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Constraining Systematics for Future Sterile Neutrino Analysis at NOvA Experiment

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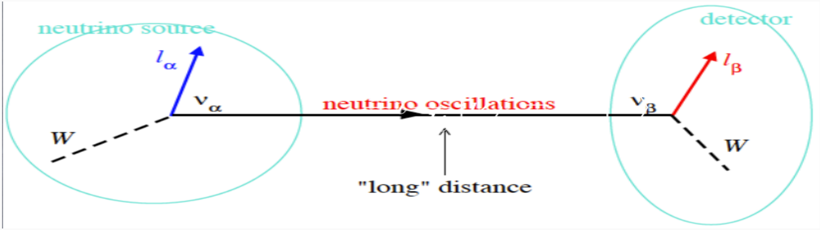
Table of contents

1. Neutrino Oscillations
2. NOvA Experiment
3. Sterile Neutrino
4. Currrent Results and Improvement
5. Conclusion

Neutrino Oscillations

Neutrino Oscillations



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

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

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

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

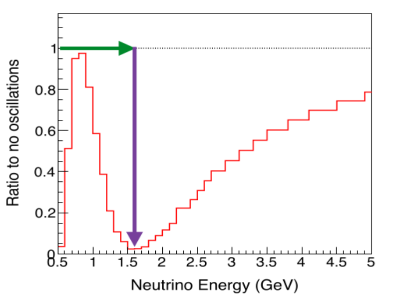
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}}_{\text{“atmospheric”}} \times \underbrace{\begin{pmatrix}c_{13} & 0 & s_{13}\,e^{\iota\delta}\\ 0 & 1 & 0\\ -s_{13}\,e^{\iota\delta} & 0 & c_{13}\end{pmatrix}}_{\text{“reactor”}}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

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:

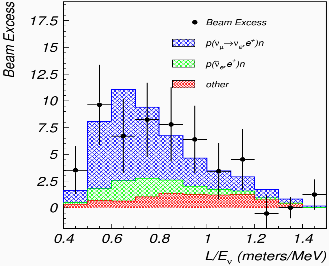
$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2 \left(\frac{\Delta m^2_{32} L_\nu}{4E_\nu} \right)$$

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



Is Three Flavor Picture Enough?

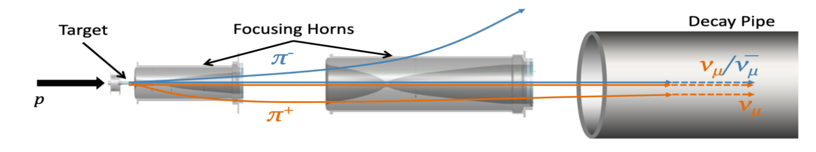
- Several anomalous results observed by various experiments could suggest a possible explanation beyond the active three-flavor oscillations.



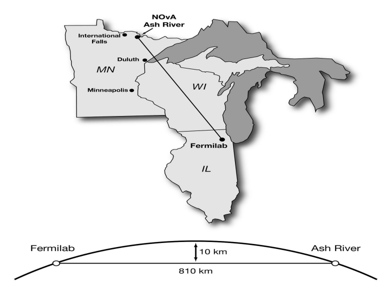
- LSND observed a 3σ excess above the expected beam background [1].
- More than one sterile neutrino is possible, but the minimal solution uses the 3+1 model.
- This leads to adding an extra dimension to the PMNS mixing matrix, also leading to an additional oscillation frequency Δm^2_{41}.

NOvA Experiment

The NuMI Beam



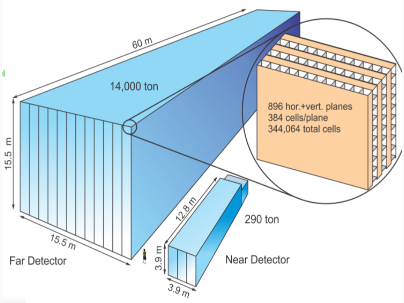
- NOvA is a long-baseline experiment with two functionally identical liquid scintillator detectors.

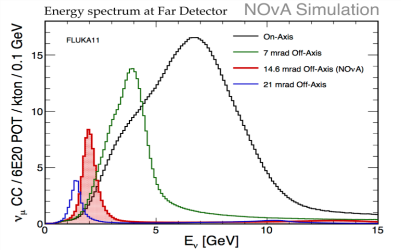


- **120 GeV** protons from the Fermilab Main Injector strike the target to produce secondary particles.
- Two focussing horns focus the secondary particles that decay into the decay tunnel to produce the $\nu(\bar{\nu})$ beam.

NOvA Experiment

- 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.



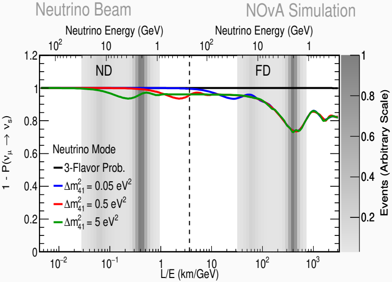


- The detectors are placed 14 mrad off-axis.
- The off-axis configuration reduces the neutrino flux but peaks at 2 GeV

Sterile Neutrino

Sterile Neutrino at NOvA: Neutral Currents

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

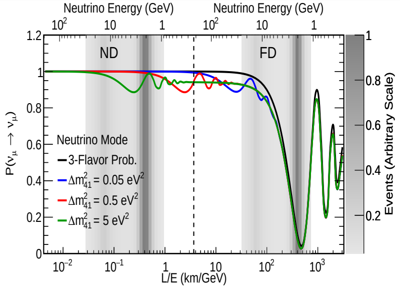


$$1 - P(\nu_\mu \to \nu_s) \approx 1 - \cos^4\theta_{14}\cos^2\theta_{34}\sin^2 2\theta_{24}\sin^2\Delta_{41}$$
$$- \sin^2\theta_{34}\sin^2 2\theta_{23}\sin^2\Delta_{31}$$
$$+ \frac{1}{2}\sin\delta_{24}\sin\theta_{24}\sin 2\theta_{23}\sin\Delta_{31}$$

- Oscillations begin to manifest at ND for Δm^2_{41} >0.5eV^2.
- Highlighted text is the short baseline approximation.
- Sensitivity to $\sin^2\theta_{34}$ at FD NC can be measured independent of $\sin^2\theta_{24}$.

Sterile Neutrino at NOvA: ν_μ disappearance

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



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

- Highlighted text is the FD oscillation intermixed with the 3-flavor oscillations.
- Charged Current ν_μ is sensitive to the θ_{24} at both ND and FD.

Currrent Results and Improvement

Sterile Neutrino at NOvA

- Latest NOvA Sterile Neutrino results showing a leading limit on $\sin^2\theta_{24}$ at high Δm^2_{41} [2].
- 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.

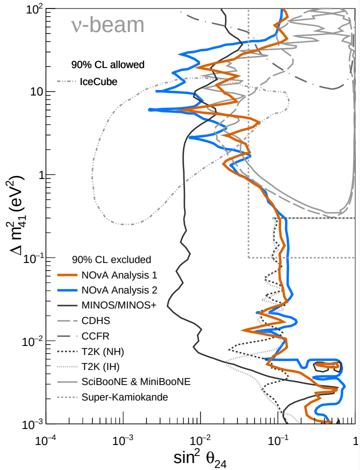


Figure 1: NOvA's 90 % confidence limits in (a) $\sin^2\theta_{24}$ vs Δm^2_{41} space with other allowed regions and exclusion contours.[2]

Sterile Neutrino at NOvA

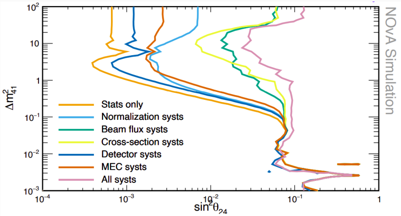


Figure 2: Sensitivity Contour (at 90% CL) for $\sin^2\theta_{24}$ vs Δm^2_{41}

- 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.

Figure 3: Example showing two prongs.

- Single prong Sample
- 2 and 3 Prong Sample
- 4 Prong Sample
- >4 Prong Sample

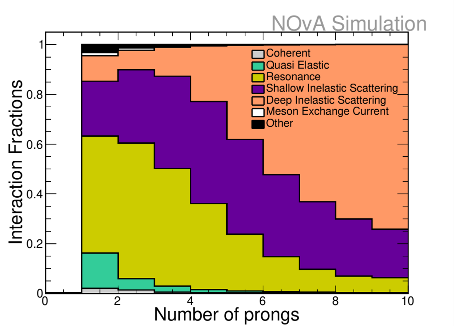


Figure 4: Distribution of Reconstructed number of prongs and the interaction fraction

Conclusion

Conclusion

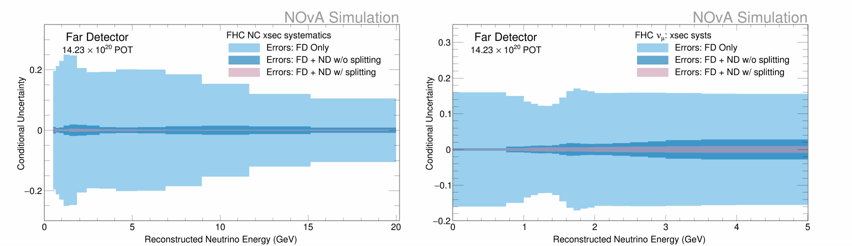


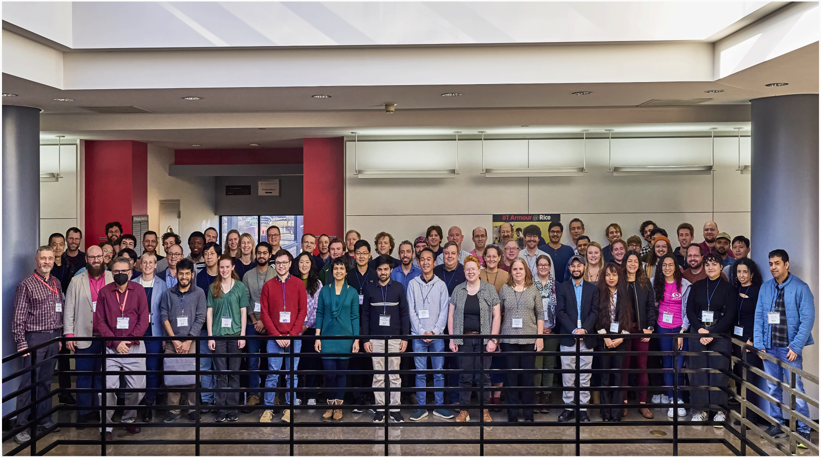
Figure 5: Fractional Uncertainty distribution showing the effect of ND constraint on the cross-section systematics for NC sample on the left and ν_μ sample on the right

- 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.

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

References

- LSND Collaboration, A. Aguilar *etal.*, Evidence for neutrino oscillations from the observation of $\bar{\nu}_e$ appearance in a $\bar{\nu}_\mu$ beam, Phys. Rev. **D** 64, 112007 (2001)
- https://arxiv.org/abs/2409.04553

Backup Slides

Neutrino Interactions at NOvA

- Before understanding sterile neutrino in NOvA, let's see how we find the interactions in NOvA.

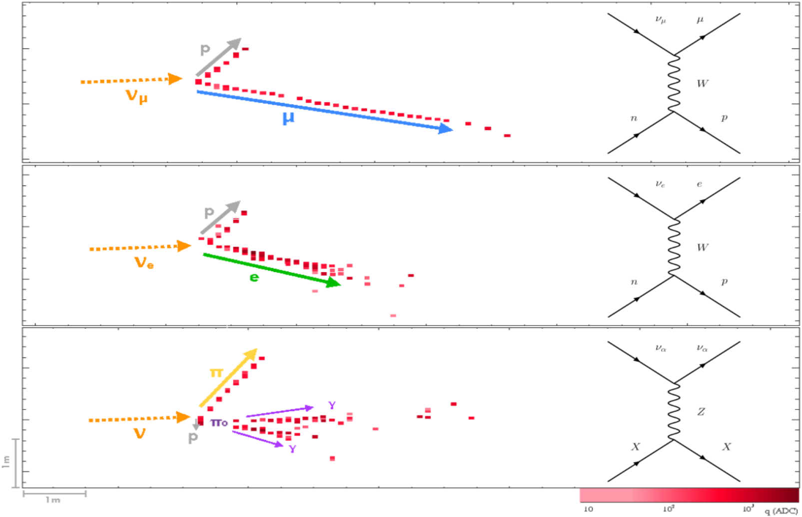


Figure 6: Classification of different types of interaction in the detector

Prong Reconstruction

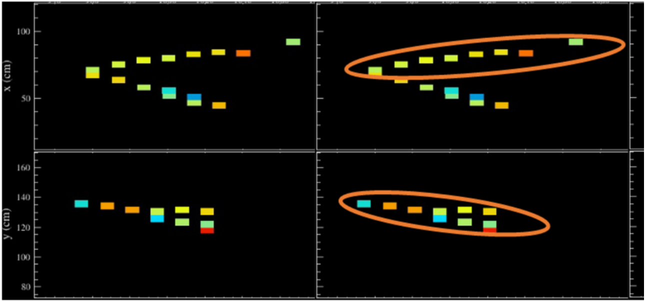


Figure 7: 3D prong formation

- 2D prongs are formed in each X and Y views (as depicted in the left event displays)
- Then to form the 3D prongs, 2D prongs from both the X-Y views are matched (as depicted in right event displays)

Fraction with each prong

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 number of prongs.

- 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.