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Constraining Systematics for Future Sterile Neutrino Analysis at NOvA Experiment

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Abstract. In this article, we report an approach used to constrain the impact of cross-section systematic parameters in the future sterile neutrino analysis at the NOvA experiment. NOvA is a long-baseline neutrino experiment built to investigate the intricate properties of neutrinos, with the principal emphasis on active three-flavor neutrino mixing phenomena. Besides that, NOvA also explores exotic oscillations, including sterile neutrino search. Uncertainties on the neutrino flux, cross-section, and detector systematic parameters significantly contribute, complicating the disentanglement of genuine physics events from background noise. We present the impact of systematic reduction via near detector neutral current sample splitting and its implications on oscillation parameters, leveraging results primarily from Monte Carlo simulations.

1 Introduction

While NOvA focuses on the standard three-flavor neutrino oscillation, results from some short-baseline experiments, such as LSND [1] and MiniBooNE [2], suggest possible deviations from this model. These anomalies hint at physics beyond the Standard Model, particularly the potential existence of sterile neutrinos. NOvA explores this possibility by using the 3+1 model, which posits mixing the three known active neutrino flavors with a hypothetical fourth, sterile neutrino. In this framework, the neutrino mixing matrix (PMNS) dimension extends from a 3×3 to a 4×4 matrix, parameterized as described in [3]. The 4x4 neutrino mixing matrix U introduces three new mixing angles, θ_{14}, θ_{24}, and θ_{34} alongside two CP-violating phases, δ_{14} and δ_{24}, and one additional mass-splitting, Δm^2_{41}. The neutral current disappearance probability in the 3+1 model, under the long-baseline approximation and first-order expansion in small mixing angles, can be expressed as [3]

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

For the short-baseline approximation, relevant at the Near Detector, the oscillation probability simplifies to

$$1 - P(\nu_\mu \to \nu_s) \approx 1 - \cos^4\theta_{14}\cos^2\theta_{34}\sin^2 2\theta_{24}\sin^2\Delta_{41}. \tag{1}$$

The neutral current (NC) disappearance channel is particularly valuable for sterile neutrino searches, as it is independent of standard three-flavor oscillations. Therefore, any observed deficit in NC events would provide direct evidence for active-sterile neutrino oscillations.

2 NOvA Experiment

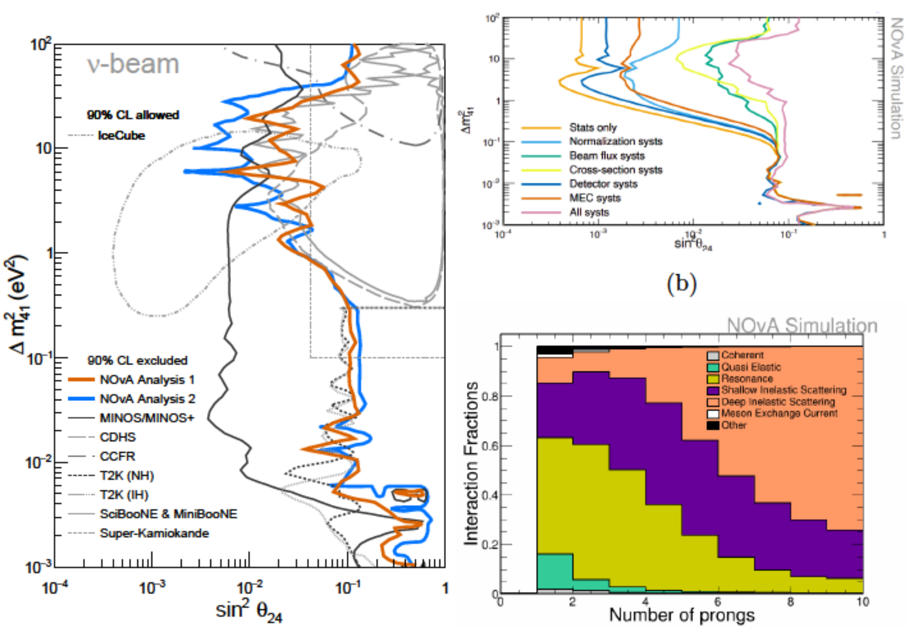
The NOvA experiment employs two functionally identical detectors, with the Near Detector located 1 km from the neutrino source and 100 meters underground. In contrast, the far detector is positioned 810 km away on the surface. Both detectors are placed 14 milliradians off-axis of the beam to produce a narrow neutrino or antineutrino beam that peaks at 2 GeV. The NuMI beam is generated by accelerating protons (H^+ ions) to about 120 GeV using Fermilab's main injector and directing them onto a graphite target [4]. This process produces hadrons, primarily pions and kaons, which are then focused by magnetic horns. The focused hadrons decay in a dedicated decay pipe, yielding either a ν_μ or $\bar{\nu}_\mu$ beam, depending on the charge of the hadrons.

3 Motivation and Analysis Strategy

1a shows the dual-baseline sterile neutrino search results at the NOvA experiment. This analysis exploits the ν_μ and NC disappearance channels to look for the active-sterile neutrino mixing. Due to high frequency oscillations at high Δm^2_{41}, the limits are driven by the ND, and we have very high statistics there, so the systematic parameters are more important. On the other hand, the low Δm^2_{41} region is driven by the FD, which is statistically limited, and to improve the results, we need more data. 1b shows the breakdown of NOvA results into different subgroups, indicating the dominant effects of the cross-section and flux systematic parameters. Large datasets like Near Detector have enough statistics and a variety of neutrino interaction events ranging from quasi-lastic to Deep Inelastic Scattering. We divide the ND NC sample into various subsamples based on interaction types. The rationale is that if an event deficit is due to the sterile oscillation signal, it should consistently affect all subsamples. Conversely, if the deficit is due to a cross-section effect, it will be visible in the particular subsample. By analyzing the behaviour of different subsamples, we gain better control over cross-section systematic parameters, thereby improving our ability to constrain these uncertainties.

We must rely on reconstructed variables to separate out the true interaction types. The number of reconstructed prongs is a relatively good proxy for interaction types which should also be robust against systematic uncertainties. 1c shows the number of prongs with different interaction fractions and forms the basis to define sample categories as:

- Single prong Sample: QE events are typically characterized by a single-prong sample.
- 2 and 3 Prong Sample: This sample is highly enriched in Res but has a contribution from SIS interaction as well.
- 4 Prong Sample: For 4 Prongs events, the DIS interaction starts appearing, but SIS events dominate this region.
- >4 Prong Sample: The DIS interaction category highly dominates the events once we have more than four prongs.



(a) (c)

Fig. 1: (a) NOvA's 90 % confidence limits in $\sin^2\theta_{24}$ vs Δm^2_{41} space with other allowed regions and exclusion contours.[5]. (b) Breakdown of NOvA's 90 % confidence limits for $\sin^2\theta_{24}$ vs Δm^2_{41} for different systematic groups. (c) Distribution of Reconstructed number of prongs and the interaction fraction.

4 Results and Conclusion

We look for the effect of splitting on the cross-section systematic parameters through the conditional uncertainty distributions. Conditional uncertainty assesses the impact of introducing various constraints on the FD energy spectrum by adding different auxiliary samples. We load the systematic uncertainties in the covariance matrix for the joint two detector fit, where we look at the FD energy spectrum and add the constraints to it by adding more samples, which gets reflected as an effect on the FD spectrum. 2 represents the effect of conditional uncertainty distribution for the cross-section systematic parameters for ν_μ sample on the right and NC sample on the left, showing a positive impact in constraining the cross-section systematic parameters.

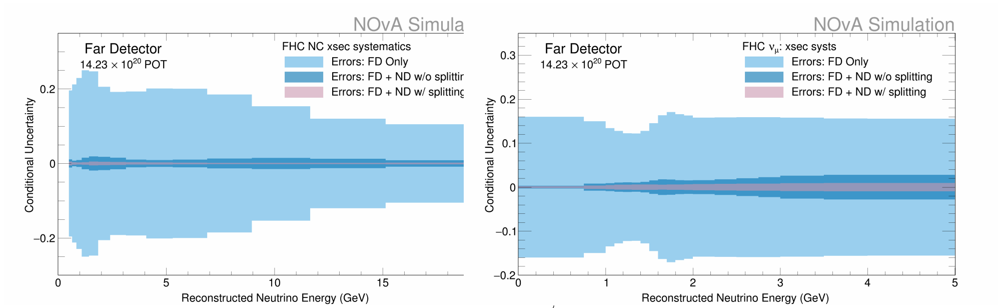


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Fig. 2: Fractional Uncertainty distribution showing the effect of ND constraint on the cross-section systematic parameters for NC sample on the left and ν_μ sample on the right

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