Recent three-flavor neutrino oscillation results from the NOvA experiment

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Abstract. NOvA is a long-baseline experiment studying primarily neutrino oscillations in the NuMI beam from Fermi National Laboratory (FNAL), USA. It consists of two functionally identical, finely granulated detectors which are separated by 810 km and situated 14.6 mrad off the NuMI beam axis from FNAL. By measuring the transition probabilities \( P(\nu_\mu \rightarrow \nu_e) \) and \( P(\bar{\nu}_\mu \rightarrow \nu_e) \), NOvA is able to probe the following parameters: \( \Delta m^2_{32} \), the mixing angle \( \theta_{23} \), the CP violating phase \( \delta_{CP} \) and the neutrino mass hierarchy. This document is devoted to the latest NOvA measurements of the neutrino oscillation parameters using neutrino and antineutrino disappearance and appearance obtained in 2020.

1. Introduction
NOvA [1] is a long-baseline experiment devoted to studying neutrino oscillations in the muon (anti-)neutrino beam. It consists of two functionally identical, finely granulated tracking calorimeter detectors. The NuMI facility at FNAL creates a neutrino beam that travels 810 km to the Far Detector, which is placed at Ash River (Minnesota, USA).

The proton beam at FNAL with 120 GeV energy hits the carbon target and produces mesons which can decay into leptons and neutrinos. The resulting neutrino beam composition is as follows: 95% \( \nu_\mu \), 4% \( \bar{\nu}_\mu \), 1% \( \nu_e/\bar{\nu}_e \) (93% \( \bar{\nu}_\mu \), 6% \( \nu_\mu \), 1% \( \nu_e/\bar{\nu}_e \) in the case of antineutrino beam). Magnetic horns placed after the target are used for focusing the mesons with specific electric charges. Thus NOvA can work with relatively pure neutrino or antineutrino beams. The statistics of accelerator neutrino experiments is measured in terms of protons delivered to the target (POT). Currently, NOvA has collected \( 13.6 \times 10^{20} \) POT with neutrino beam and \( 12.5 \times 10^{20} \) POT with antineutrino beam which is \( \sim 50\% \) more statistics with neutrino beam than was used for the previous analysis [2].

Both NOvA detectors are placed 14.6 mrad off the beam axis which helps to obtain a narrow energy peak at 1.8 GeV. The Near Detector (ND) has dimension \( 4.2 \times 4.2 \times 16 \) m and 300 t mass. It is placed about 1 km after the target and used for measuring unoscillated neutrino beam composition. The Far Detector (FD) is used for measuring the neutrino flux after oscillations at a distance of 810 km. It has dimensions of \( 15.6 \times 15.6 \times 60 \) m and a 14 kt mass.

The NOvA detectors were designed to observe electron and muon (anti-)neutrinos. In order to identify and classify events, the Convolutional Visual Network [3] is used. It is an image recognition technique which uses the map of event hits as an input. We control the CVN...
classification performance for $\nu_e$ sample by creating the Muon Removed events and checking efficiency differences for data and Monte-Carlo [4].

Resulting neutrino energy spectra at the FD are sensitive to certain oscillation parameters: $\Delta m^2_{32}$, $\theta_{23}$, $\delta_{CP}$ and the neutrino mass hierarchy. This document will describe NOvA’s result produced in 2020 [5] with data collected between February 2014 and March 2020 with neutrino and antineutrino beams.

2. Near and Far Detector data
There are two main oscillation channels in NOvA: electron neutrino appearance and muon neutrino disappearance in an initial predominantly muon neutrino beam.

NOvA’s unoscillated high statistics ND data are used to constrain the FD predictions. The $\nu_\mu$ candidates selected in the ND are the source of both $\nu_\mu$ and $\nu_e$ signals in the FD. In case of $\nu_\mu$ selected energy spectra, we split it into four quartiles. This decision is based on the reconstructed hadron energy fraction to the full reconstructed neutrino energy. Quartile no.1 has the best energy resolution ($\sim$8\%) and the lowest hadron energy fraction. On the contrary, quartile no. 4 has the worst energy resolution ($\sim$12\%) and the highest hadron energy fraction. The energy spectra selected in the ND for 2020 analysis are shown in the Figure 1.

![Figure 1](image1.png)

Figure 1. ND $\nu_\mu$ (first row) and $\bar{\nu}_\mu$ (second row) spectra split into four quartiles. The black dots are real data, the violet line is Monte-Carlo prediction with 1\(\sigma\) systematic error.

The $\nu_e$ events detected in the ND are used for $\nu_e$ background prediction in the FD. These events are originating in admixture of $\nu_e$’s initially presenting in the beam and misidentified NC and $\nu_\mu$ events. There is a special data-driven procedure called "decomposition" that is used for correcting these prediction types independently (Figure 2). Similarly to $\nu_\mu$ events $\nu_e$ sample is also split into sub-samples of PID classifier ranges.

Constrained ND predictions are the input for the next analysis procedure which is called "extrapolation". Extrapolation is used for propagating the corrected ND predictions to the FD. This procedure also helps to reduce the effect of certain systematic uncertainties (namely correlated between two detectors: cross-sections, flux, detector response). Modified predictions are translated to the true energy spectra and multiplied by far-to-near ratio and oscillations to get modified prediction in the FD. This year we first time used additional kinematic space as bins of lepton transverse momentum [6]. Near and Far detectors have different acceptance due to different size and containment restrictions (Figure 3). This is solved by splitting and extrapolating each sample in three independent bins of $|p_T|$ to the FD (Figure 4). All $|p_T|$ bins for each sub-sample are collapsed into single energy spectra before fitting. It helps to balance the kinematics between detectors and has a positive effect on systematic uncertainties (Figure 5).
Figure 2. ND $\nu_e$ (a) and $\bar{\nu}_e$ (b) spectra split into two spectra corresponding to different sub-ranges of CVN classifier values in the analysis region. Dotted lines illustrate component prediction before decomposition. Solid lines are corrected predictions that are used for extrapolation.

Figure 3. Selected $|p_T|$ spectrum in the ND and FD illustrates different acceptance.

Figure 4. Boundaries of $|p_T|$ bins for one $\nu_\mu$ quartile.

Figure 5. Systematic uncertainties for the joint $\nu_e + \nu_\mu$ analysis with neutrino and antineutrino beam. Yellow bar and red bars illustrate systematic size for extrapolation with and without additional $|p_T|$ space.
In the FD NOvA observed in neutrino running mode 211 $\nu_\mu$ candidates with background expectation 8.2 and 82 $\nu_e$ candidates with background expectation 26.8 events. In antineutrino mode there are 105 $\bar{\nu}_\mu$ candidates with background expectation 2.1 and 33 $\bar{\nu}_e$ candidates with background expectation 14.0 events. Final $\nu_\mu$ and $\bar{\nu}_\mu$ ($\nu_e$ and $\bar{\nu}_e$) FD spectra are shown in the Figures 6-7 (Figures 8-9).

3. Analysis results
A joint fit of spectra shown in the Figures 6-9 was performed. It allowed to make the following conclusions:

- NOvA’s best fit in the Normal neutrino mass hierarchy and Upper octant of $\theta_{23}$:
  \[
  \sin^2 2\theta_{23} = 0.57^{+0.03}_{-0.04}, \quad \Delta m^2_{32} = (2.41 \pm 0.07) \times 10^{-3} \text{ eV}^2, \quad \delta_{CP} = 0.82\pi;
  \]
- Lower octant of $\theta_{23}$ is disfavored at 1.2$\sigma$;
- Inverted hierarchy is disfavored at 1$\sigma$.
The $1, 2, 3\sigma$ contours in $\sin^2\theta_{23} - \Delta m^2_{32}$ and $\sin^2\theta_{23} - \delta_{CP}$ are shown in the Figure 10. The exclusion significances at which each value of $\delta_{CP}$, $\Delta m^2_{32}$ and $\sin^2\theta_{23}$ is disfavored are shown in the Figure 11.

**Figure 10.** The $1, 2, 3\sigma$ contours in $\sin^2\theta_{23} - \Delta m^2_{32}$ (a) and $\sin^2\theta_{23} - \delta_{CP}$ (b) in Normal (left) and Inverted (right) hierarchy. Feldman-Cousins corrections are applied. Best fit is shown by star marker.

**Figure 11.** The exclusion significance for each value of $\Delta m^2_{32}$ (a) and $\sin^2\theta_{23}$ (b), $\delta_{CP}$ (c) in Normal (blue) and Inverted (orange) mass hierarchy, dashed lines denote the octant (when it’s applied).
There is no strong asymmetry in the rates of $\nu_e$ and $\bar{\nu}_e$. Thus octant–hierarchy–$\delta_{CP}$ combinations that produce such asymmetries are disfavored: excluded Inverted hierarchy $\delta_{CP} = \pi/2$ at $> 3\sigma$, and Normal hierarchy $\delta_{CP} = 3\pi/2$ at $\sim 2\sigma$. Which shows up a clear tension with T2K recent result [7]. Announced joint T2K + NOvA analysis [8] can shed a light on underlying physics.

NOvA is expected to take data until 2025. Such an extended running plan can result in potential 3–5$\sigma$ sensitivity to neutrino mass hierarchy and $\sim 2\sigma$ for $\delta_{CP}$ determination (for favorable true parameters in nature). Some improvements are taken into account for projecting these values. Beam intensity will be increased according to the PIP-II [9] plan of the FNAL accelerator complex upgrade. NOvA’s Test beam program [10] will improve the detector response model. We’re anticipating number of analysis and simulation improvements as well.

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