FERMILAB-SLIDES-24-0152-PPD

Constraining Systematics for Future Sterile Neutrino Analysis at NOvA Experiment

New Perspective Meeting

Shivam

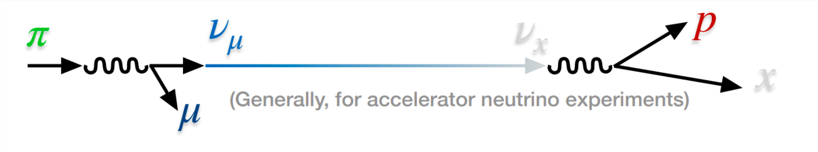
July 5, 2024

Indian Institute of Technology, Guwahati

Table of contents

Neutrino Oscillations

Neutrino Oscillations



- Neutrinos produced in one flavor state change its flavor during its travel across the distance.

- ν_l, flavor eigenstate which is a superposition of ν_i, mass eigenstates.

$$|\nu_l\rangle = \sum_{i=1}^{3} U^*_{si}|\nu_i\rangle$$

$U = R(\theta_{23})R(\theta_{13})R(\theta_{12}) \longrightarrow$ mixing matrix

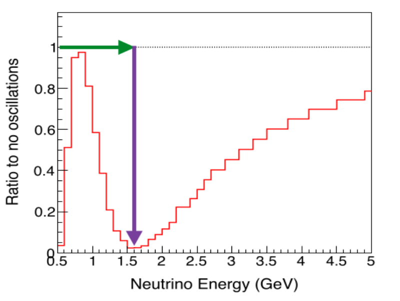
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}}_{\text{"atmospheric"}} \times \underbrace{\begin{pmatrix}c_{13} & 0 & s_{13}e^{\iota\delta}\\ 0 & 1 & 0\\ -s_{13}e^{\iota\delta} & 0 & c_{13}\end{pmatrix}}_{\text{"reactor"}} \times \underbrace{\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\text{"solar"}} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Neutrino Oscillations

- In most of the long baseline experiments, we use the ν_μ disappearance or ν_e appearance channels to study the neutrino oscillation parameters.
- As an example, in two flavor approximation ν_μ **disappearance probability** is defined as:

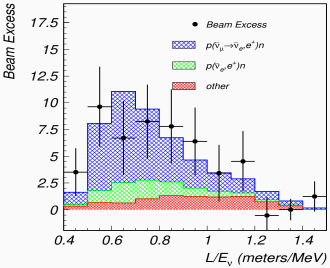
$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{23} L_\nu}{E_\nu}\right)$$

- mixing angle determines the magnitude of oscillations.
- mass splitting determines the frequency of oscillations.



Is Three Flavor Picture Enough?

- Several anomalous results observed by various experiments could suggest a possible explanation beyond the active three-flavor oscillations.

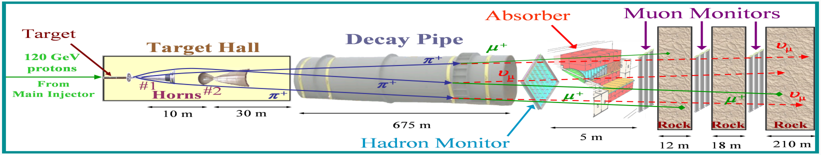


- LSND observed a 3σ excess above the expected beam background.

- One possible solution is adding an extra neutrino flavor.
- Any additional neutrino flavor should not interact with the known forces (not even through weak interactions).
- More than one sterile neutrino is possible, but the minimal solution uses the 3+1 model.
- This leads to adding an extra dimension to the PMNS mixing matrix, also leading to an additional oscillation frequency Δm^2_{41}.

NOvA Experiment

NuMI Beam



- 120 GeV protons from the Fermilab Main Injector strike the target to produce secondary particles.
- Two focussing horns focus the secondary particles that decay into the decay tunnel to produce the $\nu(\bar{\nu})$ beam.

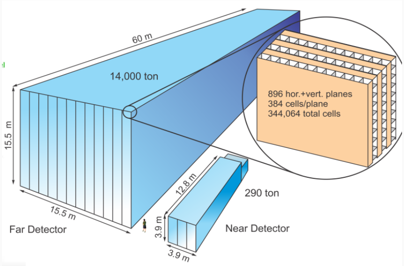


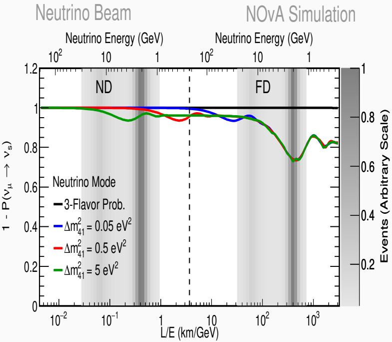
Figure 1: NOvA Detectors

- NOvA is a long baseline experiment with two functionally identical liquid scintillator detectors.
- The Near Detector is placed 100 m underground at 1 km from the source, and the far detector at 810 km on the surface from the near detector.

Sterile Neutrino

Sterile Neutrino at NOvA: Neutral Currents

- Neutral Current Disappearance gives a clean measurement of 3+1 oscillations because of their flavor independency.



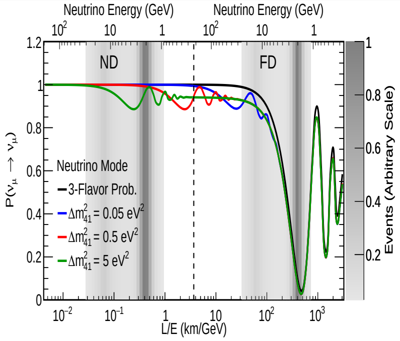
$$1 - P(\nu_\mu \to \nu_s) \approx 1 - \cos^4\theta_{14}\cos^2\theta_{34}\sin^2 2\theta_{24}\sin^2\Delta_{41}$$
$$- \sin^2\theta_{34}\sin^2 2\theta_{23}\sin^2\Delta_{31}$$
$$+ \frac{1}{2}\sin\delta_{24}\sin\theta_{24}\sin 2\theta_{23}\sin\Delta_{31}$$

- Sensitivity to $\sin^2\theta_{34}$ at FD NC can be measured independent of $\sin^2\theta_{24}$.

- Oscillations begin to manifest at ND for $\Delta m^2_{41} >$0.5eV^2.
- Highlighted text is the short baseline approximation.

Sterile Neutrino at NOvA: ν_μ disappearance

- Any additional ν_μ disappearance above the expected 3-flavor oscillation can be manifested as sterile neutrino.



$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2 2\theta_{24} \sin^2 \Delta_{41} + 2\sin^2 2\theta_{23} \sin^2 \theta_{24} \sin^2 \Delta_{31} - \sin^2 2\theta_{23} \sin^2 \Delta_{31}$$

- Charged Current ν_μ is sensitive to the θ_{24} at both ND and FD.

- Highlighted text is the FD oscillation intermixed with the 3-flavor oscillations.

Motivation: Constraining Systematics

Sterile Neutrino at NOvA

- NOvA 2022 Sterile Neutrino mode results showing a leading limit on $\sin^2\theta_{24}$ at high Δm^2_{41}.
- On one hand, the low Δm^2_{41} region is driven by the FD data and is statistically limited.
- On the other hand, at high Δm^2_{41} region where sensitivity is driven by ND is systematically limited.

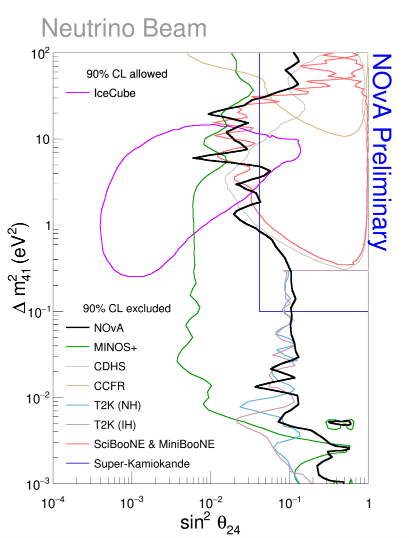


Figure 2: NOvA's 90 % confidence limits in (a) $\sin^2\theta_{24}$ vs Δm^2_{41} space with other allowed regions and exclusion contours.

Sterile Neutrino at NOvA

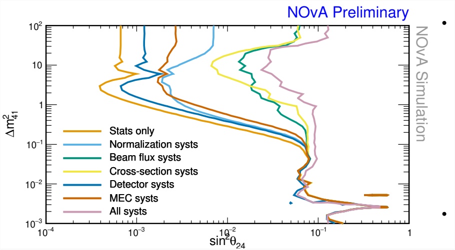


Figure 3: Sensitivity Contour (at 90% CL) for $\sin^2\theta_{24}$ vs Δm^2_{41}

- We are taking more and more data, which improves the statistics, but with more statistics, we also need to deal with the systematics.
- The figure on the left shows the Sensitivity Contour (at 90% CL) for $\sin^2\theta_{24}$ for different systematic groups.

- We can see that the cross-section and flux systematics are the dominant ones, and the future analysis includes constraining the systematics.

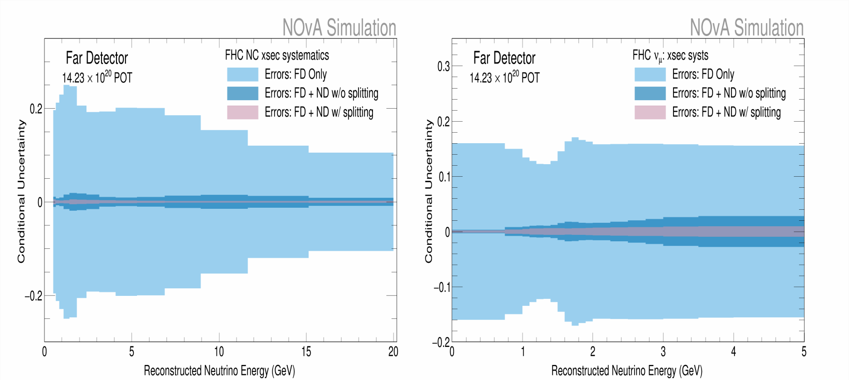
Splitting the Near Detector NC Sample

We used a new approach to implement the ND NC sample, where instead of using the sample as a whole, we divided it into subsamples based on the number of prongs associated with the event.

- Single prong Sample: the events with single prong are mostly enriched with the SIS, QE and dominated by Res.
- 2 and 3 Prong Sample: This sample is highly enriched in Res but has a contribution from SIS interaction as well.
- 4 Prong Sample: DIS starts appearing, but this region is dominated by SIS events.
- >4 Prong Sample: Once we have more than 4 prongs, the DIS interaction highly dominates the events.

Results and Conclusion

Results and Conclusion

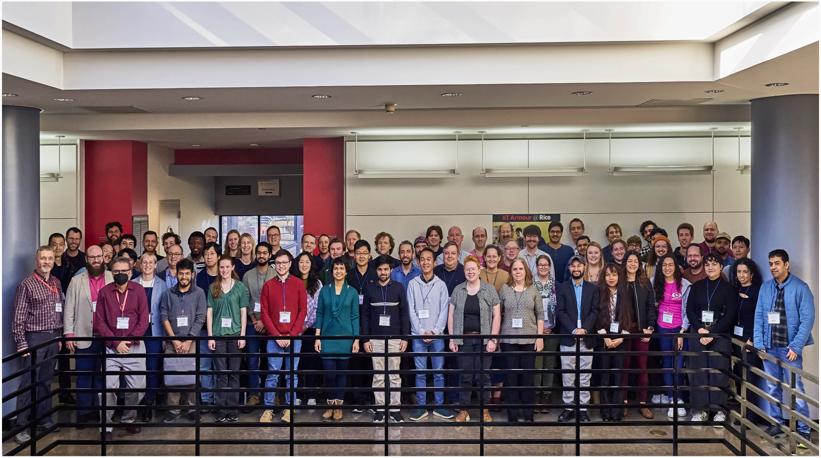


- The distribution in light blue shows the uncertainty at FD without any constraint from the ND.
- Dark Blue distribution represents the FD uncertainty knowing the information about the ND without splitting.
- Pink distribution represents the FD uncertainty with additional information with ND splitting.

Results and Conclusion

- Conditional uncertainty distributions show better constraints on the cross-section uncertainties.
- This split sample approach will allow us to disentangle the signal and systematic effects and help improve the sensitivity at higher Δm^2_{41} region.
- More studies are underway, including zero horn current and ν-on-e studies to improve the flux systematic uncertainties.

NOvA Collaboration



Thank You

Backup Slides

Fraction with each prong:: True NC only (ND NC CVN $>$0.1)

pngs	Coh	DIS	SIS	QE	Res
1	0.029(**0.071**)	0.055 (**0.046**)	0.236 (**0.254**)	0.147 (**0.091**)	0.531 (**0.535**)
2	0.016 (**0.038**)	0.051 (**0.051**)	0.315(**0.326**)	0.039 (**0.022**)	0.577 (**0.561**)
3	0.005(**0.011**)	0.103(**0.115**)	0.384(**0.393**)	0.022(**0.011**)	0.484(**0.467**)
4	0.001(**0.004**)	0.220(**0.247**)	0.414(**0.418**)	0.013(**0.006**)	0.350(**0.322**)
5	0 (**0.001**)	0.382 (**0.400**)	0.379 (**0.387**)	0.006 (**0.004**)	0.230 (**0.206**)
6	0 (**0.001**)	0.527 (**0.534**)	0.322 (**0.328**)	0.001 (**0.001**)	0.146 (**0.133**)
7	0 (0)	0.644 (**0.641**)	0.261 (**0.278**)	0 (**0.001**)	0.091 (**0.077**)
8	0	0.725 (**0.727**)	0.198 (**0.278**)	0 (0)	0.075 (**0.066**)
9	0	0.751 (**0.763**)	0.190 (**0.210**)	0	0.058 (**0.026**)

Table 1: Fraction of each interaction with # of prongs for **CVN>0.1**

- The table shows the different interaction fractions with loose CVN scores.
- Losening the CVN score reduces the fraction of QE events and increases the DIS and Res fractions.

Fraction with each prong:: True NC only (ND NC CVN >0.98)

pngs	Coh	DIS	SIS	QE	Res
1	0.056 (**0.151**)	0.048 (**0.054**)	0.149 (**0.172**)	0.280(**0.147**)	0.465(**0.473**)
2	0.048 (**0.113**)	0.058 (**0.039**)	0.206(**0.216**)	0.046 (**0.024**)	0.640(**0.605**)
3	0.018 (**0.044**)	0.150 (**0.123**)	0.219 (**0.256**)	0.030 (**0.014**)	0.580 (**0.559**)
4	0.008 (**0.004**)	0.403 (**0.247**)	0.206 (**0.418**)	0.019 (**0.006**)	0.362 (**0.322**)
5	0.003 (**0.001**)	0.655 (**0.400**)	0.155 (**0.987**)	0.010 (**0.004**)	0.175 (**0.206**)
6	0.000 (0)	0.792 (**0.534**)	0.122 (**0.328**)	0.001 (**0.001**)	0.081 (**0.133**)
7	0 (0)	0.830 (**0.641**)	0.114 (**0.278**)	0 (0.001)	0.054 (**0.077**)
8	0 (0)	0.841 (**0.727**)	0.110 (**0.205**)	0 (0)	0.047 (**0.066**)
9	0 (0)	0.879 (**0.763**)	0.051 (**0.210**)	0 (0)	0.069 (**0.026**)

Table 2: Fraction of each interaction with # of prongs for CVN>0.98

- To see the different interactions, DIS has been split into two categories (DIS and SIS) based on the Q^2 and W value.
- It appears that, beyond five prongs, most events fall into the DIS category.