Systematic Uncertainties Across NOvA Measurements:

3-Flavor, NSI, Sterile ν's & Scattering

Alex Himmel, Fermilab

for the NOvA Collaboration

Theoretical Physics Uncertainties to Empower Neutrino Experiments

Institute for Nuclear Theory

November 1st, 2023

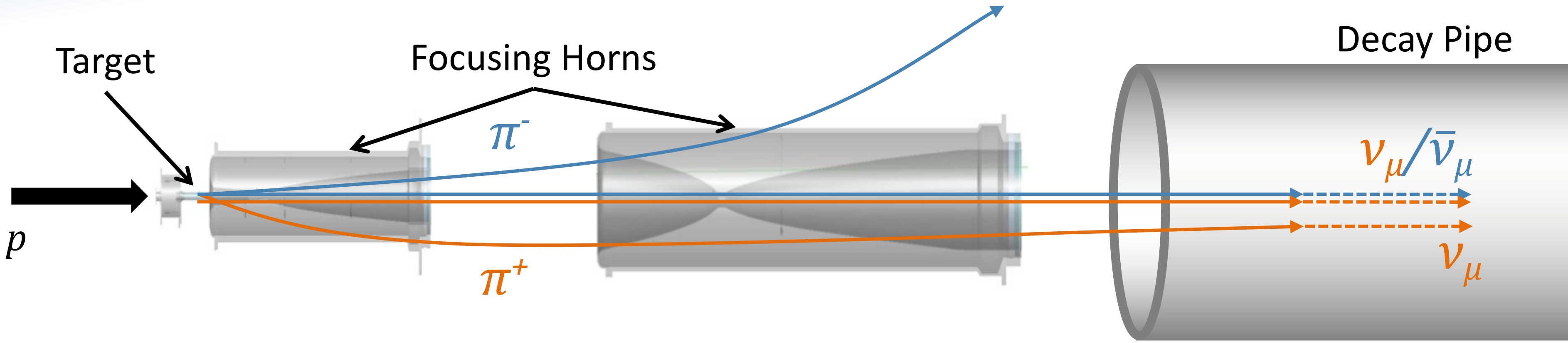
Introduction

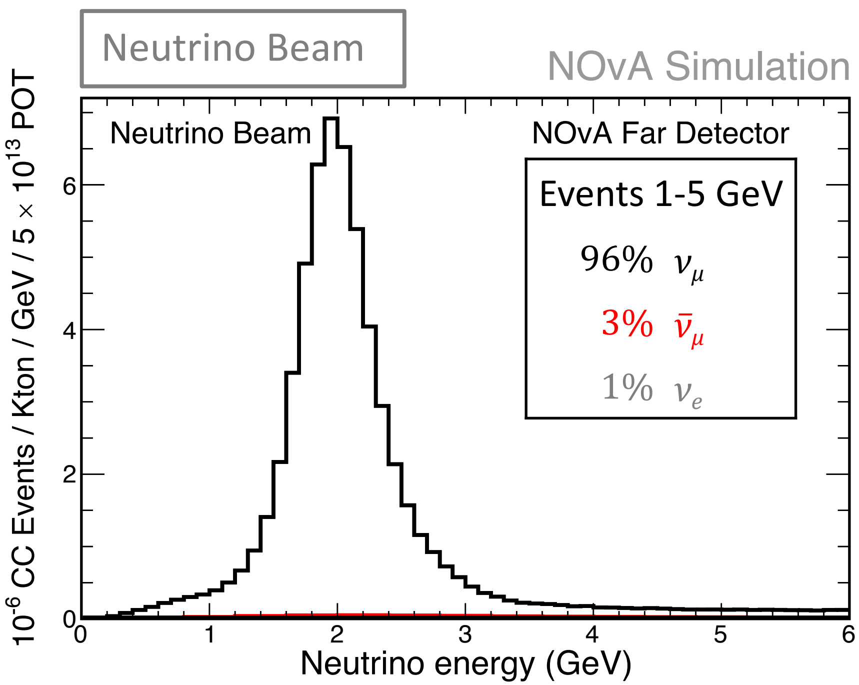
- This is a weird talk: we'll be digging through the weeds, and the *results* are all in the backups.
- Focus of this workshop is theoretical uncertainties for neutrino experiments. Here I want to focus on how those uncertainties apply across different kinds of analyses.
- Roadmap:
  - NOvA overview
  - Flux and flux uncertainties
  - The NOvA detectors and detector uncertainties
  - Our neutrino interaction model and its uncertainties
  - Summary of analyses and relative sizes of uncertainties
    - 3-flavor oscillations
    - Non-standard interactions
    - Sterile neutrino searches
    - Neutrino scattering
  - Summary, and what's coming next

The NOvA Experiment

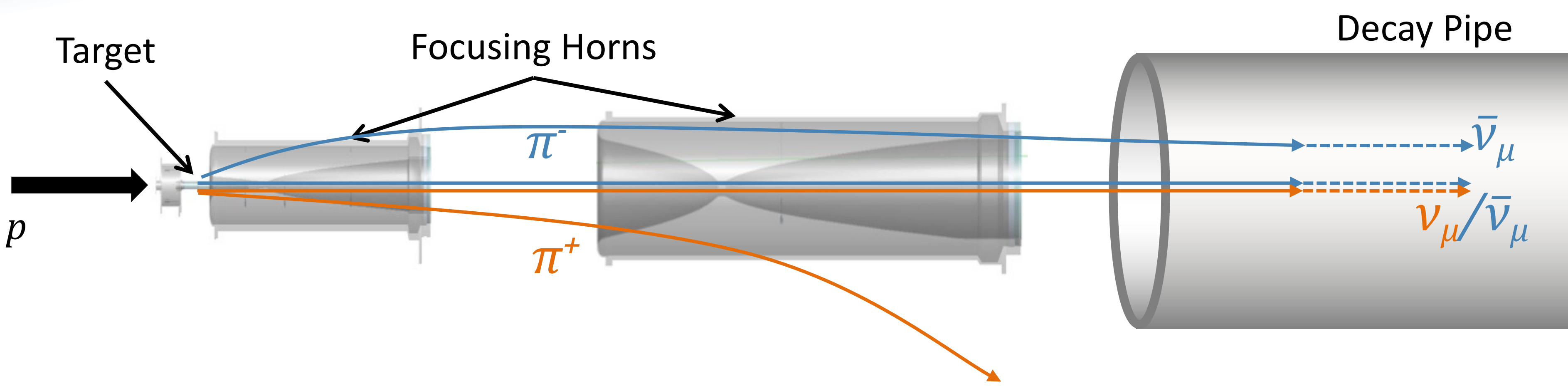
- Long-baseline neutrino oscillation experiment
- NuMI beam: ν_μ or $\bar{\nu}_\mu$
- 2 functionally identical, tracking calorimeters
- Designed for oscillations, but we also do:
  - Neutrino cross sections
  - Astroparticle physics
  - Cosmic ray physics
  - BSM searches

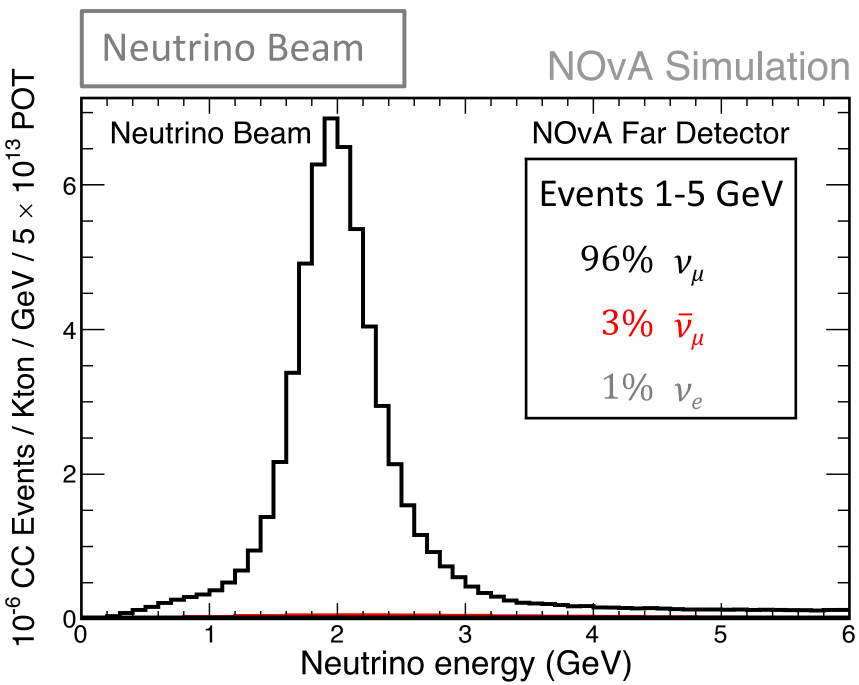
How We Make Neutrinos: The NuMI Beam

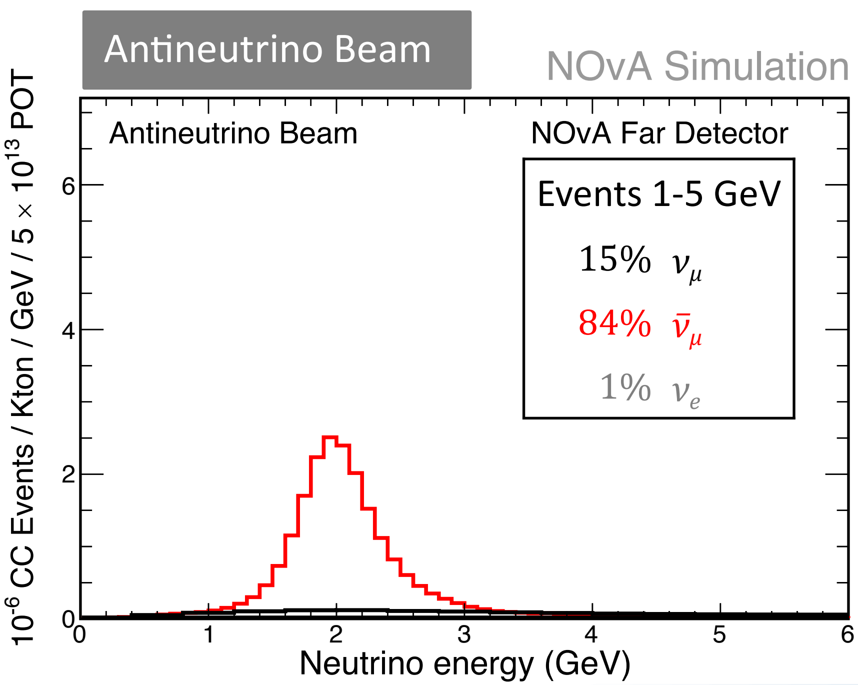




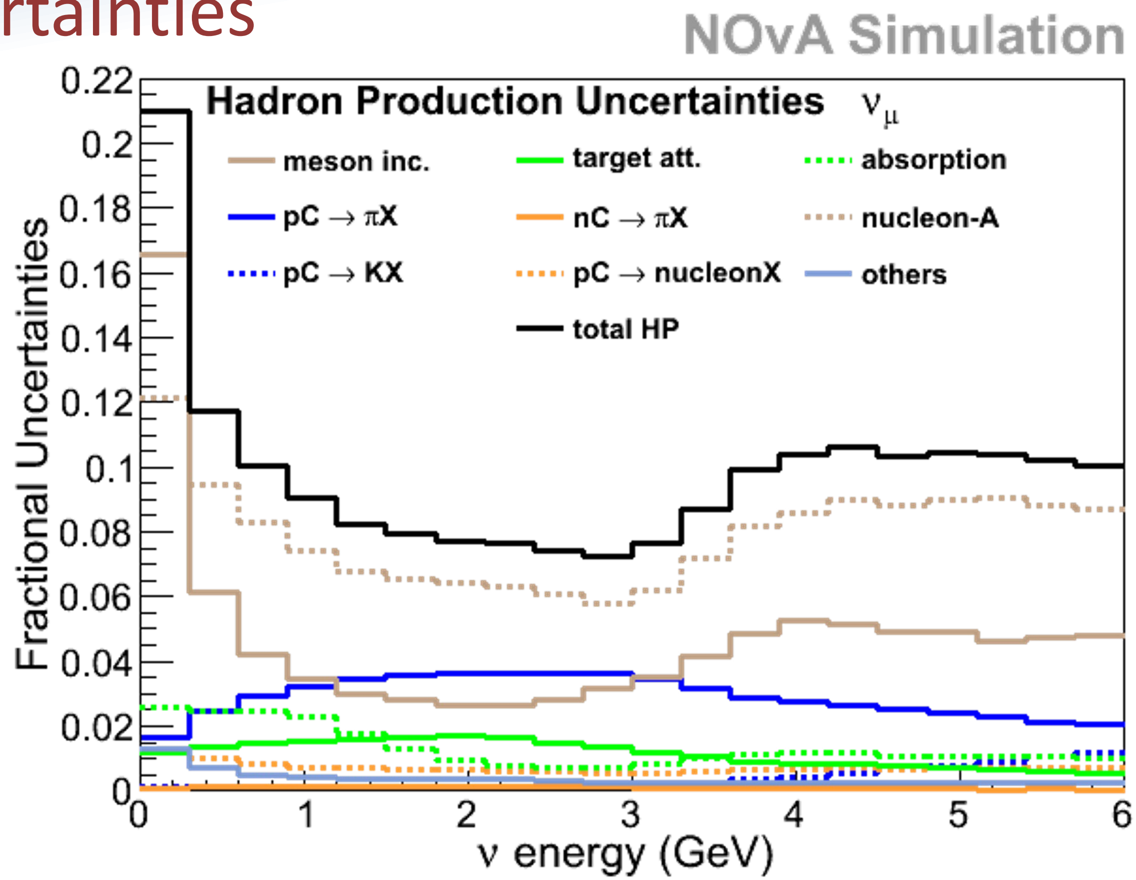
How We Make Neutrinos: The NuMI Beam





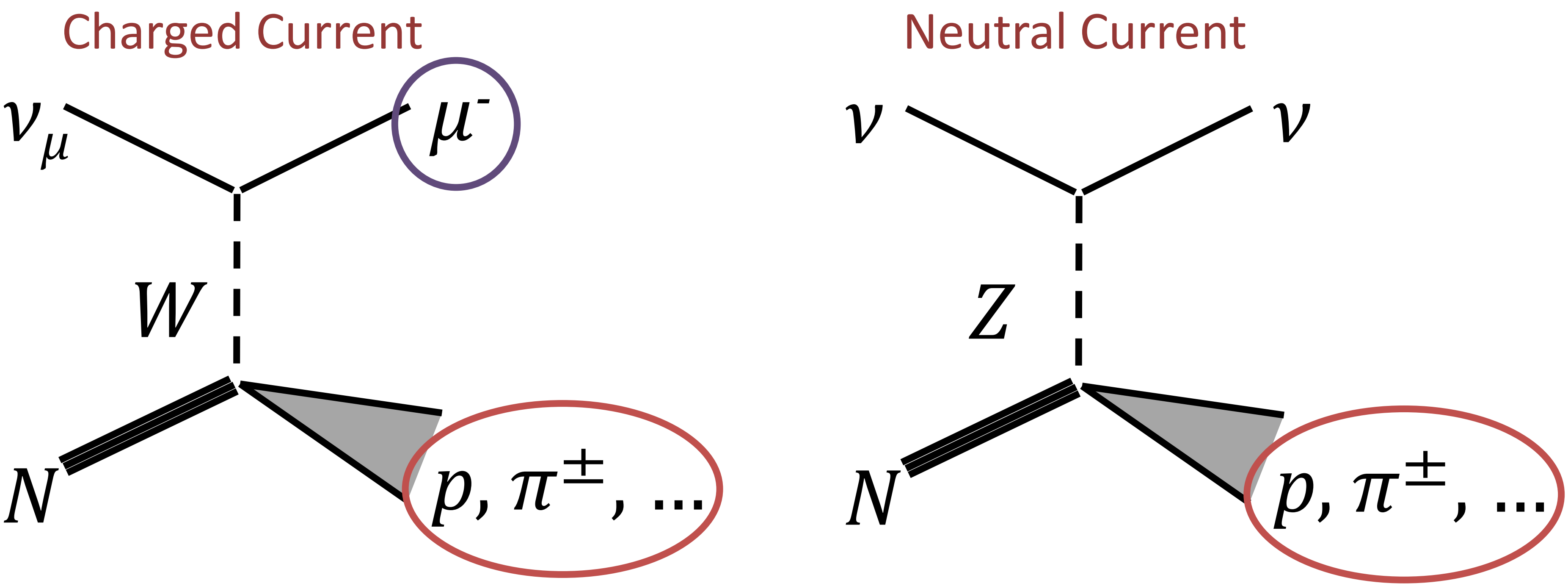


Flux Uncertainties



- Flux central value and uncertainty from the **Package to Predict the Flux (PPFX)**.
  - Developed in Minerva, but now a shared tool.
  - Incorporates several external datasets to reduce hadron production uncertainties.
  - PRD 94, 092005 (2016)
- Additional sub-dominant errors related to the focusing system.
- PPFX provides uncertainties as "universes" with correlated systematic throws.
  - Cross-section analyses generally use these directly to create covariance matrices.
  - Other analyses typically use PCA to create a limited number of "knobs."

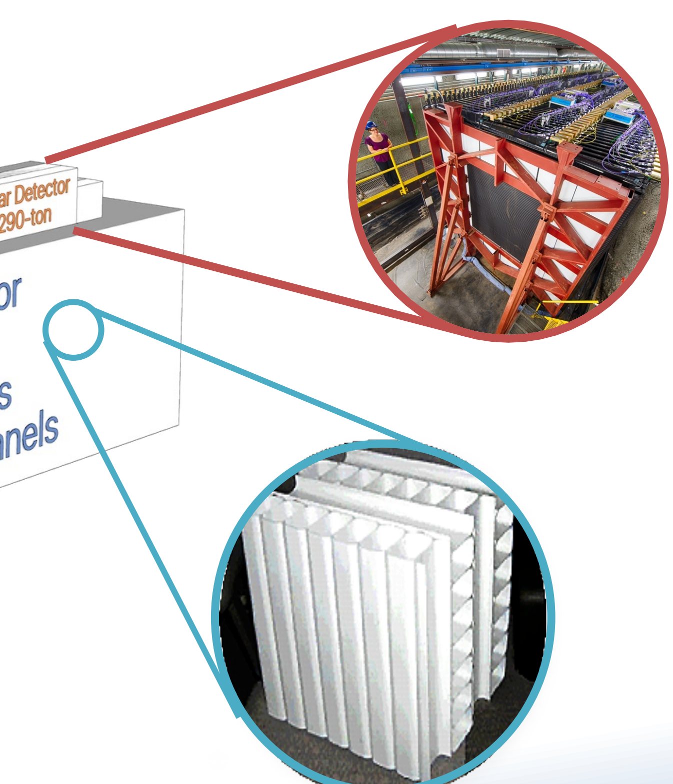
How to Detect a Neutrino



- Observe the charged particles after a neutrino interacts with a nucleus:

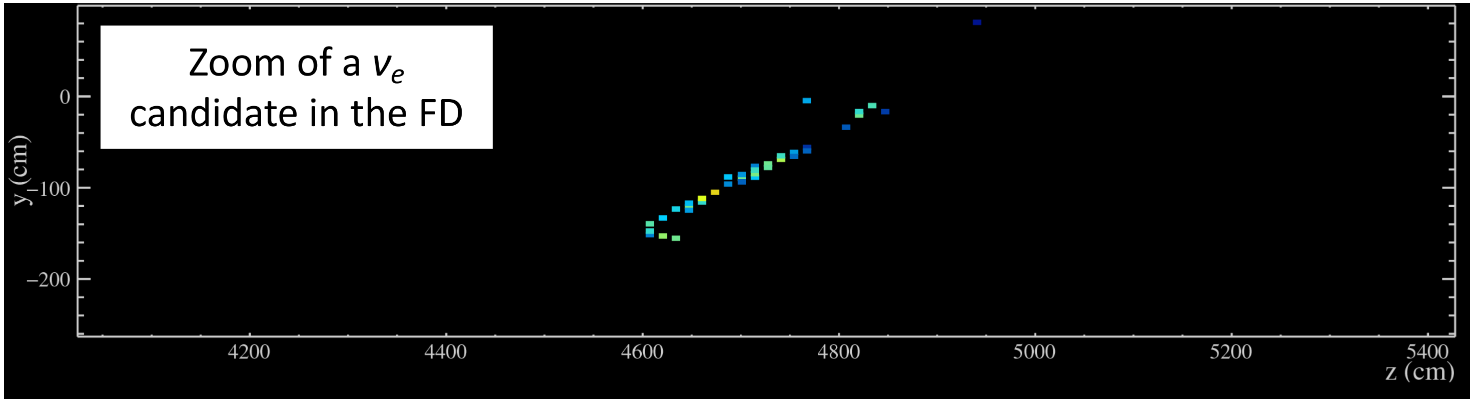
- Lepton
  - CC $\nu_\mu \rightarrow \mu^-$, CC $\nu_e \rightarrow e^-$
  - NC $\rightarrow$ no visible lepton
- Hadronic shower
  - Neutrinos typically produce a proton
  - Antineutrinos typically produce a neutron
  - May one or more $\pi^\pm$, additional p, n, etc.
  - May also contain EM from $\pi^0 \rightarrow \gamma\gamma$

- Plastic cells filled with liquid scintillator
- Arranged in alternating directions for 3D reconstruction
- Light collected on wavelength-shifting fibers and carried to avalanche photodiodes

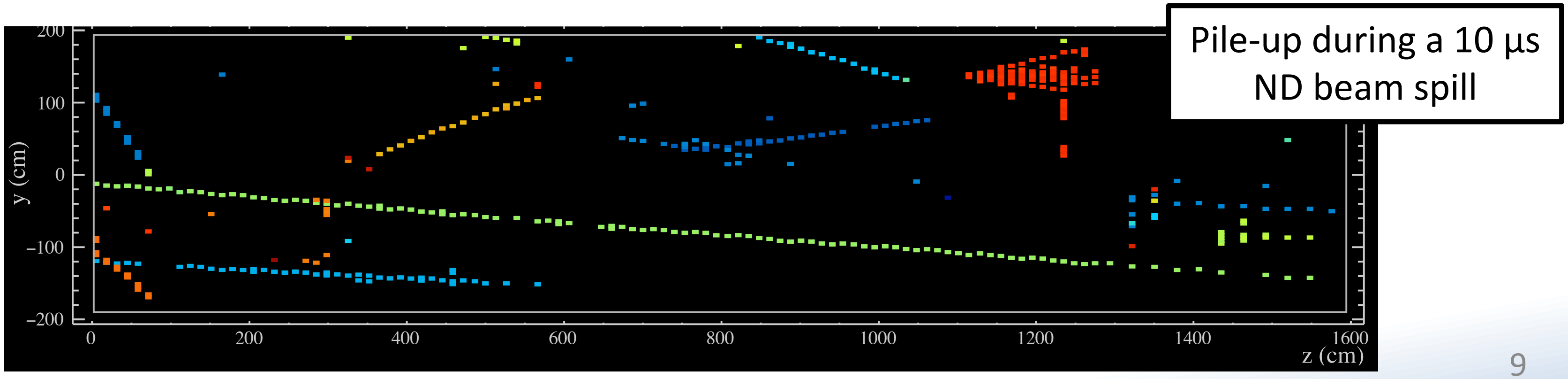



The NOvA Detectors

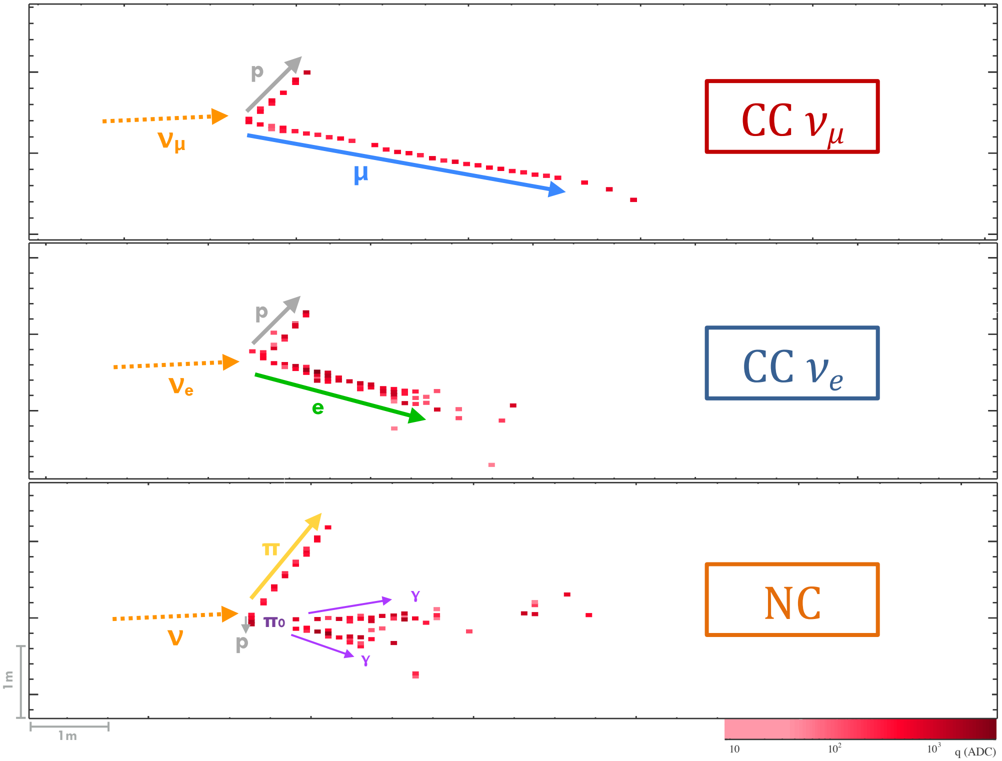
- Segmented liquid scintillator detectors provide 3D tracking and calorimetry
- Optimized for electron showers: ~60% active and ~6 samples per X_0



- Time resolution of a few ns, and spatial resolution of a few cm
  - Allows clear separation of individual interactions



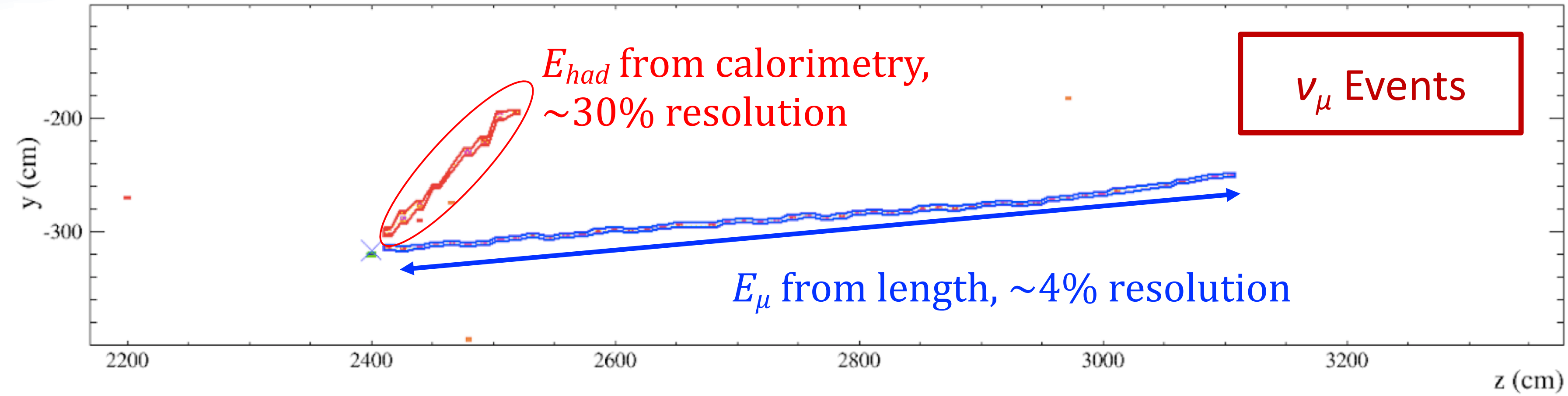
Selecting and Identifying Neutrinos

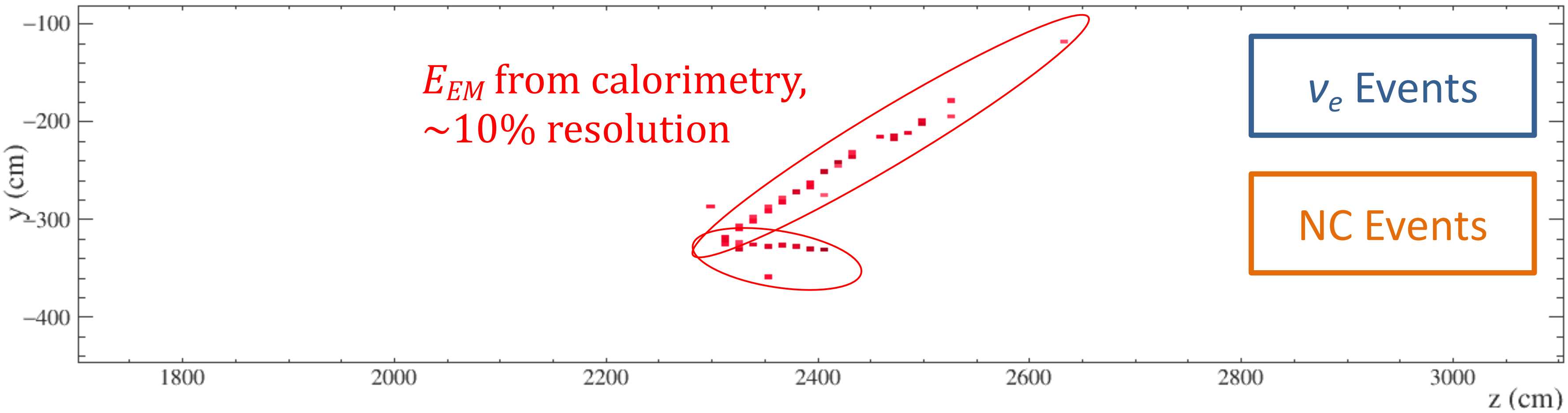


- Most analyses use **convolutional neural networks** for event ID.
  - A deep-learning technique from computer vision
  - Multi-label ID shared across samples
- Event-level ID used in oscillation-related measurements.
- Particle-level ID used in cross section measurements.
  - Works on individual "prongs," not the whole event.
  - Trained without any generator information.
- Also use likelihood-based Muon IDs for tracks.

First CNN in HEP result: A. Aurisano, et al. JINST 11 (2016) 09, P09001

Energy Reconstruction

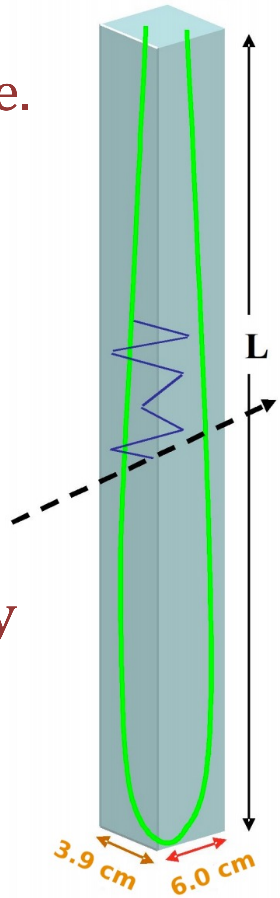




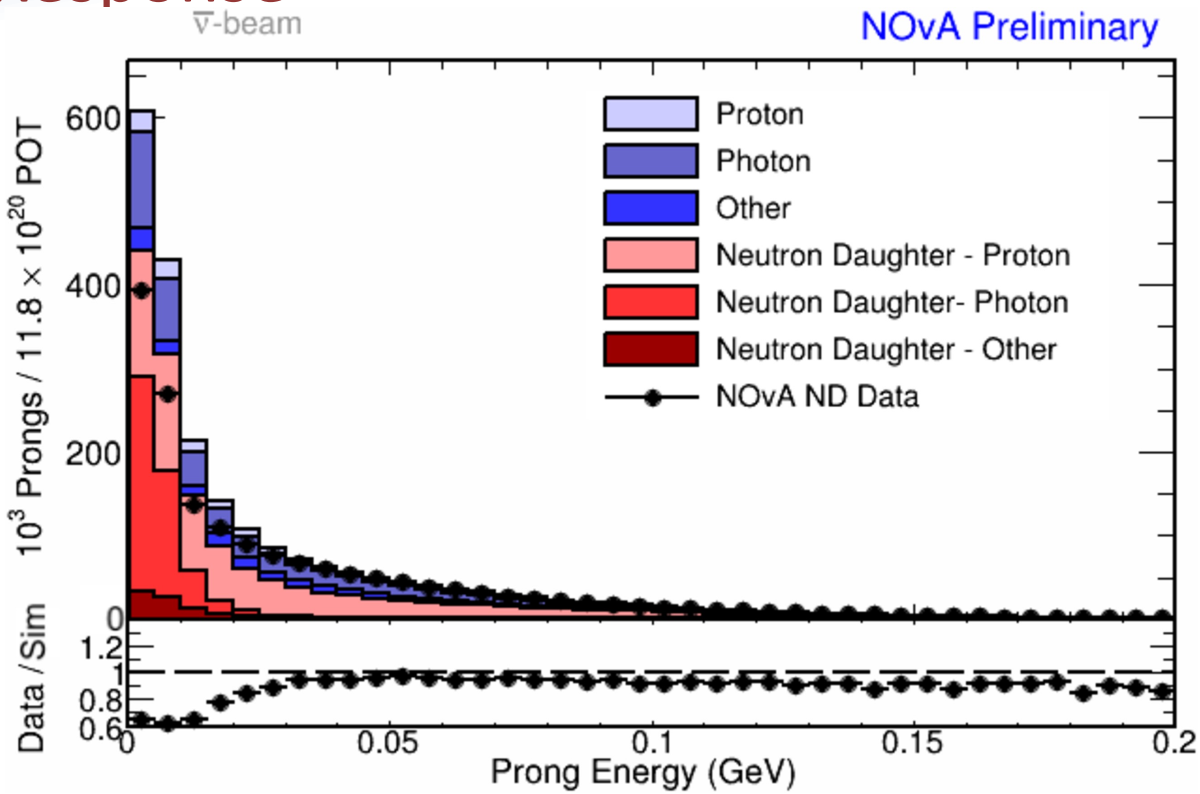
- These are inputs to analysis-specific energy estimators.
  - For example: ν_e energy uses another particle ID CNN to separate hadronic from electromagnetic energy deposits.

Detector Uncertainties

- Often the largest category of uncertainty.
- Calibration
  - Effectively a 5% uncertainty on the calorimetric energy scale.
- Light level
  - Threshold effects
  - Amount of Cherenkov light
    - Relative brightness of protons vs. lighter particles.
- Lepton reconstruction
  - Uncertainty on conversion between muon length and energy
    - Several effects, but <1% all together.
  - Lepton angle
- Normalization
  - Detector mass account, POT accounting, etc.



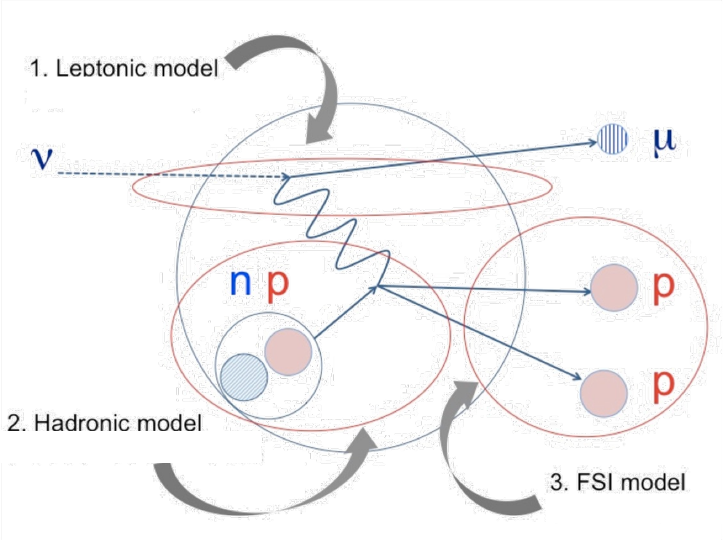
Neutron Response



- So far, this uncertainty has been based on data-simulation discrepancies in neutron-enhanced samples.
  - Introduce post-hoc modifications to event energies to "correct" the above disagreements, treat as the uncertainty.
- Aiming to improve this with a more first-principles uncertainty in future analyses.
  - Note above that the disagreement seems to suggest over-production of photons by Geant's medium-energy neutron model.

Neutrino Interaction Model

- Currently using GENIE 3.0.6 → freedom to choose models
- Chose the most "theory-driven" set of models.
- Some custom tuning is still used in some circumstances.
  - Substantially less than was needed with GENIE 2.12.2, which required tweaks to most models.



Process	Model	Reference
Quasielastic	Valencia 1p1h	J. Nieves, J. E. Amaro, M. Valverde, Phys. Rev. C 70 (2004) 055503
Form Factor	Z-expansion	A. Meyer, M. Betancourt, R. Gran, R. Hill, Phys. Rev. D 93 (2016)
Multi-nucleon	Valencia 2p2h	R. Gran, J. Nieves, F. Sanchez, M. Vicente Vacas, Phys. Rev. D 88 (2013)
Resonance	Berger-Sehgal	Ch. Berger, L. M. Sehgal, Phys. Rev. D 76 (2007)
DIS	Bodek-Yang	A. Bodek and U. K. Yang, NUINT02, Irvine, CA (2003)
Final State Int.	hN semi-classical cascade	S. Dytman, Acta Physica Polonica B 40 (2009)

Fig: Teppei Katori, "Meson Exchange Current (MEC) Models in Neutrino Interaction Generators" AIP Conf.Proc. 1663 (2015) 030001

Neutrino Interaction Uncertainties

ν_e/ν_μ cross section ratio
Radiative corrections: 2% **un**correlated for ν/anti-ν
Second-class currents: 2% **anti**correlated for ν/anti-ν

(Quasi)elastic Interactions
z-expansion normalization +20%/-15% from GENIE
z-expansion a_1-a_4 re-implemented to maintain correlations
RPA nuclear model uncertainty from MINERvA Previously a correction, now just an uncertainty
NC Elastic M_A, η from GENIE

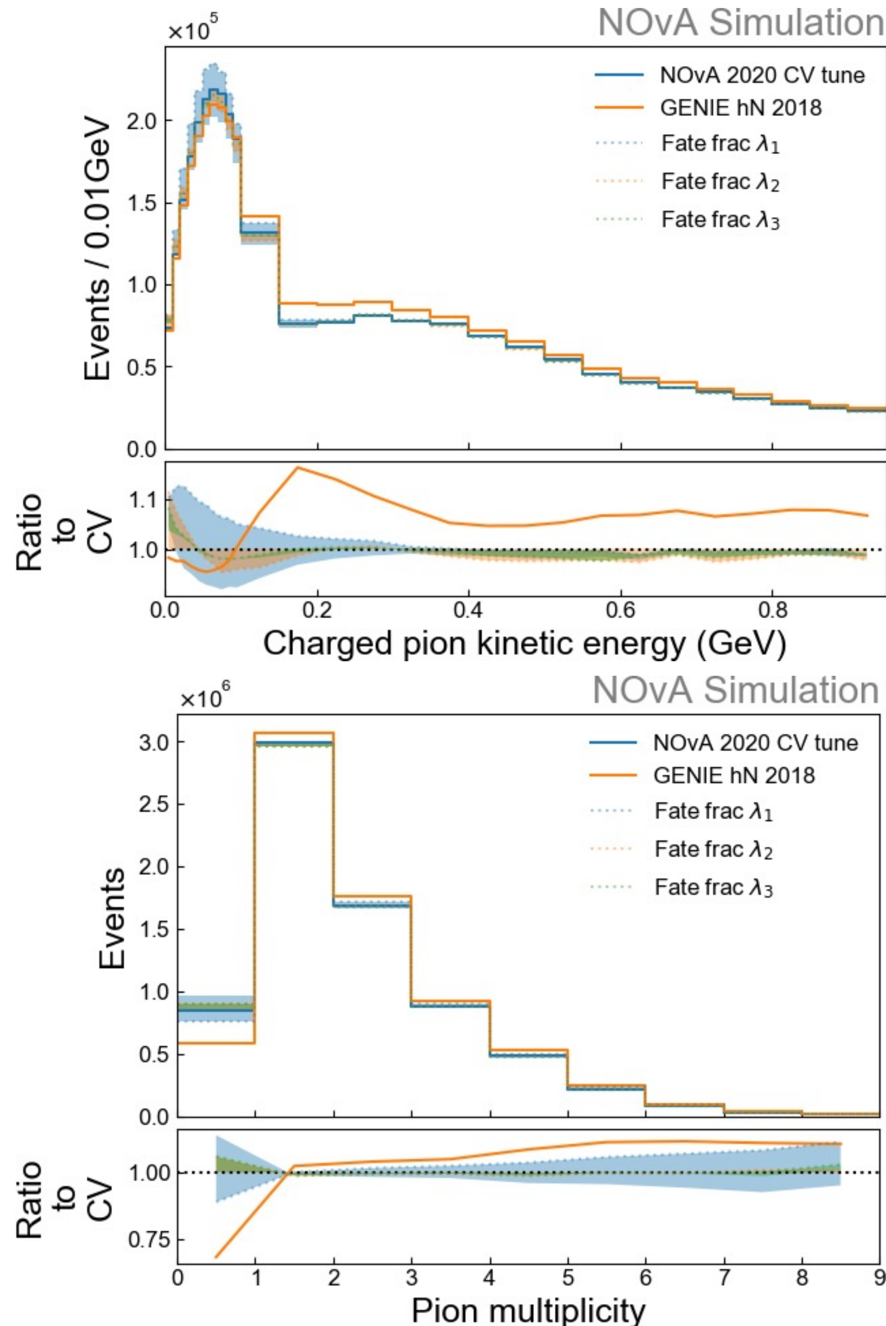
Neutrino Interaction Uncertainties

Resonance Interactions
CC & NC RES M_A, M_V from GENIE
BR($R \rightarrow X+1\gamma$), BR($R \rightarrow X+1\eta$), Angular distro. ($\Delta \rightarrow \pi N$)
Low Q^2 (<0.2 GeV^2) suppression inspired by MINOS/MINERvA

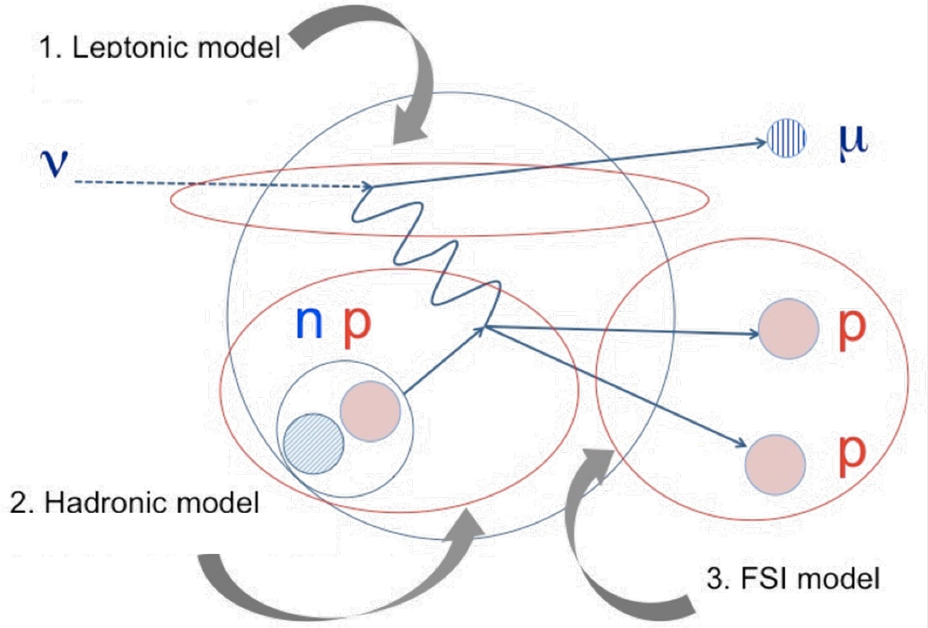
DIS Interactions & Hadronization
GENIE Bodek-Yang uncertainties: A_{HT}, B_{HT}, C_{V1u}, C_{V2u}
GENIE AGKY uncertainties: $x_F 1\pi$, $p_T 1\pi$
GENIE Formation Zone
Custom Nonresonant Nπ production uncertainty 50% at W < 3 GeV, linearly decreasing to 5% for W > 5 GeV

FSI Tune and Uncertainties

- Using hN 2018
  - Believed more rigorous than hA model
  - Challenge: not directly reweightable
- Systematics → Tuning to external data
  - Constructed uncertainty bands in the same spirit as work by T2K
    - PRD 99, 052007
  - 4 uncertainties:
    - Mean free path
    - 3x "fate" fractions
  - Adjust central value of model to match external data using BDT reweighting adapted from DUNE
- Ultimately gave 5-10% uncertainties on pion kinematics
  - Small uncertainty for nova analyses thanks to calorimetric reco.



2p2h/MEC/Multi-nucleon Interactions

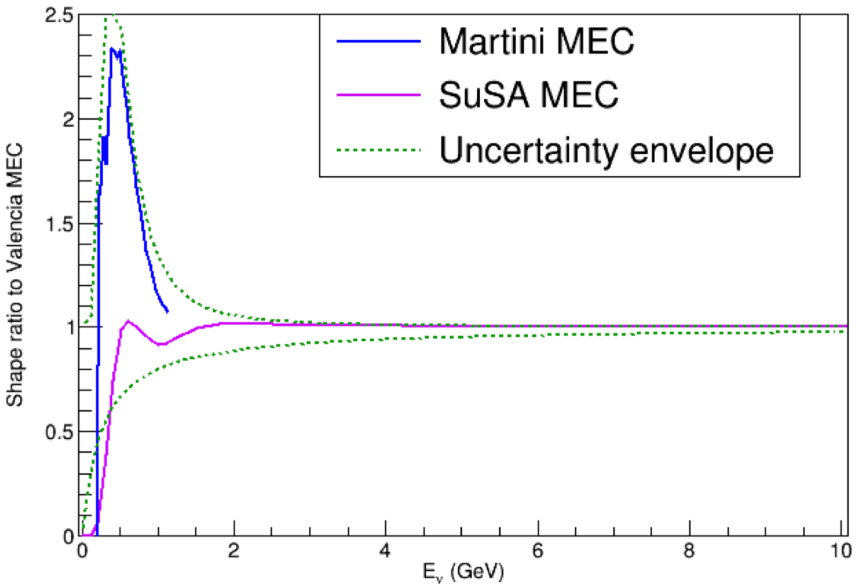


- Using Valencia 2p2h model, better than "Empirical," but…
  - doesn't match our data well.
  - need to create uncertainties.
- 3 components to the uncertainty:
  1. Energy dependence
  2. Nucleon pair fractions
  3. Kinematic shape ← 2 different approaches

Fig: Teppei Katori, "Meson Exchange Current (MEC) Models in Neutrino Interaction Generators" AIP Conf.Proc. 1663 (2015) 030001

Common 2p2h Uncertainties

Energy Dependence



- Define an envelope in E_ν to cover energy dependence in different models.

Nucleon Pair Fractions

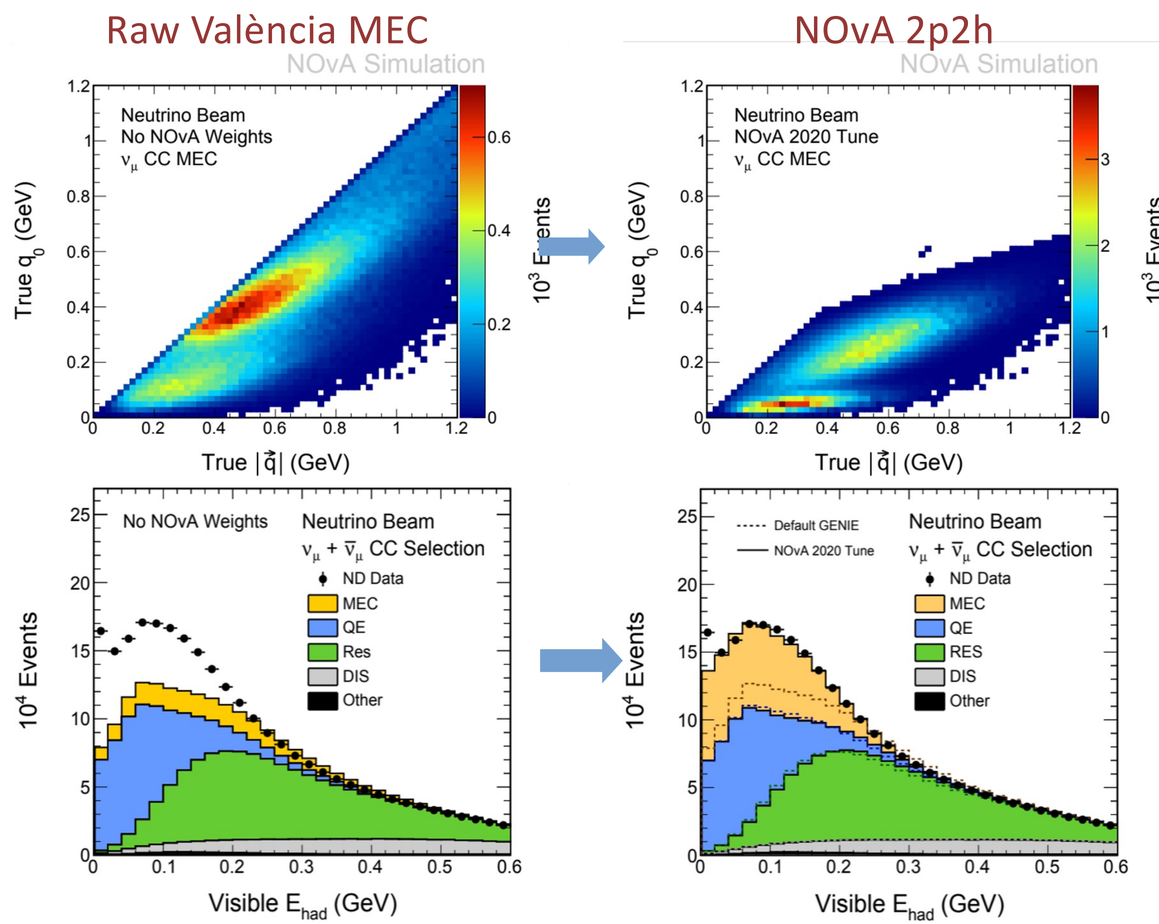
ν: $$\frac{np}{np+nn} = 0.69 \begin{cases} +0.15\sigma \\ -0.05\sigma \end{cases}$$

$\bar{\nu}$: $$\frac{np}{np+pp} = 0.66 \begin{cases} +0.15\sigma \\ -0.05\sigma \end{cases}$$

- Uncertainty range again comes from spread among models.
- Central values are from Valencia.

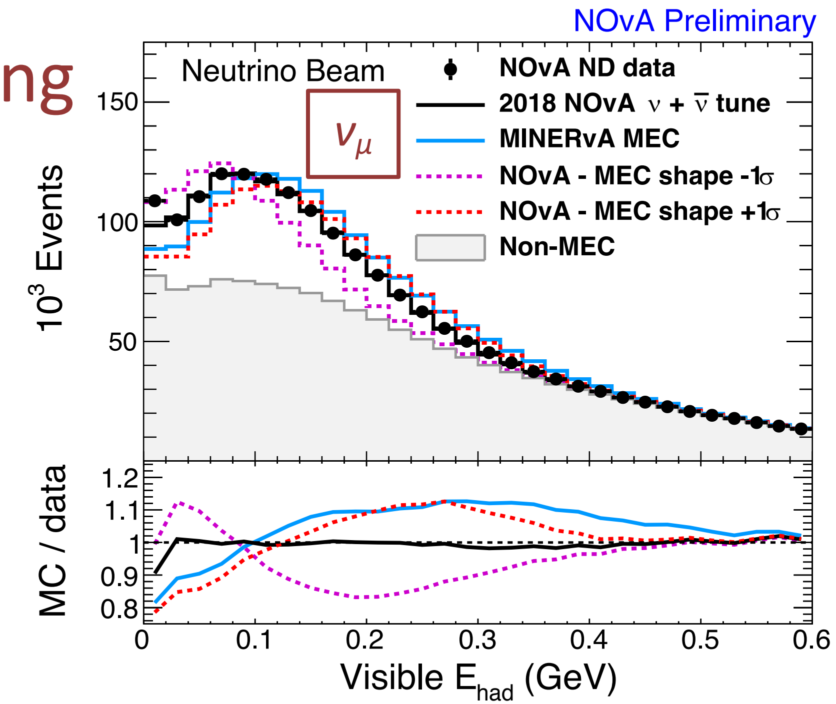
2p2h Shape Uncertainty: Tuning

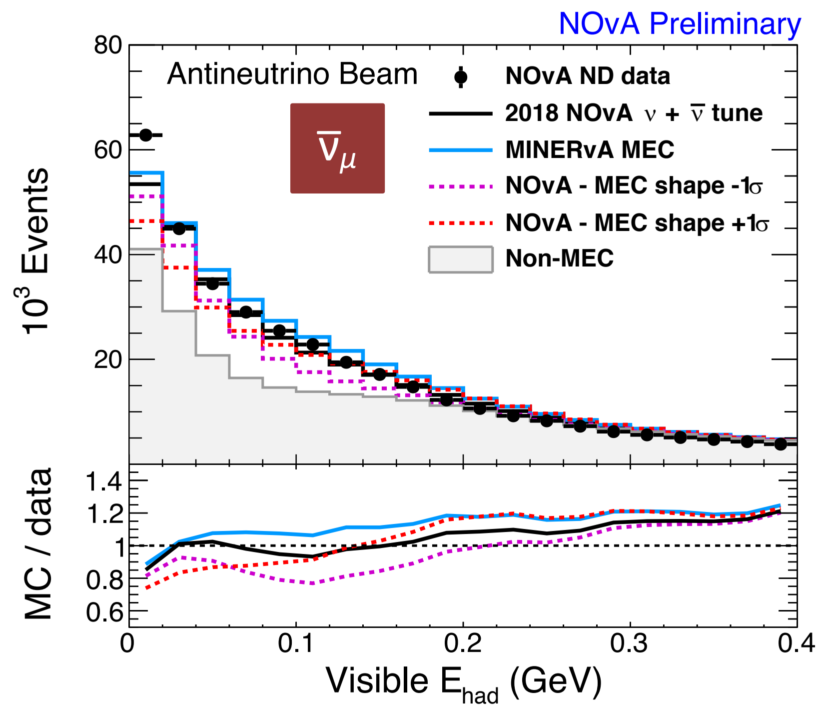
- Tune the central value to ND data
  - Double-gaussian fit in q_0- $|\boldsymbol{q}|$ space.
- Define shape uncertainty by coherently adjusting other cross section knobs.
  - Make 2p2h more RES-like by enhancing QE strength.
  - Make 2p2h more QE-like by enhancing RES strength.
- Most NOvA analyses use the tuned central value and related uncertainty.



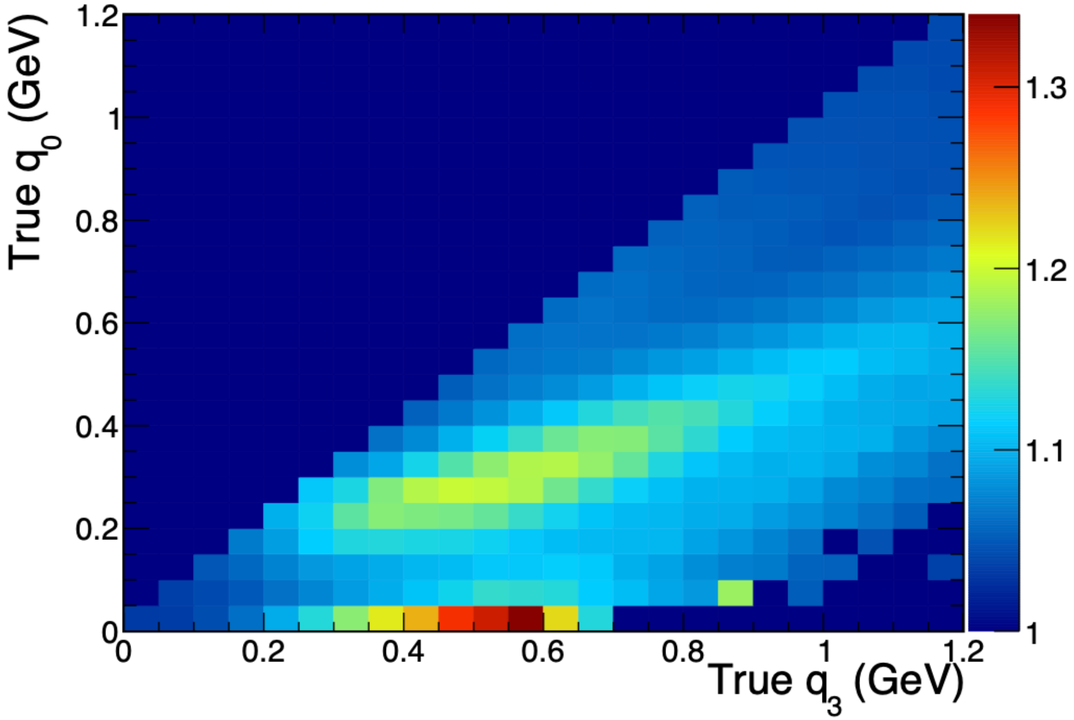
2p2h Shape Uncertainty: Tuning

- Tune the central value to ND data
  - Double-gaussian fit in q_0- $|\boldsymbol{q}|$ space.
- Define shape uncertainty by coherently adjusting other cross section knobs.
  - Make 2p2h more RES-like by enhancing QE strength.
  - Make 2p2h more QE-like by enhancing RES strength.
- Most NOvA analyses use the tuned central value and related uncertainty.



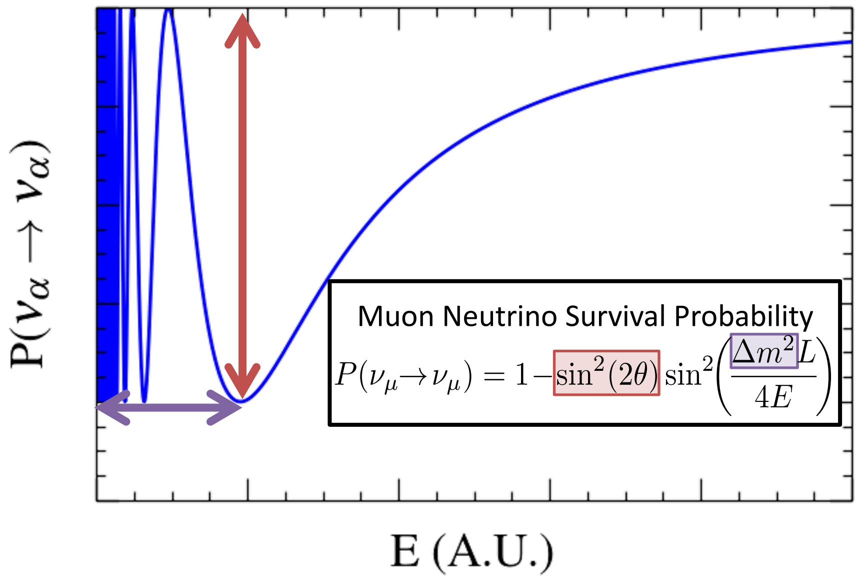


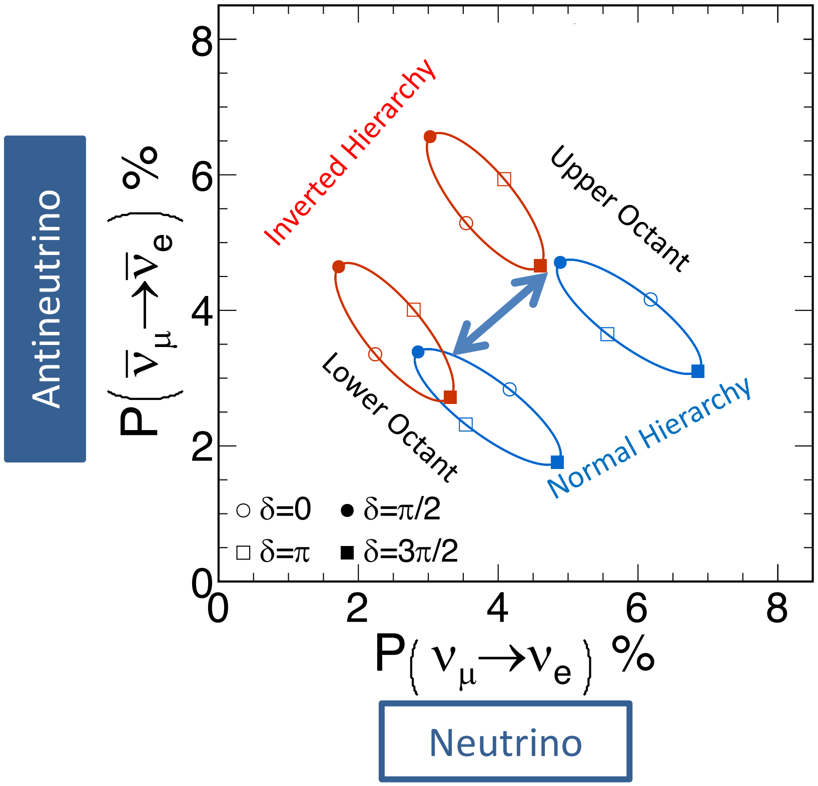
2p2h Shape Uncertainty: Model Spread



- Some analyses cannot use the tune due to possible signal in the ND.
  - Sterile ν search
  - $|\boldsymbol{q}|$-E_{av} cross section analysis
- Instead, we use the spread-among-models method in q_0-$|\boldsymbol{q}|$ space.
- Based on spread among Valencia, SuSA, and Dytman models.
  - For scale, this just touches our ND data at 1σ.

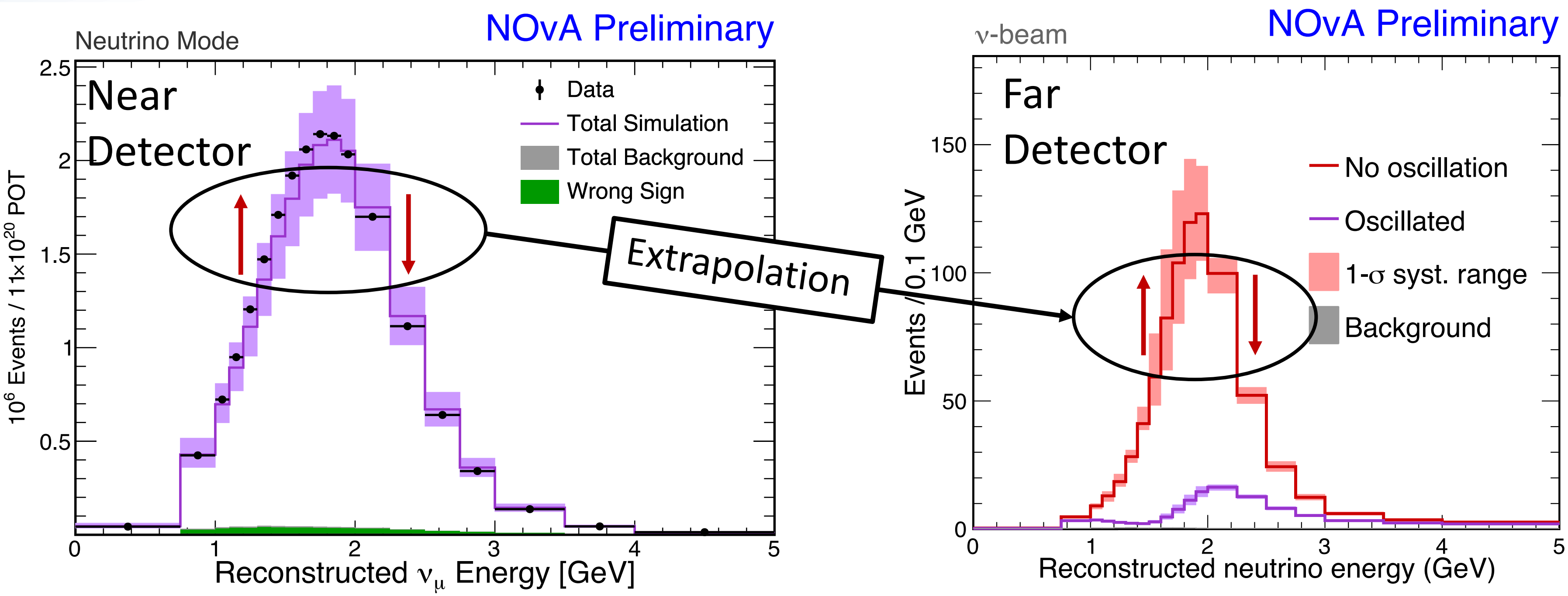
How to Measure 3-Flavor Oscillations





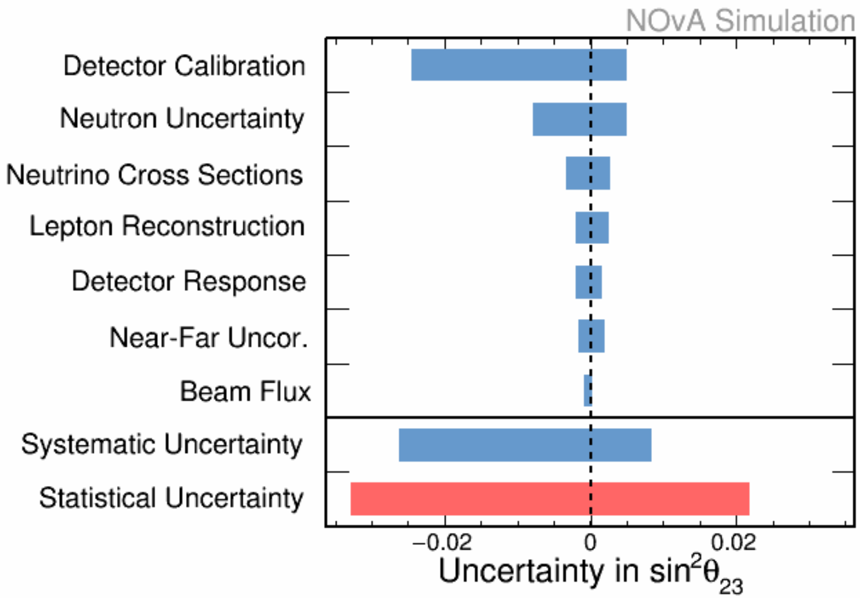
- Measure ν_μ disappearance and ν_e appearance with neutrinos and antineutrinos.
- Disappearance is sensitive to $\sin^2(2\theta_{23})$ and Δm^2_{32}.
- Appearance is sensitive to θ_{23} octant, mass ordering, and δ_{CP}.

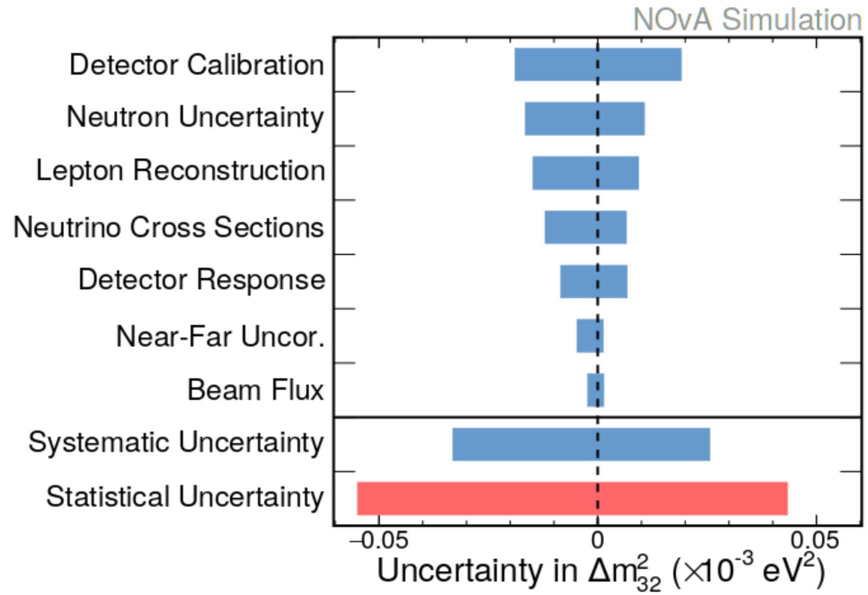
Extrapolating from Near to Far Detector

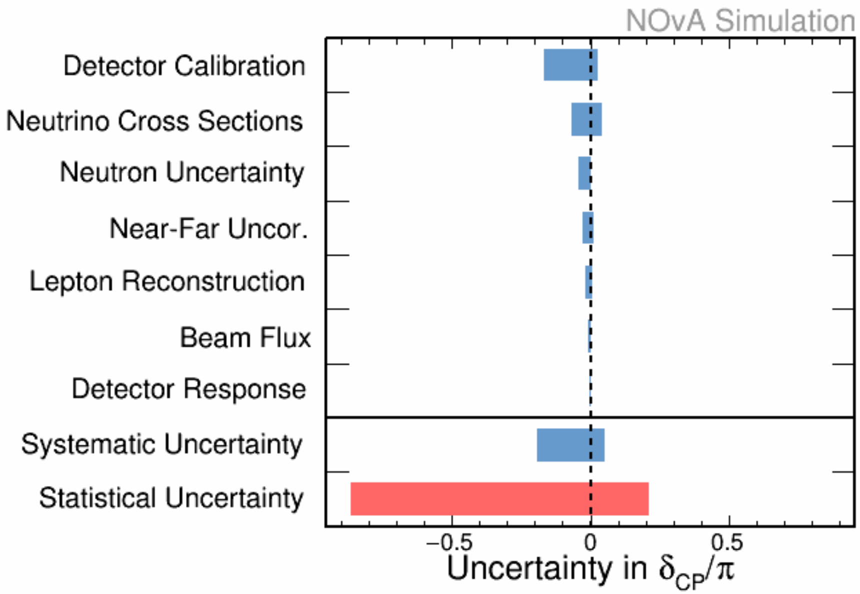


- Observe data-MC differences at the ND, use them to modify the FD MC.
- Extrapolate in multiple dimensions to reduce systematic uncertainty
  - Hadronic energy bins separate interaction modes as well as resolution
  - Transverse momentum bins are used just during extrapolation to account for the difference in angular acceptance due to the difference in detector size.
- Significantly reduces the impact of uncertainties correlated between detectors
  - Especially effective at rate effects like the flux (7% → 0.3%).

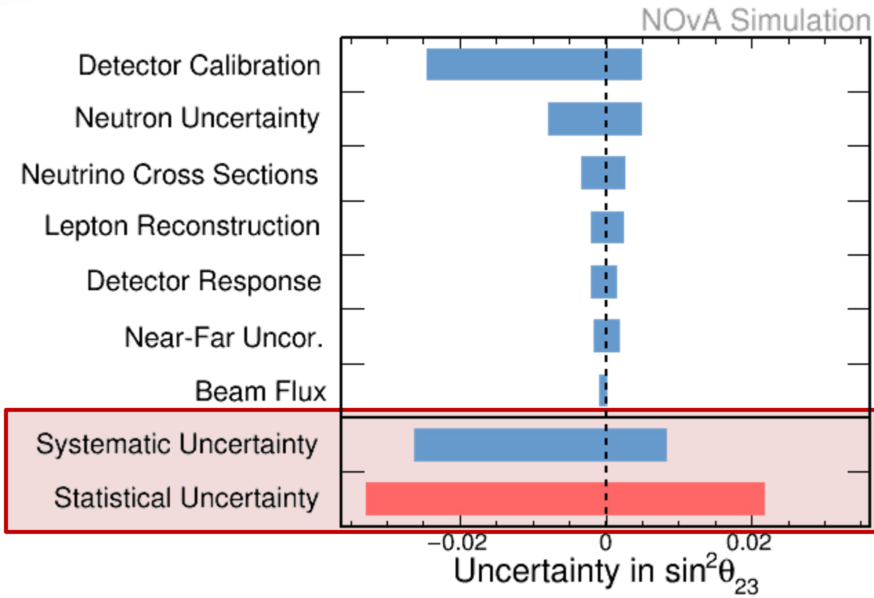
Systematic Uncertainties in 3-Flavor

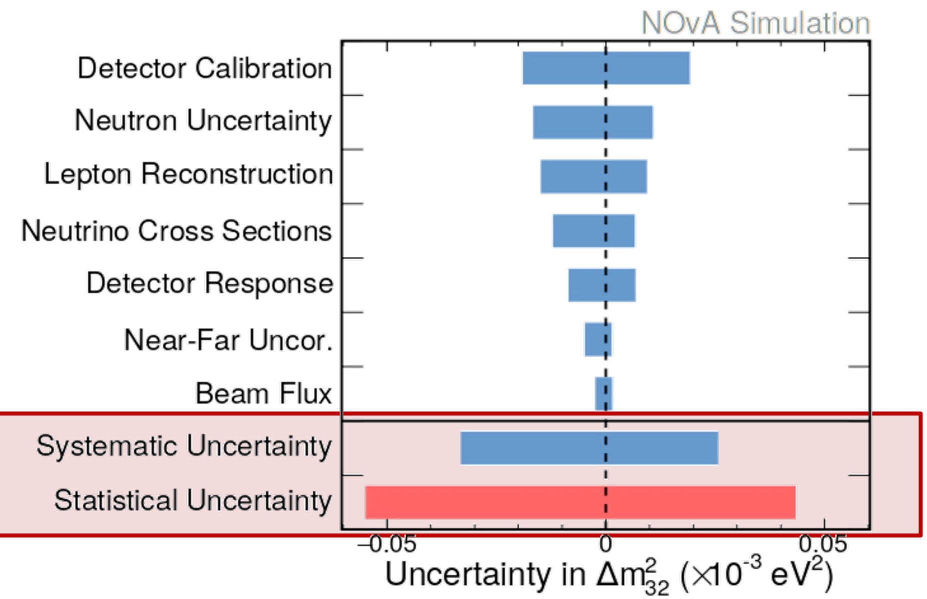


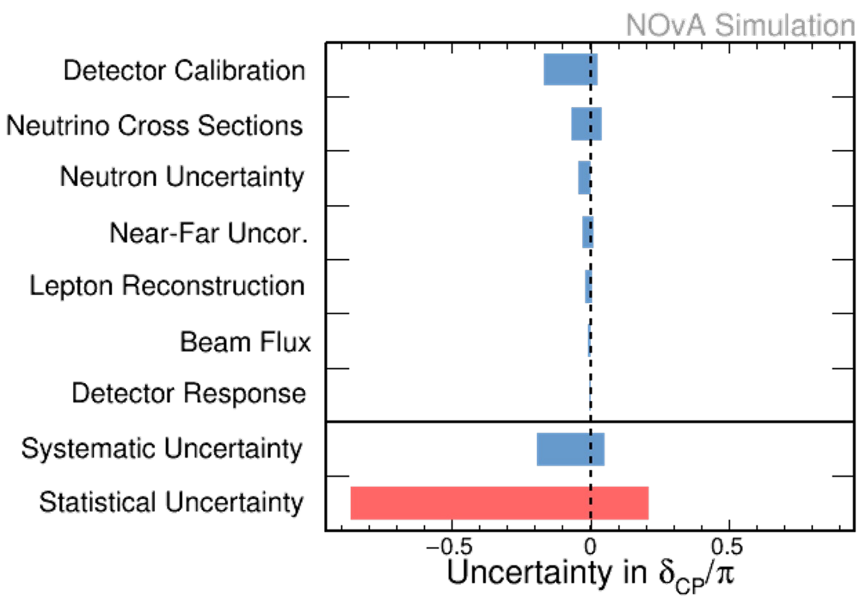




Systematic Uncertainties in 3-Flavor

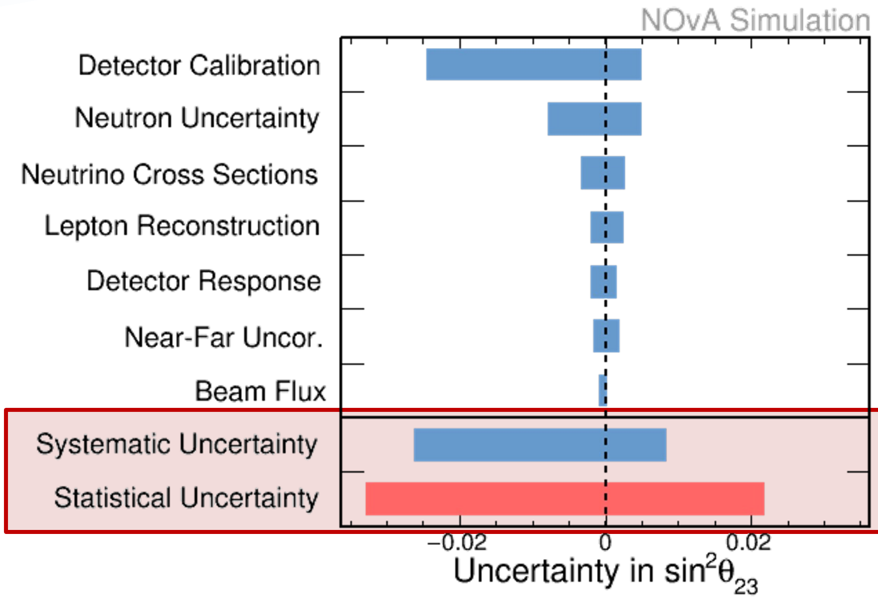


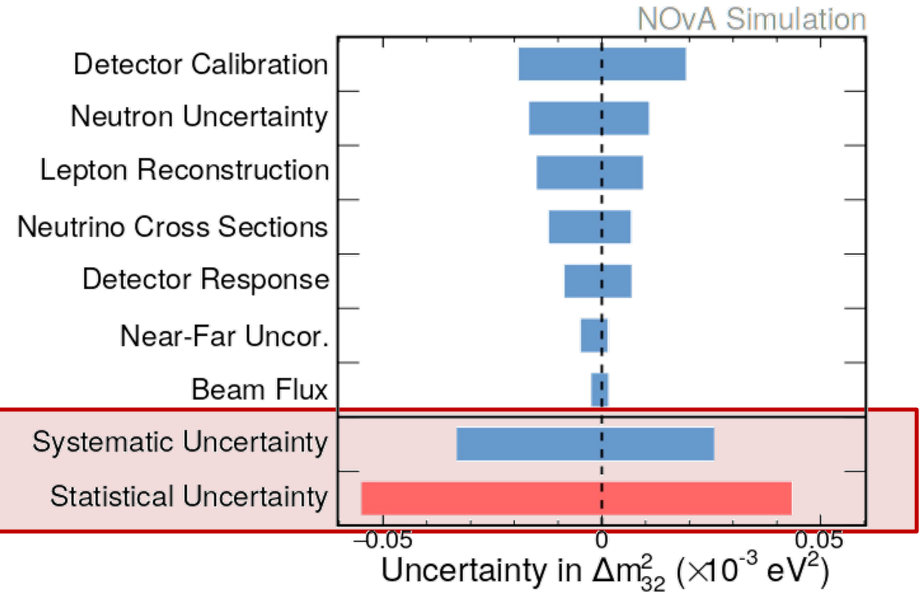


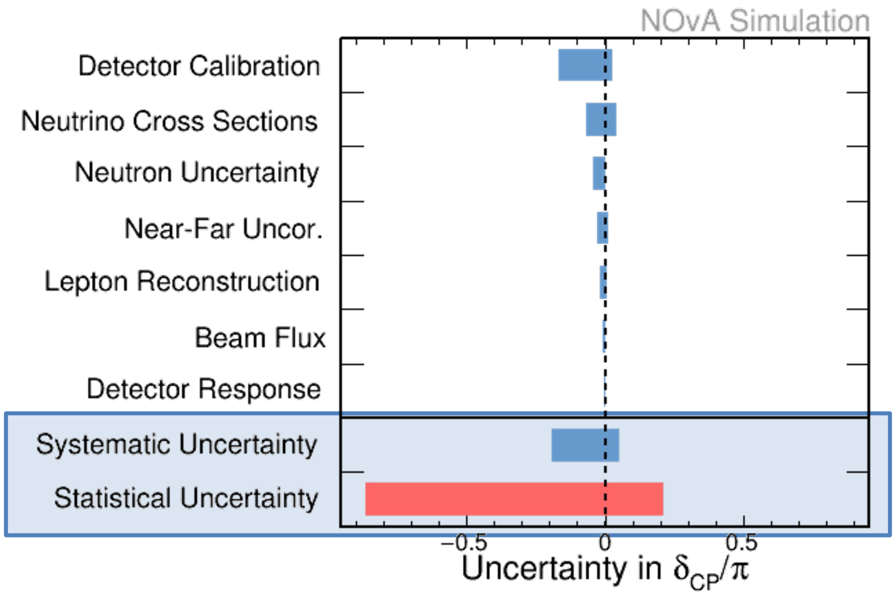


- Systematics more important for primarily ν_μ-measured parameters.
  - Expect ~parity at final exposure.

Systematic Uncertainties in 3-Flavor

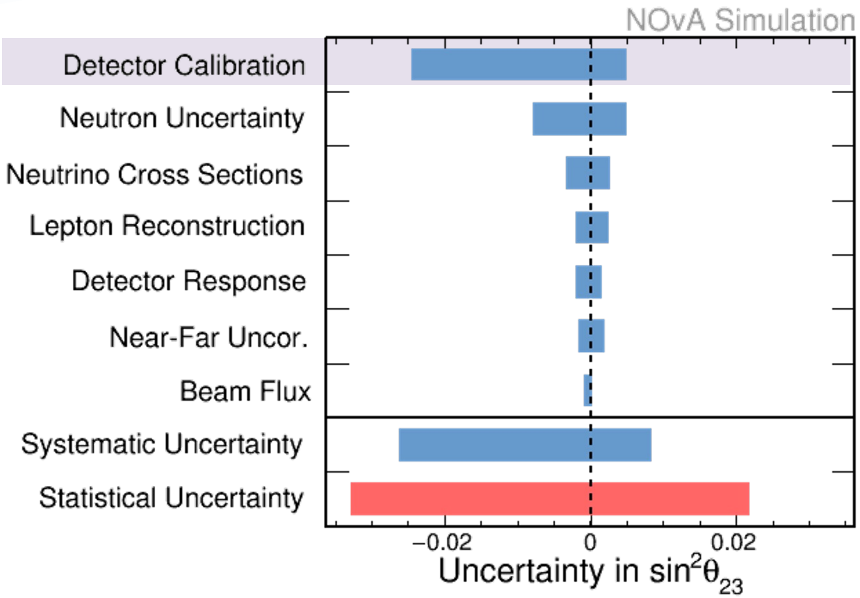


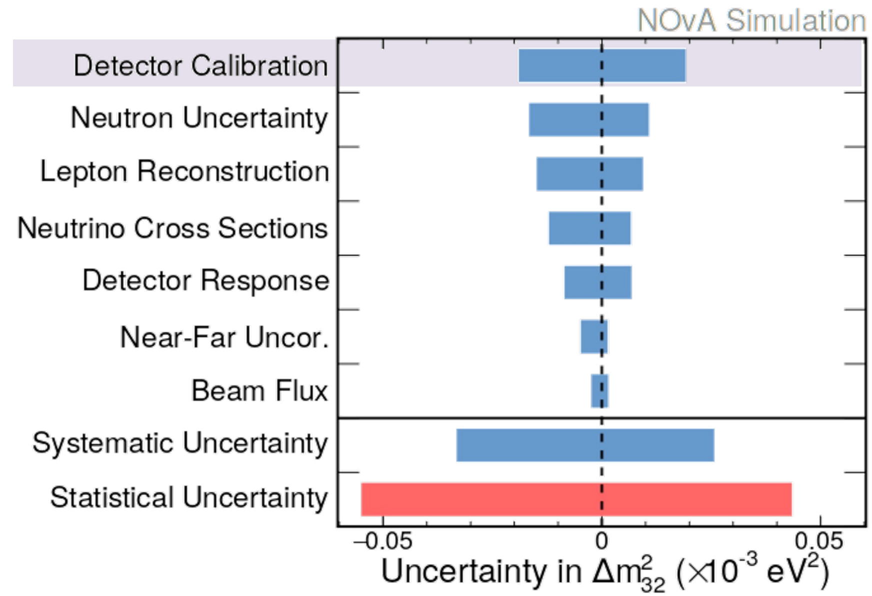


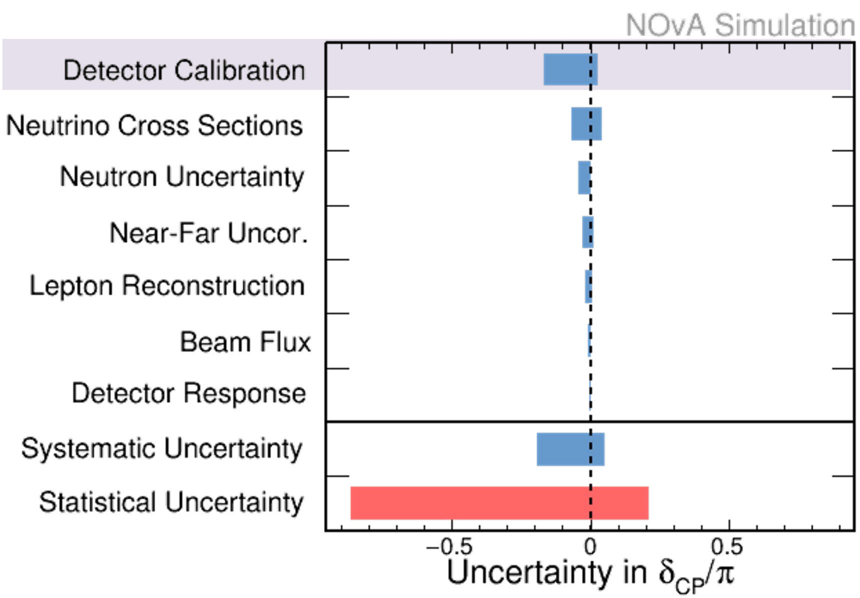


- Systematics more important for primarily ν_μ-measured parameters.
  - Expect ~parity at final exposure.
- Primarily ν_e measurements are dominated by statistical uncertainty.
  - Shown at left for δ, similar story for mass ordering.

Systematic Uncertainties in 3-Flavor

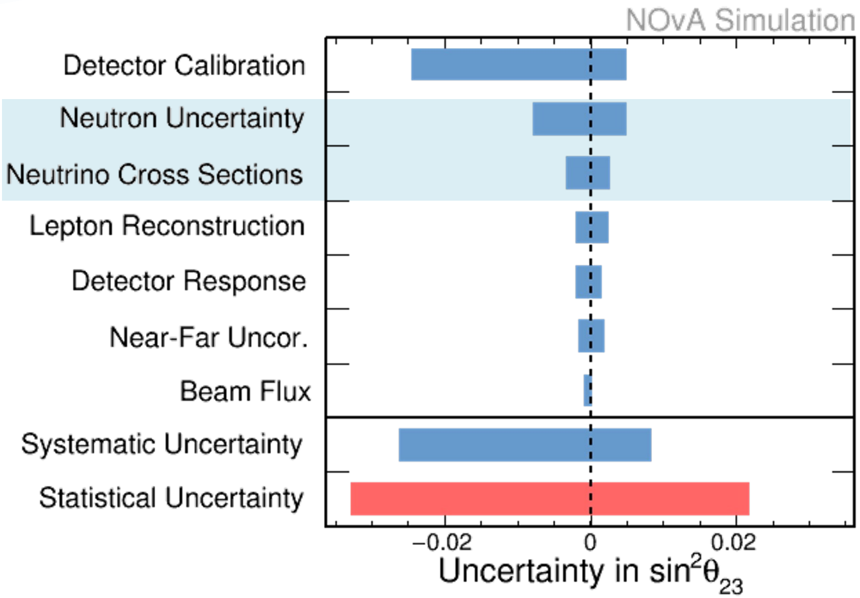


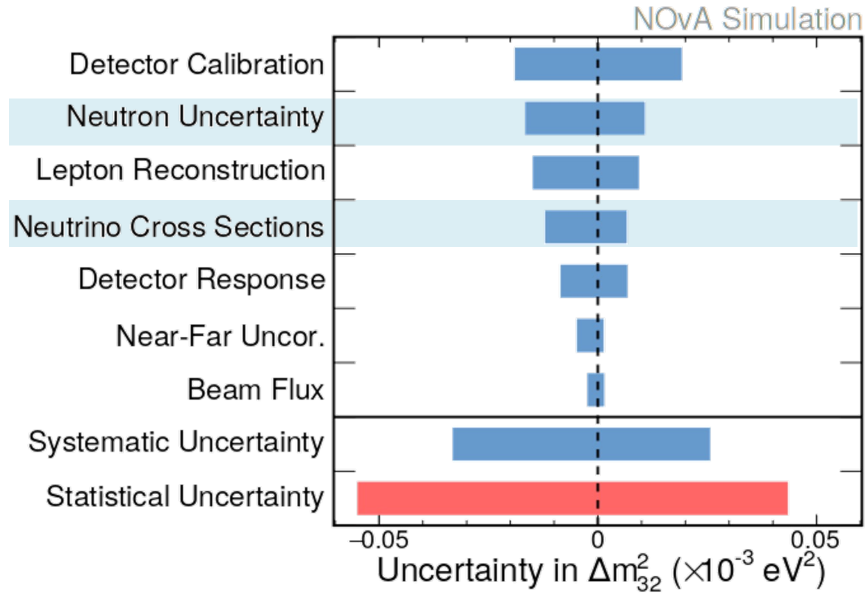


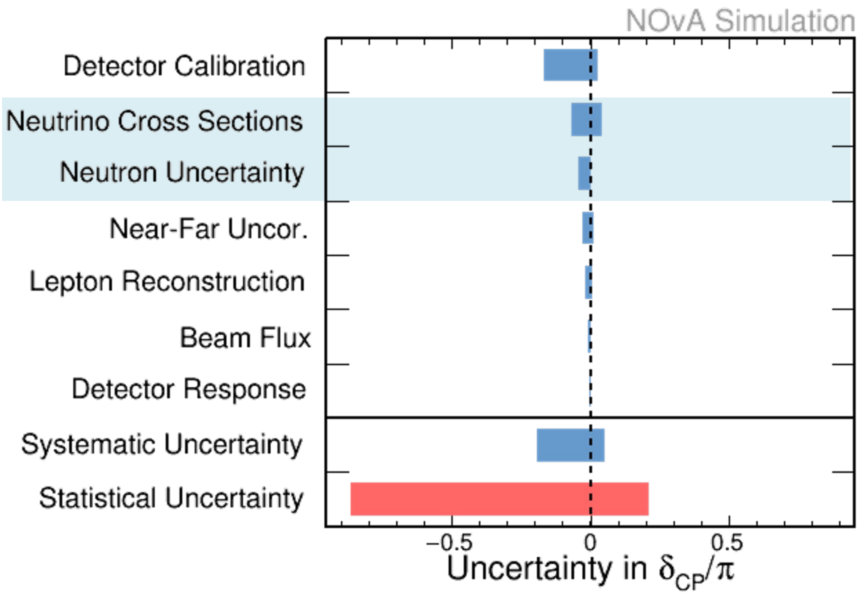


- Detector energy scale (calibration) is the leading systematic for all parameters.
  - It is important in ~all analyses which use calorimetric energy.

Systematic Uncertainties in 3-Flavor

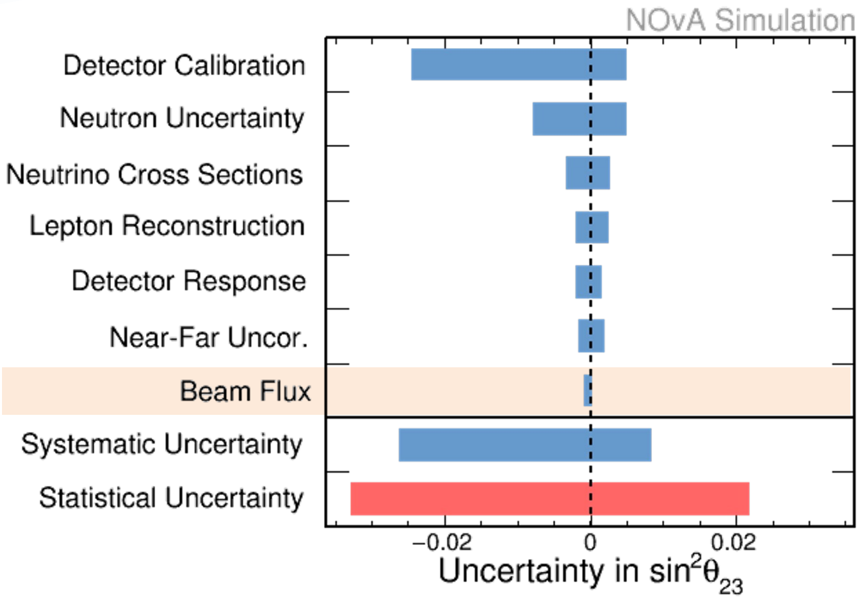


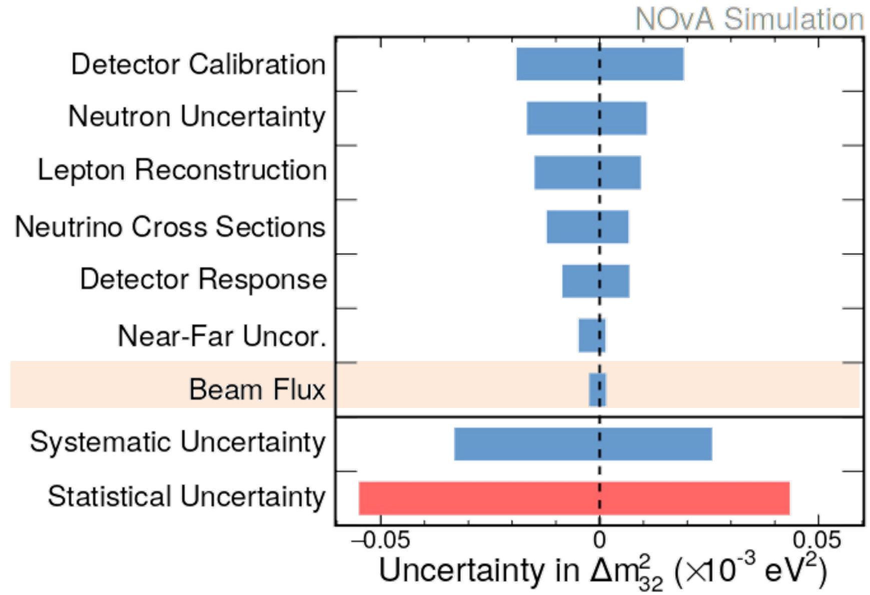


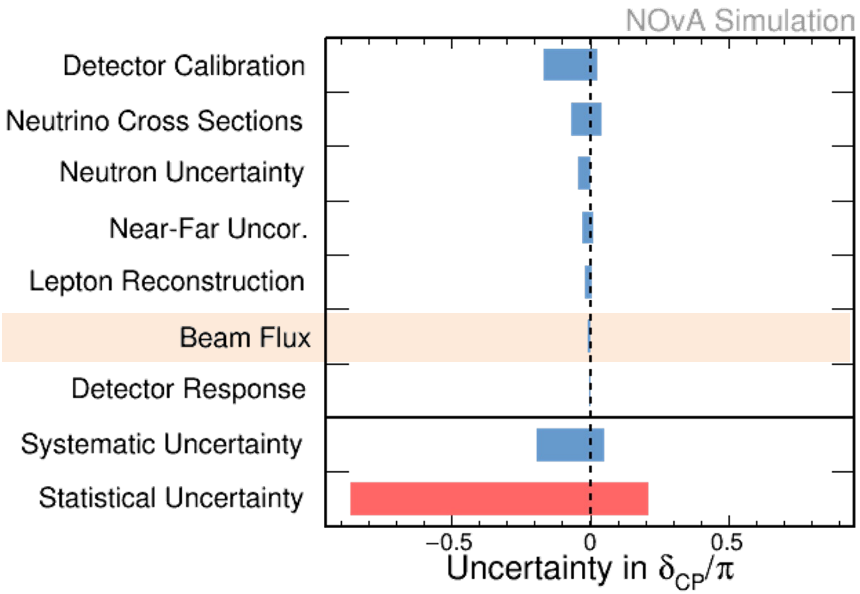


- Detector energy scale (calibration) is the leading systematic for all parameters.
  - It is important in ~all analyses which use calorimetric energy.
- Theory uncertainties are typically important, but non-leading.

Systematic Uncertainties in 3-Flavor





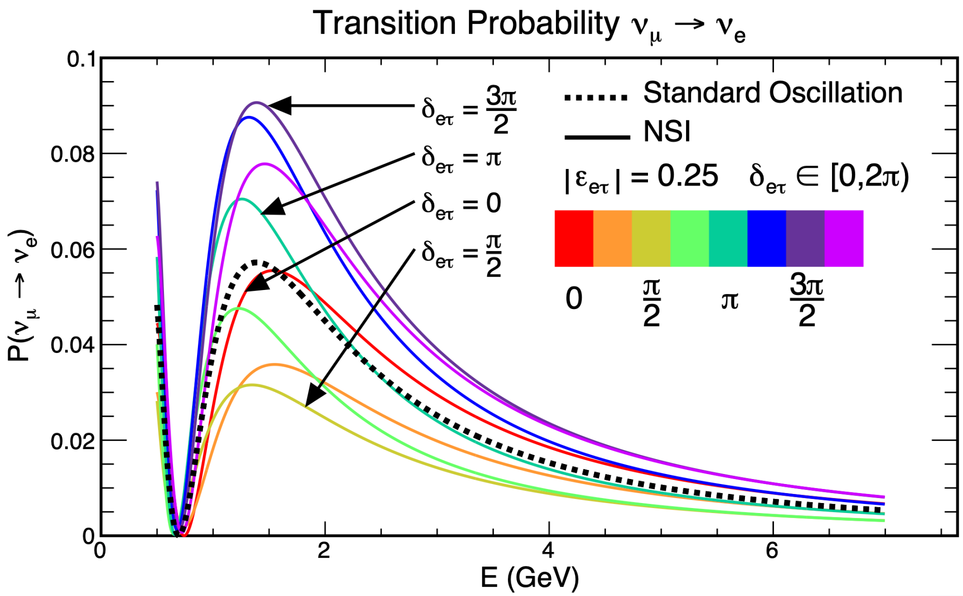


- Detector energy scale (calibration) is the leading systematic for all parameters.
  - It is important in ~all analyses which use calorimetric energy.
- Theory uncertainties are typically important, but non-leading.
- Flux uncertainty is substantially reduced by extrapolation.

How to Search for Non-standard Interactions

$$\mathcal{H} = U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta_{21} & 0 \\ 0 & 0 & \Delta_{31} \end{pmatrix} U^\dagger + V \begin{pmatrix} \delta_e + \varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ (\varepsilon_{e\mu})^* & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ (\varepsilon_{e\tau})^* & (\varepsilon_{\mu\tau})^* & \varepsilon_{\tau\tau} \end{pmatrix}$$

- Uses the *same* ν_μ disappearance and ν_e appearance analysis with neutrinos and antineutrinos.
- Add parameters to the Hamiltonian which capture possible NSI.
  - Not dependent on a specific model.
  - Each $\varepsilon_{\alpha\beta}$ has a phase $\delta_{\alpha\beta}$
- NOvA is most sensitive to the ***eμ*** and ***eτ*** sectors via ν_e appearance.
  - ***μτ*** sector is well covered by atmospheric experiments

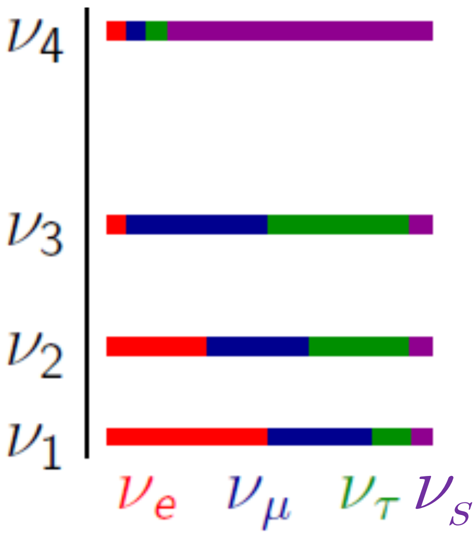


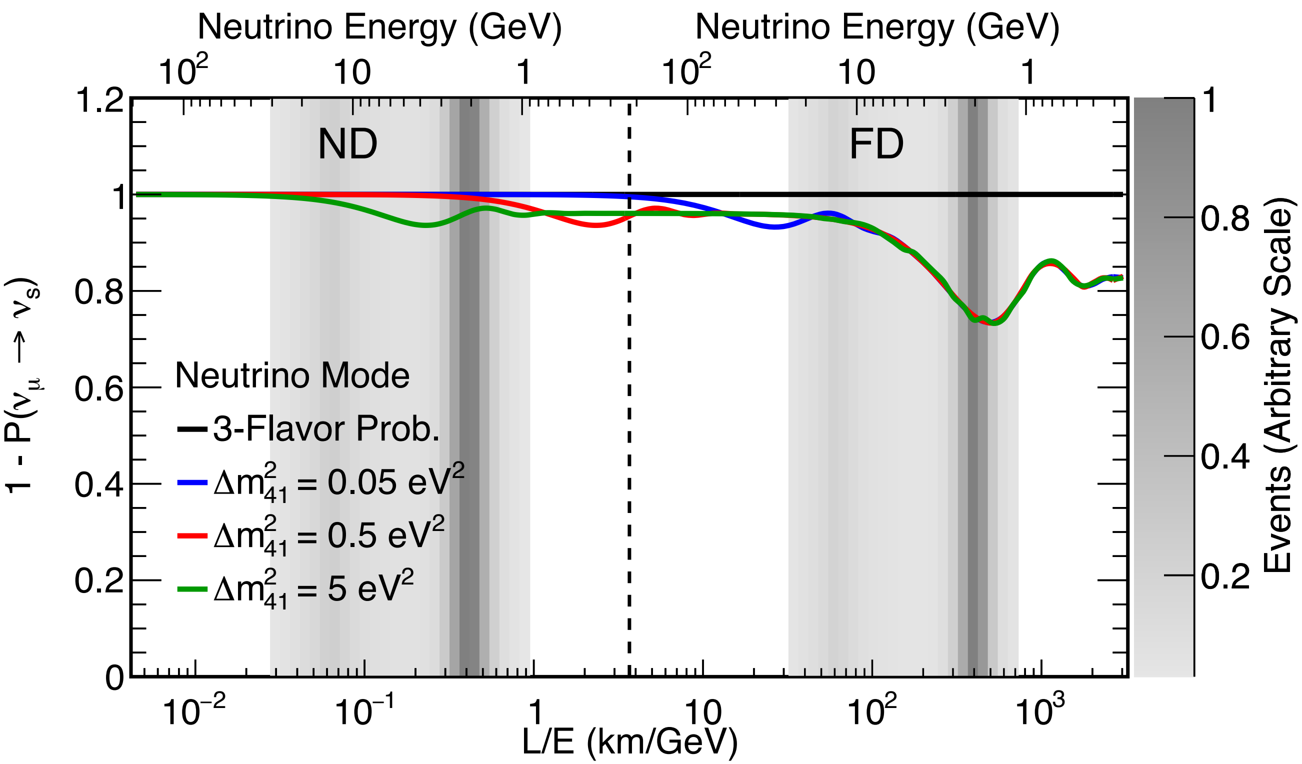
Systematic Uncertainties in NSI Search

	Total	Stat	Syst
$\varepsilon_{e\mu}$	0.23	0.21	0.09
$\varepsilon_{e\tau}$	0.64	0.63	0.11

- NSI added one unique systematic, which is a 3.7% uncertainty on the earth matter density, but its impact is small even relative to other systematics.
  - Relative breakdown is similar to δ, but I don't have a handy plot to share.

How to Search for Sterile Neutrinos

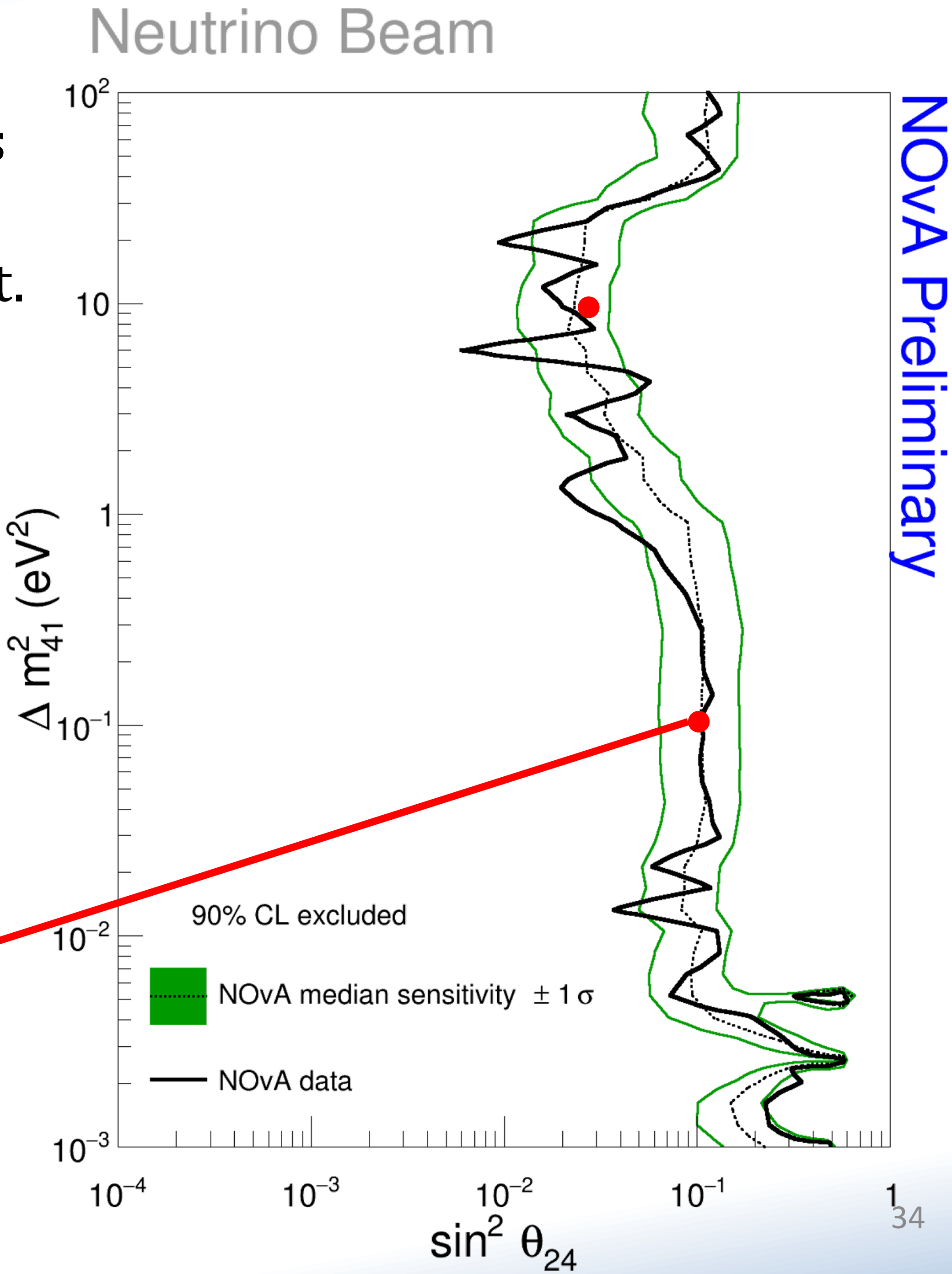


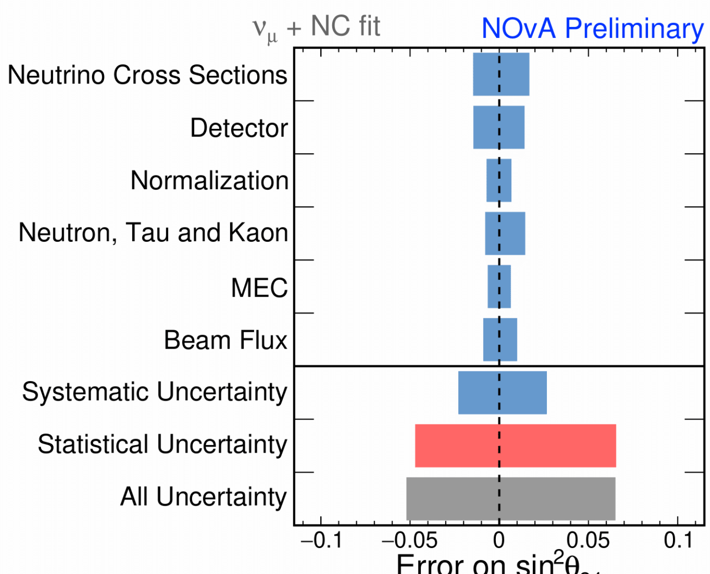


- Different samples: ν_μ disappearance and neutral current disappearance
  - Potential for oscillation signals in **both detectors** requires a different analysis with a simultaneous fit
- We are focusing on a 3+1 model, adding $\boldsymbol{\theta_{24}}$, $\boldsymbol{\theta_{34}}$, $\boldsymbol{\Delta m^2_{41}}$
  - Treating θ_{14} as negligible based on current limits

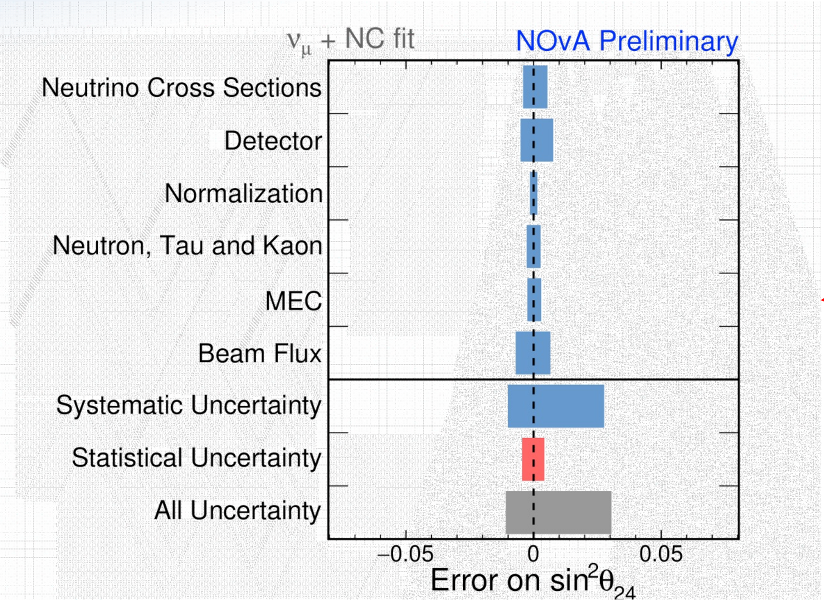
Uncertainties in Steriles

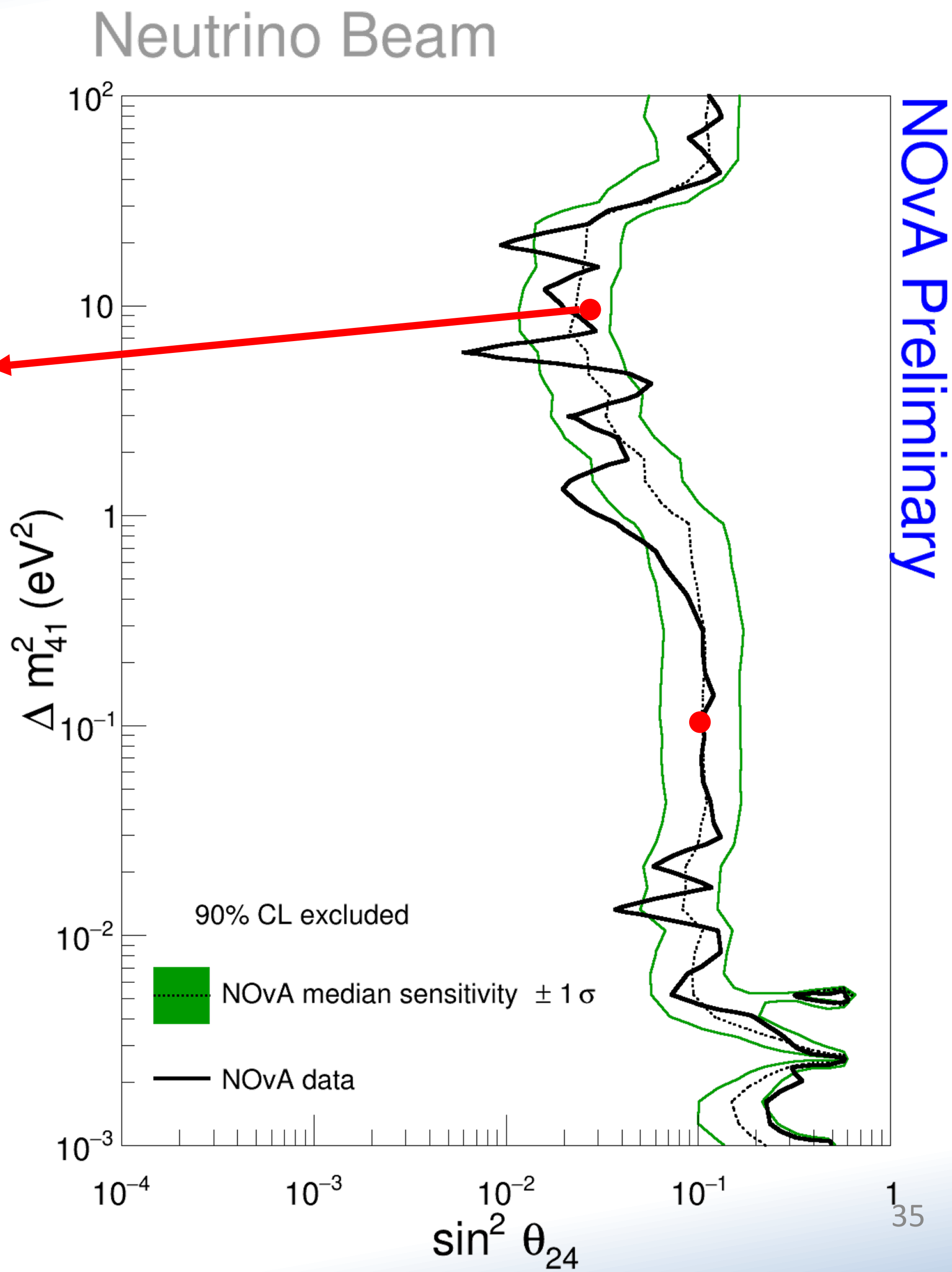
- At small Δm^2, most signal is in the FD, so statistical uncertainties are important.
- No single dominant systematic.
  – And the relative balance varies as we move around parameter space





Uncertainties in Steriles





- At large Δm^2, the dominant effect is a change in rate at the ND.
  - Since the ND has a large event sample, statistical errors are small.
- Flux, cross-sections, and detector response have ~equal contributions.

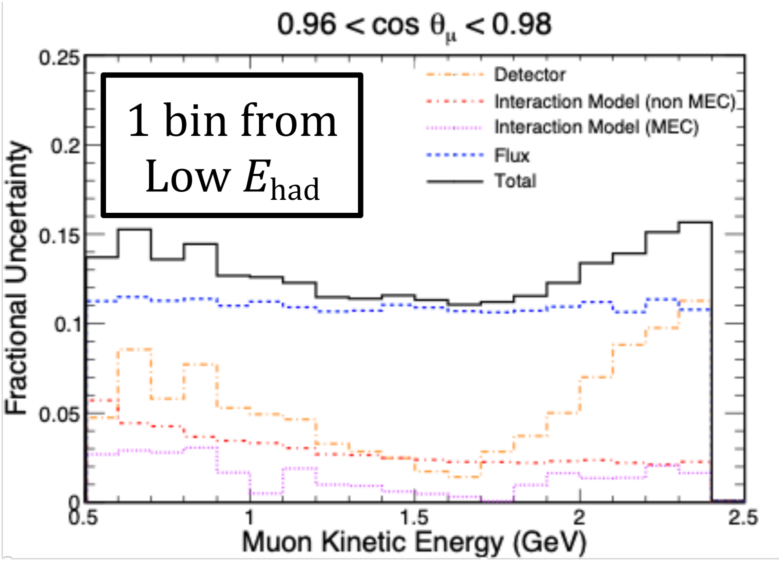
How to Measure Neutrino Scattering

$$\left(\frac{d\sigma}{dX}\right)_i = \frac{\sum_j U_{ij}(N^{\mathrm{sel}}(X)_j P(X)_j)}{\epsilon(X)_i (\Delta X)_i N_{\mathrm{target}} \phi(X)}$$

- Unfolding matrix: U_{ij}
- Selected data events: $N^{\mathrm{sel}}(X)_j$
- Purity: $P(X)_j$
- Efficiency: $\epsilon(X)_i$
- Bin width normalization: $(\Delta X)_i$
- Number of target: N_{target}
- Beam flux: $\phi(X)$

ν_μ CC Inclusive	ν_e CC Inclusive	Low E_{had}	$\lvert q \rvert$-E_{avail}	ν_μ CC π^0
• Differential in p_μ, $\cos\theta_\mu$ • Select solely based on muon ID	• Differential in E_e, $\cos\theta_e$ • Template fits in Electron-ID due to high backgrounds	• Differential in p_μ, $\cos\theta_\mu$ • Select on muon ID and only 1 track • Aims to enhance 2p2h sensitivity	• Differential in $\lvert \boldsymbol{q} \rvert$, E_{avail} • Select solely based on muon ID • Aims to enhance 2p2h sensitivity	• Single diff. in: p_μ, $\cos\theta_\mu$, p_π, $\cos\theta_\pi$, Q^2, W • Require 1 μ-like track and 1 γ-like prong • Template fit in π^0-ID.

Uncertainties in Cross Sections



	ν_μ CC	ν_e CC	$\lvert q\rvert$-E_{av}	ν_μ CC π^0
Flux	9.1	10.3	11.4	8.3
E-Scale + Det Model	6.1	8.6	3.8	7.6
Cross Section Model	1.9	9.8	5.6	4.6
Neutron Modeling	1.5			
Statistical		7.4		
2p2h Model			7.1	
Pi Charge Exchange				3.8

- Flux is universally the largest systematic, and detector modeling is usually important as well.
- 2 analyses where the theory uncertainties are large:
  - ν_e CC inclusive, due to backgrounds since only a few percent of the beam
    - It's also the only analysis with non-trivial statistical uncertainty
  - Inclusive $\lvert \boldsymbol{q}\rvert$-$E_{\mathrm{avail}}$ measurement analysis design has accepted a significant model dependence.

Why do uncertainties differ?

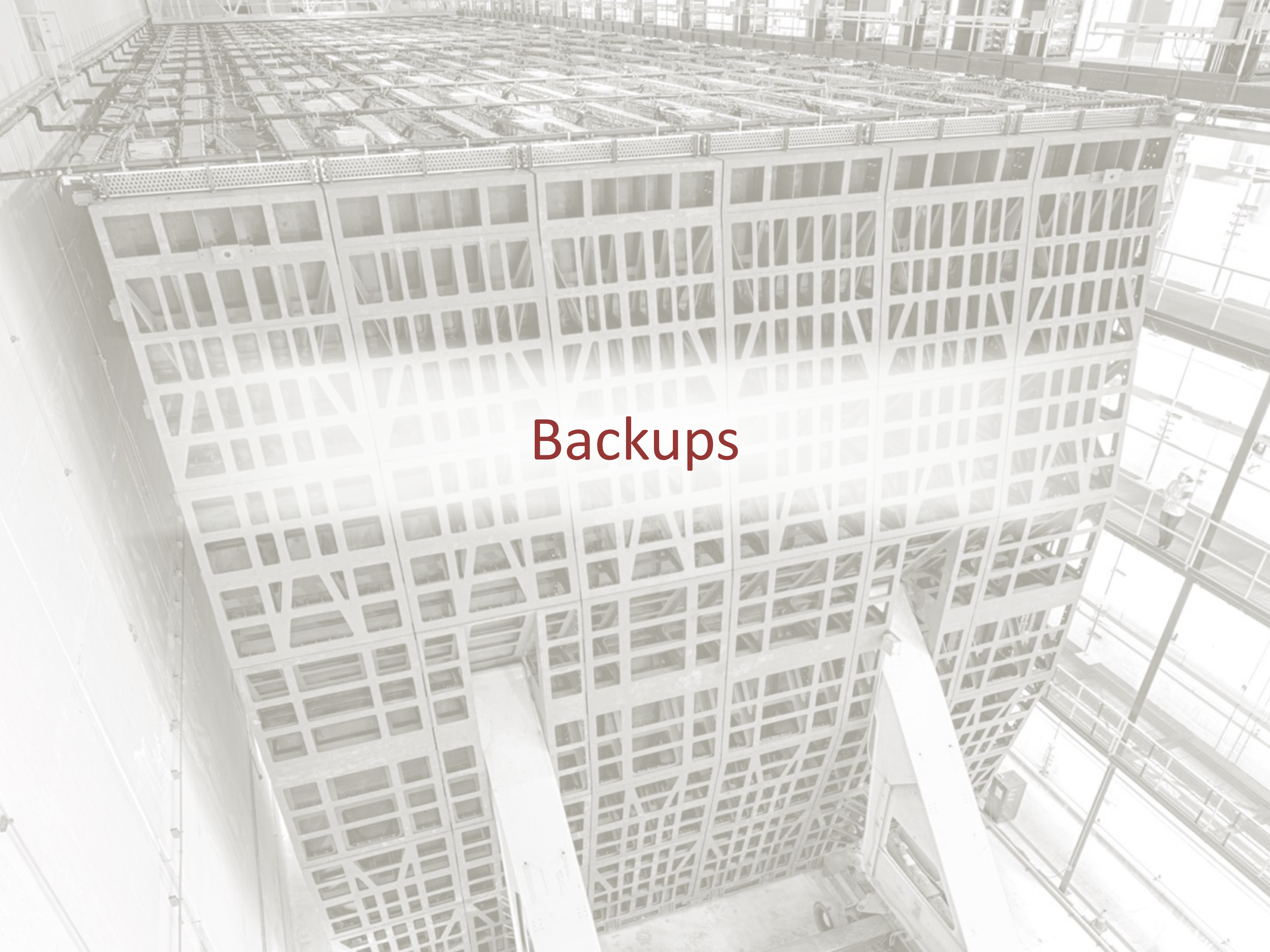
Analysis	Near Detector	Far Detector	Main Uncertainties
3-Flavor	Systematic Control	Signal	Statistics, Calibration
NSI	Systematic Control	Signal	Statistics
Sterile ν	Signal	Signal	Variable
Cross Section	Signal	-	Flux (mostly)

- Analyses where the ND just controls systematics tend to have small flux and cross section uncertainties and are dominated by detector uncertainty.
- Analyses which use the FD for signal tend to have large statistical uncertainty.
- Analyses with possible signal in the ND have significant impact from flux and cross section uncertainties.
- Cross section measurements tend to be dominated by flux uncertainties.
  - With a couple exceptions.

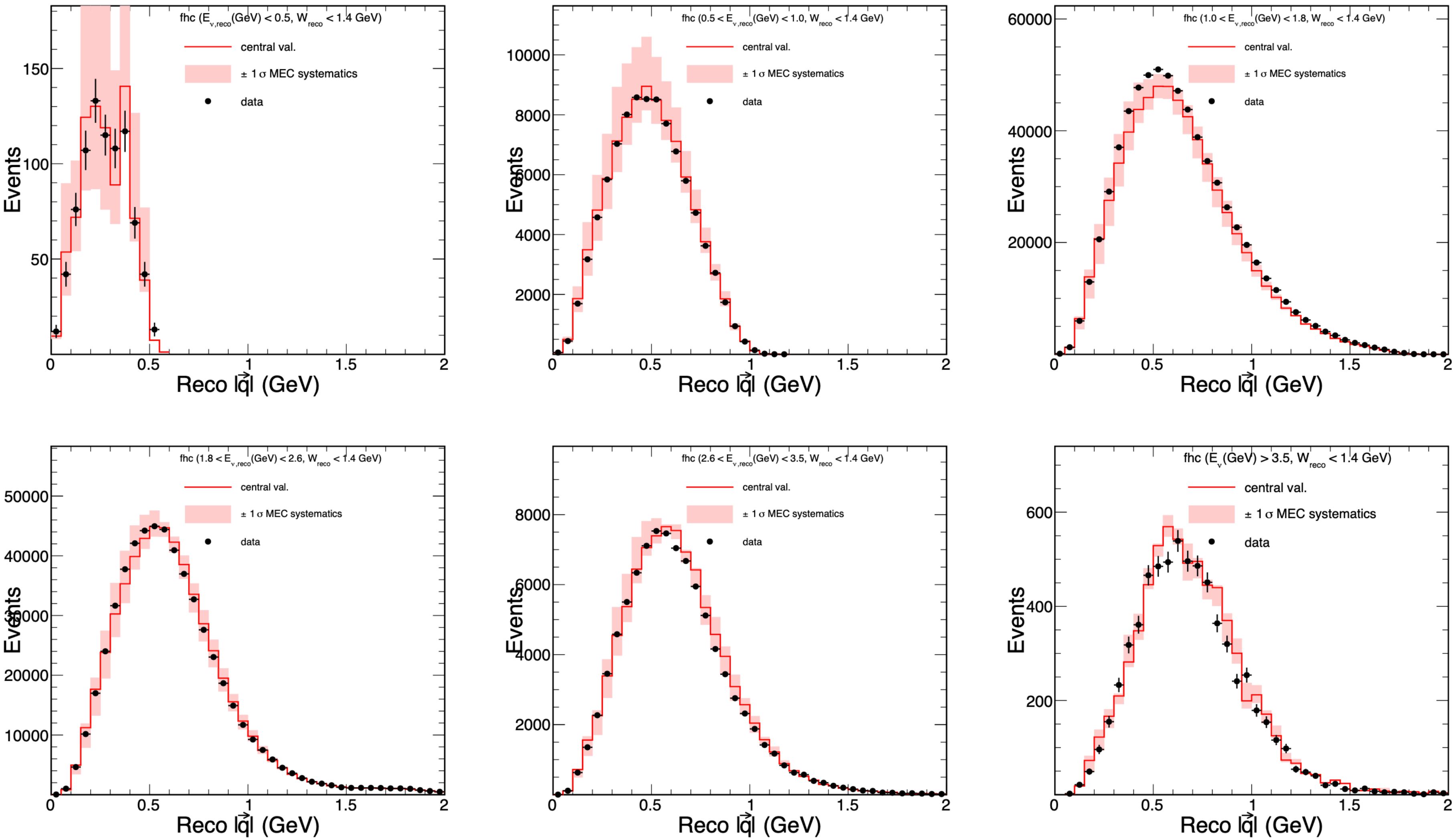
Summary, and what's coming next?

- Neutrino interaction uncertainties are generally not limiting sensitivity in NOvA.
  - We want to make sure they are correct (and sufficient).
  - Reducing them will probably not substantially improve sensitivity.
- Planning to move to the same base model as DUNE for our next major production.
  - Would start to apply to post-2024 analyses.
  - Hoping by moving to a shared base model, we can collaborate on better shared interaction uncertainties for the future.
- Neutron production and response remain important uncertainties.
  - We are making progress on improved modeling and uncertainties for neutron response.
  - Requires care, since better-motivated neutron response uncertainty may leave "gaps" on the production side uncertainty.

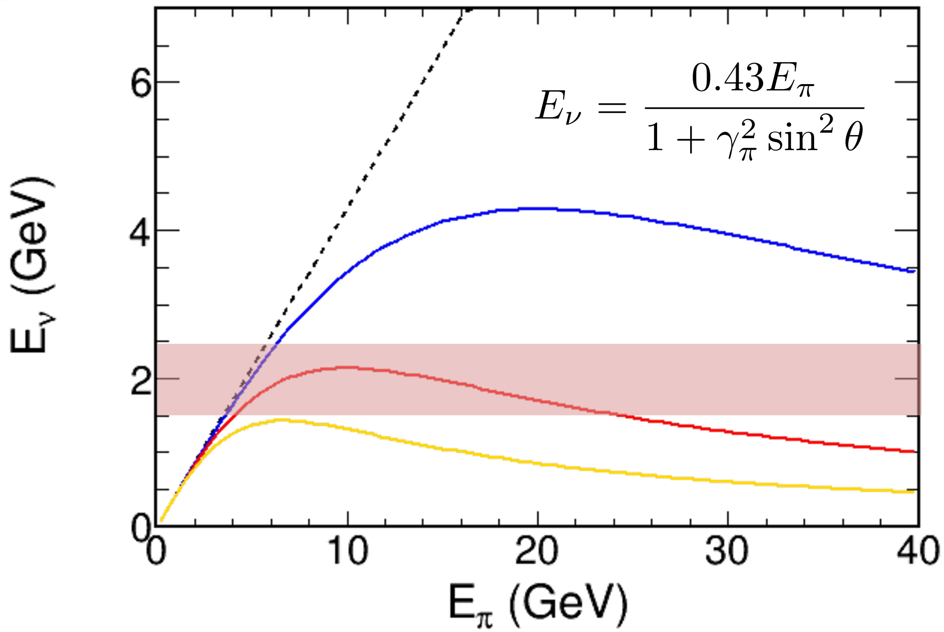
Backups

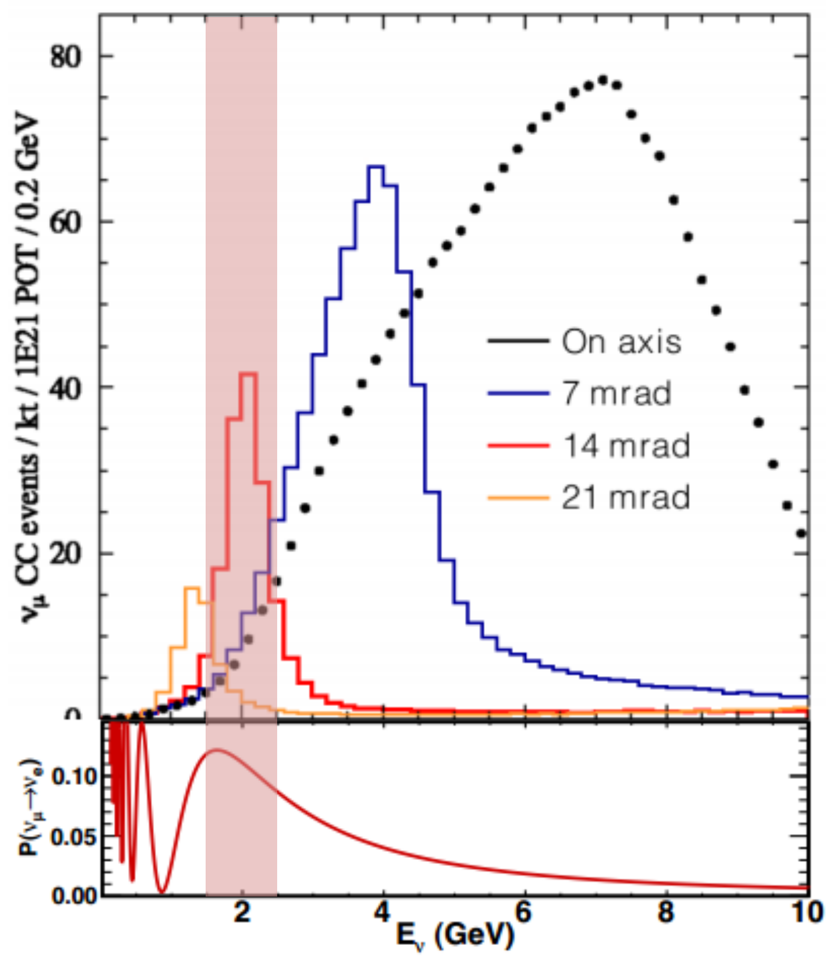


2020 MEC Uncertainties



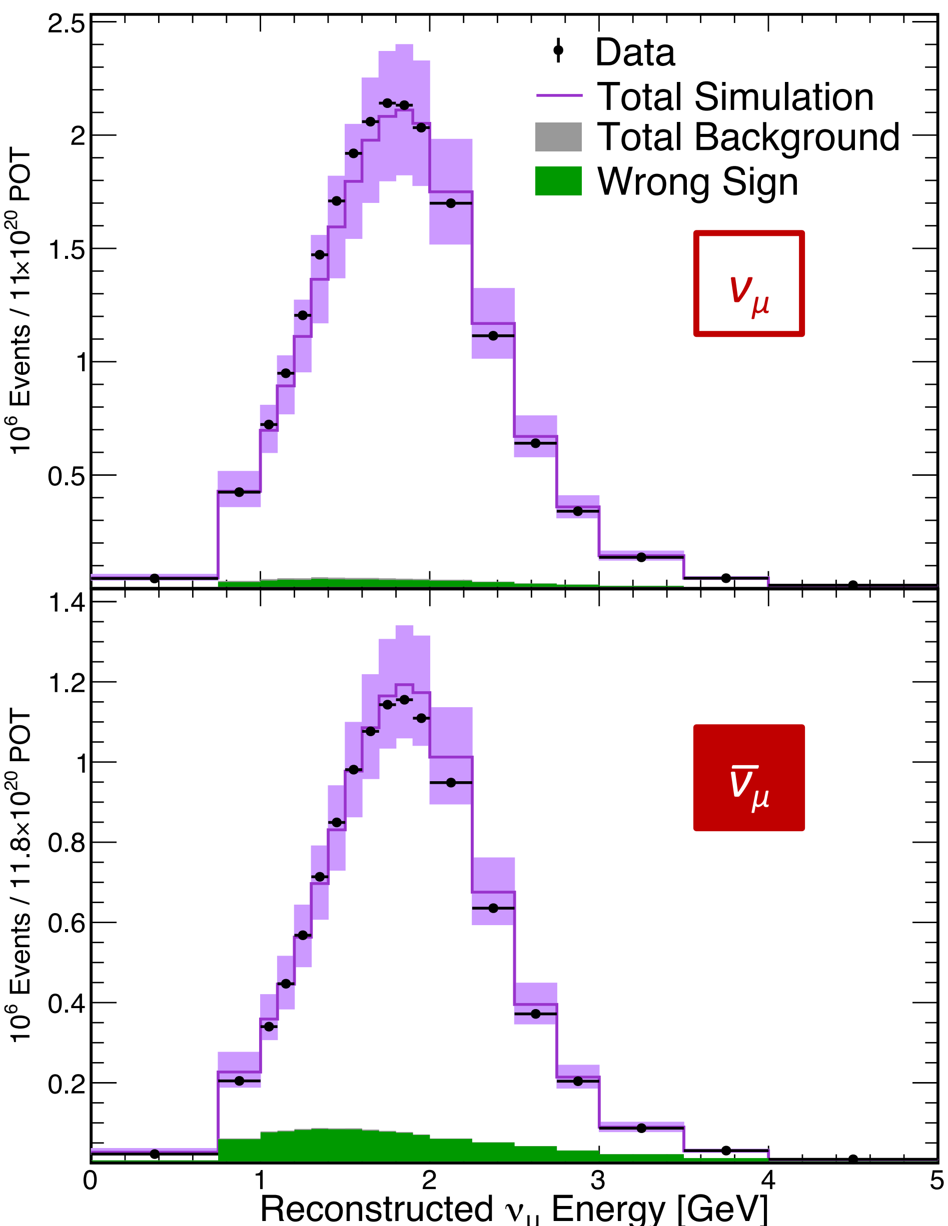
Off-Axis Detectors





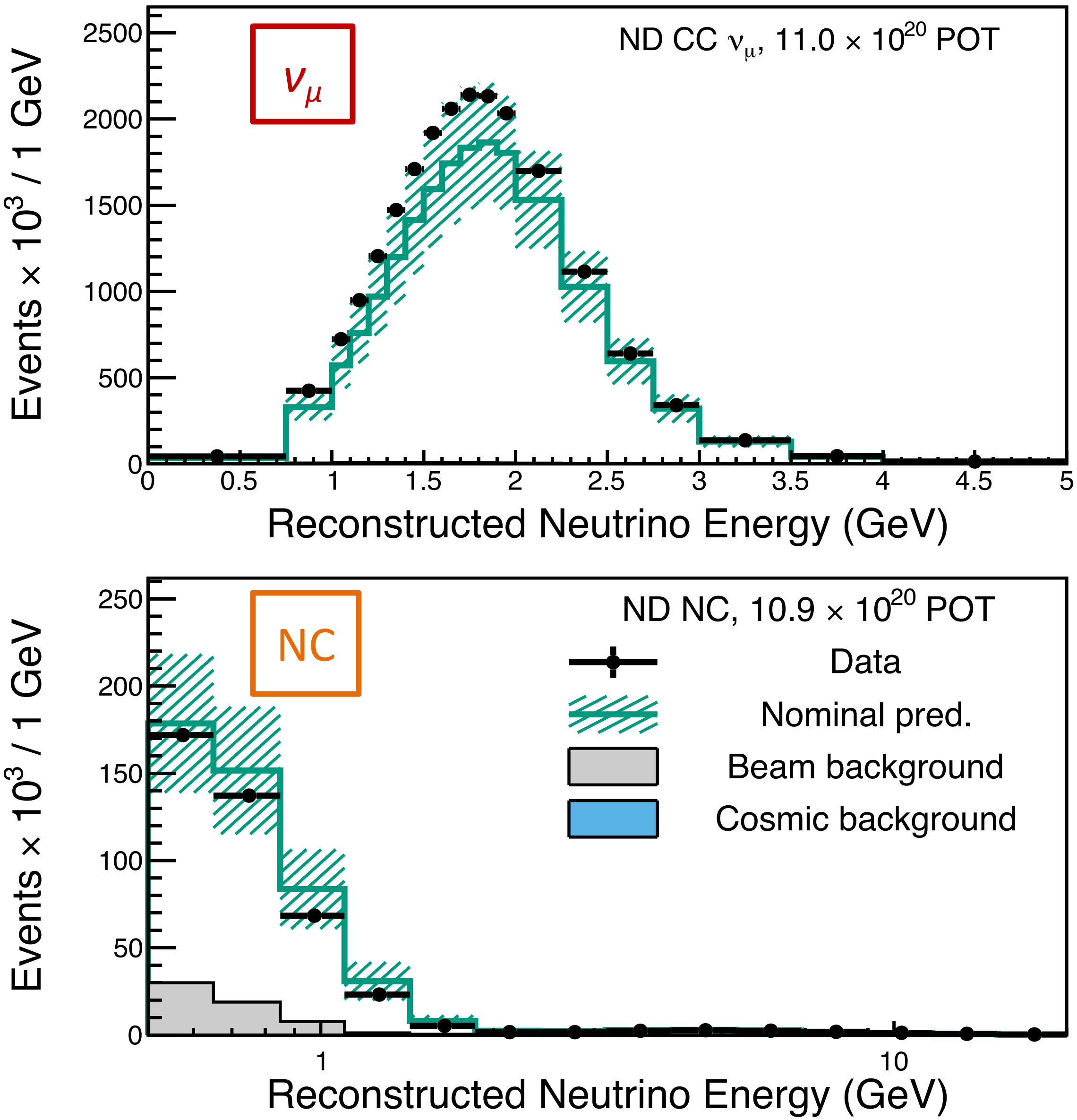
- 14 mrad off-axis angle
  - 2-body π decay gives narrow range of ν energies
- Tune peak energy for oscillations
  - More events at oscillation max
  - Less background

Near Detector ν_μ Spectra



- Used in 3F, NSI, and Sterile analyses
- Band around the MC shows the large impact of flux and cross-section uncertainties in only a single detector.
  - Includes the data-driven tune of our multi-nucleon model.
- This sample **predicts both ν_μ signal and ν_e signal** at the Far Detector in 3F and NSI.
  - Appearing ν_e's are still ν_μ's at the ND

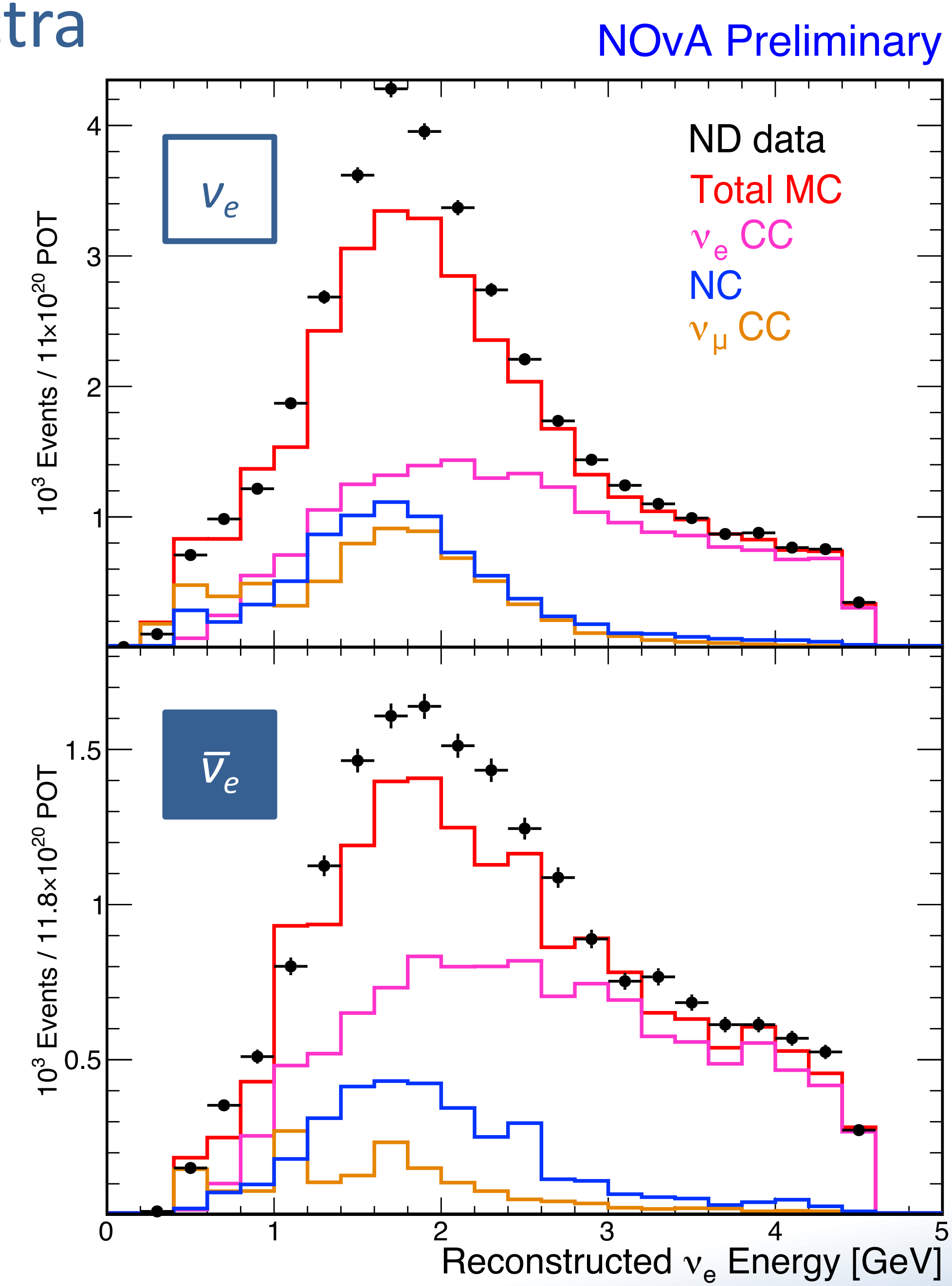
Near Detector NC and ν_μ Spectra



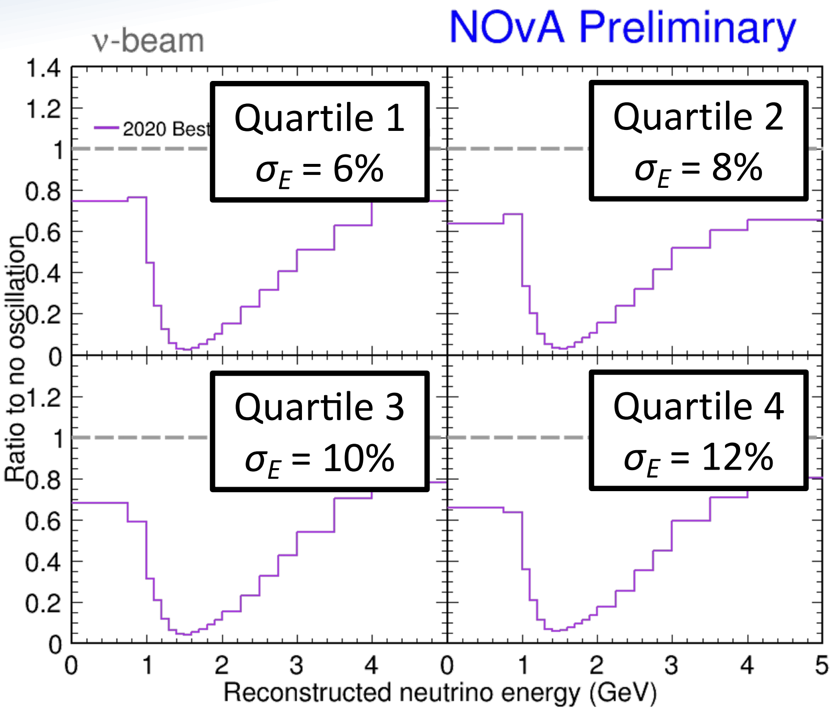
- These two ND spectra used in the sterile analysis.
- Again, band shows large flux and cross section uncertainties.
  - Includes non-data-driven multinucleon uncertainties
- No cross-section tune has been used, so worse *a priori* data-MC agreement.
  - Incorporated into fit for sterile oscillations due to possible signal in the Near Detector.
- These samples both **constrain systematics** and contain **possible signal.**

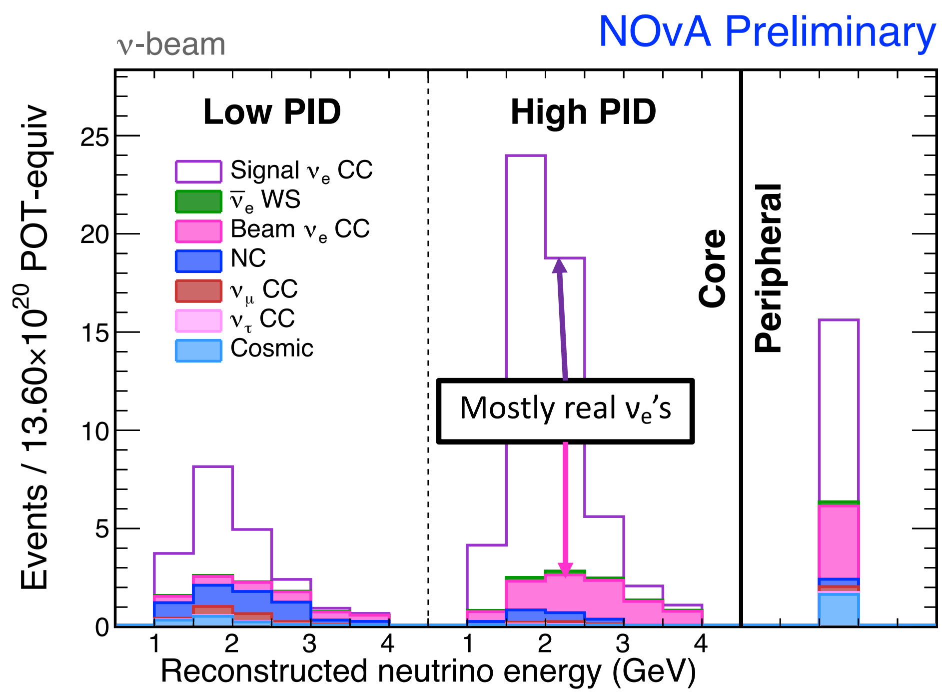
Near Detector ν_e-like Spectra

- Used in the 3F and NSI analyses
- The ND ν_e-like spectrum contains the **background** to the appearing ν_e's at the FD.
- Largest background is the irreducible $\nu_e/\bar{\nu}_e$ flux component.
  - 50% in neutrino-mode
  - 71% in antineutrino mode
- We use this sample to predict the background to ν_e appearance.
  - Use data-driven methods to constrain the ν_e, ν_μ, and NC components.
  - Cannot just use the total disagreement since they extrapolate differently between dietectors.



Enhancing Sensitivity to Oscillations (3F & NSI)





ν_μ sample

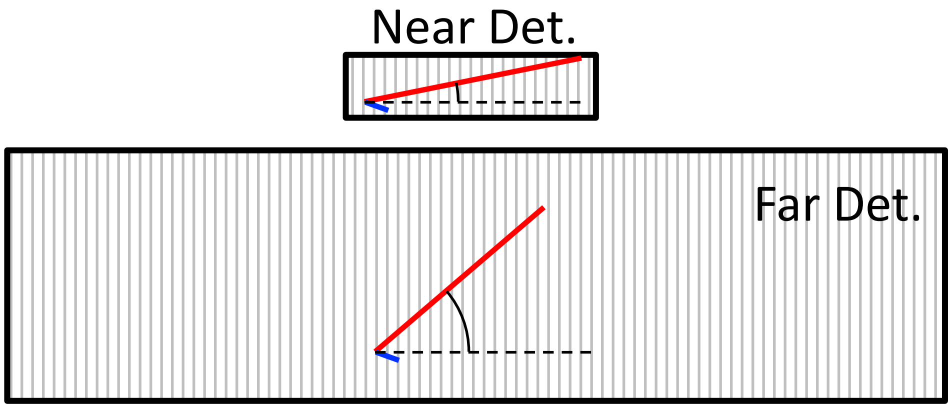
- Sensitivity depends primarily on the shape of the energy spectrum.
- Bin by *energy resolution* → bin by hadronic energy fraction

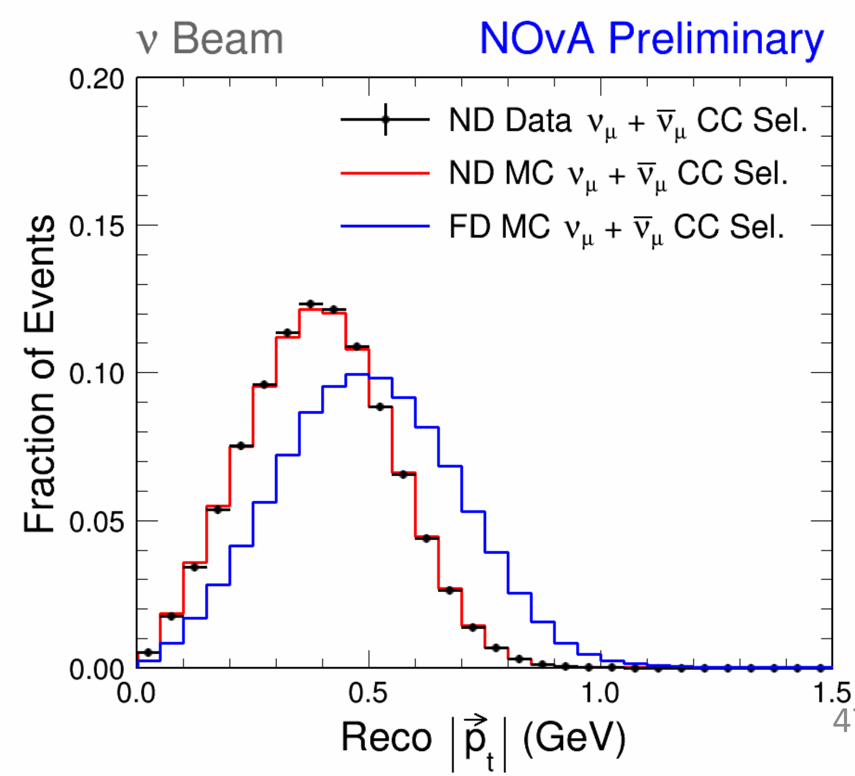
ν_e sample

- Sensitivity depends primarily on separating signal from background.
- Bin by *purity* → bins of low & high PID
- Peripheral sample:
  - Captures high-PID events which might not be contained close to detector edges.
  - No energy binning.

Extrapolating Kinematics

- Containment limits the range of lepton angles more in the Near Detector than in the Far.
  - The ND is 1/5 the size of the FD.
- Mitigate by extrapolating in bins of **lepton transverse momentum, p_t**
  - Transverse to the ν-beam direction ≈ the central axis of the detectors
- Split the ND sample into 3 bins of p_t, extrapolate each separately to the FD.
  - Effectively "rebalances" the kinematics to better match between the detectors.
  - Re-sum the p_t bins before fitting.

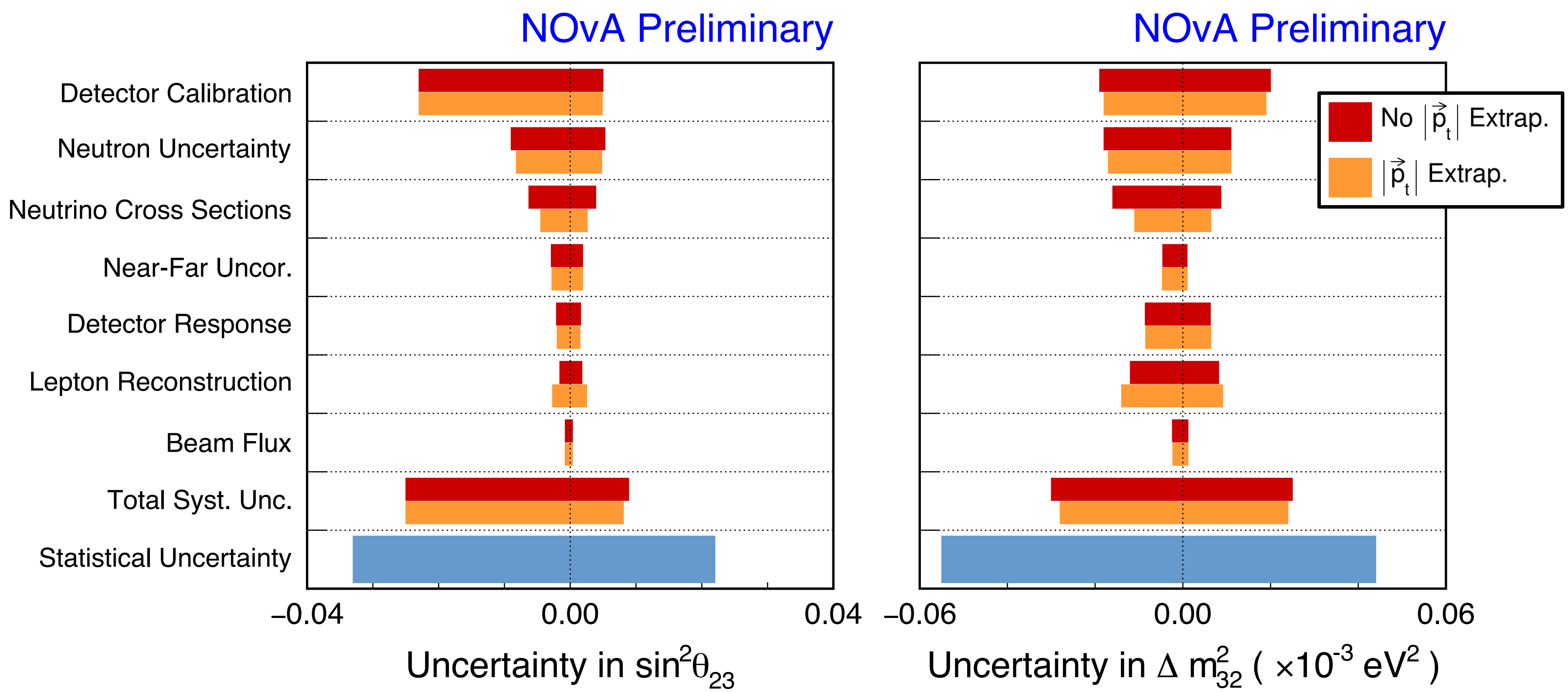




Posters

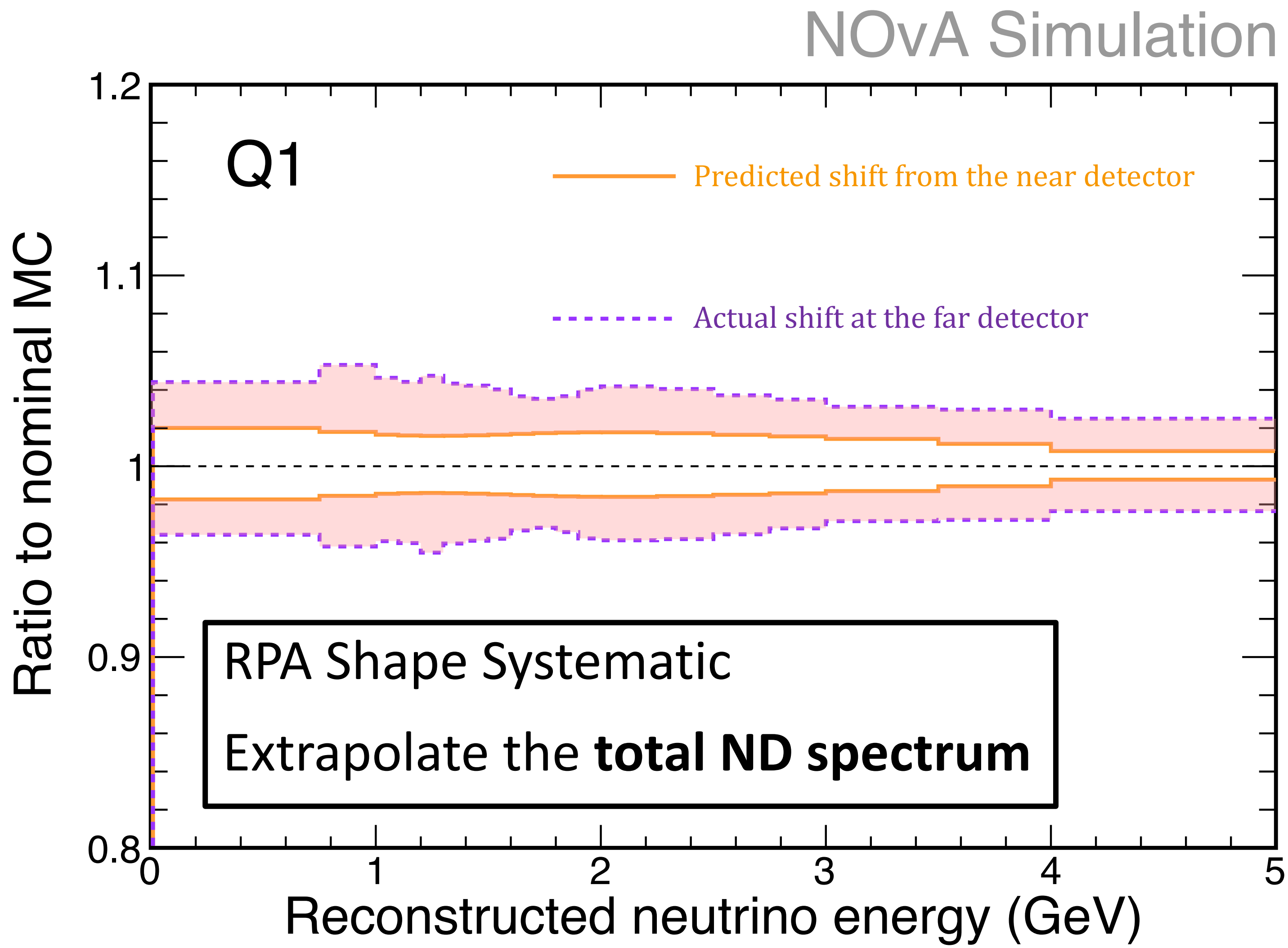
354. Near-to-Far Extrapolation in Transverse Momentum at NOvA
  - Aaron Mislivec

Systematic Uncertainties with p_t Extrapolation

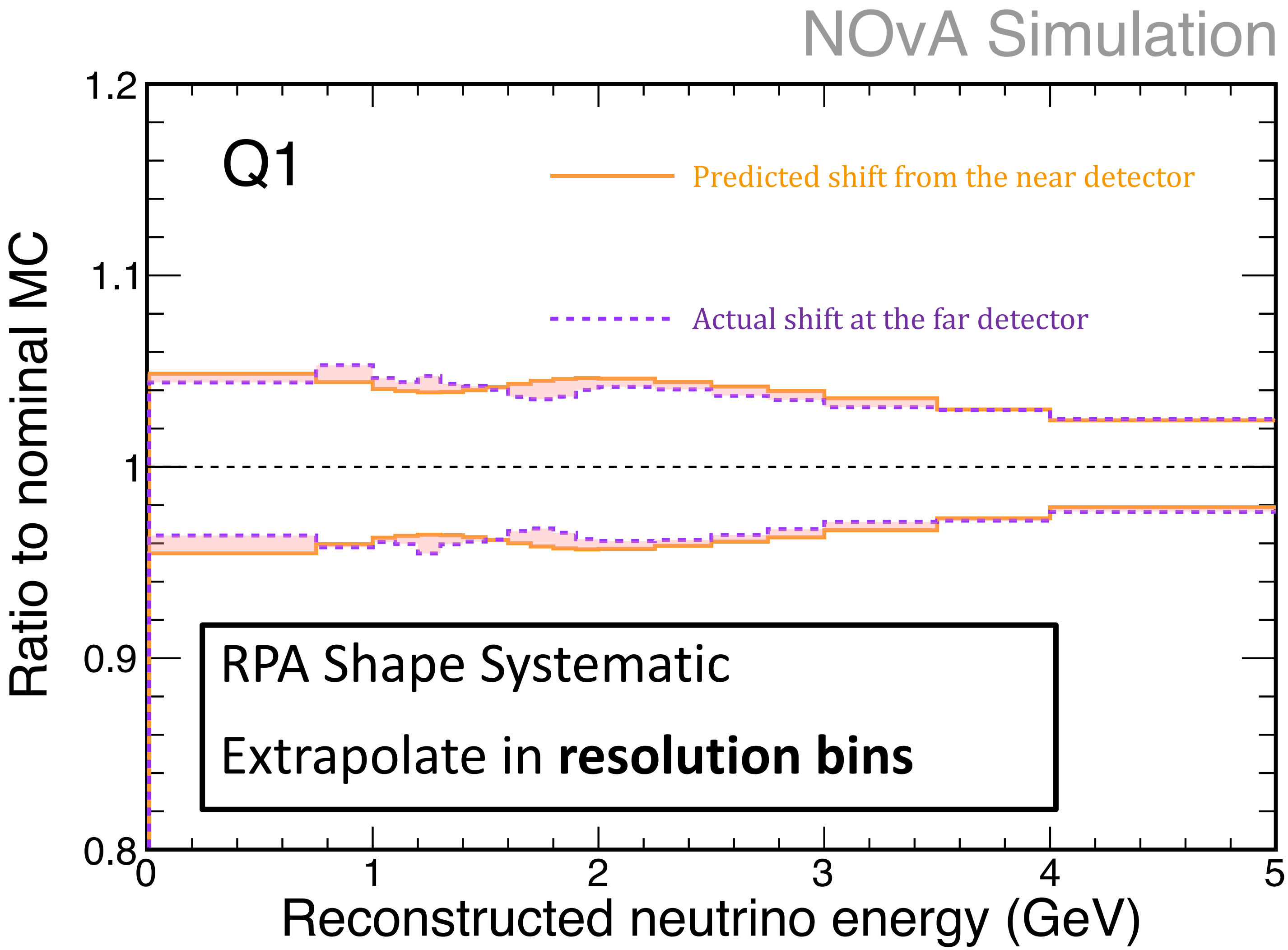


- Increased robustness also leads to a 30% reduction in cross section uncertainties.
  - Reduces the size of the systematics most likely to contain "unknown unknowns"
  - Slightly increase the sensitivity to well-understood systematics on lepton reconstruction.
- Overall systematic reduction is 5-10%,
  - The largest systematics come from the detector energy scale.

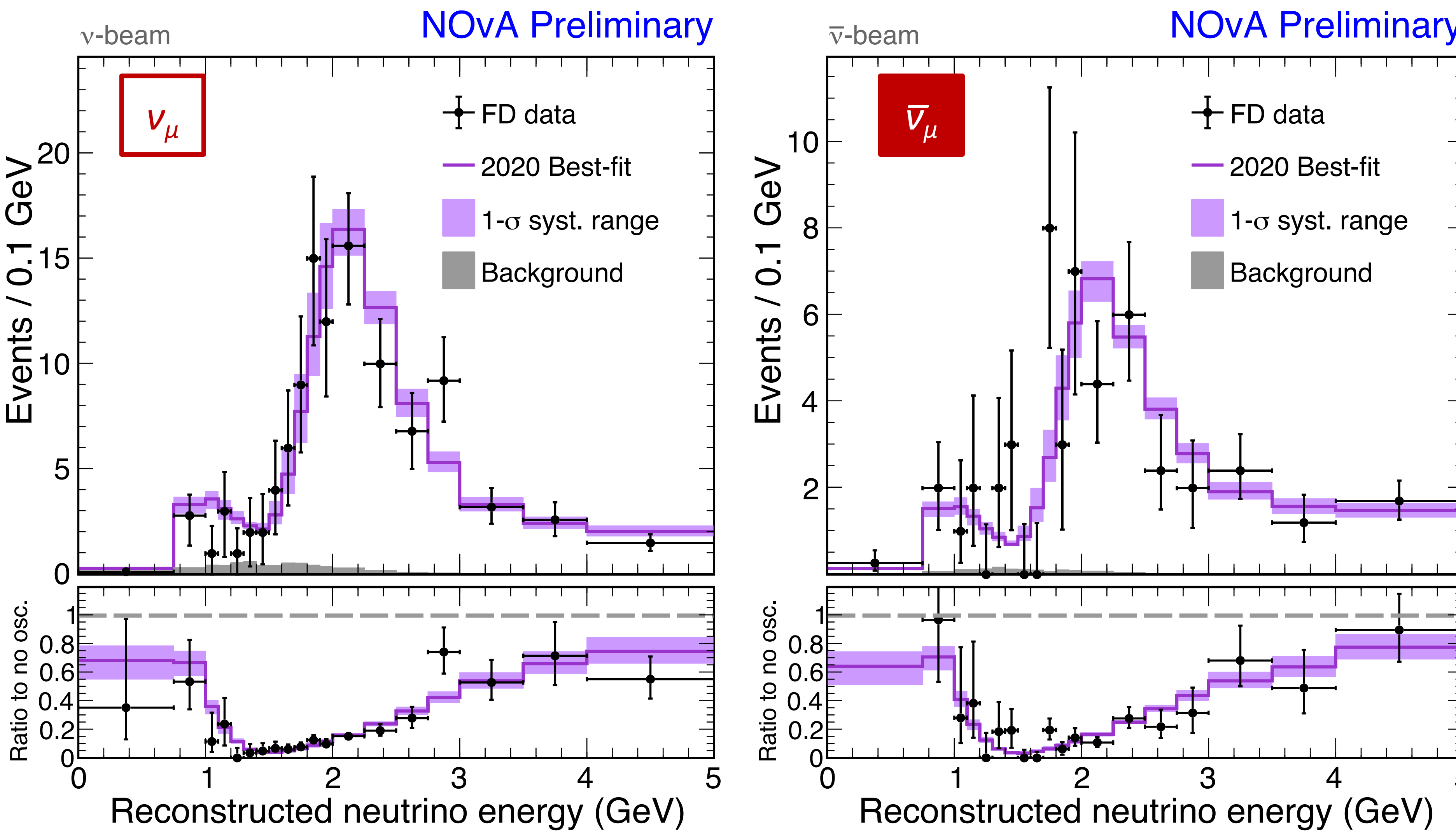
Extrapolation with Resolution Bins



Extrapolation with Resolution Bins



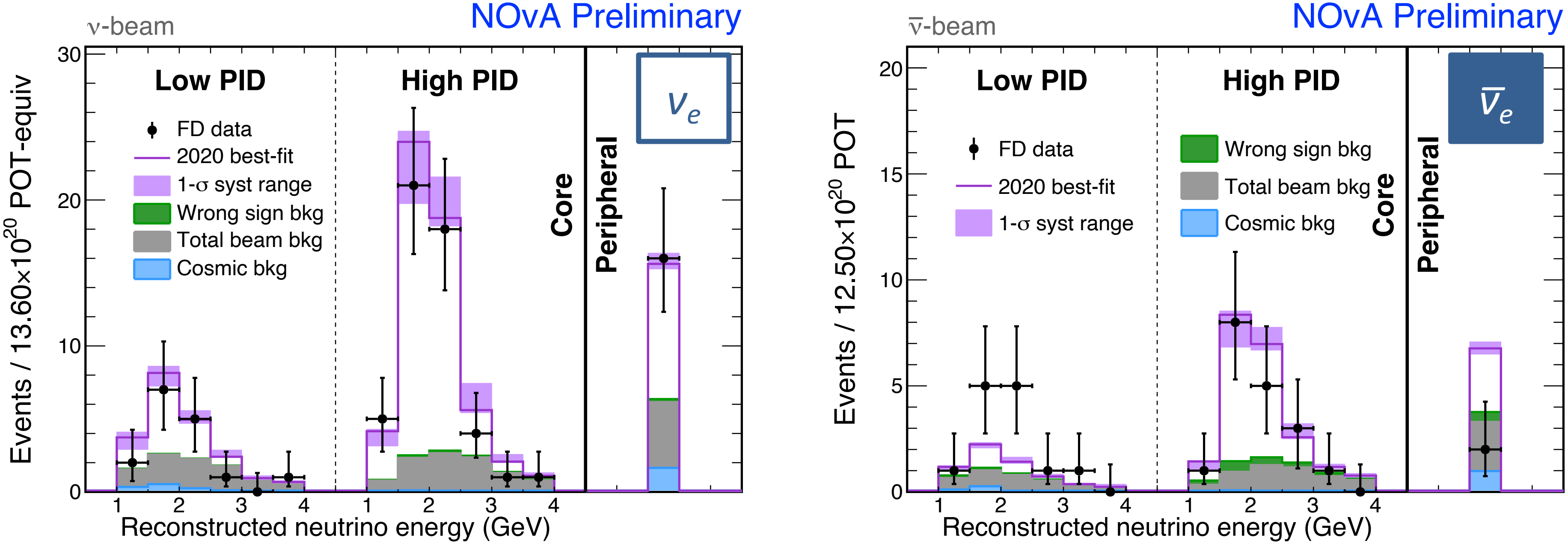
ν_μ and $\bar{\nu}_\mu$ Data at the Far Detector



211 events, 8.2 background

105 events, 2.1 background

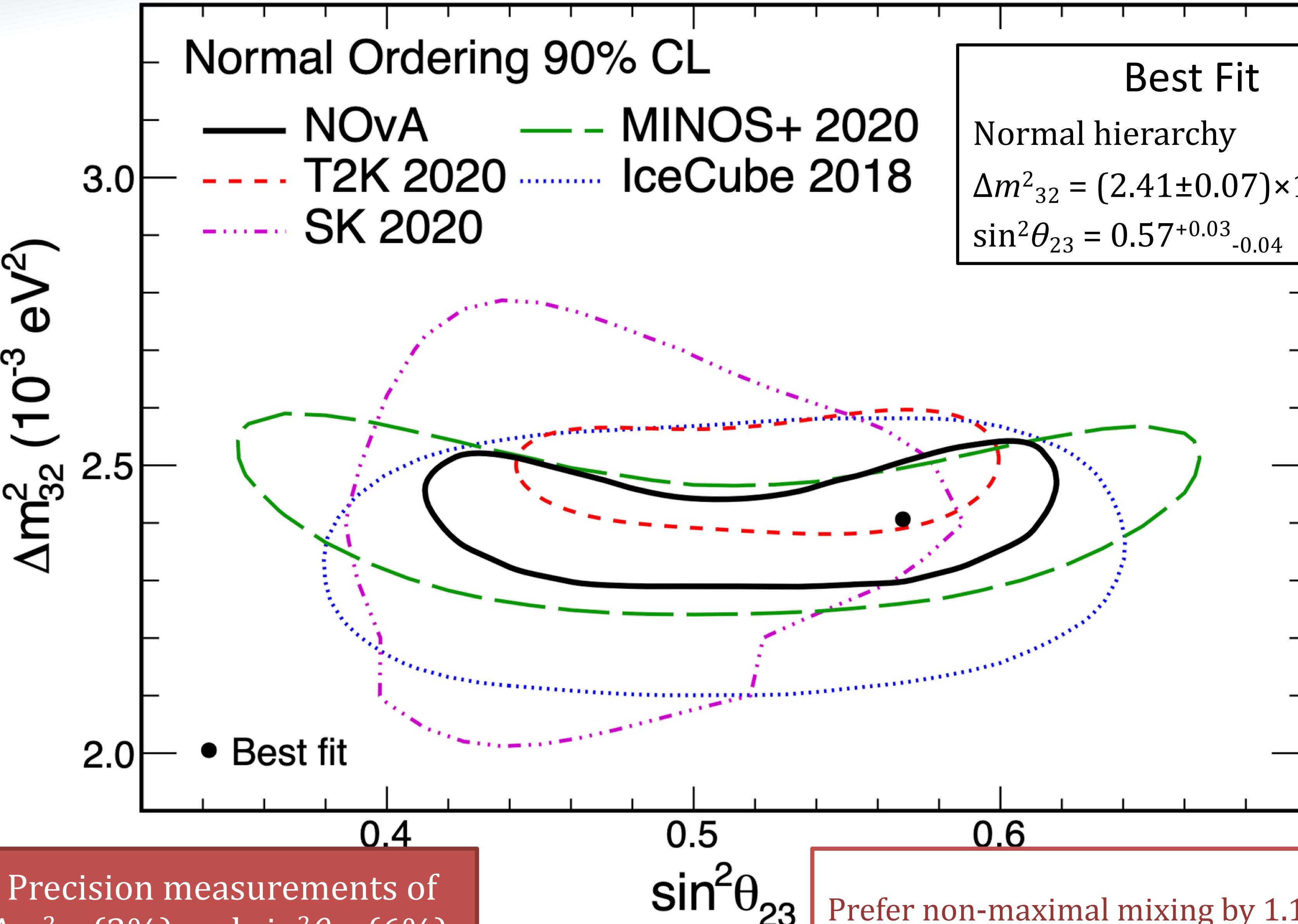
ν_e and $\bar{\nu}_e$ Data at the Far Detector



Total Observed	82	Range
Total Prediction	85.8	52-110
Wrong-sign	1.0	0.6-1.7
Beam Bkgd.	22.7	
Cosmic Bkgd.	3.1	
Total Bkgd.	26.8	26-28

Total Observed	33	Range
Total Prediction	33.2	25-45
Wrong-sign	2.3	1.0-3.2
Beam Bkgd.	10.2	
Cosmic Bkgd.	1.6	
Total Bkgd.	14.0	13-15

>4σ evidence of $\bar{\nu}_e$ appearance



Best Fit

Normal hierarchy

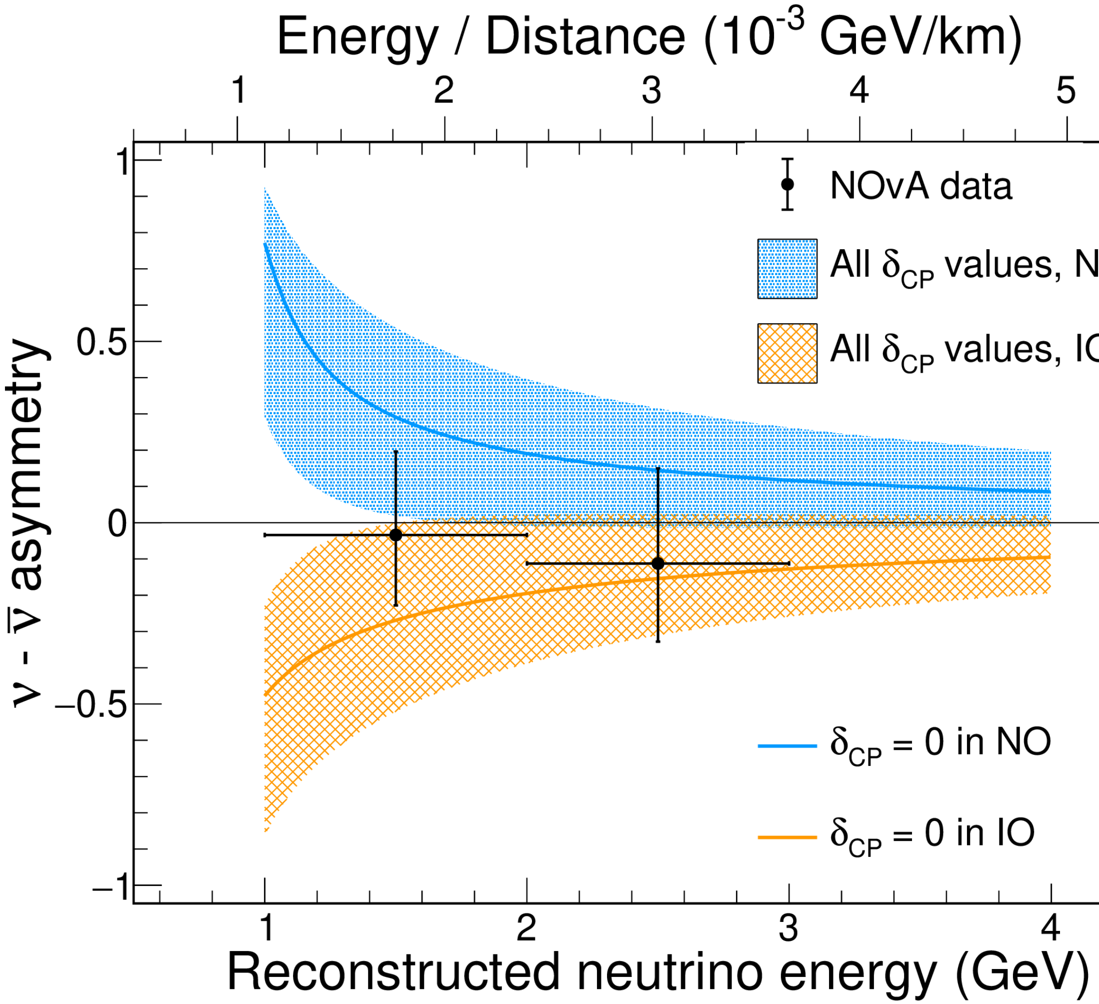
Δm^2_{32} = $(2.41 \pm 0.07) \times 10^{-3}$ eV^2

$\sin^2\theta_{23}$ = $0.57^{+0.03}_{-0.04}$

Precision measurements of Δm^2_{32} (3%) and $\sin^2\theta_{23}$ (6%).

Prefer non-maximal mixing by 1.1σ.

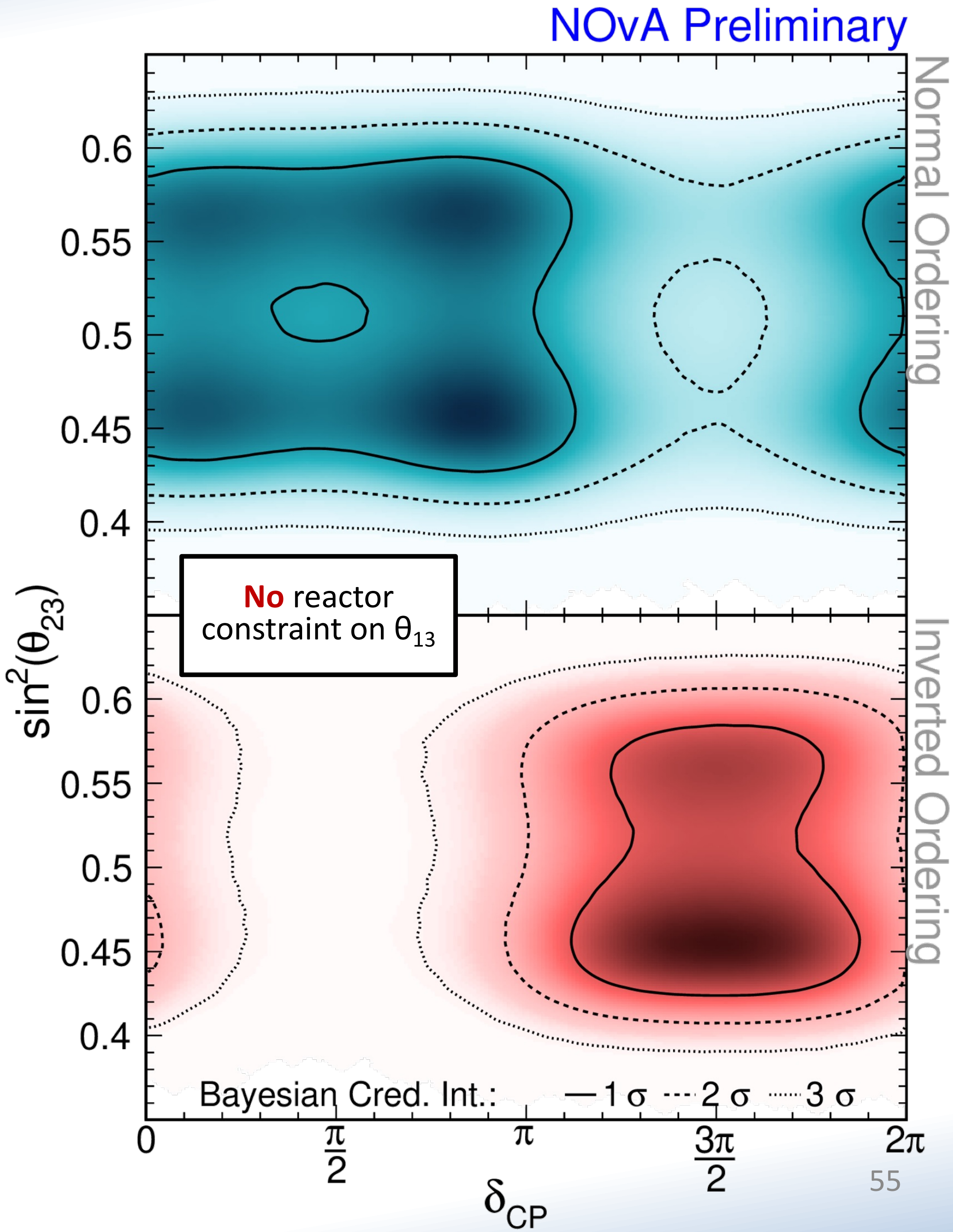
Appearance Asymmetry



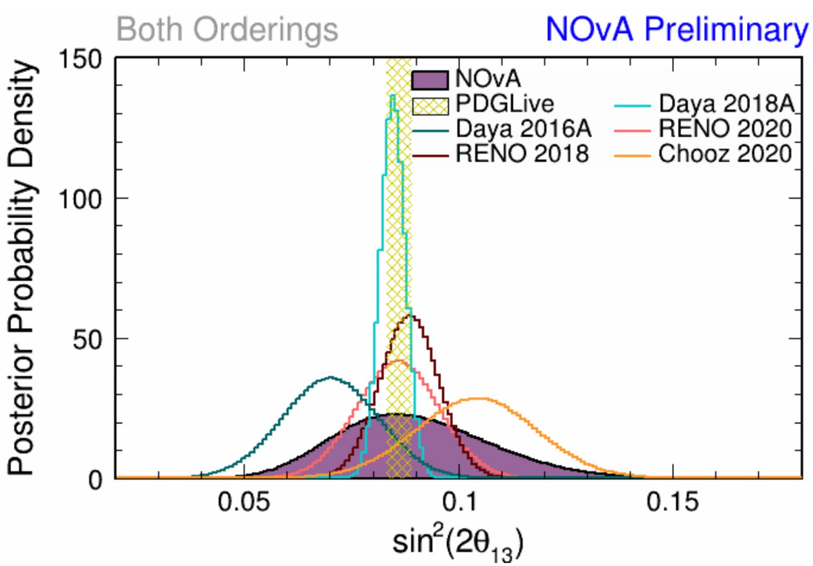
$$A = \frac{P(\nu_e) - P(\bar{\nu}_e)}{P(\nu_e) + P(\bar{\nu}_e)}$$

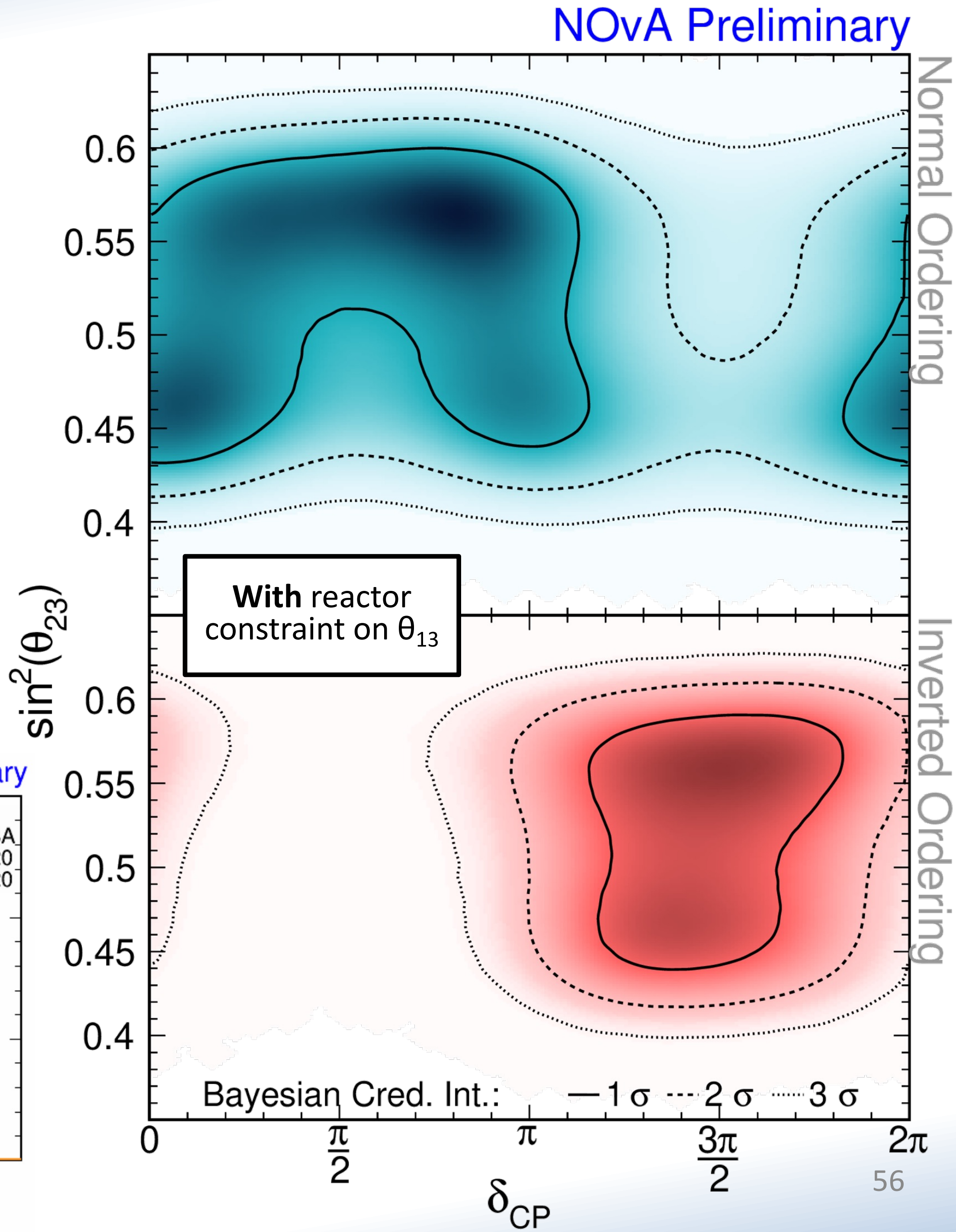
- Consistent with zero asymmetry to ~25% precision
  - A=0 is *not* δ=0
- Disfavor ordering-δ combinations which generate large asymmetries.

- Disfavor ordering-δ combinations which generate large asymmetries.
  - NO, $\delta = 3\pi/2$ at ~2σ
  - IO, $\delta = \pi/2$ at > 3σ
  - Consistent with or without reactor θ_{13} constraint.



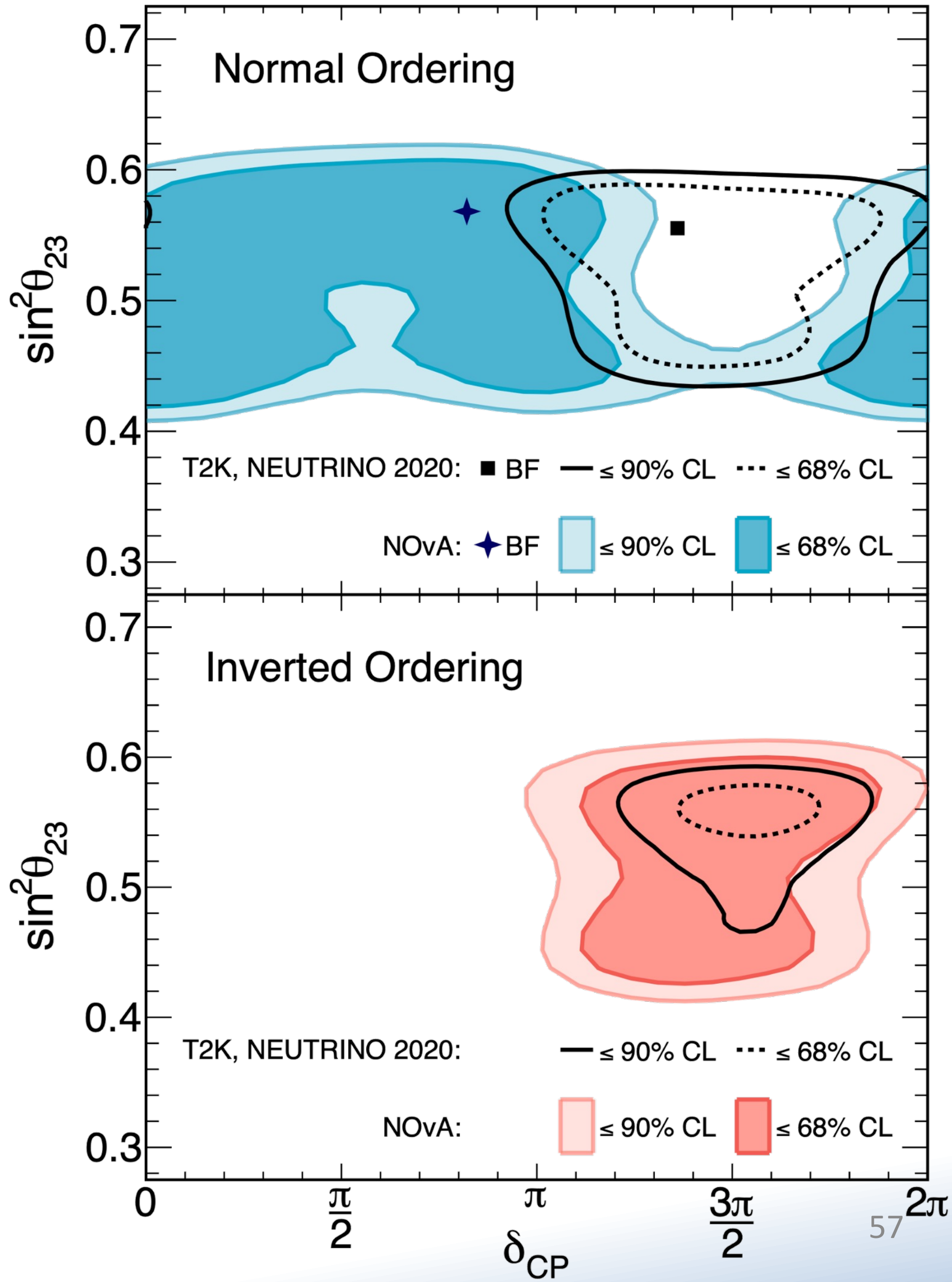
- Disfavor ordering-δ combinations which generate large asymmetries.
  - NO, $\delta = 3\pi/2$ at $\sim 2\sigma$
  - IO, $\delta = \pi/2$ at $> 3\sigma$
  - Consistent with or without reactor θ_{13} constraint.
- Adding the reactor constraint gives $\sim 1\sigma$ preferences:
  - Upper Octant
  - Normal Ordering



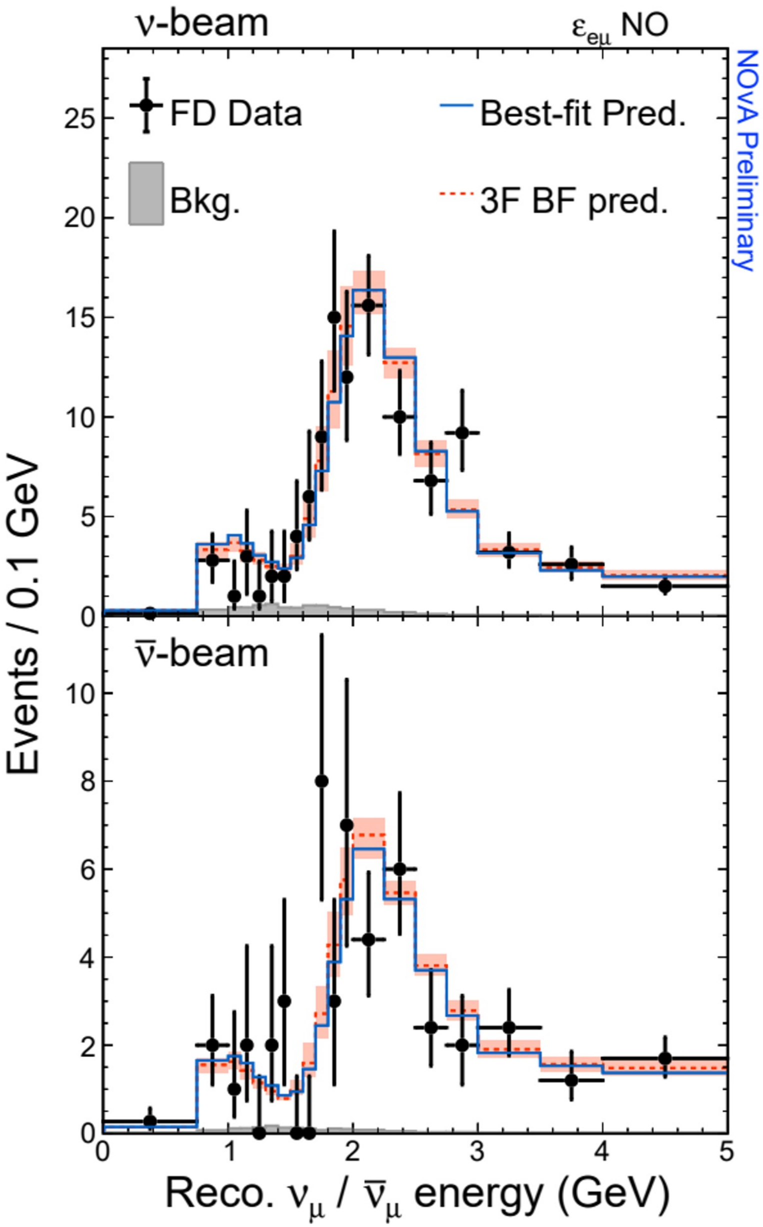


NOvA & T2K

- NOvA and T2K make complimentary measurements.
  - Longer baseline in NOvA means a larger effect from mass ordering.
  - Combining can break δ-octant-ordering degeneracies.
- T2K results favor a larger asymmetry towards ν_e's
  - Short baseline leads to a similar δ range in both orderings.
  - Means NOvA & T2K are consistent in IO, but disagree in NO.
- Working hard to take advantage of the complementarity with a joint analysis!

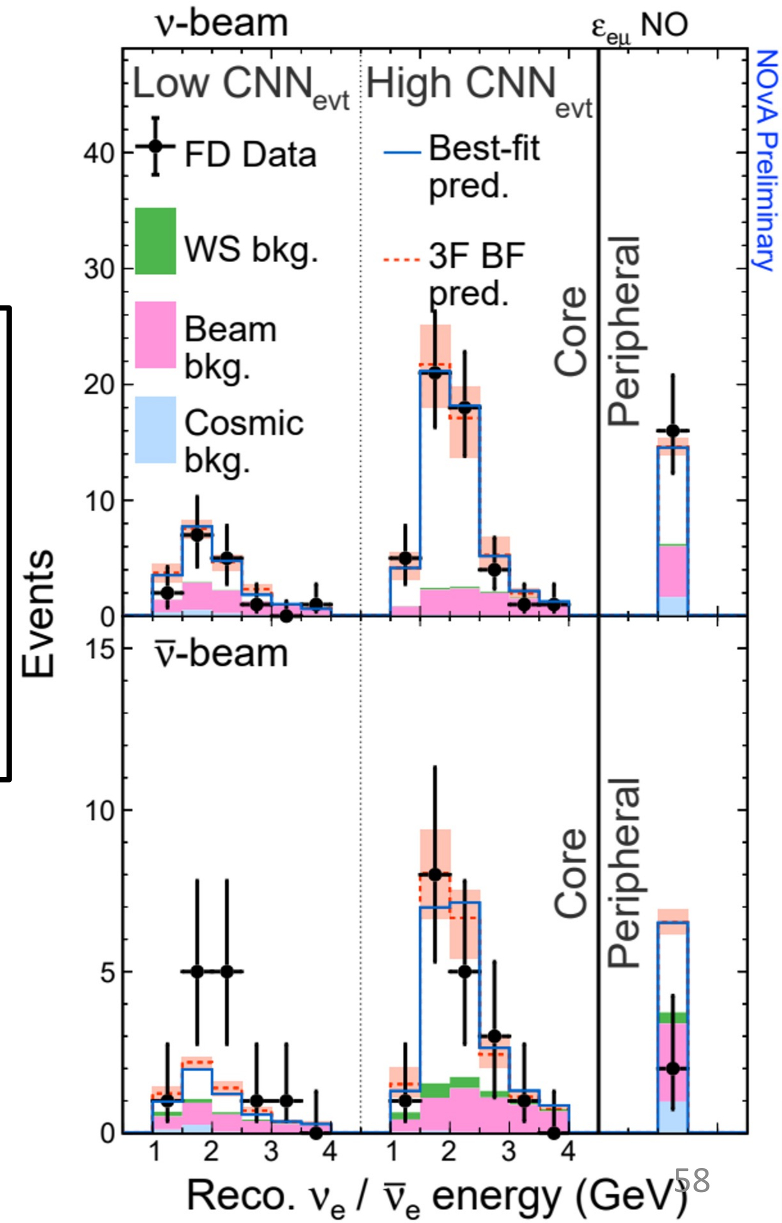


Spectra with *eμ* fit

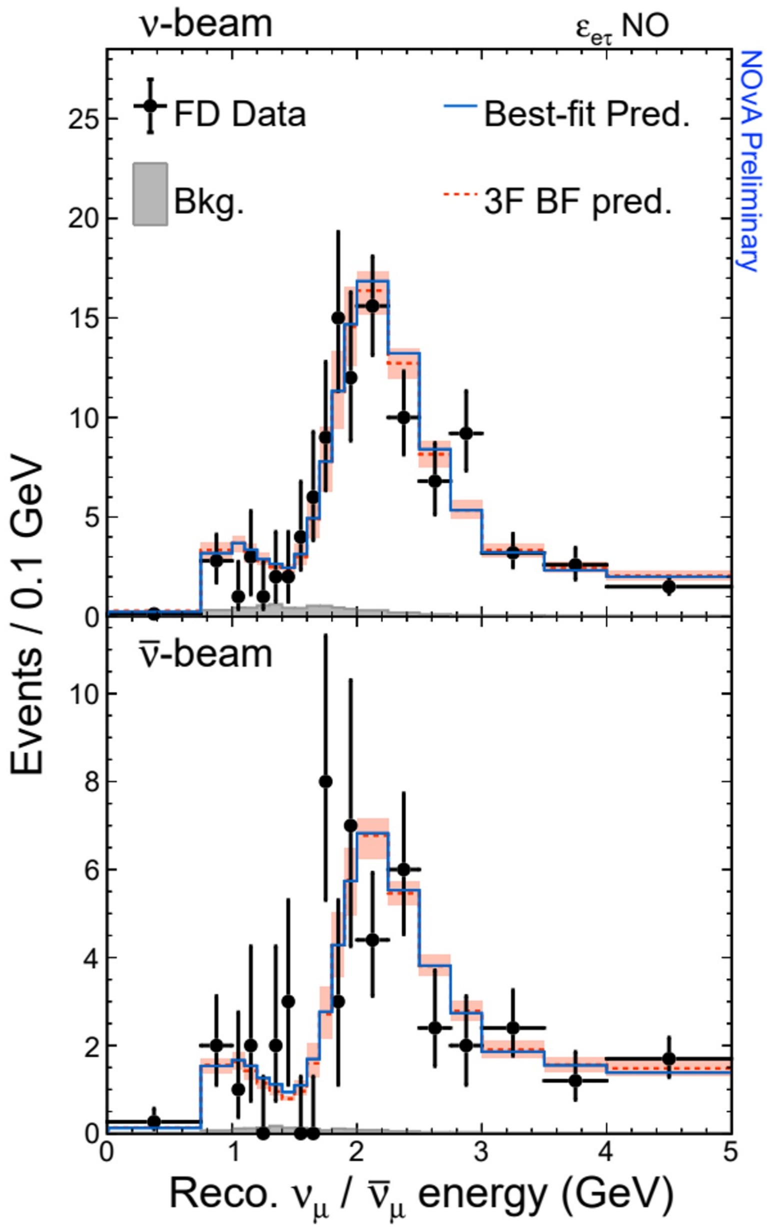


NSI *not* needed to explain NOvA spectra.

χ^2 improvement of only ~0.65 for 2 additional parameters.

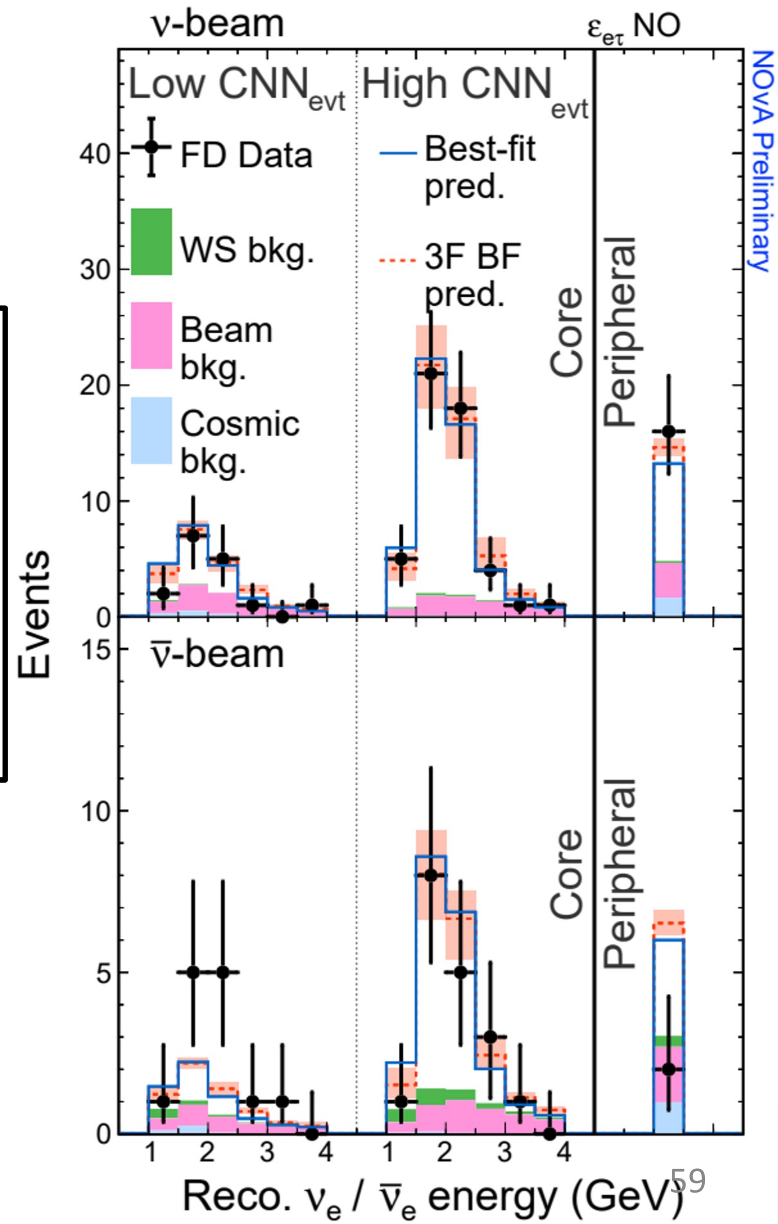


Spectra with $e\tau$ fit



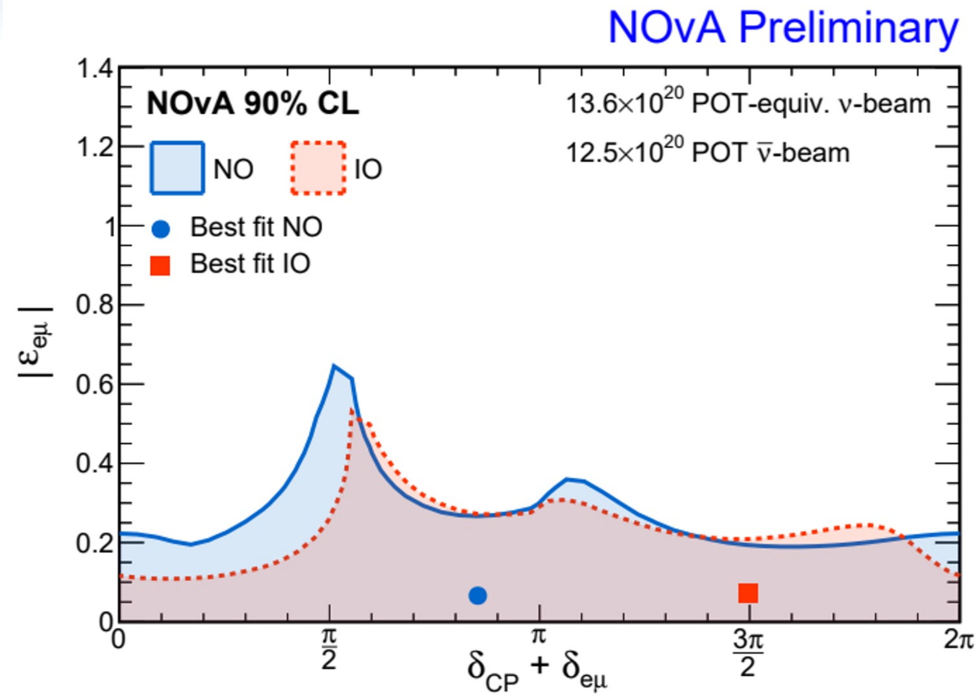
NSI *not* needed to explain NOvA spectra.

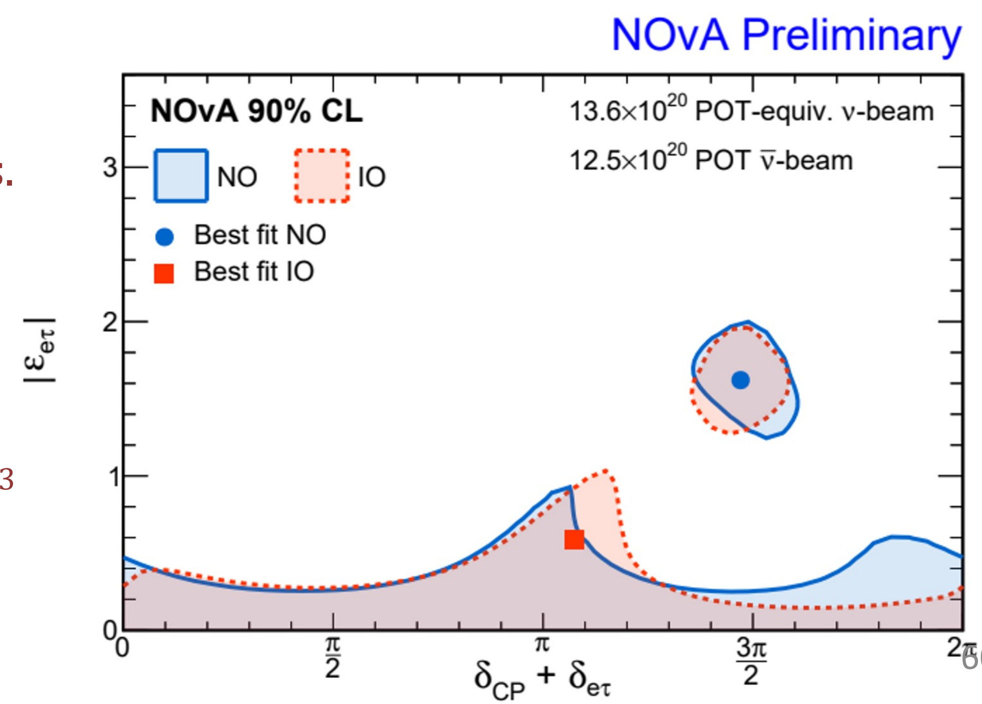
χ^2 improvement of only ~0.65 for 2 additional parameters.



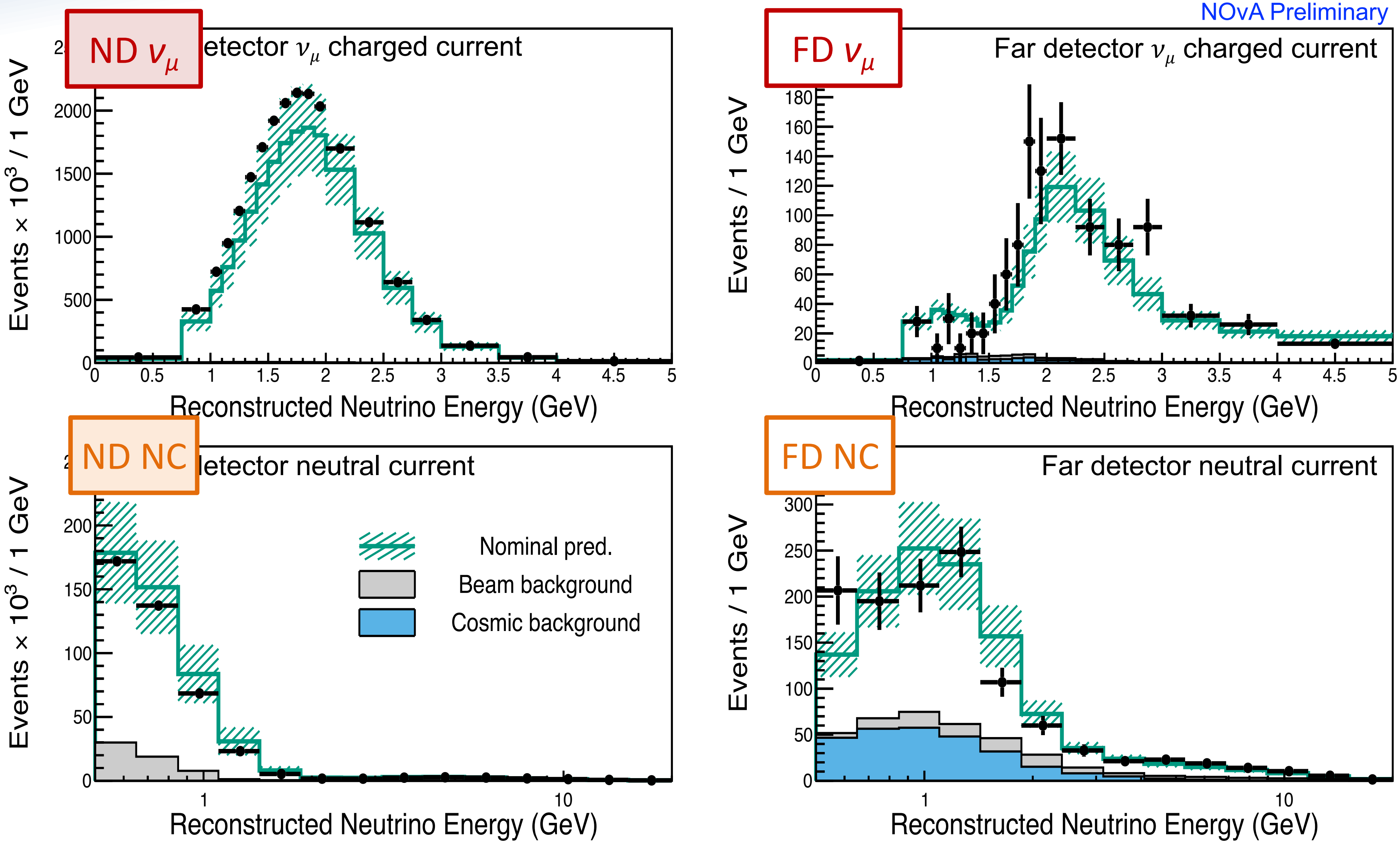
NSI Parameter Intervals

- Plotting magnitude vs. phase.
  - Strong degeneracy between δ_{CP} and δ_{NSI}, so plotting the sum.
  - Difference taken as a nuisance parameter.
- $|\varepsilon_{e\mu}| < 0.3$ and $|\varepsilon_{e\tau}| < 0.4$ for most values of δ.
  - The island in the bottom plot is related to a "double" degeneracy with neutrinos and antineutrinos.
- Including NSI parameters severely limits sensitivity to octant, ordering, and δ_{CP}.
  - Little impact on Δm^2_{32} and $\sin^2\theta_{23}$

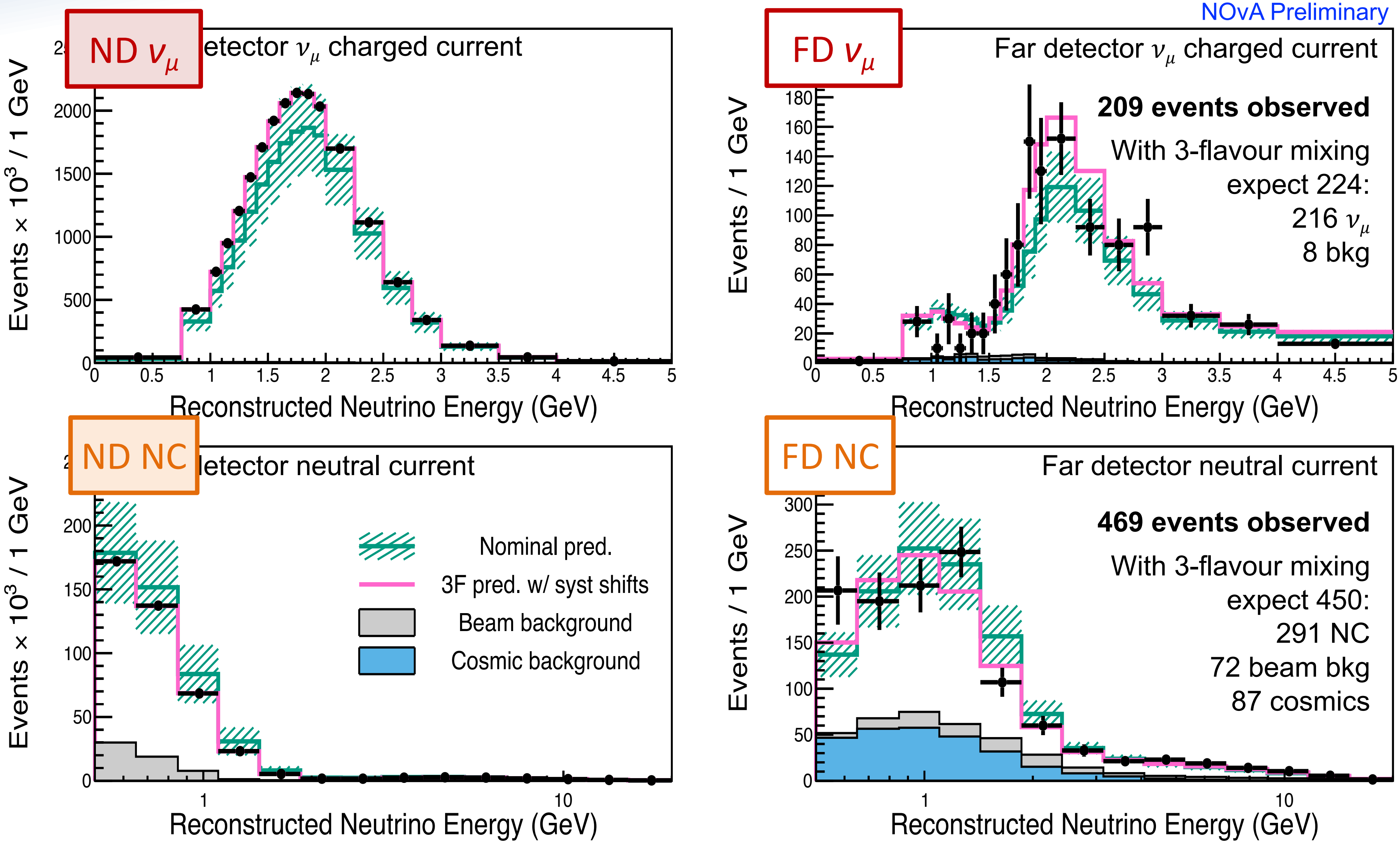




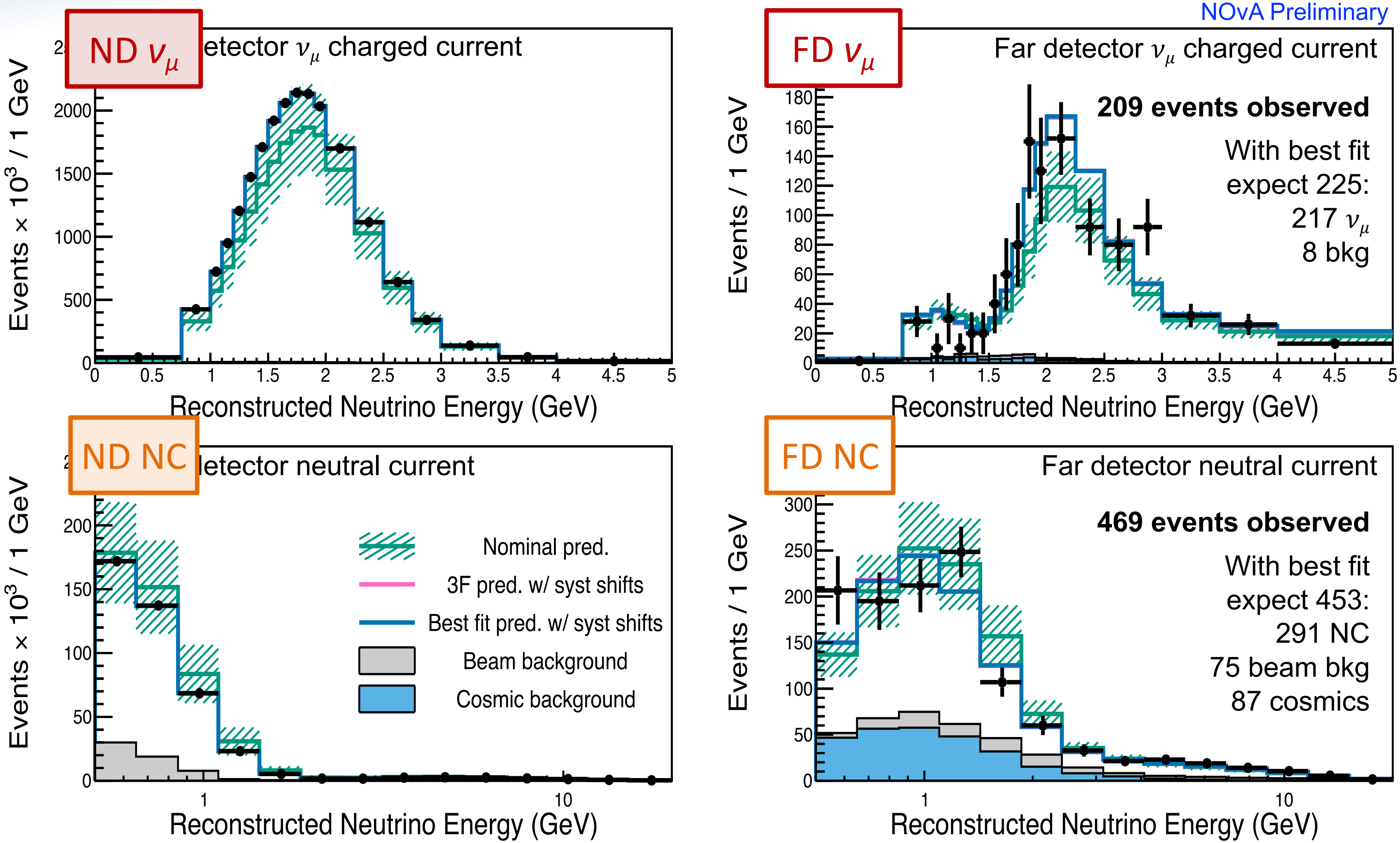
Pre-fit MC Distributions



Best fit for 3-Flavor and Systematics

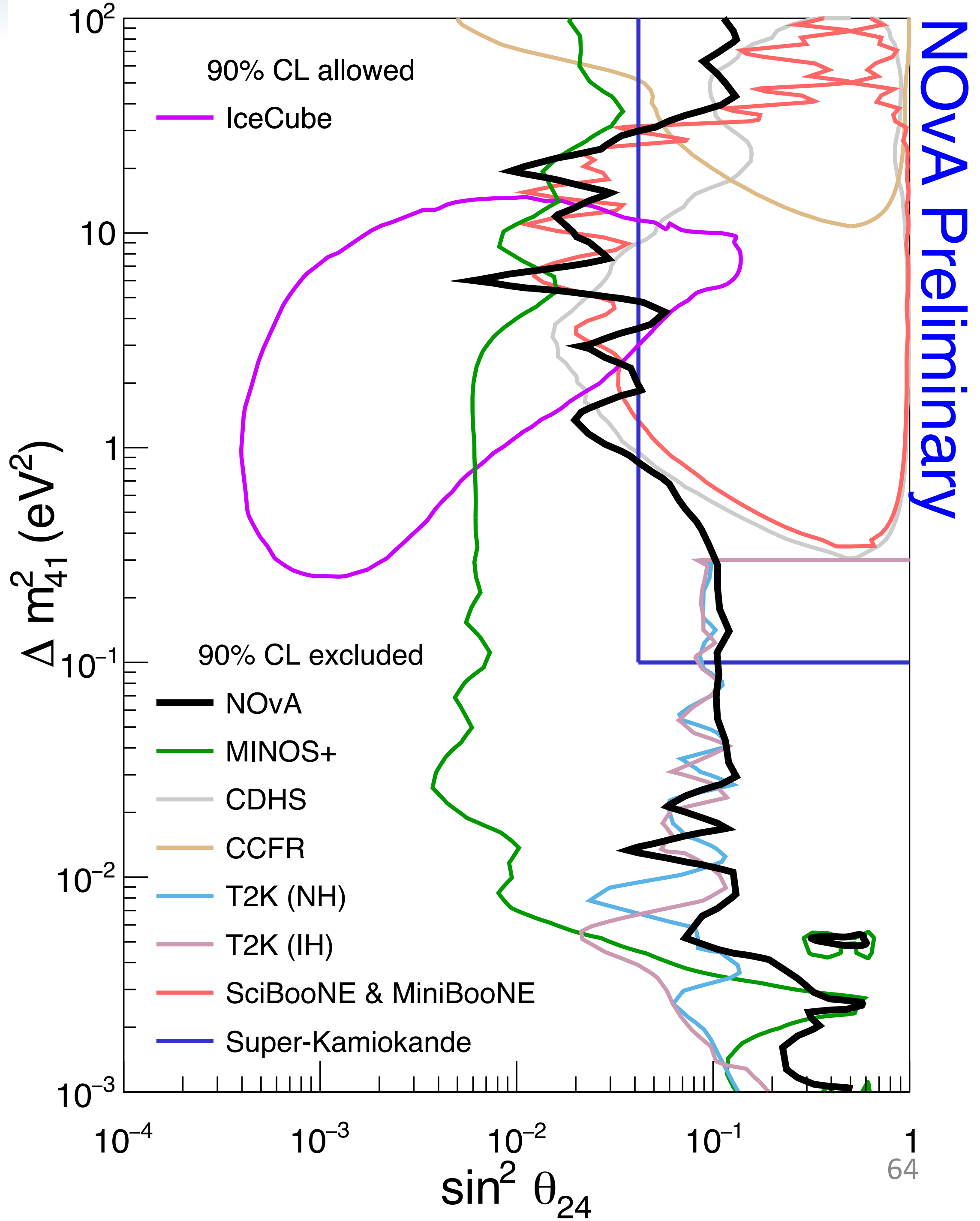


Best Fit for 3+1 Sterile Neutrino



Best sterile fit and best 3F fit nearly identical

- Fit for Δm^2_{41} vs. $\sin^2\theta_{24}$
- No evidence for a sterile neutrinos
  - Best fit at small θ_{24} and θ_{34} with low significance
  - $\chi^2/\text{d.o.f.} = 56.4/66$
- Competitive limits on θ_{24} for $\Delta m^2_{41} = \sim 10 \text{ eV}^2$
- Systematics limited at large Δm^2_{41} (Near det.)
- Statistics limited at small Δm^2_{41} (Far det.)



- Fit for Δm^2_{41} vs. $\sin^2\theta_{34}$
  - Mixing between ν_τ and a sterile ν
  - Historically studied via ν_τ appearance searches at short baselines as $\theta_{\mu\tau}$
  - Comparisons with those experiments not included
- Sensitivity due to **neutral current** events
  - enhanced by constraints on θ_{24} from ν_μ charged current events
- New constraints on θ_{34} at small Δm^2_{41}
  - Long-baseline providing sensitivity