Electron neutrino appearance in the NOvA experiment

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Abstract. NOvA is an off-axis, two-detector experiment studying neutrino oscillations with the $\nu_\mu$ beam from Fermilab. This paper describes the $\nu_e$ appearance analysis, including data-driven constraints from Near Detector measurements. The data set corresponds to an exposure equivalent to $6.05 \times 10^{20}$ protons-on-target in the Far Detector. We observed 33 $\nu_e$ candidates with a predicted background of $8.2 \pm 0.8$ (syst.), for a significance of appearance higher than $8\sigma$. Preliminary results for the allowed values of $\delta_{CP}$ and $\theta_{23}$ in both hierarchies are presented.

1. Introduction
NOvA is a long-baseline accelerator neutrino experiment using the NuMI muon neutrino beam. The NuMI beam is produced by directing 120 GeV proton spills onto a graphite target [1]. The resulting hadrons are focused by two magnetic horns, and decay into neutrinos and other particles inside a long pipe. The neutrinos are observed by two detectors, Near (ND) and Far (FD), located 1 and 810 km away from the target and 14 mrad off the beam axis. The beam spectrum is narrowly peaked around 2 GeV, optimal to observe $\nu_\mu \to \nu_e$ transitions. This allows NOvA to draw conclusions about the neutrino mass hierarchy, the $\theta_{23}$ octant and $\delta_{CP}$. In Sec.2, we explain data-driven methods that improve the prediction from the simulation. In Sec.3, we compare the final prediction with the FD data and highlight some results. Further details about the experiment and $\nu_e$ event classification (CVN), are discussed elsewhere in these Proceedings.

2. Far Detector prediction using data-driven constraints
2.1. Signal prediction using ND $\nu_\mu$ data
The prediction of the $\nu_\mu \to \nu_e$ signal in the FD is constrained using the observed $\nu_\mu$ spectrum in the ND. Discrepancies between $\nu_\mu$ data and simulation are interpreted as an inexact modeling of the underlying true energy spectrum [2]. The $\nu_e$ spectrum in the FD is adjusted accordingly. The exact distribution of the predicted $\nu_e$ signal will further depend on the oscillation parameters. The signal expectation varies between 11 and 28 total events for fixed $\sin^2 \theta_{23} = 0.5$, corresponding to (IH, $\delta_{CP} = \pi/2$) and (NH, $\delta_{CP} = 3\pi/2$) respectively.

2.2. Beam background prediction using ND $\nu_\mu$ and $\nu_e$ data
Three types of beam-related backgrounds are estimated using the ND: neutral currents (NC), $\nu_\mu$ charged currents (CC), and the intrinsic $\nu_e$ component in the NuMI beam (beam $\nu_e$ CC). Since each one propagates differently to the FD, we use a combination of data-driven techniques to correct their relative proportions from the simulation.
Muon neutrinos that contribute to the 2 GeV peak mainly result from the decay $\pi^+ \rightarrow \nu_\mu + \mu^+$. A few anti-muons that subsequently decay as $\mu^+ \rightarrow \bar{\nu}_\mu + e^+ + \nu_e$ give rise to the intrinsic $\nu_e$ component. At higher energies, the majority of $\nu_\mu$ and $\nu_e$ originate in kaon decays. We use $\nu_\mu$ events selected in the ND to constrain the pion and kaon yields, and consequently the beam $\nu_e$ component. Figure 1(a) compares the spectra of contained $\nu_\mu$ events in data and simulation; most events have a pion ancestor. After subtracting the background, the differences between data and the simulated sample are translated into weights as function of pion forward ($p_T$) momenta, and then applied to the $\nu_e$ CC from pions. Similarly, uncontained $\nu_\mu$ events with energies above 4.5 GeV predominantly have kaon ancestors, as seen in Figure 1(c). Any data/MC discrepancy is used to correct the kaon yield. The result of both corrections is a 2% decrease for $\nu_e$ CC from pions, and a 17% increase for $\nu_\mu$ CC from kaons.

![Figure 1](image1.png)

**Figure 1.** (a) Contained and (c) uncontained $\nu_\mu$ events in the ND used to correct the beam $\nu_e$ from pions and kaons. (b) Pion weights from $\nu_\mu$ as function of the pion momentum ($p_T$), overlaid with the $\nu_e$ CC distribution (boxes).

The $\nu_\mu$ CC and NC components are corrected using the number of Michel Electrons (ME) in data and MC (Figure 2). On average, $\nu_\mu$ CC interactions have one more ME than NC or beam $\nu_e$, resulting from the decay of the muon. Combining the beam $\nu_e$ estimation above and a fit to the number of ME in ND data, all three components are constrained. On average, the beam $\nu_e$ component is scaled up by 4%, NC up by 10% and $\nu_\mu$ CC up by 17%. The corrections obtained with the ND data are translated to FD background expectations using Far/Near ratios. Unlike the signal prediction, these have small variations with the oscillation parameters. An additional background component, $\nu_e$ CC, is read directly from the simulation. The expected background counts in the FD are 3.7 NC, 3.1 beam $\nu_e$, 0.7 $\nu_\mu$ CC and 0.1 $\nu_\tau$ CC.

2.3. Cosmic background prediction using FD data

The NOvA FD is on the surface and thus susceptible to cosmogenic background. A rejection of 1 part in $10^8$ cosmic ray interactions is achieved using the time structure of the NuMI beam, event topologies, and particle identification; analysis cuts are optimized for higher signal efficiency, and tuned using an independent sample. Using FD $\nu_e$ candidates outside of the beam time window, we estimate a total of 0.53 cosmic events that could coincide with the appearance signal.

2.4. Systematic uncertainties

The two-detector technique described mitigates the impact of many sources of systematic uncertainty. Residual effects are assessed via variations in the simulation. These can be classified as: normalization, flux, calibration, cross section, and detector response. The overall effect in the FD event count is 5% for signal and 10% for background. In the binned fit, systematic uncertainties are included as nuisance parameters.
3. Results

33 electron neutrino candidates were observed. With an expected background of 8.2±0.8 events, the significance of νe appearance is greater than 8σ. A comparison between the FD data and the final prediction is presented in Figure 3; the reconstructed energy spectra are split in three ranges of the event classifier (CVN). A combination of the NOvA νe measurement with global θ13 and Δm23 constraints gives best fit values for NH, δCP = 1.59π, and sin2 θ23 = 0.45. The preference for these parameters has low statistical significance: several values are compatible with the data, both in NH and IH. The fit was also run using NOvA’s νμ disappearance results, in the form of a constraint for sin2 θ23 and Δm23. This is a preliminary combination; a joint fit including correlations of systematic uncertainties and Feldman-Cousin corrections is in progress. The resulting two-dimensional contours using Gaussian limits are presented in Figure 4. The global best fit occurs at NH, δCP = 1.49π, and sin2 θ23 = 0.40. Both octants and hierarchies are allowed at the 1σ level. In inverted hierarchy, there is some rejection of the lower octant for all values of δCP; the region around δCP = π/2 is excluded at the 3σ level.

![Figure 3. Reconstructed energy spectrum of νe events in the FD, split in three ranges of the event classifier. Data (circles) are compared to the final prediction (red) for NH, δCP = 1.49π, and sin2 θ23 = 0.40.](image1)

![Figure 4. Allowed values of δCP and sin2 θ23 from the preliminary combination of νe appearance and νμ disappearance data, for both hierarchies.](image2)

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References

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