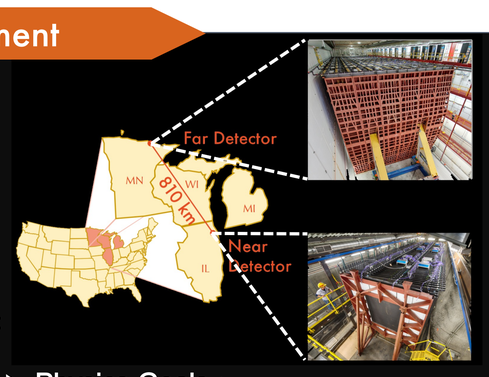
PISCES two-detector covariance matrix fit for the NOvA Experiment

Miriama Rajaoalisoa for the NOvA Collaboration
Department of Physics, University of Cincinnati – rajaoama@mail.uc.edu

UNIVERSITY OF Cincinnati
U.S. DEPARTMENT OF ENERGY | Office of Science

1 The NOvA Experiment

- **NOvA** is a long-baseline neutrino experiment based at Fermilab using the 700 kW NUMI muon neutrino beam.
- **NOvA** uses functionally identical Near (ND) and Far (FD) Detectors:
  - ND placed 1 km from neutrino source (300 tons).
  - FD placed 810 km from the source at Ash River (14 ktons, 14 mrad off-axis).
  - Detectors are liquid scintillator tracking calorimeters.



- **Physics Goals :**
  - Precise measurements of θ_{23} and Δm^2_{32}.
  - Determination of the neutrino mass hierarchy and constraining the value of δ_{CP}.
  - Look for New Physics.

2 The PISCES Method

- **Extracting oscillation parameters**
  - Currently, NOvA uses an extrapolation technique :
    $$FD_{prediction} = \frac{FD_{MC}}{ND_{MC}} \times ND_{data}$$ → Ratio is limited by large statistical uncertainties in the FD.
  - Current method : treats systematic uncertainties as nuisance parameters → suffers from poor scalability.
  - Sterile neutrino searches : a simultaneous ND and FD fit is required to be able to probe sterile oscillations in both detectors.
- **Exploring a new technique : PISCES** (**P**arameter **I**nference with **S**ystematic **C**ovariance and **E**xact **S**tatistics)
  - Encodes systematic uncertainties in a covariance matrix → supports as many systematic uncertainties as necessary.
  - Enables a joint Near and Far Detector Fit that fully takes advantage of high statistics samples in the ND.
- Parameter Inference with Systematic Covariance and Exact Statistics

$$\chi^2 = \chi^2_{stats} + \chi^2_{systs}$$

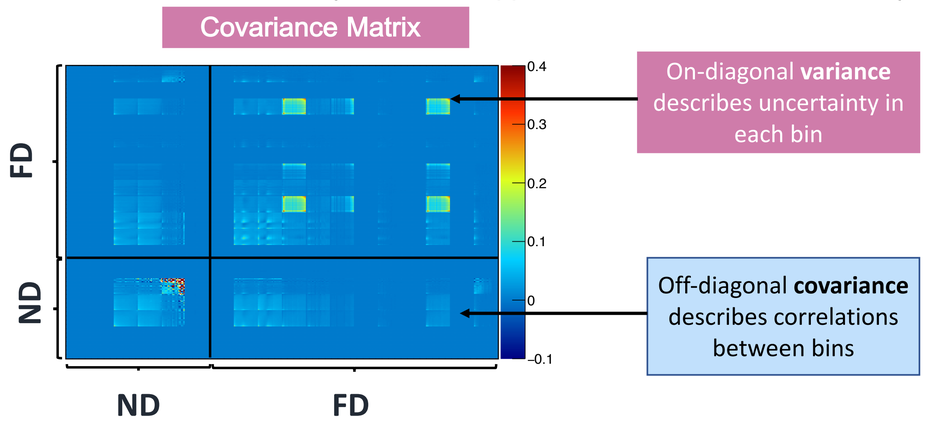
$$\chi^2_{stats} = 2\sum_i^N \left[\left(\sum_\alpha^M \boldsymbol{\mu}_{\alpha i}\, s_{\alpha i}\right) - x_i + x_i\, log\left(\frac{x_i}{\sum_\alpha^M \boldsymbol{\mu}_{\alpha i} s_{\alpha i}}\right)\right]$$

$$\chi^2_{systs} = \sum_{ij}^N \sum_{\alpha\boldsymbol{\beta}}^M (s_{\alpha i} - 1)\, V^{-1}_{\alpha i \boldsymbol{\beta} j}\, (s_{\boldsymbol{\beta} j} - 1)$$

$s_{\alpha i}$: systematic shifts
$\boldsymbol{\mu}_{\alpha i}$: prediction
x_i : data
i : analysis bin
α: beam component index
V: Covariance Matrix

3 The PISCES ND+FD Fit

- **PISCES ND+FD Fit** : Joint Near and Far Detector fit, officially used for the NOvA Sterile Neutrino Analysis and be applied to the NOvA 3-Flavor Analysis.

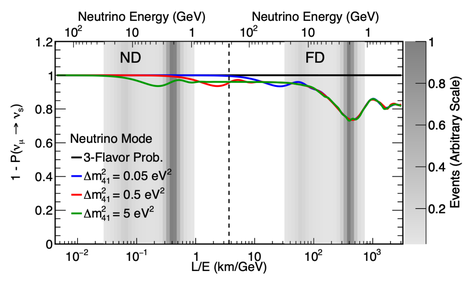


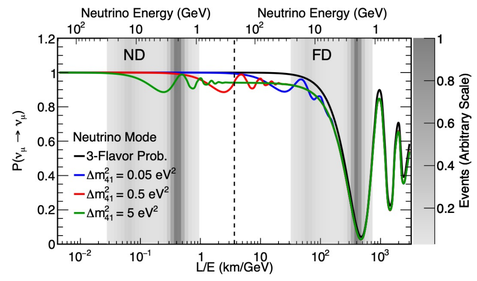
Using nominal prediction and data → Solve for optimal systematic pulls → Get shifted predictions → Fit for the oscillation parameters

- **Solving for optimal systematic pulls**
  - Minimize χ^2 with respect to systematic shift.
  - Solve for optimal systematic shifts in each bin using their Hessian matrix and gradient vector with respect to the χ^2, utilizing the **Levenberg-Marquardt algorithm** for least-squares estimation of nonlinear parameters.

4 NOvA Sterile Neutrino Analysis

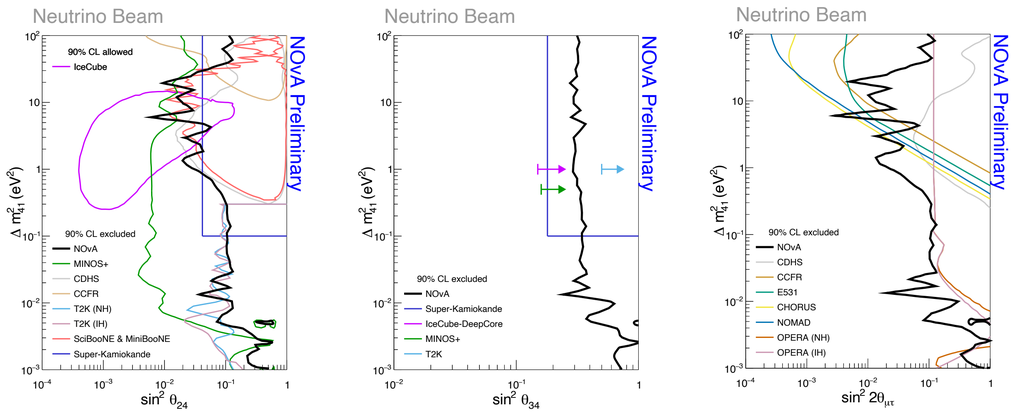
- Sterile neutrino search through **neutral current events disappearance** and **additional ν_μ disappearance**.
- Sterile oscillations can manifest in FD and ND (at higher mass splitting). The PISCES joint ND+FD fit enables to both constrain systematic uncertainties and be sensitive to sterile oscillations in both detectors.





NOvA Sterile Neutrino Analysis

$sin^2\theta_{24}$ vs Δm^2_{41} | $sin^2\theta_{34}$ vs Δm^2_{41} | $sin^2 2\theta_{\mu\tau}$ vs Δm^2_{41}

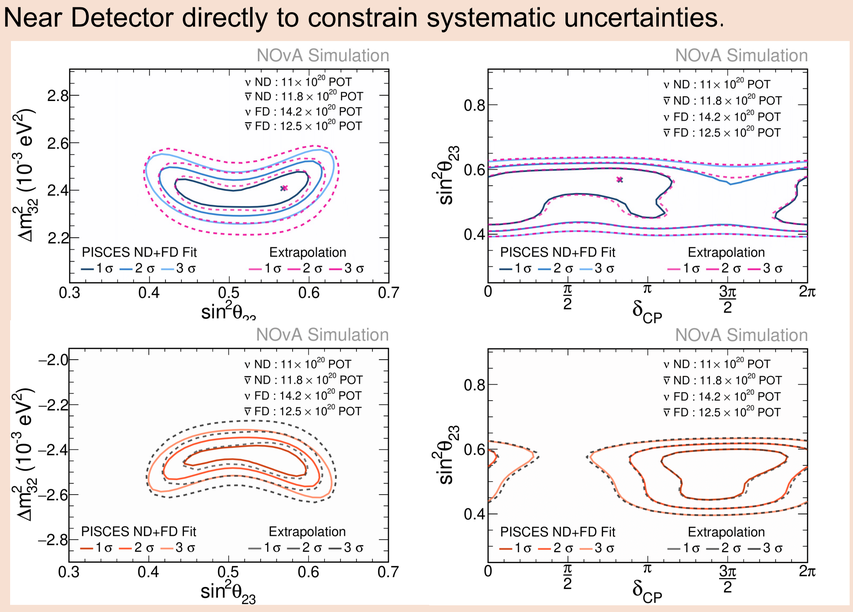


- Results obtained using neutrino datasets (no antineutrinos).
- First exclusion contour for the $sin^2\theta_{34}$ vs Δm^2_{41} parameter space and world-leading sensitivity at low mass splitting for $sin^2 2\theta_{\mu\tau}$ vs Δm^2_{41}.
- Future improvements to the analysis include adding antineutrino datasets and ν_e samples. The flexibility of the PISCES framework allows it to handle those additional samples.

5 NOvA 3-Flavor Analysis

PISCES ND+FD fit vs Extrapolation (Fake Data Analysis)

- PISCES ND+FD fit : can take advantage of the high statistic samples from the Near Detector directly to constrain systematic uncertainties.

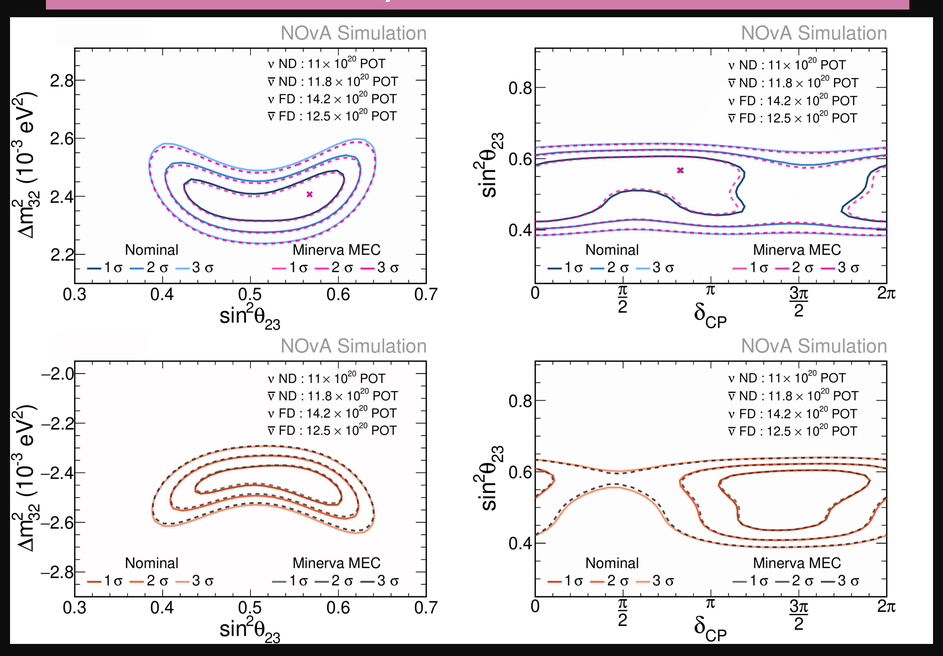


- Fake Data Comparison
  - Generated fake data at the NOvA 2020 Best Fit point to test current method used in NOvA (Extrapolation) and the PISCES joint ND+FD Fit.
  - Comparison shows advantages of ND+FD fit as the direct use of the ND information helps to constrain systematics.

6 PISCES ND+FD Robustness Test

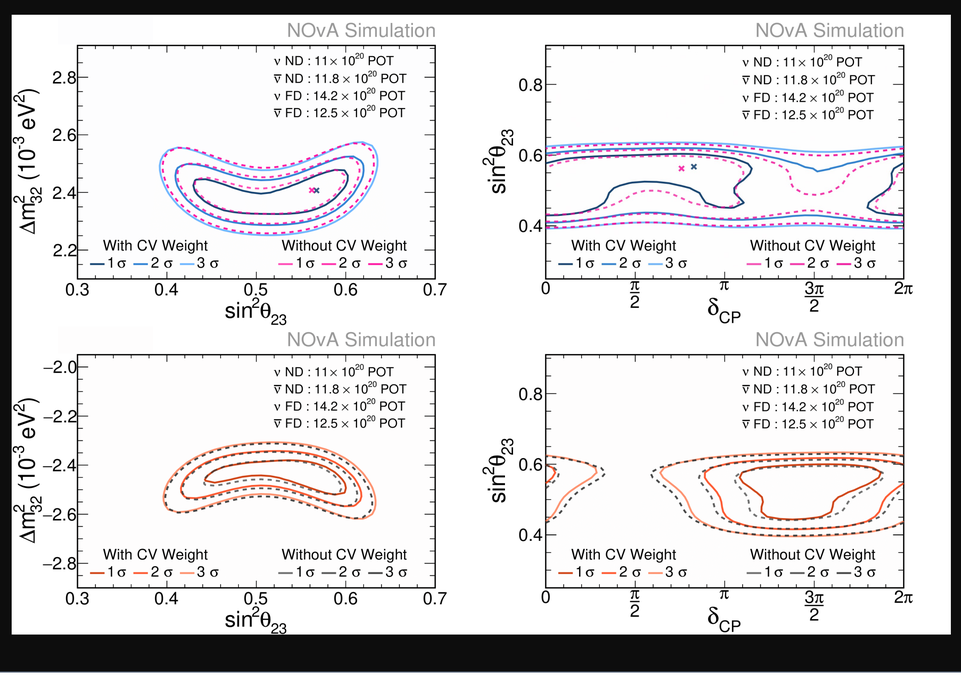
Generating fake data for different scenarios to test fit robustness

Minerva MEC Analysis - NOvA 2020 Best Fit Point



- Minerva MEC analysis: a fake data is generated using a different MEC Model (Minerva MEC) than the default MEC used for NOvA (Valencia MEC). The fit to the fake data is compared to the nominal fit to test for the bias in the fitter.
- The Minerva MEC model is an adjustment of the Valencia MEC using an enhancement shaped as a 2D-gaussian based on the data from the MINERvA experiment (same beam as NOvA but on axis).

Difference in Central Value Analysis - NOvA 2020 Best Fit Point



- Difference in Central Value analysis: the case where two predictions with considerable central value differences are used to fit for the same fake data. In this analysis we considered a prediction with a cross-section central value weight.
- These robustness tests have been done at different oscillation points, and the results showed that the shifts in contours are minimal in all considered case.

7 Conclusion

- The PISCES technique enables complex fits such as a joint ND+FD fit.
- The results from the NOvA sterile oscillations using the NOvA neutrino samples shows promising sensitivity and can be further improved by adding in extra samples such as the antineutrino or the ν_e samples. The PISCES framework's flexibility allows for such addition.
- The PISCES joint ND+FD fit can also be used for the 3-Flavor analysis. Preliminary fake data comparison shows advantages to the use of the joint Near and Far detector fit.
- Ongoing robustness studies show that the fitter works well even in case of simulation mis-modelling.