Report

on the results of the research theme

02-2-1099-2010/2018

and extension request for 2019-2021

1. Abstract

The research theme 02-2-1099-2010/2018 comprises the studies of neutrino oscillation phenomenon performed in three projects and several activities. All the projects were recently extended by PAC for respective periods: DB/JUNO (2018-2020), NOvA (2018-2020) and Borexino (2019). Apart from the general precision measurement of oscillation parameters and search for new (sterile) oscillation channels, the priority of the theme research is on determination of neutrino mass ordering (hierarchy), lepton CP-violation and measurement of the Solar neutrino fluxes. Additional activities of the theme are aimed to support final analysis and publications of OPERA experiment, R&D on photodetectors and feasibility studies of JINR participation in dark matter search (DarkSide) and DUNE project as a future continuation of oscillation physics program.

2. Introduction

Being itself a beautiful quantum mechanical phenomenon, the neutrino oscillations can be also used as a precision tool to get new information on the Standard Model and Beyond. One of the neutrino physics priorities of nowadays - neutrino mass ordering (MO) determination - is the goal of several contemporary projects, which attack this problem in two different ways. First of all, neutrino vacuum oscillations do depend on MO, so, precision measurement of oscillation picture can already provide this important information.

Such an approach is followed by the JUNO project, where reactor antineutrino disappearance will be studied at an optimal distance of 53 km with the unique 20 kt liquid scintillator detector being constructed by international collaboration in China. Based on a very successful experience of participation in the Daya Bay experiment, the JINR group is significantly involved in the JUNO detector construction and preparation for the data analysis. The JUNO detector is due by the year 2020 and in 6 years it is planned to reach statistical significance of ~3-4 sigma on the MO determination.

The second method is to measure neutrino oscillations in matter, which depend on MO in a unique way. At the same time matter effect also depends on the size of a lepton CP violation and both dependencies in this measurement come into interplay.

At present, such an approach is exploited by the Fermilab long baseline neutrino experiment NOvA, which started its operation in 2014 with the 14 kt Far detector at a distance of 810 km from the neutrino production area. By the year 2024 the sensitivity of NOvA to the MO determination is expected to be ~ 4 sigma and also ~ 2 sigma level is expected for measurement of CP violating phase parameter.

As a continuation of this line the DUNE project is anticipated by the international community aiming to disentangle those effects and reach unambiguous conclusions on MO and CP collecting the data after the start around 2025. The JINR group in NOvA already performed an important hardware studies used for better understanding of the detector performance and is developing the basic oscillation as well as additional (SN, Monopole, etc.) physics subjects analyses.

It is clear that finally the best knowledge on MO (and CP) will come from the combination of two approaches mentioned above. Being involved in the analysis details of both JUNO and NOvA experiments we are already developing the global neutrino analysis tools to perform the combination task.

The Borexino detector has already proven to register sub-MeV neutrinos in real time, performing direct observations of ^{7}Be, pep, pp and ^{8}B solar neutrinos. The most important task for Borexino remains the measurement (or constraining) of the CNO-neutrino flux. Another important task will be an improvement of geo-neutrino flux measurement. In addition, precision of the pp-neutrino flux measurement can still be improved down to 6-7%.

3. Present status and results obtained

With the discovery and precise measurement of a non-zero θ_{13} mixing angle the neutrino physics has entered a new era of tackling the problems of neutrino mass hierarchy and lepton CP violation. An important role in this measurement was played by the Daya Bay experiment, which first has announced the 5 sigma discovery and has now the most precise measurement as well. The present status of θ_{13} mixing angle measurement is presented in Fig.1.

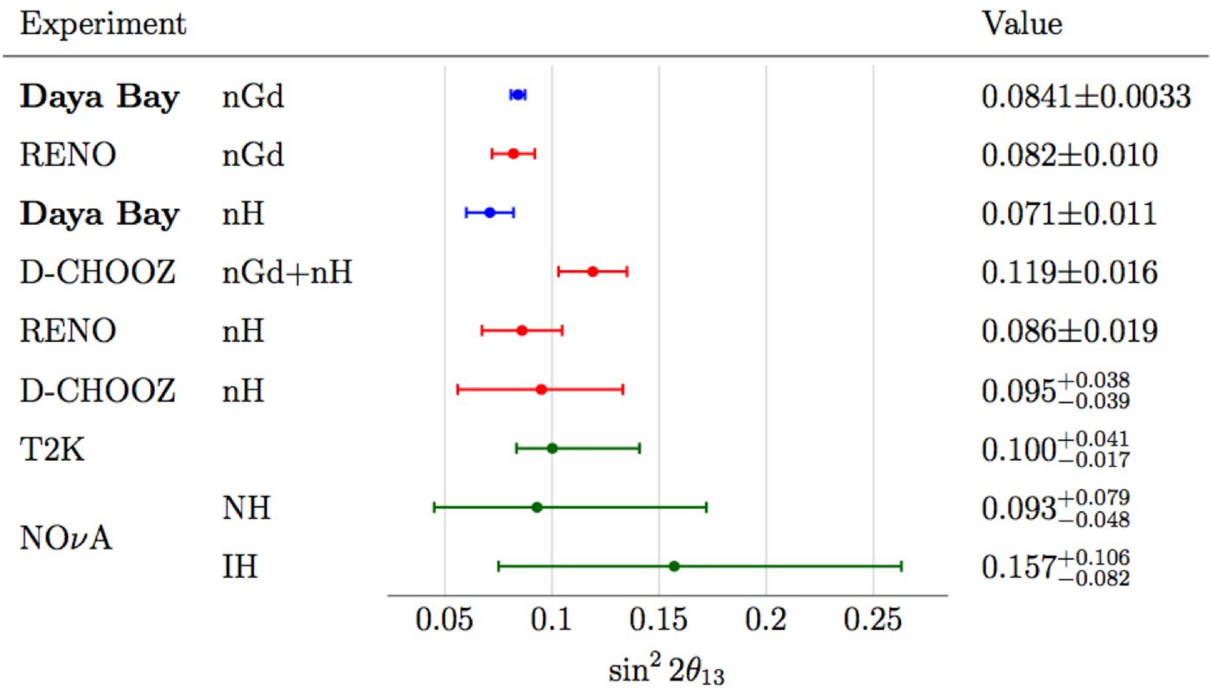

Figure 1. Status of θ_{13} measurement.

The JINR group takes part in the Daya Bay experiment since 2007. The contribution includes: suggestion of the muon veto system based on plastic scintillator, production and purification of the scintillation additive PPO for the liquid scintillator, event selection, background estimation and data analyses.

In order to analyze Daya Bay data our group has developed its own fitter. The fitter is being used in parallel analyses since beginning of the data taking leading to a discovery of the non-zero value of the θ_{13} mixing angle.

The JINR contribution to the data analysis is significant and is recognized by the collaboration. The latest published most precise measurement of the oscillation parameters θ_{13} и Δm^2_{32} is based on the analysis of the JINR group (**Phys.Rev. D95 (2017) no.7, 072006**). The most precise Daya Bay measurement of L/E oscillation dependence is presented in Fig.2.

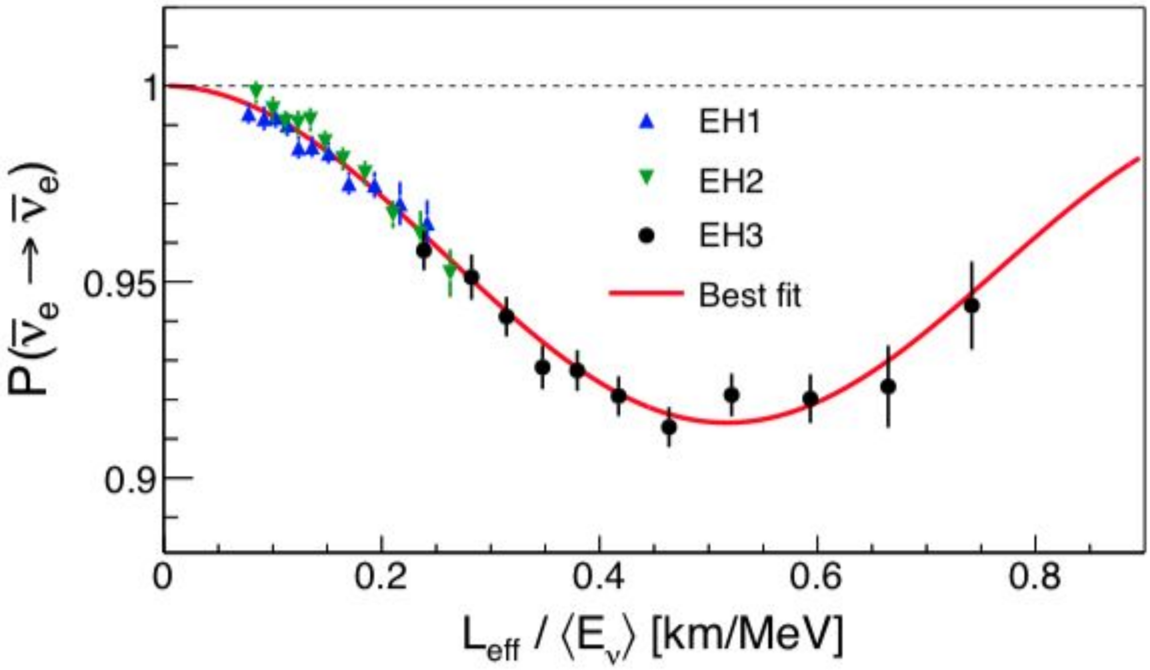

Figure 2. Daya Bay measurement of L/E oscillation dependence.

Also the JINR group has suggested and carried out the analysis which set the first limits on the decoherence of reactor neutrino oscillations (**Eur.Phys.J. C77 (2017) no.9, 606**).

Daya Bay Collaboration (including JINR members) have received multiple awards including Breakthrough prize in Fundamental Physics 2016 and JINR Prize 2012.

NOvA is a new generation experiment studying oscillations of muon to electron flavor neutrinos. The NOvA complete 14 kton Far Detector and 220 ton Near Detector have been taking data since 2014, and a number of important measurements have been performed on the basis of statistics collected so far (Fermilab JETP seminar. Jan. 12, 2018. Talk). The results from NOvA data corresponding to the neutrino beam exposure of ~9x1020 POT (Protons on Target) are presented in Fig.3.

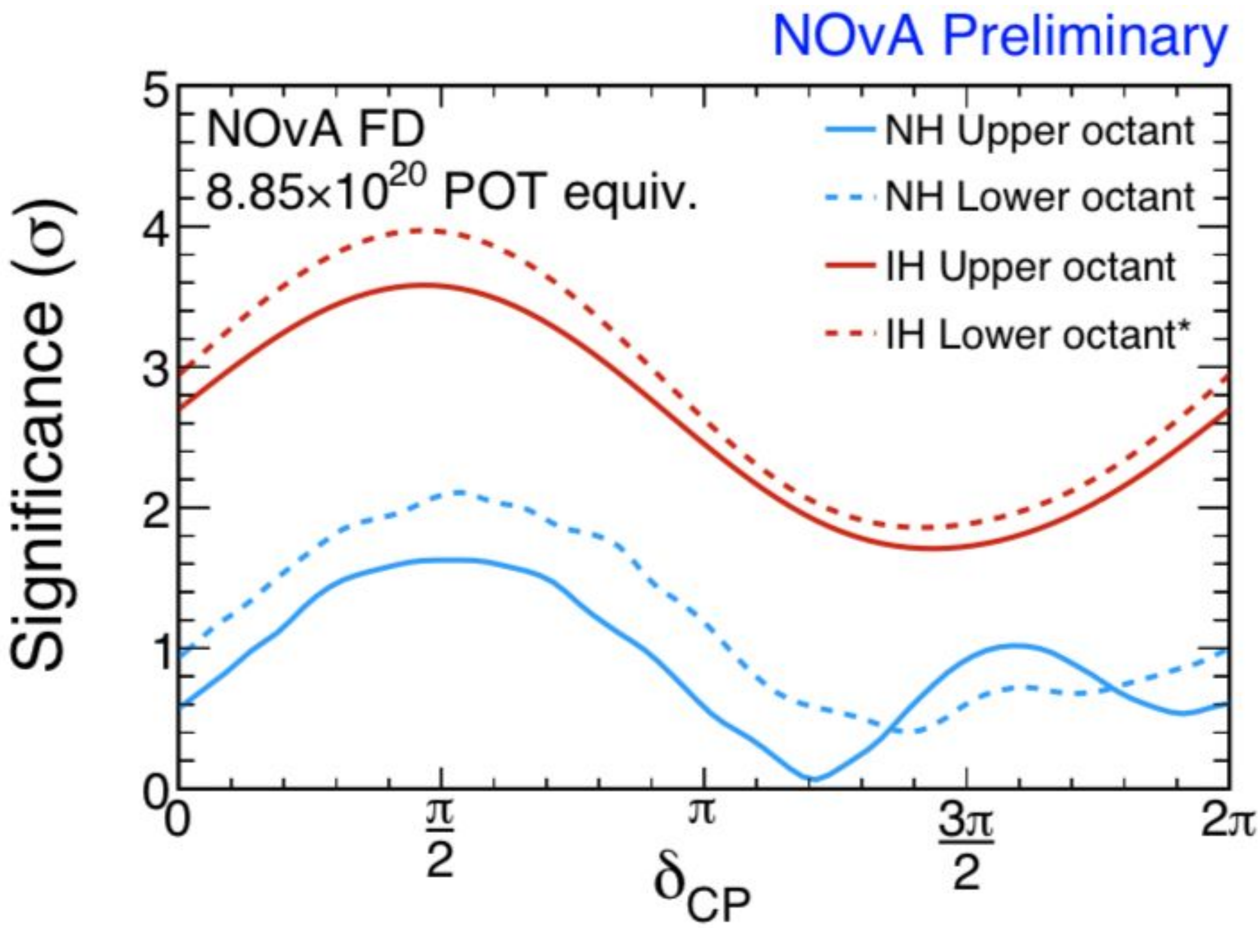

Figure 3. NOvA recent results for MO and CP.

At present NOvA is closely approaching the 2 sigma level of excluding Inverse Hierarchy (IH) for all values of CP violation parameter. Continuing the data collection, and importantly, altering neutrino and antineutrino beams, NOvA can largely improve its sensitivity.

The JINR group in NOvA has contributed significantly to the NOvA results. The Remote Operation Center (ROC-Dubna) was developed at JINR, giving the possibility to fully participate in the data taking and quality monitoring. The scheme of the ROC-Dubna Remote Operation Center is presented in Fig.4.

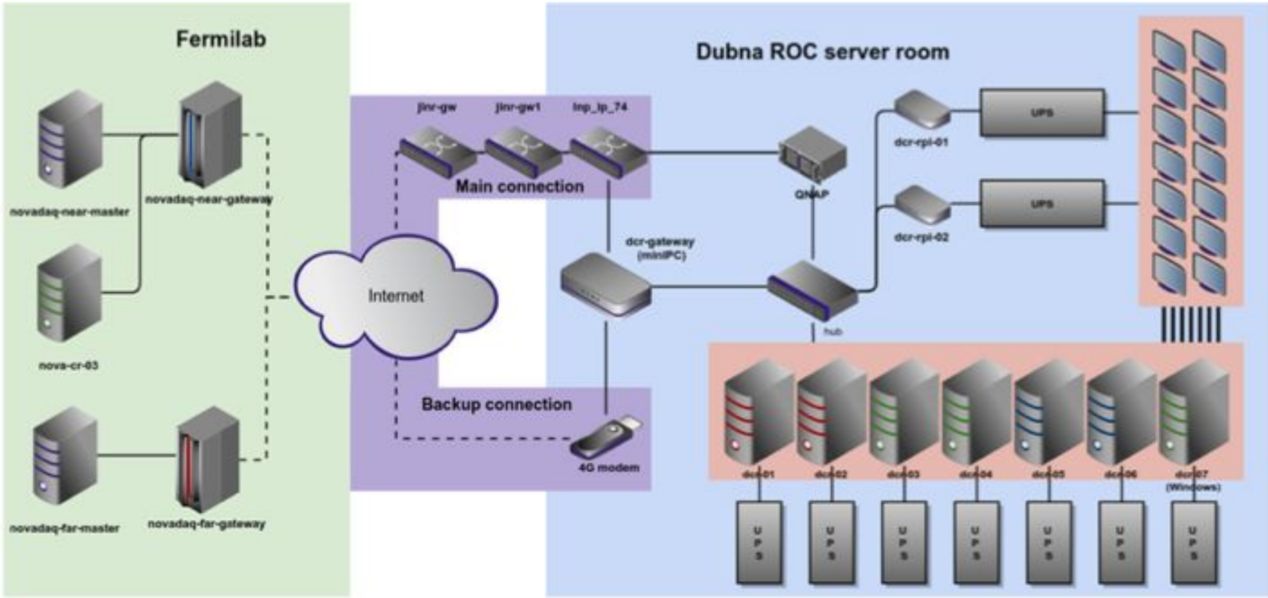

Figure 4. NOvA ROC-Dubna scheme.

The JINR computer infrastructure on the basis of GRID and Cloud technologies was developed. It is efficiently used for the home-based running of jobs and is also a part of the NOvA distributed computing resources system for the use at peak loads (e.g., before conferences). The NOvA electronics test bench was set up at JINR and provided important measurements of electronics parameters used for simulation and calibration.

Members of the JINR group are deeply involved in the ongoing analyses and in the preparation of new ones. This comprises the muon neutrino disappearance, electron neutrino appearance, search for Supernova, Slow monopole, Cosmic Ray and measurements in the Near Detector. They are also involved in the development of simulation and analyses software, and are serving as a Detector Simulation convener, Offline and DAQ Software Release Managers, DAQ, DDT and ROC experts, etc. Projected sensitivity of the NOvA detector to the Supernova burst is presented in Fig.5.

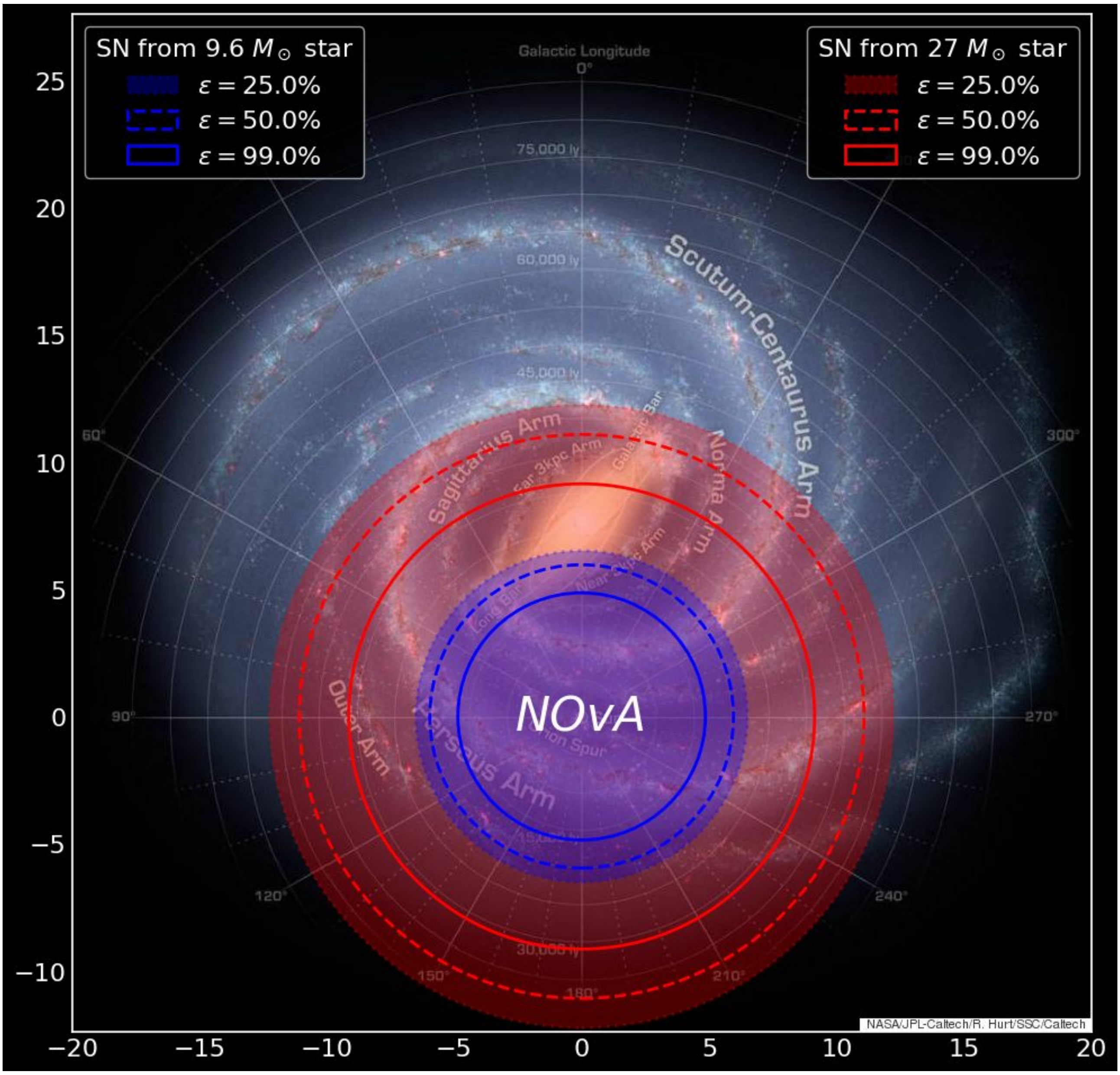

Figure 5. NOvA sensitivity to the Supernova burst.

Borexino is a unique detector able to perform measurement of solar neutrinos fluxes in the energy region around 1 MeV or below because of its low level of radioactive background. After several years of efforts and tests with the prototype CTF the design goals have been reached and for some of the radioactive isotopes (namely from the daughter isotopes from the decay chains of ^{238}U and ^{232}Th) largely exceeded.

Dubna scientists are working in the Borexino collaboration starting from the initial stage of the project. The group participated in the construction of a prototype of the Borexino detector, the Counting Test Facility (CTF), and its further exploitation (including the regular shifts during the data taking). The specific responsibility of the group were mainly the on-line software and the data analysis. Another significant contribution provided by Dubna group consisted in building and operating the so called PMT test facility used for testing all PMTs for the both CTF campaigns (200 PMTs in total) and Borexino (2400 PMTs in total). The PMT test facility is still in operation and will be used in a number of important tests for future developments.

Our group significantly contributed to the mainstream physics results, especially in the ^{7}Be neutrino flux analysis, antineutrino flux analysis (including geo-neutrino analysis, awarded the DLNP first prize for experimental work in 2013) and analysis of rare processes. We provided the major contribution to the pp-neutrino measurement, the result was awarded the JINR first prize for the best scientific work of 2014 and was selected by EPS experts to be one of the top 10 breakthroughs in physics in 2014. We provided also the major contribution to the work on the electric charge conservation and limit on the effective magnetic moment of neutrino. The so-called "analytical approach" in the Borexino solar neutrino analysis was developed by our group. Solar and geo neutrino fluxes as measured by Borexino detector are presented in Fig.6 and Fig.7, respectively.

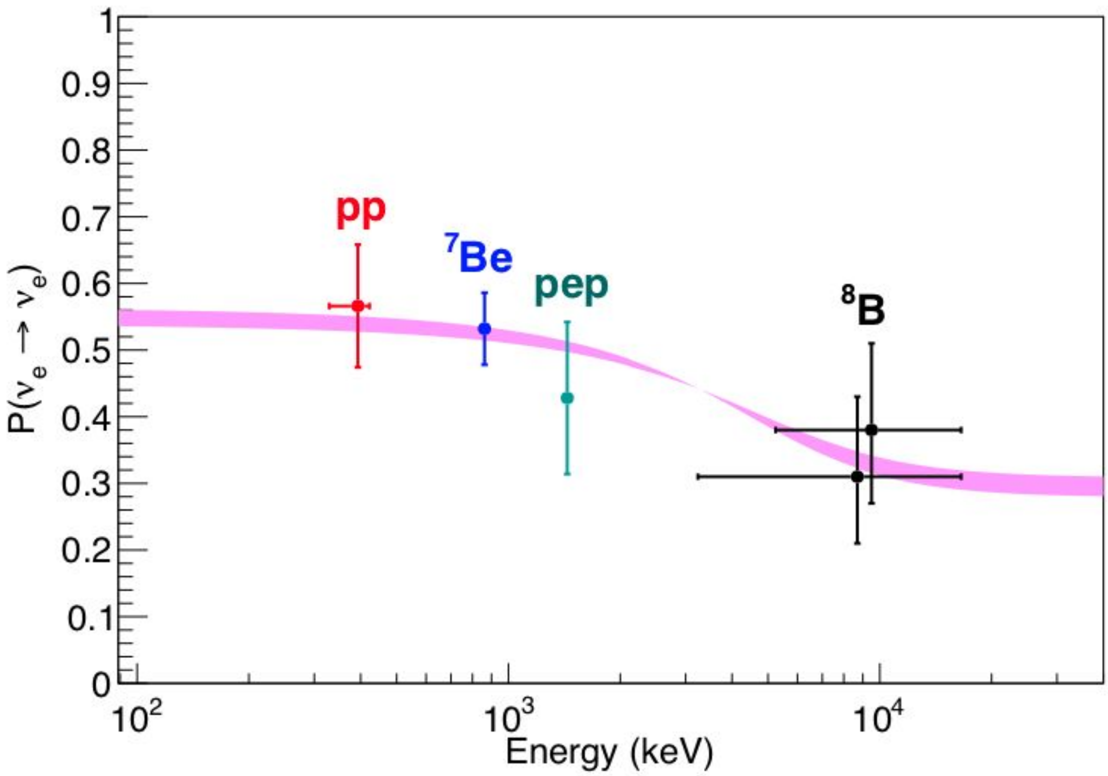

Figure 6. Borexino measurement of solar neutrino fluxes (arXiv:1707.09279).

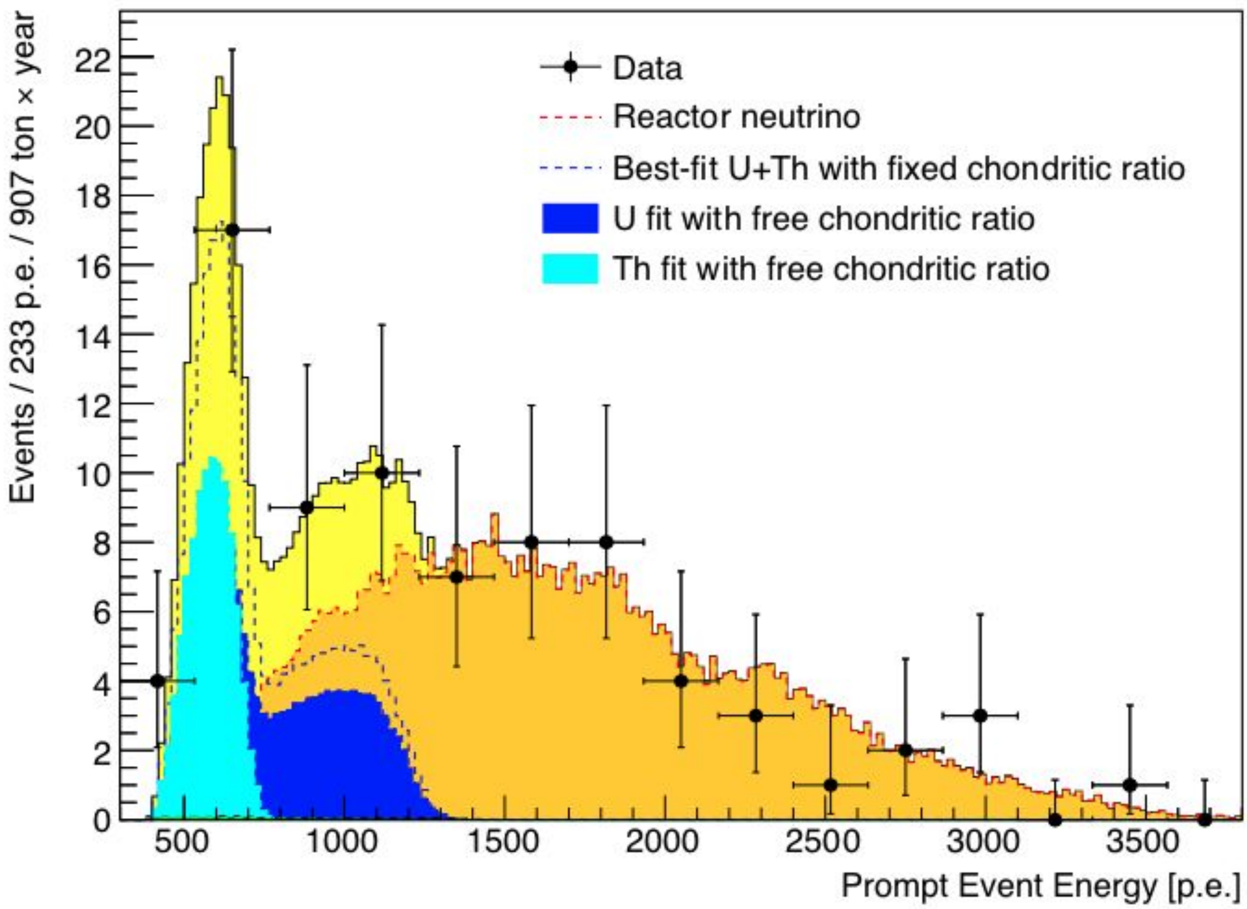

Figure 7. Borexino geoneutrino results (**Phys.Rev. D92 (2015) no.3, 031101**) .

The data taking of OPERA experiment has been completed and the result on the discovery of muon to tau neutrino oscillation was already published. The JINR group has contributed significantly to the Target Tracker detector construction, operation, data taking and to the physics analysis of the OPERA data. Final OPERA result was submitted for publication (https://arxiv.org/pdf/1804.04912.pdf) just now: 10 observed events with expected background of 2 events allowed OPERA to improve the significance of muon to tau neutrino oscillation observation in appearance mode to 6.1 sigma. In addition, an estimate of the tau neutrino CC cross section was performed with the OPERA data (see Fig.8).

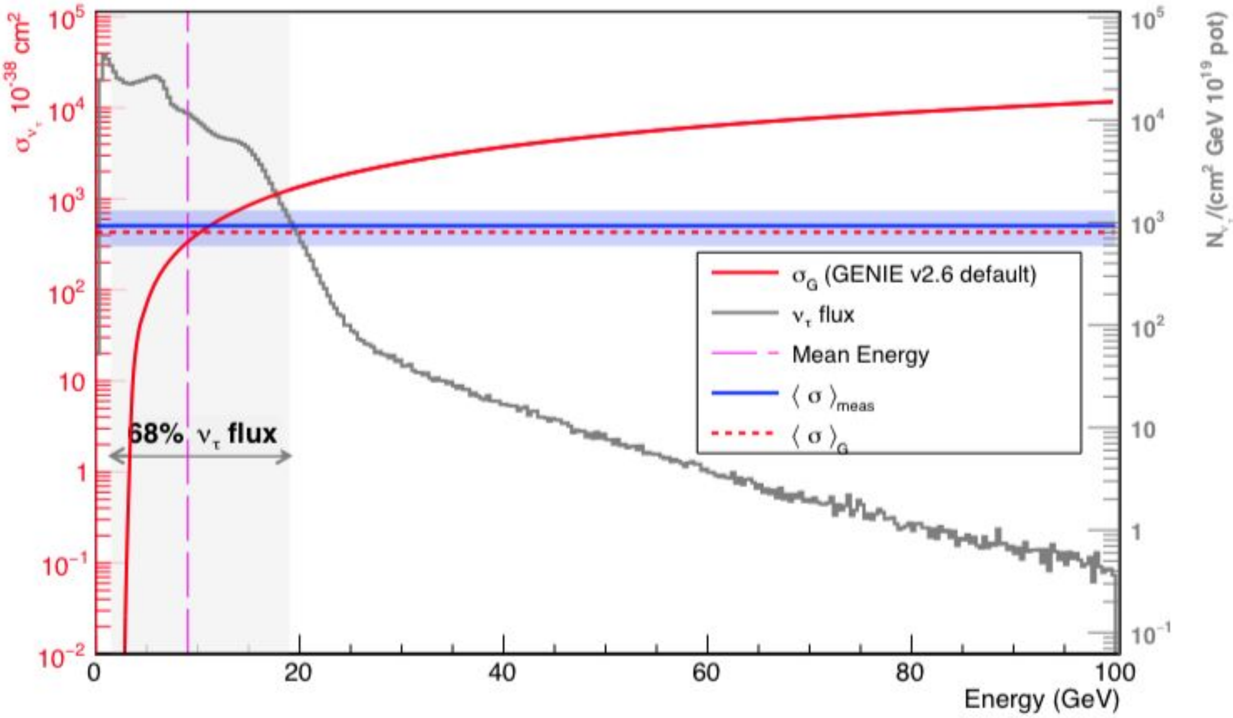

Figure 8. Flux-averaged measurement of the CC tau neutrino cross section on a lead target.

Several additional analyses and preparation of papers are now in progress. In particular, the JINR team was responsible for finalising and publishing of OPERA results on the muon to electron oscillation measurement (https://arxiv.org/abs/1803.11400), which was just submitted to JHEP. OPERA electron (anti) neutrino event results are presented in Fig.8 along with different components contributing to this measurements.

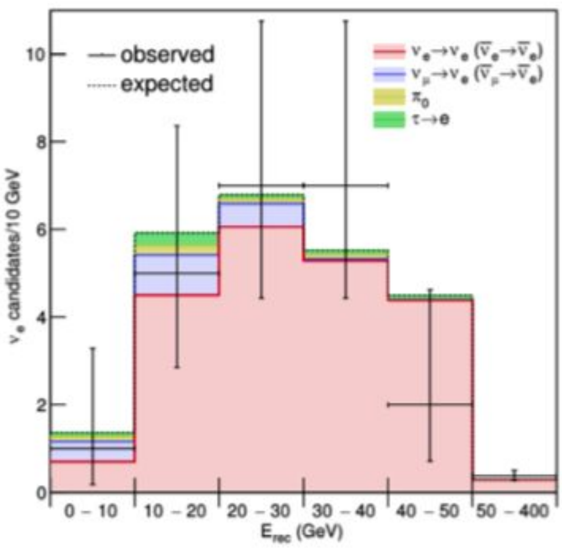

Figure 9. OPERA muon->electron neutrino oscillation result.

R&D activity on photo detectors performed in the framework of the research theme allowed the JINR group to be fully prepared for the tasks in future projects. In particular, for JUNO project this resulted in the development of the scanning station for PMT acceptance tests. In addition, the feasibility study for JINR participation in DUNE project has started recently. In this study we develop an option of scintillation light detection in liquid argon for DUNE near detector. The scheme of a first light collection prototype is presented in Fig.10.

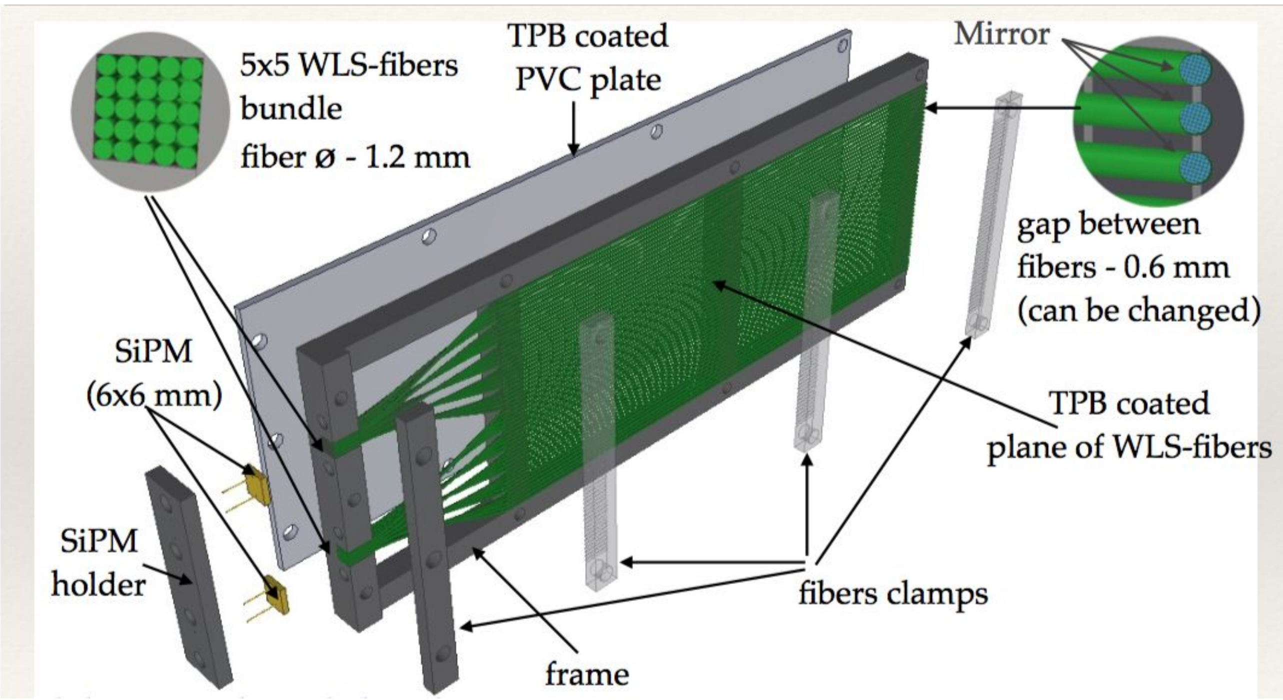

Figure 10. Design of a prototype for LiAr scintillation light readout.

4. Proposed research program

The details on the research program have been presented in separate projects approved recently by the JINR PAC on Particle Physics for extensions: DB/JUNO (2018-2020), NOvA (2018-2020) and Borexino (2019). In addition the research theme will include activities aimed to support final analysis and publications of OPERA experiment, R&D on photodetectors and feasibility studies of JINR participation in dark matter search (DarkSide) and DUNE project as a future continuation of oscillation physics program. In the following we present brief description of the JINR tasks in those projects and activities.

Our participation in the Daya Bay experiment will be concentrated on performing new oscillation analysis, measurement of reactor isotopes spectra, development of new methods of event selection and background estimations.

The JUNO project is now in the construction stage. The JINR group has a number of important contributions including:

— R&D and production of high voltage units for 20 000 PMTs of 20″ diameter and 25 000 PMTs of 3″ diameter.
— R&D and production of the precision muon Top Tracker based on the plastic scintillator technology.
— Development of methods for individual and mass testing of PMT.
— Detector simulation, reconstruction, events selection and background determination.
— Development of methods and software for the data analysis. Our group will take part in the oscillation data analysis in the JUNO experiment based on our best experience from Daya Bay.

Further running of the NOvA experiment will provide very competitive data for the measurement of neutrino mass ordering, CP-violation effects, disentangling the octants of θ_{23} mixing angle, among many others. There are also plans to extend NOvA data collection beyond 2020, which will further increase the physics potential of this experiment.

Members of the JINR group are deeply involved in the ongoing analyses and in the preparation of new ones. This comprises the disappearance of muon neutrino, appearance of electron neutrino, search for Supernova burst, Slow monopole, measurement of Cosmic Ray and neutrino cross sections in the Near Detector. We are also involved in the development of simulation and analyses software, and are serving as a Detector Simulation convener, Offline and DAQ Software Release Managers, DAQ, DDT and ROC experts, etc.

The JINR team is planning to continue and extend its involvement in the NOvA data taking and analyses. As a part of this work we are planning maintenance of ROC-Dubna and the hardware test bench facility, as well as a further increase of the NOvA computing power at JINR to cope with the large amount of data, and the continuation of the aforementioned analyses. The work of NOvA at JINR attracts a lot of attention from students and young staff, which provides a good potential for growing and extending the JINR participation in this excellent physics.

The Borexino/DarkSide project presented at the PAC has been approved in its Borexino part and postponed in the DarkSide one for clarification of the general situation with this project and detailisation of a possible JINR contribution. According to this recommendation we plan to perform feasibility study for DarkSide at JINR as one of activities of the theme.

The Dubna group is taking an active part in the Borexino data analysis. The group has played a leading role in the ^{7}Be neutrino flux analysis (including analysis of the limits on the neutrino effective magnetic moment), analysis of the antineutrino data, analysis of rare processes and pp-neutrino analysis. In the coming years we are planning to continue the analysis of the pp-neutrino flux and the analysis of the rare processes, including study of nonstandard interactions. We will also contribute to the CNO neutrino flux analysis and in the geoneutrino analysis.

Activity on the OPERA experiment will be concentrated on finishing analysis of muon to electron neutrino oscillations and publishing the result. The JINR team is responsible for this work in OPERA collaboration.

Finally, also as one of activities of the theme, we plan to study the possibility to detect scintillation light emitted in liquid argon proposed as an option for the DUNE near detector. Such a task is in significant demand because it can provide information for trigger and complementary (to the argon ionization) information on the event energy measurement. Scintillation light in the liquid argon is emitted in the, so-called, vacuum ultraviolet region and needs to be shifted to the visible light in order to be detected by modern silicon photomultipliers (SiPM). Our previous experience on this photo detectors allows to propose and test an optimal design with wavelength shifters and light collection scheme using SiPM operating at cryogenic temperatures.

5. Manpower

№	Name	DB/JUNO	NOvA	Borexino	OPERA	Photo	Total
1	Allakhverdian V.		0,4				0,4
2	Amvrosov V.		0,1				0,1
3	Antoshkin A.		1				1
4	Antoshkina T.	1					1
5	Anfimov N.	0,5	0,3			0,2	1
6	Balashov N.		0,3				0,3
7	Baranov A.		0,1				0,1
8	Biktemerova S.	1					1
9	Bilenky S.		0,1				0,1
10	Bolshakova A.		1				1
11	Butorov I.	0,5					0,5
12	Biare D.	0,5					0,5
13	Vasina S.				1		1
14	Velikanova D.		0,1				0,1
15	Vishneva A.			1			1
16	Gonchar M.	1					1
17	Gornushkin Yu.	0,5			0,5		1

18	Gorchakov O.	0,5		0,5			1
19	Gromov V.	1					1
20	Dmitrievskiy S.	0,8			0,2		1
21	Dolbilov A.		0,1				0,1
22	Kakorin I.		0,5				0,5
23	Klimov O.		1				1
24	Kolupaeva L.		1				1
25	Kolganov N.	0,3					0,3
26	Korablev D.	0,5		0,4		0,1	1
27	Krasnoperov A.	0,3					0,3
28	Kuzmin K.		0,1				0,1
29	Kuznetsov E.		0,1				0,1
30	Kullenberg C.		0,6				0,6
31	Matveev V.		0,1				0,1
32	Morozov N.	0,3					0,3
33	Morozova A.		0,3				0,3
34	Naumov D.	1					1
35	Naumov V.		0,3				0,3
36	Naumova E.	1					1
37	Nemchenok I.	0,6					0,6
38	Olshevskiy A.	0,4	0,5			0,1	1
39	Petrova O.		1				1
40	Rybnikov A.	0,5					0,5
41	Sadovskiy A.	0,5					0,5
42	Samoylov O.		0,7	0,3			1
43	Selyunin A.	0,5				0,5	1
44	Smirnov O.	0,3		0,7			1
45	Sokolov S.	0,8				0,2	1

46	Sotnikov A.	0,3	0,1	0,4		0,2	1
47	Strizh M.	0,3					0,3
48	Treskov K.	1					1
49	Fatkina A.	0,1					0,1
50	Fedoseev D.	0,5				0,5	1
51	Fomenko K.	0,5		0,5			1
52	Formozov A.	0,5		0,5			1
53	Chukanov A.	1					1
54	Sheshukov A.		0,7	0,3			1
55	Shutov V.	0,2					0,2
	Total FTE	18,7	10,5	4,6	1,7	1,8	**37,3**

6. SWOT analysis

The details on SWOT analysis were presented recently for each of the theme projects. Overall, the **strength** of the theme research is that the main goals are planned to be achieved in different projects and by different complementary methods. Moreover, Daya Bay, NOvA and Borexino experiments are already in the data taking stage since several years and have proven that those experiment's projected parameters were achieved (or even exceeded).

There are many **opportunities** to perform additional measurements with Daya Bay/JUNO, NOvA and Borexino detectors. In particular, those unique experiments are well suited to detect Supernova burst and search for new and exotic physics.

The main **weaknesses** and **threats** of the JUNO project are possible delays in civil construction, lower than expected integral thermal power of reactors and difficulties to achieve necessary energy resolution. Possible changes in planning of NOvA and Borexino running time due to the budget or other restrictions can decrease expected sensitivity or delay obtaining of the final result.

7. Summary

During the past period of the theme realisation important results on the measurement of neutrino oscillation parameters, measurement of solar neutrino fluxes, searches for new phenomena and construction of a new detector systems were achieved with significant and visible contribution from the JINR groups. Continuation of this high priority neutrino program was already presented and approved by PAC in the corresponding projects: DB/JUNO, NOvA and Borexino. Accordingly, we request an extension of the theme 02-2-1099 for the period of 2019-2021.

Theme Leader Signature:

D.V. Naumov

A.G. Olshevskiy