Asymmetry”, NOvA Collaboration Meeting, 4-15 May 2020.
7. Olga Petrova, “East-West Asymmetry update”, NOvA Collaboration WG, 6 October 2020.
8. L. Kolupaeva, “2020 sensitivities with mock data”, NOvA Collaboration WG, 16 Jan 2020.
9. L.Kolupaeva, “T2K - NOvA comparisons”, NOvA Collaboration WG, 15 Jul 2020.
10. A. Chukanov “Beam monitoring with ECAL+STT configuration”, DUNE collaboration meeting, 28.01.2020
11. A. Chukanov “Beam Monitoring with SAND detector”, DUNE physics meeting, 09.06.2020

2021:

1. O. Petrova, “EWA update: surface simulations and artificial asymmetry”, Exotics at NOvA collaboration Virtual Meeting, 23 February, NOvA DocDB-49259.
2. A. Kalitkina,” Summary of the horn current impact. Three approaches to compare the horn current impact on the analysis”, Beam/3F/DQ Parallel at NOvA collaboration Virtual Meeting, 01 March 2021, NOvA DocDB-49367.
3. K. Warburton, L. Suter, R. Nichol, L. Kolupaeva “3 Flavour Oscillation Group Summary”, Plenary at NOvA collaboration Virtual Meeting, 14 Jun 2021, DocDB 50882.
4. A. Sheshukov, “DDSN status and tasks”, Exotics at NOvA collaboration Virtual Meeting, 15 June 2021, NOvA DocDB-50738.
5. A. Antoshkin, “Slow monopole reconstruction”, Exotics at NOvA collaboration Virtual Meeting, 21 September 2021, NOvA DocDB-51975.
6. N. Anfimov, “Cherenkov Studying”, Detector systematics at NOvA collaboration Virtual Meeting, 28 September 2021, NOvA DocDB-52053.
7. A. Morozova, “The small updates of high energy muons”, Exotics at NOvA collaboration Virtual Meeting, 5 October, NOvA DocDB-52131.

8. O. Petrova, “East-West Asymmetry update”, Exotics at NOvA collaboration Virtual Meeting, 5 October, NOvA DocDB-52134.
9. A. Sheshukov, “Supernova trigger: post-shutdown status and plans”, Exotics at NOvA collaboration Virtual Meeting, 12 October 2021, NOvA DocDB-52218.
10. L. Kolupaeva “CP asymmetry measurement and data taking optimization checks”, NOvA Collaboration WG, 1 Apr 2021
11. A. Kalitkina, “Ana2020 MC POT accounting compared to the data”, 3-Flavor Oscillation at NOvA collaboration Virtual Meeting, 19 October 2021, NOvA DocDB-52330.
12. I.Kakorin, K. Kuzmin, V. Naumov “Comparison of NOvA ND Data and simulation with running MA model”, DocDB 52590, 03 Nov 2021
13. A. Chukanov “Beam monitoring in SAND for STT configuration”, DUNE Collaboration meeting, 19.05.2021
14. A. Chukanov “Beam monitoring with SAND”, DUNE collaboration meeting, 22.09.2021

2022:

1. A. Antoshkin “Cherenkov measurements. Angular systematic studying” NOvA Collaboration meeting. Parallel working group “Detector Systematics”. October 13, 2022, DocDB-56651.
2. A. Antoshkin, “Slow monopole reconstruction”. Working group “Exotics: monopole”, 22 March 2022, DocDB-54195.
3. A. Antoshkin, “Slow monopole freight train validation”, NOvA Collaboration meeting, Parallel working group “Exotics”, 28 June 2022, DocDB-55540.
4. A. Kalitkina, “Nue Energy Estimators retraining”. NOvA Collaboration meeting. Parallel working group “3Flavor + Reco”. October 14, 2022, DocDB-56696.
5. O. Samoylov (for the Exotics convenors), “Status of Exotics” October 2022, Plenary talk at the NOvA collaboration virtual meeting, 11-14 October 2022, DocDB-56735.
6. A. Ivanova “Task with atmospheric neutrinos: expected result and work plan”, 7 Dec 2022, docdb 57252
7. L.Kolupaeva “T2K-like Fake Data Study”, NOvA Collaboration WG , 9 Feb 2022,
8. L. Kolupaeva ”Three-flavor infrastructure improvements”, NOvA Collaboration WG, 14 Oct 2022
9. A.S. Selunin, «Light readout», Internal DUNE Collab report, 24-28 January 2022
10. A.S. Selunin, «Light readout», Internal DUNE Collab report, DUNE Collaboration meeting, Fermilab, USA, 16-20 May 2022
11. N. Anfimov «Light module and readout: status and logistics», Internal DUNE Collab report, DUNE Collaboration meeting, Manchester University, UK, 12-16 Sept 2022
12. A. Chukanov “Beam monitoring with new geometry - status update”, DUNE collaboration meeting, 25.01.2022
13. A. Chukanov “Beam monitoring with GRAIN detector”, SAND GRAIN review, 23.02.2022
14. Anna Stepanova «Wrong Sing Flux Studies» , Internal DUNE Collab report at DUNE-Prism working group, 9.06.2022
15. Anna Stepanova «Wrong-Sign Flux Matching», Internal DUNE Collab report at DUNE-Prism working group, 3.11.2022

2023:

1. L. Kolupaeva “Minerva 1 pi fits & bias metric”, NOvA Collaboration WG, 2 Mar 2023
2. A.S. Selunin «Light readout progress», Internal DUNE Collab report, DUNE Collaboration meeting, CERN, Switzerland, 23-27 January 2023
3. V. Kozhukalov “Light readout DAQ walk through”, Internal DUNE Collab report, DUNE Collaboration meeting, CERN, Switzerland, 23-27 January 2023
4. Anna Stepanova «Wrong Sign Background Update», Internal DUNE Collab report at DUNE-Prism working group, 12.01.23

2.2.7. Patent activity (if any) —-

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

ongoing project - NOvA
CDR - DUNE
PDR - ND-LAr DUNE.

2.4. Results of related activities

2.4.1. Research and education activities. List of defended dissertations.

Education activities:

1. N.Anfimov is associate professor at Dubna University (2021 - ongoing) with “Nuclear electronics” and “Electronics in physics” semi-annual courses.
2. A. Olshevsky is full professor at Moscow State University (2003 - ongoing) with “Modern research in elementary particle physics.” semi-annual courses.

Defended PhD thesis:

1. N. Anfimov “Development and application of methods for studying photodetectors”, defended 04.03.2021 at JINR
2. L.Kolupaeva “The NOvA experiment data analysis with the aim to measure neutrino oscillation parameters”, defended 04.06.2021 at Moscow State University
3. A. Sheshukov “Analysis of neutrino interactions for the search of supernova signals”, to be defended in 2023 at JINR

Defended diploma:

1. A. Pobedimov “Assessment of the possibility of registering solar and atmospheric neutrino events in the NOVA experiment”, Moscow State University, 2020, bachelor's degree
2. V. Korsunov “Sensitivity analysis of the NOvA experiment to the search for sterile neutrinos”, Moscow State University, 2020, bachelor’s degree
3. M. Petropavlova “Simulation of a neutrino signal from a supernova explosion in the NOvA experiment”, Moscow State University, 2020, master's degree
4. A. Kalitkina “Development of data analysis tools for neutrino oscillations and their application in the NOvA experiment”, Moscow State University, 2020, master's degree

5. A. Stepanova “Underground accelerator neutrino experiment DUNE – calculation of sensitivity to measuring oscillation parameters”, Moscow State University, 2021, bachelor’s degree
6. Yu. Ivaneev “A Study of the Cherenkov Light Contribution to the Liquid Scintillator Response Nonlinearity”, MSU, 2022, bachelor’s thesis
7. A. Pobedimov “A study of the possibility to register the atmospheric neutrino events in the NOvA experiment”, MSU, 2022, bachelor’s thesis
8. A. Stepanova "Calculation of the accuracy of determining the parameters of oscillations in long-baseline accelerator neutrino experiments", Moscow State University, 2023, master's degree

2.4.2. JINR grants (scholarships) received.

1. N. Balashov - AYSS grants in 2020, 2021, 2023
2. D. Fedoseev - AYSS grants in 2021, 2022
3. A. Chetverikov - AYSS grants in 2021, 2023
4. A.Stepanova - AYSS grant in 2022
5. L.Kolupaeva - AYSS grant in 2020, DLNP’s Bruno Pontecorvo scholarship in 2021

2.4.3. Awards and prizes.

1. A. Stepanova: best report in section at International conference of students, graduate students and young scientists "Lomonosov-2022", 04/11/2022 - 04/22/2022, Moscow
2. A. Stepanova: best report at Young Scientist Forum Moscow International School of Physics 2022, 24.07.2022 - 02.08.2022, Dubna, Moscow region
3. L. Kolupaeva: Prize of the Governor of the Moscow Region for young scientists and specialists in the fields of science, technology, engineering, and innovations (2022)
4. JINR First Prize for 2021 in the nomination "Research Experimental Works": "Neutrino studies in the OPERA experiment" - A.Sheshukov, A.Olshevsky, S.Vasina

2.4.4. Other results (expert, scientific-organisational, scientific-popularisation activities). **Expert activities:**

—-

Scientific-organisational activities:

1. O. Samoylov - NOvA’s exotics co-convener (2020 - ongoing);
2. N.Anfimov - DUNE's light readout NDLAr (L3 manager) (2020 - ongoing);
3. L.Kolupaeva - NOvA’s production co-convener (2023-ongoing), NOvA’s three-flavor framework review taskforce leader (2021-ongoing);
4. A.Antoshkin - ROC-Dubna liaison (2017-ongoing);

Scientific-popularization activities:

1. Regular excursions to green laboratory facilities - A.Selyunin, A.Antoshkin, V. Sharov, N.Anfimov
2. Festival of Science and Technology “TechnoEnvironment at VDNKh” (2021), JINR stand - V. Sharov
3. All-Russian Science Festival “Nauka 0+”, Lecturer at the Kurchatov School (2022) - V.Sharov

4. JINR UC lectoria, periodic lectures for students and school children - V.Sharov, N.Anfimov, L.Kolupaeva
5. Marathon “JINR visiting Dubna schools” (2021-2022) - V.Sharov, N.Anfimov
6. Lecture for “Particle physics for kids” (2022) - N.Anfimov
7. Lecture for Moscow State University students (2022) - L.Kolupaeva
8. Lecture at Vinca Institute. Serbia (2022) - N.Anfimov
9. Series of lectures "Neutrino experiments" at Baikal School of Particle Physics and Astrophysics, (2022) - A.Sheshukov

3. International scientific and technical cooperation.

Actually participating countries, institutions and organisations

Organisation	Country	City	Participants	Type of 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)

№№ п/а	Category employee	Core staff Amount of FTE	Associated personnel Amount of FTE
1.	scientific staff		
2.	engineers		
3.	specialists		
	Total:		

4.2 The actual estimated cost of the project/ subproject of the LRIP

Names of costs, resources, funding sources		Cost (thousands of dollars) resource requirements	Proposal from the laboratory for allocation of funding and resources				
			1 year	2 year	3 year	4 year	5 year
	International cooperation (IC)						
	Materials						
	Equipment and third-party services						
	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						
		– The amount of FTE,						
		– accelerator/installation,						
		– reactor, ...						
Sources o funding	**Budgetary resources**	JINR budget *(budget items*						
	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 - Tapes	0.5 PB (Cloud)	0.7 PB (Cloud)	1 PB (Cloud)		
Tier 1 (core-hour)	0	0	0		
Tier 2 (core-hour)	0	0	0		
SC Govorun (cores-hours) - CPU - GPU	0	0	0		
Clouds (CPU cores)	1000	1000	1000		

5. Conclusion

Over the last three years JINR group made a noticeable contribution to the NOvA experiment via both physics and methodic studies. At the same time JINR group reaffirmed participation in the DUNE experiment via very noticeable involvement in detector building. Some very important milestones were passed and more to come on the way to exciting physics results.

6. Proposed reviewers

Theme / LRIP Leader

____________/______________/
"_____"_________________ 202_г.

Project leader (project code) / sub-project of the LRIP
____________/____/
"_____"___________ 202_г.

Laboratory Economist
______/____/
"_____"___________ 202_ г.