Annex 1.

Form of renewal for Theme

APPROVED

JINR Vice-Director

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THEME RENEWAL FORM

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

1. General information on the theme

1.1. Theme code (for extended themes)

02-2-1099-2010/2023

1.2. Laboratory

DLNP (VBLHEP, MLIT, BLTP)

1.3. Scientific field

Elementary Particle and Relativistic Nuclear Physics

1.4. The title of the Theme

Study of Neutrino Oscillations

1.5. Theme Leader(s)

D.V. Naumov, A.G. Olshevskiy

1.6. Theme Deputy Leader(s)

2. Scientific case and theme organization

2.1. Annotation

Neutrino physics is now considered as one of the most promising subjects for the discovery of phenomena beyond the Standard Model. This is mainly due to the special role, which neutrino can play as a unique neutral fermion with a very small, but non-zero mass - the fact, which was recently proved through the experimental discovery of neutrino oscillations.

The JINR has a very long tradition of developing and studying this phenomenon. In particular, the Institute has made very valuable contributions to the neutrino oscillation experiments like: NOMAD, OPERA, Borexino, Daya Bay, etc. The present proposal for extension of the theme "Study of Neutrino Oscillations" comprises an extension of the JINR participation in JUNO and NOvA/DUNE - top level mega-science scale projects, which are continuing this remarkable list of oscillation studies. In addition, in the framework of the theme we perform several smaller-scale activities.

2.2. Projects in the Theme

1. JUNO
2. NOvA/DUNE

2.3. Scientific case (no more than 20 pages)

(aim, relevance and scientific novelty, methods and approaches, techniques, expected results, risks).

Current goals of contemporary neutrino oscillation experiments are measurements of yet unknown parameters of this process: neutrino Mass Ordering and CP-violating phase and also improving precision of the others. This information is very valuable for understanding the neutrino sector and theory in general.

The term “neutrino mass ordering” (MO) refers to establishing an appropriate ordering of neutrino mass states $m_3 > m_1$ or $m_1 > m_3$. At present, one of the most feasible ways to determine MO looks to be the precise study of the neutrino oscillation probabilities, which are sensitive to the MO in both appearance and disappearance channels (accelerators and reactors, respectively).

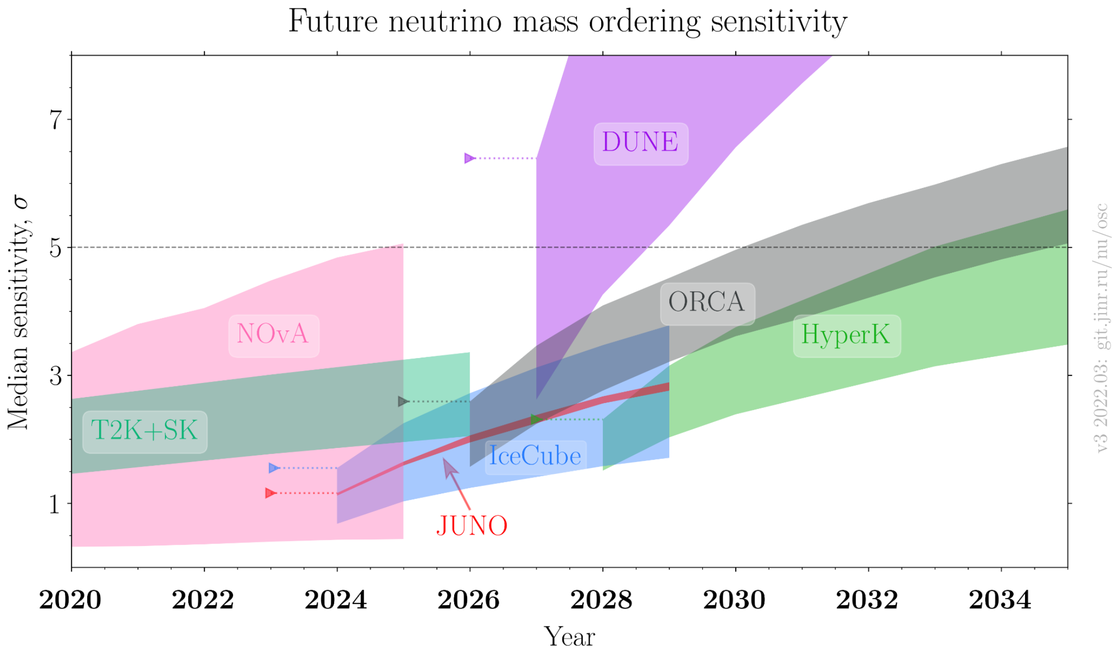
The disappearance channel is insensitive to the CP-violation phase which is currently unknown. On the contrary, the appearance channel suffers from the degeneracy due to an unknown CP-violating phase which biases the MO for neutrino energy of GeV range and baselines below ~1000 km. At a larger baseline the degeneracy is relaxed due to an increasing matter effect.

JUNO exploits the disappearance channel using reactor electron antineutrinos. Its data taking should begin in the end of 2023 and in six years JUNO should be able to determine the mass hierarchy at 3 standard deviations alone, i.e. without external constraints on the value of Δm^2_{31} or combination with another measurements.

NOvA (and T2K) accelerator neutrino experiments are taking data and currently both favor the normal mass ordering ($m_3 > m_1$) at about 1 and 1.6 standard deviations, respectively. NOvA is planning to take data until 2026 (inclusively) and by this time its sensitivity can reach up to 5 standard deviations (but only in the most favorable case of δ_{CP}).

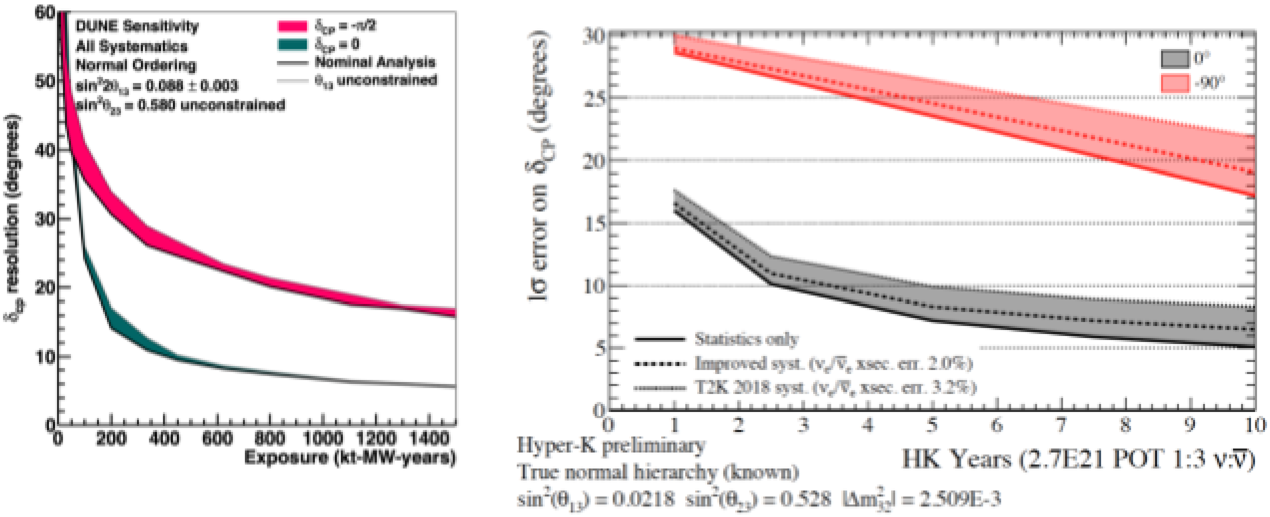
DUNE, an accelerator neutrino experiment following NOvA at the NuMI facility at Fermilab, should start data taking in 2026 with 50% of the final beam power and 50% of the total detector mass. The final upgrade is expected in 2030. DUNE should be able to determine the MO at 5 standard deviations just after two years of running.

Atmospheric experiment IceCube(PINGU), ORCA and accelerator HyperK project will also participate in the MO determination.



The future sensitivity to the neutrino mass ordering by reactor, accelerator and atmospheric neutrino oscillation experiments.

The only oscillation experiments currently reporting δ_{CP} measurements in addition to mass ordering are NOvA, Super-Kamiokande and T2K but the precision of these measurements is yet rather limited. In spite of the fact that T2K, Super-Kamiokande and NOvA will run a few more years it is clear from current estimations that they wouldn't be able to finalize mass ordering and CP phase measurement. This task is assigned to the two future accelerator long baseline experiments: DUNE at Fermilab and HyperK at J-PARCk. Both experiments will have similar resolution in δ_{CP} parameter determination, but will significantly complement each other from the point of view of systematic uncertainties due to different baselines and detector techniques used.



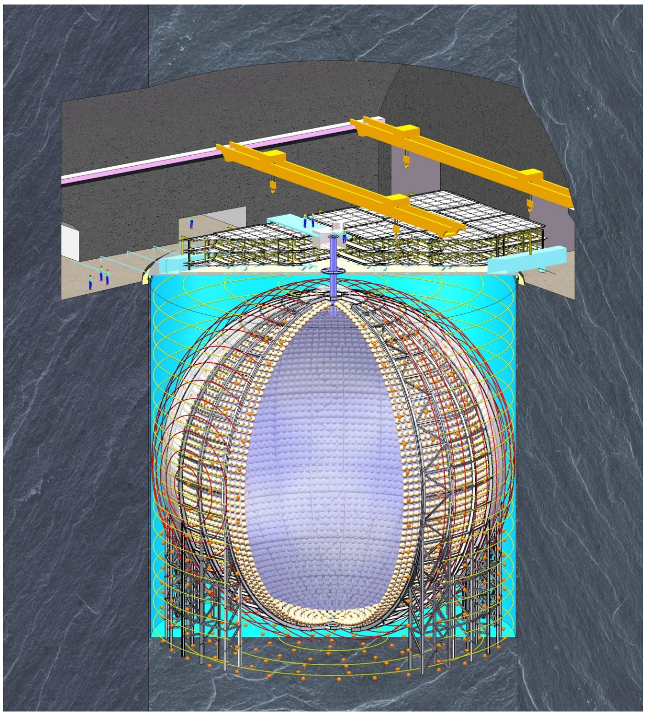
Expected sensitivity of DUNE (left) and Hyper-Kamiokande (right) experiments to CP resolution for CP violation phase equals to 0 and 3pi/2 cases.

In the framework of the theme the JINR group is using both aforementioned approaches participating in neutrino long baseline reactor and accelerator experiment oscillation studies.

The JUNO project

Apart from the main task of determination of neutrino mass ordering the JUNO experiment is planning determination of Δm^2_{32}, Δm^2_{21}, θ_{12} with sub-percent precision; search for proton decay; search for SN neutrino; detection of geo-, atmospheric and solar neutrinos; searches for physics beyond the Standard Model and some others.

The JUNO central detector (CD) is a spherical acrylic tank with 35m diameter filled with 20 ktons of liquid scintillator (LS). The scintillation light is detected by about 18k 20" PMTs (LPMT) and about 26k 3" PMTs (sPMT) providing about 78% surface coverage. The CD is placed at 52.5 km from Yangjian and Taishan NPP with a total power of 26.6 GW.



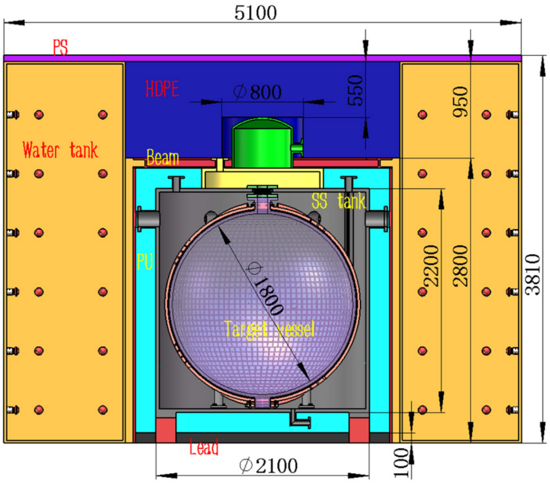
JUNO Central detector and its Top Tracker. The CD acrylic sphere diameter is about 35m. The CD is surrounded by a set of Helmholtz coils to compensate for the Earth Magnetic Field.

In six years of the data taking JUNO will collect about 100k of inverse beta decay (IBD) events determining the flux and antineutrino energy spectrum with precision better than 3% at 1 MeV of the energy visible in the LS. The precise measurement of the IBD energy spectrum allows the determination of the neutrino mass ordering.

JUNO's sensitivity has no degeneration due to unknown values of CP-violation phase and $\sin^2\theta_{23}$. The main challenge of this method is the energy resolution which should not be worse than 3% at 1 MeV.

Another issue is a possible fine structure in the reactor energy spectrum. If present, it might potentially bias the mass ordering determination and/or deteriorate the sensitivity of the experiment. In order to eliminate the dependency on the antineutrino spectrum there will be a satellite (near) detector TAO which will measure the energy spectrum of reactor antineutrino at a very short distance from reactor core with precision even better than in the JUNO CD.

TAO detector is a spherical barrel of 1.8 meters filled with the 2.8 tonnes of gadolinium-doped LAB liquid scintillator similar to the CD in order to have similar systematic uncertainties. To reach a resolution better than in the central detector, TAO will exploit silicon photomultipliers (SiPM) with higher PDE compared to conventional vacuum phototubes (PMTs). One of the nuisance parameters of the SiPM use is a huge Dark Count Rate (DCR) at room temperature. Which can impact the energy resolution and vanish all benefits of high PDE. To neglect the DCR in three orders of magnitude, the setup will operate at the negative temperature of −50C.



Schematic view of the TAO detector.

The JINR group has contributed significantly to the construction and preparation of the analyses of JUNO and TAO detectors. This work will be continued through the years of project running:

- The group from JINR is one of the key groups in JUNO providing statistical analysis of data and sensitivity estimation. A dedicated software GNA (Global Neutrino Analysis) was developed (C++) in order to provide a common base for the oscillation analysis of the reactor antineutrino data in Day Bay and JUNO experiments. The GNA was further extended to support experiments with accelerator neutrinos and atmospheric neutrinos. It was in particular used as a parallel analysis tool in the final analysis of the data of the Daya Bay experiment and the sensitivity of the JUNO experiment with satellite detector TAO.
- We are developing software for muon tracks reconstruction with the help of spherical functions. In this case we can describe a signal from muon track that passed through the detector with a limited number of parameters which is much less than the number of PMTs and in that way we can speed up our reconstruction procedure.
- JINR is one of the sites of JUNO Distributed Computing Infrastructure (DCI) which is intended to be used for storage, processing and analysis of enormous amounts of JUNO data. Along with two other European data centers the JINR is expected to play important roles within JUNO DCI: Raw Data Center, Regional Data Center and Simulation Production Data Center.
- One of the main JINR contributions to the construction of the JUNO experiment is the design and production of the HV electronics for all the JUNO PMT: ~18000 LPMT and ~27000 sPMT in the CD and ~2000 LPMT in the Cherenkov Veto. Since the HVU is a part of electronics located underwater near PMT, special attention was paid to the reliability of the design, components, and production processes. This includes prototyping, components selection, development of factory test protocols, and temperature-accelerated aging tests. In addition, materials used in the HVU were tested for radioactivity. The full production was finished by the end of 2021 (25000 pieces) and HV Units are being installed now at JUNO detector together with the rest of underwater electronics.
- The JUNO Top Tracker (TT) detector was built reusing modules previously produced by JINR for the OPERA experiment. In addition to providing those modules, the JINR group is responsible for the design, fabrication and construction of the mechanical support of the TT detector; monitoring of the performance of the TT modules during the period of their storage; takes part in a development of the data acquisition system software and the offline software development for the analysis of the TT data.
- The JUNO central detector contains about 20000 large 20-inches PMTs. All PMTs passed testing in the warehouse, where 4 containers and 2 scanning systems are placed. The scanning

systems were developed at JINR and were used to provide detailed knowledge of the PMT performance. All 20000 PMTs were tested in the containers and about 4000 PMTs were qualified by the JINR scanning system for almost three years of running tests in 2020-2022. The PMTs are now installed in the detector and connected to electronics.

- One of the main JINR responsibilities in the TAO detector is to develop and provide power to ~4100 SiPM tiles (arrays). The whole system includes power distribution lines which are 3M 68-lines shielded cables. In total, we need 900 meters for the outer part and 300 meters to distribute inside the cryostat. The production and procurement plan includes 40 VME units, 12 hundred meters of cable, 3 VME crates, and a dozen of feed-through boards. We plan to build up the system during 2023-2024 and put it in operation in 2024.
- One of the crucial aspects of TAO design is proper operation of SiPM photodetectors. The JINR took part in the development of the criteria for acceptance of SiPM. In total, we have to test about 4100 SiPM tiles and their performance at negative 50 C and a special technique was developed, which allows the characterization of SiPM in terms of PDE, Gain, Cross-talks, afterpulses, SPE, and IV-curve. The setup is put into operation now and will be used for tests, which we plan to finish by the end of 2024.

During the project extension in 2024-2026 we expect the following results to be obtained:

1. Reconstruction (2024):
    a. Reconstruction of muon tracks and electromagnetic showers with electronics simulation.
    b. Reconstruction of clipping muons in central detector.
    c. Efficiency and quality of reconstructed muon tracks.
    d. Adaptation of muon track reconstruction procedure to real data.
2. VETO TT installation and running
3. PMTs:
    a. Final PMT testing with HV-units.
    b. PMT installation to the JUNO Central Detector.
4. Filling and running JUNO ~ 2024.
5. TAO:
    a. All SiPM for TAO tested and installed to the detector.
    b. Production and commissioning of the TAO SiPM power system.
    c. Filling and running TAO.
6. Oscillation analysis:
    a. First measurement of neutrino oscillation parameters Δm^2_{31}, Δm^2_{21} and $\sin^2 2\theta_{12}$ in the JUNO experiment.
    b. First constraints on the parameters of the sterile neutrino oscillations $\sin^2 2\theta_{14}$ and Δm^2_{41} based on the data from the detector TAO.

The JUNO experiment is expected to be a huge step forward in scale and precision among both the reactor neutrino experiments and liquid scintillator experiments. The JUNO detector will be 20 times larger than the current largest reactor antineutrino detector KamLAND. Experiment requirements include maximal PMT coverage and 3% energy resolution at 1 MeV of released energy. Such a unique detector has a number of technical challenges, but the potential risks are minimized by extensive subsystem testing and high reliability requirements on the detector components and electronics.

The NOvA/DUNE project

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. 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 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.

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. 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 and is an input parameter for experiments on direct measurement of neutrino masses and search for relic neutrinos. 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.

Both NOvA and DUNE are long baseline accelerator neutrino experiments. NOvA is an on-going program in this area, one of the two currently running most powerful accelerator neutrino oscillation experiments.

In the case of NOvA, the NuMI accelerator complex at Fermilab is used to produce 120 GeV protons that are delivered to the carbon target. Magnetic horns, placed after the target, focus either positively or negatively charged mesons, which after decay in the decay pipe produce neutrino or antineutrino. Therefore, switching the horn current allows experiment working with neutrino or antineutrino beams.

The accelerator complex at Fermilab is constantly being upgraded to produce more neutrinos. Currently the experiment works at 850kW proton beam power and the most up-to-date analysis of NOvA refers to 13.6×10^{20} POT (neutrino beam) and 12.5×10^{20} POT (antineutrino beam). NOvA is expected to roughly double this exposure by the end of data taking expected by the end of 2026.

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. 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. Near and Far NOvA detectors are identical tracking calorimeters made of PVC cells filled with a liquid organic scintillator and a light readout by wavelength shifting fibers. 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).

The JINR group is involved in NOvA for many years with various contributions including detector studies and physics analyses. In particular, the team contributed significantly to the main three- flavor oscillation analysis, development of supernova detection methods, magnetic monopole searches, cosmic ray studies, etc. For example, in the three-flavor oscillation analysis group in NOvA the JINR collaborators are at present working on neutrino energy estimation, data fitting and sensitivities calculation for 2024 analysis release.

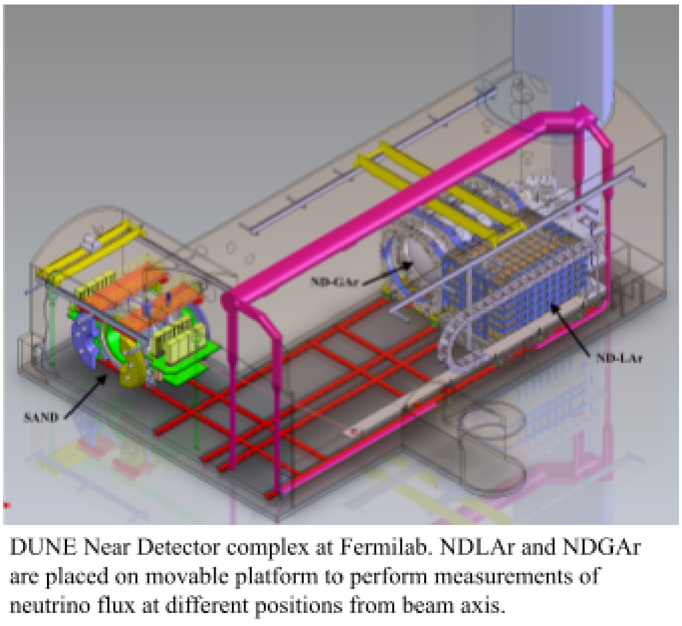
Compared to NOvA, the DUNE experiment will have several major differences. This experiment is expected to start data-taking in the late 2020s. The accelerator complex at Fermilab is currently being upgraded to provide a proton beam of ~1.2 MW for DUNE (Phase-I of experiment), with plans to upgrade the beam power to 2.4 MW after several years of running by replacing some subparts of the accelerator complex (Phase-II). Additionally, all components of the neutrino beamline (target, horns, decay pipe) will be different from NOvA, and neutrinos will travel 1300 km to the Far Detector complex. Both Far and Near 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 will consist of three detectors: 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 charge 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 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.

The JINR group joined DUNE in 2020 with a contribution in building near detectors of this experiment and analysis preparations. In particular, an experience which was gained in NOvA is extended to the DUNE main oscillation physics analysis and exotic searches. In addition, the JINR collaborators are also working on the preparation of the SAND measurements physics program and development of the DUNE-PRISM predictions for Far Detector’s oscillation analysis.

On the DUNE detector construction side the JINR is deeply involved in the NDLAr project being responsible for design, production and operation of the Light readout system in the liquid argon TPC 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.



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.

During the NOvA/DUNE project extension the following results are expected to be obtained with significant contribution from 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.

More details on the JUNO and NOvA/DUNE projects are given in the corresponding project extension forms, which are presented simultaneously with this theme extension request.

In addition to these two projects several small scale activities will be continued in the framework of the theme:

- To ensure the possibility of further work with Borexino data at JINR, their full copy, as well as the necessary software, was placed on the servers of the Institute. We will further continue to analyze data of this experiment, which already performed several unique solar neutrino spectra and also some other measurements.
- The activities are continued on the creation of the DarkSide-20k detector. At the same time, the analysis of the DarkSide-50 data is being completed.
- NA65/FASER(v) experiment successfully started data taking. The JINR group will continue working on the data analysis and development of the detector components, in particular, the system of detector thermic stabilization.

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).

2.5. Participating countries, scientific and educational organizations:

Organization	**Country**	**City**	**Participants**	**Type of agreement**
IHEP	China	Beijing	Yifang Wang + 10	JUNO MoU

SYSU	China	Guangzhou	Wei Wang + 10	JUNO MoU
SINP MSU	Russia	Moscow	Alexander Chepurnov, Maxim Gromov	JUNO MoU
INFN	Italy	Catania, Rome	Giuseppe Adronico +1 Stefano Maria Mari +1	JUNO MoU JUNO MoU
FZJ-IKP	Germany	Jülich	Livia Ludhova +4	JUNO MoU
EKUT	Germany	Tübingen	Tobias Lachenmaier +1	JUNO MoU

FNAL	USA	Batavia, IL	Alex Himmel + 3 Jennifer Raaf + 4	JINR-FNAL agreement extension
University of Bern	Switzerland	Bern	Michele Weber + 2	Consortium agreement
CERN	Switzerland		Francesco Lanni, Filippo Resnati	Neutrino 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. Key partners *(those collaborators whose financial, infrastructural participation is substantial for the implementation of the research program on the theme. Example – JINR participation in the LHC experiments at CERN).*

- Institute for High Energy Physics, Beijing, China
- Fermi National Accelerator Laboratory (FNAL), USA
- The University of Bern (UniBe), Bern, Switzerland
- University of South Carolina, Columbia, USA
- CERN

3. Manpower

3.1. Manpower needs in the first year of implementation

No.	Personnel category	JINR staff, FTE amount	JINR associated personnel, FTE amount
1.	research scientists	24	-
2.	engineers	14	-
3.	students	-	11
	Total:	**38**	**11**

3.2. Available manpower

3.2.1. JINR staff (total number of participants)

No.	Personnel category	Division	Position	Amount FTE
1.	research scientists			30
2.	engineers			10
3.	students			13
	Total:			**53**

3.2.2. JINR associated personnel (already accounted in 3.2.1)

No.	Personnel category	Partner organization	Amount of FTE
1.	students	Moscow State University, Irkutsk State University, MIPT, Almaty State University, Dubna State University	13
	Total:		**13**

4. Financing

4.1. Total estimated cost of the theme / LRIP

No.	Items of expenditure	Cost	Expenditure per year (thousands of the US dollars)		
			1st year	2nd year	3rd year...
1.	International cooperation	1290	430	430	430
2.	Materials	630	230	210	190
3.	Equipment, Third-party company services	290	110	90	90
4.	Commissioning	30	10	10	10
5.	R&D contracts with other research organizations	130	40	50	40
6.	Software purchasing	120	40	40	40
7.	Design/construction	15	5	5	5
8.	Service costs (*planned in case of direct affiliation)*	15	5	5	5
TOTAL:		**2520**	**870**	**840**	**810**

4.2. Extra funding sources

Expected extra funding from partners/customers (total for all projects).

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AGREED:

Chief Scientific Secretary

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"_____"__________________ 202_г.

Laboratory Director

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"_____"__________________202_г.

Head of BEPD

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"_____"__________________202_г.

Scientific Secretary of the Laboratory

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"_____"__________________ 202_г.

Head of DSOA

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"_____"___________ 202_ г.

Laboratory Economist

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"_____"__________________202_г.

Head of HRRMD

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"_____"___________ 202_г.

Theme leader(s)

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"_____"___________ 202_г.

Project leader (project code) /

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“_____“__________________202_г.

Project leader (project code) /

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Annex 2.

Theme Form

APPROVED

Director of Laboratory

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"_____"_________________ 202 г.

REPORT ON THEME

1. General information on the Theme

1.1. Theme

02-2-1099-2010/2023

1.2. Laboratory

DLNP (MLIT, BLTP)

1.3. Scientific field

Elementary Particle and Relativistic Nuclear Physics

1.4. Title of the Theme

Study of Neutrino Oscillations

1.5. Theme Leader(s)

D.V. Naumov, A.G. Olshevskiy

1.6. Projects in the Theme

JUNO, NOvA/DUNE

2. Scientific report on the Theme

2.1. Annotation

For the previously approved period the theme research comprised two major projects: JUNO and NOvA/DUNE, which have the main goal of studying the neutrino oscillation parameters by different techniques at nuclear reactors and accelerators, respectively. Description of the work and the results obtained are presented below.

In addition to those projects several smaller scale activities were also performed during this period of time, namely: Daya Bay, Borexino, DarkSide and NA65/FASER(v). The results obtained there are also presented below.

2.2. A detailed scientific report

2.2.1. A description of the work carried out and the results obtained for all projects and activities of the theme.

JUNO Project

Detectors construction

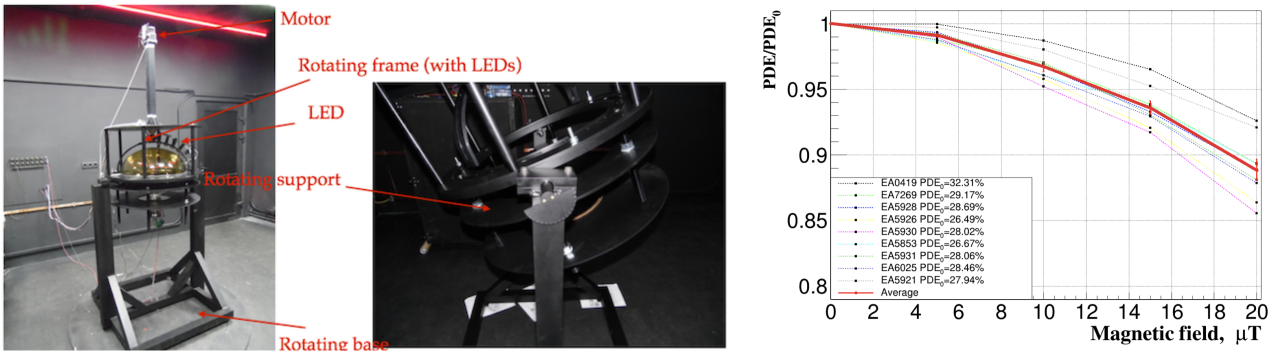
The assembly of the largest liquid scintillator detector JUNO started in China in 2022. For this detector the JINR has constructed the PMT High Voltage power supply system. All of the system units (>25'000) were produced, tested and are ready for installation. The JINR team has also done R&D for the power supply for the silicon photomultipliers (SiPM) of the JUNO/TAO detector. The power supply units were designed and prepared for production in China. Also, the design of the station for the mass testing of the SiPMs was developed.

PMT Mass-testing

The JUNO central and Veto detectors contain about 20000 large 20-inches PMTs. All PMTs passed testing in the warehouse, where 4 containers and 2 scanning systems are placed.

The container is a tool where PMT is tested by means of uniform flashed illumination from LED or picosecond laser. The instrument was developed by German collaborators, and it is a standard 20 feet light-tight container in-lined with a magnetic shield where 36 PMTs can be simultaneously tested. It is extracting, so-called, integral measurements of a PMT's characteristics as PDE, gain, TTS, SPE and Dark noise rate at the operating voltage. One of the containers led by JINR group is equipped for PMT long-term stability testing, where 36 PMTs of different types experienced accelerating aging to predict and guarantee their performance for the whole of JUNO's operation period of 20 years.

The scanning system is a much more sophisticated tool developed at JINR and can extract the same parameters from 168 points on PMT's surface. The scanning is providing better knowledge of the PMT performance, but is rather slow compared to container testing. A very important PMT performance parameter is its operation in presence of a Magnetic field. The instrument is placed inside the black room surrounded by Helmholtz coils to vary and compensate for the Earth's Magnetic Field. All PMTs were tested in the containers and about 4000 PMTs were qualified by the scanning system for almost three years in 2020-2022.



The scope of the scanning system (left). The Photon Detection Efficiency of Hamamatsu R12860 tubes vs Magnetic Field (right).

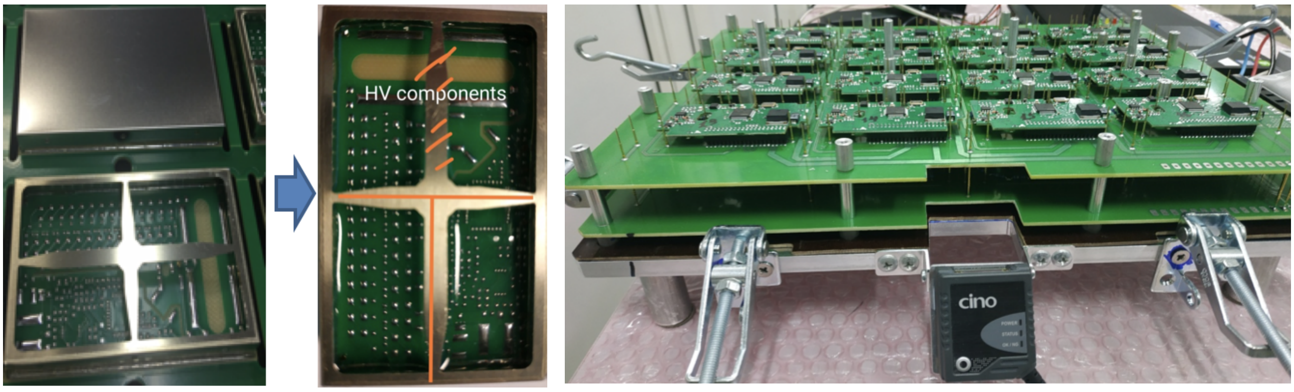
PMT HV

During previous years of the project the JINR has completed the design, prototyping and extensive tests of the HV Units (HVU) to be used in the JUNO experiment.

Since HVU is a part of electronics located under water near PMT and has no chance for repair or exchange, special attention was paid to the reliability of the design, components and production processes. This includes prototyping, components selection, development of factory test protocols and temperature accelerated aging tests. In addition, materials used in HVU were tested for radioactivity.

All of the tests were passed successfully and HVU was found to be compliant with JUNO requirements. The design of HVU has been approved by the Collaboration in a series of reviews, which examined full correspondence to the requested parameters, especially the reliability. Finally, the

Production Readiness Review was passed and the production contract was signed with the electronics factory in Shenzhen. The full production was finished by late 2021 (25000 pieces) and HV Units are being installed now at JUNO detector together with the rest of underwater electronics and PMTs.



High voltage unit and mass-testing equipment.

Protection against Earth Magnetic Field

Magnetic field shields for the large PMTs of the OSIRIS (facility for monitoring of the liquid scintillator during filling phase of JUNO) are manufactured and delivered to Germany. The amorphous alloy tape of domestic origin is used as an Earth magnetic field screen. The 64 screens made using potassium-free carbon fiber texture as a base will be used in the main detector. The 12 screens made using cheaper fiberglass (some potassium is acceptable) will be used in the muon veto.

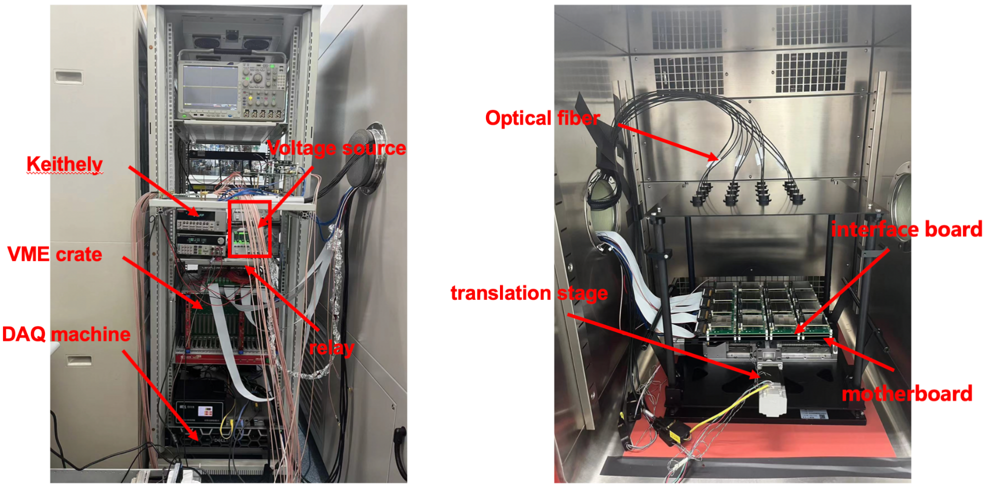
A paper on the magnetic shield for large photomultipliers of the OSIRIS facility of the JUNO detector submitted to JINST ([2212.02562]. The presented magnetic shield could be used in the proposed upgrade of the OSIRIS facility for the detection of solar pp-neutrino (Eur.Phys.J.C 82 (2022) 9, 779, [2109.10782]).

Veto: Top Tracker

The stainless steel structure for the Top Tracker is produced. The Top Tracker assembly and installation procedure are developed. The core part of TT DAQ software already exists. It is intensively testing and debugging on a remote test bench in Strasbourg. More functions will be added later. The integration with Juno global DAQ starts in June 2023. The paper on the Top Tracker description has been prepared for publication.

SiPM mass testing

The TAO detector will exploit almost 4100 32-channel SiPM arrays (tiles) operating at the temperature of –50°C to read out the scintillation light. Potential SiPM candidates operating at temperatures below 0°C were studied [N. Anfimov et al. Study of silicon photomultiplier performance at different temperatures. NIMA 997:165162, 2021]. The methods and design of the setup for SiPM tiles mass tests at –50°C were developed and tested at DLNP JINR. The results are accepted for use by the JUNO collaboration and successfully passed Final Design Review (FDR) . The technique allows testing a single array and will be scaled up to test 16 tiles together. To test simultaneously multiple tiles the optical fiber splitter has been designed (fig) [Rybnikov, A.V. et al. Optical Fiber Splitter for Photodetector Testing. Phys. Part. Nuclei Lett. 19, 797–802 (2022)]. The setup for the mass testing was produced and assembled at IHEP and is under commissioning now.



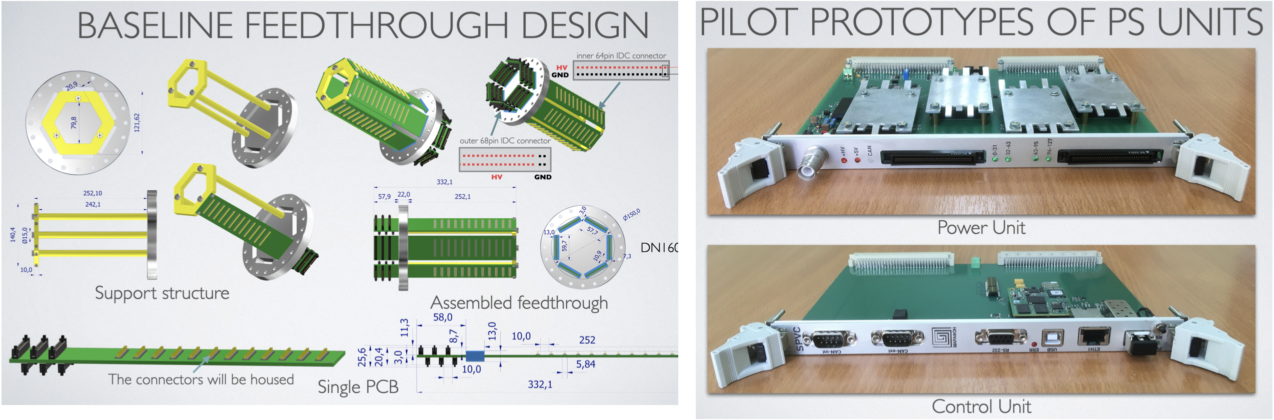
outside of cryogenic chamber

Inside of cryogenic chamber

SiPM Mass-testing setup at IHEP.

SiPM power system

A multi-channel SiPM power supply VME module for 128 channels has been developed. The module allows biasing detectors from 0 to 200V with a maximum current load of 500mA. Current and short-circuit monitoring is implemented. The modules are designed to power 4100 SiPM arrays in the TAO detector. Pilot versions have been produced, tested and passed the FDR. All components for modules production were procured and await the manufacturing in China. We also developed the feedthrough to guide all power lines inside the cryostat and find suitable cables for transferring up to 200V at −50°C in LAB.



The scope of the feedthrough design and assembly (left). A photograph of the power module and its control unit (right).

Solar neutrinos

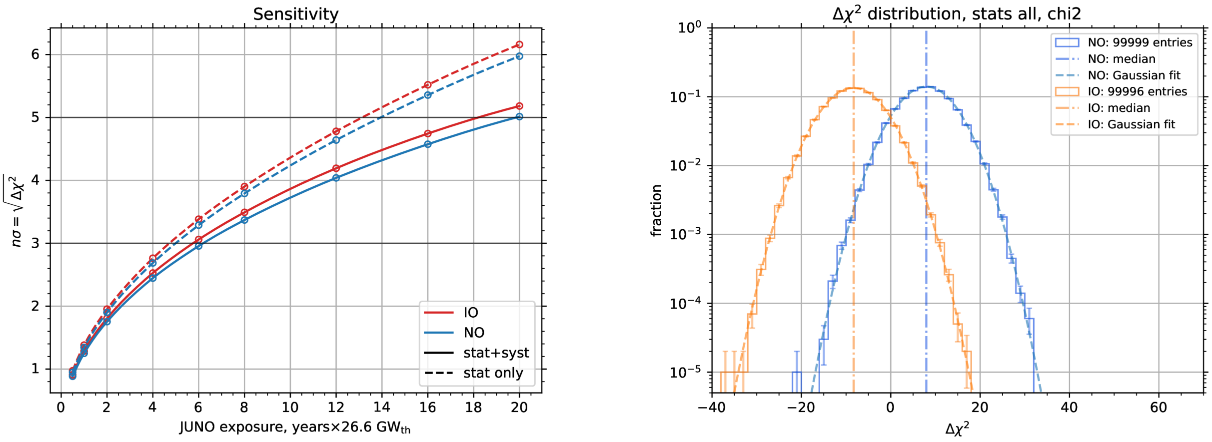
DLNP JINR scientists took part in the proposal to use the upgrade of the OSIRIS facility (Serappis) for the detection of the Solar pp-neutrino flux with high precision: L.Bieger, … M.Gromov….O.Smirnov, ... “Potential for a precision measurement of solar pp neutrinos in the Serappis Experiment ", arXiv:2109.10782. A possibility to use a magnetic field shield combined with a light concentrator is considered for the Serappis detector. Together with the manufacturer we are developing the process of argentum deposition on the carbon fiber texture.

The sensitivity of the JUNO experiment

It is shown that JUNO will be able to measure the neutrino oscillation parameters Δm^2_{31}, Δm^2_{21} and $\sin^2 2\theta_{12}$ with precision below 0.5% during 6 years of data taking (Chin.Phys.C 46 (2022) 123001 [2204.13249]). Moreover the precision of 1% will be reached already after 100 days of data taking.

A new estimation of the JUNO sensitivity to neutrino mass ordering taking into account the data from the satellite detector TAO and recent knowledge of the detector and experimental setup was released. The sensitivity reaches 3σ after 6 years of the data taking. The result was obtained via two methods: based on the Asimov data set (with no fluctuations) and based on the extensive MC study. The methods provide consistent results. The draft of the paper is under the collaboration review.

Two groups from JINR provided their own analysis for each of the studies, passing all the steps of the analysis preparation, cross checks and review.



Sensitivity of the JUNO experiment versus exposure (left). The distribution of the test statistic for 6 years of data acquisition (right).

Event reconstruction

The results of a study of application of methods of machine learning the the reconstruction of the primary vertex and energy in the JUNO detector were published in NIMA: Qian Z. et al. “Vertex and energy reconstruction in JUNO with machine learning methods", [physics.ins-det/2101.04839]. The group from DLNP JINR has made a major contribution to the energy reconstruction and performed the overall coordination of the analysis.

The new algorithms for the reconstruction of the energy of positron for the JUNO detector were developed by the JINR group (Eur.Phys.J.C 82 (2022) 1021). It is shown that the algorithms may reach the desired energy resolution of $\sigma=3\%$ at 1 MeV.

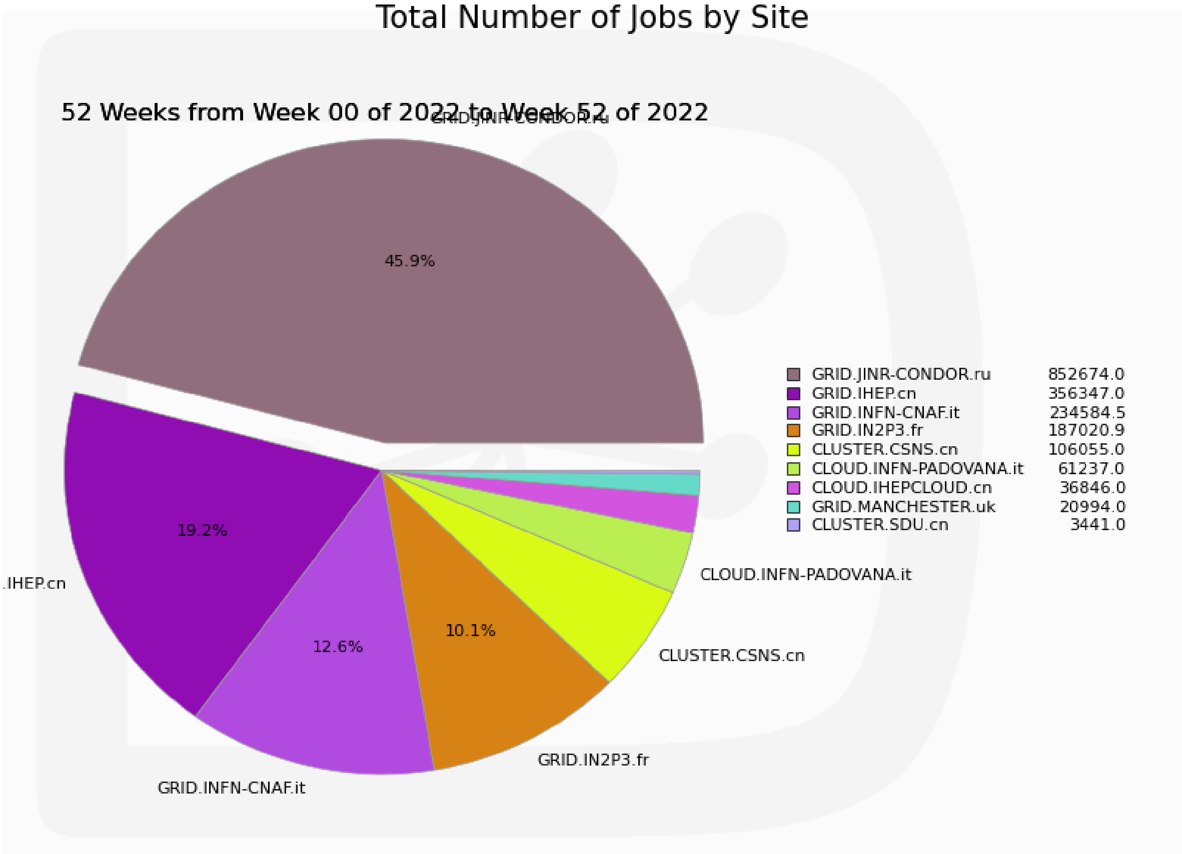
An algorithm of muon tracks and electromagnetic shower with the help of spherical functions has been developed and tested. We wrote a procedure of closest muon tracks separation, proposed a new method of muon tracks reconstruction quality estimation, and also we made preliminary conditions for Li/He isotopes isolation with taking into account muon track reconstruction quality.

With our method we can reconstruct a single muon track with precision ~25cm (maximal distance between true and reconstructed muon track in central detector).

Computing infrastructure

During 2022 the usage of the computing resources increased a lot. Out of 2.04 millions of jobs performed within JUNO distributed computing infrastructure JINR processed 46%. In 2021 JINR’s cluster processed 31% out of all JUNO jobs.

JINR is providing CPU nodes with large memory per CPU (15 Gb) making JINR the only provider to perform memory demanding simulation, e.g. high energy muons. As for storage the JINR provides 1 PB quota of effective disk space (2 PB of raw disk space due to 2x replication) for JUNO (65% of which is used) and 650 TB (1.3 PB) for Daya Bay (92% is used).



The usage of the shared CPU resources within JUNO distributed infrastructure.

Apart from providing CPU and storage resources the following JUNO DCI services replicas were deployed at JINR to make JUNO DCI more redundant and thus its functioning more reliable as well as to increase an overall JUNO DCI performance:

- WebApp and Configuration Services;
- Secondary VOMS server for JUNO VO;
- Full replica of JUNO CVMFS Stratum-1 repository (/cvmfs/juno.ihep.ac.cn) and /cvmfs/dcomputing.ihep.ac.cn;
- JUNO offline Condition Database.

NOvA/DUNE Project

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 the 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 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.

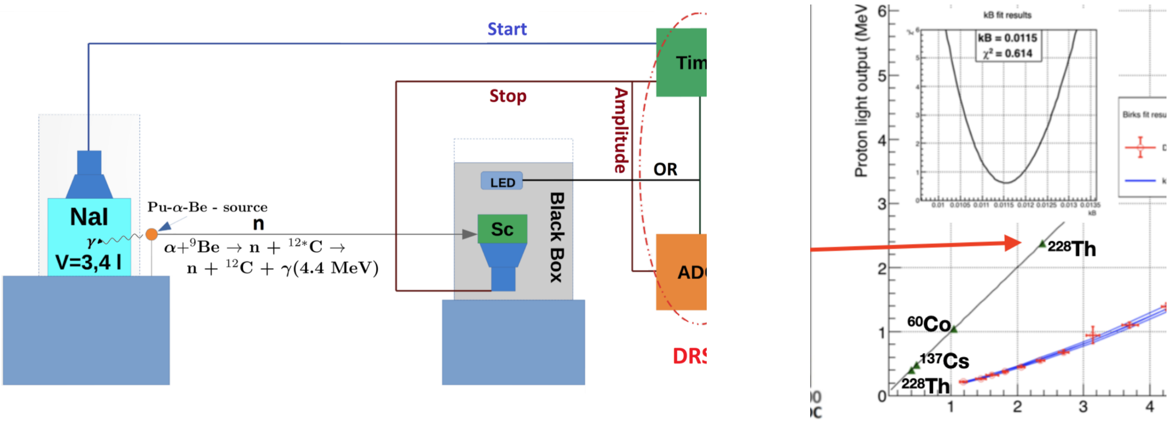
NOvA Scintillator Studies

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.

The following scheme of the setup was used.



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.

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. And eventually the Birks constant was found as k_B=1.15$\pm$0.07 g/(MeV$\cdot cm^2$).

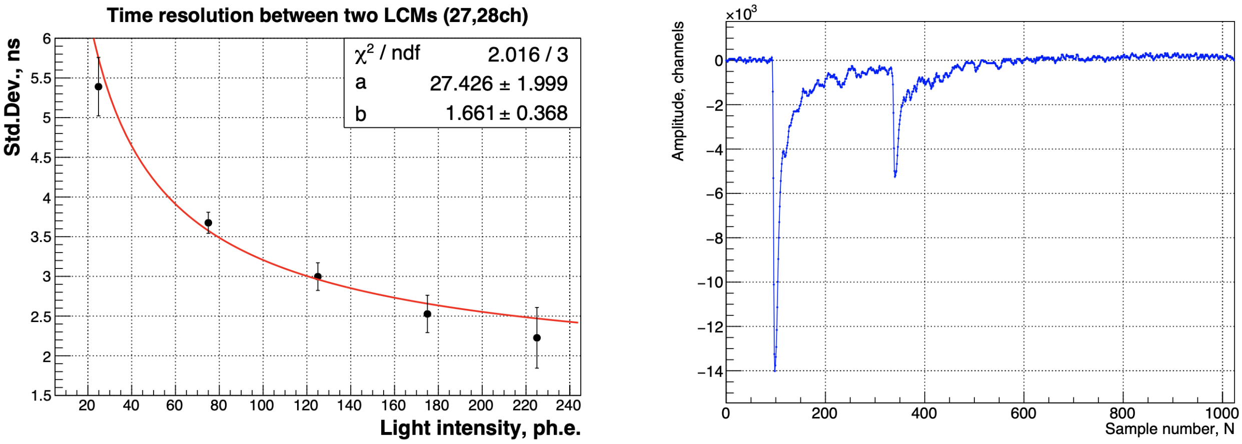
Now we prepared the stand for Cherenkov light measurements to improve Birks measurements and expect to finish scintillator studies in 2024.

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 time stamped flag for identifying coincidences between charge and light readout.

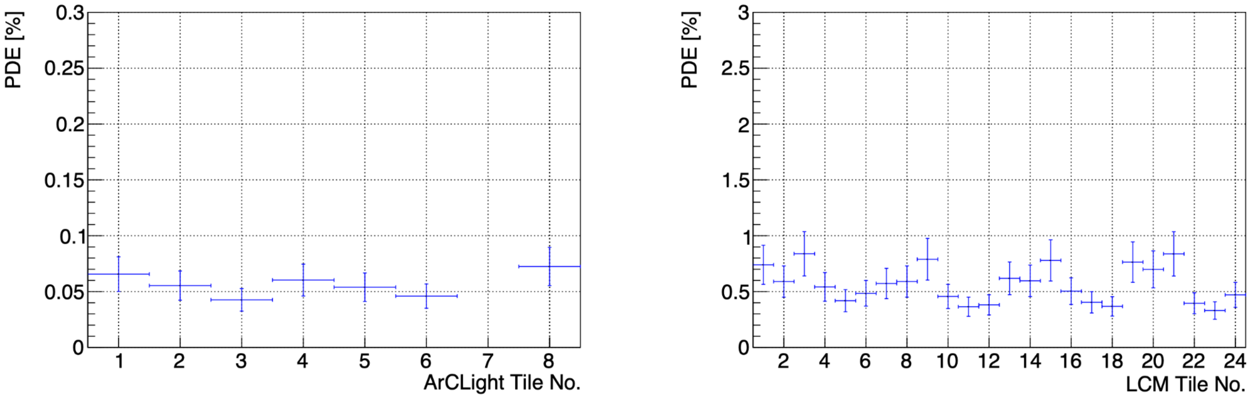


Module-0: The time resolution between two LCMs as a function of the signal response (left). Signals of the stopping muon and delayed Michel electron detected by the LCM (right).

Events induced by cosmic muons traversing the TPC volume were used to extract the time resolution of the light detectors. 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 from stopping muon decays, where the relative timing between the muon and electron signals is dominated by the mean lifetime of the muon, $\boldsymbol{\tau}\sim 2\,\mu\text{s}$.

Two examples of signals from a stopping muon and a delayed Michel electron detected by the LCM are shown in the next Figure. 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.



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.

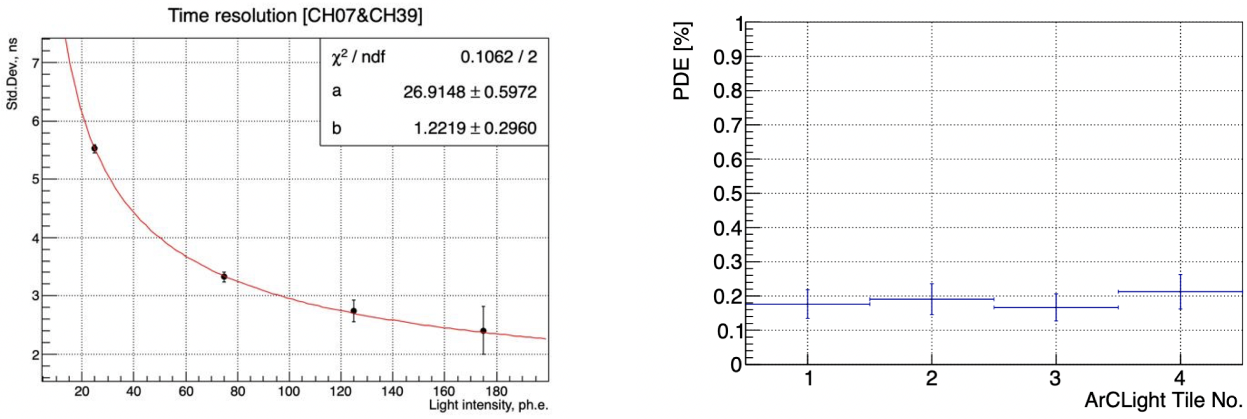
The number of photons hitting the detector surface is estimated by multiplying the geometrical acceptance by the number of emitted photons per unit track length and integrating over the full track length. Here, the number of emitted photons per unit track length has been calculated for the nominal electric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



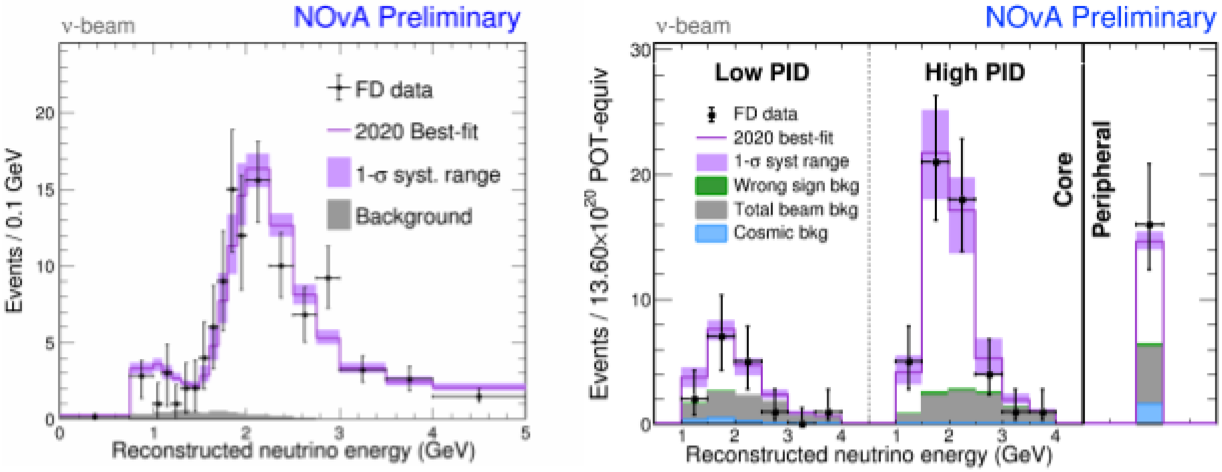
Module-1: The time resolution between two LCMs as a function of the signal response (left). Absolute PDE for each LCM (right) tile (arbitrary numbering).

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 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.

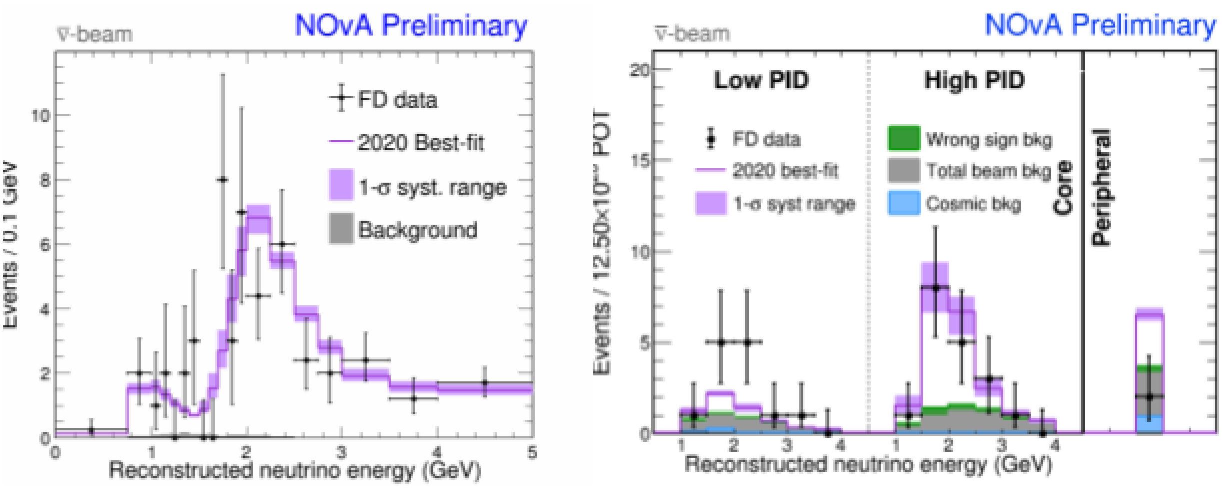
Modules-1,2,3 have used SiPM with improved efficiency, PDE=35% compared to PDE=25% (mod-0), used to read out the light detectors. The ArcLight technology was significantly improved by applying new mirroring techniques. All four modules have been assembled, tested, and shipped to Fermilab for 2x2 testing.

NOvA data analysis results.

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 ($\bar{\nu}$) in statistics. NOvA aims to study $\nu_\mu \rightarrow \nu_\mu$, $\nu_\mu \rightarrow \nu_e$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ 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.



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

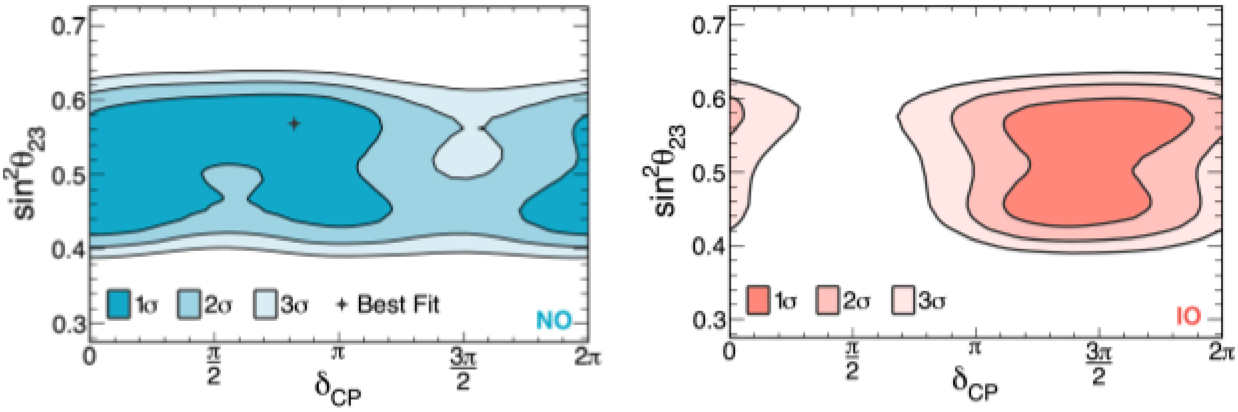


Muon and electron antineutrino spectra of events selected in the NOvA Far Detector during antineutrino mode operation. These spectra were used for data fits.

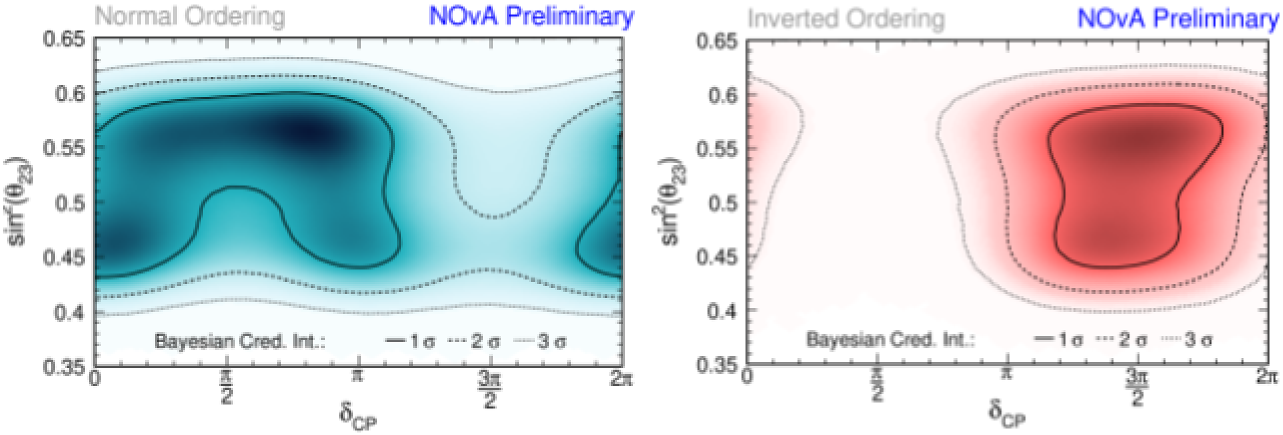
Spectra of selected events are combined in a joint fit to extract the neutrino oscillation parameters.The result obtained in 2020 was done within the framework of the Frequentist paradigm. Due to the lack of statistics, the fit was corrected using the Feldman-Cousins approach. The 2022 reanalysis for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

NOvA's best fit value is in the point $\delta_{CP} = 0.82\pi$, $sin^2\theta_{23} = 0.57^{+0.03}_{-0.04}$, $\Delta m^2_{32} = +(2.41 \pm 0.07)\times 10^{-3}\ eV^2$. 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 $>3\sigma$. The value $\delta_{CP} = 3\pi/2$ in the Normal ordering and the upper octant θ_{23} is excluded at the level $\sim 2\sigma$.

Thus NOvA sees no asymmetry in neutrino/antineutrino appearance.



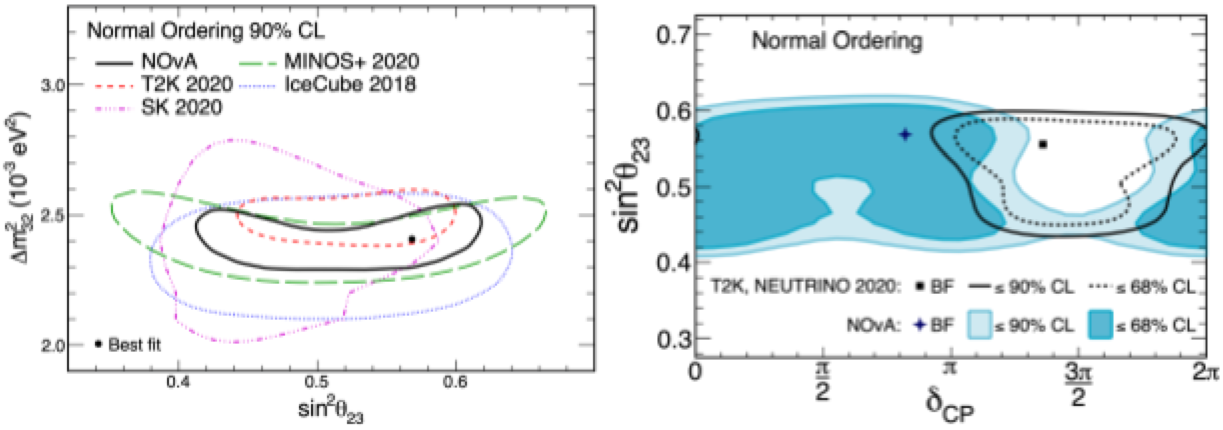
Confidence contours obtained by the NOvA experiment with 2020 data fit with the hypothesis of the normal order of neutrino masses (left) and the inverted order (right). Frequentist approach used.



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 have had the following activities in three-flavor group: energy estimation of neutrino events, Near Detector spectra 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 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.



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 a joint analysis of collected data. JINR group members are involved in this analysis on the NOvA experiment side.

The search for slow magnetic monopoles 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 a test stand at 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.

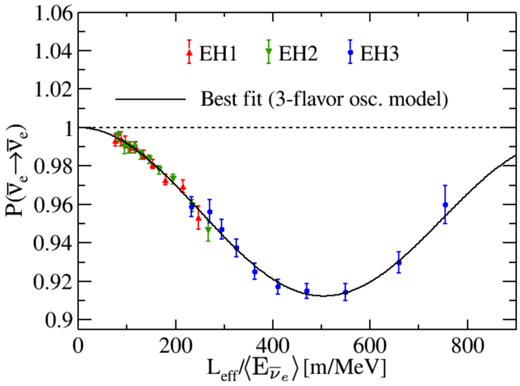
The analysis of combining neutrino signals from Supernova in various experiments has been performed (JCAP12(2021)053). Supernova neutrino detection in neutrino and dark matter experiments is usually implemented as a real-time trigger system based on counting neutrino interactions within a moving time 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 pre-supernova 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 pre-supernova 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).

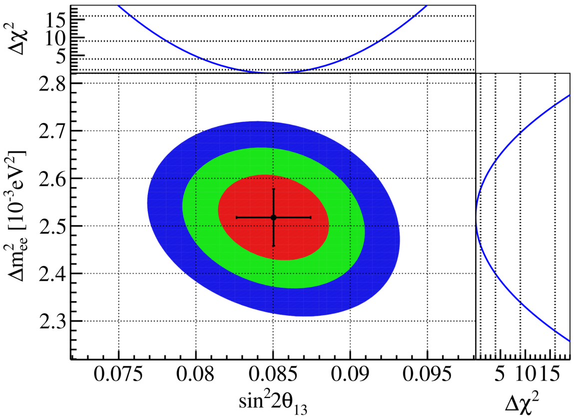
A few analyses on atmospheric muons are on-going. The Dubna group analyzes geomagnetic effects in the east-west asymmetry of muon spectra and tests the technique for measuring the spectrum of high-energy muons proposed by R.P. Kokoulin et al.

Daya Bay

The Daya Bay experiment has finished operation in 2020. In 2022 the measurement of the neutrino oscillation parameters based on the complete dataset was finished. The obtained result $\sin^2 2\theta_{13}=0.0851\pm0.0024$ and $\Delta m^2_{32}=2.466\pm0.060$ (-2.571 ± 0.060) eV^2 for the normal (inverted) neutrino mass ordering is the most precise to the date measurement ([2211.14988], submitted to PRL). The precision of the measurement of $\sin^2 2\theta_{13}$ will be dominated by the Daya Bay at least for 10-15 years.

The group from JINR traditionally participated in the preparation of the result, including the selection of inverse beta-decay events, estimation of the backgrounds and oscillation analysis.





The ratio of the observed events without the backgrounds to the expectation without oscillations.
The confidence interval for the neutrino oscillation parameters $\sin^2 2\theta_{13}$ and Δm^2_{31}.

Borexino

The Borexino data analysis continues. After analyzing the complete Phase-III dataset, the flux of solar neutrinos resulting from the CNO-cycle thermonuclear reactions has been refined (Phys. Rev. Lett. 129 (2022) 25, 252701, [2205.15975]). The measured flux was $6.6^{+2.0}_{-0.9} \times 10^8$ cm^{-2} c^{-1}, and the hypothesis of the absence of the neutrino CNO signal is excluded with about 7σ C.L. The measured flux made it possible to evaluate the carbon and nitrogen abundances in the Sun with respect to the hydrogen abundance for the first time with neutrinos. The ratio is equal to $N_{CN} = 5.78^{+1.86}_{-1.00} \times 10^{-4}$. In parallel, the principal feasibility of determining the direction to the source (in this case, to the Sun) in a large liquid scintillation detector using neutrino radiation is shown (*Phys.Rev.Lett.* 128 (2022) 9, 091803 [2112.11816]; *Phys.Rev.D* 105 (2022) 5, 052002 [2109.04770]). The search for neutrino events in the Borexino detector in correlation with the most intense fast radio bursts (FRB) has also been completed (*Eur.Phys.J.C* 82 (2022) 3, 278 [2111.14500]). No statistically significant excess over the background was observed. As a result, the strongest upper limits on FRB-associated neutrino fluences of all flavors were obtained in the 0.5-50 MeV neutrino energy range.

To ensure the possibility of further work with data at JINR, their full copy, as well as the necessary software, is placed on the servers of the Institute.

DarkSide

The activities are continued on the creation of the DarkSide-20k detector. At the same time, the analysis of the DarkSide-50 data is being completed. One of the recent studies was devoted to the possible photoionization of the cathode and impurities in the target. The first process was confirmed and indications of the presence of the second one were found (Astropart. Phys. 140 (2022) 102704, [2107.08015]). Also, the search for the process of two neutrino double electron capture on ^{36}Ar is ongoing.

NA65/FASER

In the NA65 experiment a successful physics run with 17 W-emulsion modules exposed at 400 GeV/c SPS proton beam was conducted in 2022. Data analysis of the 2021 run is ongoing. A paper on the detector performance based on the primary proton interaction studies is under preparation. Software analysis instruments for proton interaction vertex reconstruction is under development by JINR group.

FASER had a successful first run, collecting ~40 fb^{-1}. All indicators of detector performance and data quality are positive, and data reprocessing will take place once all final calibrations, alignment, magnetic map and software improvements are implemented.

The FASERν detector had an equally successful run, with the exposure of 3 sets of emulsions, covering the initial phase of the run (0.5 fb^{-1}), and two successive periods of high luminosity (~10 and ~30 fb^{-1}, respectively). The first two modules have been developed and analyzed, showing excellent track resolution ($\sigma(\Delta x,y)=0.2\mu m$) and an overall track density consistent with simulation. According to simulations, a total of about 2000 LHC neutrino interactions are expected to emerge from the analysis of the full dataset. JINR group works on the data analysis and development of the system of detector thermic stabilization.

2.2.2. Key publications (list of bibliographic references) including collaboration papers with principal contribution by the JINR authors and small author list papers.

1. Abuselme A.,..., Gonchar M.,..., Malyshkin Yu. et al., Sub-percent precision measurement of neutrino oscillation parameters with JUNO, e-Print: 2204.13249 [hep-ex], Published in: Chin.Phys.C 46 (2022) 12, 123001
2. JUNO Collaboration, JUNO physics and detector, e-Print: 2104.02565 [hep-ex], Published in: Prog.Part.Nucl.Phys. 123 (2022), 103927
3. An F.P.,..., Dolzhikov D.,..., Gonchar M.,..., Naumov D.,..., Olshevkiy A.,..., Treskov K.,..., Zavadskyi V. et al., Precision measurement of reactor antineutrino oscillation at kilometer-scale baselines by Daya Bay, e-Print: 2211.14988 [hep-ex], submitted to PRL.
4. Angel Abusleme,..., Dmitrievsky S.,..., Gornushkin Yu.,..., Korablev D. et al., The JUNO experiment Top Tracker, e-Print: 2303.05172 [hep-ex], to be submitted.
5. Arsenii Gavrikov, Yury Malyshkin, Fedor Ratnikov (Higher Sch. of Economics, Moscow and Dubna, JINR), Energy reconstruction for large liquid scintillator detectors with machine learning techniques: aggregated features approach, e-Print: 2206.09040 [physics.ins-det], Published in: Eur.Phys.J.C 82 (2022) 11, 1021, Eur.Phys.J.C 82 (2022), 1021
6. Xu H.,..., Anfimov N.,..., Gromov M.,..., Rybnikov A. et al., Calibration strategy of the JUNO-TAO experiment, e-Print: 2204.03256 [physics.ins-det], Published in: Eur.Phys.J.C 82 (2022) 12, 1112
7. Bieger L.,..., Gromov M.,..., Smirnov O. et al., Potential for a precision measurement of solar pp neutrinos in the Serappis experiment, e-Print: 2109.10782 [physics.ins-det], Published in: Eur.Phys.J.C 82 (2022) 9, 779
8. Qian Z.,..., Gavrikov A.,..., Gonchar M.,..., Malyshkin Yu.,..., Treskov K. et al., Vertex and energy reconstruction in JUNO with machine learning methods, e-Print: 2101.04839 [physics.ins-det], Published in: Nucl.Instrum.Meth.A 1010 (2021), 165527
9. O. Smirnov, D. Korablev, A. Sotnikov et al., Magnetic shielding for large photoelectron multipliers for the OSIRIS facility of the JUNO detector, e-Print: 2212.02562 [physics.ins-det], submitted to JINST.
10. A. Stepanova (Dubna, JINR), M. Gonchar (Dubna, JINR), L. Kolupaeva (Dubna, JINR), K. Treskov (Dubna, JINR), Deep Underground Neutrino Experiment DUNE—Calculation of Sensitivity to the Measurement of Oscillation Parameters, Published in: Phys.Part.Nucl.Lett. 19 (2022) 5, 505-508

11. Rybnikov, A.V., Anfimov, N.V., Fedoseev, D.V. et al. Optical Fiber Splitter for Photodetector Testing. Phys. Part. Nuclei Lett. 19, 797–802 (2022). https://doi.org/10.1134/S1547477122060255
12. Abusleme, A.,..., Anfimov N,. et al. Mass testing and characterization of 20-inch PMTs for JUNO. Eur. Phys. J. C 82, 1168 (2022). https://doi.org/10.1140/epjc/s10052-022-11002-8
13. L. Kolupaeva, O. Samoylov "Study of Neutrino Oscillations in the NOvA Experiment", Yad.Fiz. 84 (2021) 1, 48-52
14. A. Sheshukov, A. Vishneva, A. Habig "Combined detection of supernova neutrino signals" *JCAP* 12 (2021) 12, 053
15. M. A. Acero et al. (NOvA Collaboration) "Search for Slow Magnetic Monopoles with the NOvA Detector on the Surface", Phys. Rev. D 103, 012007
16. 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
17. 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)
18. 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)
19. 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
20. V Hewes at el (Dune Collaboration) "Deep Underground Neutrino Experiment (DUNE) Near Detector Conceptual Design Report" Instruments 5 (2021) 4, 31
21. Luis Alvarez-Ruso et al (GENIE Collaboration) "Recent highlights from GENIE v3" Eur.Phys.J.ST 230 (2021) 24, 4449-4467
22. I.Kakorin, K.Kuzmin "Resonance axial-vector mass from experiments on neutrino-hydrogen and neutrino-deuterium scattering" Phys.Rev.D 104 (2021) 9, 9
23. 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
24. 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
25. 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
26. M. Acero et al (NOvA Collaboration) "Improved measurement of neutrino oscillation parameters by the NOvA experiment" Phys.Rev.D 106 (2022) 3, 032004
27. 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
28. Julia Tena-Vidal et al (GENIE Collaboration) "Neutrino-nucleus $CC\pi_0$ cross-section tuning in GENIE v3", Phys.Rev.D 106 (2022) 11, 112001
29. 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
30. 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
31. 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)

32. A.Olshevskiy “Results of Neutrino Oscillations and the Search for Sterile Neutrino States” accepted to be published in PEPAN letters (2023)
33. A. Stepanova, L. Kolupaeva «Joint fit of long-baseline accelerator neutrino experiments in GNA software», sent to PEPAN Letters (2023)
34. S.Appel et al., Improved measurement of solar neutrinos from the Carbon-Nitrogen-Oxygen cycle by Borexino and its implications for the Standard Solar Model, Phys. Rev. Lett. 129 (2022) 25, 252701
35. M.Agostini et al., First Directional Measurement of sub-MeV Solar Neutrinos with Borexino Phys.Rev.Lett. 128 (2022) 9, 091803
36. M.Agostini et al., Correlated and Integrated Directionality for sub-MeV solar neutrinos in Borexino, Phys.Rev.D 105 (2022) 5, 052002
37. S.Appel et al., Search for Low-Energy Signals from Fast Radio Bursts with the Borexino Detector, Eur.Phys.J.C 82 (2022) 3, 278
38. S. Appelet et al. (BOREXINO collaboration), Independent determination of the Earth’s orbital parameters with solar neutrinos in Borexino, Astroparticle Physics Volume 145, March 2023, 102778
39. P.Agnes et al., A study of events with photoelectric emission in the DarkSide-50 liquid argon Time Projection Chamber, Astropart. Phys. 140 (2022) 102704
40. F.P.An et al, Precision measurement of reactor antineutrino oscillation at kilometer-scale baselines by Daya Bay, https://arxiv.org/abs/2211.14988
41. Gromov M., Westerdale S., Goncharenko I., Chepurnov A. (α, n) and (α, $n\gamma$) yield calculations with a new version of NeuCBOT for low background experiments. Phys. At. Nucl. **86** (2) (2023) 1-8.

42. Zykova M. et al. Hybrid Ultra-Low-Radioactive Material for Protecting Dark Matter Detector from Background Neutrons. Materials. **14** (13) (2021). 3757.

43. Agafonova, N. et al. (OPERA Collaboration) «OPERA tau neutrino charged current interactions», *Sci Data* 8, 218 (2021).
44. Agafonova, N. et al. «Updated constraints on sterile neutrino mixing in the OPERA experiment using a new *ve*identification method», PTEP **3**(2023) 033C01
45. H. Abreu et al. (FASER Collaboration), «The trigger and data acquisition system of the FASER experiment», *JINST* 16 (2021) P12028
46. H. Abreu et al. (FASER Collaboration), «The tracking detector of the FASER experiment», Nucl. Instrum. Methods Phys. Res., A 1034 (2022) 166825 2303.14185

2.2.3. A complete list of publications on the theme (electronic annex) comprises ~ 90 publications.

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

1. V.Sharov ”Development of a multi-channel power supply for the TAO and DUNE experiments”, AYSS-2021, 13.10.2021 (oral talk)
2. 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.
3. 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)
4. Y.M. Malyshkin, plenary, “Status and Physical Potential of JUNO”, NUCLEUS 2021, remote, September 1−11, 2021
5. Y.M. Malyshkin, parallel, “Application of machine learning techniques for event reconstruction in JUNO”, NuFact 2021, Cagliari/online, Italy, September 6−11, 2021.
6. Y.M. Malyshkin, parallel, “Oscillation Physics in JUNO”, NeuTel 2021, online, February 18-26, 2021.

7. M. Gonchar, parallel, "GNA: data flow approach for the neutrino oscillation experiments", Innovative Workflows in Astro and Particle Physics IWAPP (remote), March 8−12, 2021.
8. M. Gonchar, parallel, "Neutrino Oscillation Physics in JUNO", European Physical Society conference on high energy physics EPS-HEP 2021 (remote), July 26-30, 2021
9. M. Gonchar, plenary, "The JUNO experiment: status and prospects", Nucleus-2022, Moscow, 11−16 July, 2022
10. V. Zavadskyi, poster, "Search for Sterile Neutrinos with JUNO-TAO", Neutrino 2022, May 30−June 4, 2022 (remote).
11. D. Dolzhikov, poster, "JUNO Neutrino Mass Ordering Sensitivity with Subdetectors", 57th meeting of the PAC for Particle Physics, Dubna, 2023.
12. L. Kolupaeva, "Current status and future prospects of three flavor neutrino oscillations", AYSS-2021, 11-15 Oct, Almaty, Kazakhstan (Hybrid Event). (invited plenary talk)
13. 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)
14. 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)
15. N.V. Anfimov, "Liquid-argon TPC of the near detector of the DUNE experiment", DLNP JINR seminar, May 20, 2021
16. 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. (oral talk)
17. 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
18. V.Sharov "Development of a multi-channel power supply for the TAO and DUNE experiments", AYSS-2021, 13.10.2021 (oral talk)
19. S. Sokolov "Light detection system prototype for DUNE Near Detector TPC", AYSS-2021, 13.10.2021 (oral talk)
20. 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
21. 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
22. 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)
23. 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)
24. A. Sheshukov, "Neutrino signals of the next galactic supernova" 06 June 2022, JINR AYSS Conference "Alushta-2022" (oral talk)
25. A. Sheshukov, "SuperNova Early Warning System", ICPPA-2022, 29.11-02.12.2022, Moscow, Russia (poster talk)
26. 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.
27. 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

28. 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
29. 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
30. 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
31. 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
32. O. Samoylov “Study of neutrino oscillations in NOvA/DUNE accelerator experiments” DLNP Seminar March 16, 2023
33. 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
34. 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
35. 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
36. 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
37. L. Kolupaeva “JINR neutrino program”, seminar at INP, Almaty, Kazakhstan, 5.01.23
38. O.Smirnov, “Unveiling the engine of the Sun: measurements of the pp-chain solar neutrinos with Borexino”, Sixteenth Marcel Grossmann Meeting, MG16 Virtual Meeting - July 6, 2021
39. A.Vishneva “First detection of solar neutrinos from the CNO cycle of thermonuclear reactions” AYSS Conference «Alushta-2022» 5-12 June 2022
40. A.Vishneva “Borexino experiment and its impact to neutrino physics ” 18th Rencontres du Vietnam 17-23 June 2022
41. A.Vishneva “Detection of solar neutrinos from the CNO cycle with Borexino” ICPPA-2022, 29 Nov - 2 Dec 2022
42. Lychagina O.E. Evaluation of the sensitivity of the DarkSide-50 experiment to two neutrino double K-capture on ^{36}Ar. ICPPA-2022, 29.11-02.12.2022. Moscow. (Oral presentation, parallel
43. Lychagina O.E. Evaluation of the sensitivity of the DarkSide-50 experiment to two neutrino double K-capture on ^{36}Ar. AYSS-2022, 24-28.10.2022. Dubna. (Oral presentation)
44. Westerdale S., Gromov M., Goncharenko I., Chepurnov A. (α, n) and $(\alpha, n\gamma)$ yield calculations with a new version of NeuCBOT for low background experiments. Nucleus-2022. 11-16.07.2022. Moscow. (Oral presentation, parallel session)
45. Vasina on behalf of the DsTau (NA65) Collaboration «Study of tau neutrino production with nuclear emulsion at CERN-SPS», 17th International Conference on Topics in Astroparticle and Underground Physics (TAUP 2021), Valencia (online), Spain (online)
46. S. Vasina on behalf of the FASER Collaboration «Status of the FASER experiment at LHC», 6th International Conference on Particle Physics and Astrophysics (ICPPA 2022), Moscow Engineering Physics Institute, Moscow, Russia
47. Miloi M. M. on behalf of DsTau collaboration, ”The DsTau experiment: measuring the tau-neutrino production cross section” (2021) 57th Karpacz Winter School of Theoretical Physics and PHAROS COST Action CA16214 Training School – ”Equation of state of dense matter and multi-messenger astronomy”, Karpacz-Poland, 19 June - 26 June

48. Miloi M. M. on behalf of DsTau collaboration, ”The DsTau experiment: measuring the tau-neutrino production cross section” (2021), 21st JINR-ISU Baikal Summer School on Physics of Elementary Particles and Astrophysics, online, 12 July - 19 July
49. Yu. Gornushkin "Study of tau neutrino production in NA65 experiment at CERN SPS" 20th Lomonosov Conference, 19-25 August 2021, Moscow

2.2.5. Patent activity (if any).

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2.3 Results of related activities

2.3.1. Scientific and educational activities. List of theses defended.

1. A. Olshevsky is full professor at Moscow State University (2003 — ongoing) with “Modern research in elementary particle physics.” semi-annual courses.
2. D. Naumov is full professor at Moscow State University with an annual course on the Standard model.
3. Anfimov is associate professor at Dubna University (2021 — ongoing) with “Nuclear electronics” and “Electronics in physics” semi-annual courses.

Defended dissertations:

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. Gavrikov, “Machine Learning Methods for the Event Energy Reconstruction: JUNO Experiment”, HSE, 2022, master’s degree.
2. A. Stepanova “Deep underground accelerator neutrino experiment DUNE - calculation of sensitivity to the measurement of oscillation parameters”, Moscow State University, 2021, bachelor’s degree
3. M. Strizh, “Daya Bay Determination of the arrival direction of antineutrino from a reactor – model and data analysis of the Daya Bay experiment”, MSU, 2021, master’s degree.
4. A. Shaydurova “Application of the Magnus expansion for the calculation of the oscillation probabilities of atmospheric neutrino”, Moscow State University, 2021, master’s degree.
5. V. Zavadskyi “Search for the sterile neutrinos in the Daya Bay and JUNO experiments”, MIPT, 2021, master’s degree.
6. E. Sitnikova “Development of an algorithm for searching decays of short-living particles in the DsTau (NA65)”, MIPT, 2021, master’s degree.
7. Yu. Ivaneev “A Study of the Cherenkov Light Contribution to the Liquid Scintillator Response Nonlinearity”, MSU, 2022, bachelor’s thesis
8. A. Pobedimov “A study of the possibility to register the atmospheric neutrino events in the NOvA experiment”, MSU, 2022, master’s thesis
9. Lychagina O.E. “Evaluation of the sensitivity of DarkSide-50 experiment to two-neutrino double K-capture on Ar-36” MSU, master's thesis, 2022
10. A. Stepanova "Calculation of determination of neutrino oscillation parameters precision in long-baseline accelerator neutrino experiments", Moscow State University, 2023, master's degree

2.3.2. 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 grant in 2023
4. V. Sharov — AYSS grant in 2022
5. M. Zavadskyi — AYSS grant in 2023
6. A.Stepanova - AYSS grant in 2022
7. L.Kolupaeva - AYSS grant in 2020, DLNP’s Bruno Pontecorvo scholarship in 2021

2.3.3. Awards and prizes.

1. JINR First Prize for 2021 in the nomination "Research Experimental Works": "Neutrino studies in the OPERA experiment" — S.Vasina, Yu. Gornushkin, S.Dmitrievsky, et al.
2. 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
3. A. Stepanova: best report at Young Scientist Forum Moscow International School of Physics 2022, 24.07.2022 - 02.08.2022, Dubna, Moscow region
4. 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)

2.3.4. Other results (expert investigations, organizational, outreach activities).
Expert activities:

D.Naumov and A.Olshevskiy are section editors in PEPAN Letters and experts in grants awarding committees.
N. Anfimov is a reviewer in: Nuclear Instruments and Methods in Physics Research, A — 4 assignments; Instruments, MDPI — 1 assignment; PEPAN Letters — 4 assignments.
A. Selyunin is a reviewer in PEPAN Letters — 2 assignments

Scientific organizational 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), Executive Committee member of the NOvA Collaboration (2023- ongoing);
4. A.Antoshkin - ROC-Dubna liaison (2017-ongoing);
5. M.Gonchar - Executive and Institutional Board member in Daya Bay; Speaker’s Committee member, Online Event Classification group co-convener.
6. D. Naumov - Executive and Institutional Board member in JUNO, JUNO Publication Committee member, Remote Shift and Maintenance taskforce leader,.
7. A.Olshevskiy - PMT Instrumentation L2 manager in JUNO and Institutional Board representative in NOvA and DUNE.
8. O. Smirnov - convener of low energy neutrino analysis group in Borexino

Outreach:

1. Regular excursions to the Green laboratory facilities — A.Selyunin, A.Antoshkin, V. Sharov, N.Anfimov
2. Festival of Science and Technology “Techno Environment 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
10. Seminar “Information technologies in JUNO experiment”, IT School on Data Science, 2021, MLIT — M. Gonchar
11. “Neutrino Geophysics”, Popular Science Lecture, April 27, 2021 -O . Smirnov,
12. “DLNP Neutrino Program”, several lectures for schoolchildren - O. Smirnov
13. “Search for dark matter particles with dual-phase Time Projection Chambers”, seminar of the Department of Elementary Particle Physics, Faculty of Physics, Lomonosov Moscow State University. 15.11.2022 - M. Gromov

3. International scientific and technical cooperation

The countries, institutions and organizations actually involved.

Organization	**Country**	**City**	**Participants**	**Type of agreement**
IHEP	China	Beijing	Yifang Wang + 10	JUNO MoU
SYSU	China	Guangzhou	Wei Wang + 10	JUNO MoU
SINP MSU	Russia	Moscow	Alexander Chepurnov, Maxim Gromov	JUNO MoU
INFN	Italy	Catania, Rome	Giuseppe Adronico +1 Stefano Maria Mari +1	JUNO MoU JUNO MoU
FZJ-IKP	Germany	Jülich	Livia Ludhova +4	JUNO MoU
EKUT	Germany	Tübingen	Tobias Lachenmaier +1	JUNO MoU
FNAL	USA	Batavia, IL	Alex Himmel + 3 Jennifer Raaf + 4	JINR-FNAL agreement extension
University of Bern	Switzerland	Bern	Michele Weber + 2	Consortium agreement
CERN	Switzerland		Francesco Lanni, Filippo Resnati	Neutrino 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	DUNE Collaboration

			Jianming Bian	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

4. Analysis of planed vs actually used resources: manpower (including associated personnel), financial, IT, infrastructure

4 .1. Manpower (actual at the time of reporting)

No.	Personnel category	JINR staff, FTE amount	JINR associated personnel, FTE amount
1.	research scientists	**30**	
2.	engineers	**10**	
3.	students	**-**	**13**
	Total:	**40**	**13**

4.2. Actual cost of the Theme

No.	Items of expenditure	Full cost (thousands of US dollars)	Expenditure for the last year, (thousands of US dollars)
1.	International cooperation	480	130
2.	Materials	1230	300
3.	Equipment, Third-party company services	1200	270
4.	Commissioning	-	-
5.	R&D contracts with other research organizations	100	30
6.	Software purchasing	120	25
7.	Design/construction	75	30
8.	Service costs (*planned in case of direct project affiliation)*	-	-
TOTAL:		**3205**	**785**

4.3. Other resources

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5. Conclusion

During the previously approved period of time the theme objectives were successfully fulfilled. Detector construction and preparation for data taking and analysis of the major mega-science class liquid scintillator detector JUNO is well on track with the significant contribution from JINR.

The JINR physicists also made an essential contribution to the results obtained by the NOvA experiment, which will continue data taking through 2026 and will be substituted by significantly larger mega-science scale DUNE experiment, where the JINR team will apply experience gained in NOvA.

For the DUNE project the JINR team is planning to make two main contributions to the near detector construction: light collection system of the liquid argon calorimeter modules and straw tracker of the on-axis detector. Both contributions are well motivated by the JINR expertise and experience.

In addition, several small-scale activities are performed, supporting continuation of Borexino and Dark Side data analysis and participation in the NA65/FASER(v) experiment.

6. Proposed reviewers

JUNO project - Evgeniy YAKUSHEV

NOvA/DUNE project - Vladimir KARJAVINE
Theme 1099 - Evgeniy YAKUSHEV

Theme leader(s):

_____________/D.Naumov /
"_____"_________________ 2023г.

_____________/A.Olshevskiy /
"_____"_________________ 2023г.

Project leader (project code)

_____________/D.Naumov /
"_____"_________________ 2023г.

Project leader (project code)
(in case of several projects)

_____________/A.Olshevskiy /
"_____"_________________ 2023г.

Laboratory Economist

____________/__________________/
"_____"_________________ 2023г.