Study of Neutrino Oscillations in NOvA experiment

NOvA is a new generation experiment studying oscillations of muon to electron flavor neutrinos. The NOvA apparatus consists of a Near Detector at the Fermilab site, where the muon neutrinos are produced by the NuMI facility, and a Far Detector placed 810 km away. Both detectors are of similar construction based on a large-volume liquid scintillator tracking calorimeter, and both are situated 14 mrad off-axis to the neutrino beam, optimizing the signal to background ratio.

Introduction

The NuMI Off-axis ν_e Appearance (NOvA) is a two-detector, long-baseline, atmospheric-regime neutrino oscillation experiment designed to address a broad range of open questions in the neutrino sector through precision measurements of $\nu_\mu \rightarrow \nu_e$, $\nu_\mu \rightarrow \nu_\mu$, and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ oscillations.

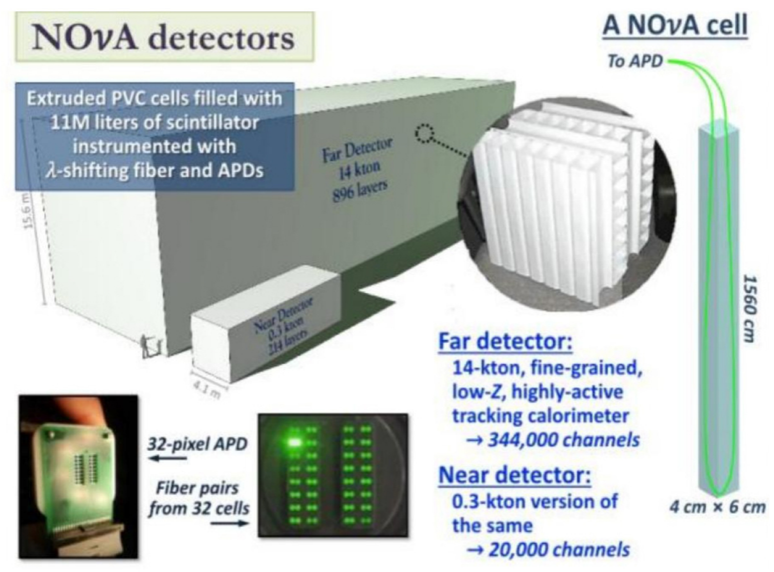
Much of the NOvA's physics scope comes from the appearance channels, as the observed rates of ν_e and ν_e interactions provide information on:

- the ordering of the neutrino masses (whether the ν3 state is heavier or lighter than the other two),
- the amount of CP violation present in the neutrino sector,
- the size of the PMNS mixing angle θ_{13},
- whether the ν3 state has more ν_μ or ν_τ admixture (whether θ_{23} is > or < than 45 degrees).

Through ν_μ and disappearance measurements, the NOvA experiment will provide improved precision on the dominant atmospheric oscillation parameters θ_{23} and Δm^2_{atm}, which is of utmost importance for the global fits and understanding of the full neutrino oscillation scheme.

The NOvA experiment uses Fermilab's NuMI beamline as its neutrino source. The NOvA detectors are situated 14 mrad off the NuMI beam axis, so, due to the kinematics of neutrino production in pion decays, they are exposed to a relatively narrow band of neutrino energies centered at 2 GeV.

The NOvA Far Detector (FD) is located off the Ash River Trail in northern Minnesota, 810 km from the NuMI target. The NOvA Near Detector (ND) is located on the Fermilab site about 1 km from the NuMI target. Neutrino oscillations are studied by comparing events in the near detector, where the neutrinos have not yet had time to oscillate, with those in the far detector. The NOvA detectors can be considered as totally active, tracking, liquid scintillator calorimeters.



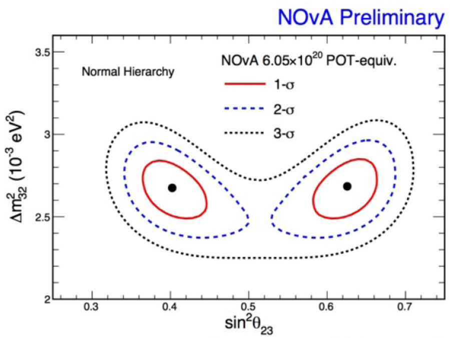
NOvA Results and Plans

The NOvA experiment started data taking on 6 February 2014 with 4 diblocks in the Far Detector, out of 14 planned. The detector construction was finally finished on 29 July 2014 and only since then the full detector operation has started. Planned beam power (700 kW) was steadily reached in 2016.

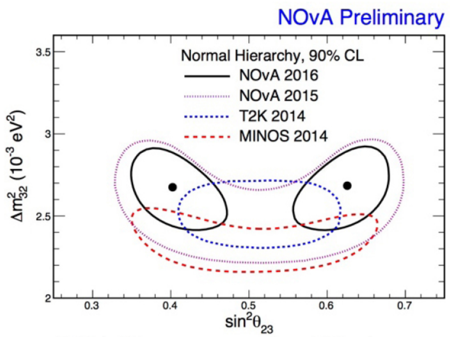
78 ν_μ CC events were detected in our analysis with an expected background of 3.4 NC, 0.23 ν_e CC, 0.27 ν_τ CC and 2.7 cosmic events. The best fit to the data gives:

1. $\Delta m^2_{32} = (+2.67 \pm 0.11) \times 10^{-3}\ eV^2$ and $\sin^2\theta_{23}$ at two statistically degenerate values $0.404^{+0.030}_{-0.022}$ or $0.624^{+0.022}_{-0.030}$ both for Normal Hierarchy.
2. For Inverted Hierarchy $\Delta m^2_{32} = (-2.72 \pm 0.11) \times 10^{-3}\ eV^2$ and $\sin^2\theta_{23} = 0.398^{+0.030}_{-0.022}$ or $0.618^{+0.022}_{-0.030}$.

As a result of the present NOvA ν_μ analyses, maximal mixing for θ_{23} was disfavored at a 2.6σ level for the first time.



ν_μ contours for normal hierarchy showing 1, 2, and 3σ with systematics.



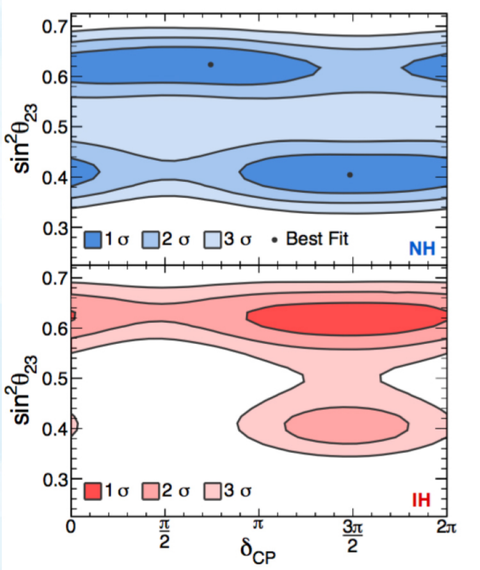
90% CL contours for NOvA ν_μ overlaid with recent T2K and MINOS results.

For background we expect a total of 8.2 events (3.1 for beam ν_e CC, 3.7 for NC, 0.7 for ν_μ CC, 0.1 for ν_τ CC and 0.5 for cosmic events) and small variations with oscillation parameters.

In order to improve sensitivity, the joint fit for ν_e and ν_μ NOvA analyses was performed for the first time. The present best fit equally prefers two points for NH:

1. δ_{CP} = 1.48π, $\sin^2\theta_{23}$ = 0.404 (Lower Octant (LO)) ;
2. δ_{CP} = 0.74π, $\sin^2\theta_{23}$ = 0.623 (Upper Octant (UO)).

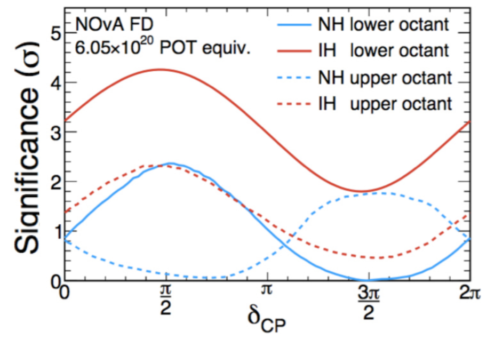
1, 2 and 3σ allowed regions using numu constraint in $\sin^2\theta_{23}$ vs δ_{CP} for normal (top) and inverted (bottom) hierarchy. No Feldman-Cousins corrections are applied.



Currently the data slightly prefer the Normal Hierarchy. The difference in the best fit for NH and IH is 0.46σ. But we have already excluded a region in IH, Lower Octant, around δ_{CP} =π/2 at 3σ and LO at greater than 93% C.L. for all values of δ_{CP}.

The significance at which the values of δ_{CP} are disfavored for each of the four possible combinations of MH and θ_{23} octant is presented in the Figure.

Significance as a function of δ_{CP} for NH (blue) and IH (red), with fixed $\sin^2\theta_{23}$=0.4 (solid) and $\sin^2\theta_{23}$=0.6 (dotted). Feldman-Cousins corrections are applied. Signal and background systematics are taken into account. Δm^2_{12} and $\sin^2\theta_{13}$ are held within global uncertainties.



Confusion in octants of θ_{23} tangle the measurement of mass hierarchy and δ_{CP}. In other words, in terms of oscillation probability we have results for both octants. In order to resolve such difficulty we need an antineutrino run.

NOvA gathered neutrino data until February 2017 (up to 9×10^{20} POT) and then switched to antineutrinos. We will run in antineutrino mode until the next spring (up to 9×10^{20} POT).

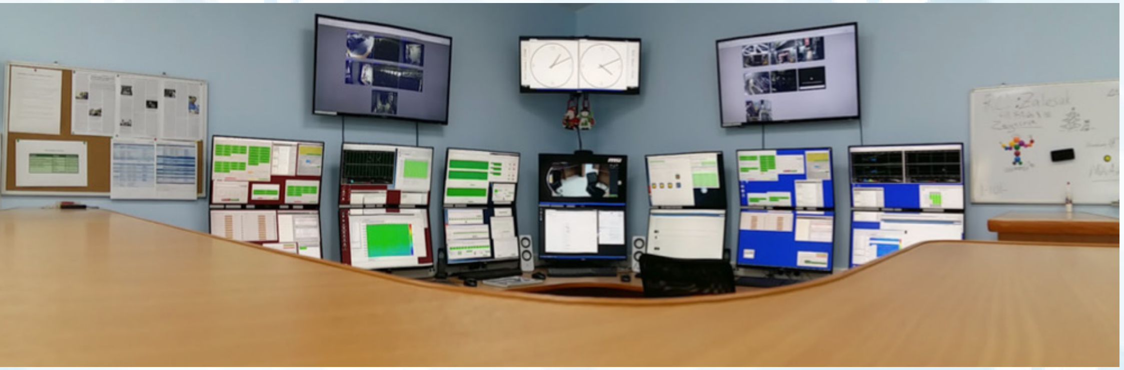
Further running of the NOvA experiment will provide very competitive data for the measurement of neutrino mass ordering, CP-violation effects, disentangling the octants of θ_{23}, among many others. There are also plans to extend NOvA data collection beyond 2020, which will further increase the physics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

For the next several years NOvA can obtain the next.

2018 year: >3σ exclusion of maximal θ_{23}; >2σ MH determination.
2019 year: >2σ octant determination.
2020 year: >3σ MH determination.
2023 year: >2σ CPV determination.
2024 year: >5σ exclusion of maximal θ_{23}; >3σ octant determination.

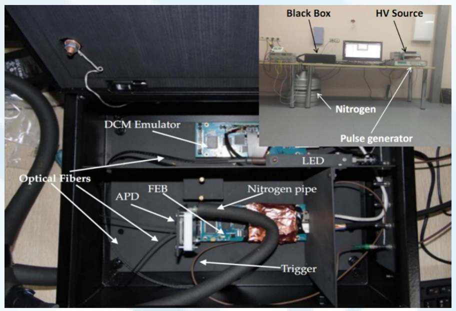
NOvA at JINR

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.



ROC-Dubna view.

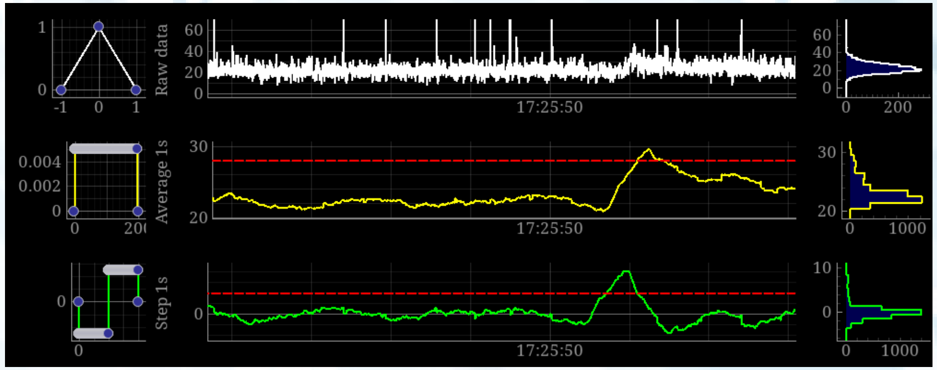
The JINR computer infrastructure on the basis of GRID and Cloud technologies was developed. It is efficiently used for the home-based running of jobs and is also a part of the NOvA distributed computing resources system for the use at peak loads (e.g., before conferences).



The NOvA electronics test bench was set up at JINR and provided important measurements of electronics parameters used for simulation and calibration.

NOvA test bench.

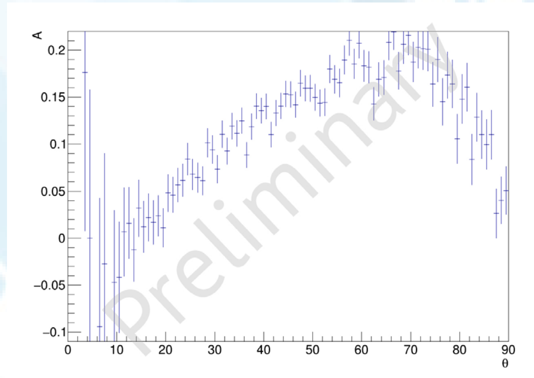
Members of the JINR group are deeply involved in the ongoing analyses and in the preparation of new ones. This comprises the ν_μ, ν_e, Supernova, Slow monopole, Cosmic Ray and Near Detector physics teams.



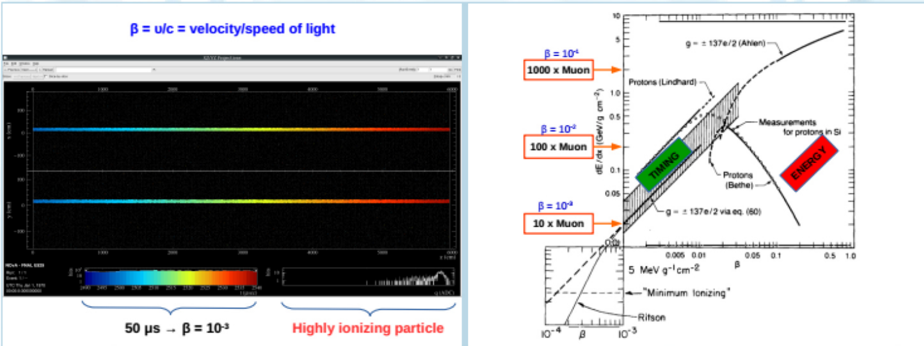
Example of supernova signal detection using filters to enhance the signal.

JINR participates in cosmic-ray studies of the NOvA collaboration, in part dealing with the cosmic muon east-west asymmetry. Measurement of the east-west asymmetry of cosmic muons can help with discrimination of the primary cosmic ray mass composition.

East-west asymmetry of cosmic-ray muons, stopped in the Far Detector of NOvA, without hill asymmetry correction. Asymmetry is defined as A=(W-E)/(W+E), where W is cosmic muon flux coming from west, E is one from east.



The NOvA far detector is well suited to the search for exotic particles due to its technical opportunities. One example of these exotic particles are the «slow» magnetic monopoles. A measurement of the expected signals from the monopoles has been performed on the NOvA test bench at JINR. It has been proposed to develop the signal simulation of the «slow» mode (the slow monopoles velocity is ~ 10^{-3} times the speed of light) in comparison with the typical signals due to elementary particles.



Simulated monopole in Far Detector (left) and monopole energy loss depending on it's beta (right).

Members of the JINR group 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.

Official web-page: *http://www-nova.fnal.gov/*
JINR web-page: *http://astronu.jinr.ru/wiki/index.php/NOvA_Experiment*