LONG-BASELINE SENSITIVITY ANALYSIS: STATUS AND RESULTS

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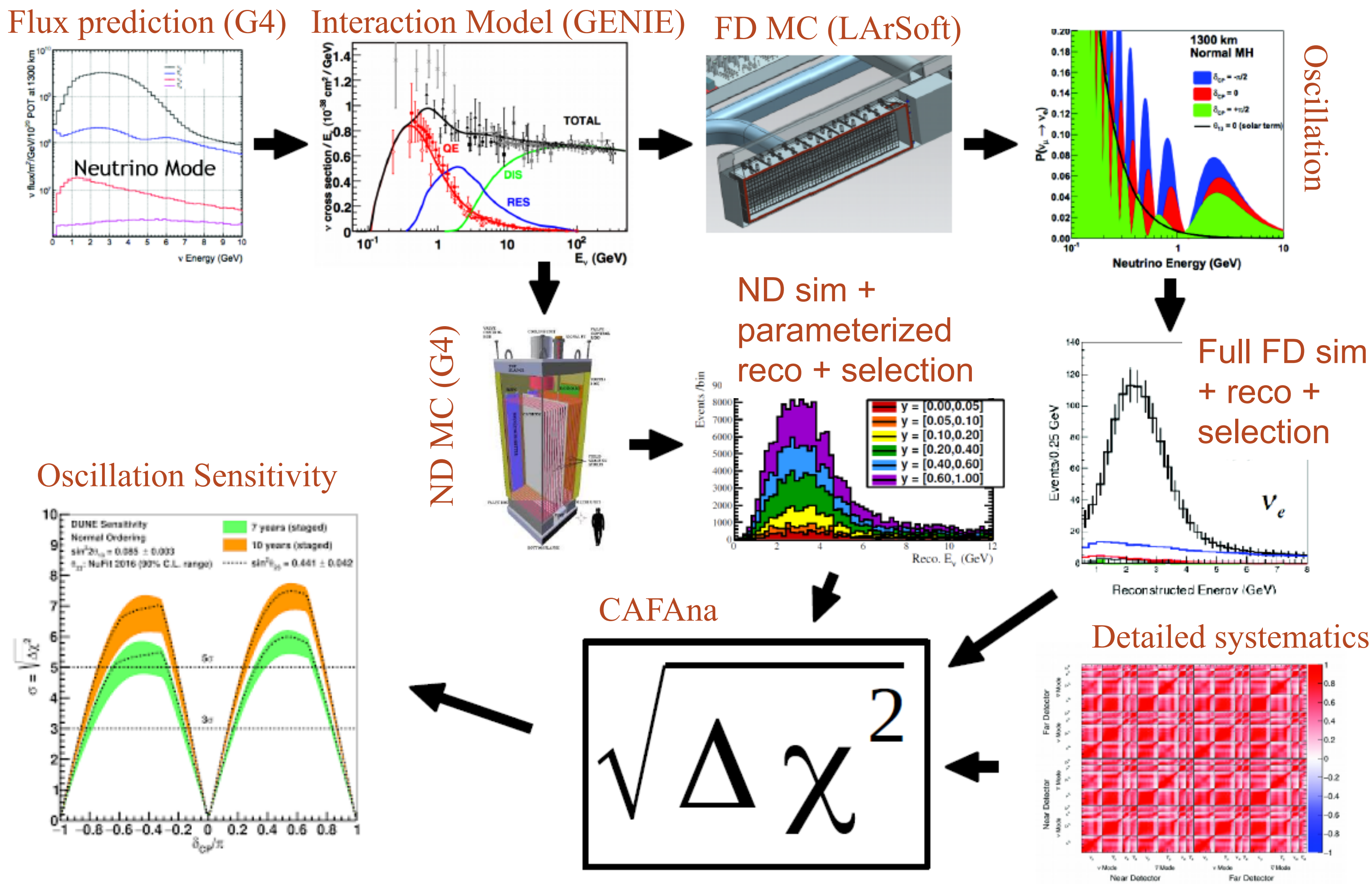
DUNE ND Review

June 4, 2019

Outline

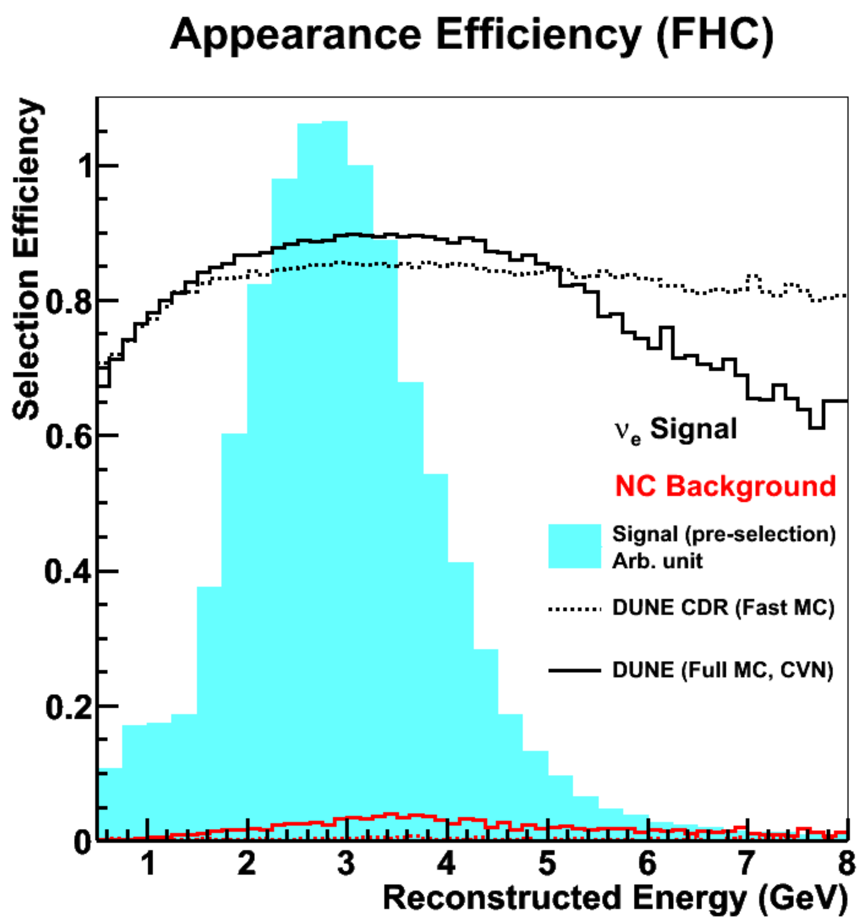
- Summary of analysis inputs
- Sensitivity Results
  - δ_{CP} Resolution and CP Violation
  - Mass Ordering and Octant
  - Oscillation Parameter Resolutions
  - Milestones
- Bias Studies
  - NuWro Study
  - Energy Bias Study
- Sanity Checks
- Plans & Summary

LBL Sensitivity Analysis (TDR)



Simulated Inputs

- Beam line designed using genetic algorithm to optimize CPV sensitivity and engineering input
  - Flux prediction from Geant4 simulation
- Neutrino interactions are simulated with GENIE version 2.12.10, with default physics list except for Valencia 2p2h model
- ND MC samples use GEANT4 and parameterized reconstruction
- FD MC samples use LArSoft full simulation, reconstruction, and event selection



Systematics

- Flux systematics included using primary component analysis of covariance matrix
- Interaction systematics use DUNEInt package
  - Implementation of interaction model & uncertainties developed by neutrino interaction experts (D.I.R.T.)
  - Makes extensive use of GENIE's reweighting framework
    - Supports kinematic shifts in addition to reweighting
  - Adds additional freedom inspired by lack of measurements on argon and informed by modeling uncertainties in running experiments
- Detector uncertainties defined using expectation of post-calibration detector performance
  - FD uncertainties: next slide
  - ND detector uncertainties implemented with covariance matrix

FD Detector Uncertainties

DEEP UNDERGROUND NEUTRINO EXPERIMENT

- Energy scale uncertainty: $E \rightarrow E_{rec}(p_0 + p_1\sqrt{E_{rec}} + p_2/\sqrt{E_{rec}})$

Particle Type	p_0 (constant)	p_1 (square root)	p_2 (inverse square)
All (charge calibration)	2%	2%	2%
μ (range)	2%	2%	2%
μ (curvature)	1%	1%	1%
p, $\pi^{\pm}$	5%	5%	5%
e, γ, π^0	2.5%	2.5%	2.5%
n (visible)	20%	30%	30%

- Energy resolution uncertainty:
  - Resolution is built in to MC sim/reco – no specific smearing applied
  - Uncertainty on resolution: 2% (50% for neutrons)
- Fiducial volume uncertainty:
  - 1% separately for ν_e and ν_μ
- Event selection uncertainty:
  - Vary selection criteria

Staging Scenario

(Same as 2017 analysis)

- Start of beam run:
  - Two FD modules (20 kt, fiducial, total)
  - 1.2 MW beam power
- After one year:
  - Add one FD module (30 kt, fiducial, total)
- After three years:
  - Add one FD module (40 kt, fiducial, total)
- After six years:
  - Upgrade to 2.4 MW beam power

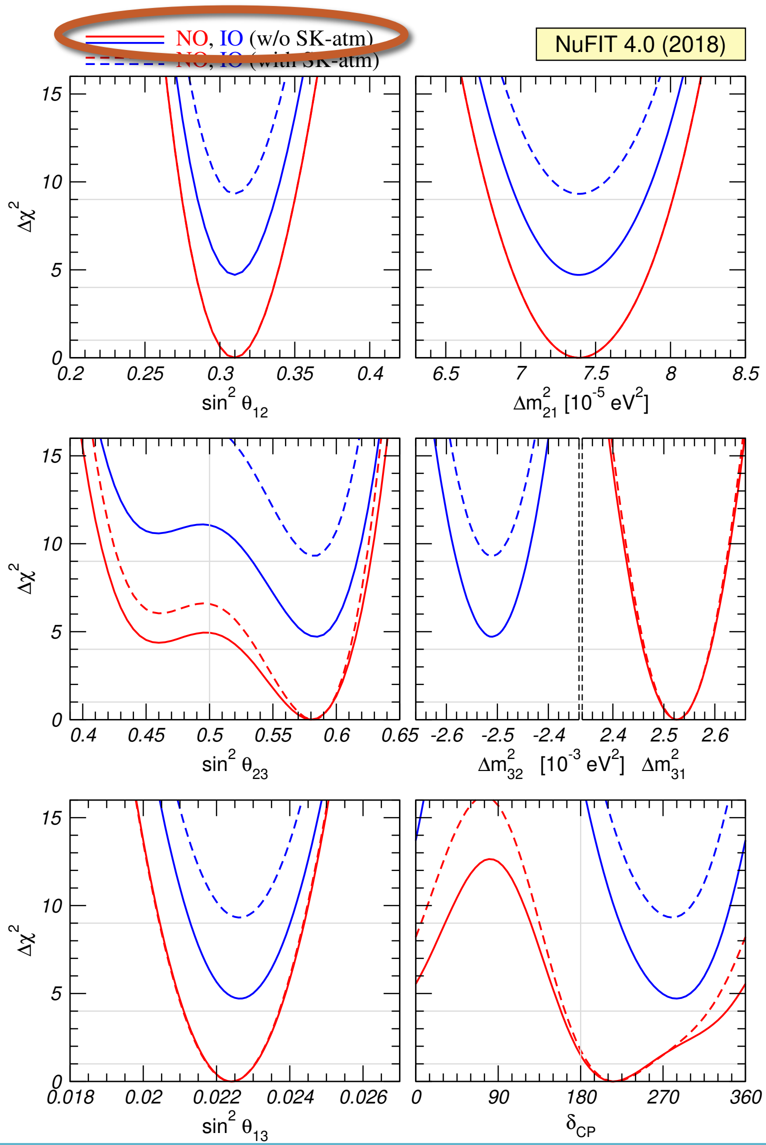
No attempt at realistic run plan regarding neutrino-antineutrino running.
All exposures assume equal running in neutrino and antineutrino mode.

NuFIT 4.0

NuFIT 4.0 (2018)

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 4.7$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
without SK atmospheric data	$\sin^2\theta_{12}$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$
	$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$
	$\sin^2\theta_{23}$	$0.580^{+0.017}_{-0.021}$	$0.418 \to 0.627$	$0.584^{+0.016}_{-0.020}$	$0.423 \to 0.629$
	$\theta_{23}/^\circ$	$49.6^{+1.0}_{-1.2}$	$40.3 \to 52.4$	$49.8^{+1.0}_{-1.1}$	$40.6 \to 52.5$
	$\sin^2\theta_{13}$	$0.02241^{+0.00065}_{-0.00065}$	$0.02045 \to 0.02439$	$0.02264^{+0.00066}_{-0.00066}$	$0.02068 \to 0.02463$
	$\theta_{13}/^\circ$	$8.61^{+0.13}_{-0.13}$	$8.22 \to 8.99$	$8.65^{+0.13}_{-0.13}$	$8.27 \to 9.03$
	$\delta_{CP}/^\circ$	215^{+40}_{-29}	$125 \to 392$	284^{+27}_{-29}	$196 \to 360$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.525^{+0.033}_{-0.032}$	$+2.427 \to +2.625$	$-2.512^{+0.034}_{-0.032}$	$-2.611 \to -2.412$

NuFIT 4.0

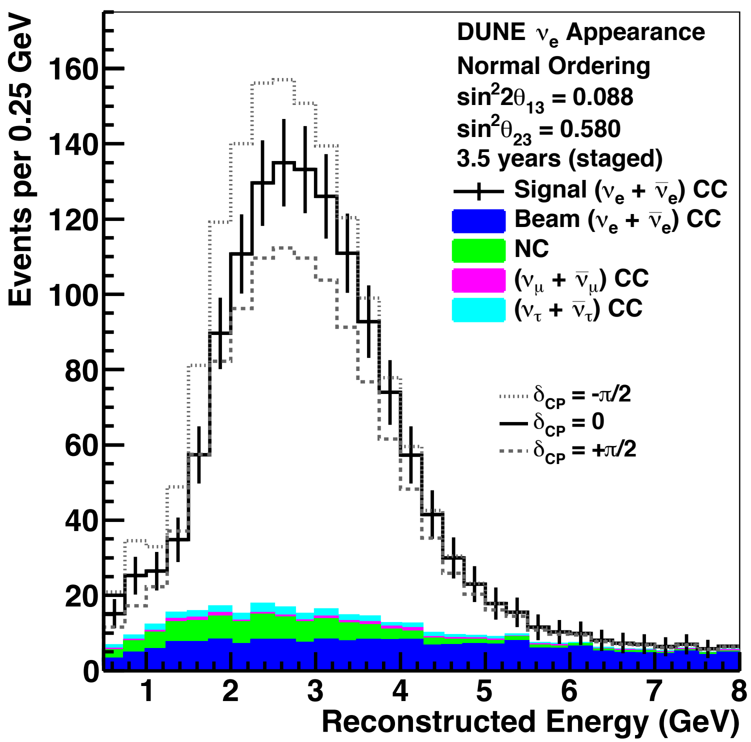

NO, IO (w/o SK-atm)
NuFIT 4.0 (2018)
Δχ²
sin² θ12
Δm²21 [10⁻⁵ eV²]
sin² θ23
Δm²32 [10⁻³ eV²] Δm²31
sin² θ13
δCP

RESULTS

Appearance Spectra

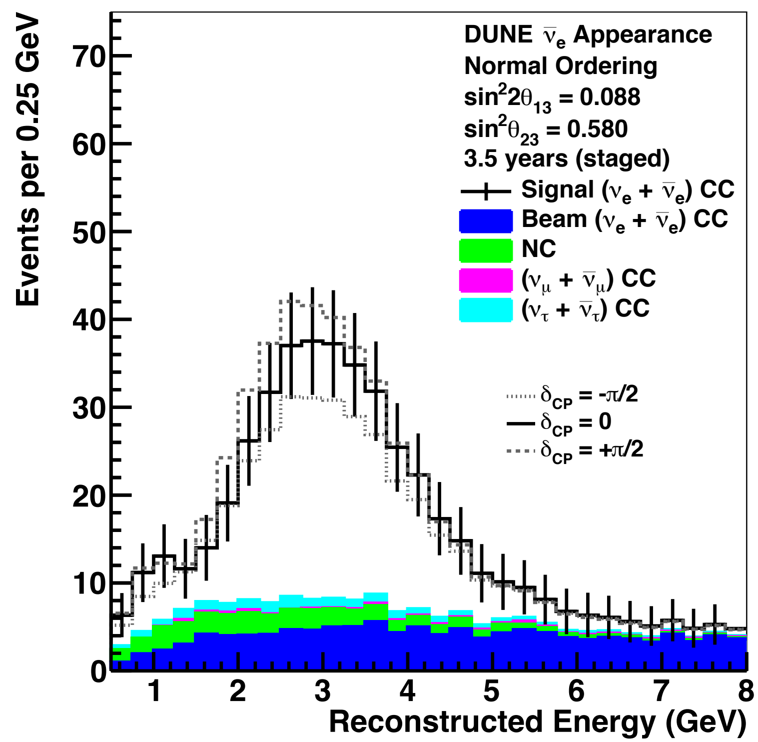
DEEP UNDERGROUND NEUTRINO EXPERIMENT

Neutrino Mode: 3.5 years



~1100 signal events

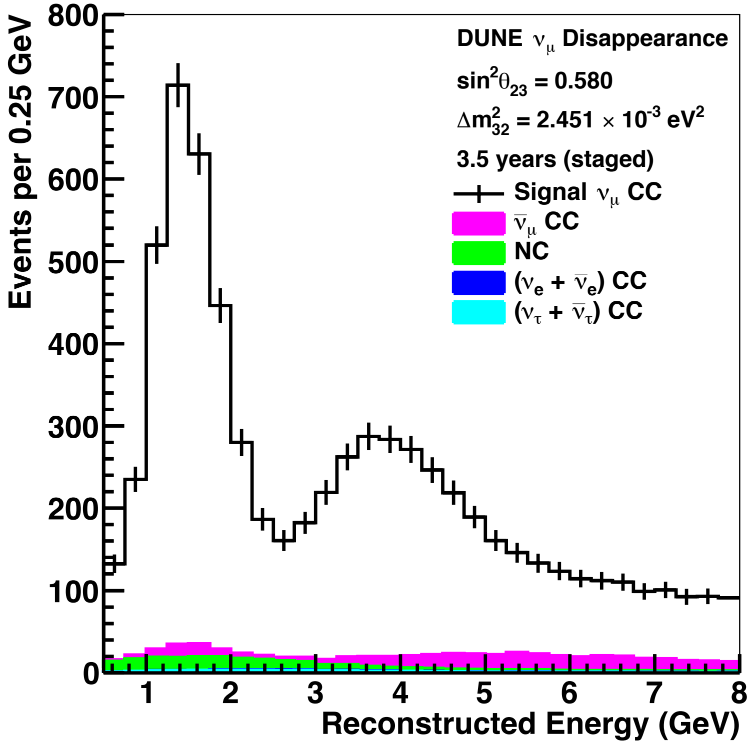
Antineutrino Mode: 3.5 years



~300 signal events

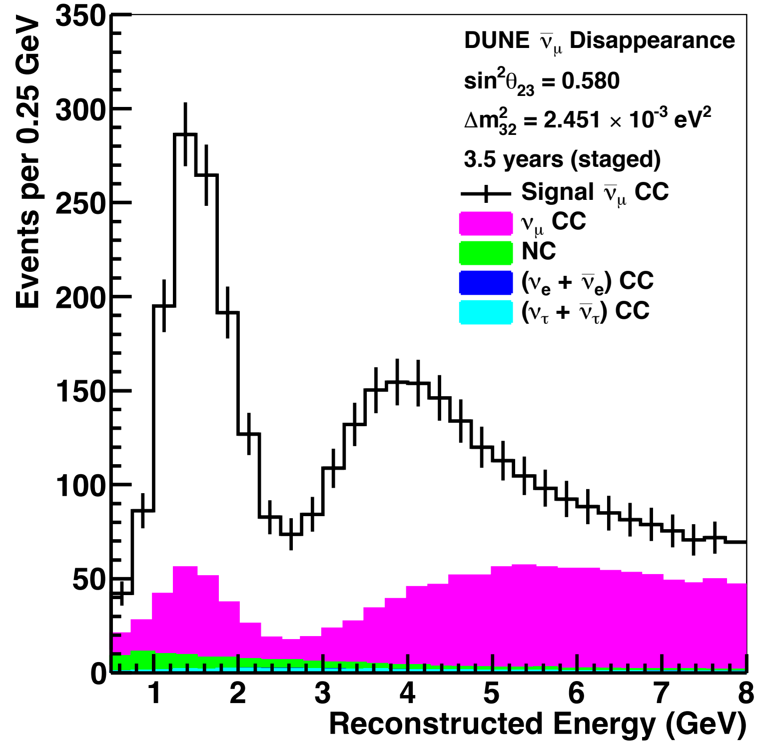
Disappearance Spectra

Neutrino Mode: 3.5 years



~6200 signal events

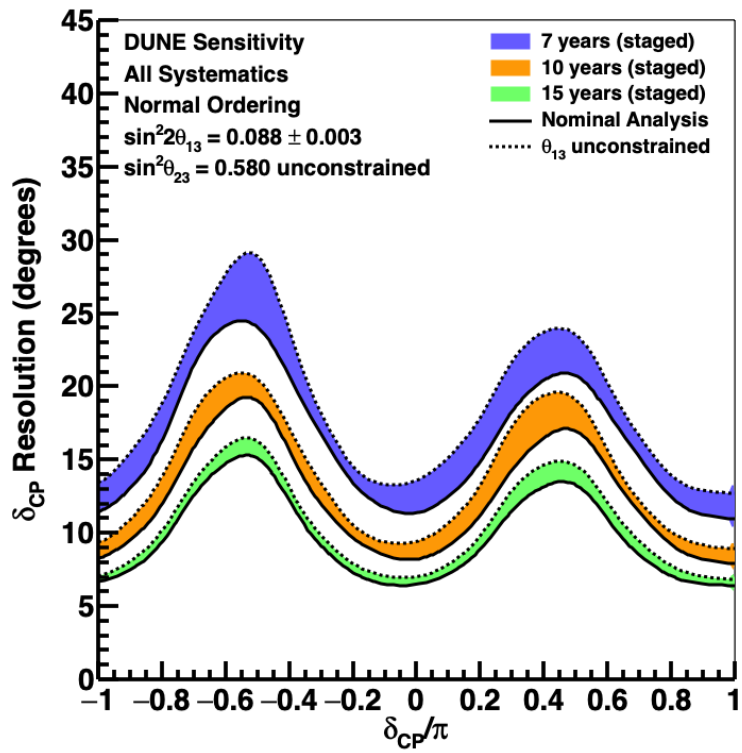
Antineutrino Mode: 3.5 years



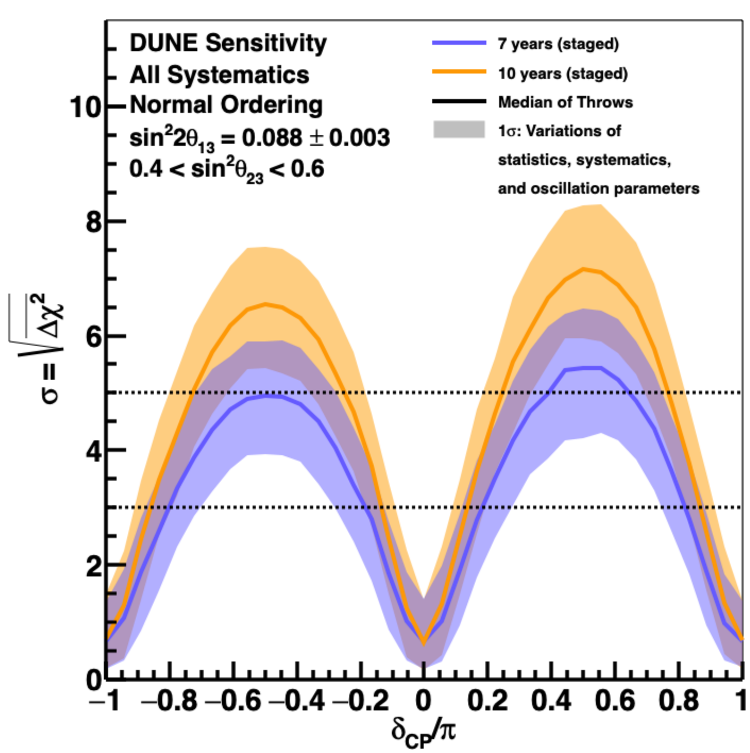
~2300 signal events

δ_{CP} & CP Violation

Resolution

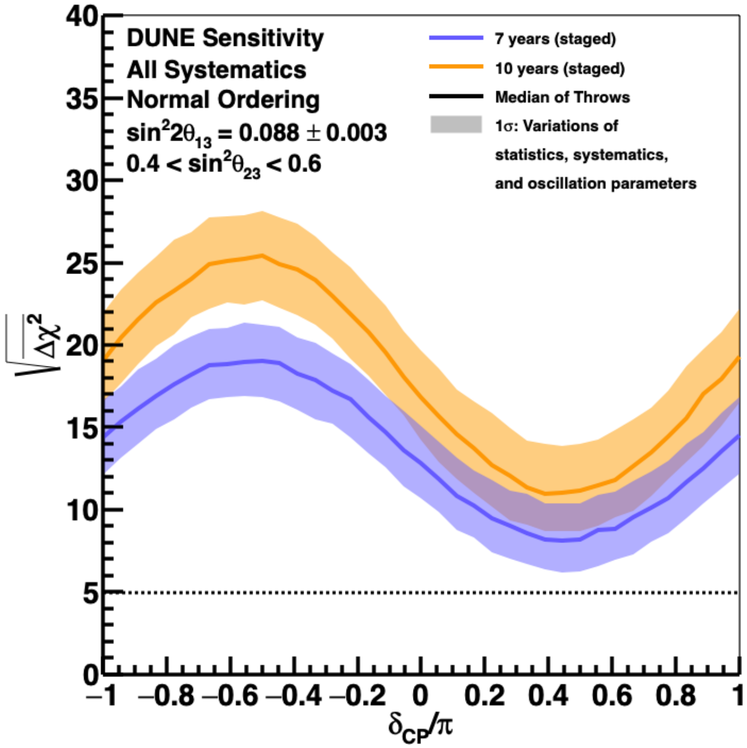


CP Violation

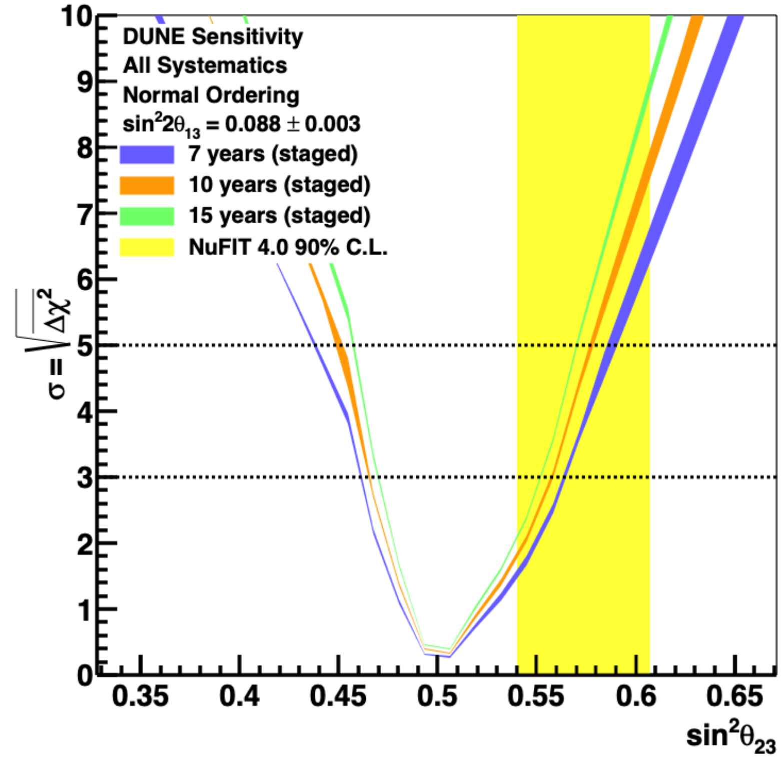


MH & Octant Sensitivity

Mass Ordering

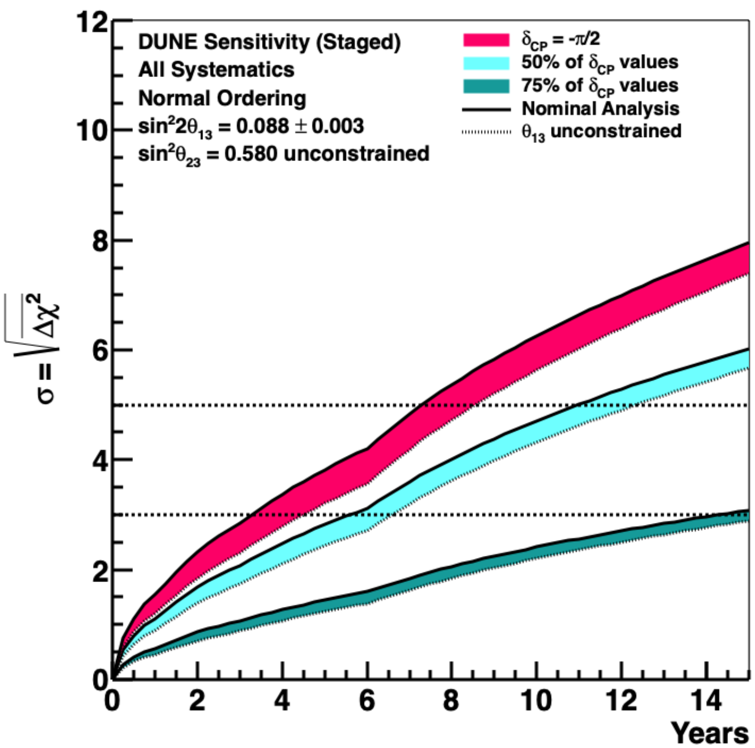


Octant

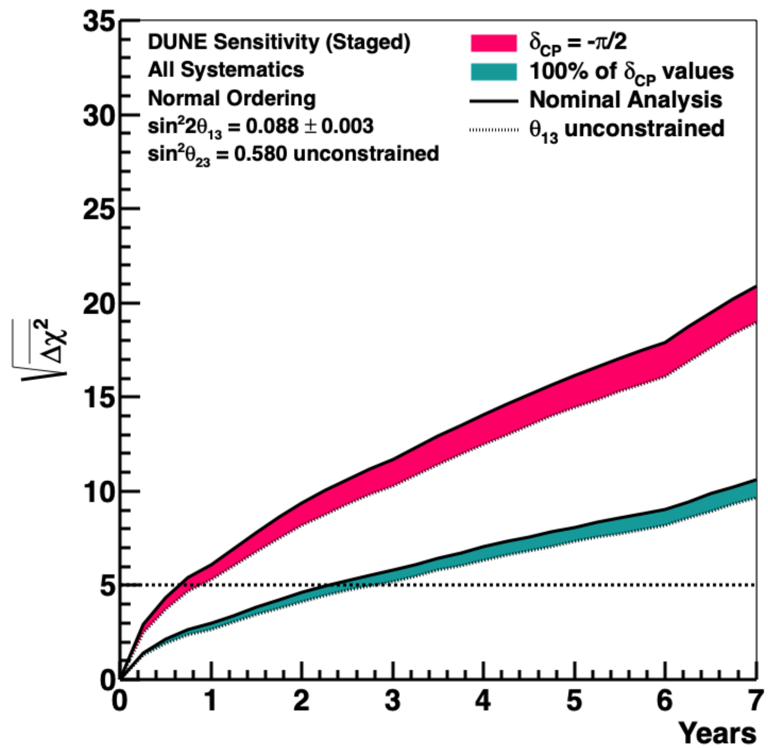


Sensitivity Over Time

CP Violation



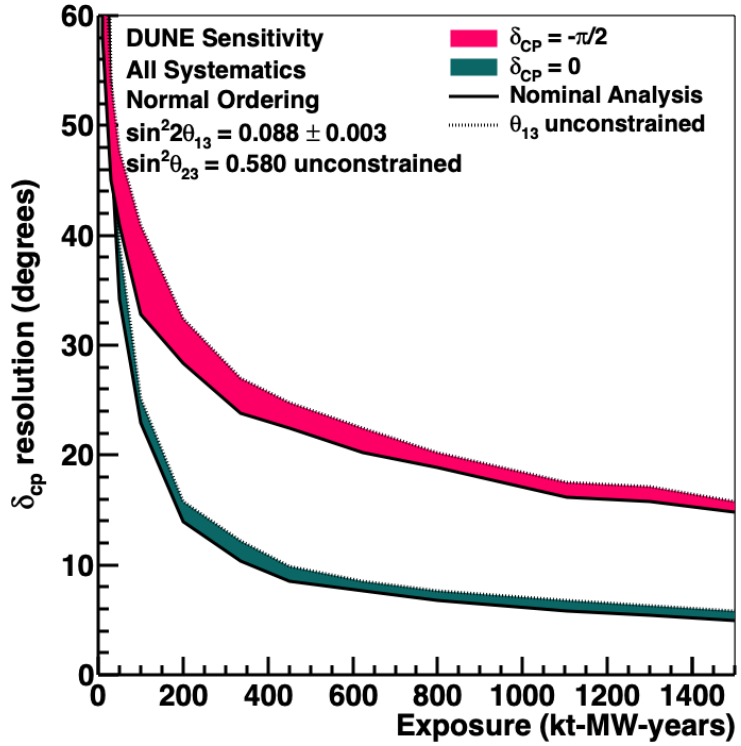
Mass Ordering



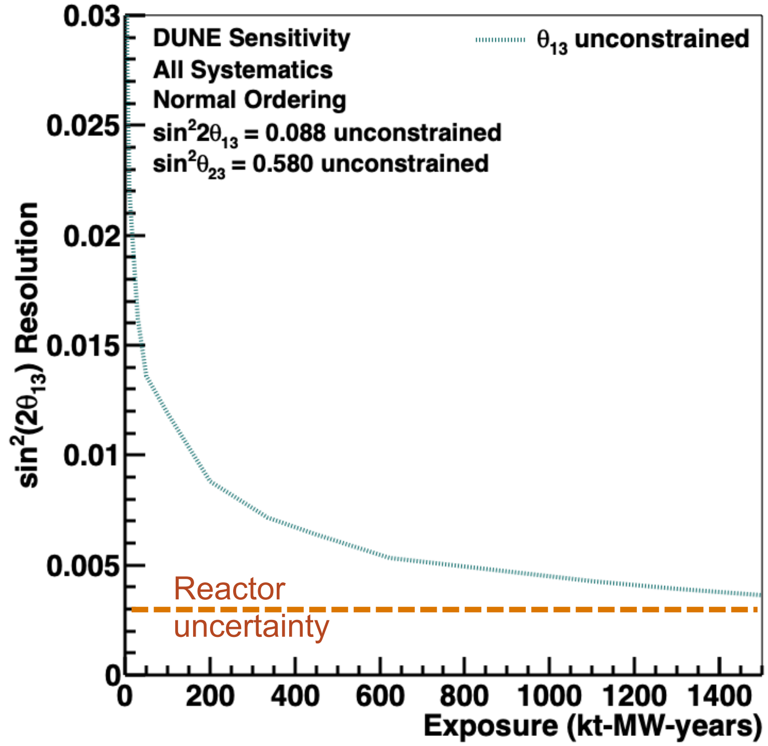
Also have these plots as a function of exposure in kt-MW-years.

Sensitivity Over Time

δ_{CP} Resolution



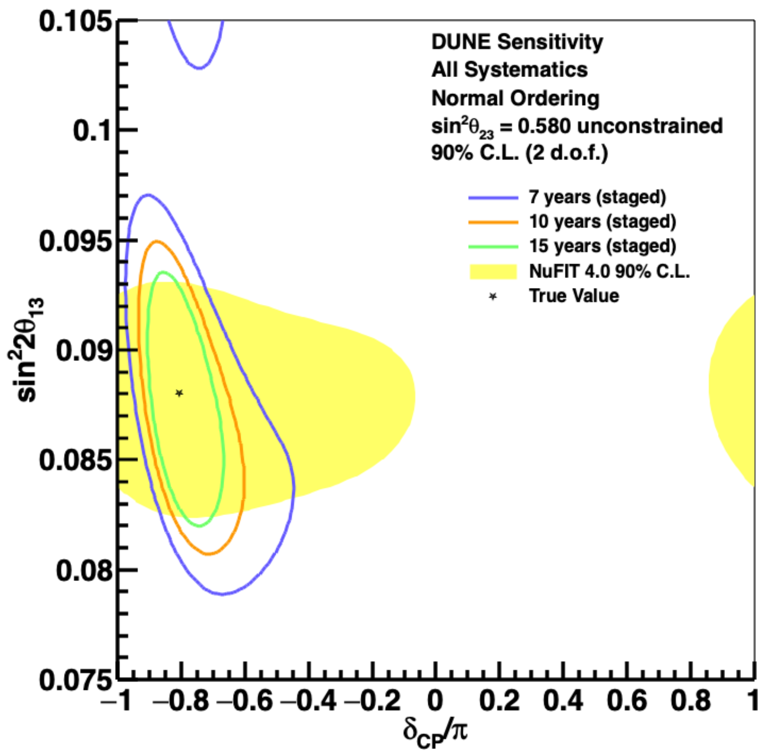
θ_{13} Resolution



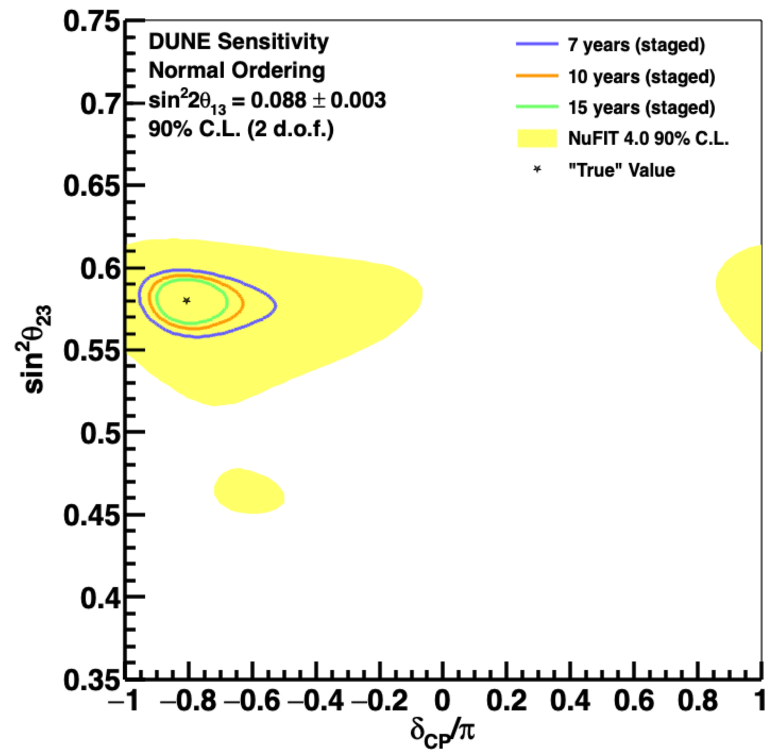
Also have resolutions as a function of exposure for $\sin^2(2\theta_{23})$ and Δm^2_{32}

2D Resolutions

$\sin^2 2\theta_{13}$ vs δ_{CP}

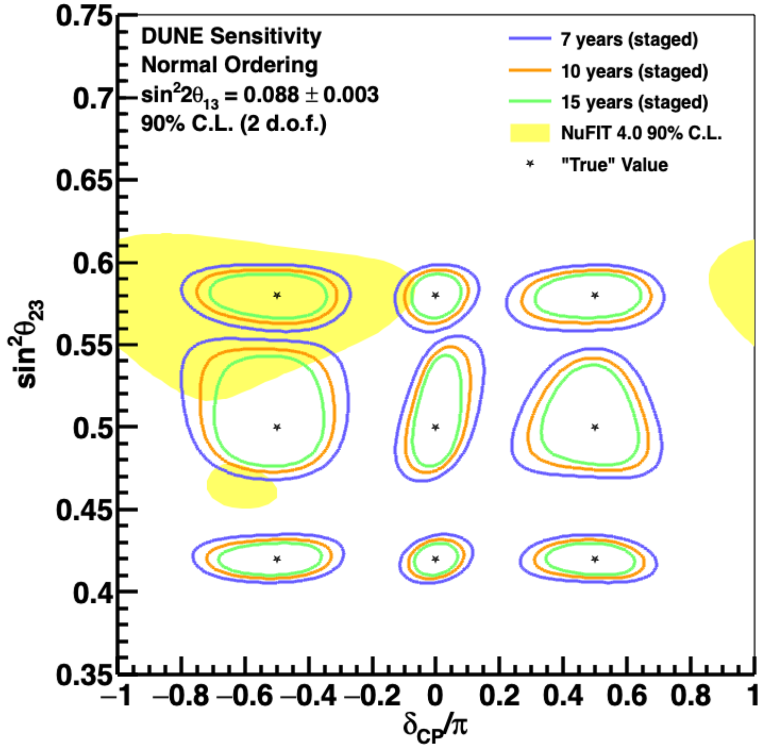


$\sin^2\theta_{23}$ vs δ_{CP}

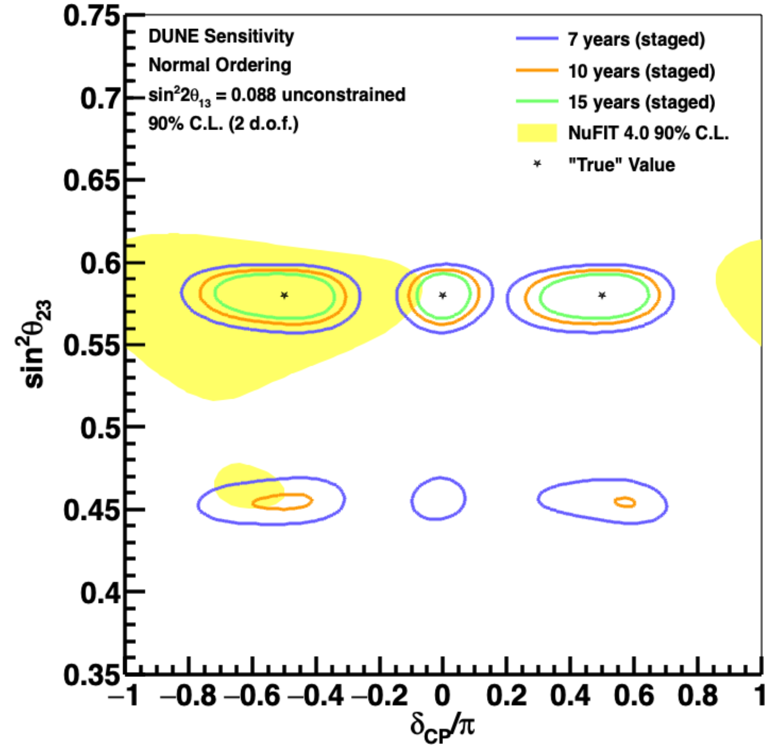


2D Resolutions

$\sin^2\theta_{23}$ vs δ_{CP} (multiple true values)



$\sin^2\theta_{23}$ vs δ_{CP} (no θ_{13} penalty)



Milestones

DEEP UNDERGROUND NEUTRINO EXPERIMENT

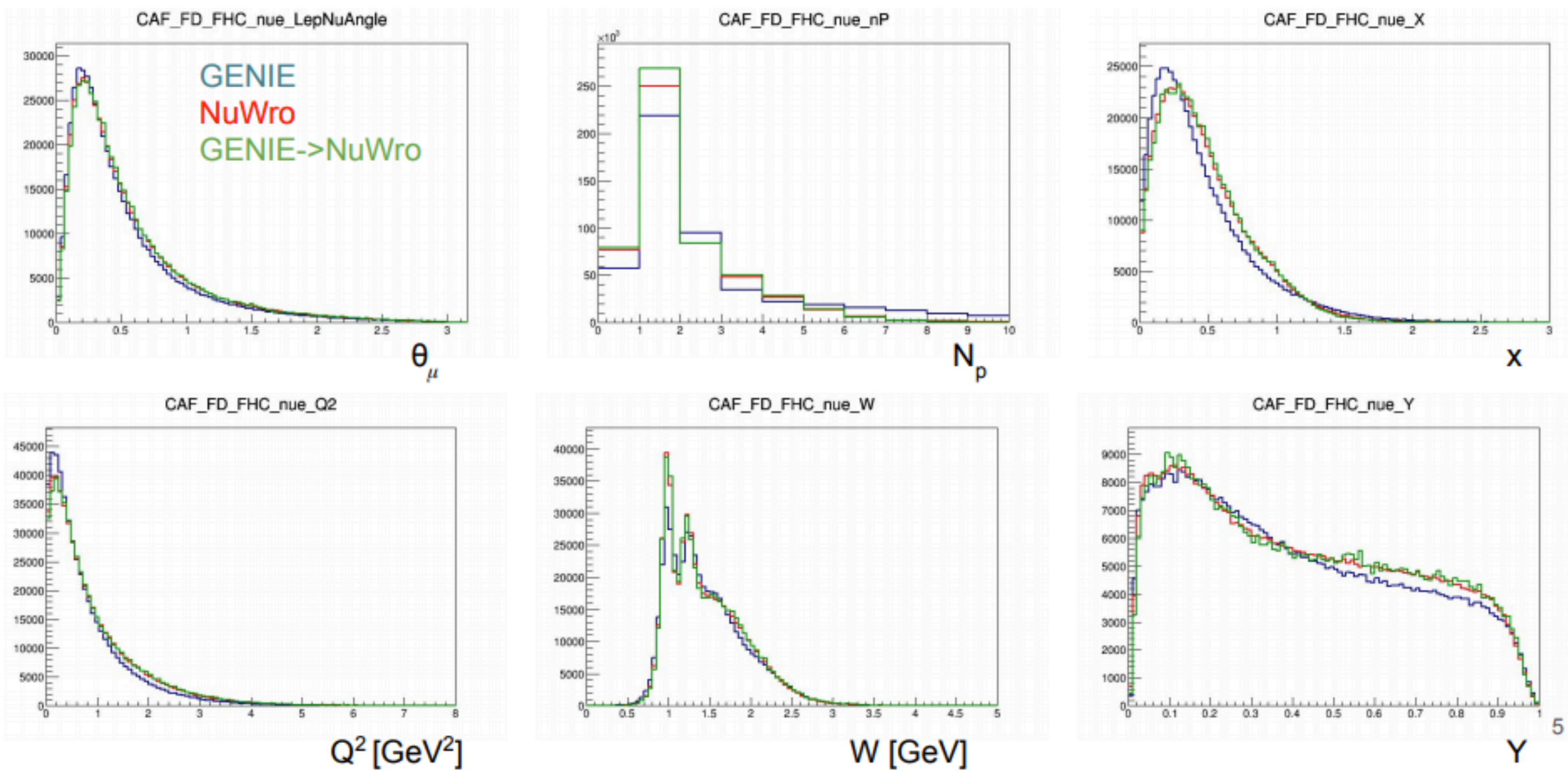
Physics Milestone	Exposure (staged years, $\sin^2\theta_{23} = 0.580$)
5σ Mass Ordering $\delta_{CP} = -\pi/2$	1
5σ Mass Ordering 100% of δ_{CP} values	2
3σ CP Violation $\delta_{CP} = -\pi/2$	3
3σ CP Violation 50% of δ_{CP} values	6
5σ CP Violation $\delta_{CP} = -\pi/2$	7
5σ CP Violation 50% of δ_{CP} values	11
3σ CP Violation 75% of δ_{CP} values	14
δ_{CP} Resolution of 10 degrees $\delta_{CP} = 0$	7
δ_{CP} Resolution of 20 degrees $\delta_{CP} = -\pi/2$	10
$\sin^2 2\theta_{13}$ Resolution of 0.004	17

Milestone ($\sin^2\theta_{23} = 0.580$)	Exposure (staged years)
5s mass ordering (100% of δ_{CP} values)	2
5σ CP Violation ($d_{CP} = -\pi/2$)	7
5σ CP Violation (50% of δ_{CP} values)	11
$\sin^2 2\theta_{13}$ resolution 0.004	17

BIAS STUDIES

Bias Study: NuWro

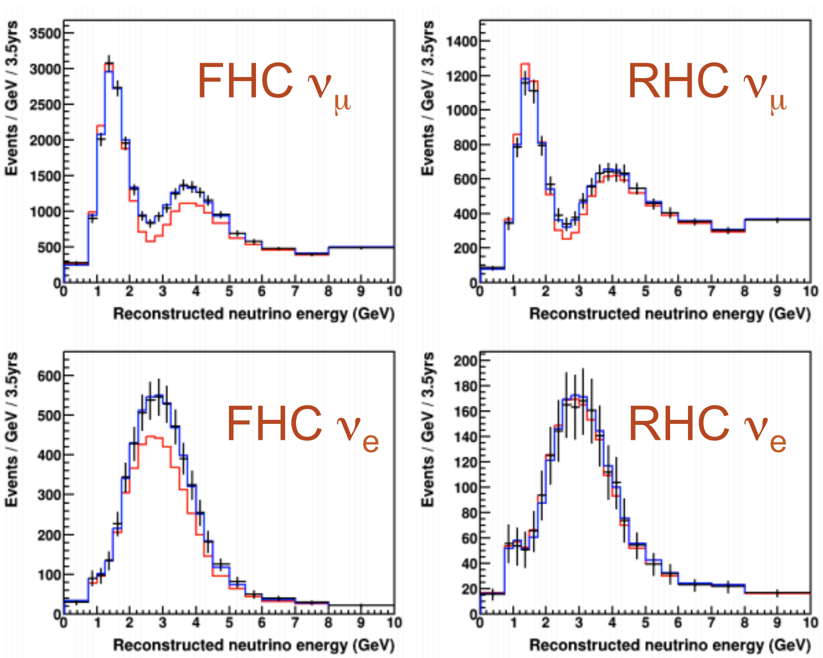
- Use BDT to reweight GENIE→NuWro in a space of 18 kinematic variables
- Separate BDT for each flux at near and far detectors



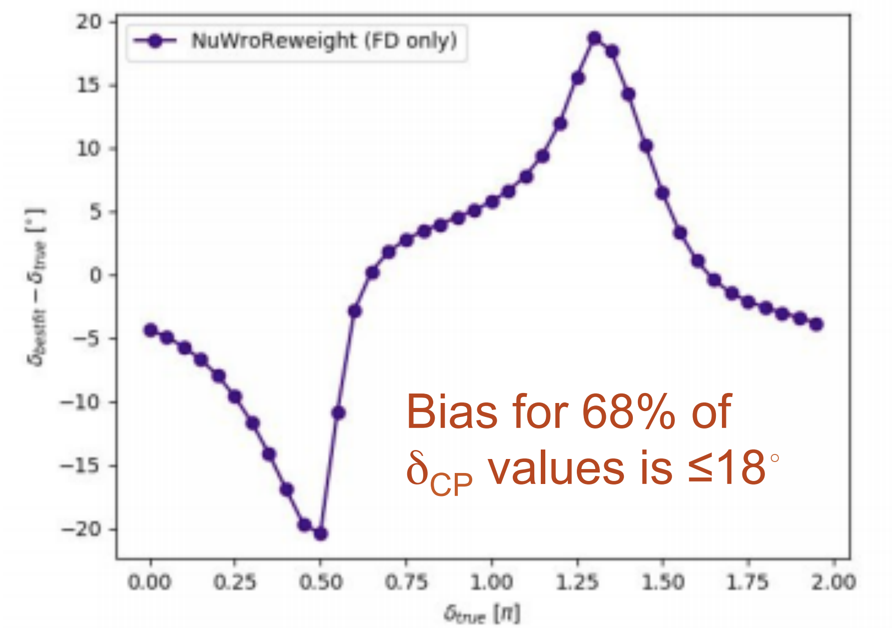
Bias Study: NuWro

- FD-only fit appears fine, but result is biased!

Fit χ^2 ~ 10



Bias depends on osc. pars – this is an example value of θ_{23}

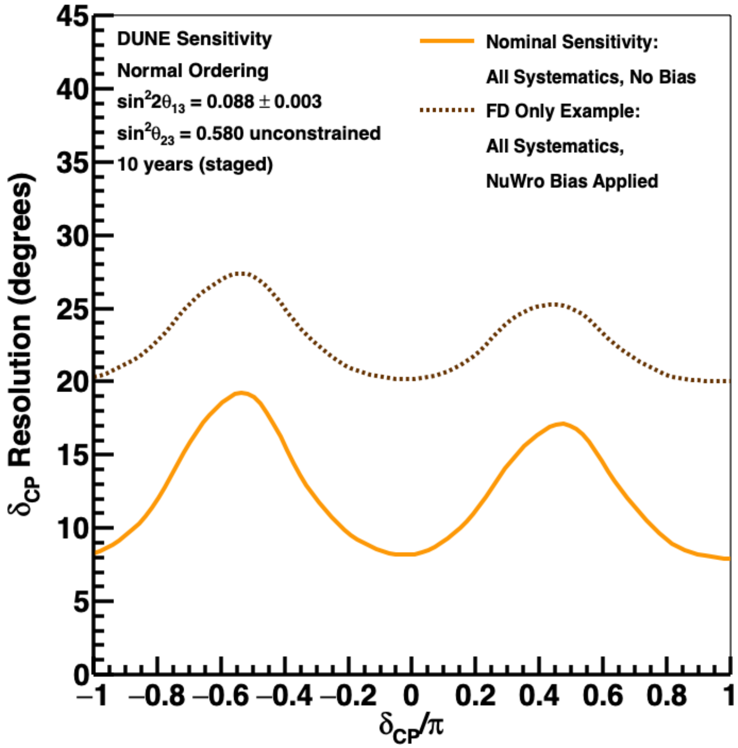


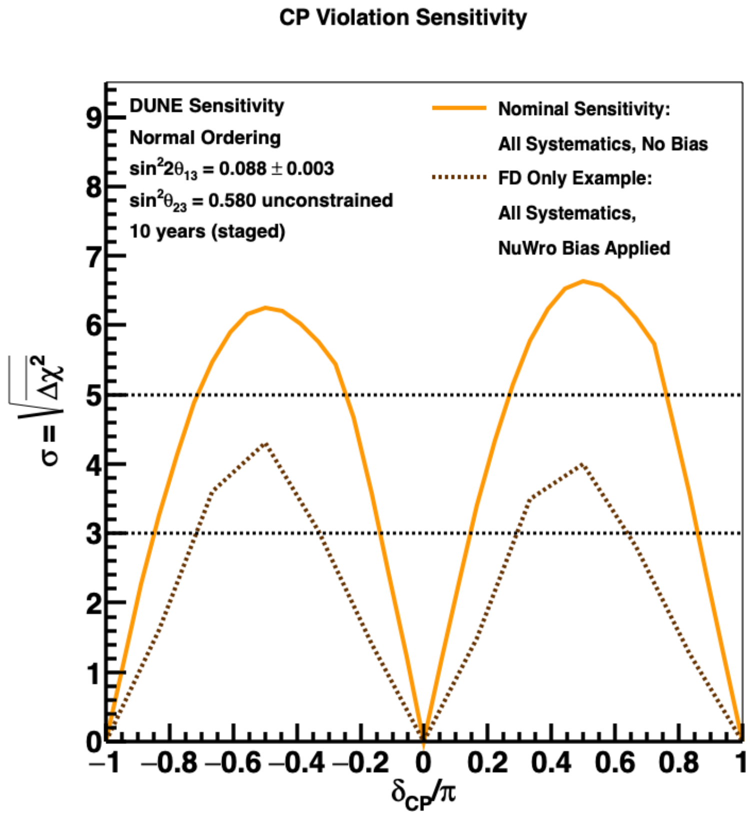
Bias for 68% of δ_{CP} values is ≤18°

- ND-FD fit has χ^2 of ~11000! With a ND we would not miss this bias. For an FD-only result, we would have to take this bias as a systematic uncertainty.

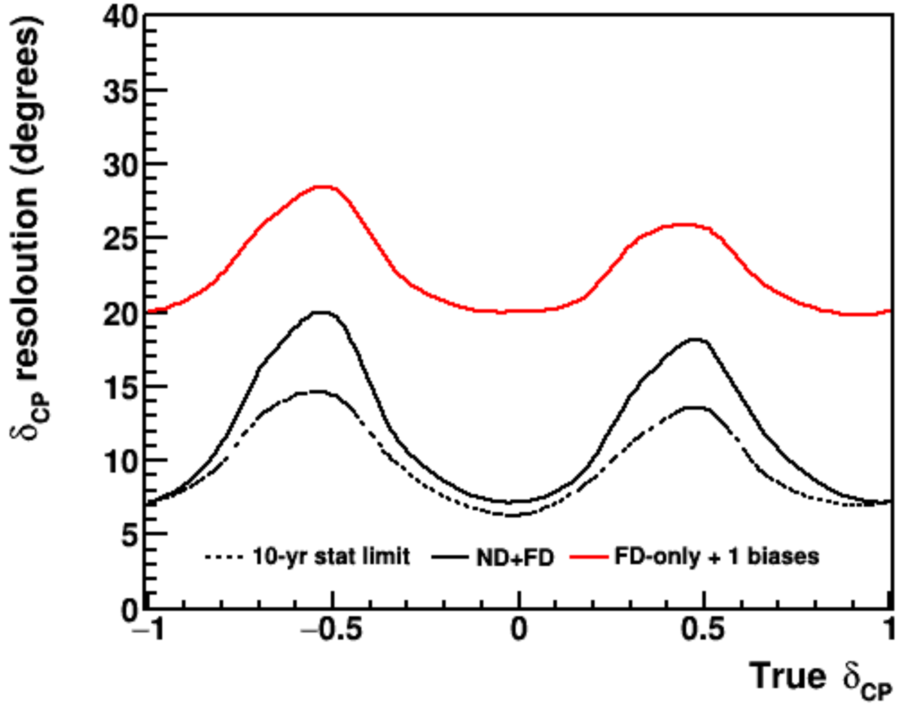
Bias Study: NuWro

Example of additional systematic required if ND were not present to validate the neutrino interaction model



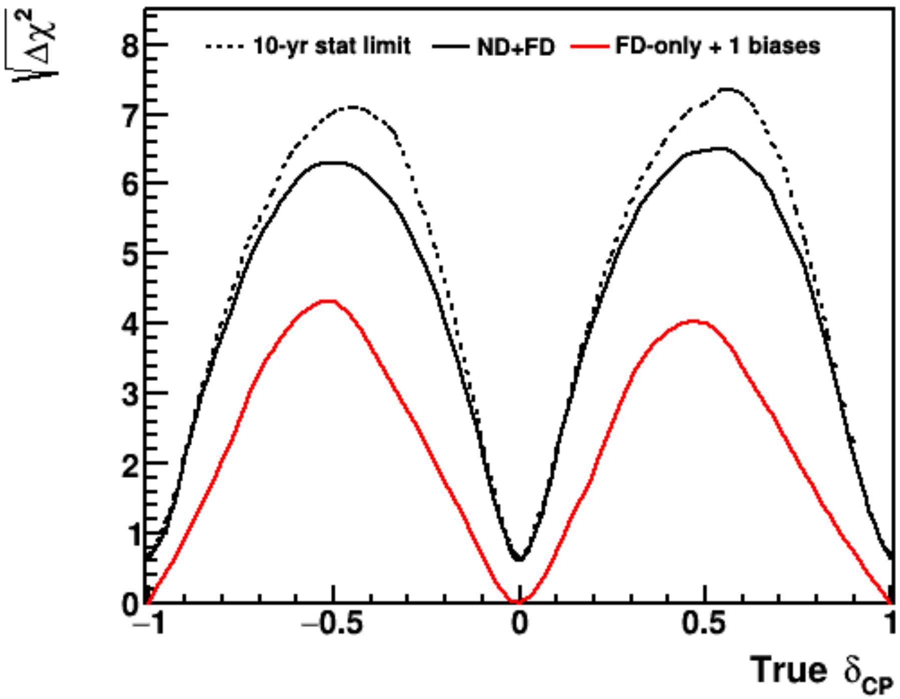


Systematics from Bias



- NuWro re-weighting study is just an example of one way our interaction model could be inadequate
- In a real FD-only analysis, there would be a multiplicity of potential biases that we would have to consider in determining a systematic uncertainty

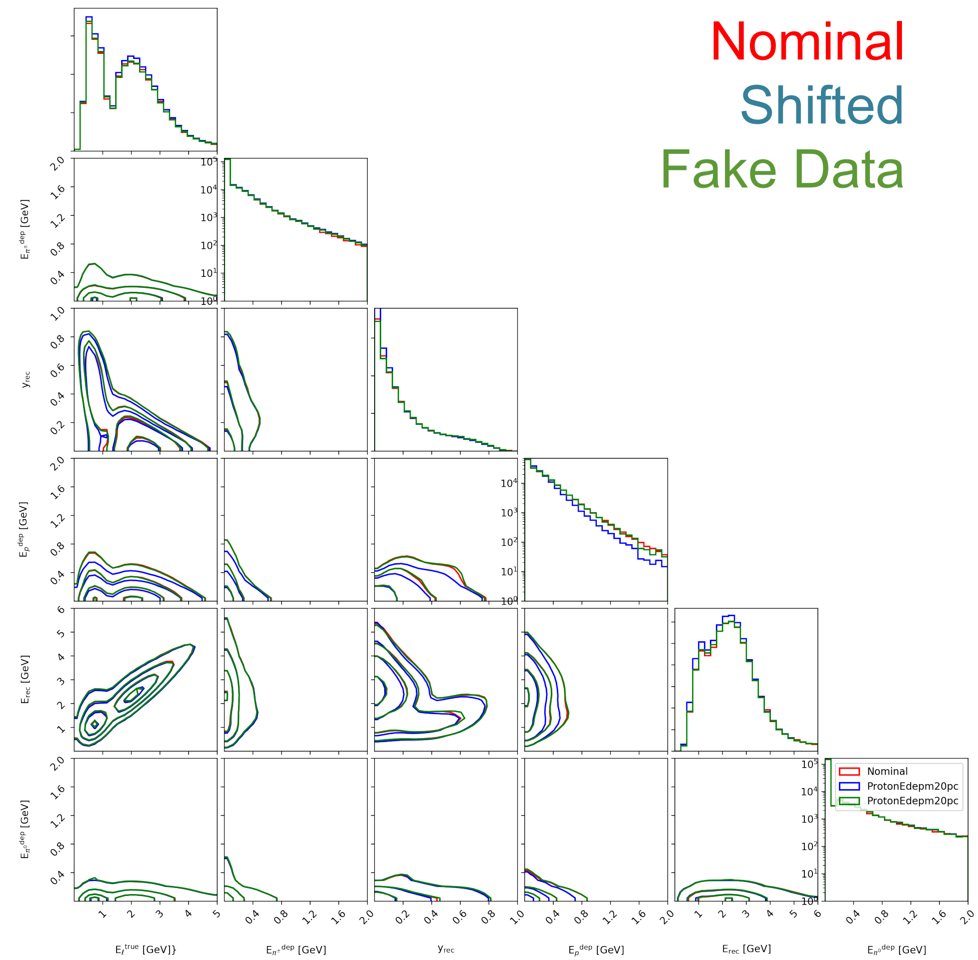
Systematics from Bias



- NuWro re-weighting study is just an example of one way our interaction model could be inadequate
- In a real FD-only analysis, there would be a multiplicity of potential biases that we would have to consider in determining a systematic uncertainty

Bias Study: Energy Bias

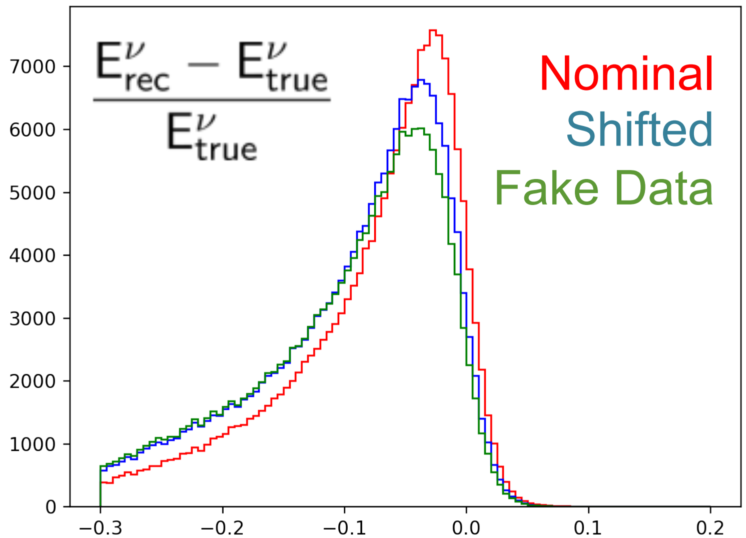
- 20% of proton energy is removed and added to (largely invisible) neutrons
  - Significant modification to relationship between reconstructed and true energy
  - An artificial but plausible example of a way in which the interaction model could be off
- Use BDT to adjust model parameters such that **on-axis** ND reconstructed distributions agree with the nominal sample
  - 6 variables: lepton energy, energy deposit from protons, charged pions, neutral pions, E_{rec}, and y_{rec}



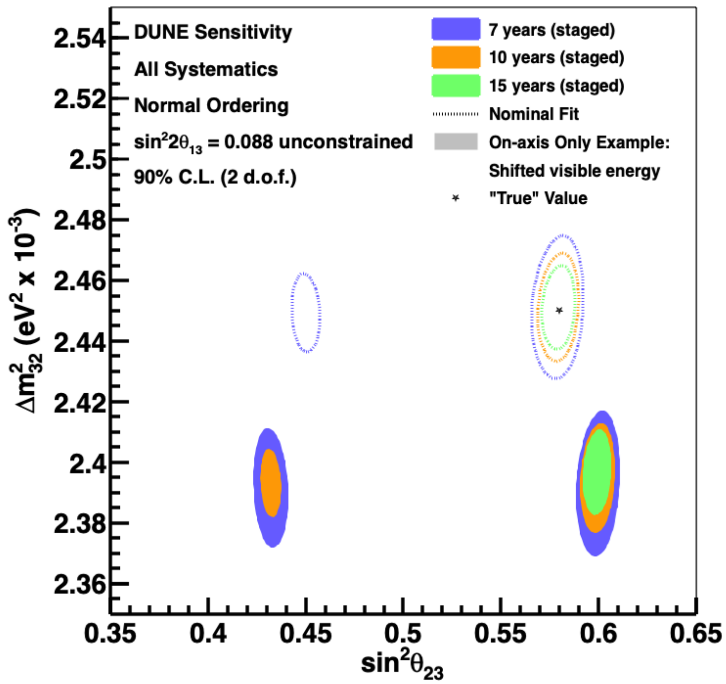
Nominal
Shifted
Fake Data

Bias Study: Energy Bias

Reconstructed E_ν



Δm^2_{32} vs $\sin^2\theta_{23}$

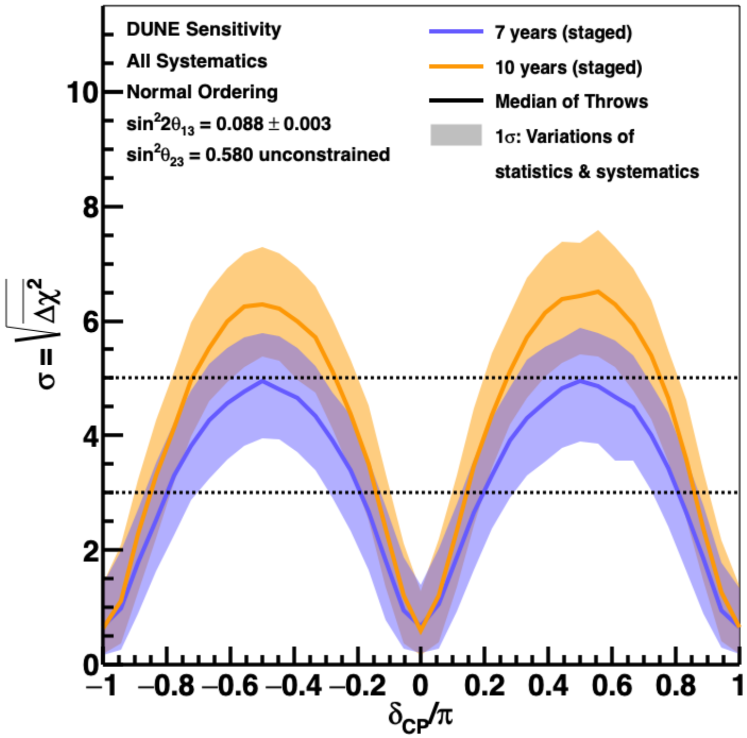


- Previous studies showed a bias in δ_{CP} (other oscillation parameters were fixed)
- In the full DUNE fitting framework, this particular bias is largely absorbed by a bias in Δm^2_{32}
- Dramatic bias in Δm^2_{32} would not be acceptable – we could not report any oscillation parameter measurements in a scenario where we had an unexplained offset in Δm^2_{32}

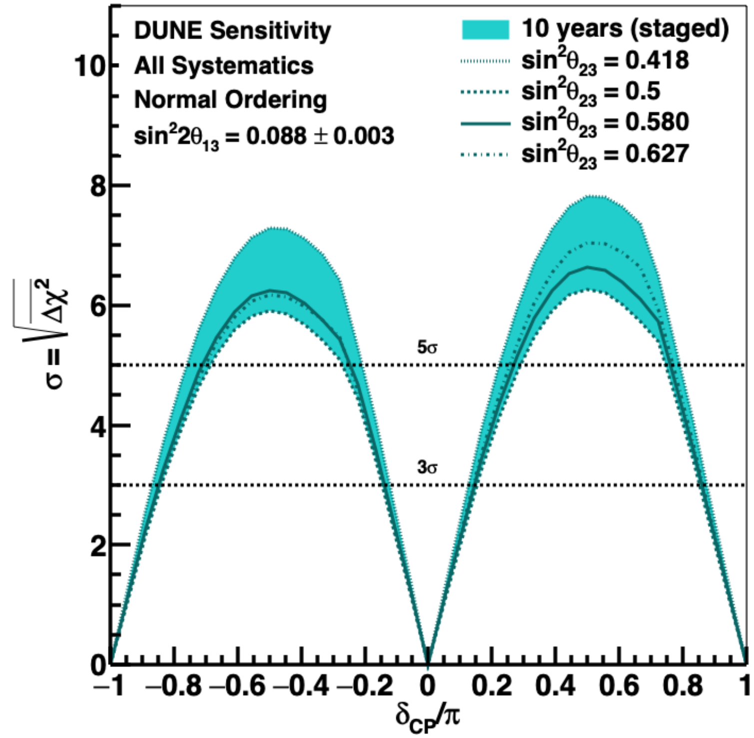
SANITY CHECKS & INTERESTING PLOT VARIATIONS

Impact of Oscillation Parameters

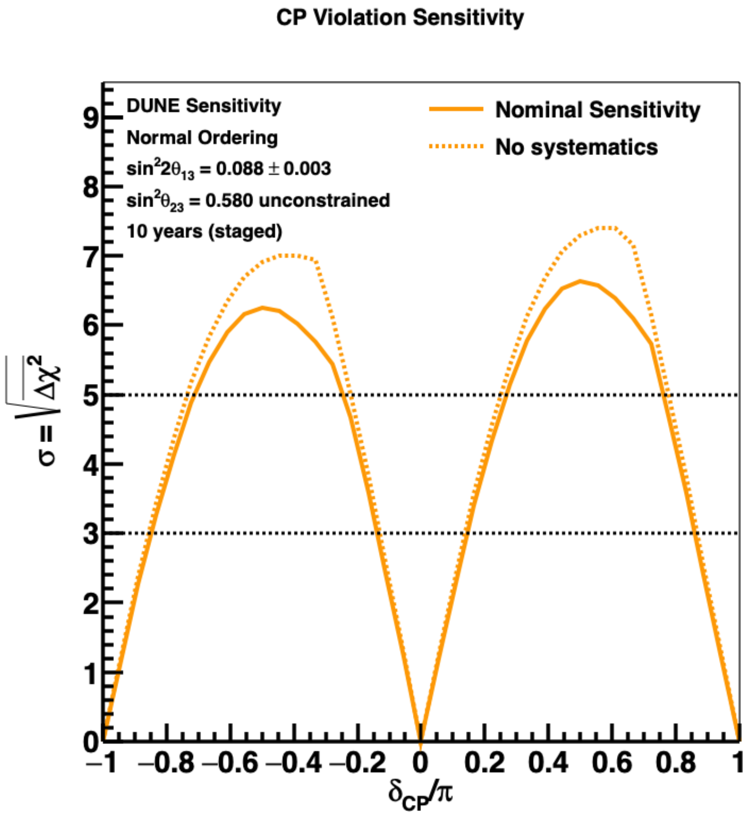
CPV: No parameter variation

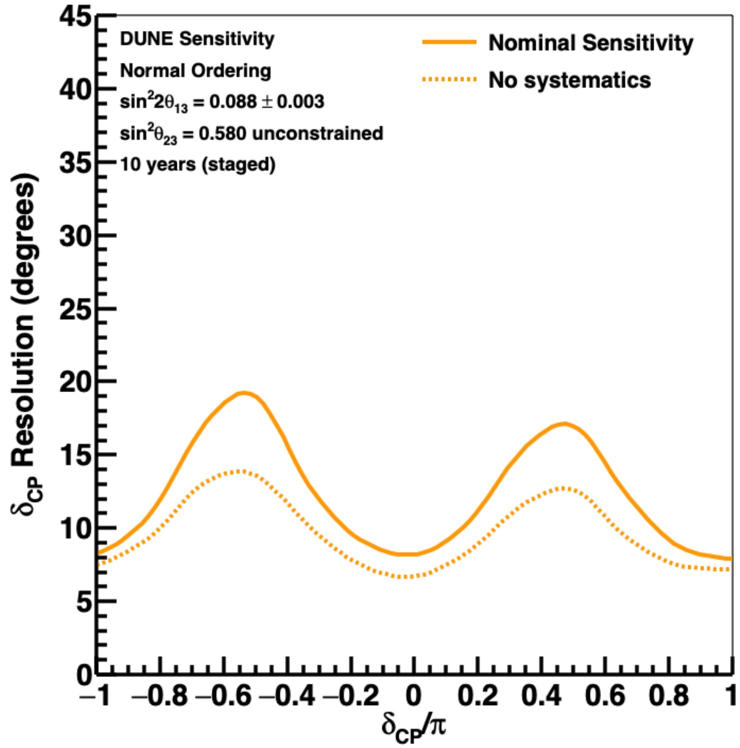


CPV: θ_{23} variation



Impact of Systematics

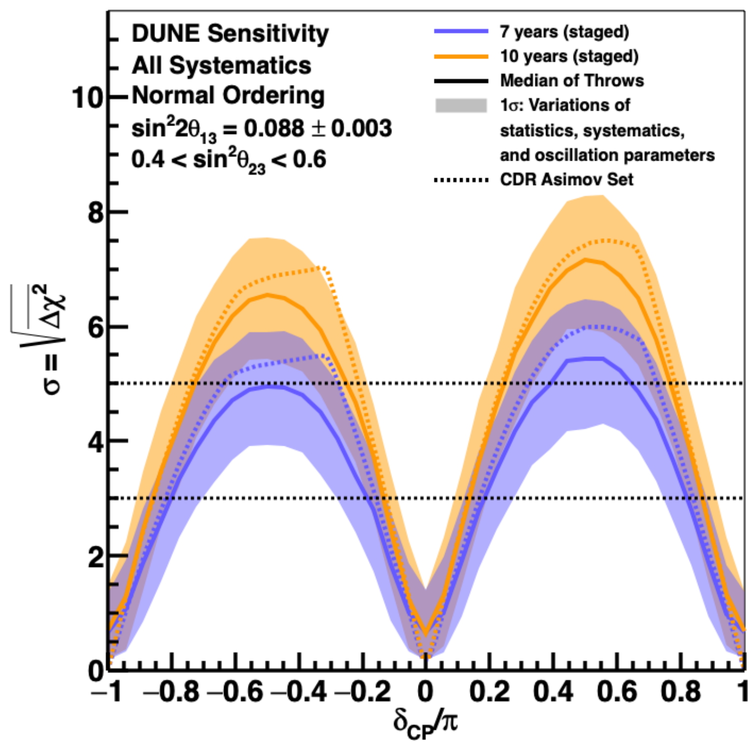




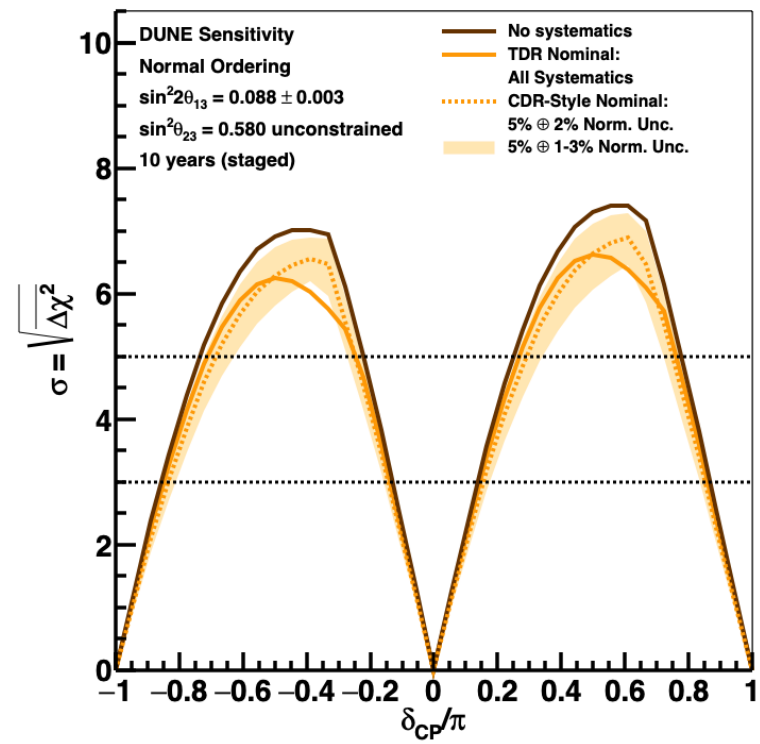
Comparisons to CDR

DEEP UNDERGROUND NEUTRINO EXPERIMENT

CPV: CDR

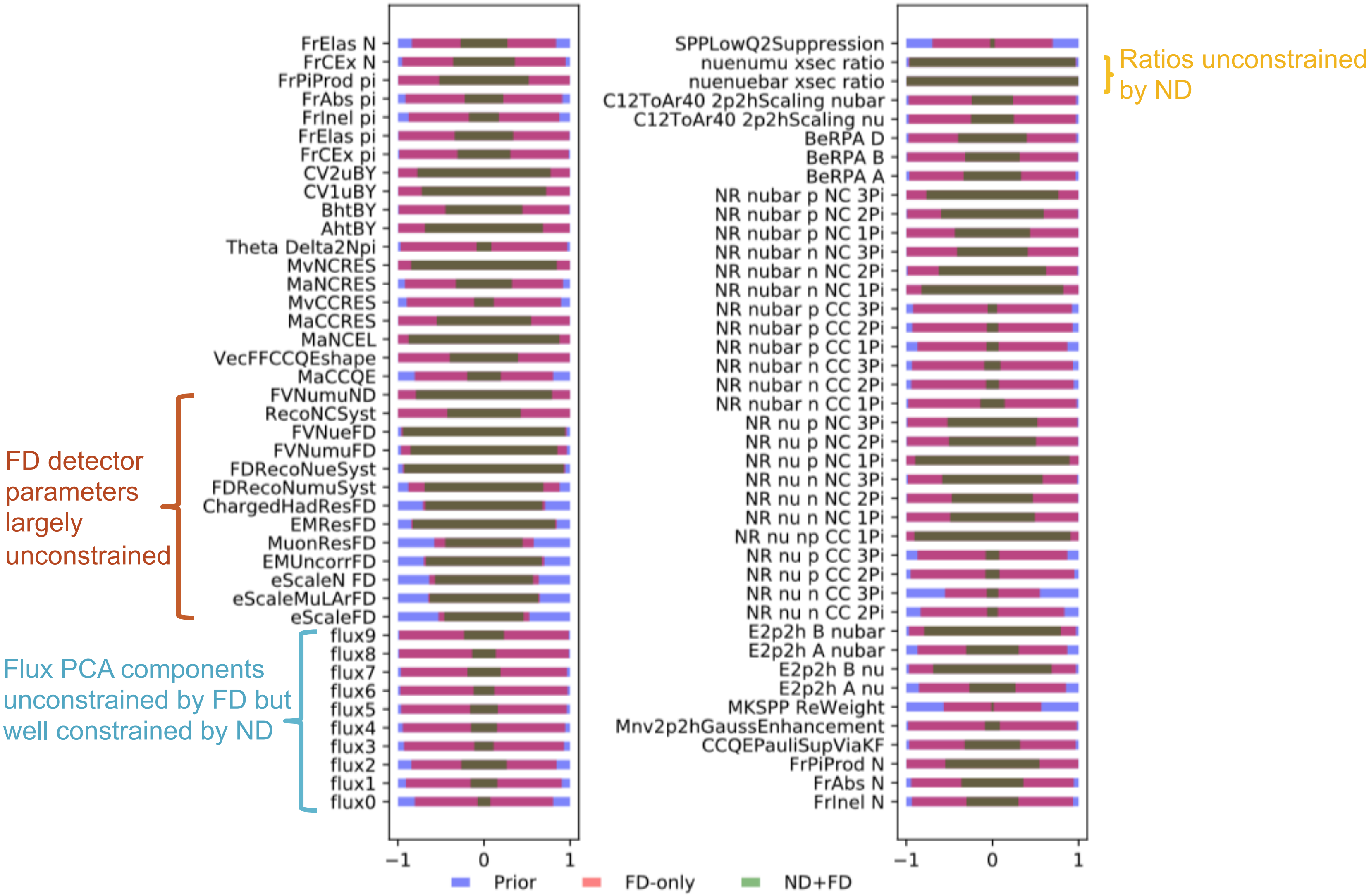


CPV: Norm. Uncertainty



New analysis results are consistent with CDR results. New suite of detailed systematic uncertainties has impact on sensitivity similar to that of normalization uncertainties applied in the CDR analysis.

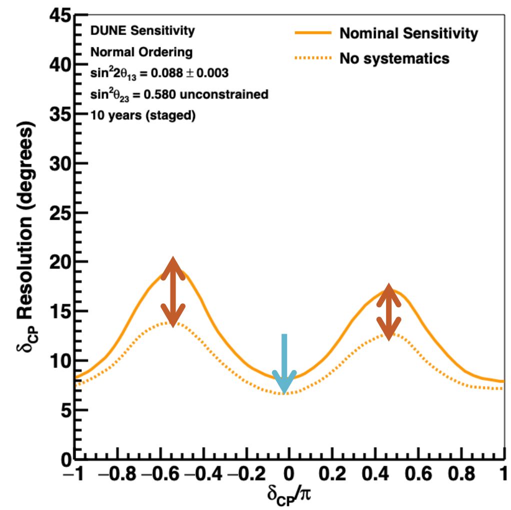
Systematics Checks



Systematics Checks

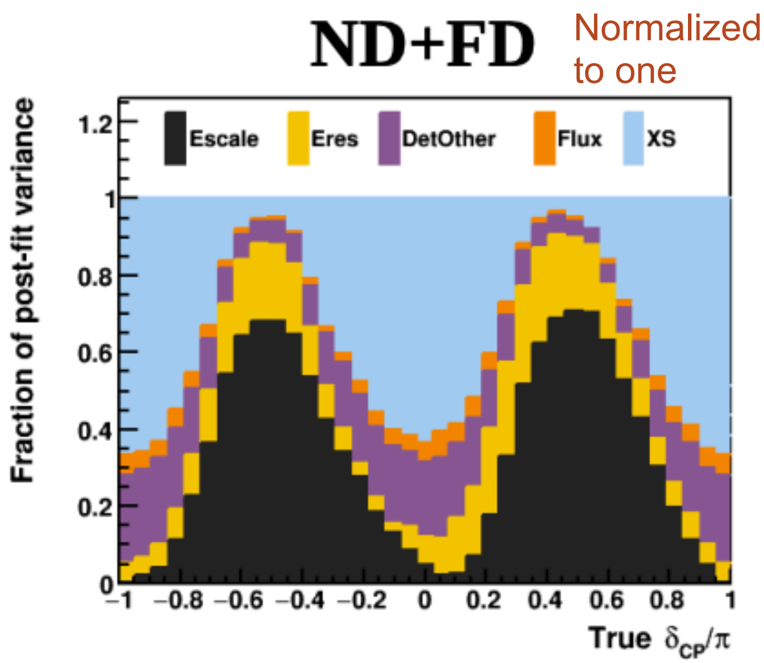
DEEP UNDERGROUND NEUTRINO EXPERIMENT

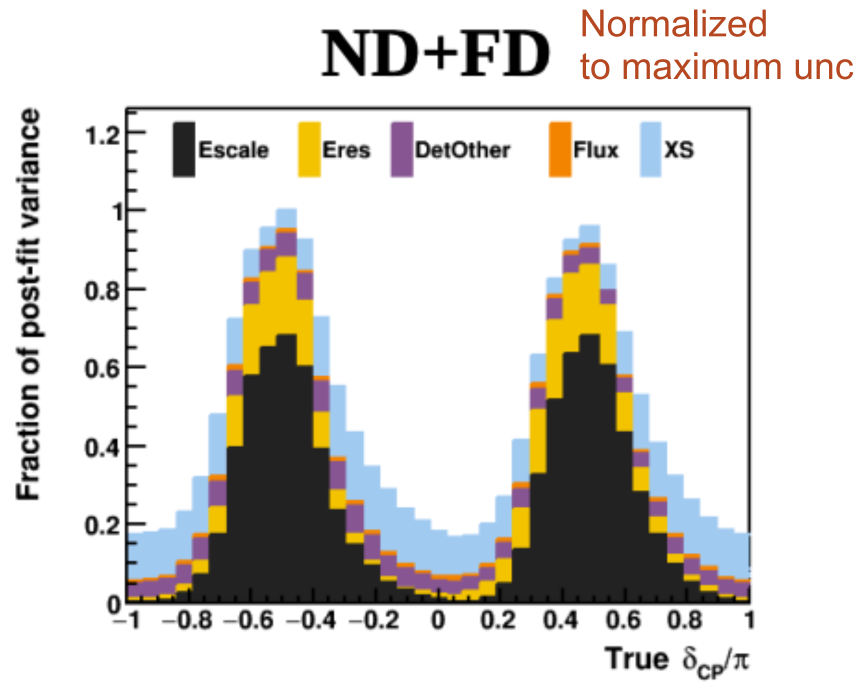
- Evaluating fractional contributions to post-fit uncertainty on δ_{CP} measurement provides a sanity check on fit behavior
  - Expect parameters of flux and cross-section models to be well constrained in the ND+FD fit
  - Expect significant contribution from detector effects (particularly EM energy scale) because these are uncorrelated with the ND in our fitting framework
- Two choices for normalization of fraction contributions
  - Fractional contribution normalized to one for each value of δ_{CP} – may overemphasize impact of systematics that have largest contribution where uncertainty is actually small
  - Fractional contribution normalized to maximum uncertainty among all possible δ_{CP} values for all systematics – folds in the size of the uncertainty while still showing relative contributions



Impact of systematic uncertainty varies with oscillation parameters – larger for maximally CP-violating values than CP-conserving values

Systematics Checks



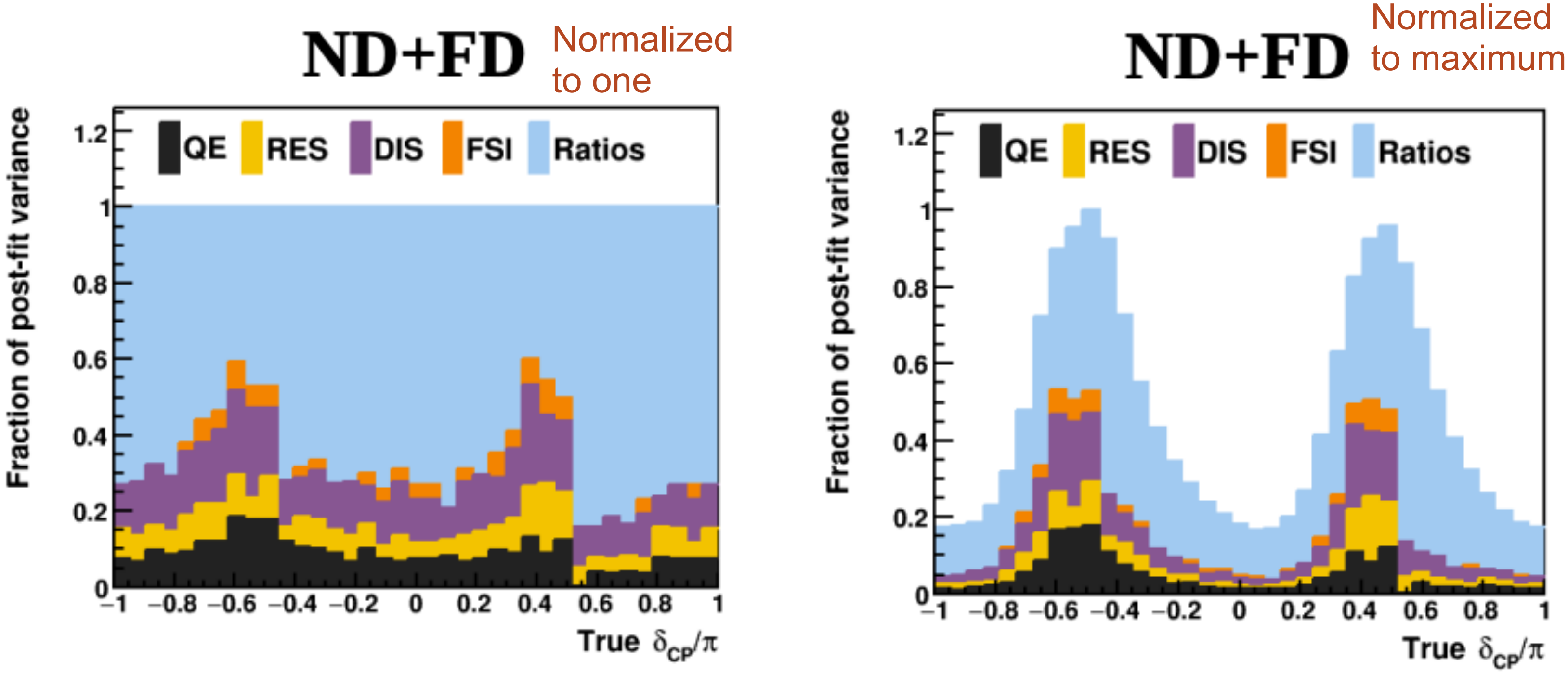


- Detector effects (esp. energy scale) are dominant uncertainty in these fits
  - Assumptions about validation of hadron production and interaction model are implicit, so not visible in this study
  - ND does a good job of constraining flux and interaction-model **parameters** in our fit
  - Detector effects based on assumed calibration uncertainty (poorly constrained in fit)

Systematics Checks

Normalized to one

Normalized to maximum unc.



- Among interaction model uncertainties, uncertainty in ν_e/ν_μ and neutrino/ antineutrino ratios dominate
  - Unconstrained by ND in these fits
  - Prior constraint from Day-McFarland (arXiv:xx)

Near-Term Plans

- Analysis will be updated to include some improvements/fixes to systematics treatment before final draft of TDR
  - Primarily a respin – no major new work
  - Will use NERSC: 8M CPU hours!
- Physics TDR currently being reviewed by DUNE collaboration and LBNC physics subcommittee
- TDR will be finalized at the end of July
- Long-baseline analysis framework will be used (and expanded) to contribute to physics studies for ND design work and ND CDR
  - Additional “fake data” studies to demonstrate impact of various detector components and exclusive samples being developed

Summary

- Long-baseline oscillation sensitivity analysis has been updated to make use of:
  - Full, automated FD simulation, reconstruction, event selection
  - Simulated ND samples (parameterized reconstruction)
  - Detailed treatment of systematics from flux, interaction model, and detector uncertainties
  - Sophisticated fitting framework
- Analysis implicitly assumes capacity to detect and correct deficiencies in hadron production and neutrino interaction models
  - This type of uncertainty is not explicitly included in the analysis framework
  - Importance of this type of uncertainty demonstrated by the bias studies
- New analysis produces results that are similar to the CDR analysis and fits behave as we would expect
- LBL analysis demonstrates that DUNE can achieve its primary oscillation physics goals assuming we have a full-scale far detector, timely beam upgrades, and a highly-capable near detector