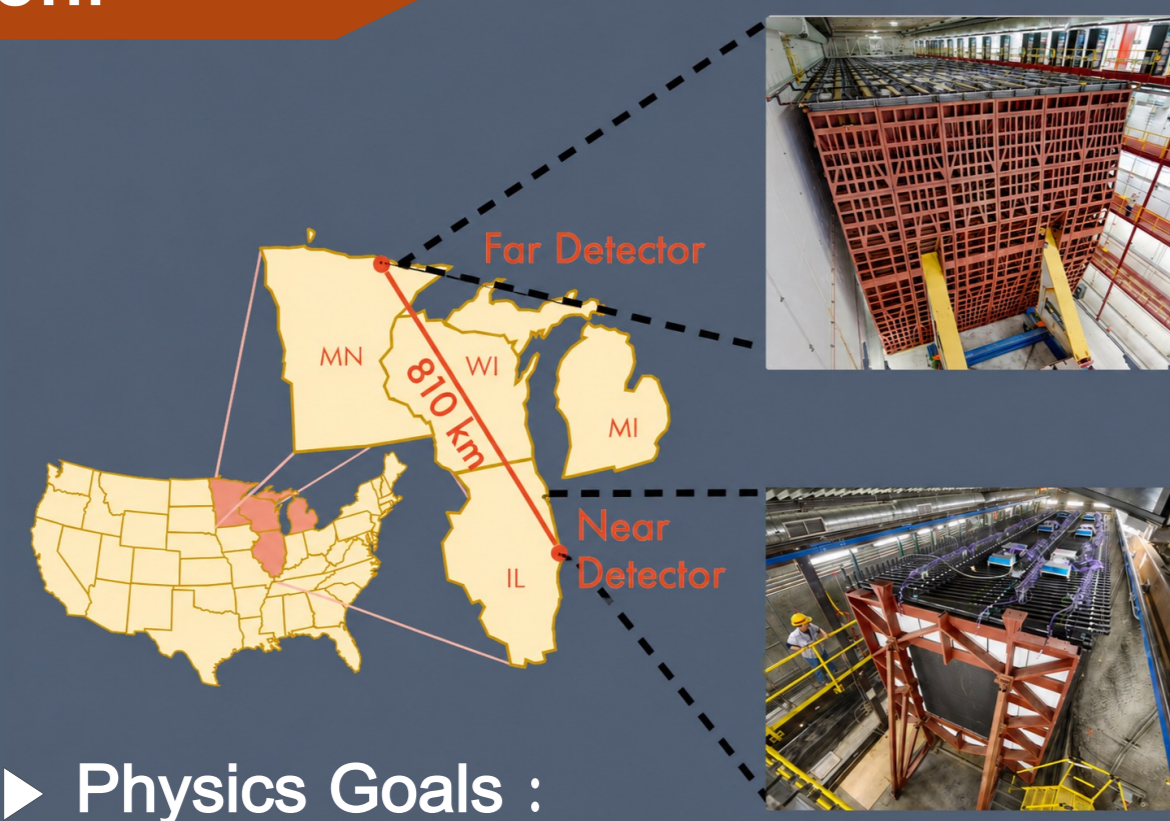


1 The NOvA Experiment

NOvA is a long-baseline neutrino experiment based at Fermilab using the NUMI muon neutrino beam.



NOvA uses functionally identical Near (ND) and Far (FD) Detectors:

- ND: 1 km from neutrino source (300 tons).
- FD: 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_{32}^2 .
- Determination of the neutrino mass hierarchy and constraining the value of δ_{CP} .
- Look for New Physics.

4 Systematic Pull Inference

Post-fit diagnostic: recover individual systematic pulls from the PISCES shifted prediction

- PISCES gives final shifted prediction \rightarrow Newton-Raphson method is used to infer the effective pulls corresponding to that shifted prediction.

Newton-Raphson method

- Solve for individual pulls α using Newton-Raphson:

$$m_i = \beta_i \mu_i \quad \text{Shifted Predictions } m_i \quad m_i = \prod_j (1 + \alpha_j V_{ij}) \mu_i$$

Shifted Pred Systematic scale Obtained with PISCES Nominal Pred Shifted Pred Systematic Pulls Nominal Pred

$$F_i(\alpha) = \sum_j \log(1 + \alpha_j V_{ij}) - \log(\beta_i) = 0$$

i: analysis bin index
j: systs index

Systematics with degeneracies

Systematics with degeneracies :

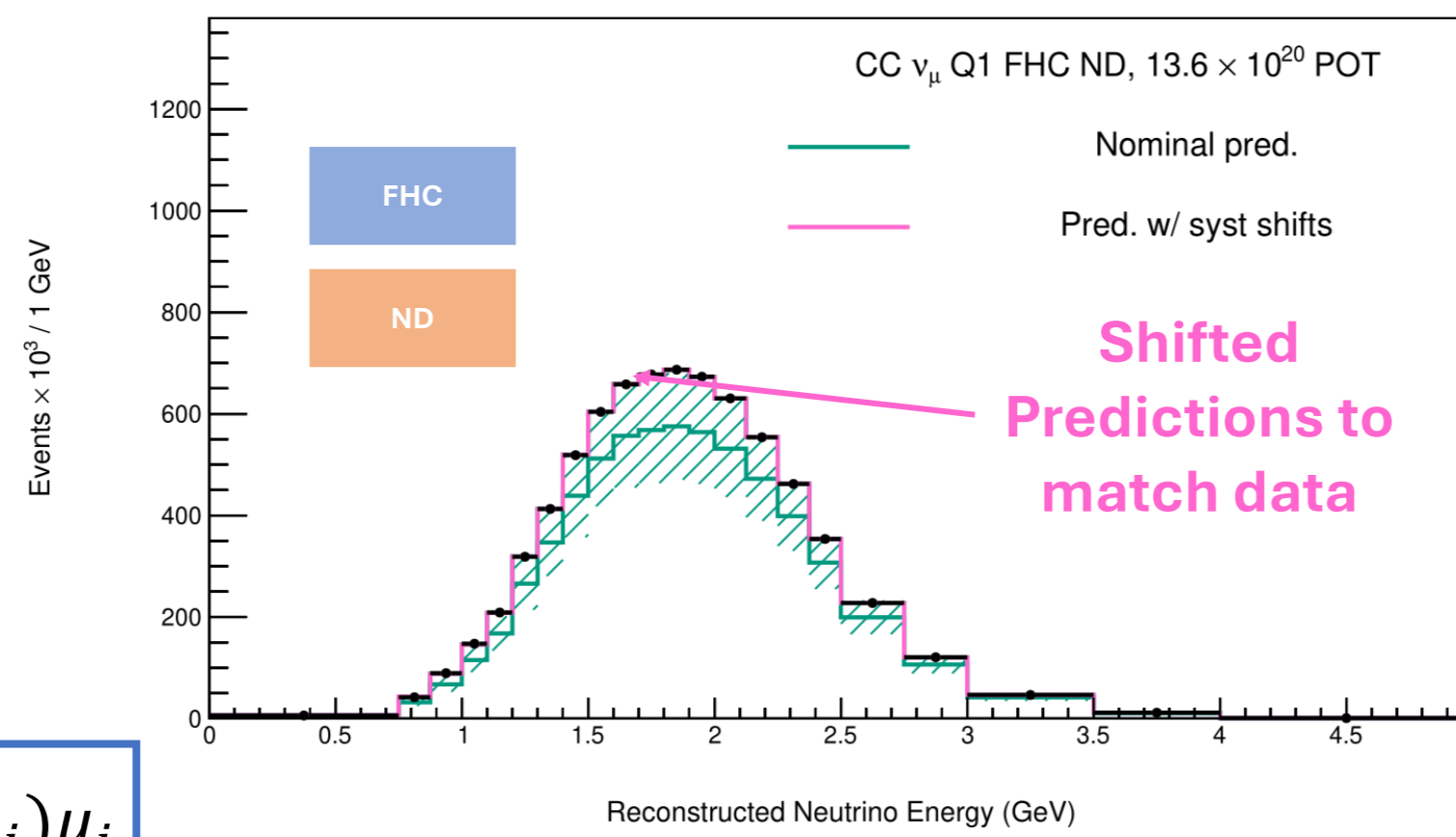
- Switch to PCA basis: No degeneracy, NR method can find a unique solution.

SHAP systematic importance

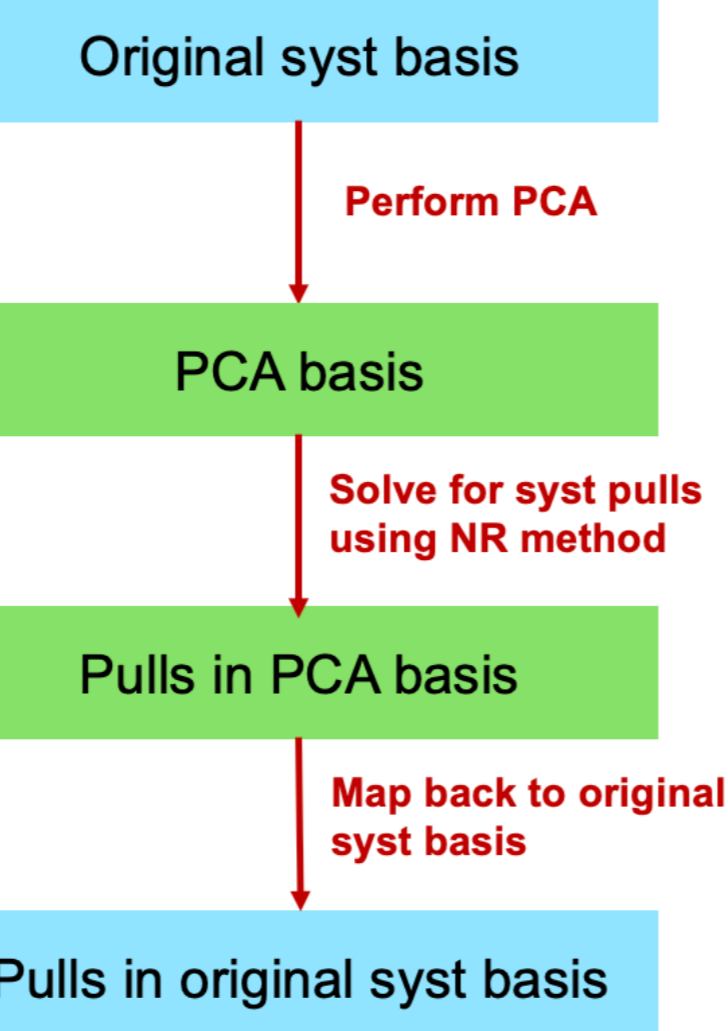
Systematics driving the fit are ranked by their SHAP score:

$$I_j = \frac{1}{N_{\text{bins}}} \sum_i |S_{ij}(a_{\text{pulls}})_j|$$

S: fractional 1 σ response of bin i to systematic j
a: pull values



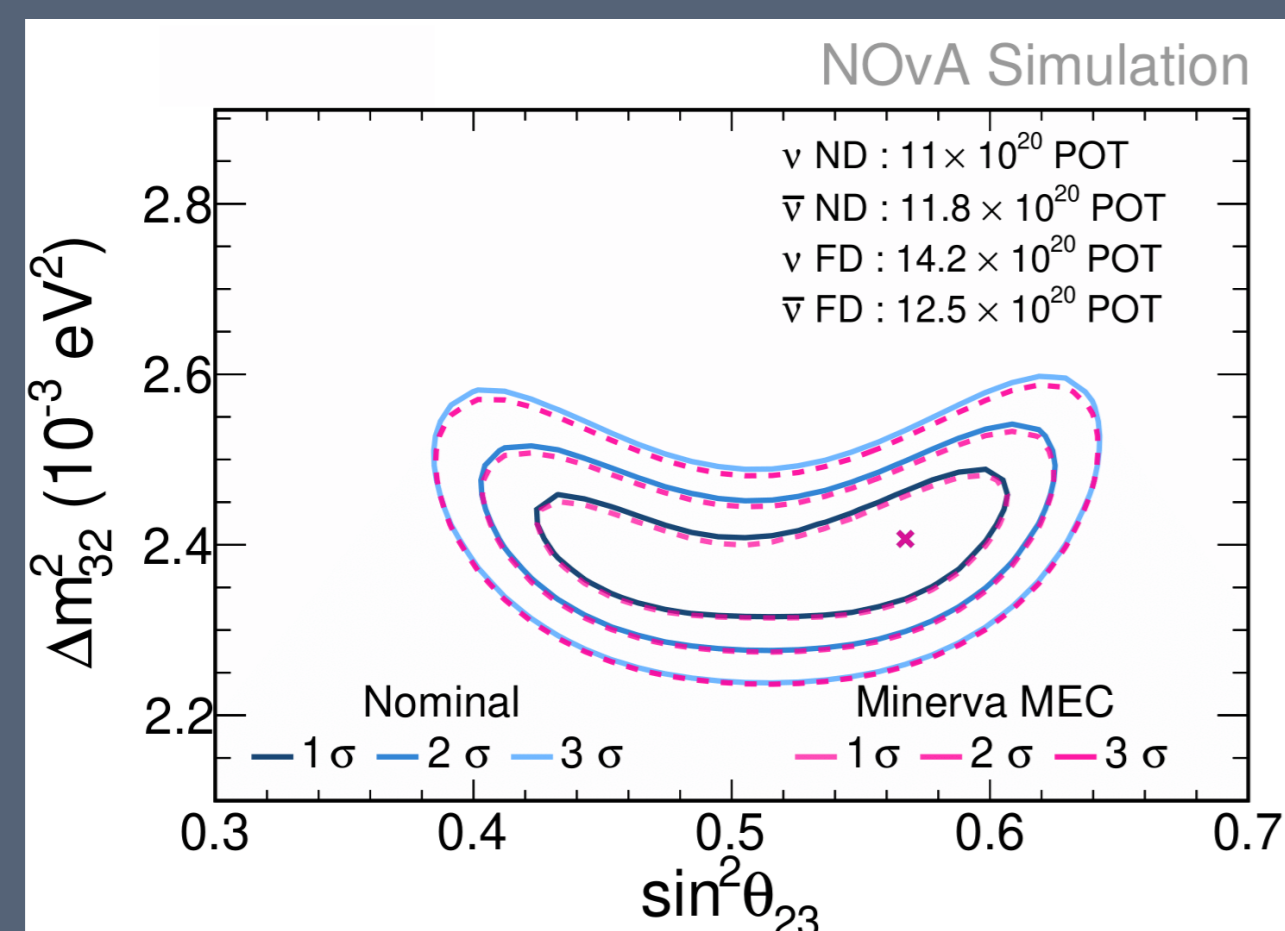
NR + PCA method



6 PISCES ND+FD Robustness test

MINERvA MEC Analysis

- MINERvA MEC:** the default interaction model for the Meson Exchange Current Model (MEC) used in NOvA is modified to the MINERvA experiment MEC model.



Objective:

Test PISCES ND+FD framework with different fake data where we change models/predictions.

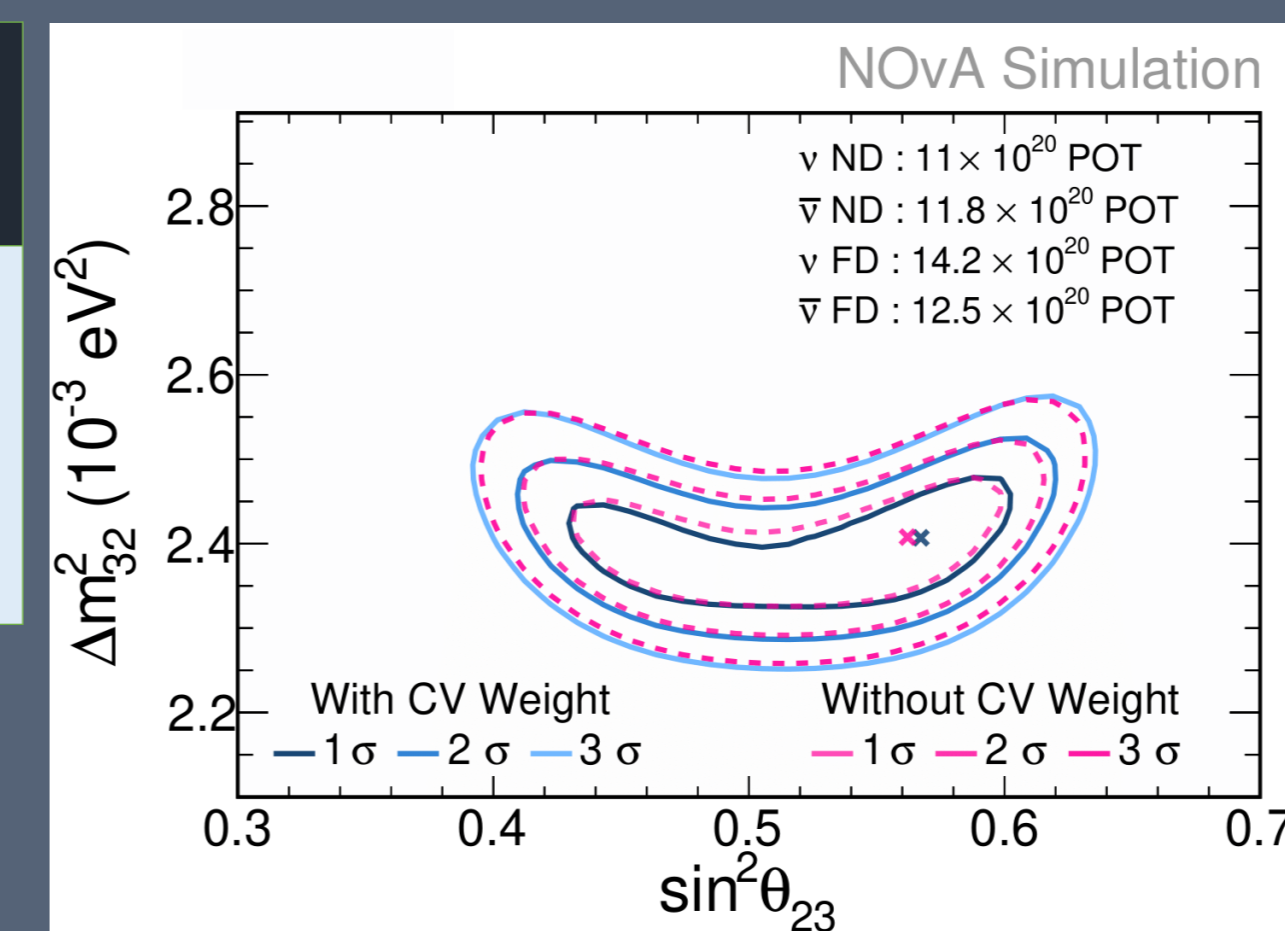
\rightarrow Evaluate shift in contours and best fit points to probe for potential bias.

Systematics driving the fit (SHAP score)	Secondary response
Cross-section/nuclear model: ~44% (MEC, QE, resonance, low-Q2, nuclear-response, and DIS effects)	FSI/hadron transport: ~22% Detector/flux: ~16–19% each

Results: Shift in contours and best fit points are minimal, in both cases. PISCES absorbs data/MC differences with the physically motivated systematic uncertainties.

Difference in Central Value Analysis

- Fit the same fake data with predictions with significant differences in central-values (with and without cross-section weights).



Systematics driving the fit (SHAP score)	Secondary response
Cross-section/Interaction model: ~50% (MEC, QE, axial Form Factor, CC pion production...)	FSI/hadron transport: ~27% Flux: ~14% / Detector: ~8%

Takeaway: No significant bias observed. Fitter responds through physically expected systematics.

2 The PISCES Method

Extracting oscillation parameters

- Current method used in NOvA: **extrapolation technique** to get corrected FD predictions \rightarrow FD only fit.
- Extrapolation technique:

$$FD_{\text{prediction}} = \frac{FD_{MC}}{ND_{MC}} \times ND_{\text{data}}$$

- \rightarrow Ratio limited by large statistical uncertainties in the FD/ does not take full advantage of high ND stats.
- Current method treats systematic uncertainties as nuisance parameters \rightarrow suffers from poor scalability.

Exploring new techniques: PISCES ND+FD fit (Parameter Inference with Systematic Covariance and Exact Statistics)

- Encodes systematic uncertainties in a covariance matrix \rightarrow 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

$$\chi^2 = \chi_{\text{stats}}^2 + \chi_{\text{systs}}^2$$

$$\chi_{\text{stats}}^2 = 2 \sum_i^N \left[\left(\sum_{\alpha}^M \mu_{\alpha i} s_{\alpha i} \right) - x_i + x_i \log \left(\frac{x_i}{\sum_{\alpha}^M \mu_{\alpha i} s_{\alpha i}} \right) \right]$$

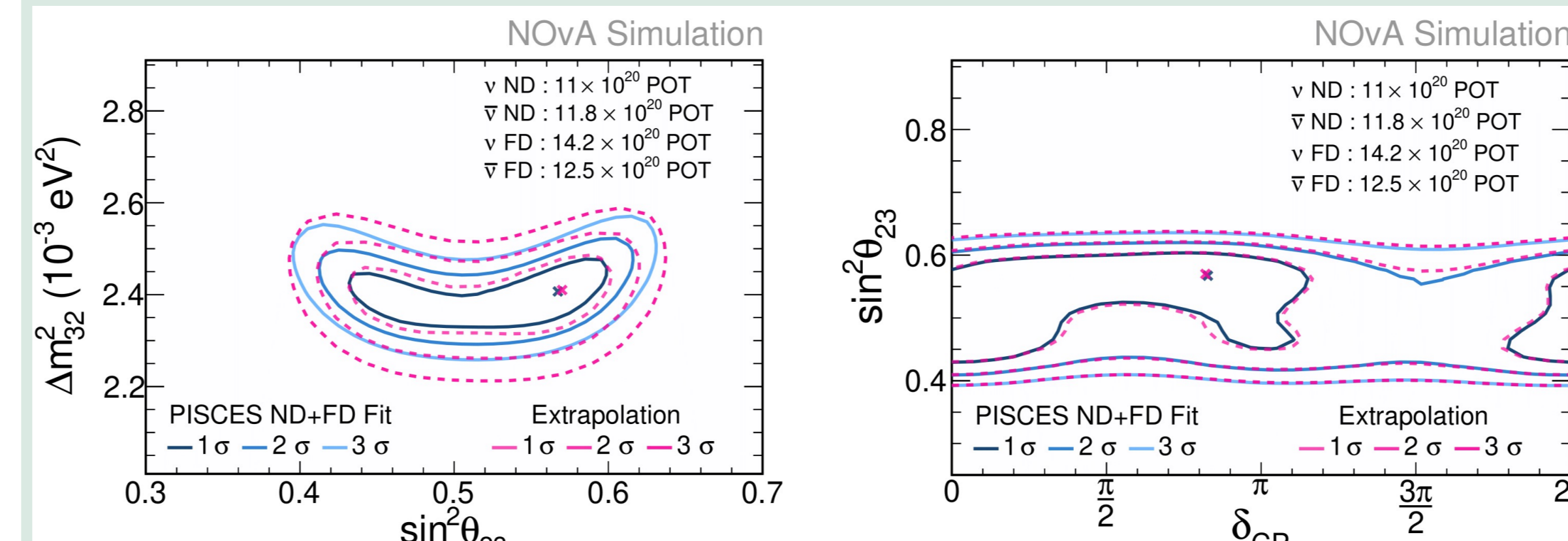
$$\chi_{\text{systs}}^2 = \sum_{ij}^N \sum_{\alpha\beta}^M (s_{\alpha i} - 1) V_{\alpha i \beta j}^{-1} (s_{\beta j} - 1)$$

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

5 NOvA 3-Flavor Analysis

- Fake Data tests to compare the current extrapolation method with the PISCES simultaneous ND+FD fit:**

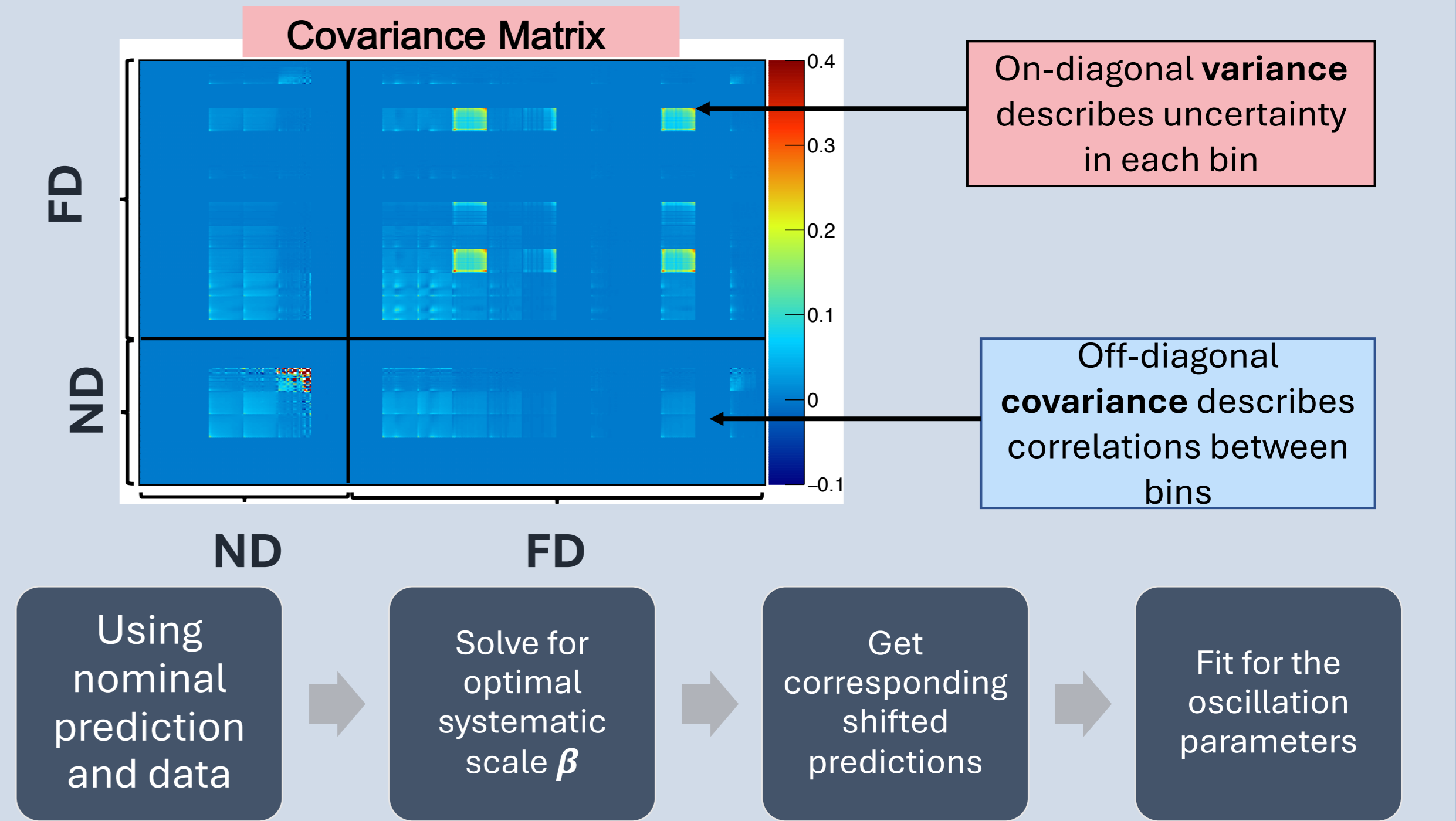
- Fake data generated at the NOvA 2020 Best Fit values.
- ND+FD fit uses ND statistics directly.



\rightarrow Results show improved constraint of systematic uncertainties with the joint ND+FD fit.

3 PISCES ND+FD Fit

- PISCES ND+FD Fit : Simultaneous Near and Far Detector fit.
- Fit space: final reconstructed-energy bins for ND+FD ν_{μ} and ν_e samples - ND reco \rightarrow true \rightarrow FD reco extrapolation is performed in PISCES.



- Fit parameters: oscillation parameters - Systematic uncertainties enter through the covariance matrix, not through explicit nuisance/pull parameters.

7 Conclusion

- Simultaneous ND+FD fit improves constraints on systematic uncertainties.
- Preliminary fake data comparisons show the advantages of the simultaneous ND+FD fit for the NOvA 3-Flavor analysis.
- Robustness tests were performed by modifying interaction models and central-value predictions to probe for potential fitter-induced bias.
- No significant bias was observed. The fitter responds through the physically expected systematic uncertainties for each tested scenario.

8 Acknowledgements

This work has been supported by the University of Cincinnati and the U.S. Department of Energy Office of Science. This document was prepared by the NOvA Collaboration using the resources of the Fermi National Accelerator Laboratory (Fermilab), a U.S. Department of Energy, Office of Science, Office of High Energy Physics HEP User Facility. Fermilab is managed by Fermi Forward Discovery Group, LLC, acting under Contract No. 89243024CSC000002.