Extracting neutrino oscillation parameters using a simultaneous fit of the $\nu_e$ appearance and $\nu_\mu$ disappearance data in the NOvA experiment

Prabhjot Singh
Department of Physics and Astrophysics, University of Delhi, India
Email: prabhjot@fnal.gov

On behalf of the NOvA Collaboration

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Abstract

NOvA is a two detector, long baseline neutrino oscillation experiment designed to study $\nu_e$ ($\bar{\nu}_e$) appearance and $\nu_\mu$ ($\bar{\nu}_\mu$) disappearance in a $\nu_\mu$ ($\bar{\nu}_\mu$) beam produced at Fermilab. The near detector (ND) is located 100 meters underground at a distance of 1 km from the target whereas the far detector (FD) is located on the surface, 810 km away from the beam source in Ash River, MN. The ND is used to measure the beam before oscillations and the FD measures the oscillated spectrum. The ND and the FD are functionally identical detectors and the ND spectra are extrapolated to the FD to predict the signal and background spectra expected in the FD. The extrapolation and data fitting techniques developed for these analyses within NOvA are presented.
I. INTRODUCTION TO THE NOVA EXPERIMENT

NOvA (NuMI Off-axis $\nu_e$ Appearance) is a two detector, long baseline, neutrino oscillation experiment. NOvA [1] observes neutrinos produced in Fermilab’s NuMI [2] (Neutrinos at Main Injector) beam line in two detectors. The NuMI beam is composed of 97.5% $\nu_\mu$, 1.8% of $\bar{\nu}_\mu$ and 0.7% of ($\nu_e + \bar{\nu}_e$). A beam of high energy, 120 GeV protons from the Main Injector impinge on a fixed graphite target producing pions and kaons [3]. Magnetic horns select pions and kaons of the desired charge and momentum and focus them into a narrow beam. Charged pions and kaons spontaneously decay into muons and neutrinos. 240 meters of rock filters out muons produced in the decay pipe and we are left with a beam of neutrinos. NOvA is 14.6 mrad off-axis from the NuMI beam to observe a neutrino energy spectrum peaked at 2 GeV which is optimized for observing $\nu_\mu \rightarrow \nu_e$ oscillations. The ND, is located 100 meters underground at a distance of 1 km from the target on-site at Fermilab and the FD is located on the Earth’s surface, 810 km away from the beam source in Ash River, MN. NOvA is designed to study ($\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$) disappearance, ($\bar{\nu}_\mu \rightarrow \nu_e$) appearance. Both NOvA detectors are functionally identical and constructed from planes of extruded polyvinyl chloride (PVC) cells [1]. NOvA cells have a rectangular cross section measuring 3.9 cm by 6.6 cm and are 15.5 m (3.9 m) long in the FD (ND). NOvA cells are arranged in alternating horizontal and vertical planes for 3D tracking and are oriented perpendiccular to the NuMI beam. There are 896 (214) planes and 344,064 (20,192) cells in the FD (ND). Each cell is filled with liquid scintillator. Wavelenght shifting fibers are used to collect the light deposited by any charged paricle in the detector. The fiber ends terminate on a single pixel of an avalanche photodiode (APD) [4]. The ND is used to measure the beam before oscillations and the FD measures the oscillated spectrum.

II. NEUTRINO EVENTS IN NOVA

The electron neutrino charged current (CC), $\nu_e$-CC interaction is the signal for the $\nu_e$ ($\bar{\nu}_e$) appearance analysis. The signature of $\nu_e$-CC interactions in the NOvA detectors is an electromagnetic shower plus any associated hadronic recoil energy. The muon neutrino charged current, $\nu_\mu$-CC, interaction is the signal for the $\nu_\mu$ ($\bar{\nu}_\mu$) disappearance anaysis. The signature of $\nu_\mu$-CC interactions in the NOvA detectors is a long track of muons and any as-
associated hadronic activity at the vertex. The largest background in both $\nu_e$-appearance and $\nu_\mu$-disappearance analyses arises from neutral current (NC) interactions of beam neutrinos. The signatures of $\nu_\mu$ CC, $\nu_e$ CC and NC interactions are shown in Fig. 1.

**FIG. 1:** Three event topologies are observed in the NOvA oscillation analyses. $\nu_\mu$-CC (top) is the signal for the $\nu_\mu$ ($\bar{\nu}_\mu$) disappearance analysis. $\nu_e$-CC (middle) is the signal for the $\nu_e$ ($\bar{\nu}_e$) appearance analysis. NC (bottom) is a background in $\nu_\mu$-disappearance and $\nu_e$-appearance analyses.

### III. FAR DETECTOR PREDICTION USING NEAR DETECTOR

The ND spectra are used to predict signal and backgrounds in the FD. Both $\nu_\mu \rightarrow \nu_\mu$ disappearance and $\nu_\mu \rightarrow \nu_e$ appearance analyses use muon neutrinos in the ND for signal prediction in the FD. Discrepancies between data and MC calculations in the ND energy spectrum are extrapolated to produce a predicted FD spectrum. We first convert the ND reconstructed energy spectrum into a true energy spectrum using the reconstructed-to-true migration matrix obtained from the ND simulation, and then multiply by the FD MC to ND MC event ratio as a function of true neutrino energy to obtain the FD true energy spectrum. The ratio also incorporates the effect of three-flavor neutrino oscillations, including matter effects, for any particular choice of the oscillation parameters. The FD true energy prediction is transformed into a reconstructed energy prediction using the simulated FD migration matrix. In the final step, the data-based cosmic and simulation-based beam-induced backgrounds are added to the prediction, which is then compared to the FD data.
The whole process of the extrapolation from the ND to the FD is shown in Fig. 2.

![Diagram showing the process of extrapolation from ND to FD](image)

**FIG. 2:** The ND spectra are used to predict the signal and backgrounds in the FD. The ND reconstructed energy spectrum is converted to the true energy spectrum. The FD-to-ND MC event ratio along with choice of the oscillation parameters are used to make prediction in the FD.

In the $\nu_e$-appearance analysis deep learning [5, 6] is used to separate the signal and backgrounds into 3 bins of identification confidence from least $\nu_e$-like to the most $\nu_e$-like as shown in Fig. 3. The $\nu_e$ selected beam $\nu_e$ CC, $\nu_\mu$ CC and NC interactions in the ND are the major backgrounds in the FD for the $\nu_e$-appearance analysis. Since the NC, $\nu_\mu$ CC, and beam $\nu_e$ CC background components are affected differently by oscillations, the total background selected in the ND data is broken down into these components, then each component is extrapolated from the ND to the FD for background predictions in the FD.

**IV. SYSTEMATIC UNCERTAINTIES IN THE $\nu_\mu$ DISAPPEARANCE AND $\nu_e$ APPEARANCE ANALYSES**

Systematic uncertainties are evaluated by reweighting or generating new simulated event samples modified to account for each uncertainty in the ND and FD. Systematic uncertainties in the analysis are extrapolated from the ND to the FD using the same extrapolation technique. The ND Data is replaced by systematically shifted ND MC under a systematic shift. The corrected ND true energy spectra is then extrapolated to the FD as shown in
FIG. 3: In the $\nu_e$-appearance analysis deep learning is used to separate the signal and backgrounds into 3 bins of identification confidence from least $\nu_e$-like to the most $\nu_e$-like.

FIG. 4: Systematic uncertainties in the analysis are extrapolated from the ND to the FD using the extrapolation technique. The ND Data is replaced by systematically shifted ND MC under a systematic shift.

Fig. 4: Systematic uncertainties are included as nuisance parameters in the fit for all analyses. For the simultaneous fit of the $\nu_e$-appearance and $\nu_\mu$-disappearance data the nuisance parameters associated with the systematic uncertainties which are common between the two data sets, are correlated appropriately. The functionally identical detectors allow most uncertainties to cancel when predicting the FD spectrum.
FIG. 5: Various sources of systematic uncertainties in the $\nu_\mu$ (left) and $\nu_e$ (right) analyses are shown. In the $\nu_\mu$-disappearance analysis uncertainties due to detector response, i.e. relative and absolute muon and hadronic energy scales, are dominant. In the $\nu_e$-appearance analysis, cross section uncertainties are important for the signal prediction. Both $\nu_\mu$ and $\nu_e$ uncertainties are small compared to statistical uncertainties.

The $\nu_\mu$-disappearance analysis accounts for systematic uncertainties in the energy scale, normalization, neutrino cross section and final state interactions, neutrino flux, and backgrounds. The uncertainties due to detector response, that is, relative and absolute muon and hadronic energy scales are dominant but smaller than the statistical uncertainties. In the $\nu_e$-appearance analysis, cross section uncertainties are important for the signal prediction, but small compared to statistical uncertainties.

V. RESULTS

A. $\nu_\mu$ FIT TO THE DISAPPEARANCE DATA

The $\nu_\mu$ disappearance data is fit for the $\Delta m_{32}^2$ and $\sin^2 \theta_{23}$ parameters [10]. Based on the predictions from the near detector in the absence of oscillation 473 $\nu_\mu$ events were expected in the FD but we observe 78 events which is clear evidence of neutrino oscillations as shown in the left and middle plots of Fig. 6. The best fit to the data gives $\Delta m_{32}^2 = (2.67 \pm 0.11) \times 10^{-3}$ eV$^2$ and the $\sin^2 \theta_{23}$ at two statistically degenerate values $0.404^{+0.030}_{-0.022}$ and $0.624^{+0.022}_{-0.030}$ both at the 68% C.L. in the normal hierarchy (NH). Maximal mixing, where $\sin^2 \theta_{23} = 0.5$, is disfavored by the data at 2.6 $\sigma$. The right plot in Fig. 6 shows the allowed 90% C.L. regions in $\Delta m_{32}^2$ and $\sin^2 \theta_{23}$. The NOvA 2015 and 2016 results are compared with MINOS and T2K.
FIG. 6: The left plot compares the $\nu_\mu$-disappearance data to the best fit prediction and also show the unoscillated prediction one would have expected in the absence of neutrino oscillations. The middle plot shows the ratio of background subtracted oscillation to the unoscillated prediction. The right plot shows the allowed 90% C.L. regions in $\Delta m^2_{32}$ and $\sin^2 \theta_{23}$ region. The NOvA 2015 and 2016 results are compared with MINOS and T2K.

**B. $\nu_e$ FIT TO THE APPEARANCE DATA**

The $\nu_e$ appearance data is fit for the $\sin^2 \theta_{23}$ and $\delta_{CP}$ parameters. The values $\sin^2 2\theta_{13} = 0.085 \pm 0.005$ and $\Delta m^2_{32} = +2.44 \pm 0.06$ (NH) are used as nuisance parameters in the $\nu_e$-appearance fit. Thirty three, 33, electron neutrino candidates were observed with an expected background of $8.2\pm0.8$ events; the significance of $\nu_e$ appearance is greater than 8 $\sigma$. The left plot in Fig. 7 shows a comparison of the event distribution with the expectations at the best-fit point as a function of the classifier variable and reconstructed neutrino energy. The right plot in Fig. 7 shows the allowed regions of $\sin^2 \theta_{23}$ and $\delta_{CP}$ parameters for both normal and inverted hierarchies.
FIG. 7: The left plot shows a comparison of the event distribution with the expectations at the best-fit point as a function of the classifier variable and reconstructed neutrino energy. The right plot shows the allowed regions of $\sin^2 \theta_{23}$ and $\delta_{CP}$ parameters. The top panel is for normal hierarchy ($\Delta m_{32}^2 > 0$) and bottom panel is for inverted hierarchy ($\Delta m_{32}^2 < 0$).

C. SIMULTANEOUS FIT OF THE DISAPPEARANCE AND APPEARANCE DATA

The constraints on the oscillation parameters can be improved by combining NOvA’s $\nu_e$ appearance data with its $\nu_\mu$ disappearance data [11]. Appearance and disappearance data are simultaneous fit for the $\sin^2 \theta_{23}$, $\delta_{CP}$ and $\Delta m_{32}^2$ parameters. The parameter $\sin^2 2\theta_{13}$ is 0.085 ± 0.005 a constraint from the reactor experiments [7,9]. Fig. 8 shows the allowed regions of $\sin^2 \theta_{23}$ and $\delta_{CP}$ parameters. There are two degenerate best-fit points, both in the normal hierarchy $\sin^2 \theta_{23} = 0.404$, $\delta_{CP} = 1.48\pi$ and $\sin^2 \theta_{23} = 0.623$, $\delta_{CP} = 0.74\pi$. The inverted mass hierarchy in the lower octant is disfavored at greater than 93% C.L. for all values of $\delta_{CP}$ and excluded at greater than 3 $\sigma$ significance outside the range $0.97\pi < \delta_{CP} < 1.94\pi$. 
FIG. 8: The allowed regions of $\sin^2 \theta_{23}$ and $\delta_{CP}$ parameters for the simultaneous fit of the NOvA’s $\nu_e$ appearance and $\nu_\mu$ disappearance data. The top panel is for normal hierarchy ($\Delta m^2_{32} > 0$) and bottom panel is for inverted hierarchy ($\Delta m^2_{32} < 0$).

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