# Systematic Uncertainties of the NOvA Neutrino Oscillation Analysis

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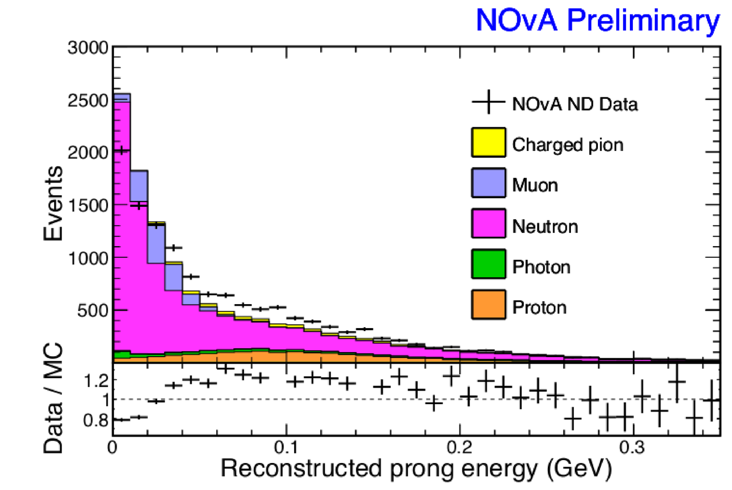
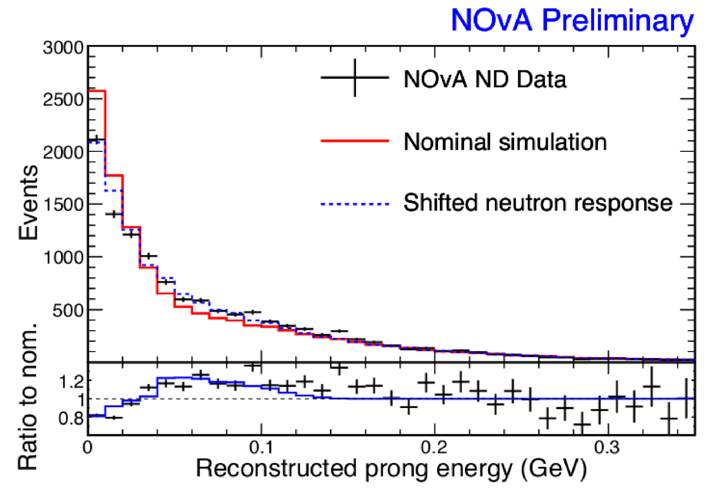
## Sources of Systematic Uncertainties

### Low energy neutrons

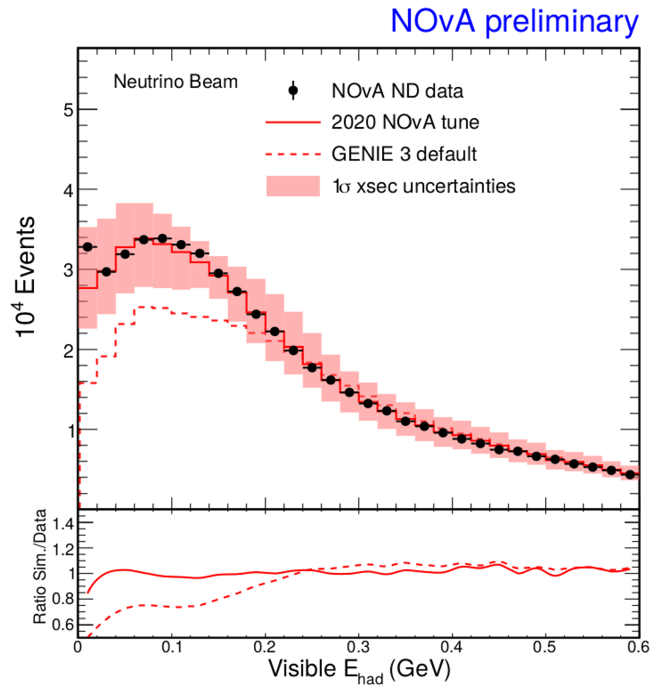
- Important uncertainty for $\bar{\nu}_\mu$ events
- Empirical uncertainty motivated by an observed data/MC disagreement in low energy neutron clusters
- Uncertainty in $\bar{\nu}_\mu$ events reconstructed energy is approximately 1%
- Studies focusing on cause of the discrepancy are under way

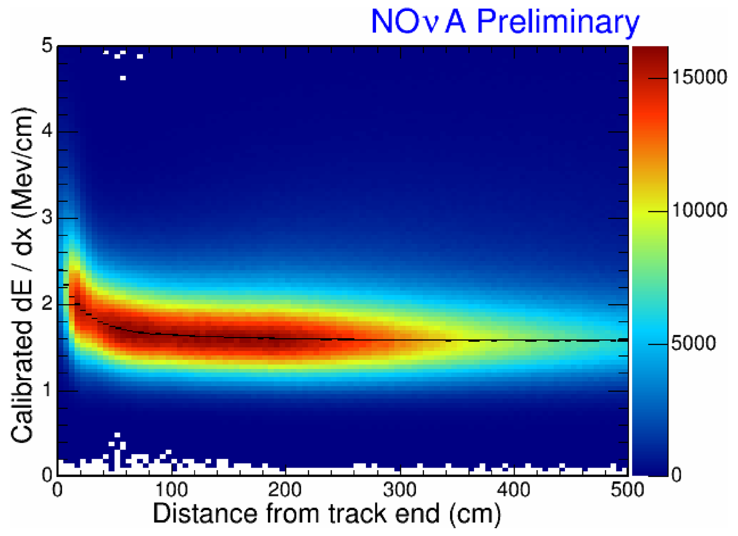



### Neutrino cross sections

- GENIE (v3.0.6, model configuration N1810k0211a) doesn't describe NOvA data
- Specific NOvA tuned model based on Xsec measurements and Near Detector data
- The uncertainties are estimated from those of the NOvA model parameters for individual interaction types (over 70)
- Larger ones are used directly in the analysis
- The rest are included using a principal component analysis approach



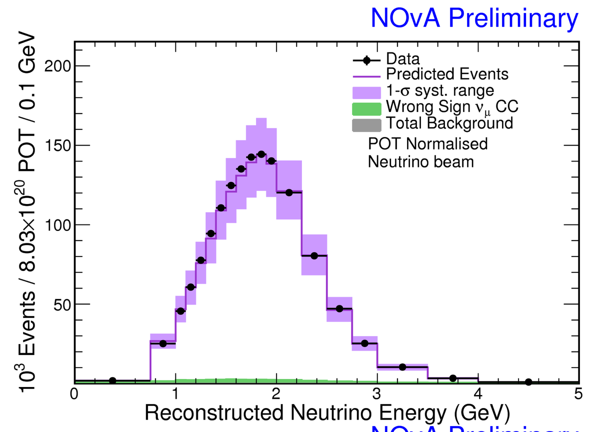



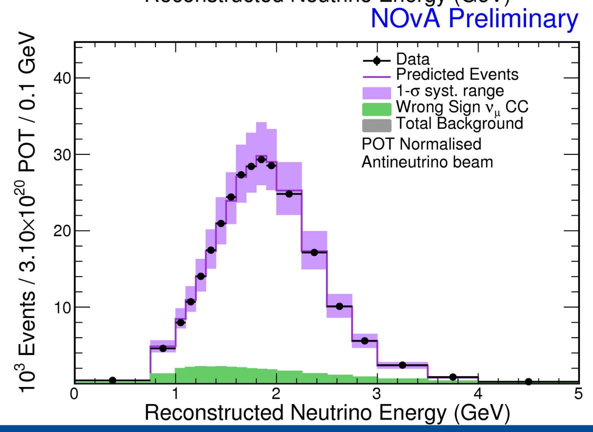

### Calibration

- Stopping $\mu$ are used to set the absolute energy scale
- The uncertainty comes from discrepancies in particle energy studies, such as the d$E$/dx of $\mu$ and most importantly $p$
- NOvA test beam program can help to study how different particles deposit energy in the NOvA detectors

### Other Sources

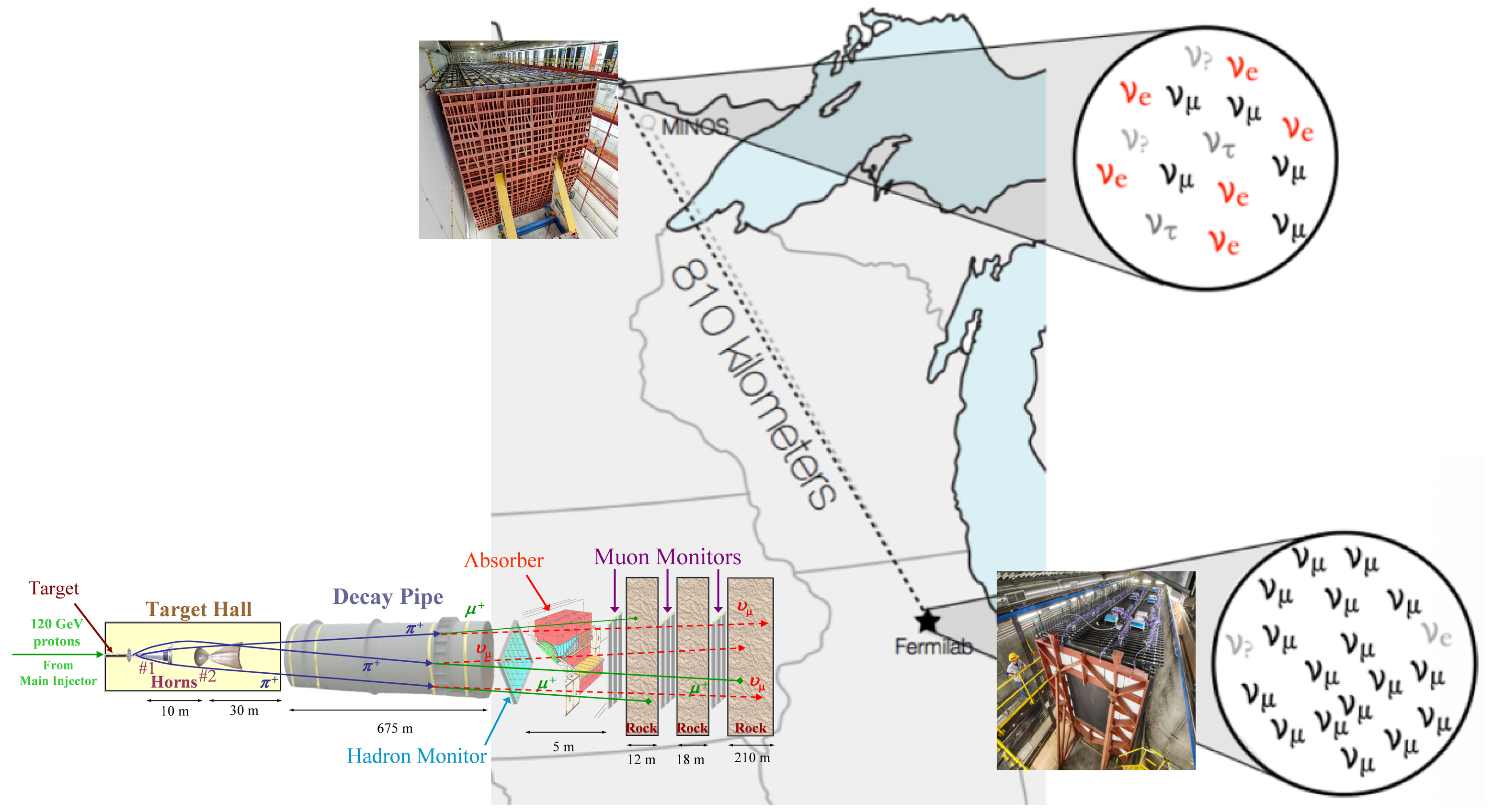
- Detector response: light yield, cherenkov/scintillation light yield ratio, detector aging
- Beam flux (with principal component analysis)
- Lepton reconstruction: $\mu$ energy scale and lepton angle reconstruction
- Near to Far uncorrelated uncertainties: rock events scale, cosmic background scale, exposure counting, detector mass, detectors acceptance



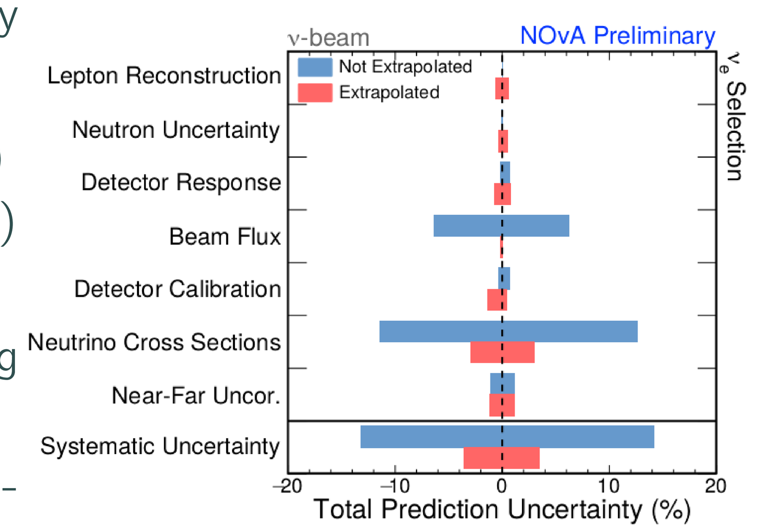

## The NOvA Experiment

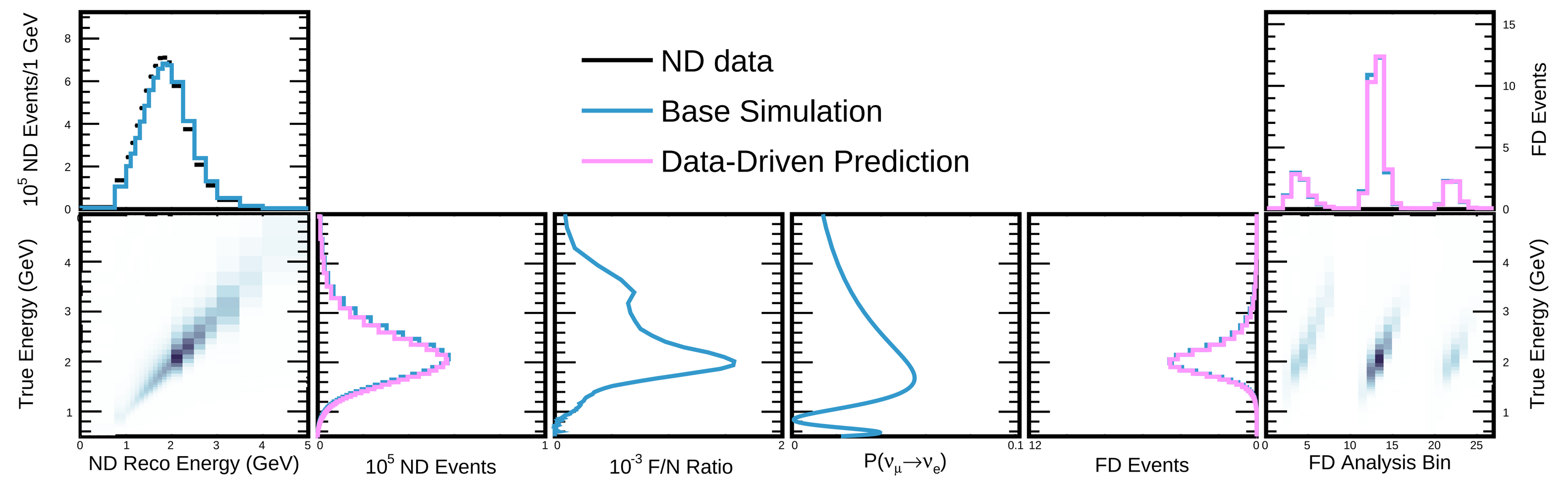
- Neutrino oscillation experiment with 810 km long baseline
- $\nu_\mu$ from Fermilab's 700 kW NuMI beam – world's most powerful neutrino beam
- $\nu_\mu$ vs $\bar{\nu}_\mu$ dominated beam modes
- 2 functionally identical, 14 kt (Far) and 0.3 kt (Near), highly segmented, low-Z liquid scintillator detectors
- 14.6 mrad off the NuMI beam axis
- **Physics interests:** probing $\nu$ mass ordering, CP violation, $\theta_{23}$ octant and beyond




## Reducing Detector Correlated Uncertainties

- For each considered systematic uncertainty shifted predictions are generated by:
  1. Weighting MC w.r.t. event type ($\pm1, 2\sigma$)
  2. Adjusting the simulated variables ($\pm1, 2\sigma$)
  3. Creating a new simulated sample ($\pm1\sigma$)
- ND predictions are translated to the FD using the Far/Near extrapolation technique
- This reduces detector correlated uncertainties such as beam flux and $\nu$ cross section

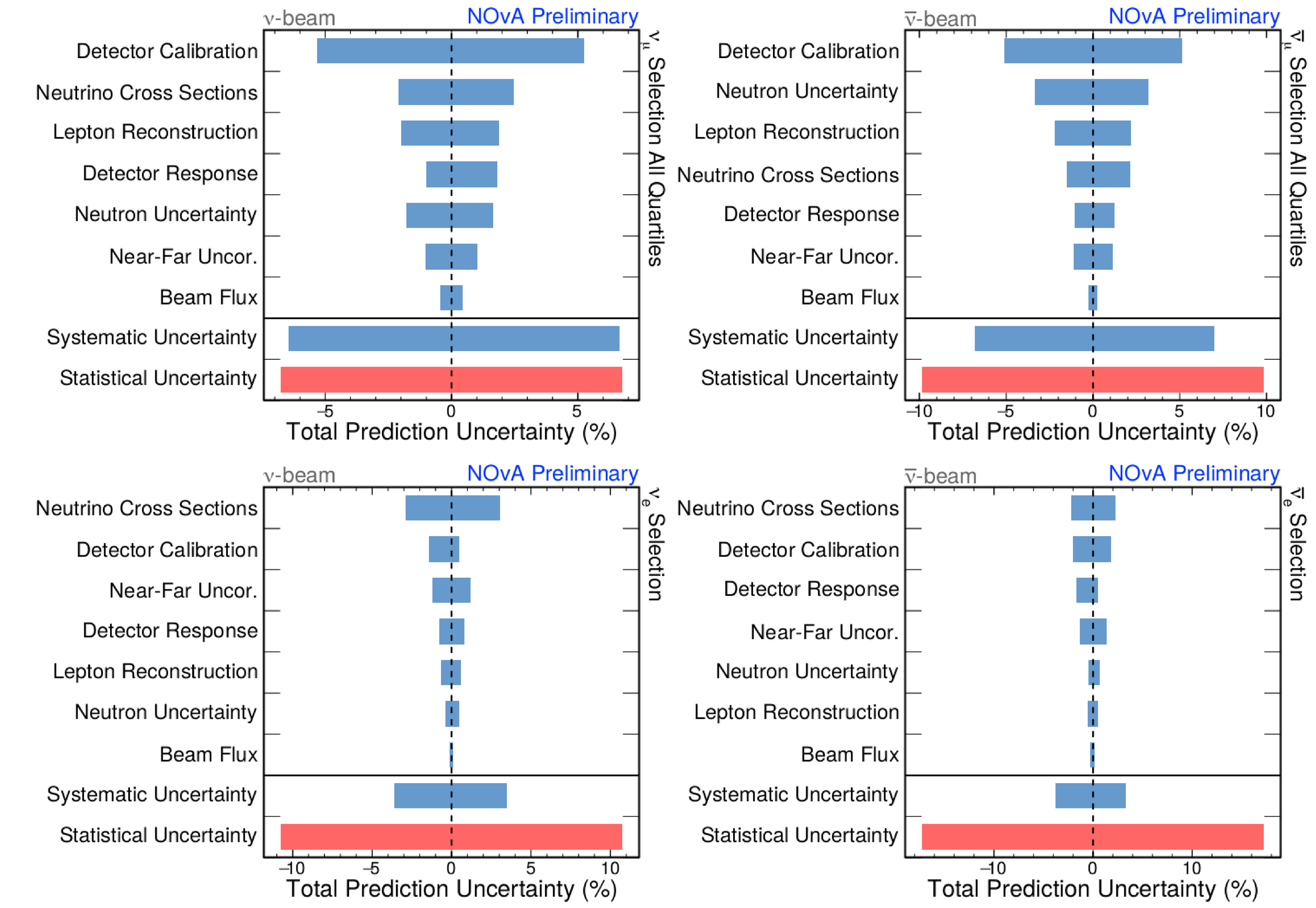


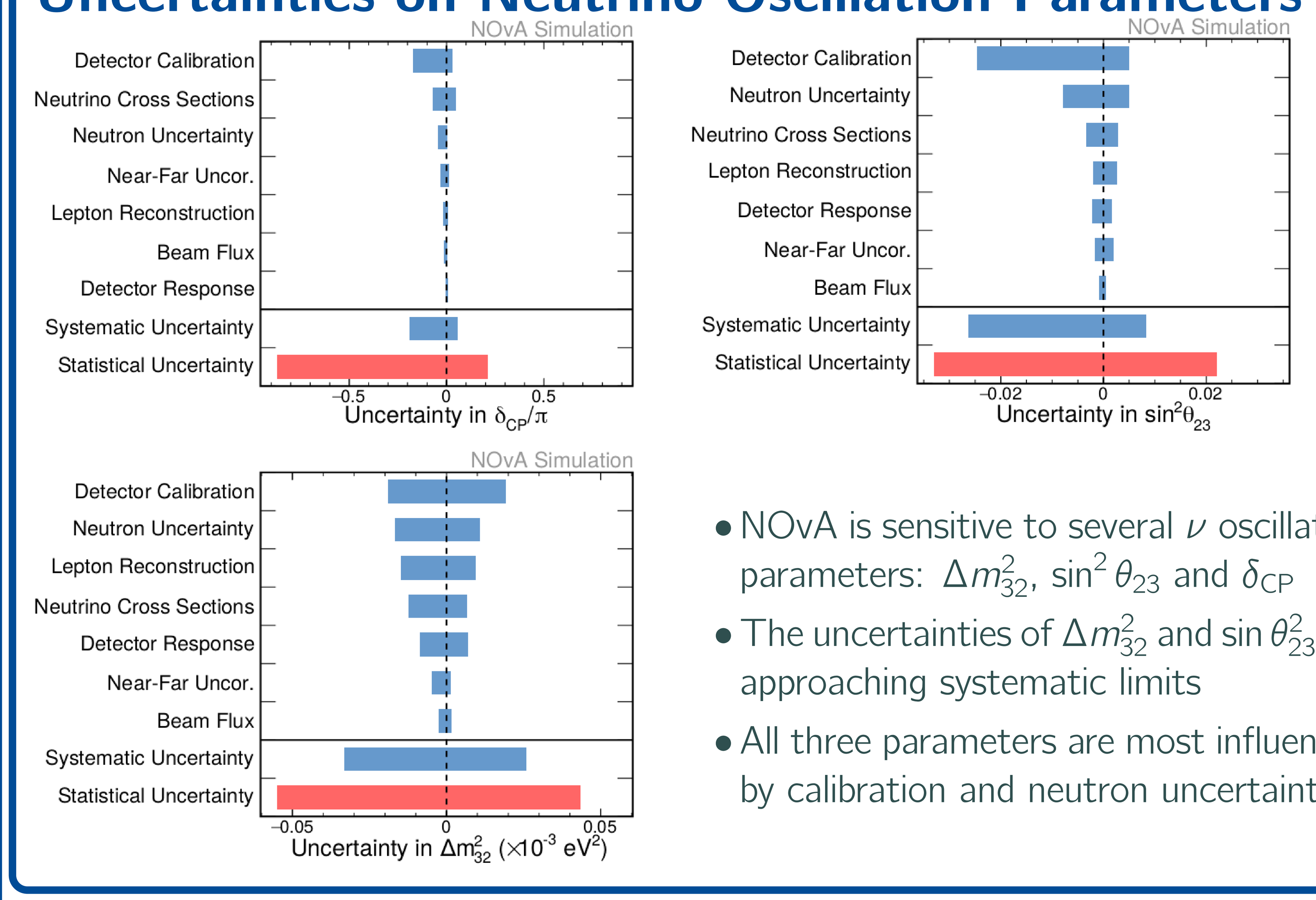

- Beam flux and $\nu$ cross sections are treated with principal component analysis (PCA)
- PCA uses eigenvalue decomposition of a covariance matrix from an ensemble of randomly generated shifted predictions in energy bins of Near and Far/Near basis
- Identifying the largest principal components helps to account for possible bin-bin correlations and reduces the number of systematic nuisance parameters included in the fit (from tens to units) and thus reduces computation time

## Far Detector Prediction Uncertainties

- Uncertainties are determined for the $\nu_e$ and $\nu_\mu$ Far Detector predictions separately
- The $\nu_\mu$ analysis sample is affected most by the detector calibration
- The $\nu_e$ prediction's largest systematic is cross section uncertainty of $\nu$ interactions, though main uncertainty comes from low statistics




## Uncertainties on Neutrino Oscillation Parameters




- NOvA is sensitive to several $\nu$ oscillation parameters: $\Delta m^2_{32}$, $\sin^2\theta_{23}$ and $\delta_{CP}$
- The uncertainties of $\Delta m^2_{32}$ and $\sin\theta^2_{23}$ are approaching systematic limits
- All three parameters are most influenced by calibration and neutron uncertainties

## Conclusions

- Functionally identical detectors and Far/Near extrapolation technique allow for notable reduction in uncertainties on beam flux and $\nu$ cross sections
- NOvA is limited by statistics but approaching its systematic limits
- Studies of systematic effects are vital for understanding detectors performance and further analysis improvements
- NOvA's test beam program might help to reduce several systematic uncertainties

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http://novaexperiment.fnal.gov