FERMILAB-SLIDES-18-088-ND

New $\nu_e + \bar{\nu}_e$ appearance results from NOvA

Bruce Howard | *Indiana University*

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New Perspectives 2018
19 June 2018

Context

- Many details in talk from J. Vasel
- Functionally-similar near and far detectors separated by 810 km
- In addition to ν_μ disappearance, can study appearance $\nu_\mu \rightarrow \nu_e$ ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$) to probe 3-flavor neutrino oscillations
  - Mixing angles and octant sensitivity?
  - Mass splitting and hierarchy?
  - CP violation?
- Updated NOvA analysis with, for the first time, antineutrino beam data
  - Antineutrino dataset 6.9×10^{20} protons on target (neutrino dataset 8.9×10^{20} full-detector equivalent protons on target)

Credit: Fermilab

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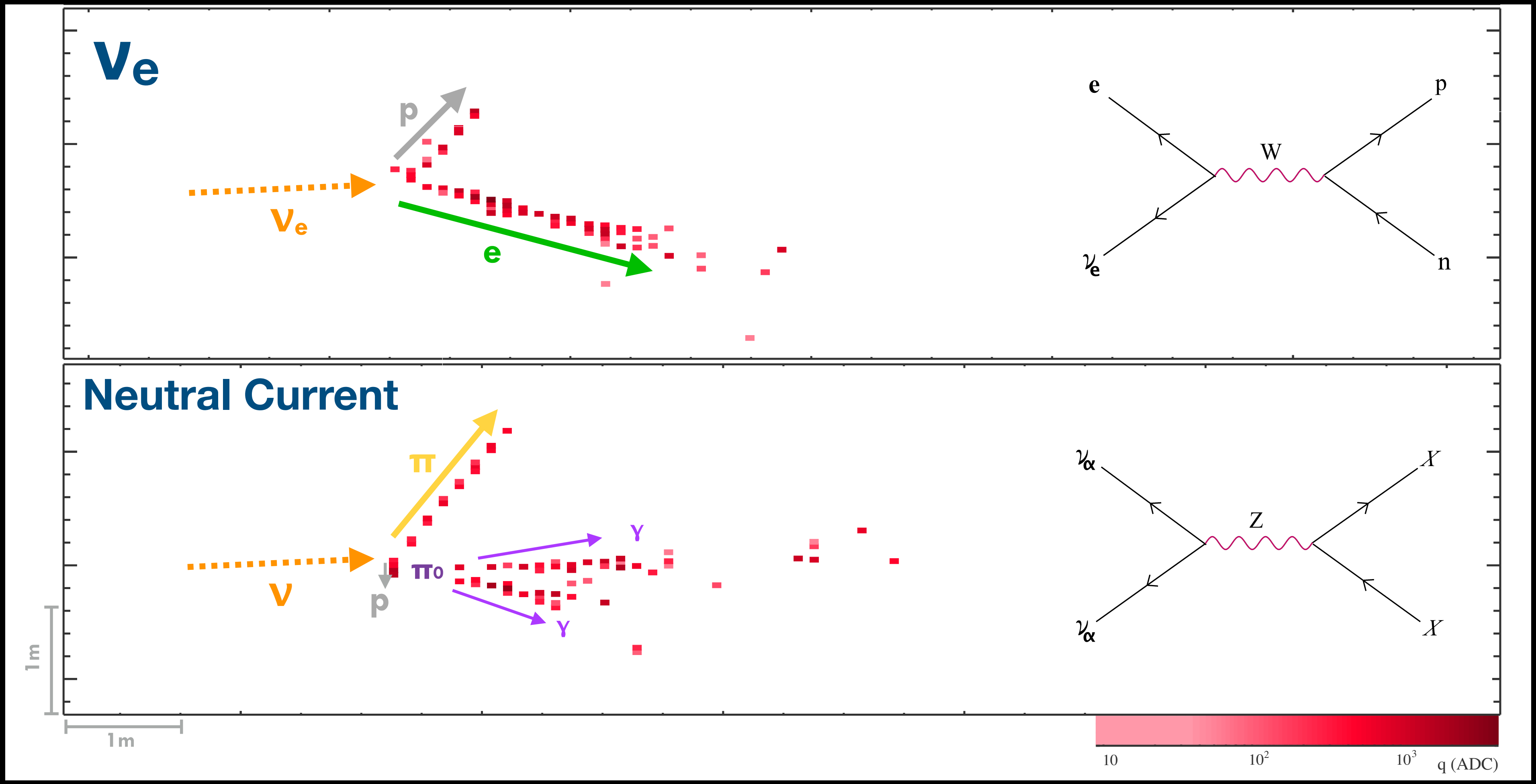
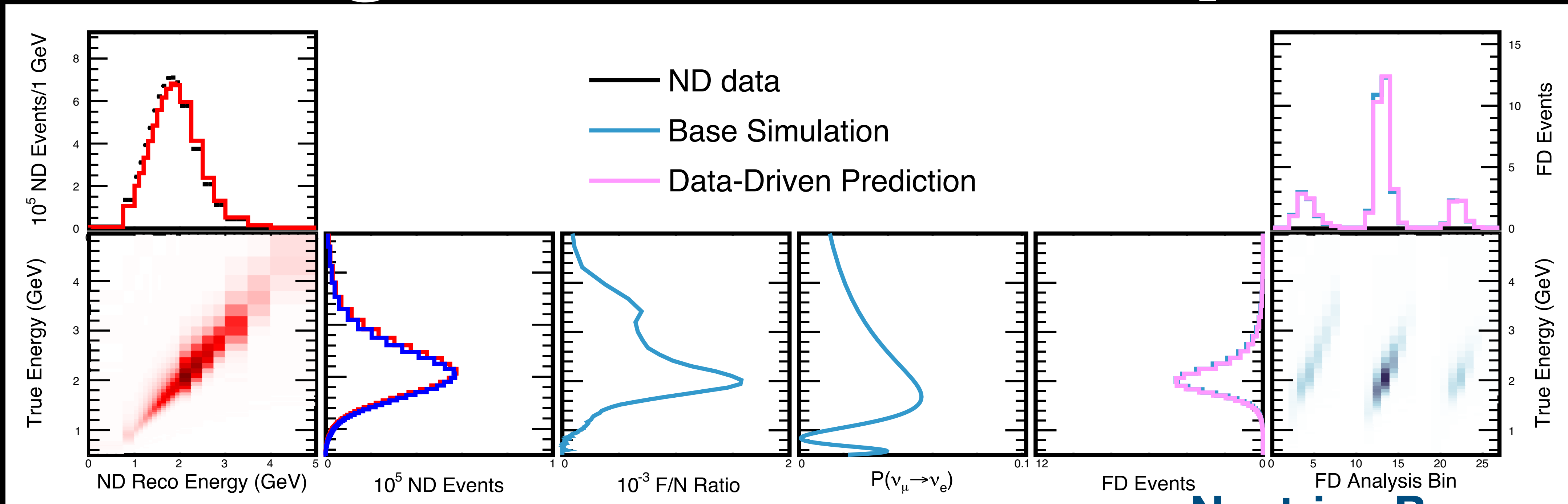
Event selection for $\nu_e + \bar{\nu}_e$

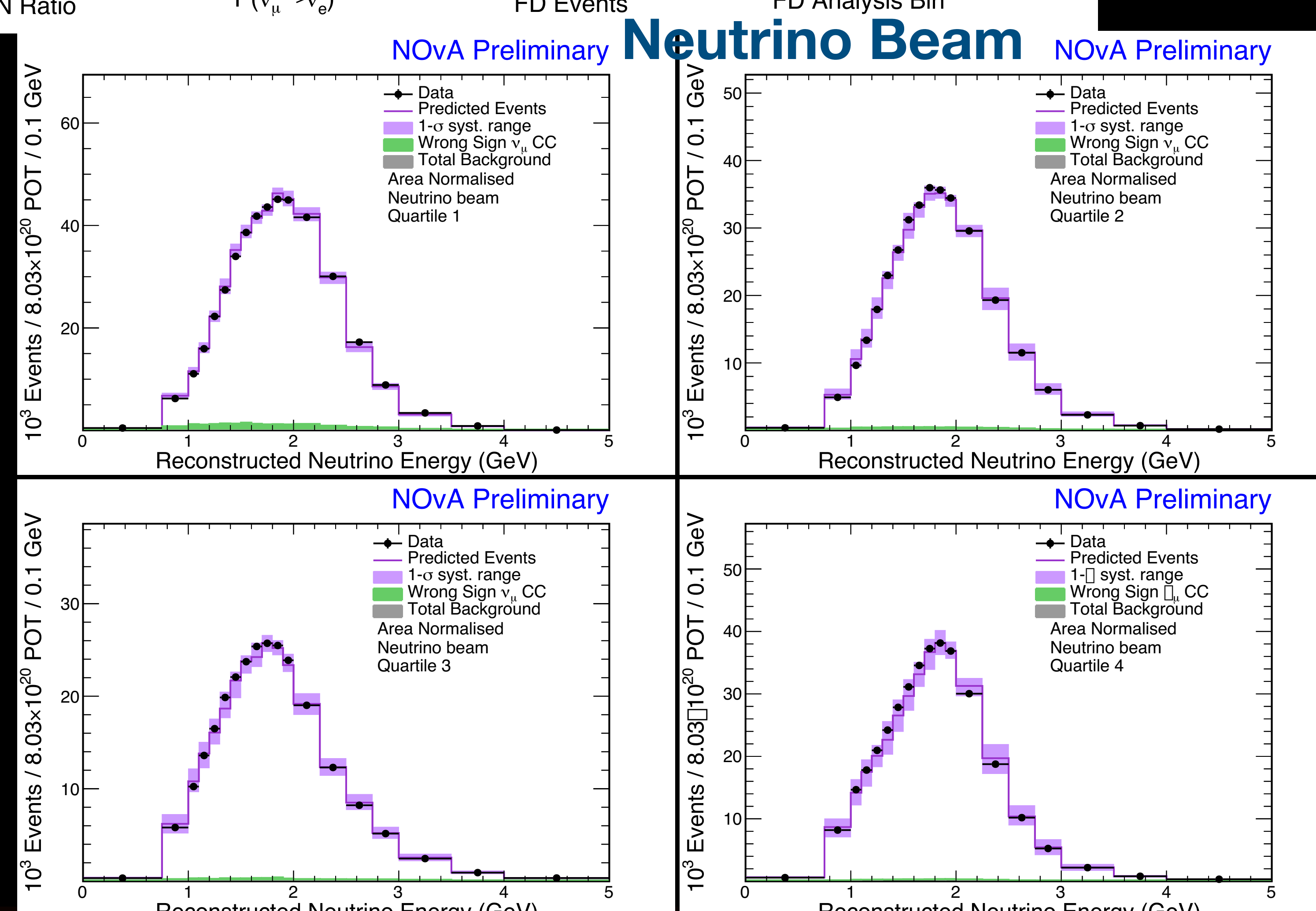


- Details of reconstruction detailed in talk by M. Groh
  - Select events w/ ν_e ($\bar{\nu}_e$) classifier score & reconstructed information indicating likely ν_e ($\bar{\nu}_e$) candidate
  - NOvA uses CVN (Convolutional Visual Network): event classification based on final state topologies
  - Selections broken into two subcategories based on CVN electron score
  - Far detector: extra peripheral sample w/ larger cosmic background but recovers appearance signal
- Energy range of interest 1-4 GeV in far detector (0-4.5 GeV in near detector, peripheral)

Predicting far detector spectra

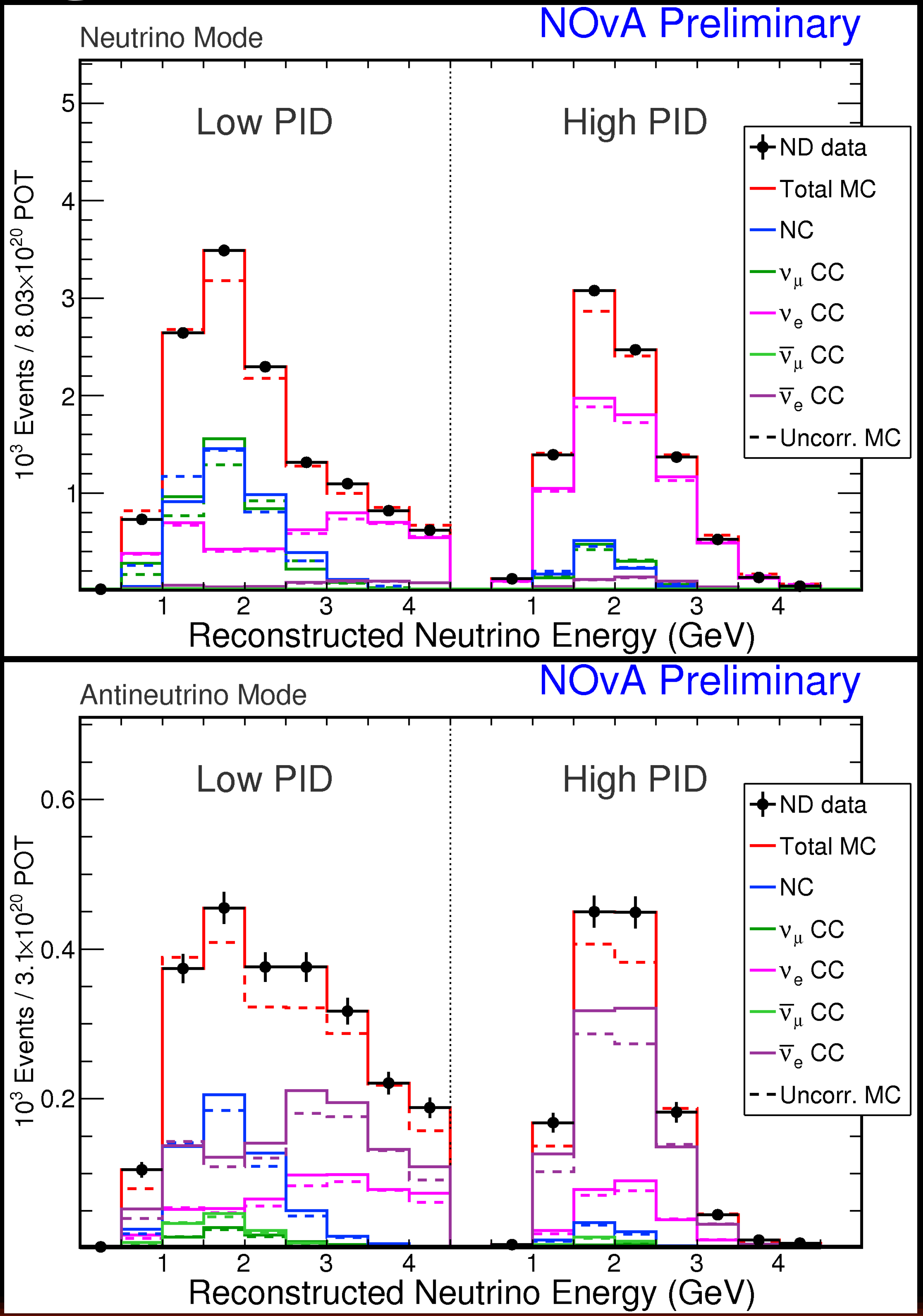


- Functionally similar near, far detectors: extrapolation reduces overall systematics (reduction factor ~2)
- Near detector ν_μ spectrum extrapolated to far detector given oscillation parameters forms appearance signal prediction
- Expect fewer signal events in antineutrino beam than in neutrino beam: (Flux⊗Cross-section) reduced for antineutrinos and somewhat less exposure in antineutrino beam



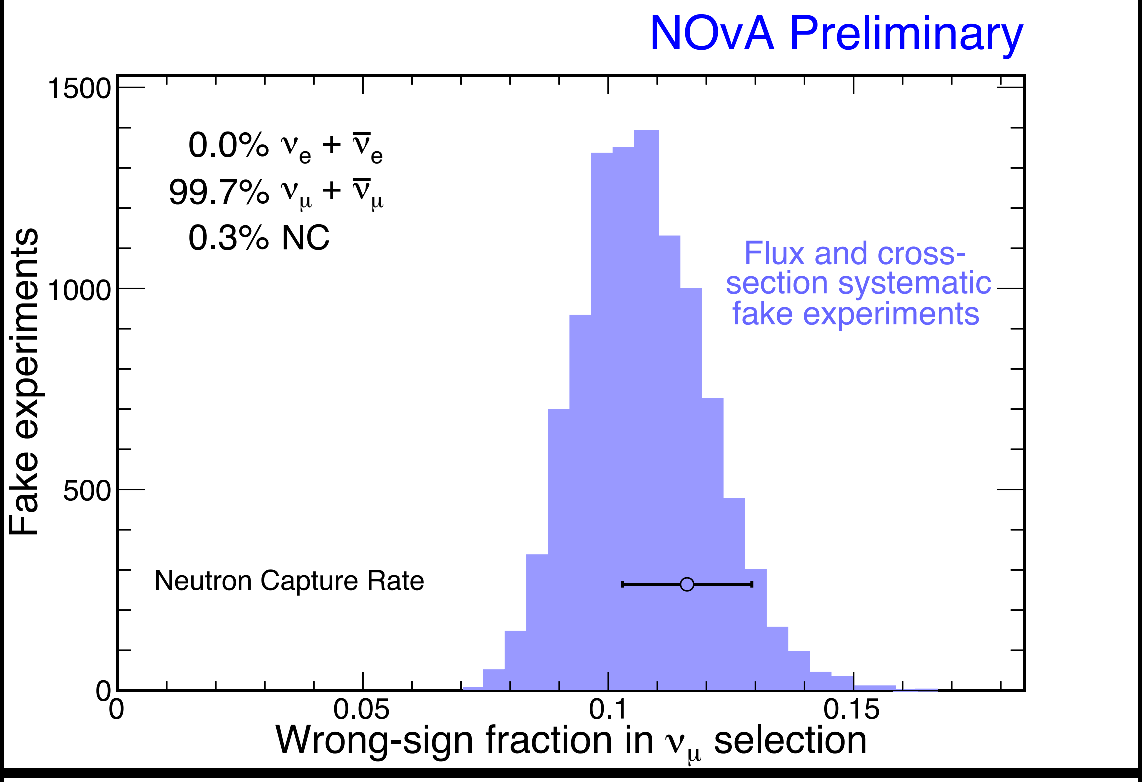
Near Detector Background

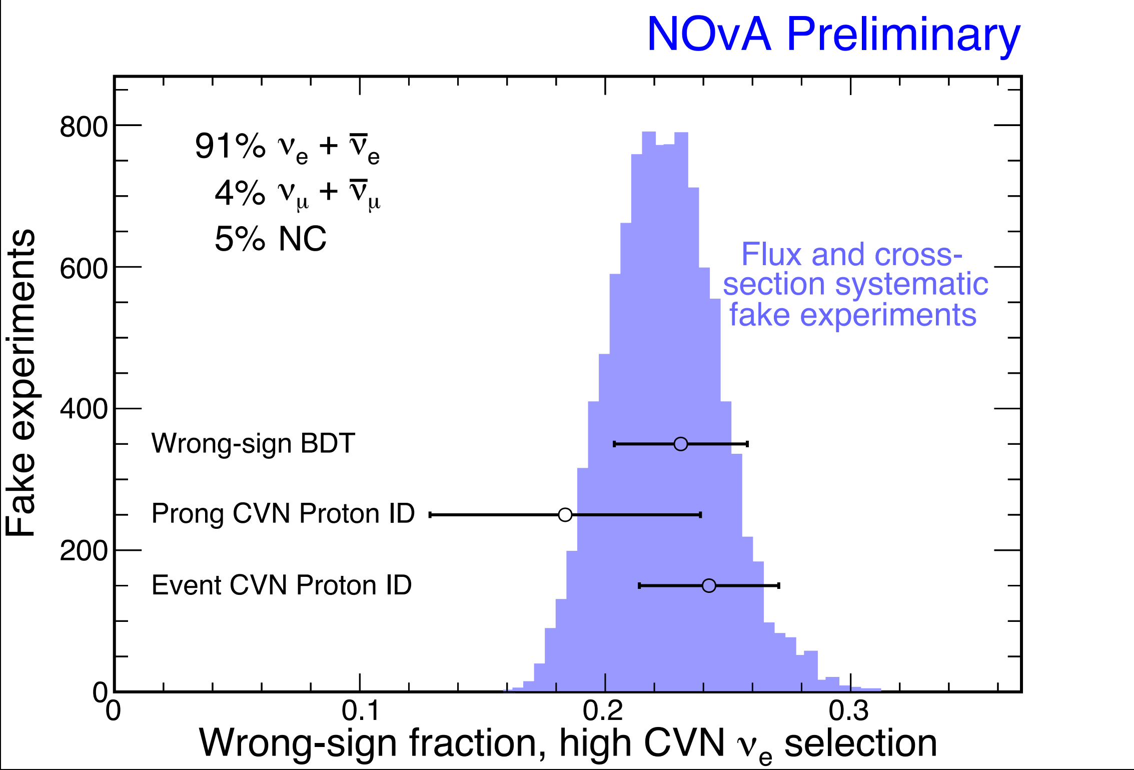
- Selected near detector candidate spectra contain only backgrounds for appearance analysis: inform far detector background prediction via far/near ratio
- Components constrained via data-driven methods
    - In antineutrino beam, for now, data/MC differences are scaled proportionally in each energy bin to the components.
    - In neutrino beam, with higher stats, more refined method used which examines components separately.
- Decomposed ND spectra agree w/ MC by construction



Near Detector Background

- Wrong-sign (ν in $\bar{\nu}$ beam) fraction estimate in near detector $\bar{\nu}_\mu$ selection 11%, checked w/ neutron capture rates
  - Oscillates to becomes appearance background
- Wrong-sign fraction estimate in near detector beam $\overset{(-)}{\nu}_e$ selected background 22% for antineutrino beam in higher (purer in $\overset{(-)}{\nu}_e$) CVN sample. Check w/ identified protons & event kinematics

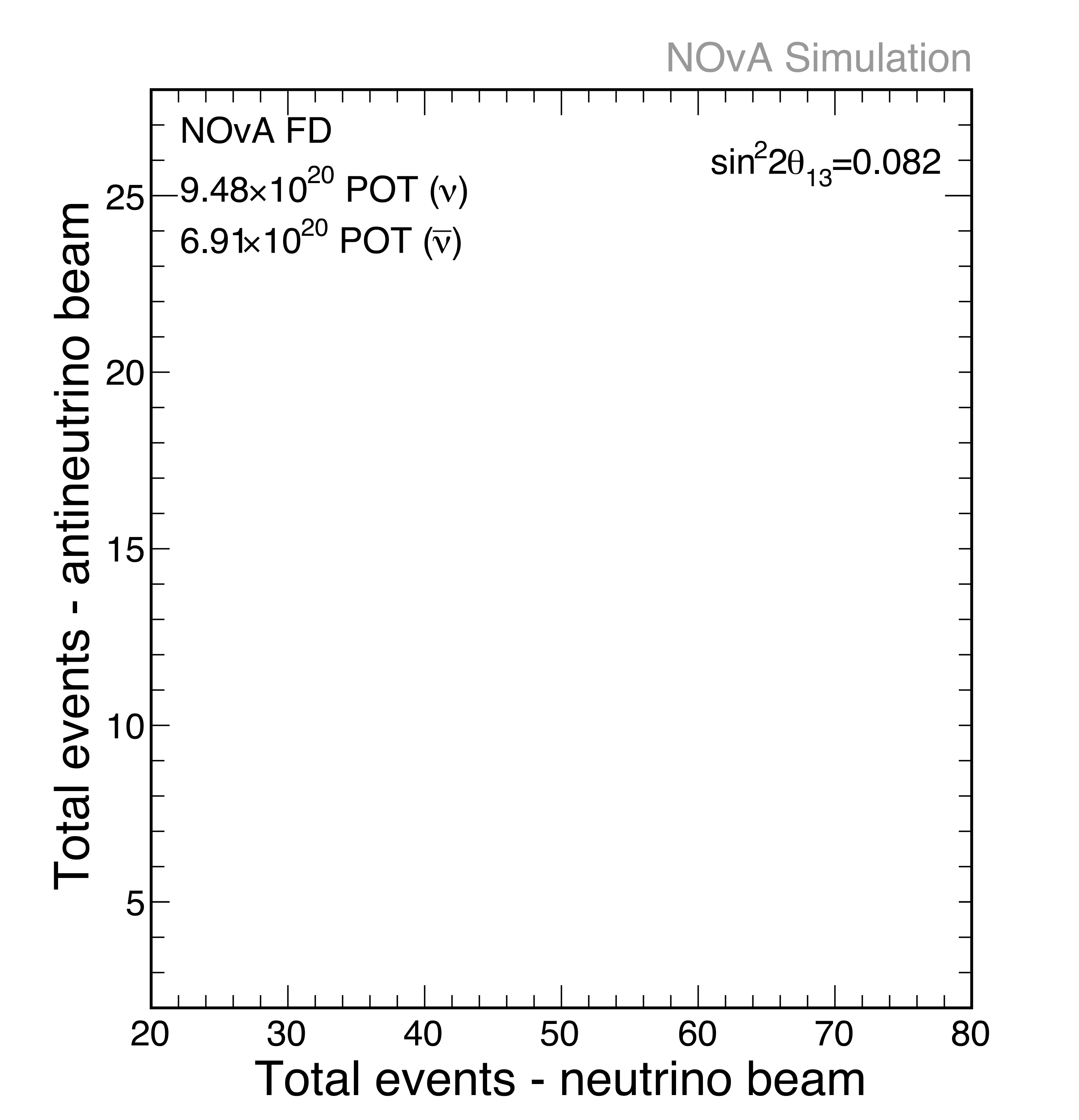




B. Howard

Predicting far detector spectra

- External constraint on $\sin^2 2\Theta_{13}$ from PDG average
- Enhancement/suppression due to matter effect based on mass hierarchy. For normal hierarchy (NH), matter effect enhances ν_e, suppresses $\bar{\nu}_e$
  - Inverted Hierarchy (IH) opposite
- Oscillation parameters determine further ν_e, $\bar{\nu}_e$ enhancement/suppression (overall and relative)
  - E.g. for $\delta_{CP}=\pi/2$, IH: suppression of ν_e candidates relative to $\bar{\nu}_e$
  - Alternatively, large suppression of $\bar{\nu}_e$ relative to ν_e for $\delta_{CP}=3\pi/2$, NH
- Predictions range from 10-22 $\bar{\nu}_e$ candidates, 30-75 ν_e candidates



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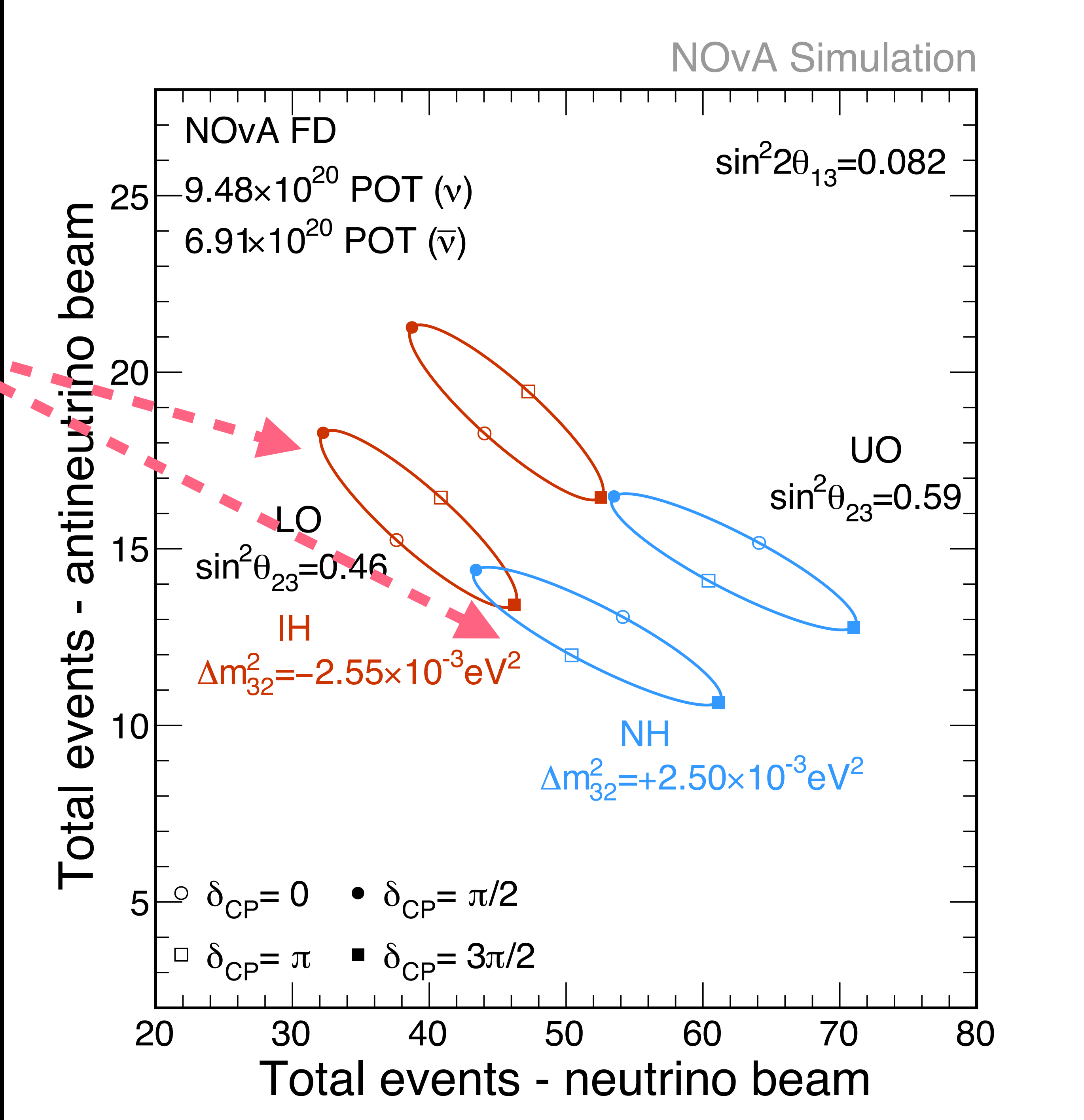

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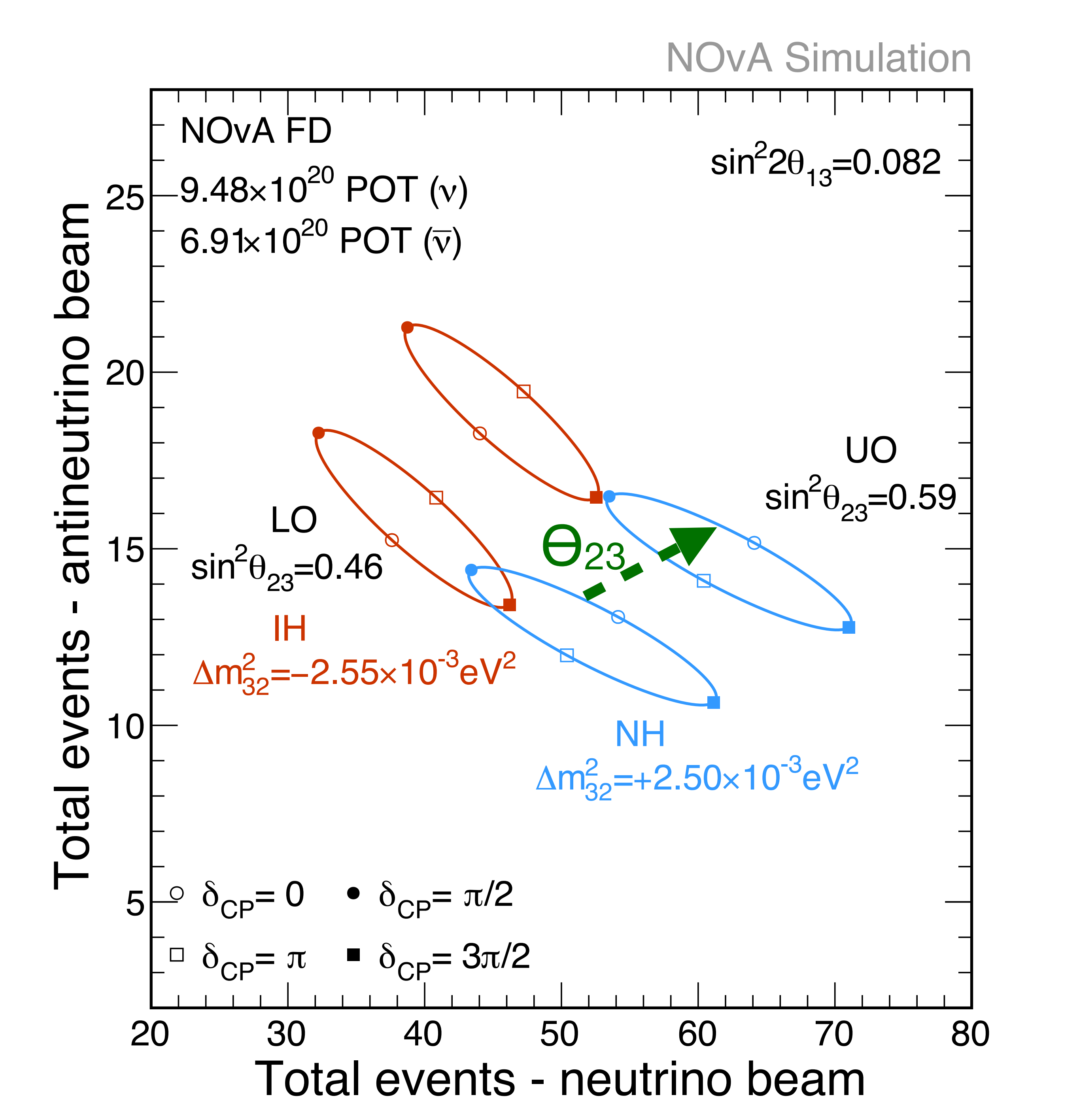

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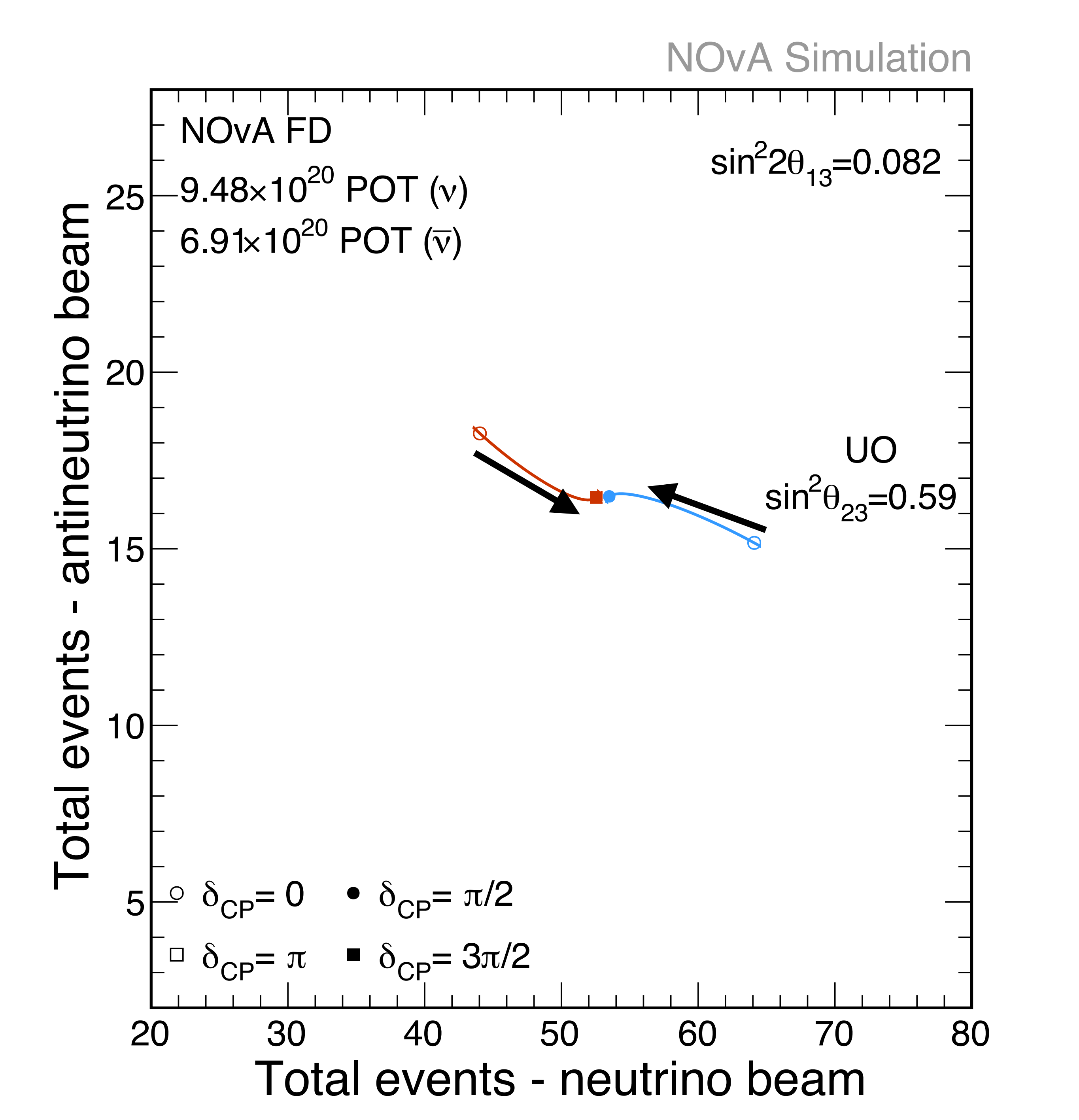

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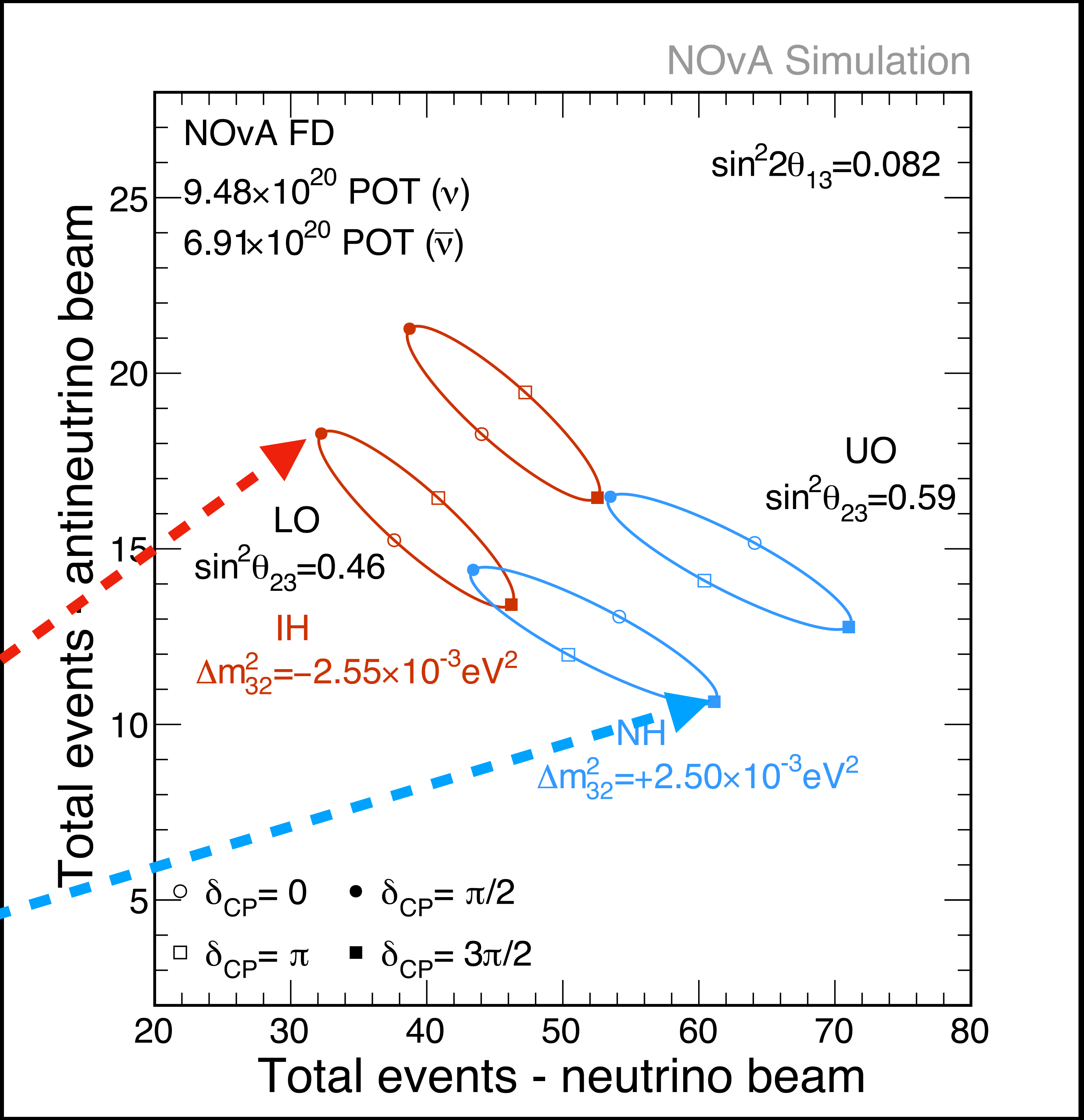

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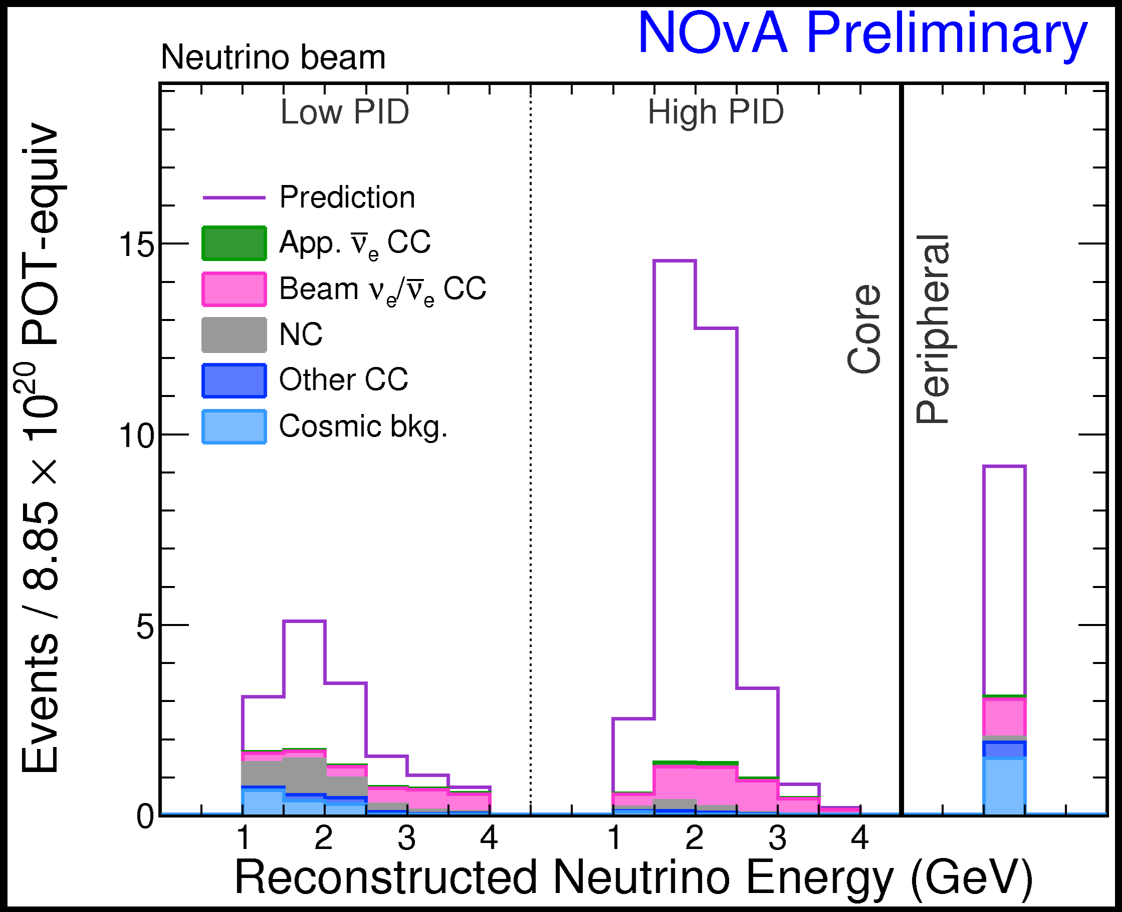
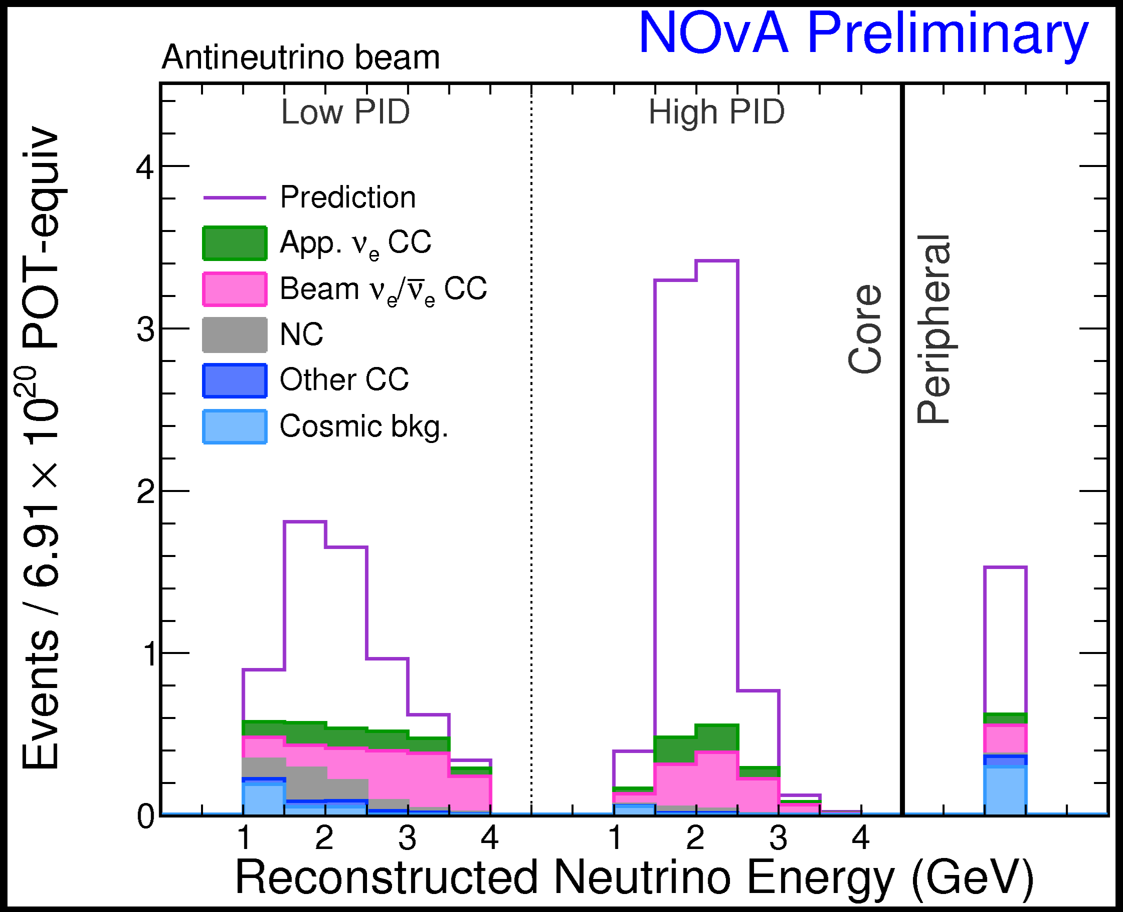
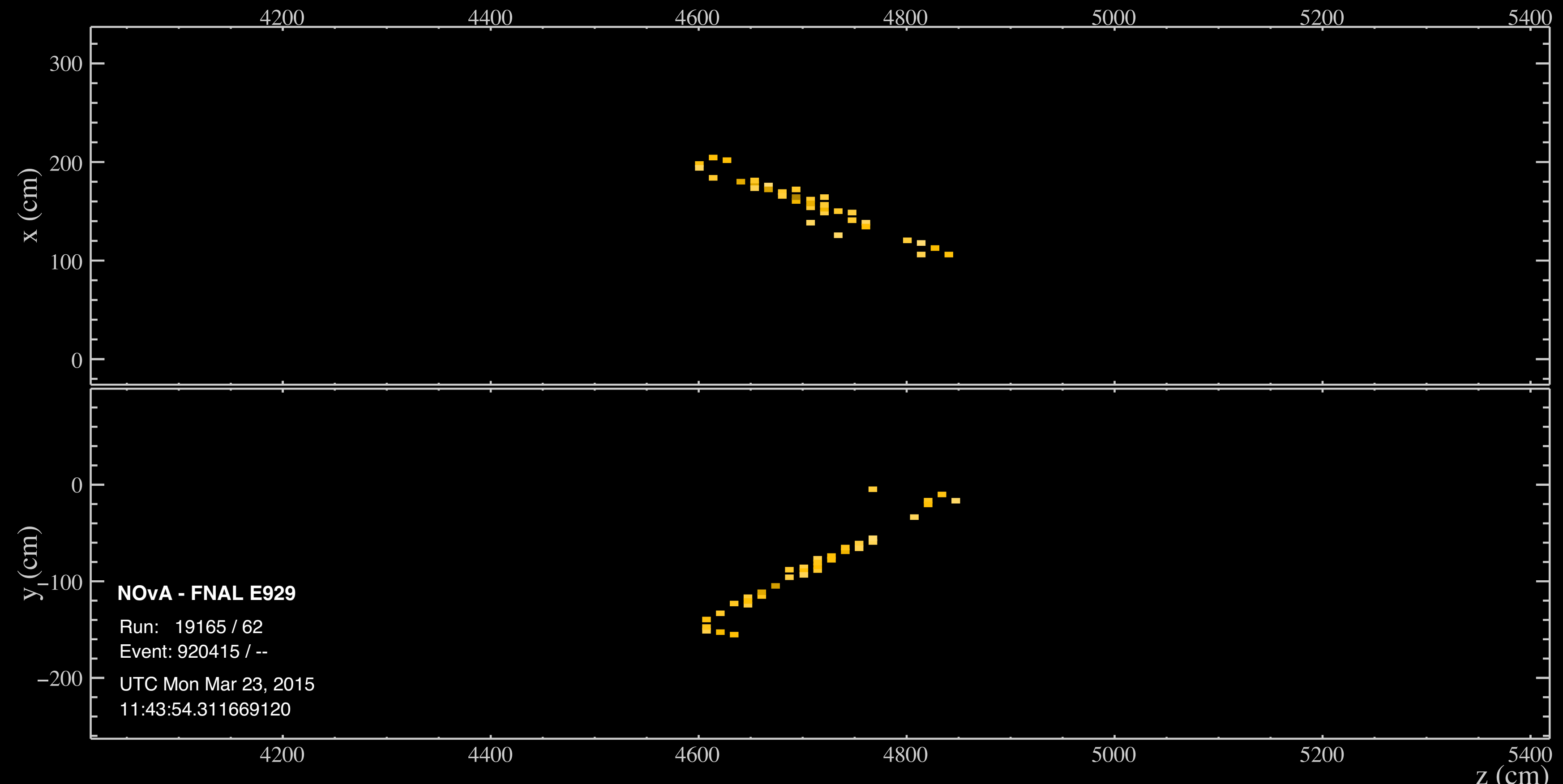


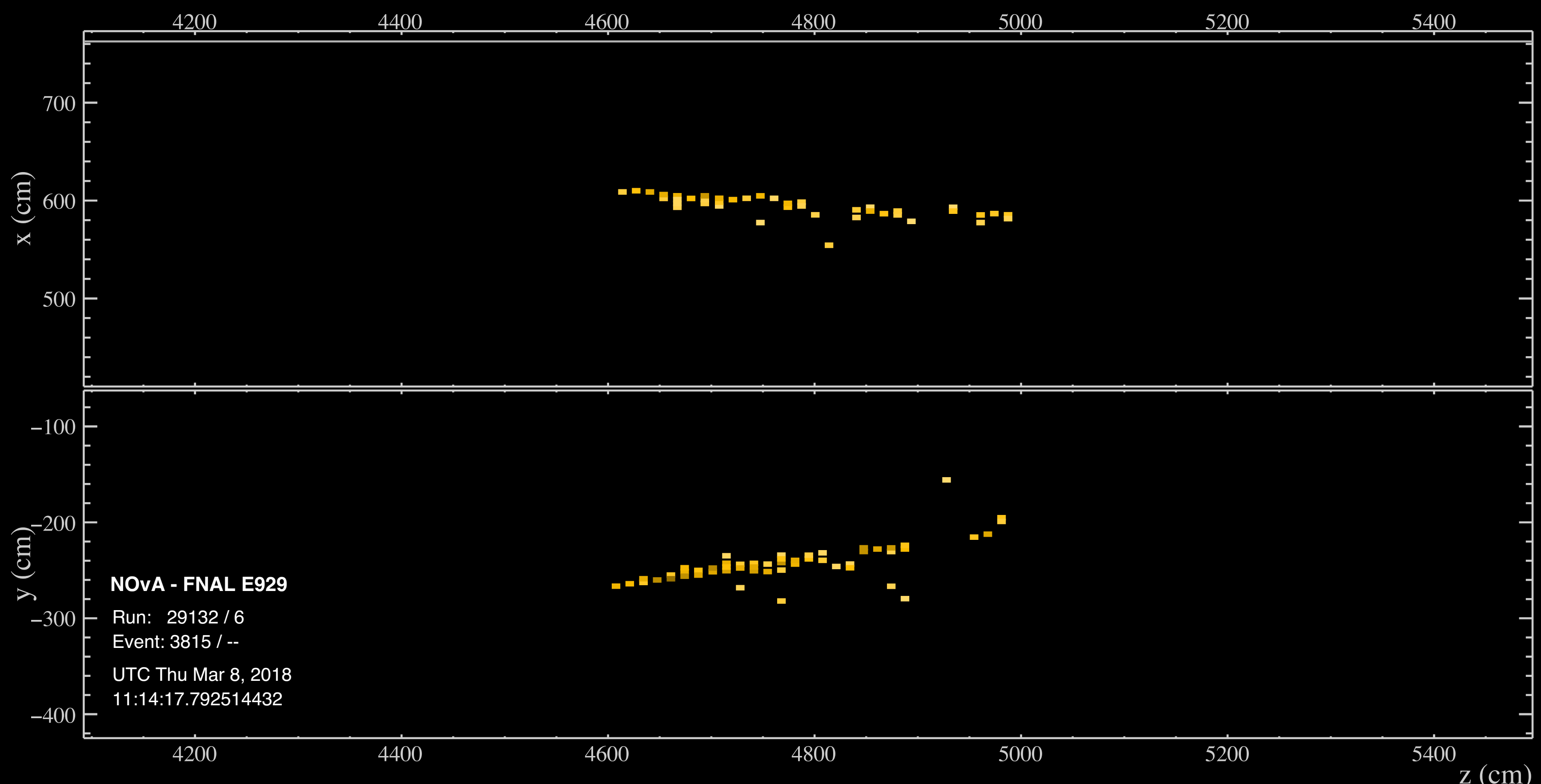


- An example for resulting prediction of candidates at far detector after constraining backgrounds with near detector and extrapolating oscillation signal prediction at a set of oscillation parameters
- Overall expectation varies based on oscillation parameters by changing the appearance signal and oscillated wrong-sign background
- Measured best-fit oscillation parameters will be the ones which give best agreement of overall expectation and the data (for *both* the $\overset{(-)}{\nu}_e$ appearance and $\overset{(-)}{\nu}_\mu$ disappearance)

Opening the box

Far detector candidate, neutrino beam

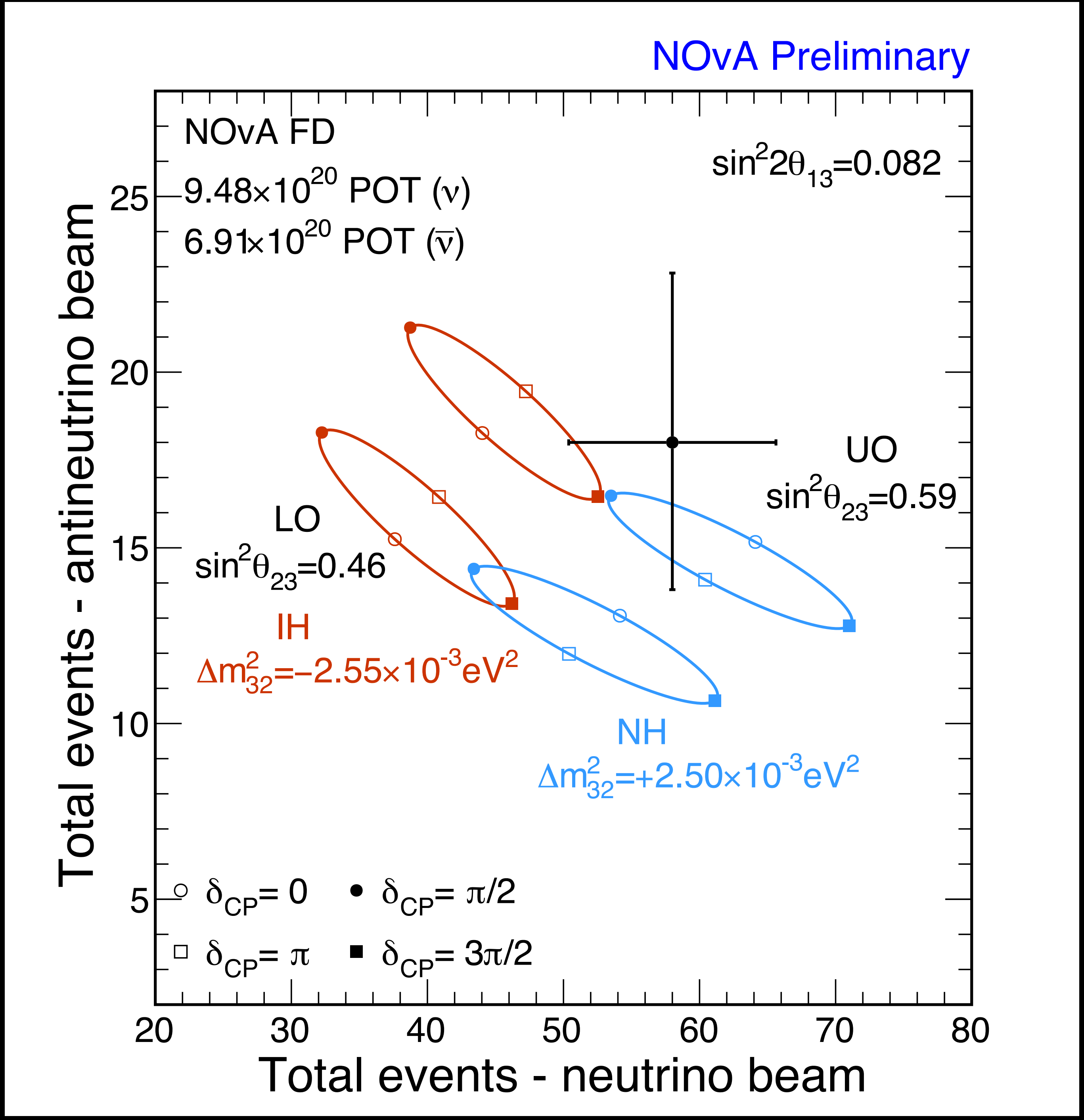




Far detector candidate, antineutrino beam

ν_e, $\bar{\nu}_e$ Results

- In neutrino beam, select
  58 ν_e candidates
  - Background prediction: 15.1 events
  - ~12 from beam (< 1 wrong-sign oscillated) and ~3 cosmic origin
- In antineutrino beam, select
  18 $\bar{\nu}_e$ candidates
  - Background prediction: 5.3 events
  - Mostly of beam origin (~1 wrong-sign oscillated), <1 cosmic
- **>4σ evidence for $\bar{\nu}_e$ appearance!**



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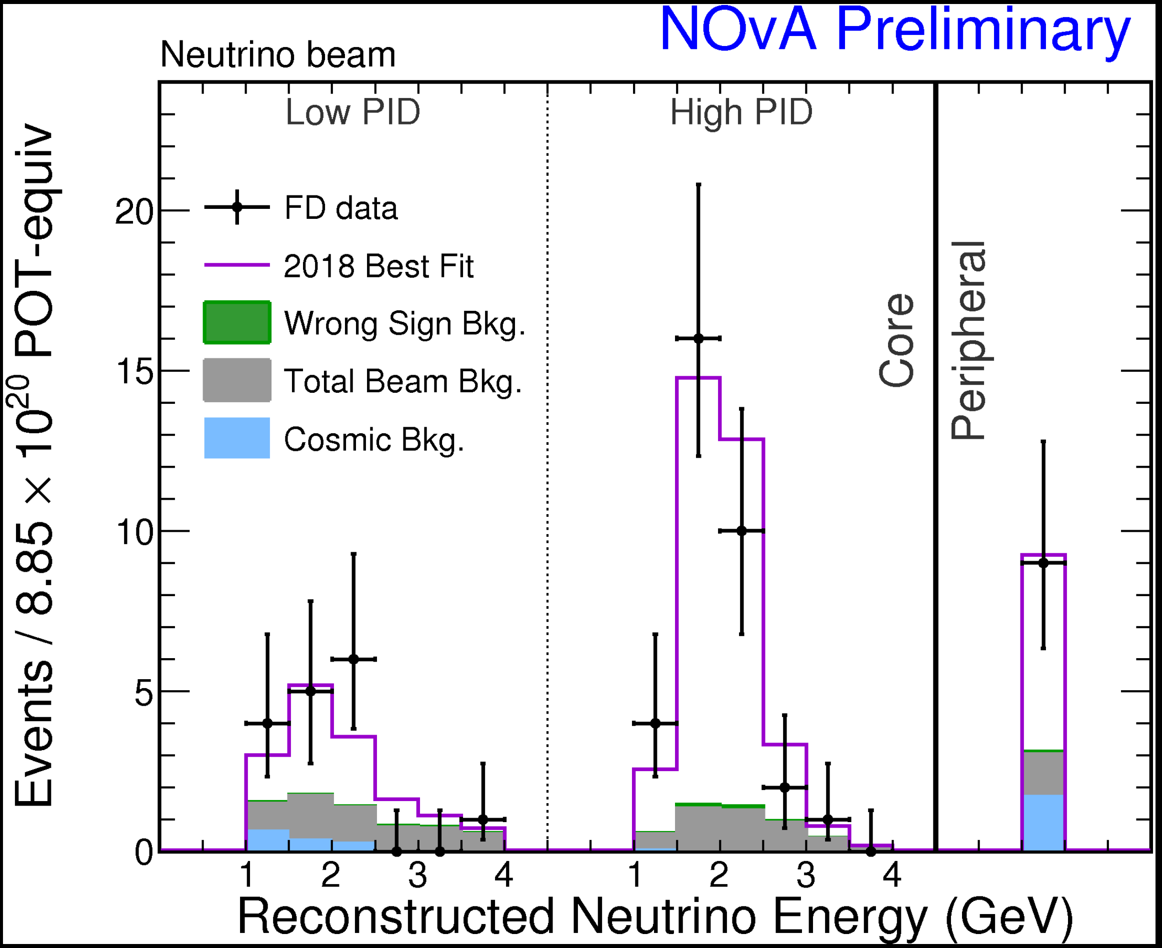
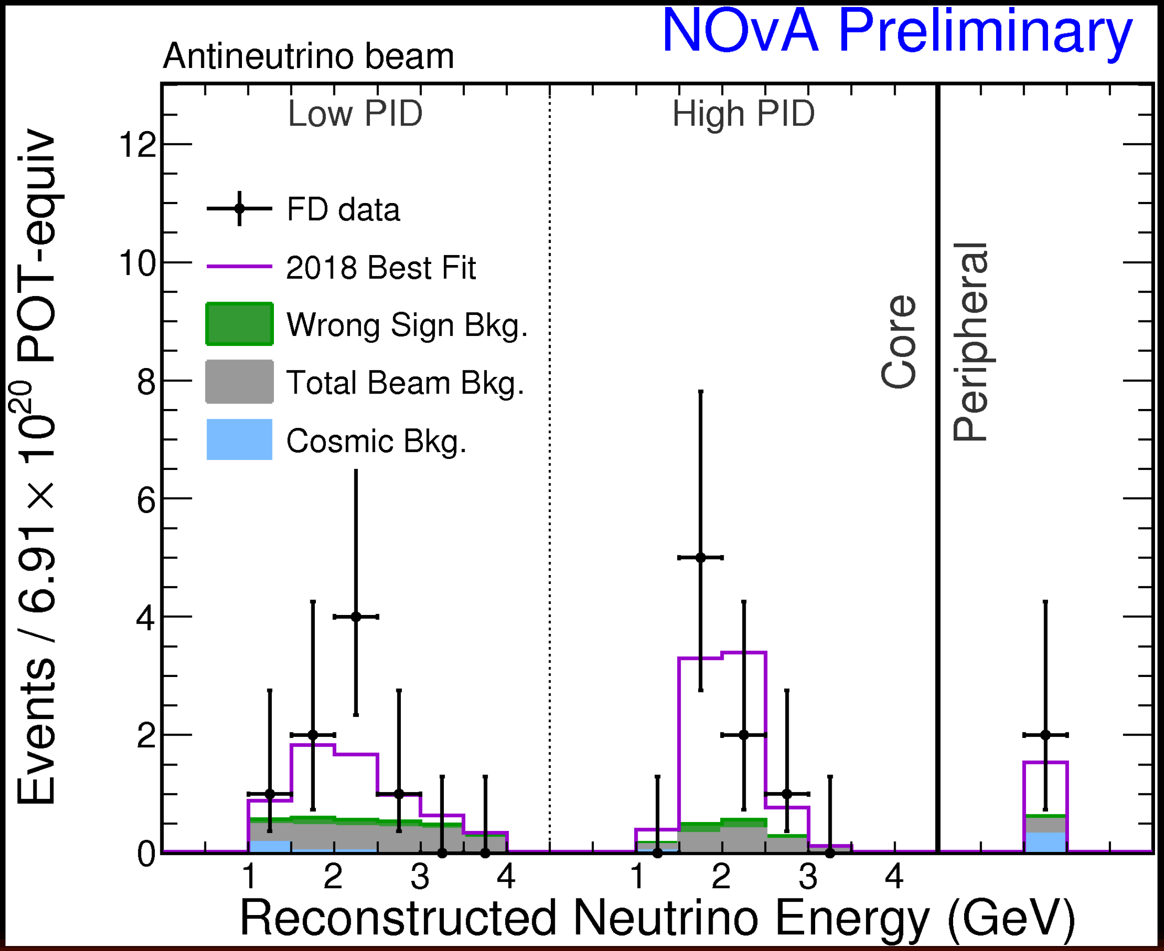
  - Background prediction: 5.3 events
  - Mostly of beam origin (~1 wrong-sign oscillated), <1 cosmic
- **>4σ evidence for $\bar{\nu}_e$ appearance!**

Best fit prediction is for 59.0 ν_e candidates and 15.9 $\bar{\nu}_e$ candidates

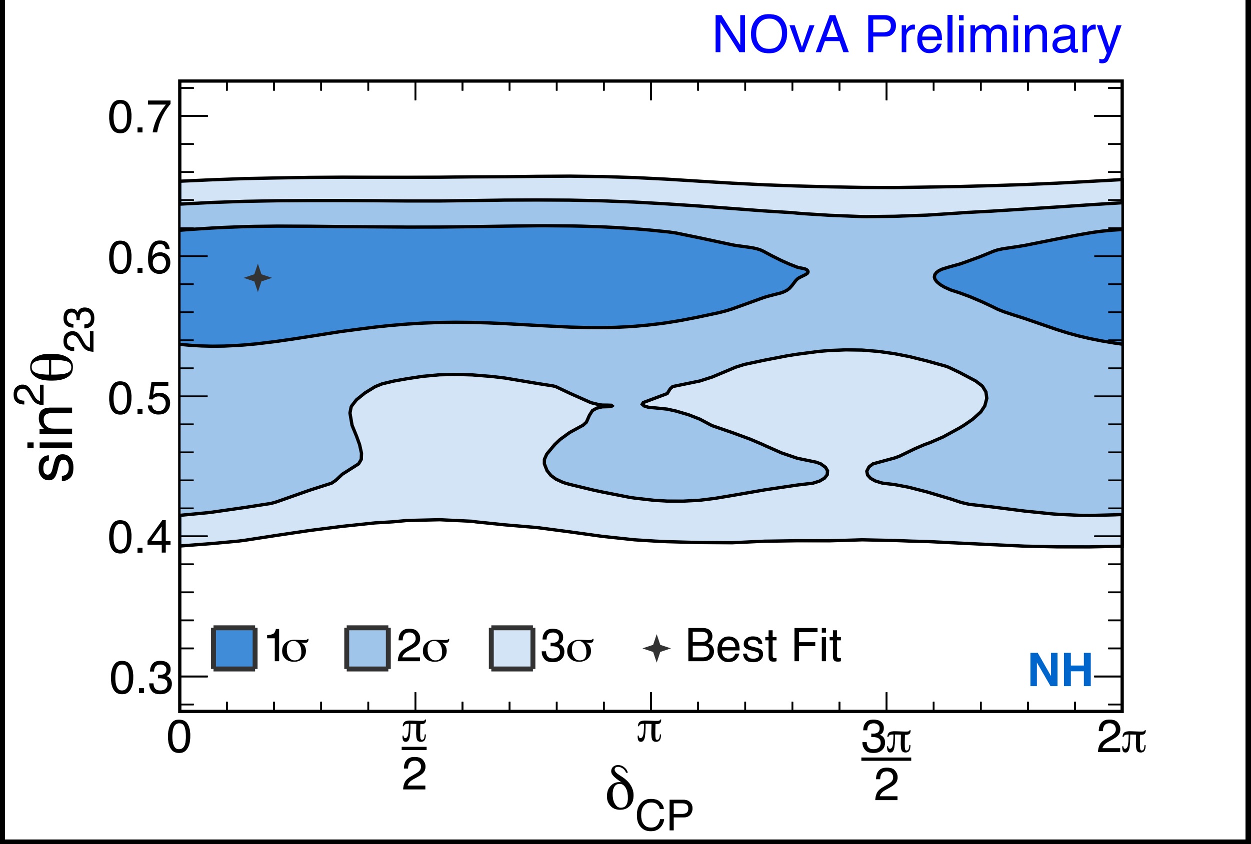


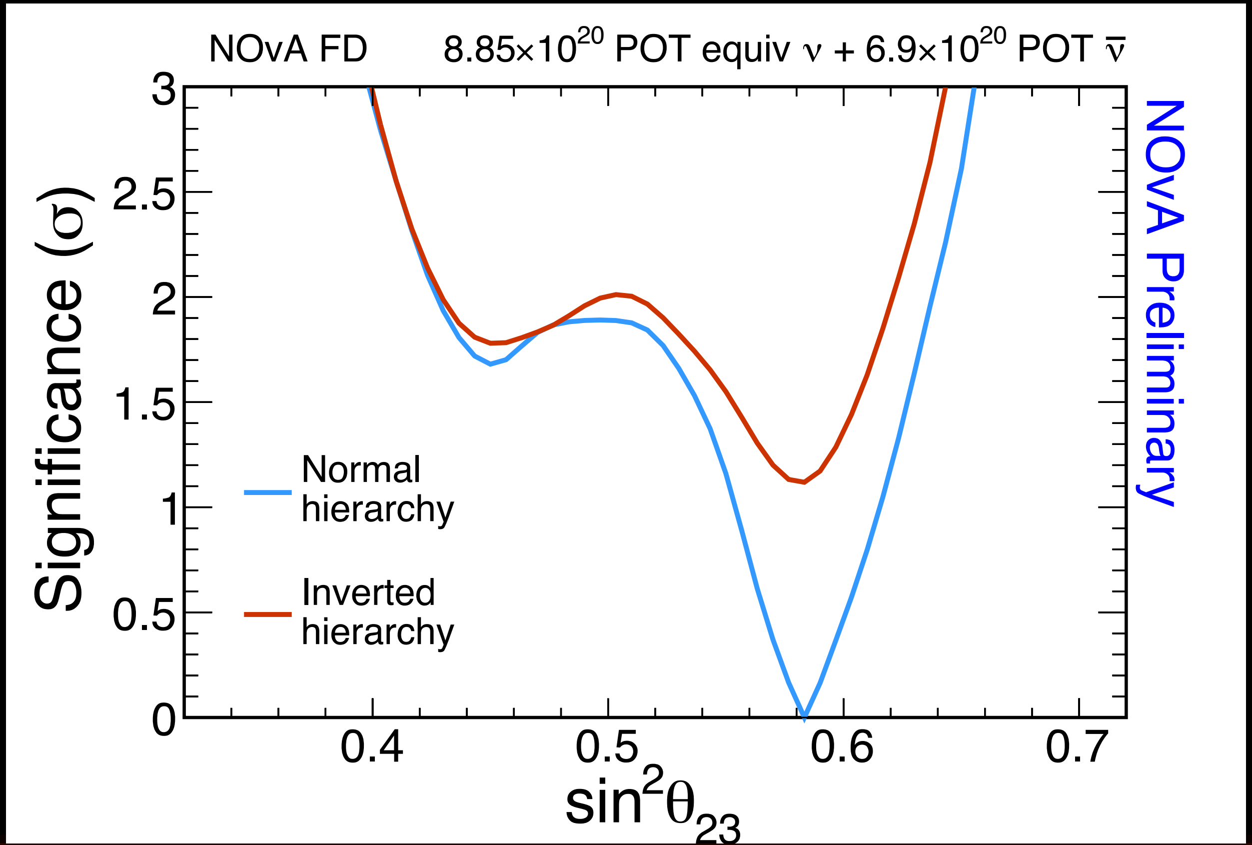


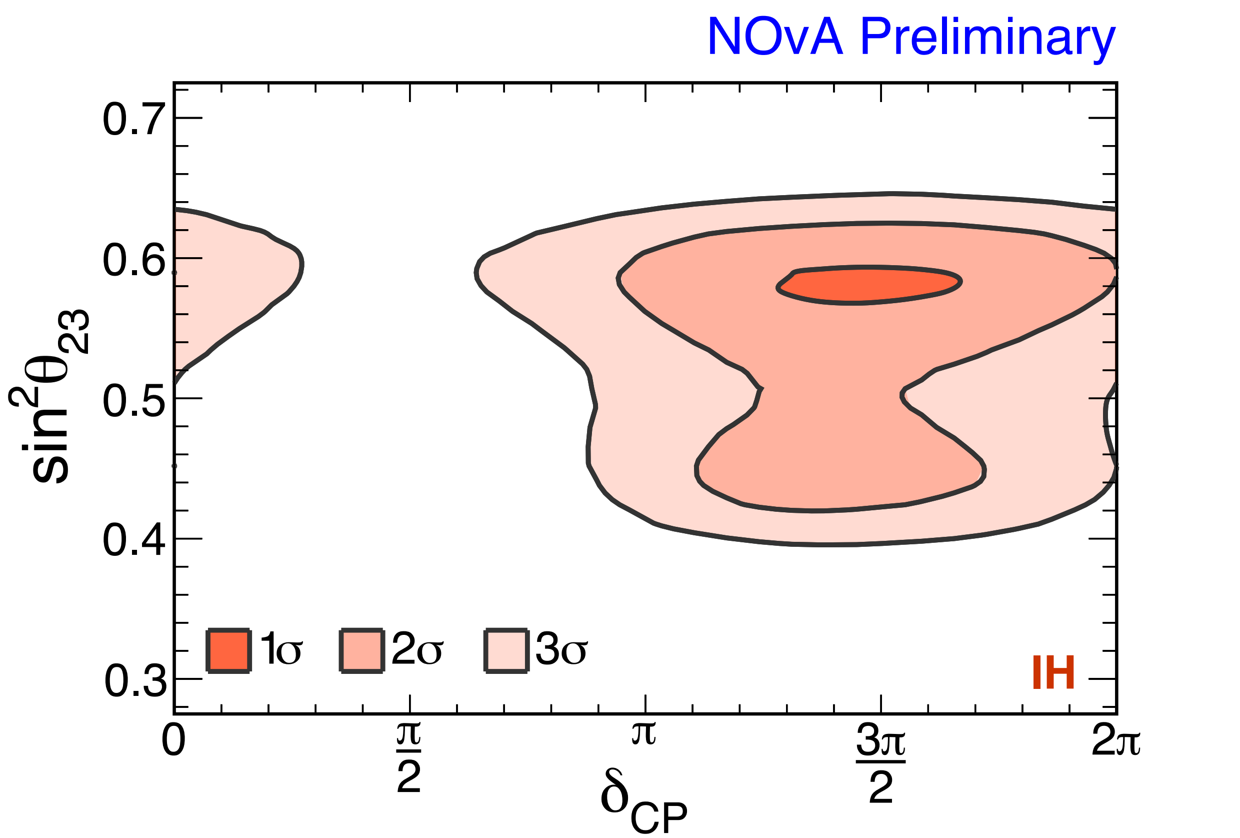
Joint $\overset{(-)}{\nu}_\mu,\overset{(-)}{\nu}_e$ Results

- Joint analysis best fit prefers:

  Normal hierarchy $\quad \sin^2\theta_{23} = 0.58\pm0.03$
  $\delta_{CP} = 0.17\pi \quad \Delta m^2_{32} = (2.51^{+0.12}_{-0.08})\times10^{-3}\ eV^2$
  Normal hierarchy preferred at 1.8σ
  Exclude $\delta_{CP} = \pi/2$ in IH at > 3σ
  Non-maximal mixing preferred at 1.8σ
  Upper octant preference at similar level
- Full joint analysis requires statistical corrections via pseudo-experiment (Feldman-Cousins procedure)
  - The story and importance of this procedure is the subject of next talk (D. Doyle)







Summary

- Updated analysis now incorporates antineutrino beam for the first time (nearly 7×10^{20} protons on target)
    - Includes previous data set of nearly 9×10^{20} (full-detector equivalent) protons on target with neutrino beam
- First strong evidence (>4σ) for long-baseline $\bar{\nu}_e$ appearance in antineutrino beam!
    - Achieved this in first $\bar{\nu}$ analysis due to excellent beam performance
- Joint $\overset{(-)}{\nu}_\mu$ disappearance and $\overset{(-)}{\nu}_e$ appearance analysis has slight preference towards normal mass hierarchy and non-maximal θ_{23} [upper octant]
- Further data and analysis upgrades are expected to provide further sensitivity to key oscillation parameters in the coming years

http://novaexperiment.fnal.gov

Backup

Neutrino Oscillation

H. Nunokawa, S. Parke, J. W. F. Valle. “CP Violation and neutrino oscillations.” *Prog.Part.Nucl.Phys., 60 (2008) 338-402*

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2\Theta_{23} \sin^2 2\Theta_{13} \frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2} \Delta_{31}^2$$

$$+ \sin 2\Theta_{23} \sin 2\Theta_{13} \sin 2\Theta_{12} \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \Delta_{31} \frac{\sin(aL)}{(aL)} \Delta_{21} \cos(\Delta_{31} + \delta)$$

$$+ \cos^2\Theta_{23} \sin^2 2\Theta_{12} \frac{\sin^2(aL)}{(aL)^2} \Delta_{21}^2$$

To first order, where

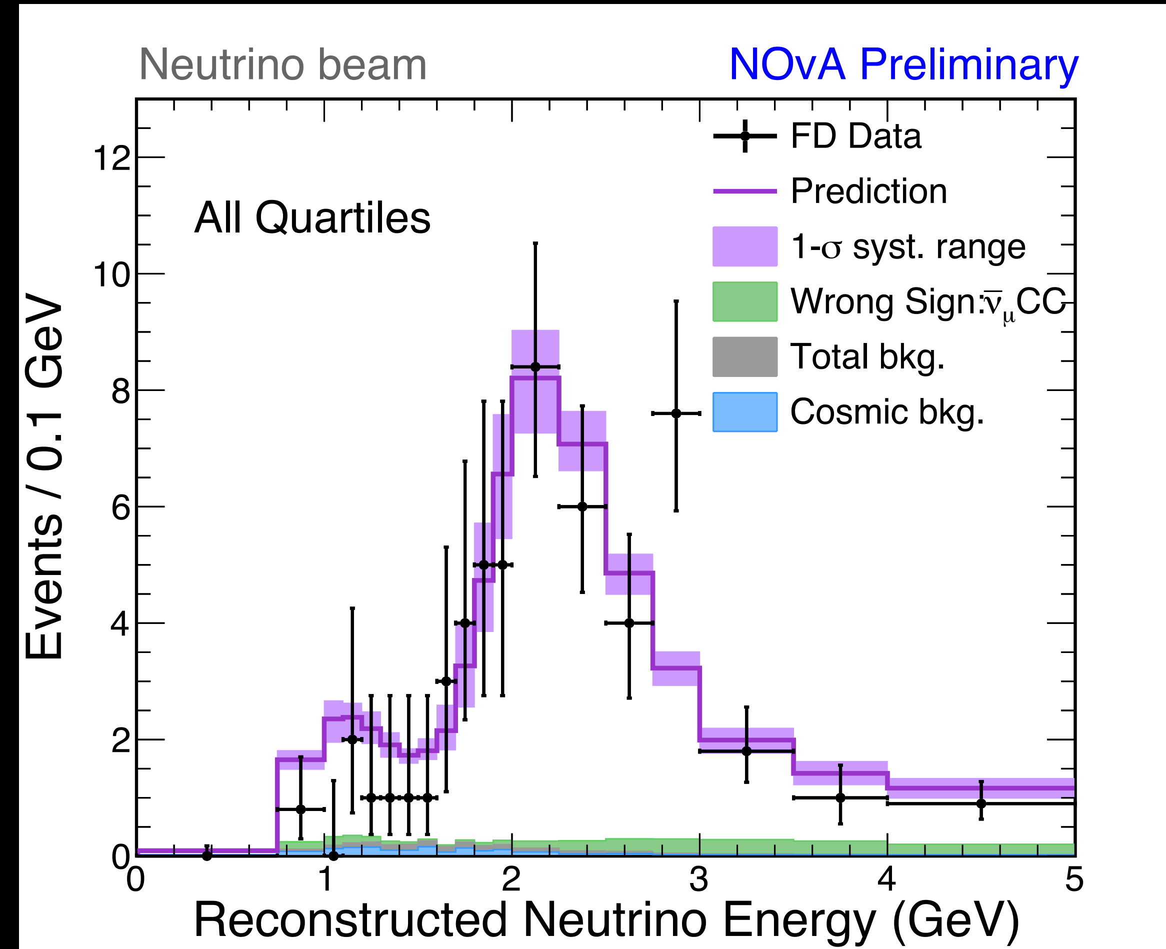
$$\Delta_{ij} = \Delta m_{ij}^2 L / 4E$$

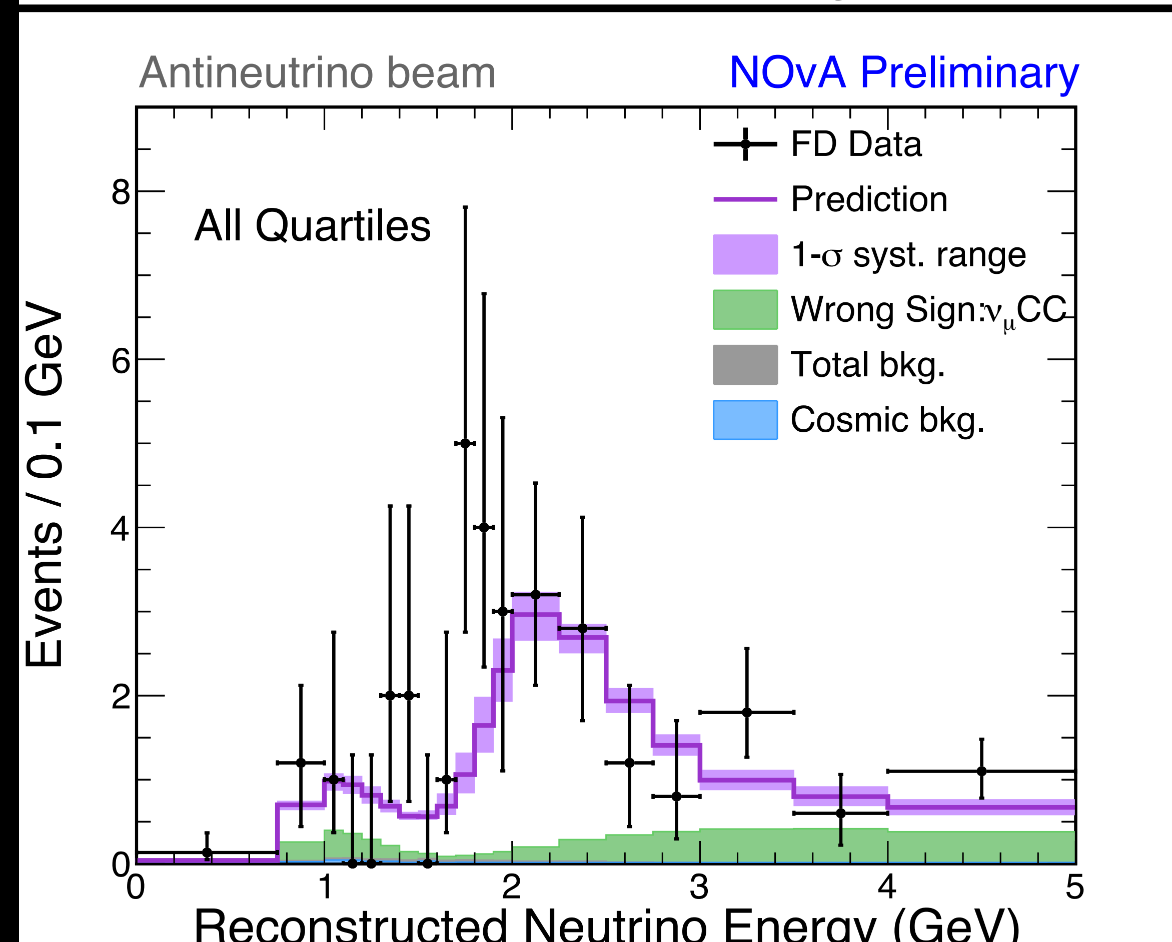
$$a = G_F N_e / \sqrt{2}$$

And in the case of antineutrinos, the sign of the CP violating phase (δ) and sign of “a" flip.

Recall $\overset{(-)}{\nu}_\mu$ Result

- Details in D. Torbunov talk
- Select 113 ν_μ candidates in neutrino beam and 65 $\bar{\nu}_\mu$ candidates in antineutrino beam
    - Expecting 730^{+38}_{-49} ν_μ candidates in neutrino beam and 266^{+12}_{-14} $\bar{\nu}_\mu$ candidates in antineutrino beam, in case of no oscillations
    - Cosmic background prediction ~2 events in neutrino beam and <1 event in antineutrino beam
- The results of the ν_μ and $\bar{\nu}_\mu$ disappearance and the ν_e and $\bar{\nu}_e$ appearance are then studied in a joint analysis and result in a joint oscillation fit in 3 neutrino paradigm





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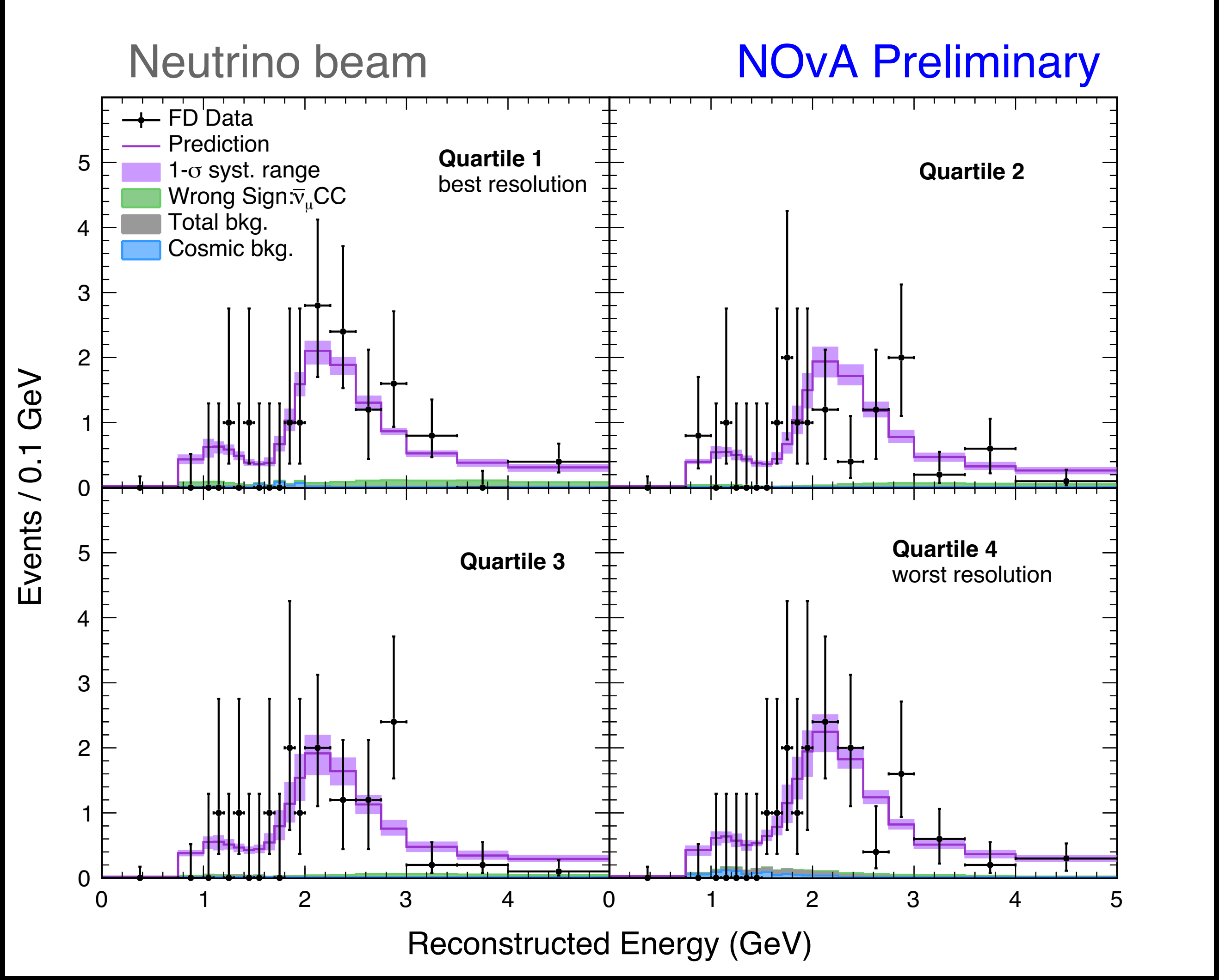
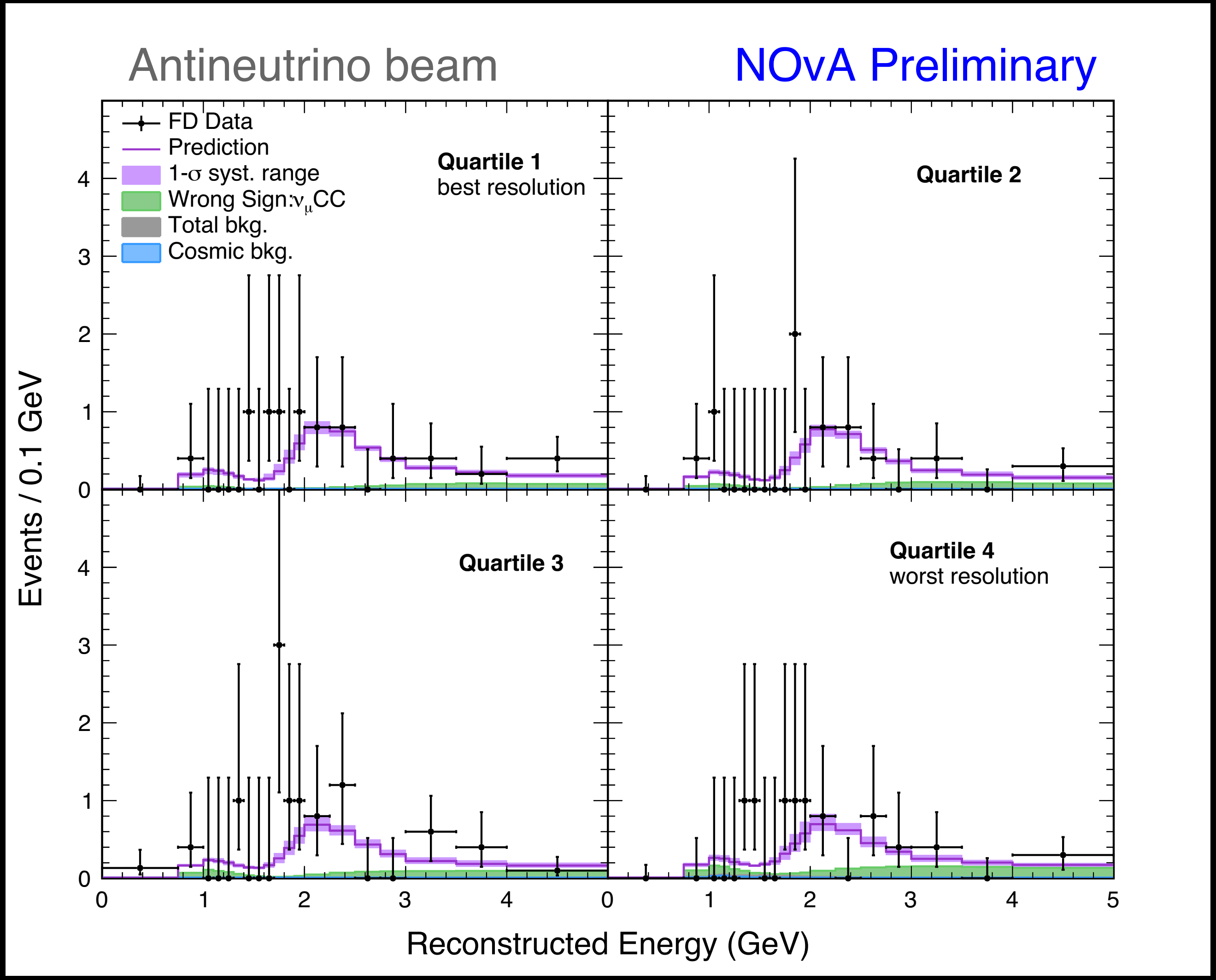
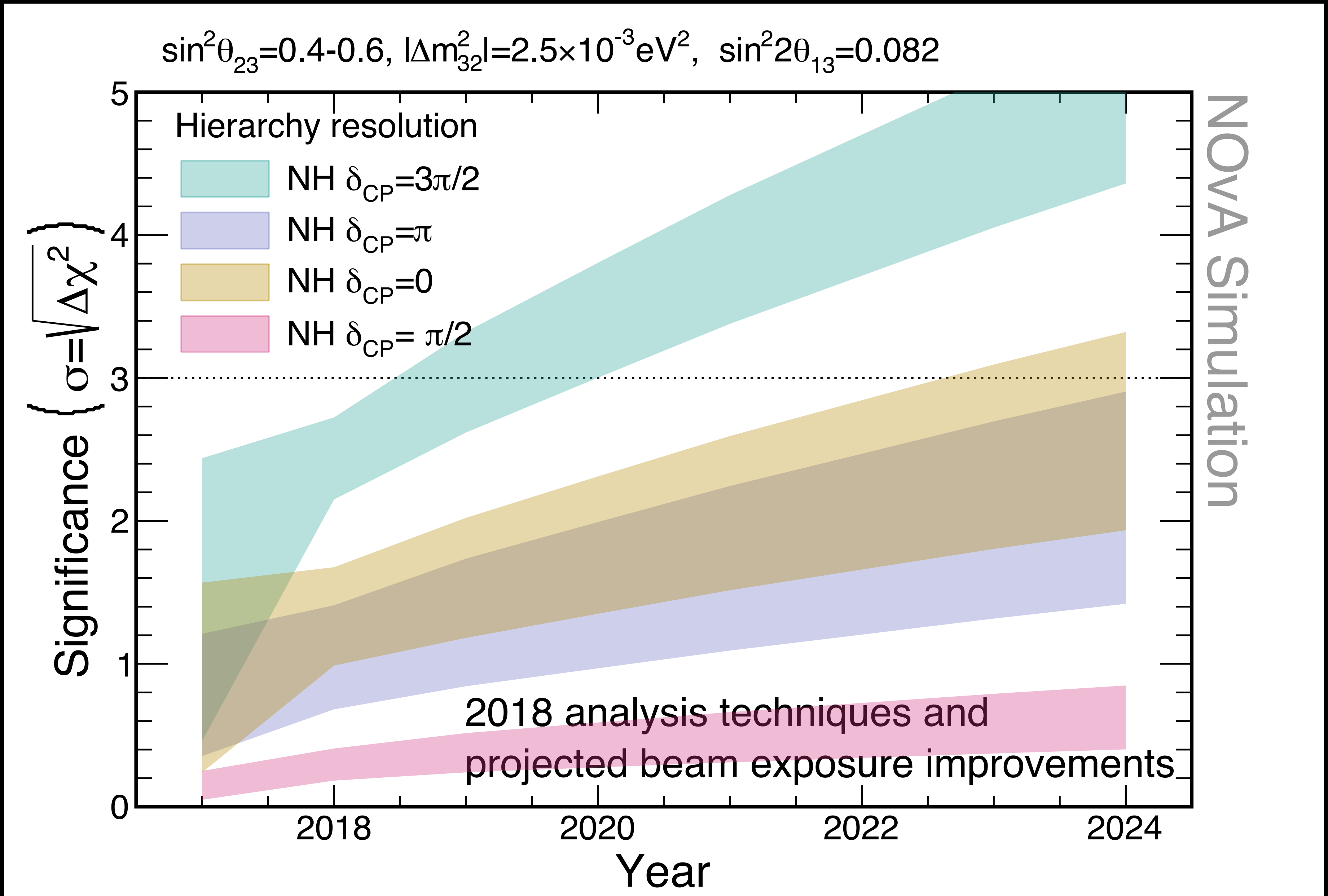




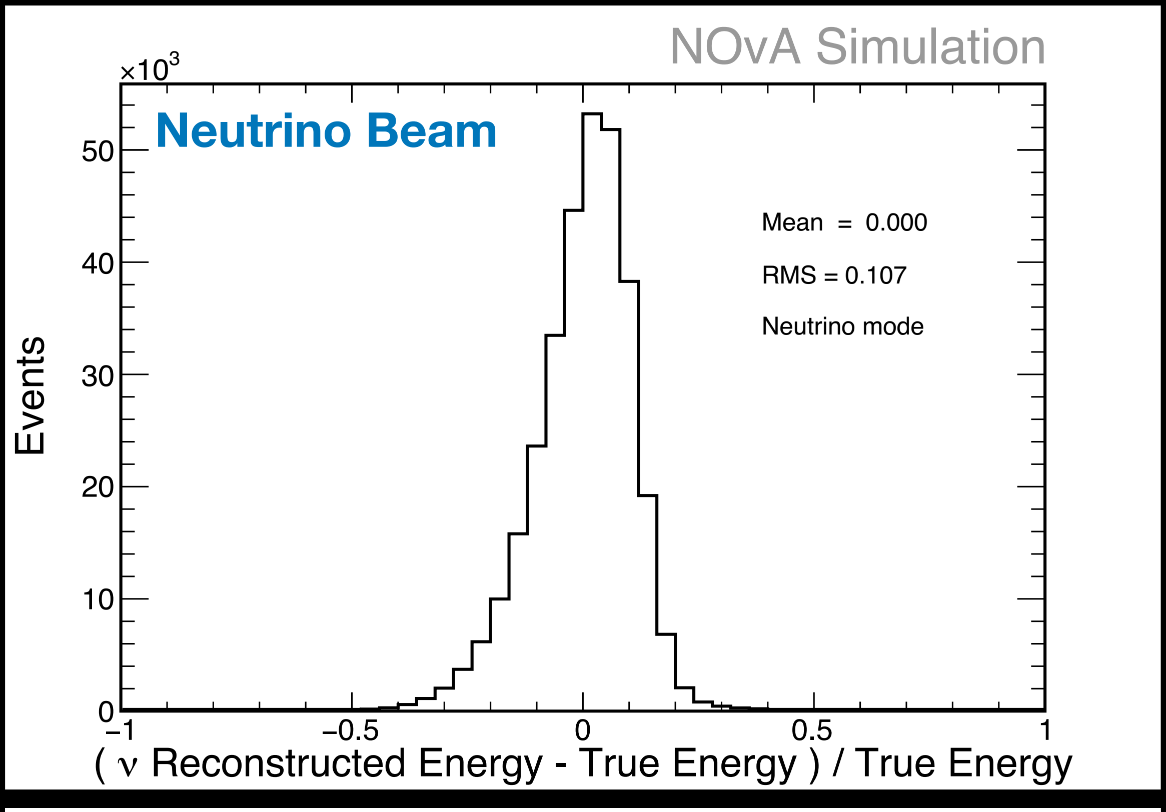
Future sensitivity

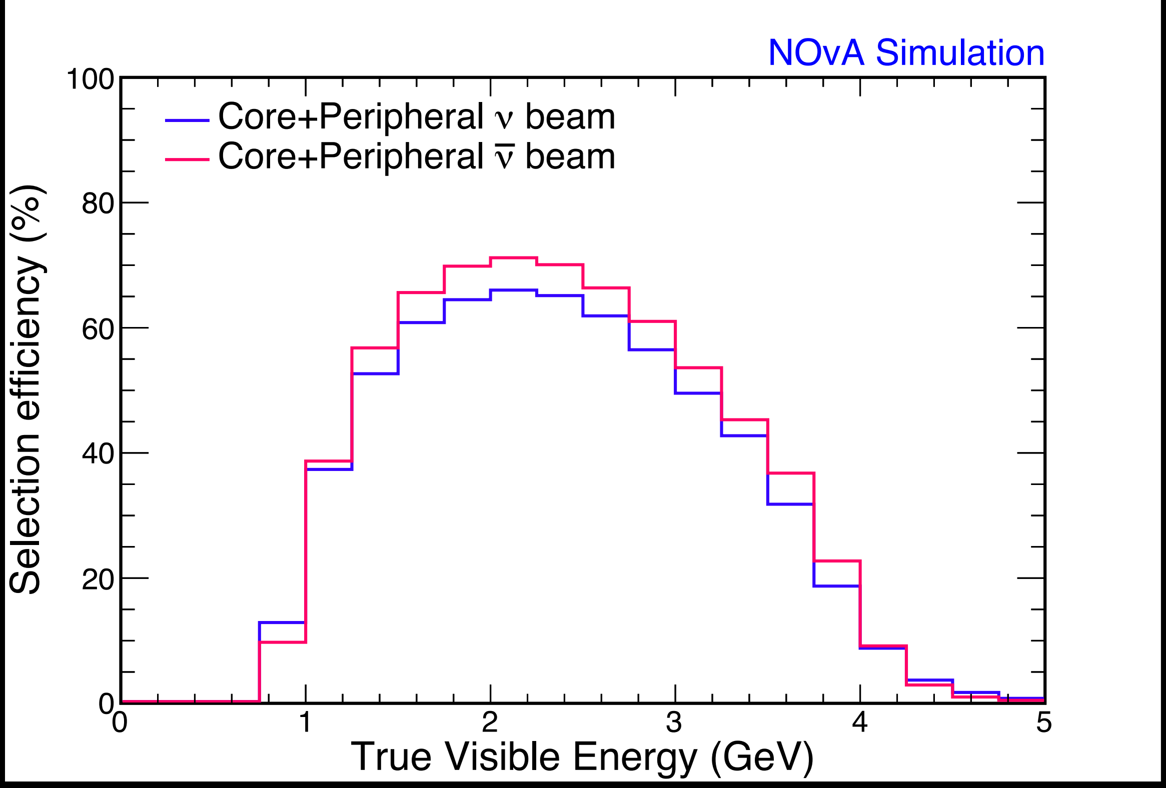


Mass hierarchy sensitivity 3σ by 2020 for most favorable parameters. Can reach 3σ by 2024 for wider range of parameters.

Event selection for $\nu_e+\bar{\nu}_e$

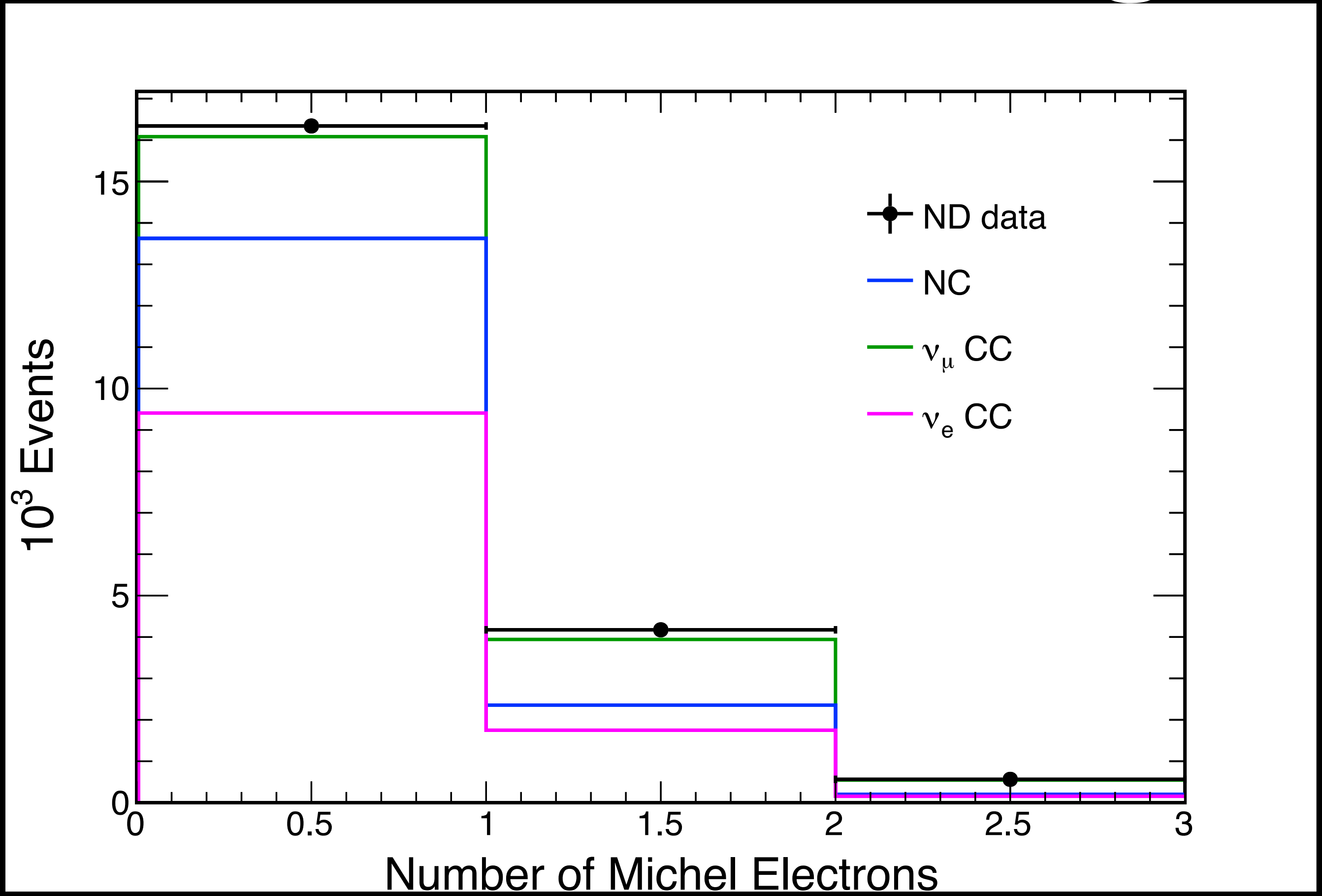
- Details of reconstruction detailed in talk by M. Groh
- NOvA uses CVN (Convolutional Visual Network) to perform event classification based on final state topologies
- Select events w/ ν_e ($\bar{\nu}_e$) classifier score & reconstructed information indicating likely ν_e ($\bar{\nu}_e$) candidate
    - Near detector and far detector selection broken into two subcategories based on CVN electron score.
    - Far detector has further peripheral sample with larger cosmic background but recovers appearance signal
- Energy estimator for $\nu_e,\bar{\nu}_e$ characterizes energy deposits as coming from EM activity (or not) utilizing CVN on specific prongs. Estimator is 2nd-order polynomial in EM energy and non-EM energy
    - 11% E resolution in neutrino beam, 9% antineutrino
    - Energy range of interest 0-4.5 GeV in near detector, 1-4 GeV in far detector (0-4.5 GeV in peripheral)





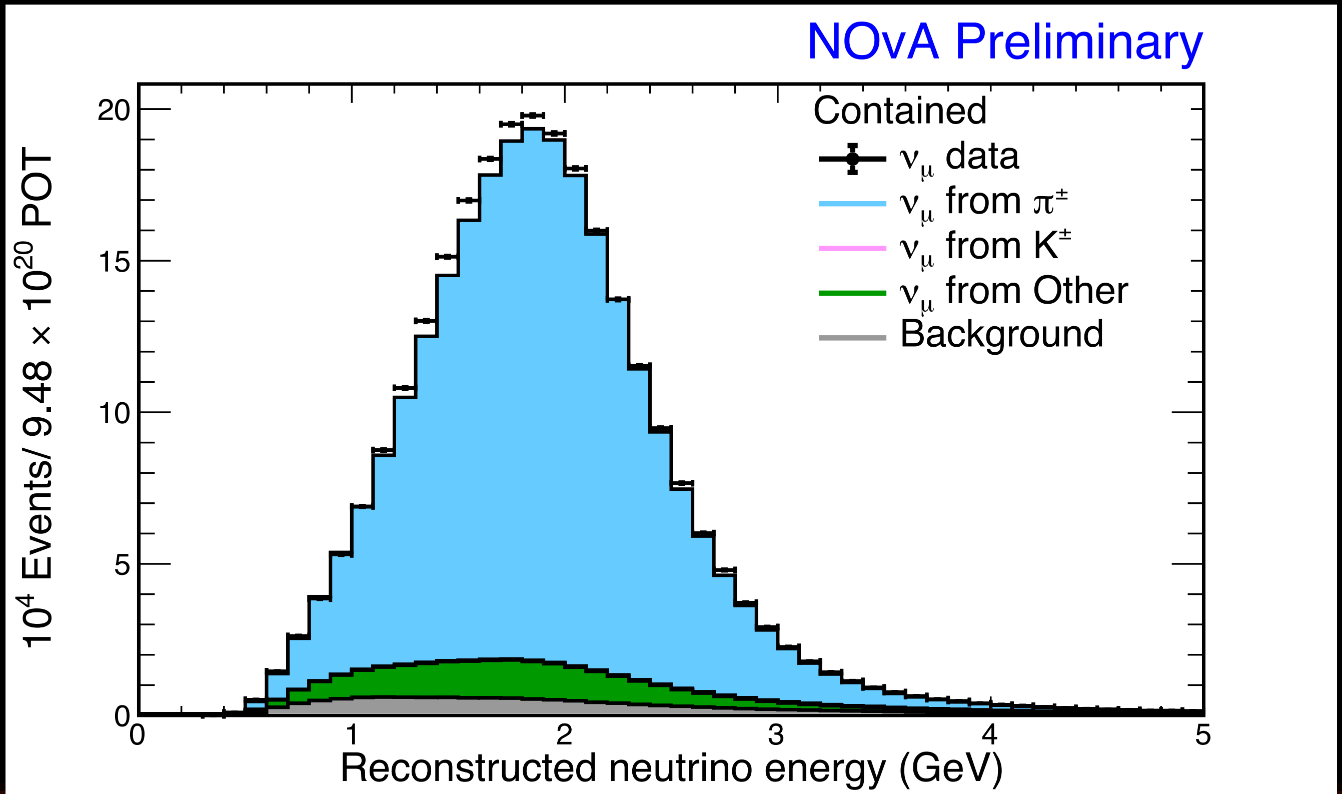
Near detector background

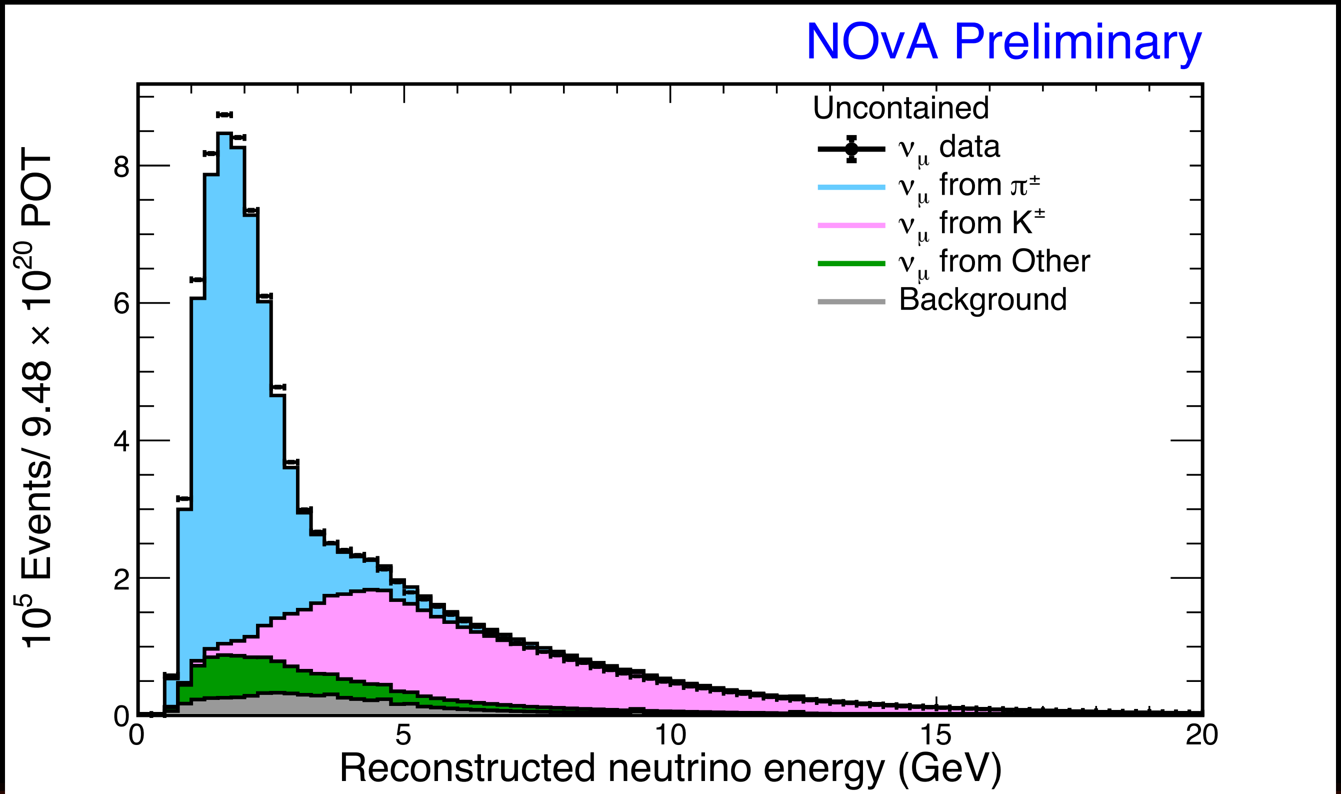
ν_μ constraint



- Muon neutrino spectrum examined to constrain flux by parent hadron, which informs beam ν_e component
- Michel electrons used to constrain ν_μ CC

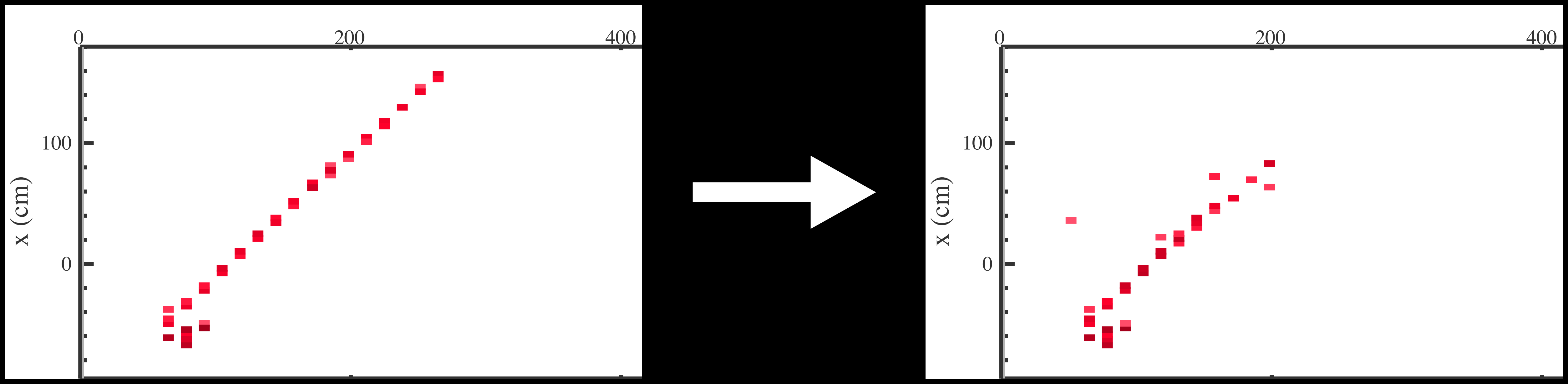
ν_e constraint





Event selection Cross-checks

- Muon-removed electron (MRE) events replace muons in selected near detector ν_μ data candidates with electron showers of same momentum
  - Takes advantage of hadronic components directly from data
  - Electron shower simulation
  - Probes understanding of selection efficiency for ν_e events



Example

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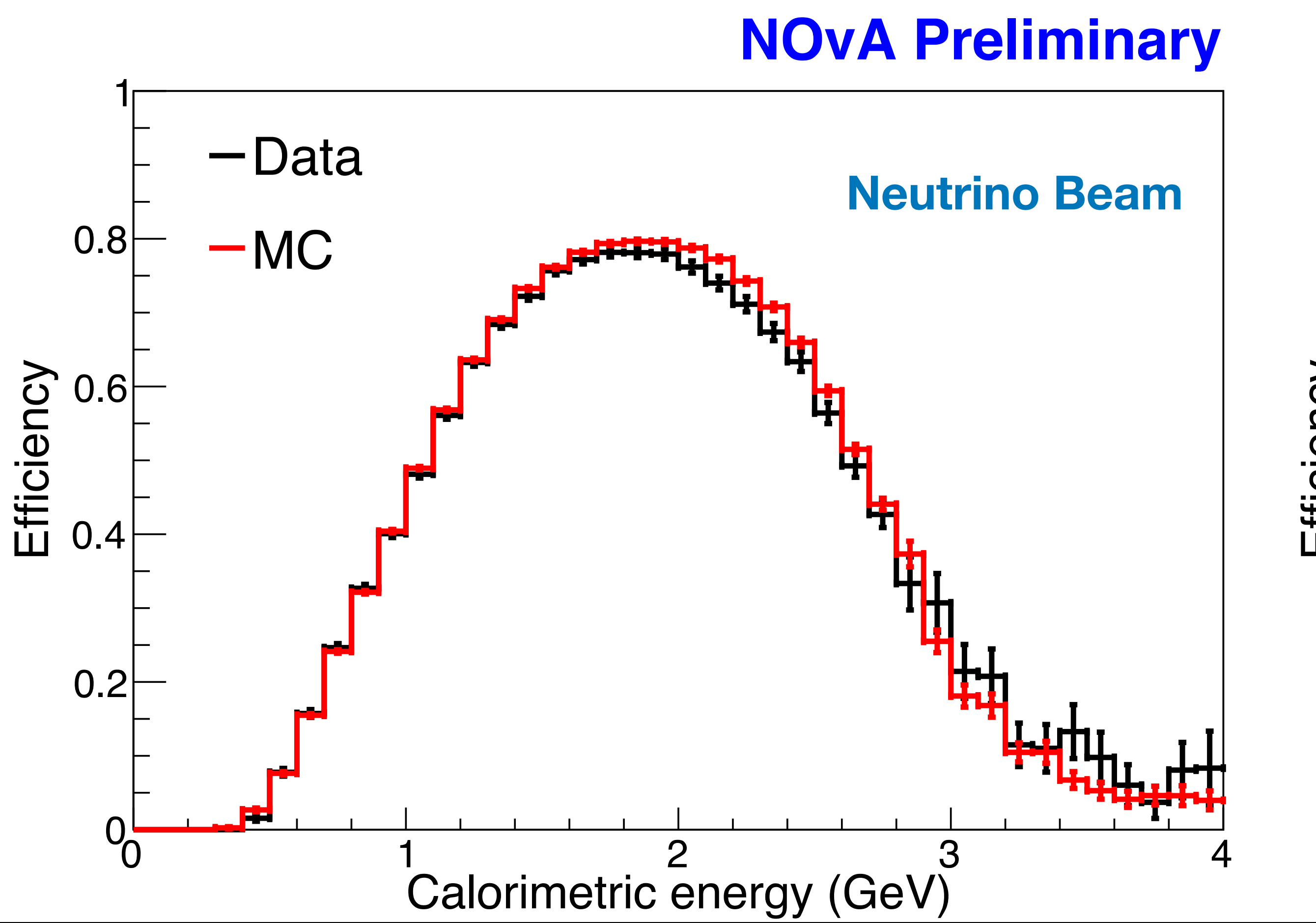

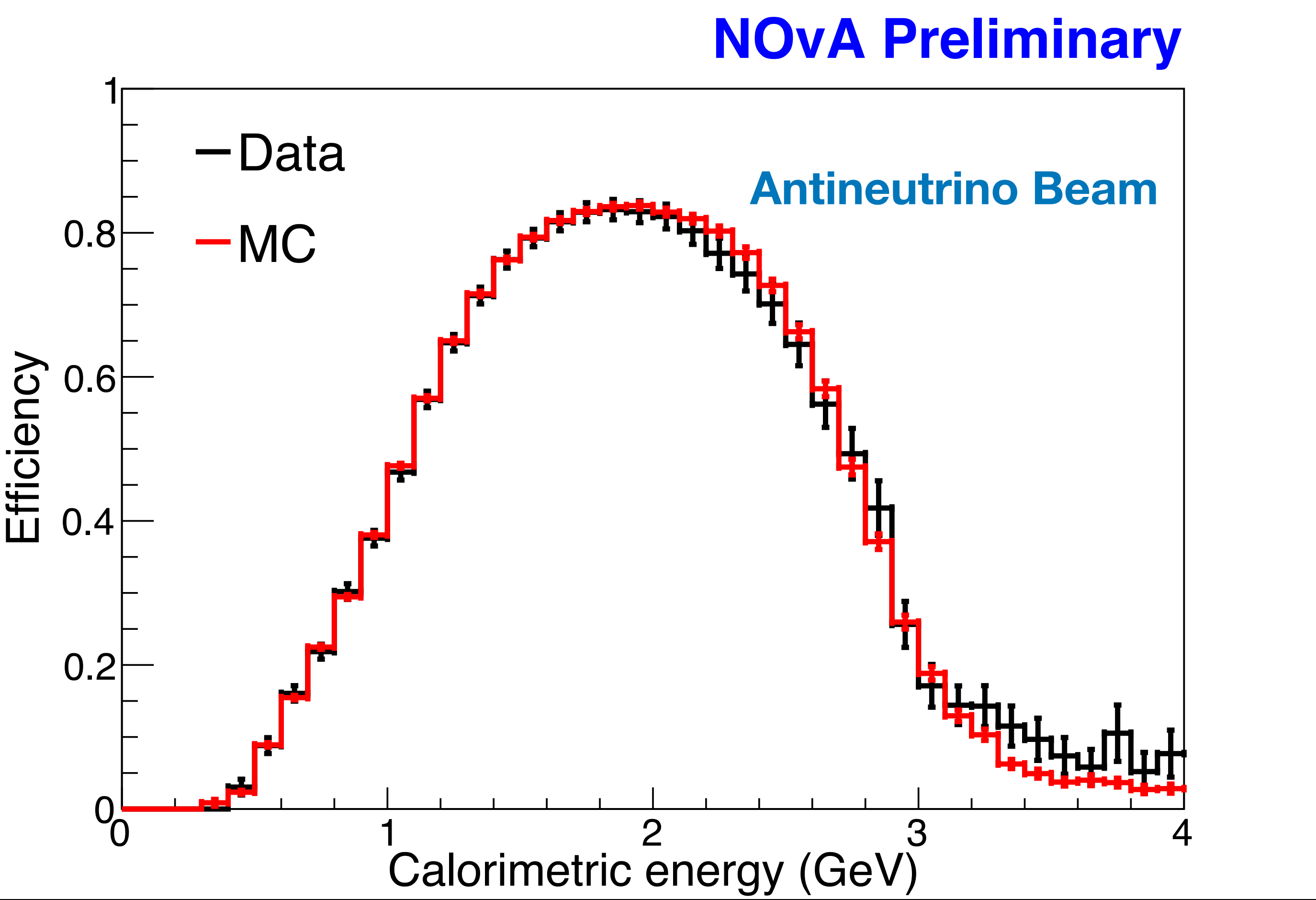

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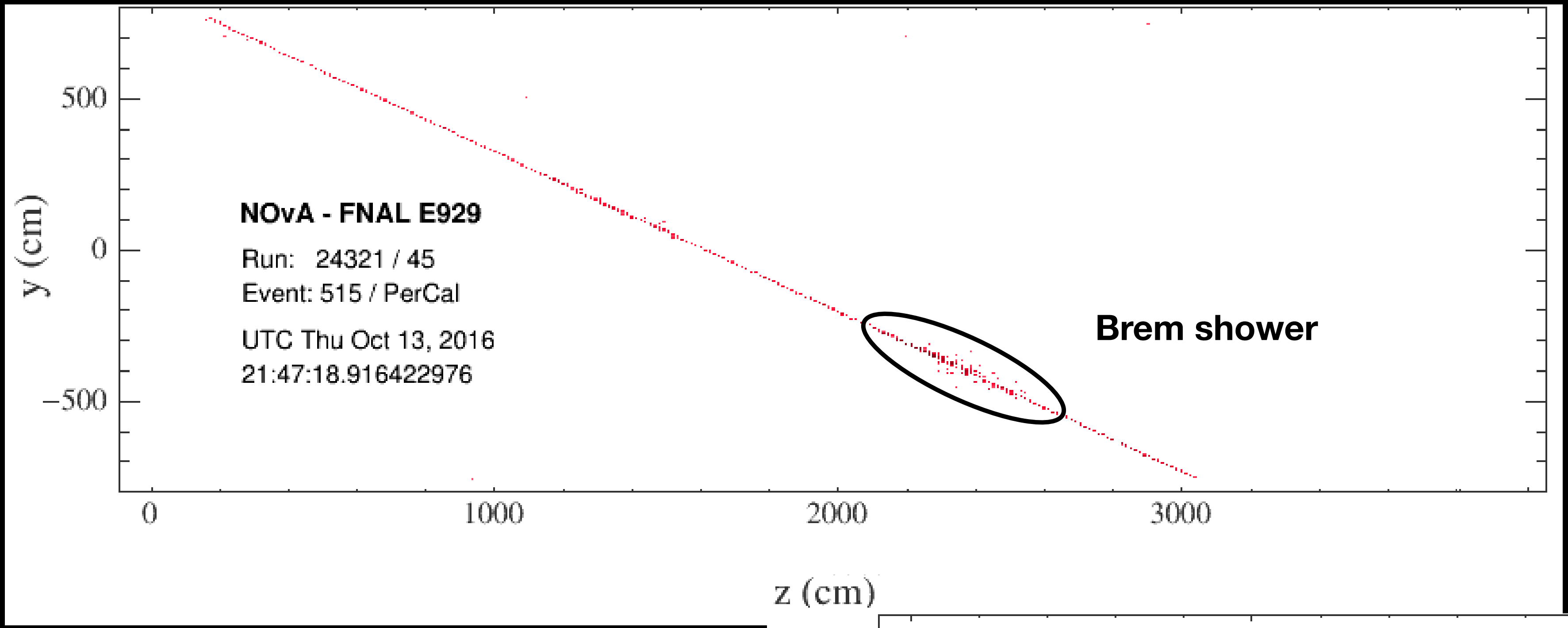

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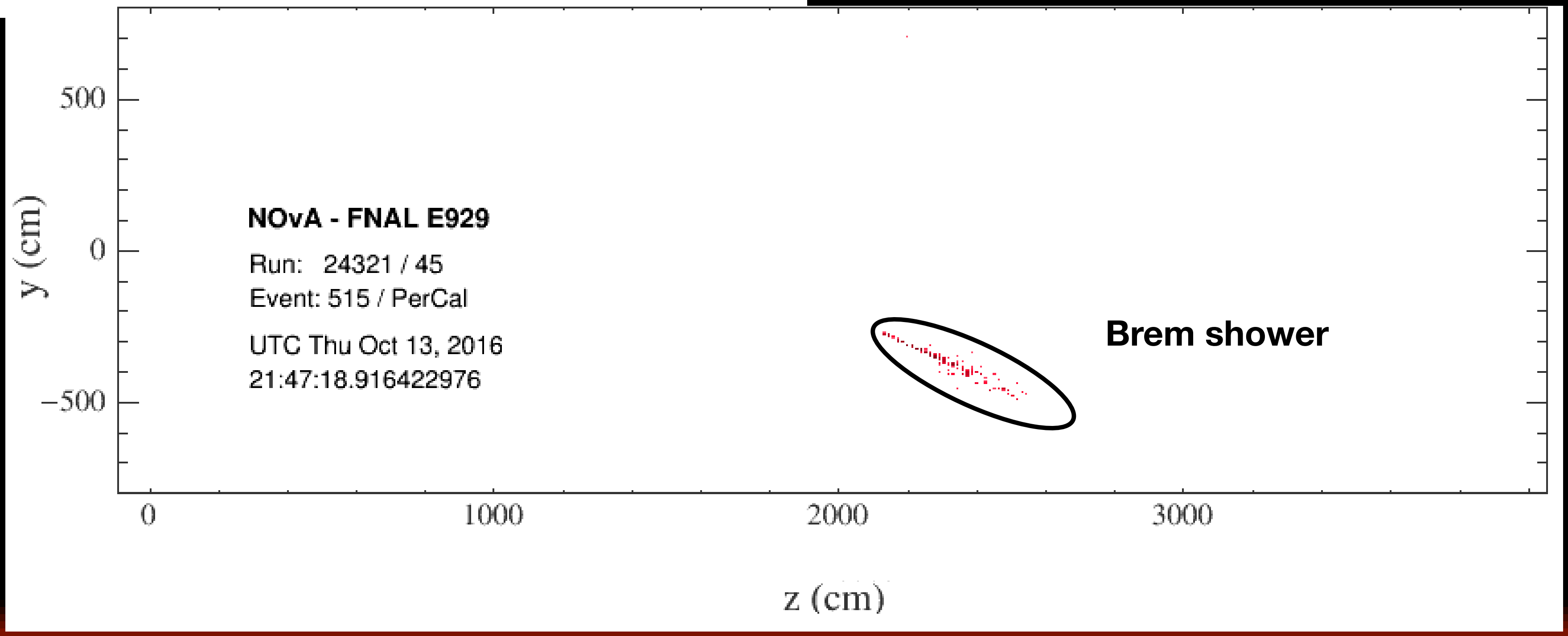

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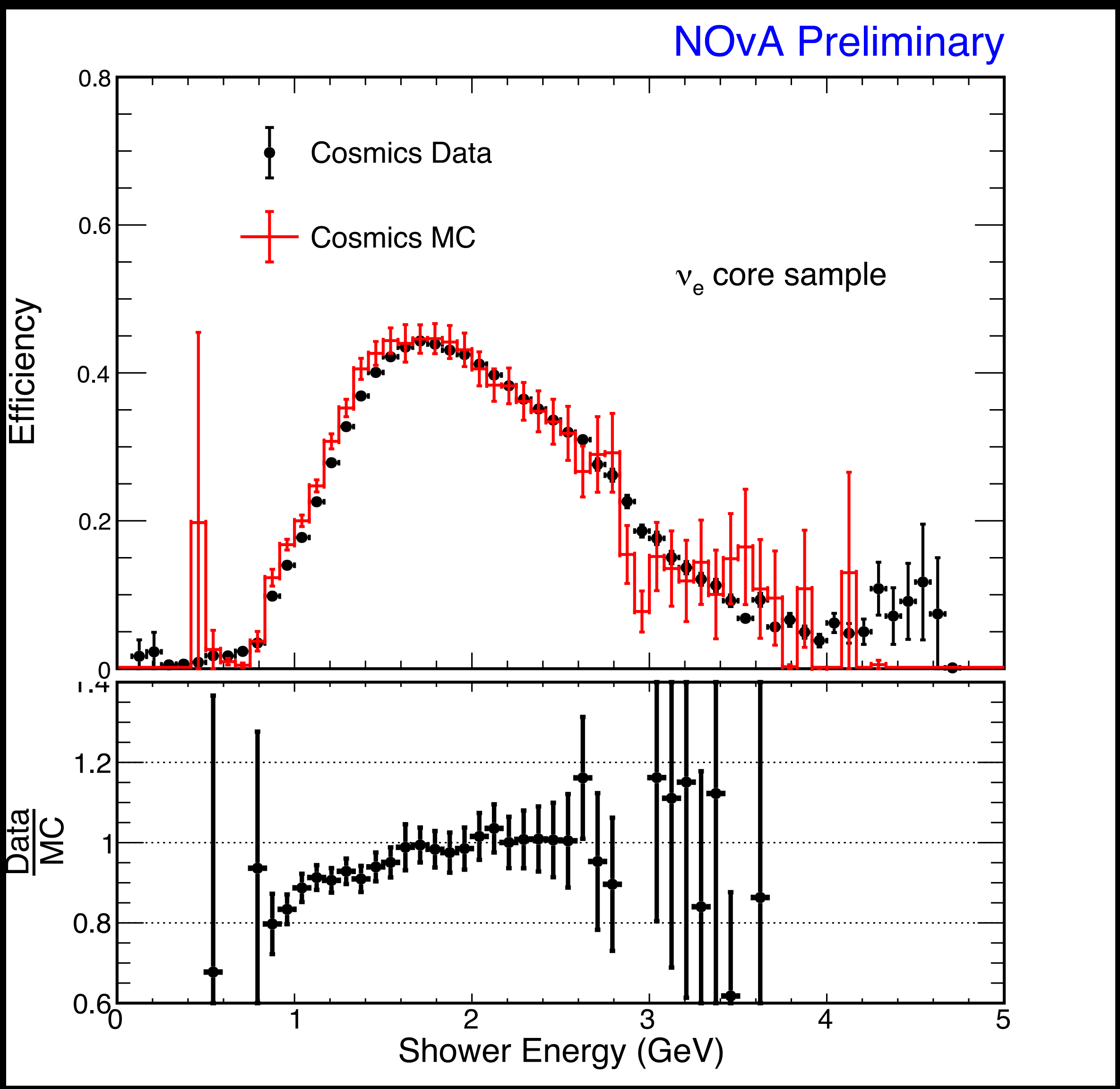
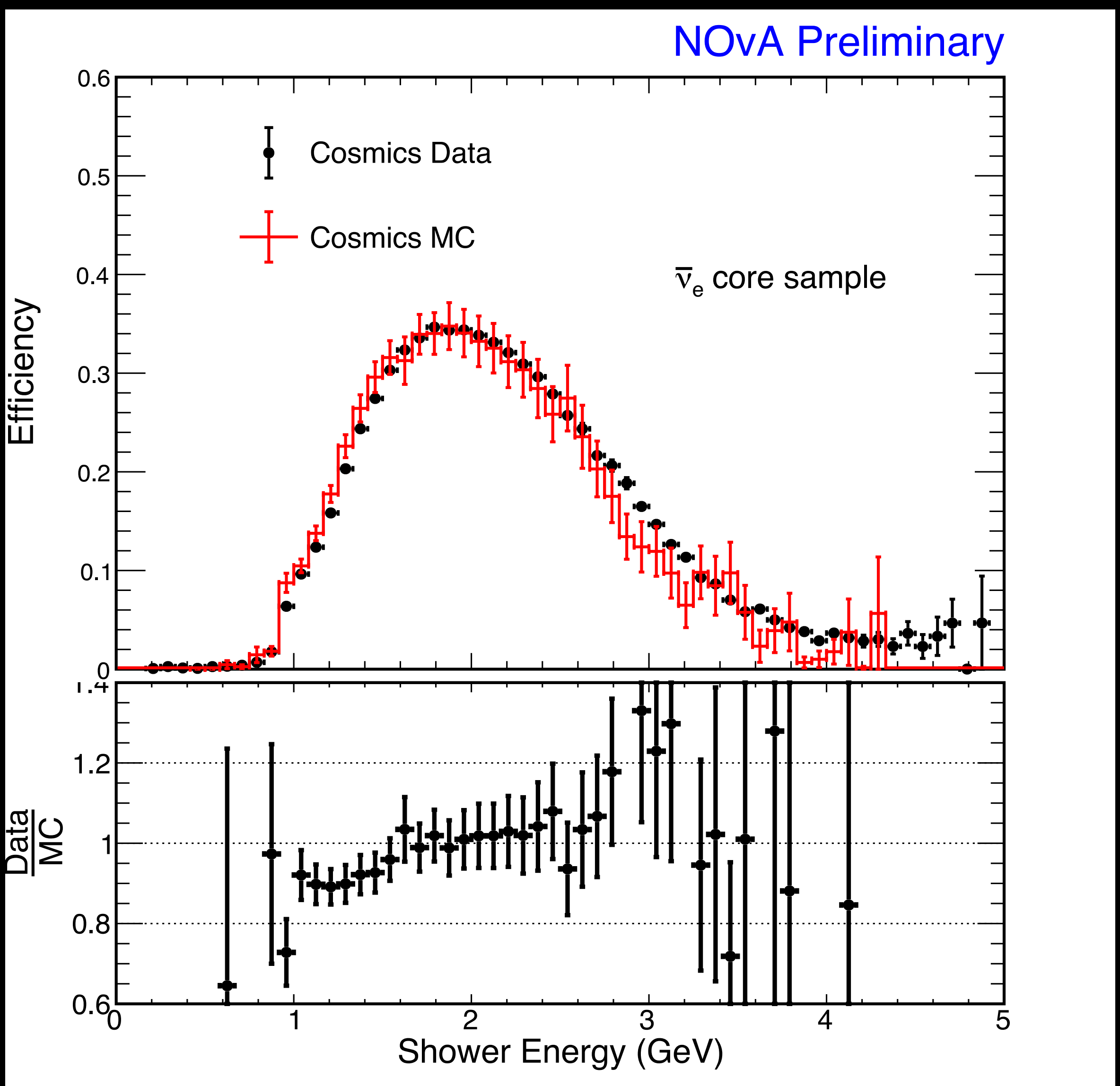
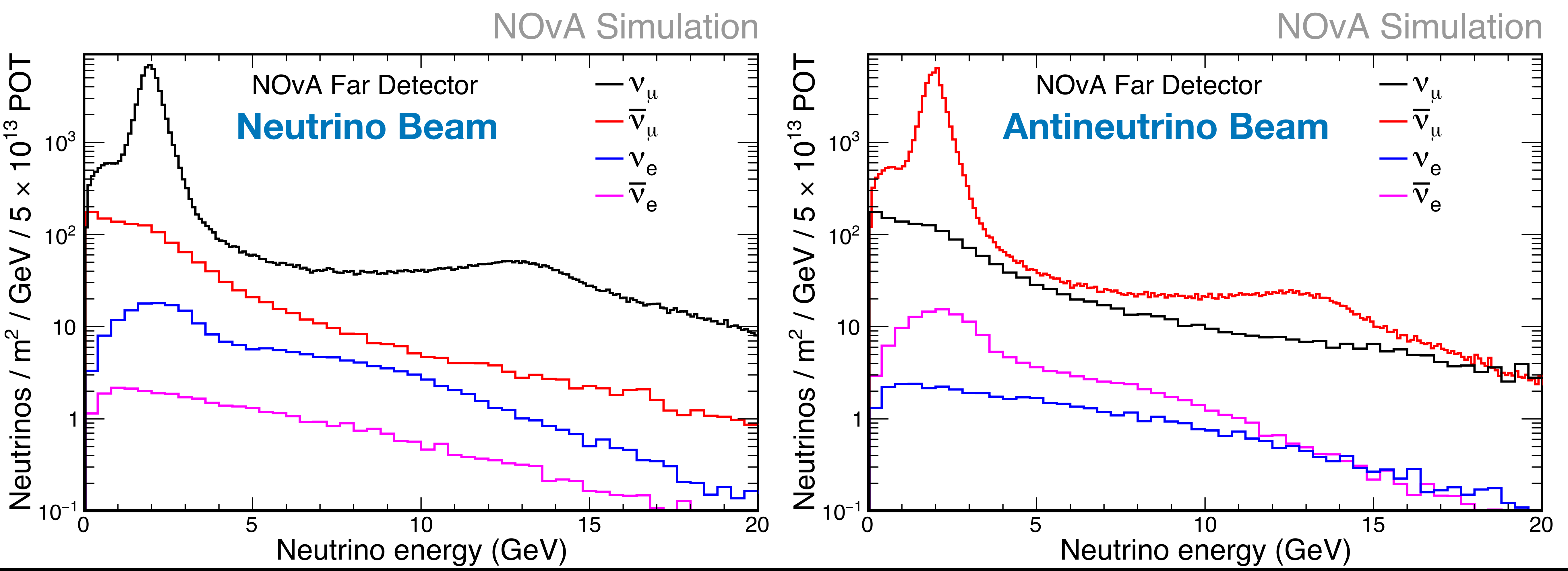




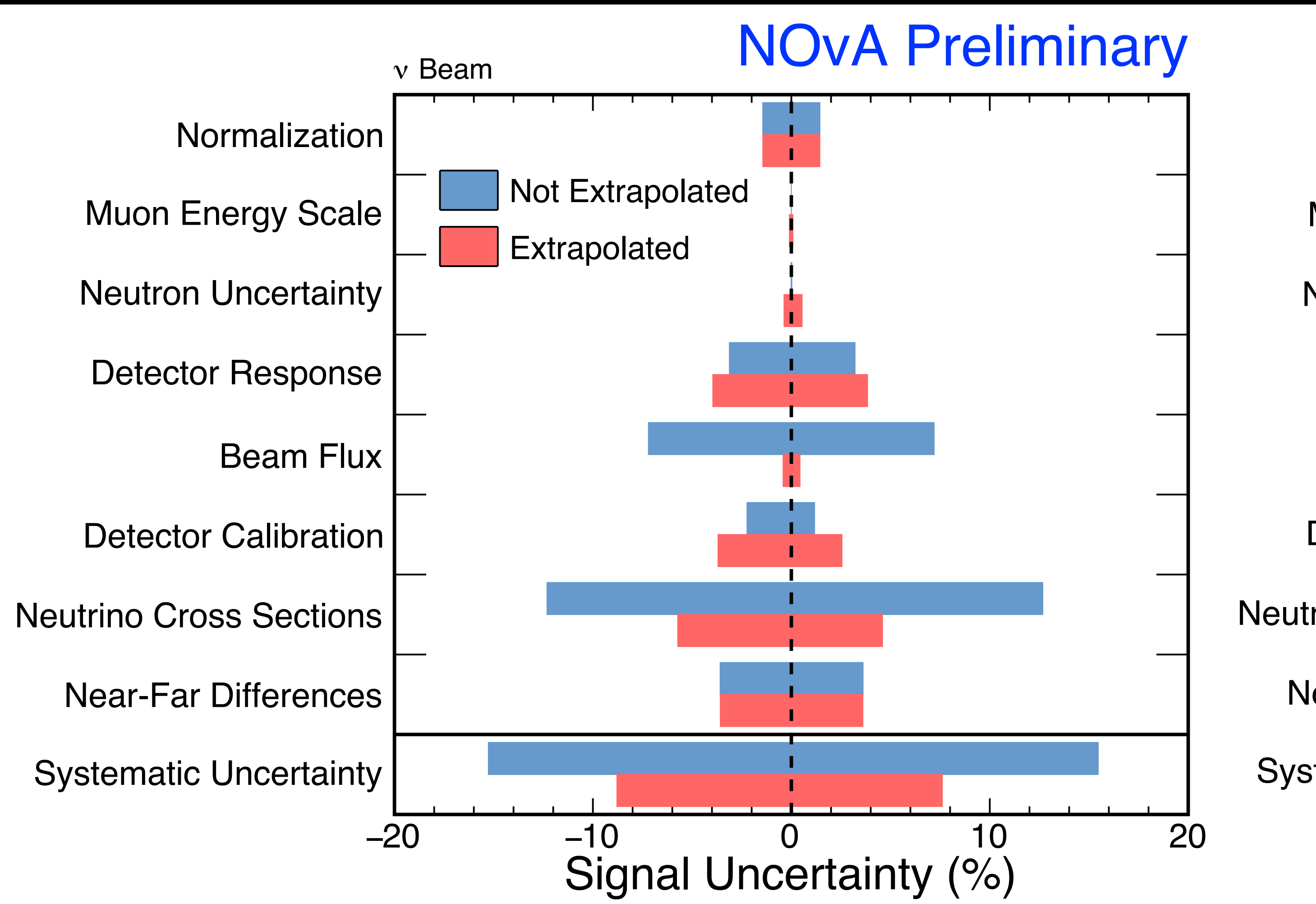
NOvA flux

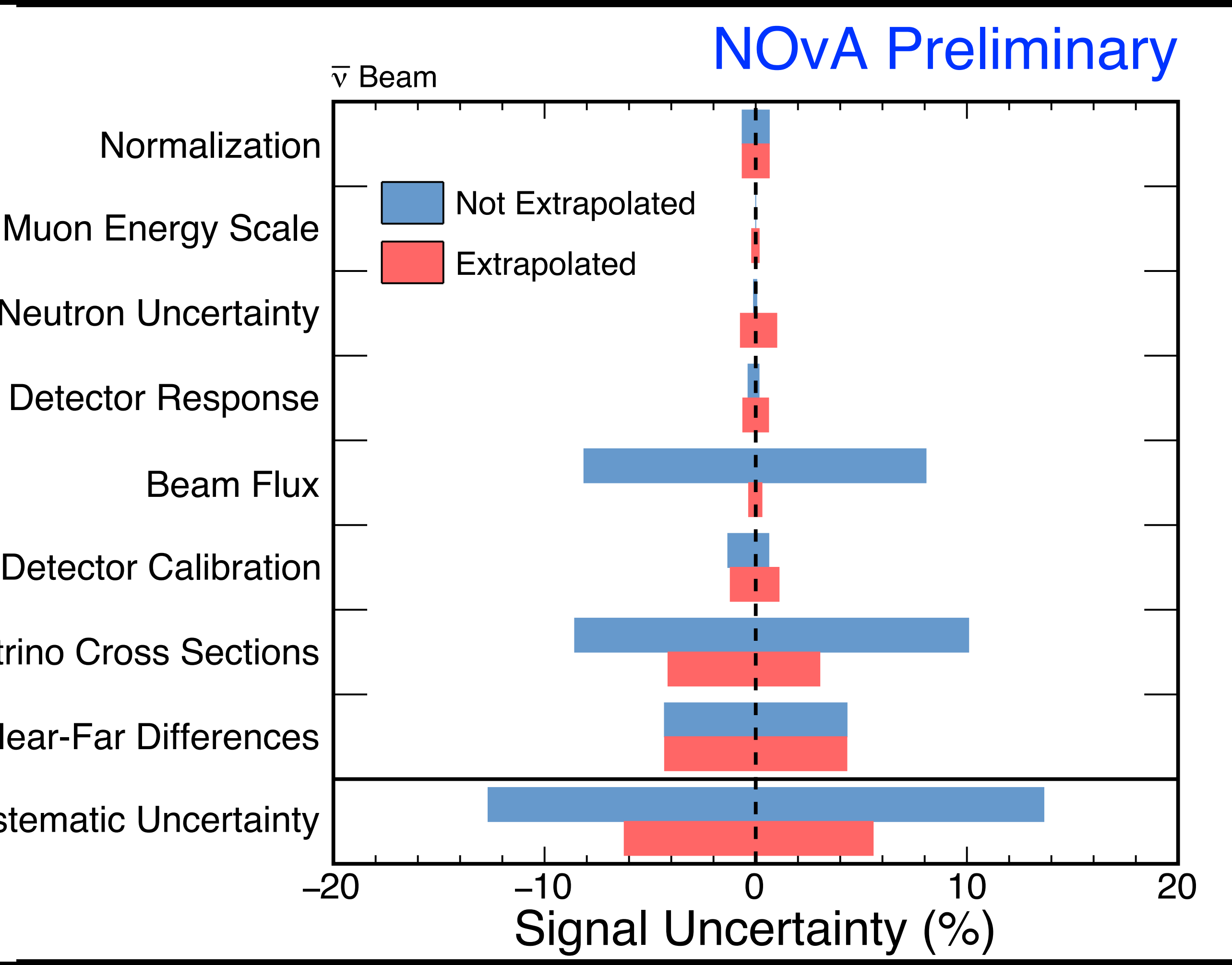
- For ν_e appearance analysis, characterization of the ν_μ beam (which oscillates to signal) and the inherent ν_e background component in the beam are important



Predicting far detector spectra

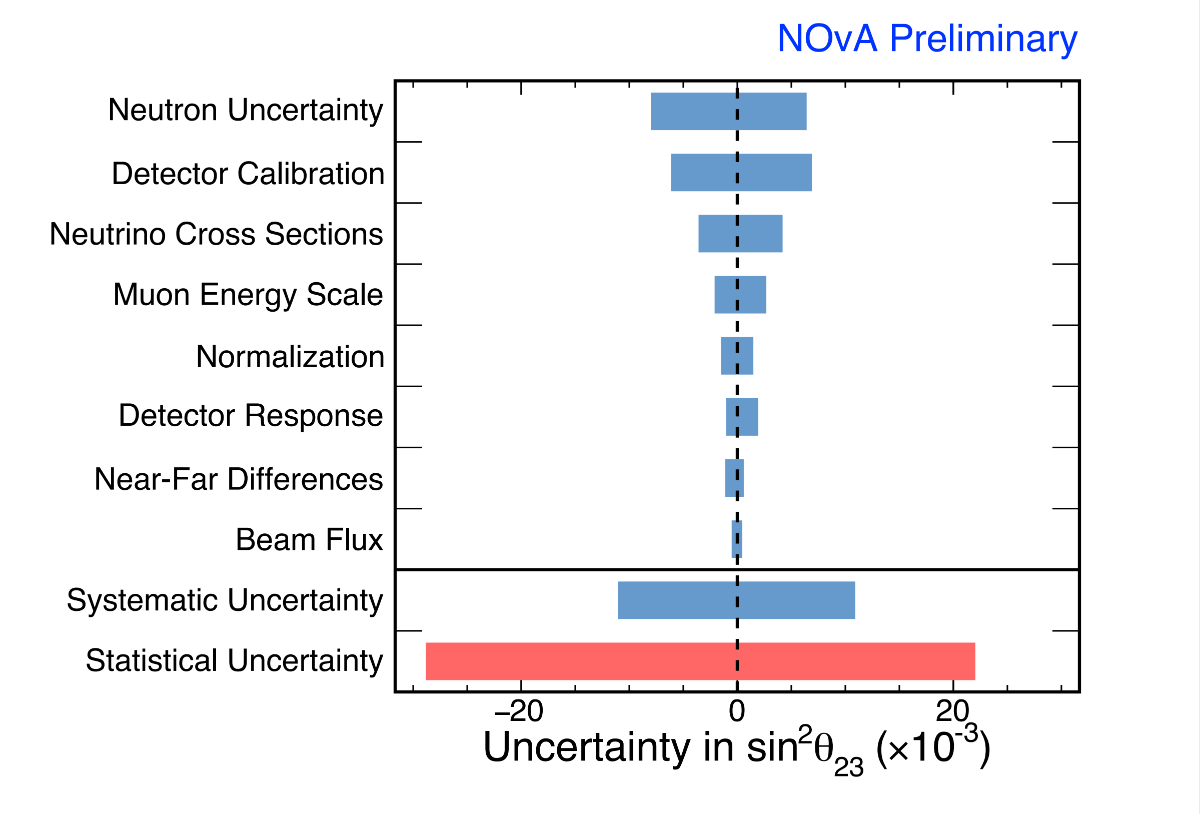
- Since NOvA has functionally similar near and far detector, extrapolation procedure reduces a number of systematic effects
  - Makes flux uncertainties quite small; greatly reduces cross-section uncertainties

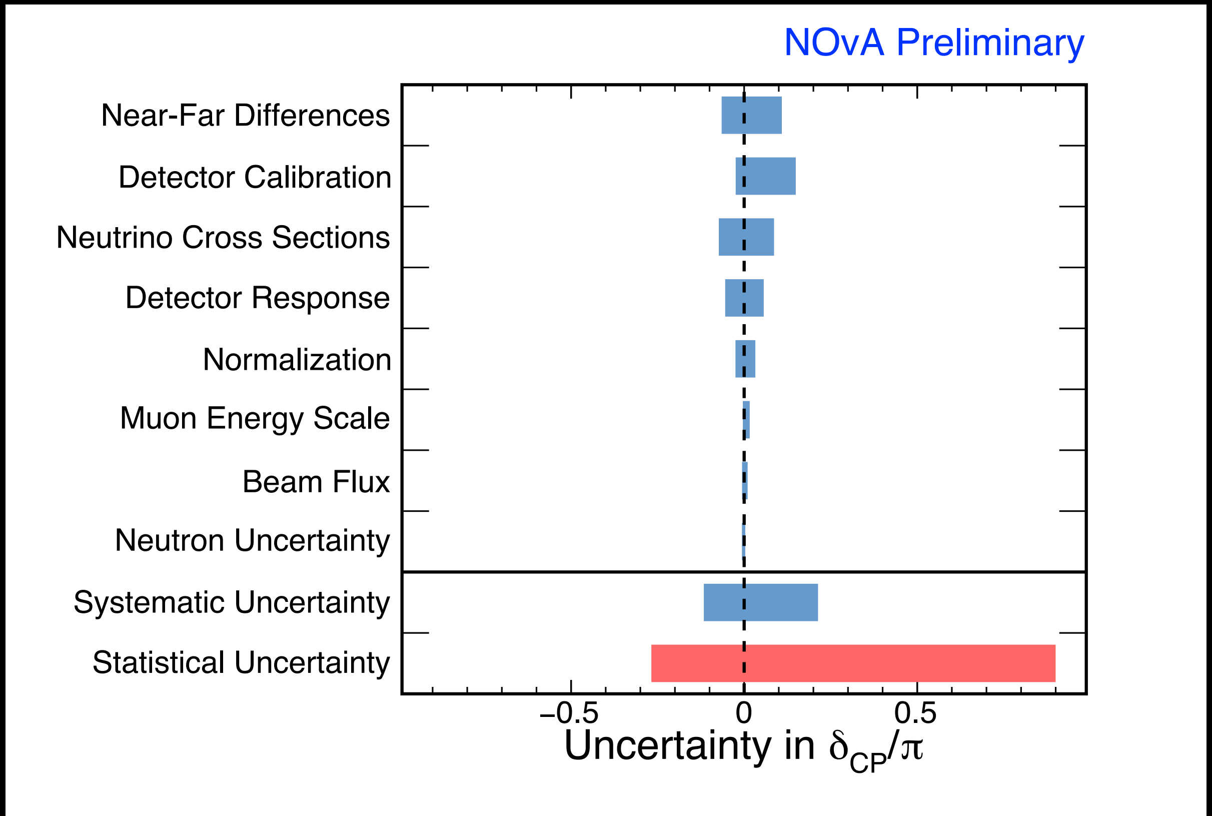


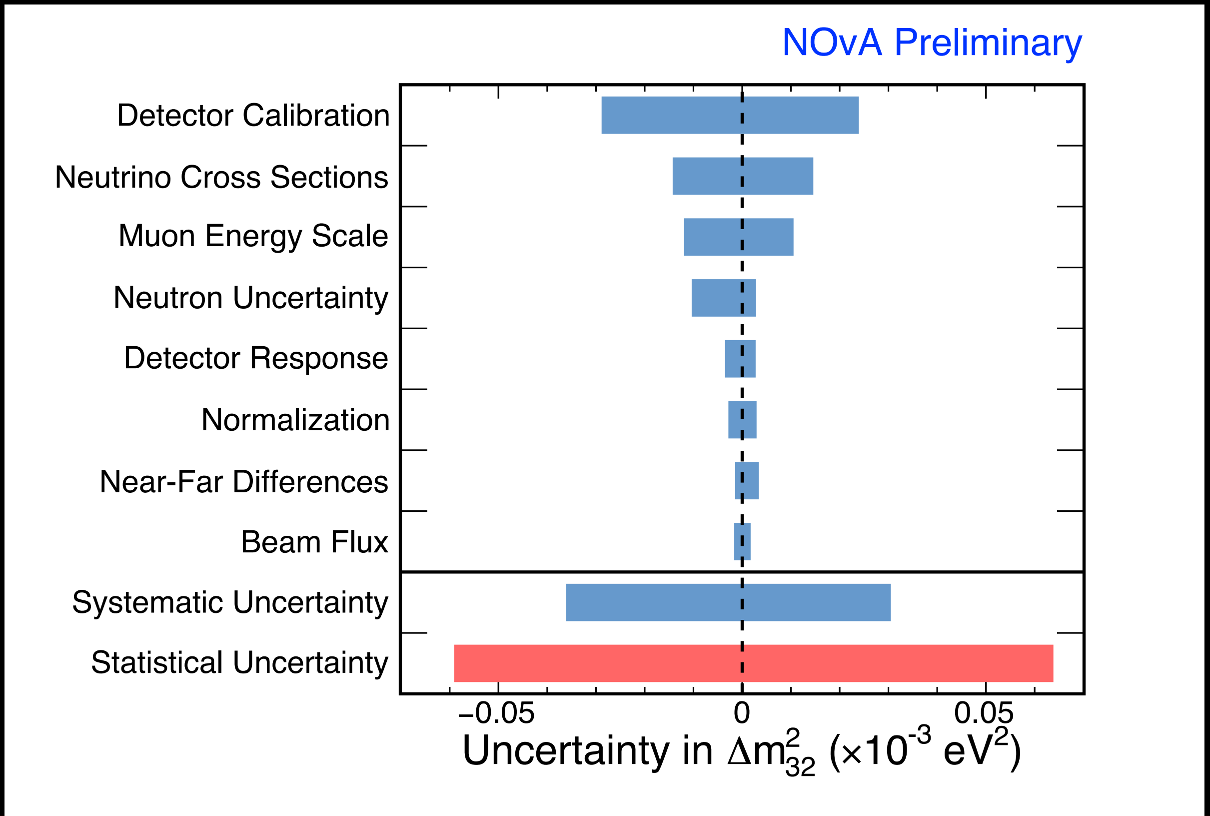


Joint $\overset{(-)}{\nu}_\mu,\overset{(-)}{\nu}_e$ Results

- Joint analysis is statistics limited in the major oscillation parameter results ($\sin^2\Theta_{23}$, Δm_{32}^2, δ_{CP})







Neutron systematic

- Scale amount of energy deposited by some neutrons to cover the discrepancy at low energy
- Shifts mean ν_μ energy by 1% in antineutrino beam and 0.5% in neutrino beam
    - Resolution changed by fractions of a percent
- Negligible impact found on selection efficiency