Maximizing NOvA's Sensitivity to Sterile Neutrinos using Covariance Matrices

New Perspectives — August 19th, 2021

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Outline

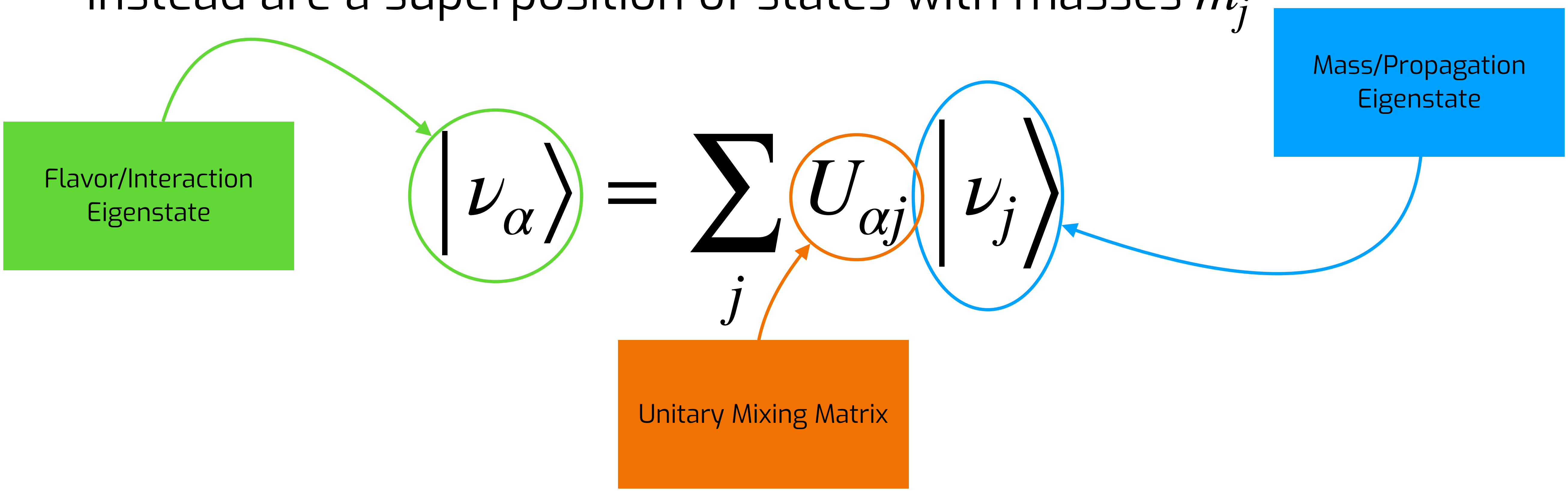
- Neutrino Oscillations
- NOvA Basics
- How NOvA Can Search for Sterile Neutrinos
- How Covariance Matrices Help Us

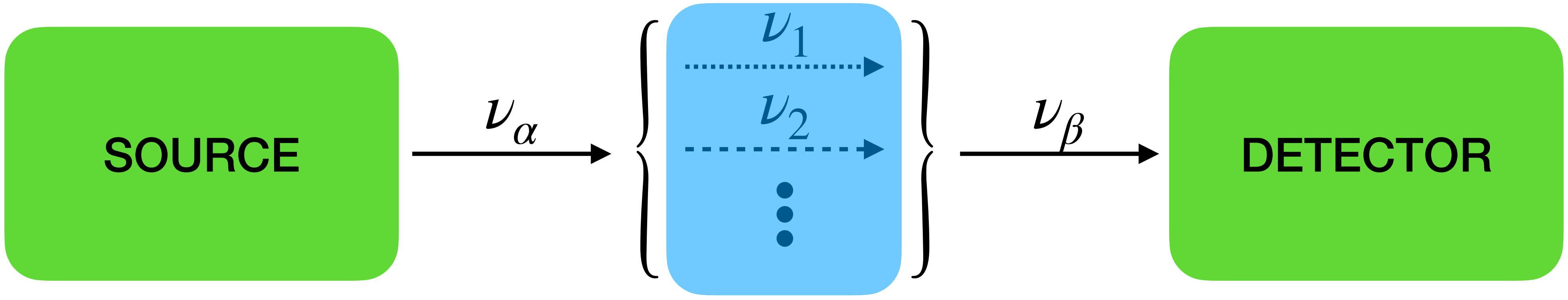
Neutrino Oscillations

Flavor and Mass

- Neutrinos of definite flavor do not have definite mass, and instead are a superposition of states with masses m_j

$$|\nu_\alpha\rangle = \sum_j U_{\alpha j} |\nu_j\rangle$$





Neutrino Oscillations

3 Flavor Paradigm

- Defining $\Delta m_{jk}^2 \equiv m_j^2 - m_k^2$, the probability of detecting a ν_β from a ν_α source is

$$P\left(\nu_\alpha \rightarrow \nu_\beta\right) = \sum_{j,k} U_{\beta j}^\dagger U_{\alpha j} U_{\beta k} U_{\alpha k}^\dagger e^{i\Delta m_{jk}^2 \frac{Lc^3}{2E\hbar}}$$

- If we assume there are only 3 flavors of neutrinos, the matrix U can be parameterized as

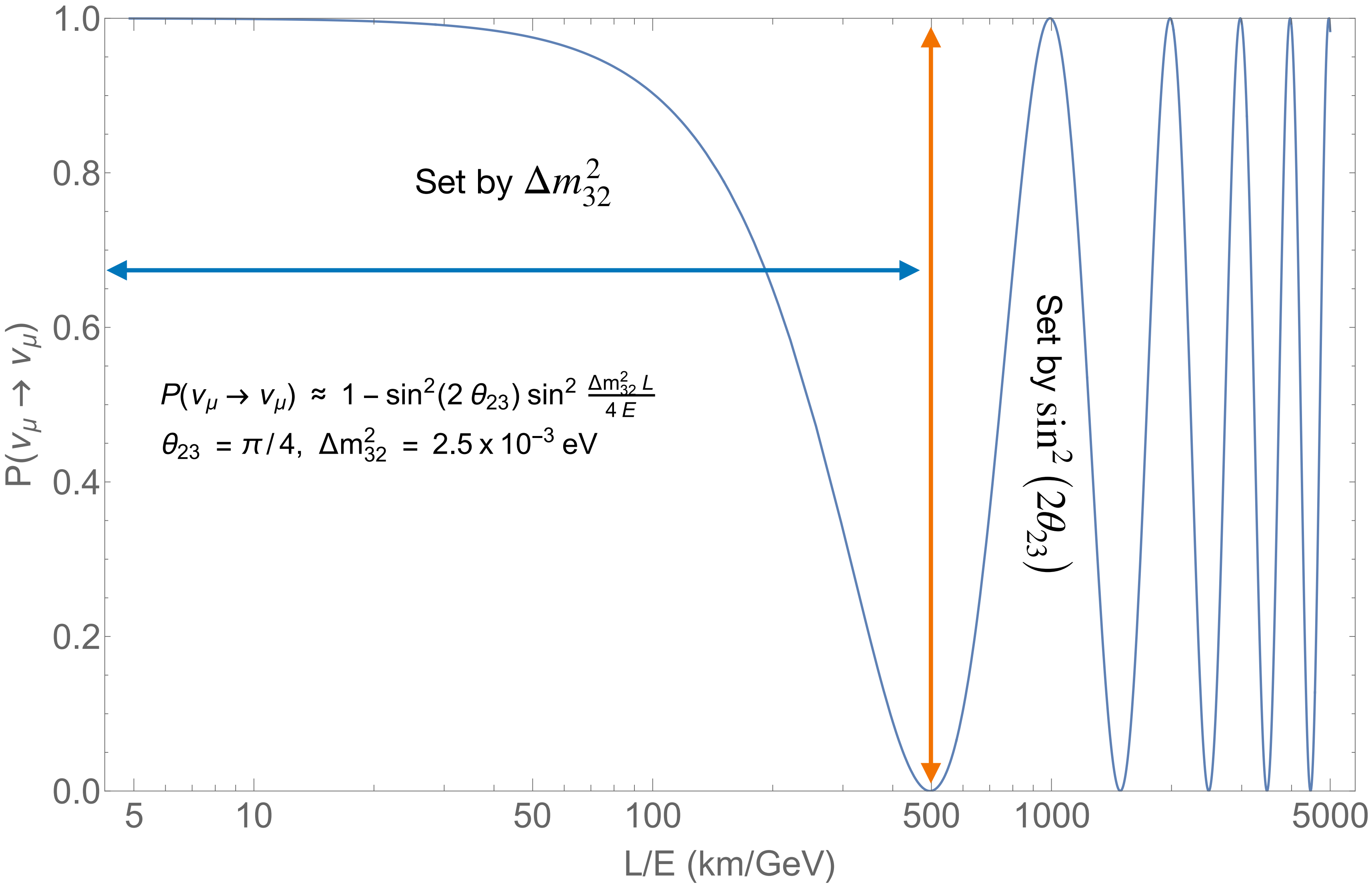
$$U = \underbrace{\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix}}_{\text{Atmospheric}} \times \underbrace{\begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix}}_{\text{Reactor/Accelerator}} \times \underbrace{\begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{\text{Solar}}$$

- Where $s_{jk} = \sin\theta_{jk}$ and $c_{jk} = \cos\theta_{jk}$ and we have ignored the Majorana phases (which are inconsequential to oscillations)

Neutrino Oscillations

Why Oscillations

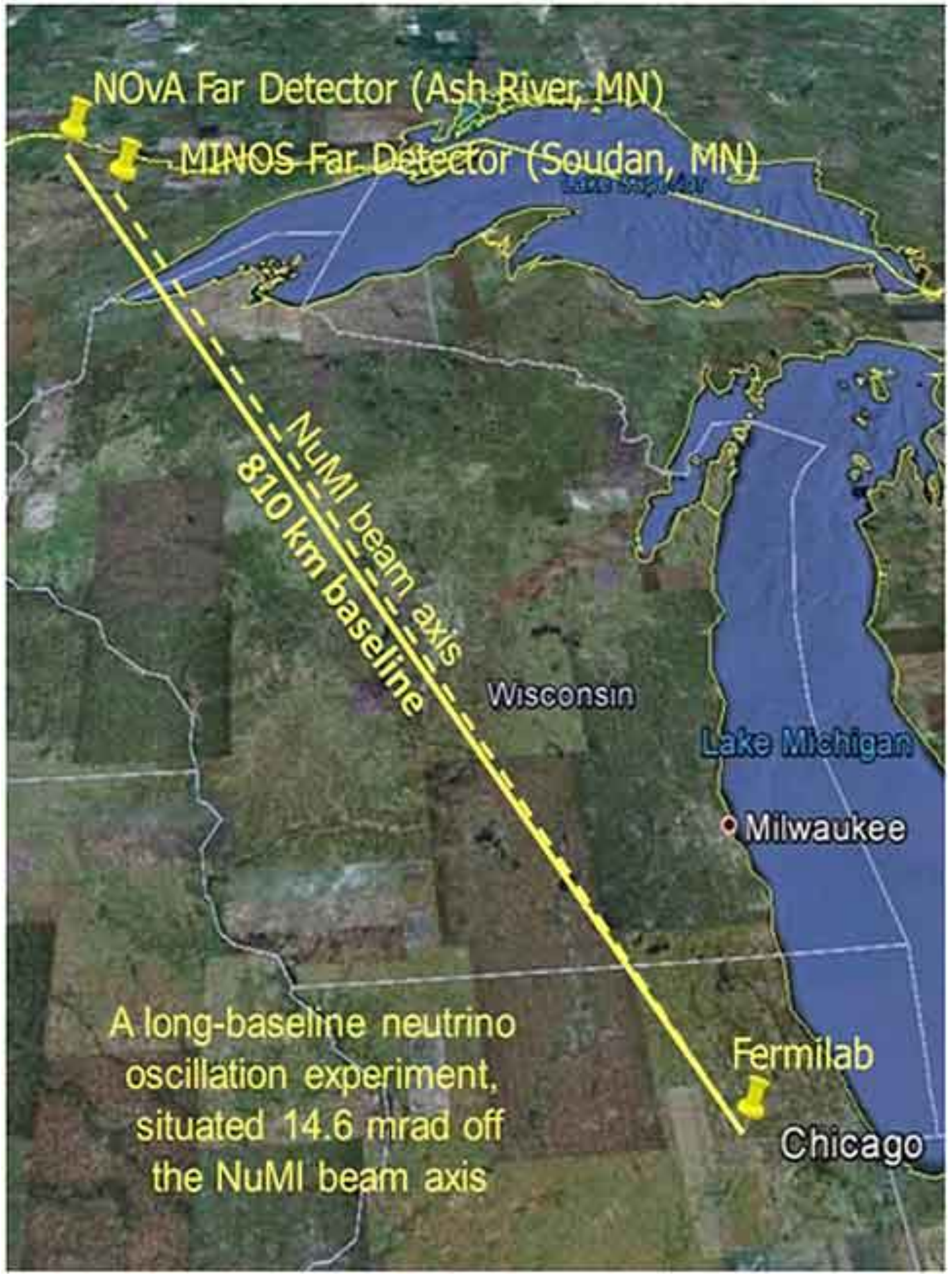
- Why do we talk about neutrino "oscillations?
- Because $P\left(\nu_\alpha \to \nu_\beta\right)$ can be expressed in terms of sines and cosines of L/E, where L is the distance from the detector and E is the neutrino energy
- The mass-squared splittings determine the frequency
- The angles θ_{jk} determine the amplitude



NOvA

What is NOvA?

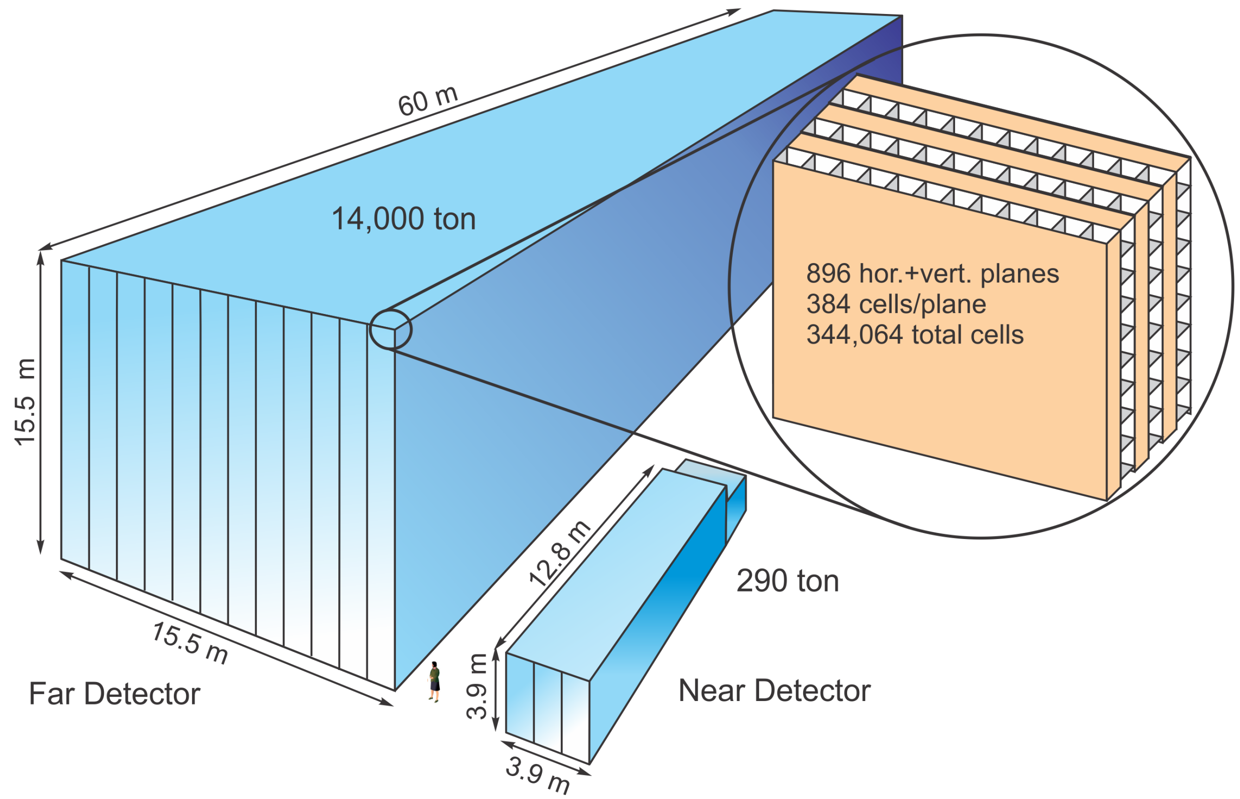
- NOvA is a long baseline neutrino oscillation experiment based at Fermilab
- The primary goal is to measure $\nu_e/\bar{\nu}_e$ appearance and $\nu_\mu/\bar{\nu}_\mu$ disappearance in the NuMI Beam
- This is done by looking for charged current interactions where the neutrino leaves behind a charged lepton of the corresponding flavor



NOvA

The Detectors

- NOvA has two liquid scintillating detectors 14.6 mrad off the NuMI beam axis

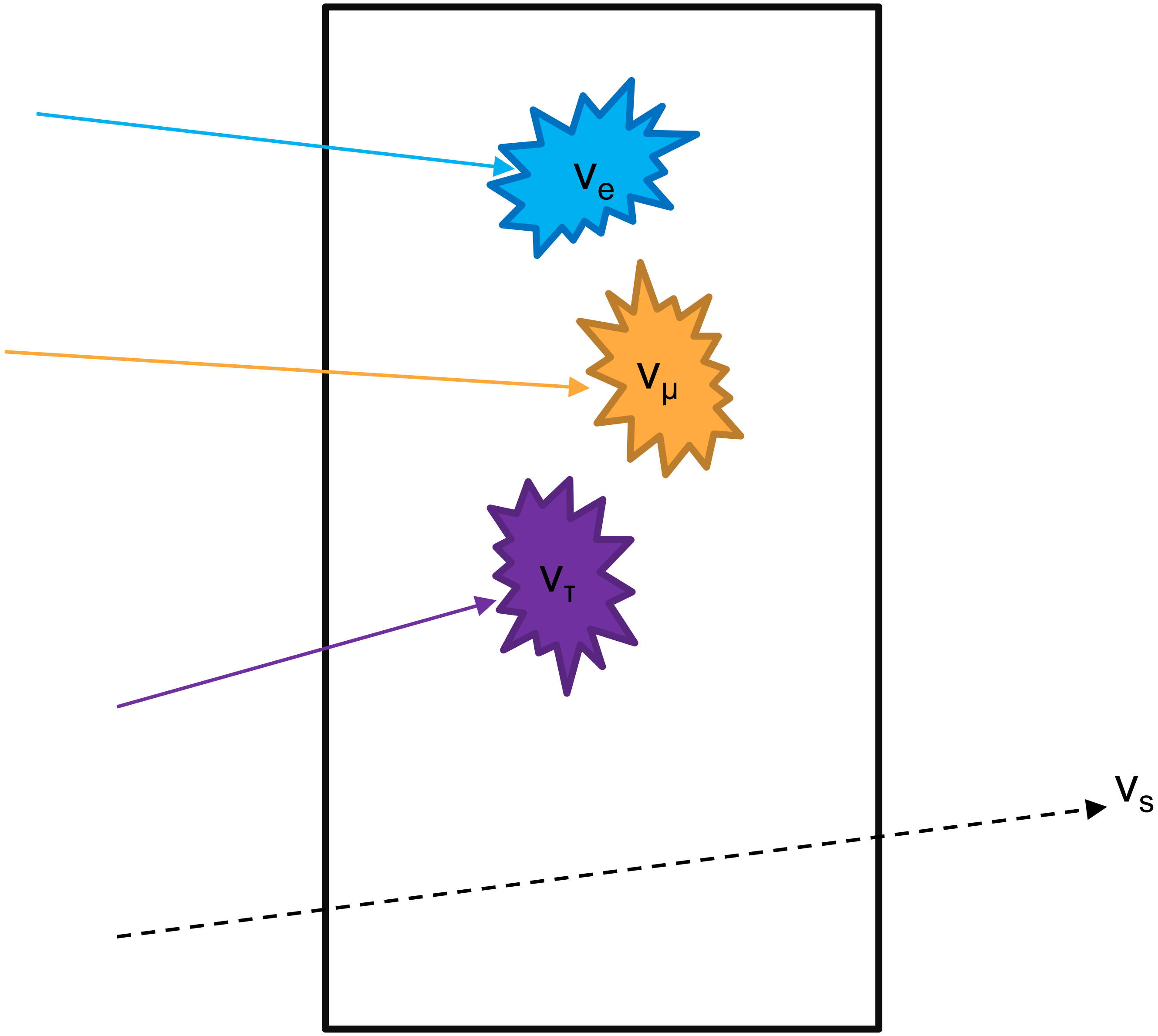


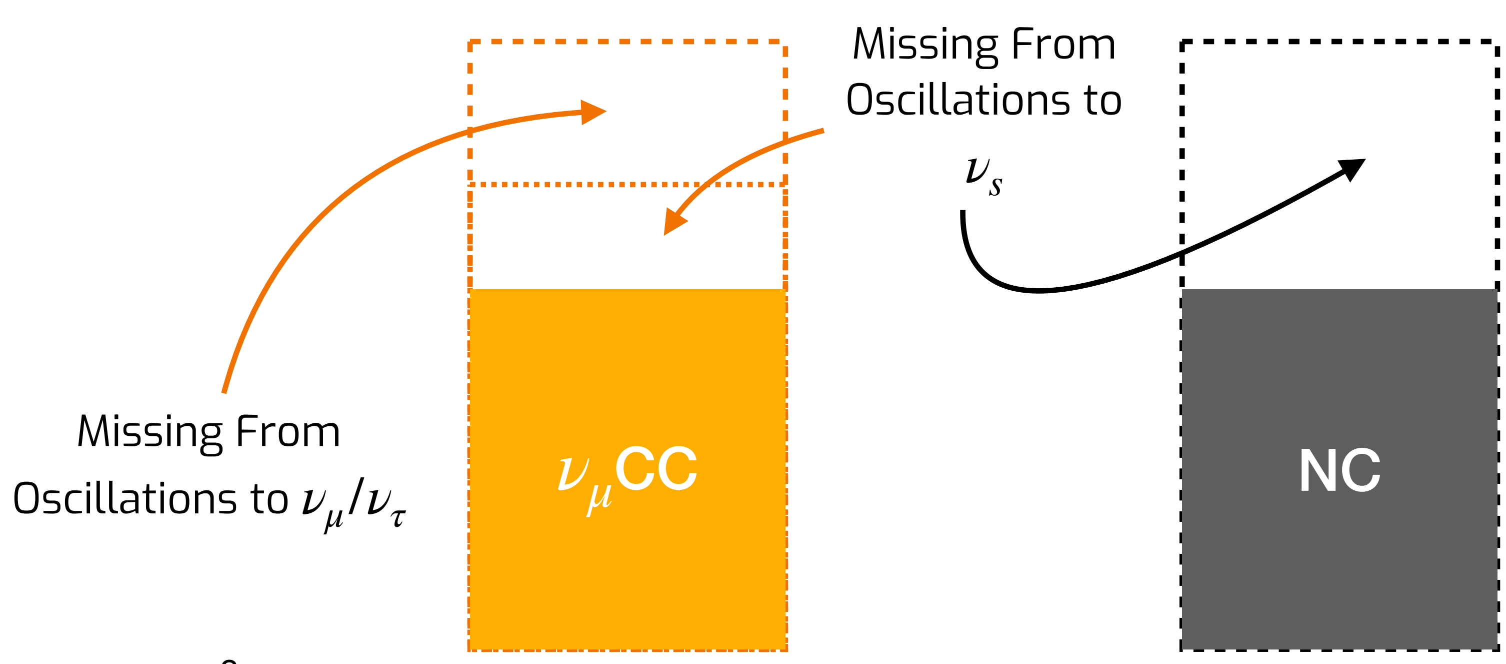
- The Near Detector (ND) and Far Detector (FD) are located 1 and 810 km from the NuMI target respectively
- The ND is typically used for predicting FD spectra
- To this end the two detectors are made to be functionally identical so most systematic uncertainties cancel

Sterile Neutrinos

A Fourth Neutrino?

- In the 3 flavor model there are ν_e, ν_μ, and ν_τ neutrinos, all of which interact via the weak force
- However, there is evidence which suggests a fourth neutrino, ν_s
- Measurements from LEP mean this neutrino must not interact
- We can supplement our ν_μ disappearance search with a NC deficit search to see if we are "missing" neutrinos
- Introducing ν_s requires 3 new angles θ_{j4}, 2 new CP-violating phases δ_{24} and δ_{14}, and 1 new mass m_4

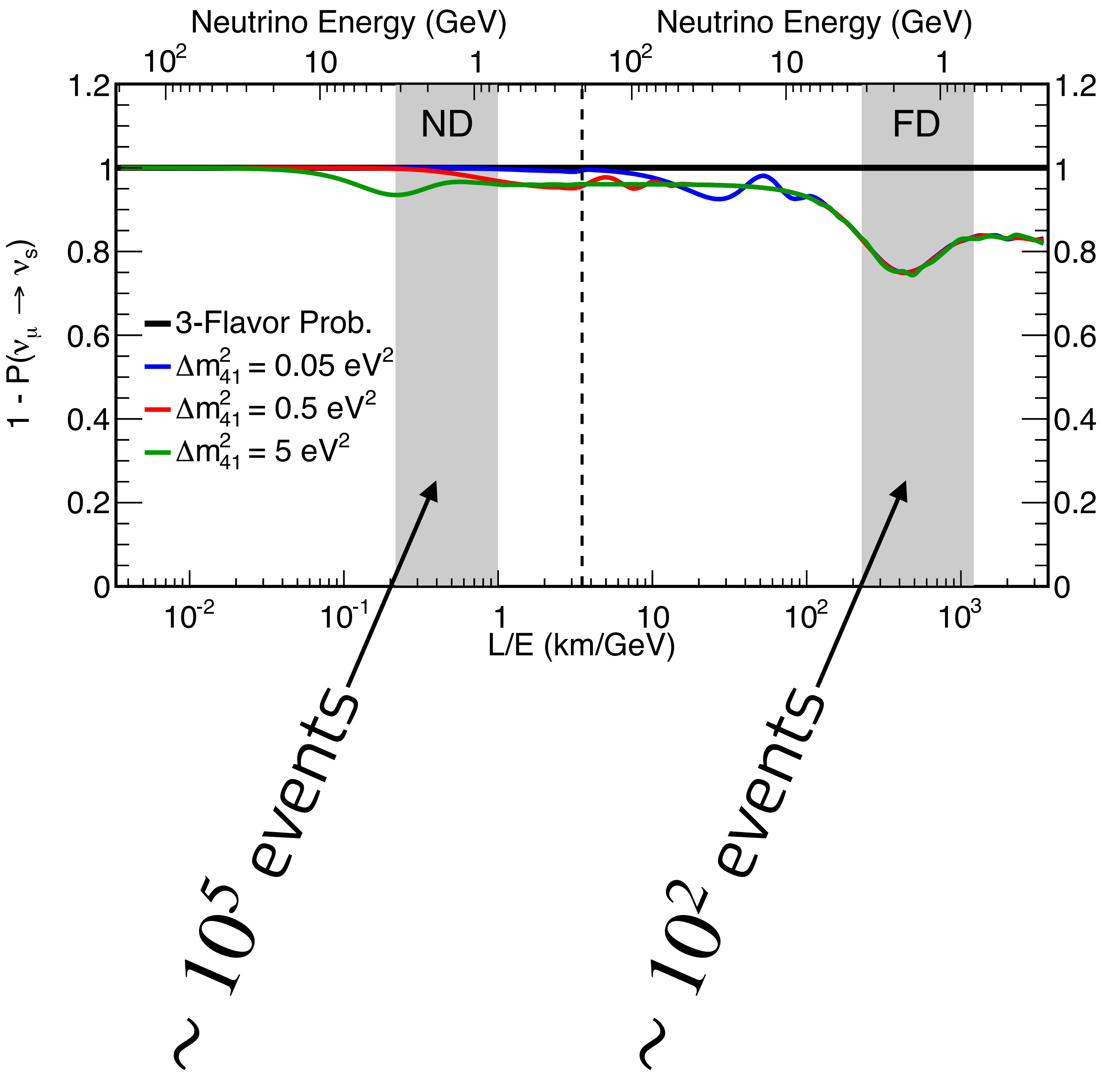




Sterile Neutrinos

Sterile Neutrinos in NOvA

- For certain values of Δm^2_{41} we can see oscillations to sterile in the ND
- We want to use the ND as part of our sample
- To access the ND events we need to change our mode of analysis

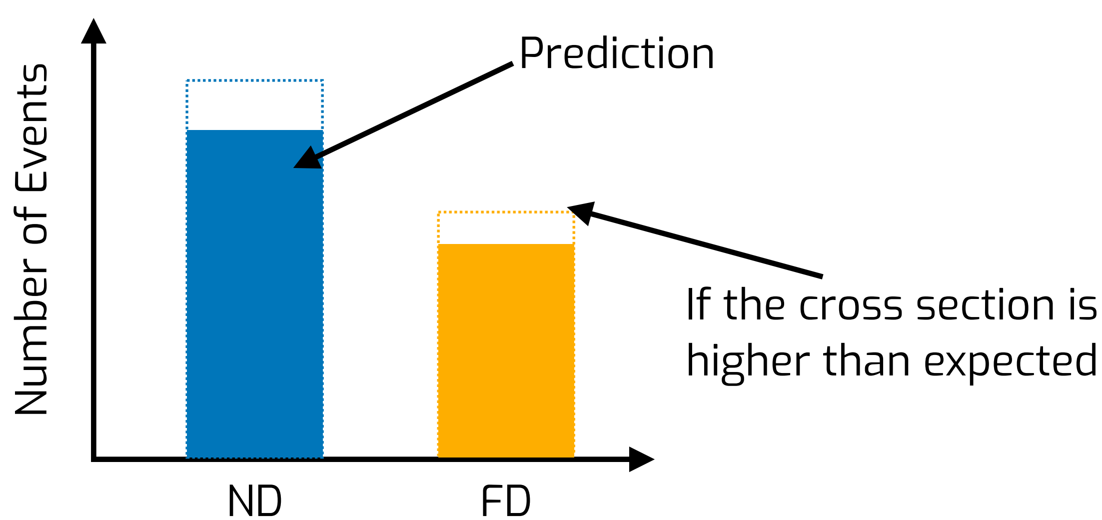


Covariance Matrices

How to handle correlations

- While we cannot use the ND as a reference for the FD, we do know that the uncertainties are correlated as they are functionally identical detectors

- For example, if we've underestimated the interaction cross section we should expect an increase in both the ND and FD simultaneously



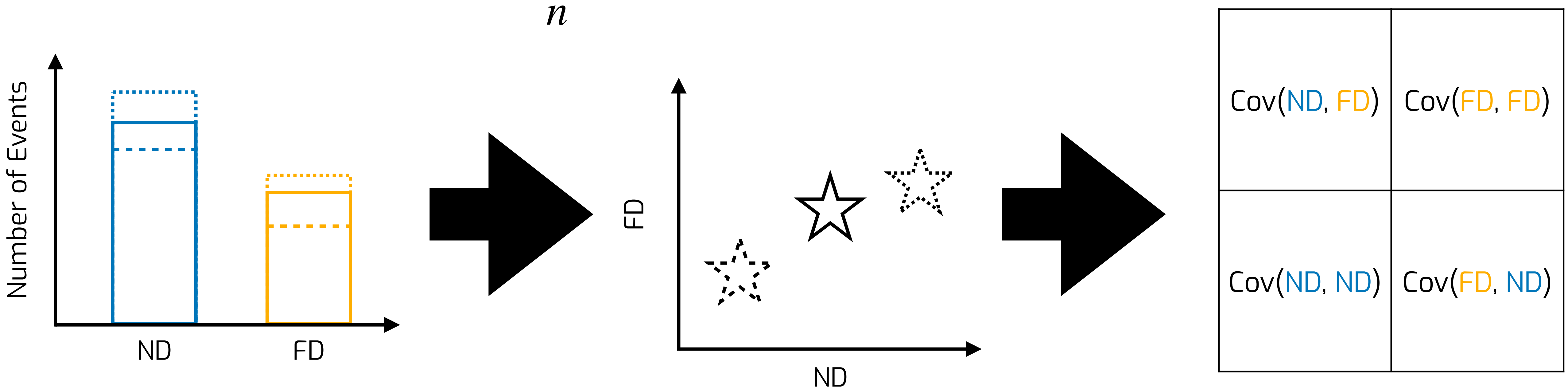
Correlation!

Covariance Matrices

How a Covariance Matrix Works

- We can encode how the two detectors vary into a matrix
- Run N pseudo-experiments, and calculate the covariance

$$\mathrm{Cov}\left(i,j\right) = \frac{1}{N}\sum_{n}^{N}\left(N_i^{\mathrm{Nominal}} - N_i^{n}\right)\left(N_j^{\mathrm{Nominal}} - N_j^{n}\right)$$



Covariance Matrix C

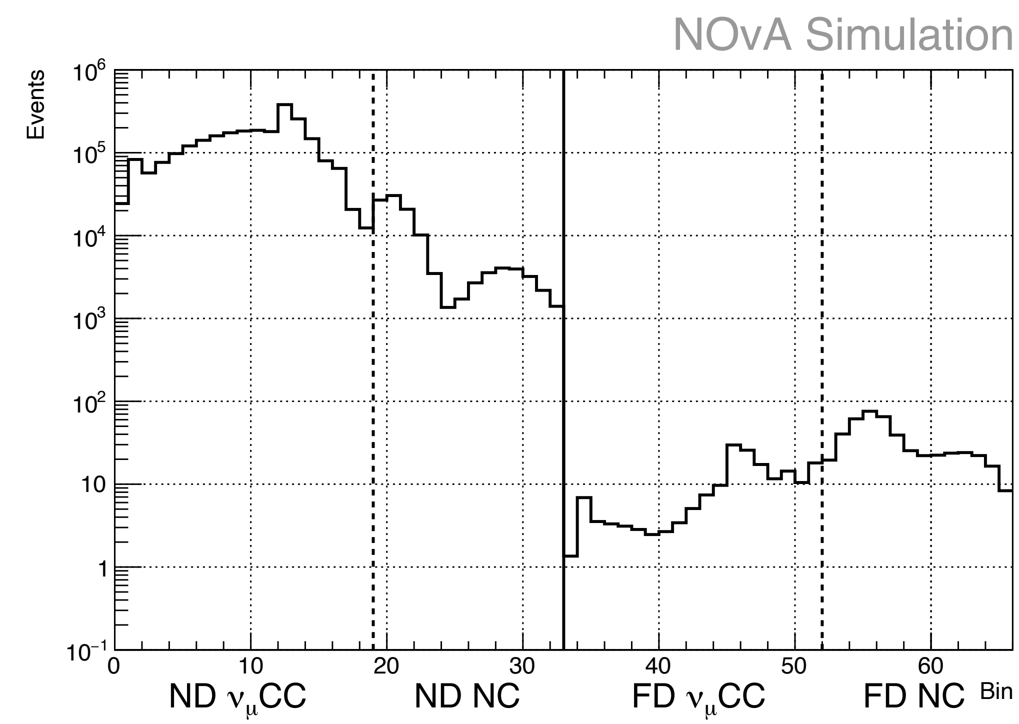
Covariance Matrices

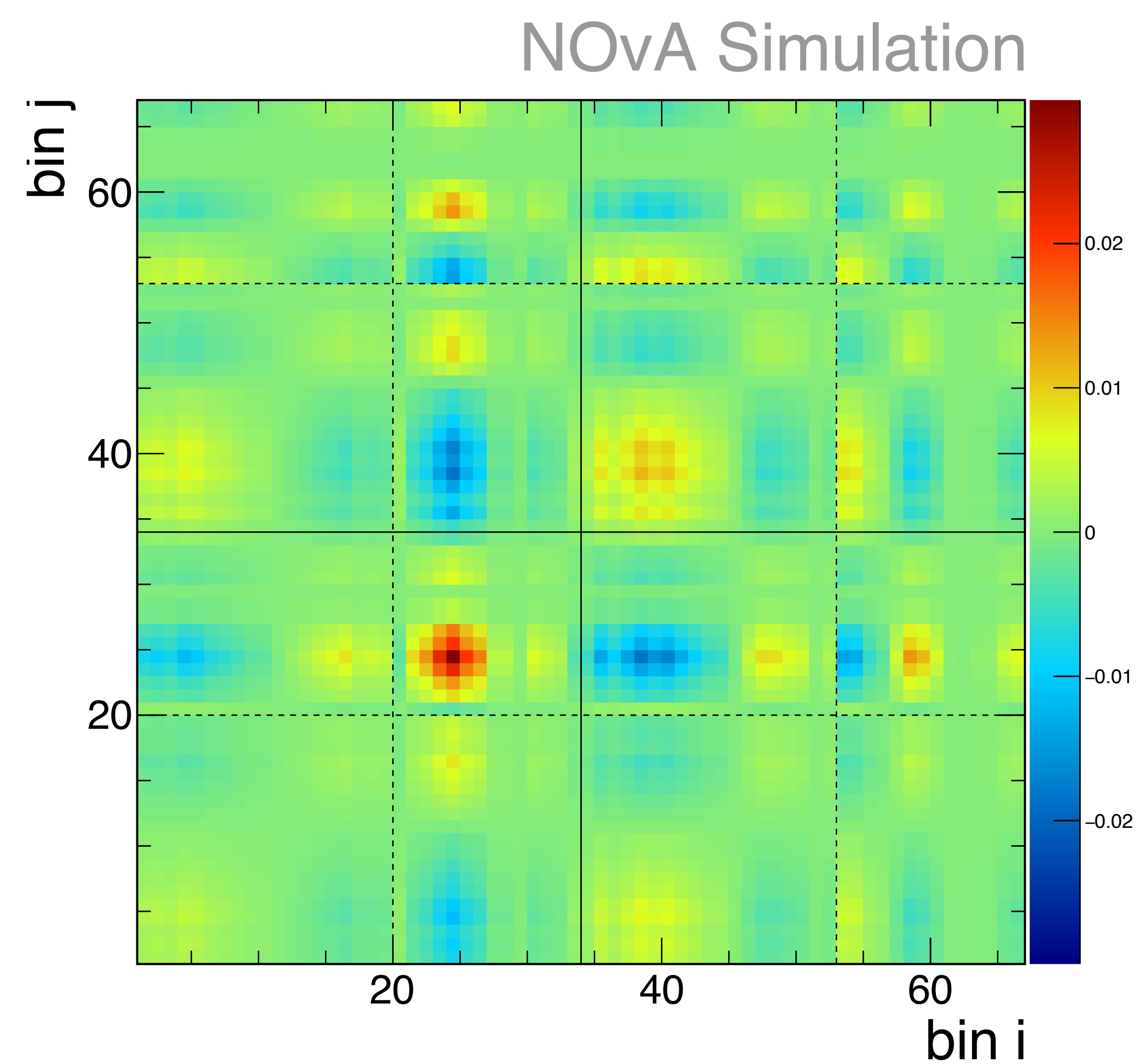
In Practice

- For each systematic uncertainty we generate 2000 pseudo experiments
- On the top right is an example Monte Carlo simulated universe where each energy/selection/detector bin is given a unique number
- We find the covariance between each bin and divide by the contents of the nominal to get a fractional covariance

$$F_{i,j} = \frac{\mathrm{Cov}\left(i, j\right)}{N_i^{\mathrm{nominal}} N_j^{\mathrm{nominal}}}$$

- The fractional covariance allows us to apply the covariance to spectra of different shape, i.e., with different oscillation parameters





Covariance Matrice

Using the Matrices

- Once we have the covariance matrices for each systematic, we can simply add them together for the total covariance

$$C_{\text{Total}} = C_{\text{XSec}} + C_{\text{Flux}} + C_{\text{Detector}} + \cdots$$

- By inverting the covariance matrix we can make a test statistic

$$\chi^2 \equiv \sum_{i,j} \left(N_i^{\text{data}} - N_i^{\text{model}}\right) \times \left(C_{\text{Total}}^{-1}\right)_{i,j} \times \left(N_j^{\text{data}} - N_j^{\text{model}}\right)$$

- If bins i and j change as we expect, then the contribution to χ^2 is smaller

Covariance Matrices

Checking our Sensitivity

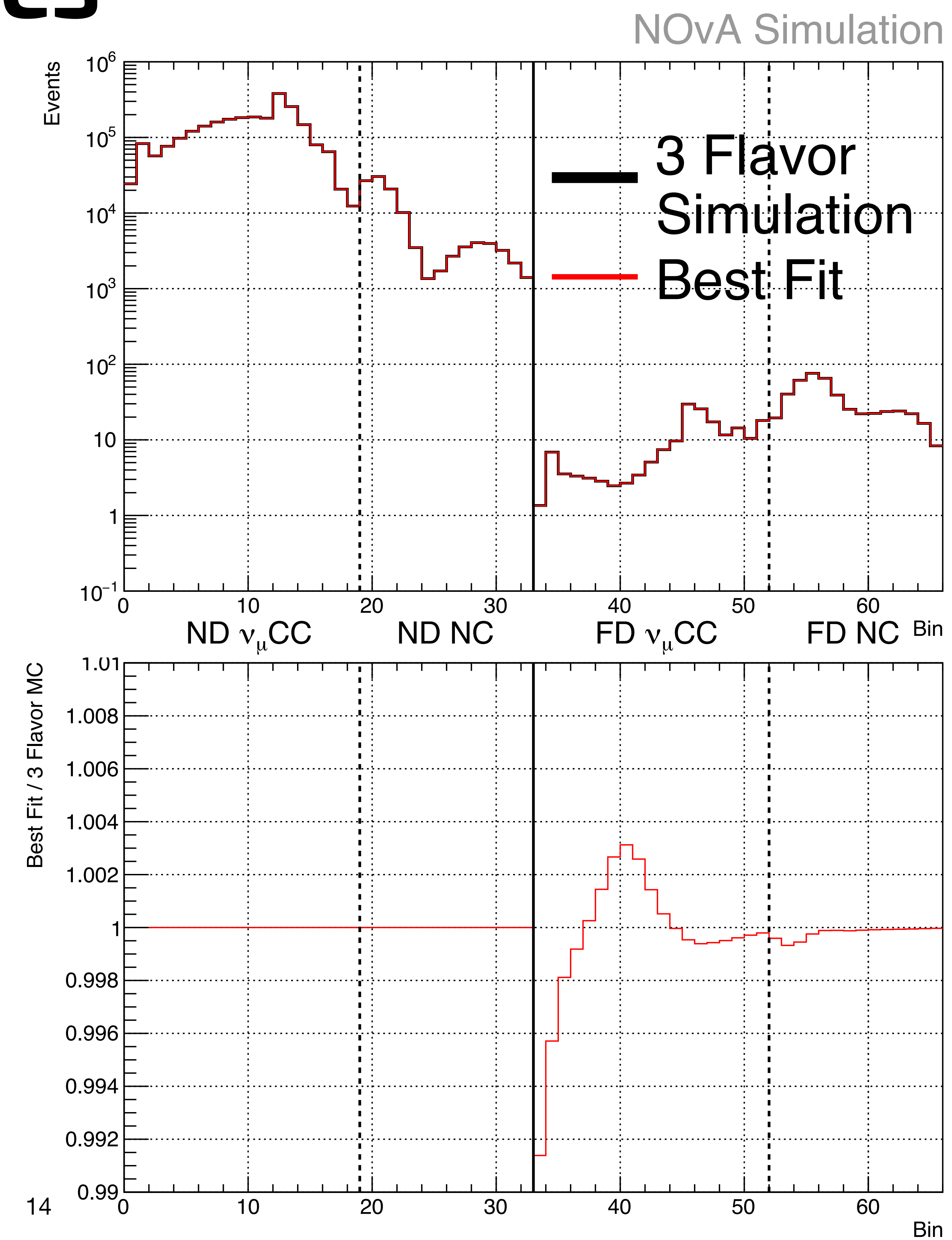
- We can check our test statistic by comparing a MC 3 Flavor prediction to a library of simulated spectra which include sterile oscillation

- The oscillation parameters in the library have $10^{-4} < \sin^2\left(\theta_{24}\right) < 1$ and $10^{-3}\ \text{eV}^2 < \Delta m^2_{41} < 10^2\ \text{eV}^2$

- On the right are some preliminary results of this test

- The 3 flavor prediction compared with the closest match from the sterile universes are shown on top

- Below is the ratio of the best fit to the 3 flavor prediction



Conclusions

- By using covariance matrices we can gain access to the neutrino events in our ND while still accounting for the functionally identical FD
- This is especially useful for sterile neutrino searches as the ND can help us search for short baseline oscillations
- This analysis still ongoing, but we look forward to showing our sensitivity in the near future