# LATEST 3-FLAVOUR OSCILLATION RESULTS FROM NOvA

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QMUL PPRC Seminar
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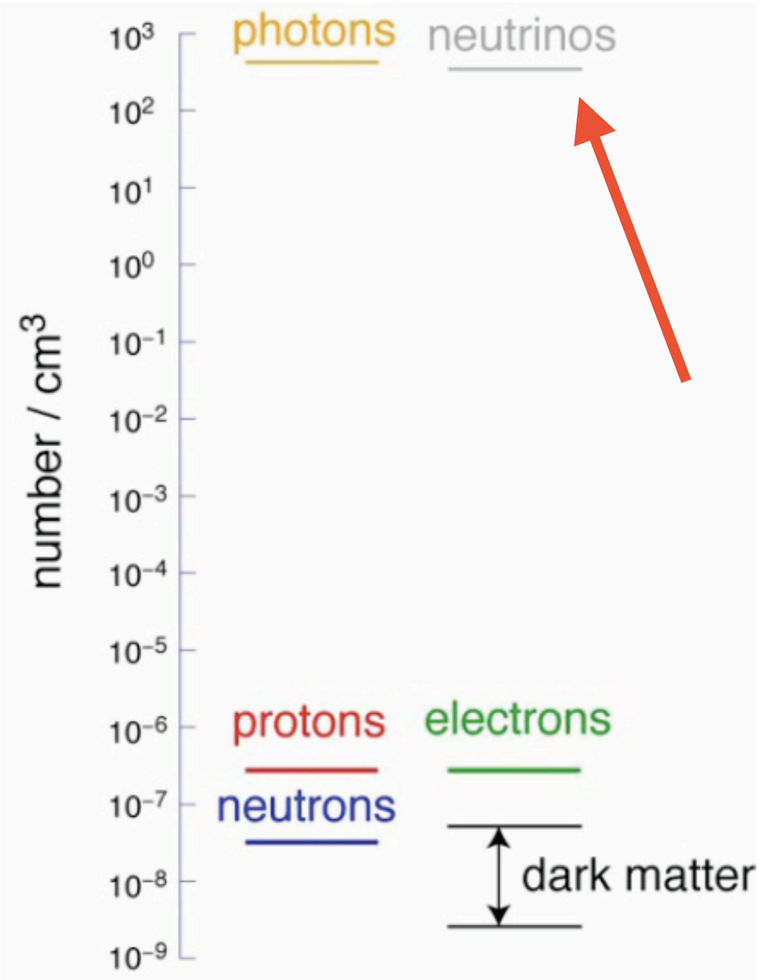
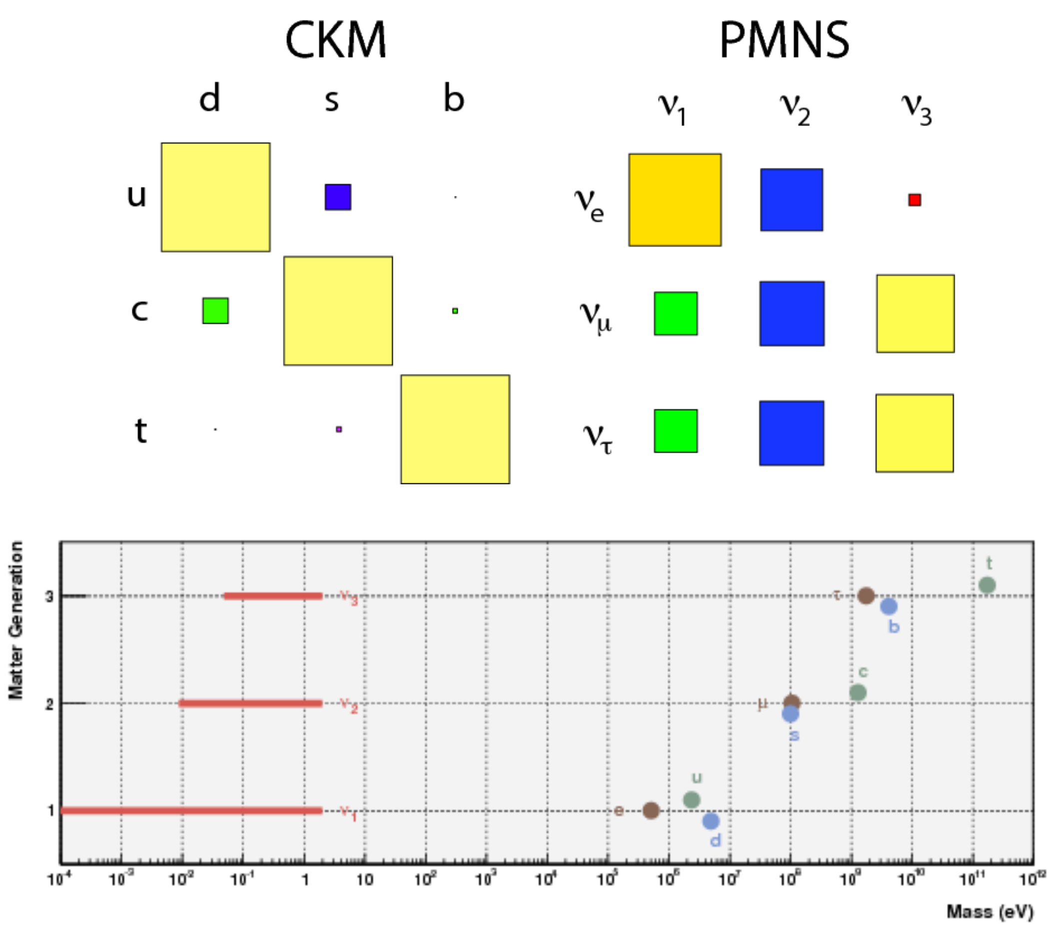
# Overview

- What are neutrino oscillations & why study them?
  - Long baseline principle, how to probe oscillations.
- NOvA experimental setup.
  - NuMI beam & NOvA detectors.
- 2020 analysis methodology.
- Latest results (Neutrino 2020).

# Why Study Neutrinos?




- Neutrinos are "weird":
  - Neutrino mixing looks very different from quark mixing.
  - Neutrino masses are tiny compared to rest of SM.
- Potentially CP-violating:
  - Window into matter-antimatter asymmetry.

**Open questions remain!**

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- Create in one flavour ($\nu_\mu$), but detect in another ($\nu_e$).

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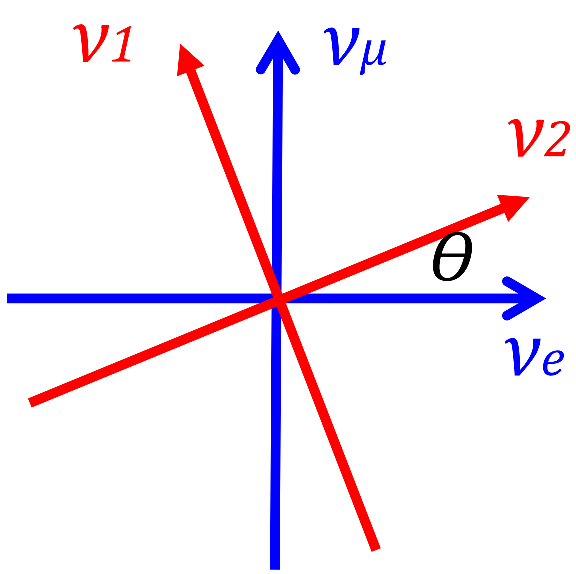
- Each flavour is a superposition of different masses.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$



# Neutrino Oscillations 101

- Create in one flavour ($\nu_\mu$), but detect in another ($\nu_e$).


- Each flavour is a superposition of different masses.

$$\begin{pmatrix}\nu_e \\ \nu_\mu\end{pmatrix} = \begin{pmatrix}\cos\theta & \sin\theta \\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\nu_1 \\ \nu_2\end{pmatrix} \xrightarrow{\text{3 flavours}} \nu_\lambda = \sum_{m=1}^{3} U^*_{\lambda m}\nu_m$$

# 3-flavour Neutrino Oscillations

$$\nu_\lambda = \sum_{m=1}^{3} U^*_{\lambda m} \nu_m$$

$\nu_e \ \nu_\mu \ \nu_\tau$

$\nu_1 \ \nu_2 \ \nu_3$

PMNS matrix

$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \quad , \qquad UU^\dagger = 1$$

**3** angles, **1** complex phase.

# 3-flavour Neutrino Oscillations

$$\nu_\lambda = \sum_{m=1}^{3} U^*_{\lambda m} \nu_m$$

$\nu_e \quad \nu_\mu \quad \nu_\tau$

$\nu_1 \quad \nu_2 \quad \nu_3$

PMNS matrix

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

"Atmospheric" sector

"Reactor" sector

"Solar" sector

**3** angles, **1** complex phase. → $\theta_{23}$ $\quad$ $\theta_{13}$ $\delta$ $\quad$ $\theta_{12}$

# 3-flavour Neutrino Oscillations

$$|\nu_k(t,x)\rangle = e^{-i(E_k t - p_k x)}|\nu_k(0,0)\rangle$$

Momentum of state

Energy of state

- Mass eigenstates produced with equal amounts of energy: $E_i = E_j = E$
- Ultra-relativistic: $t = x = L$ and $p_k x = x\sqrt{E_k^2 - m_k^2} \approx E_k \left(1 - \frac{m_k^2}{2E_k^2}\right) L$

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

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**3** angles, **1** complex phase. → $\theta_{23}$ $\theta_{13}$ $\delta$ $\theta_{12}$

# 3-flavour Neutrino Oscillations

$$|\nu_k(t,x)\rangle = e^{-i\frac{m_k^2 L}{2E}}|\nu_k(0,0)\rangle$$

$$P\left(\nu_\alpha \to \nu_\beta\right) \sim P\left(U(\theta_{23},\theta_{13},\delta,\theta_{12}), \Delta m^2_{21}, \Delta m^2_{32}, \Delta m^2_{31}, \frac{L}{E}\right)$$

$\Delta m^2_{ij} \equiv m_i^2 - m_j^2$

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

"Atmospheric" sector | "Reactor" sector | "Solar" sector

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# 3-flavour Neutrino Oscillations

$$P\left(\nu_\alpha \to \nu_\beta\right) \sim P\left(U(\theta_{23}, \theta_{13}, \delta, \theta_{12}), \Delta m^2_{21}, \Delta m^2_{32}, \Delta m^2_{31}, \frac{L}{E}\right)$$

$\Delta m^2_{32} \approx 2 \times 10^{-3}\mathrm{eV}^2$

$\Delta m^2_{31} \sim \Delta m^2_{32}$

$\Delta m^2_{21} \approx +8 \times 10^{-5}\mathrm{eV}^2$

$\frac{L}{E} = 500\mathrm{km/GeV}$

$\frac{L}{E} = 15000\mathrm{km/GeV}$

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

"Atmospheric" sector

"Reactor" sector

"Solar" sector

$\theta_{23}$

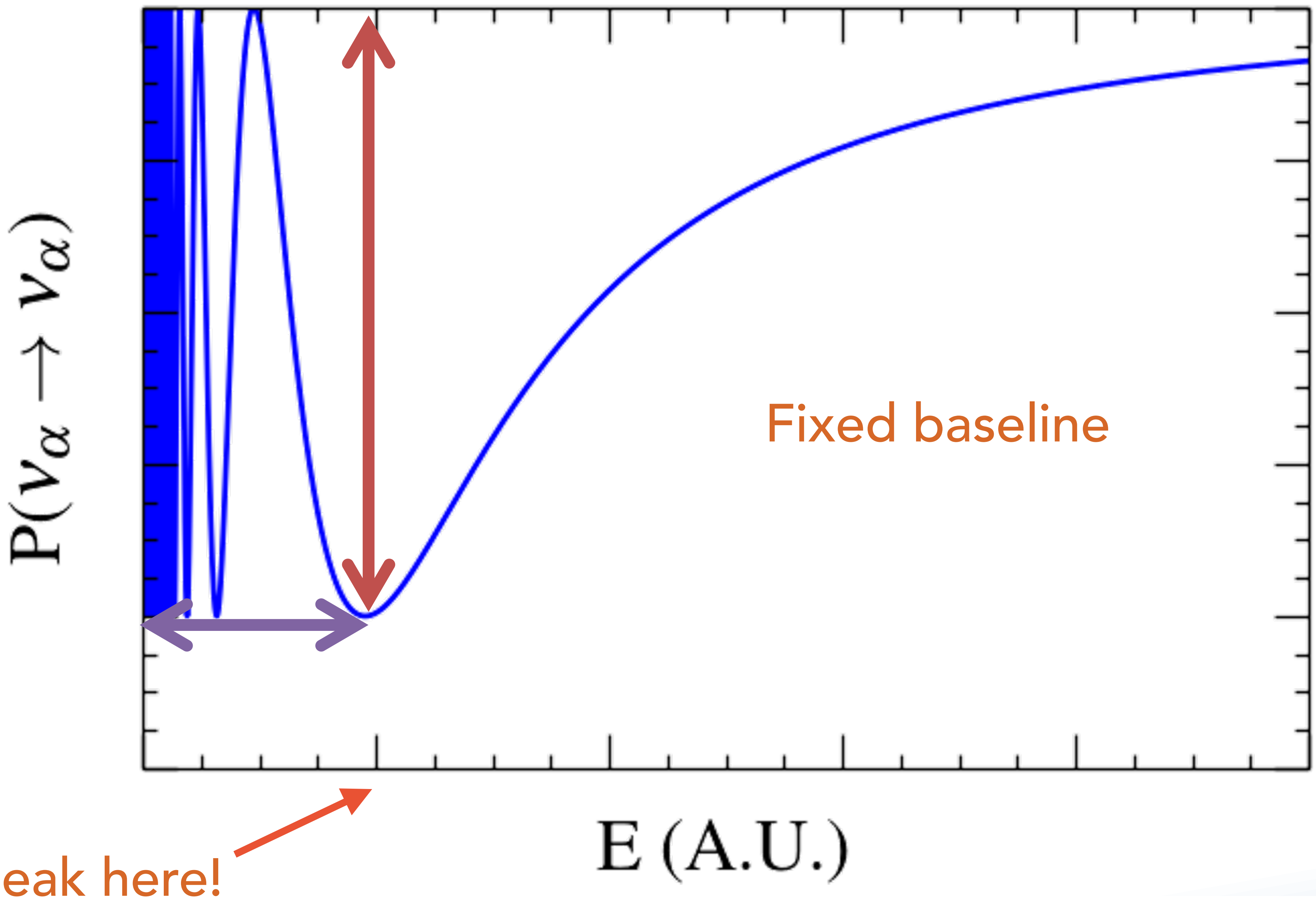
$\theta_{13}$ $\delta$

$\theta_{12}$

For given splitting, there is an L/E defining maximum (minimum) transition probability.

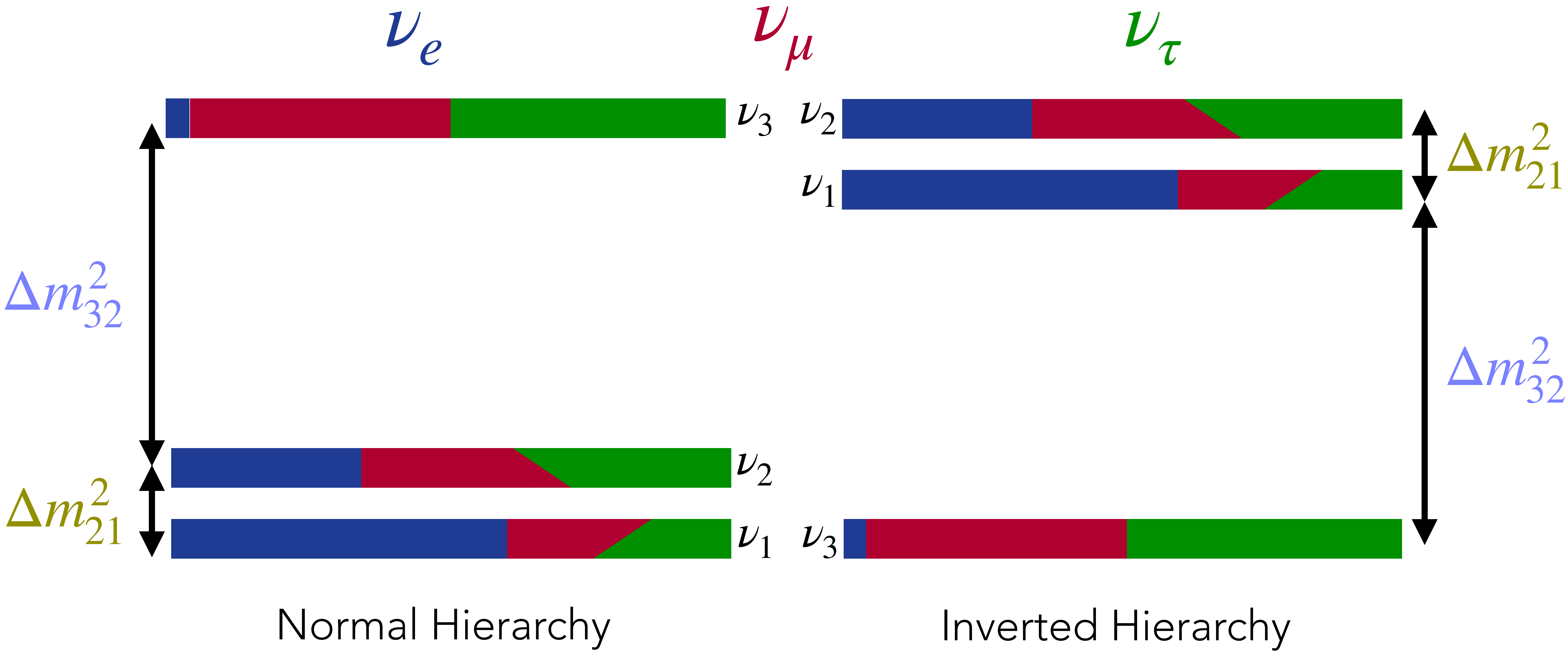
# How to: Disappearance

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2(2\theta_{23}) \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$



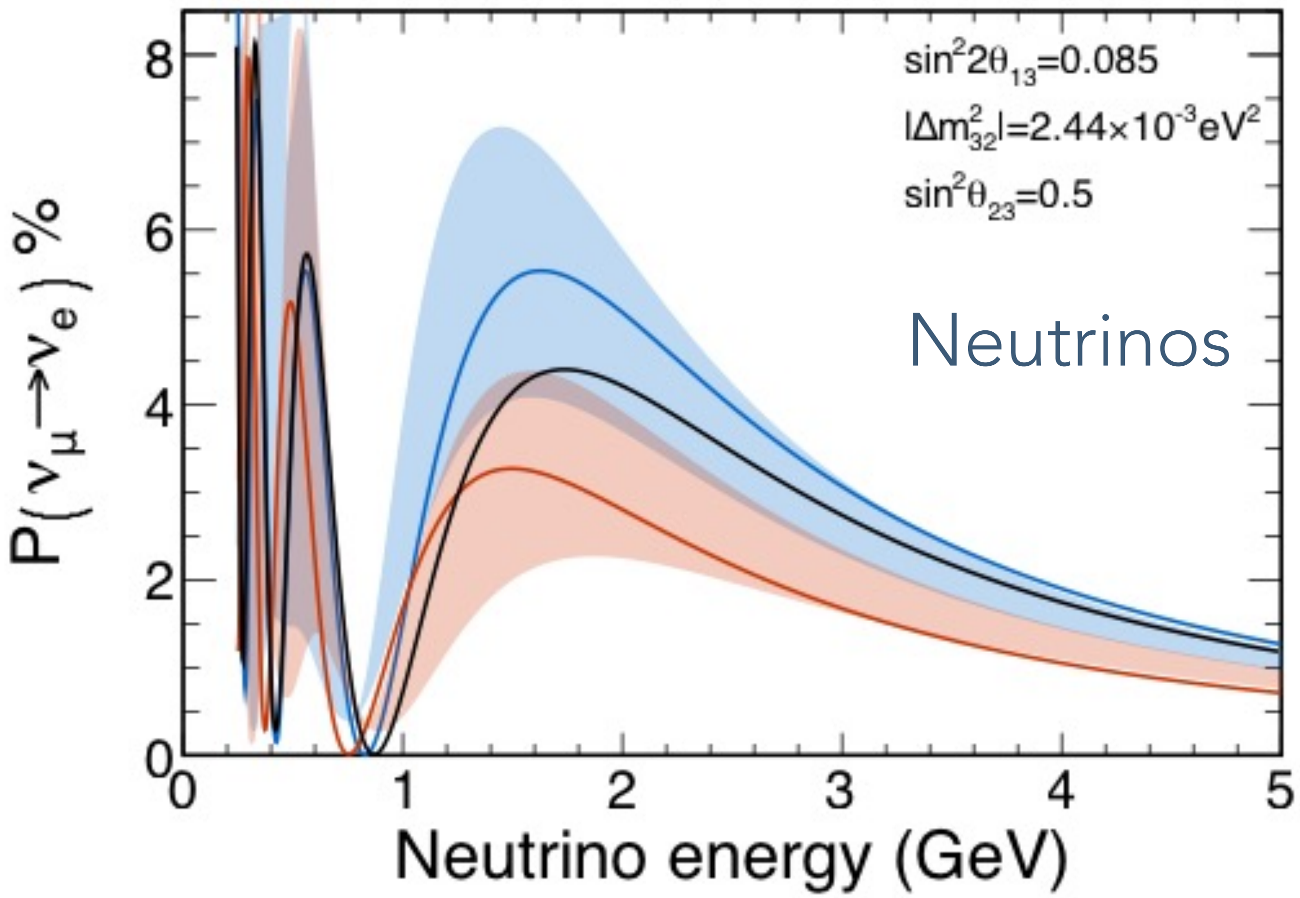

Beam peak here!

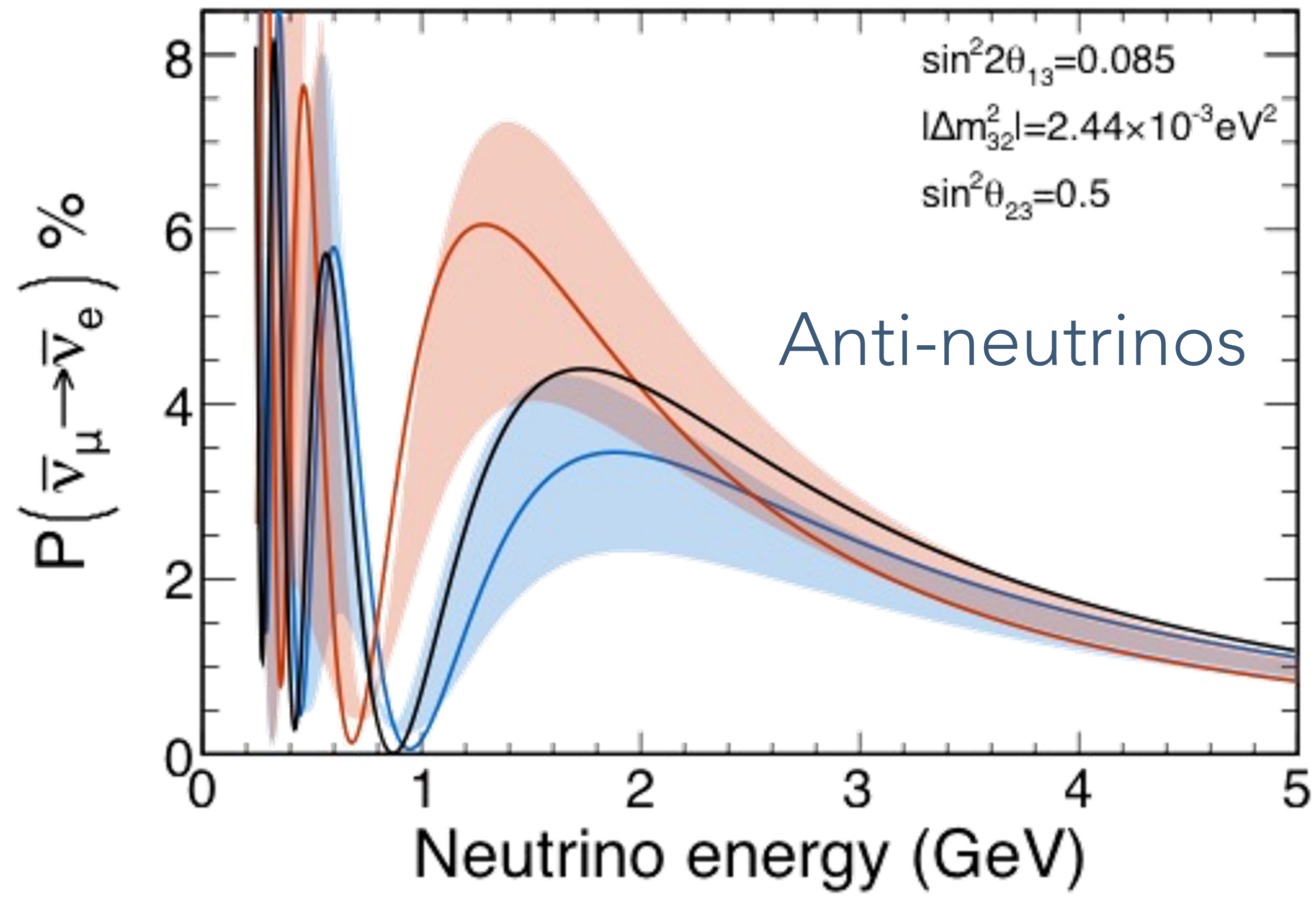
# Mass Hierarchy & MSW Effect




- Probe this using the matter effect.
- Electron neutrinos experience additional interactions with electrons in matter compared to other flavours.
- Different for neutrinos and anti-neutrinos -> **fake CP**!

# We Love the Matter Effect!




**Normal Hierarchy** **Vacuum** **Inverted Hierarchy**

- $\nu_\mu \rightarrow \nu_e$ enhanced in NH, suppressed in IH.
- $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ enhanced in IH, suppressed in NH.

# How to: Appearance

$$P\left(\nu_\mu \to \nu_e\right) \approx \left|\sqrt{P_{\text{atm}}}e^{-e(\Delta_{32}+\delta_{CP})} + \sqrt{P_{\text{sol}}}\right|^2$$

$$\approx P_{\text{atm}} + P_{\text{sol}} + 2\sqrt{P_{\text{atm}}P_{\text{sol}}}\left(\cos\Delta_{32}\cos\delta_{CP} \mp \sin\Delta_{32}\sin\delta_{CP}\right)$$

$$\sqrt{P_{\text{atm}}} = \sin(\theta_{23})\sin(2\theta_{13})\frac{\sin(\Delta_{31}-aL)}{\Delta_{31}-aL}\Delta_{31}$$

- $\nu_\mu \to \nu_e$ depends on:
  - The smallest mixing angle: $\theta_{13}$
  - Solar parameters: $\sin^2\left(\theta_{12}\right),\ \Delta m^2_{12}$
  - Mass hierarchy and matter effects.
  - Atmospheric parameters: $\sin^2\left(\theta_{23}\right),\ \Delta m^2_{32}$
  - CP phase: $\delta_{CP}$.

**Disappearance constraints:**

Reactor: $\nu_e \to \nu_e$

Solar: $\nu_e \to \nu_e$

NOvA: $\nu_\mu \to \nu_\mu$

**Open questions**

# Open Questions: Appearance

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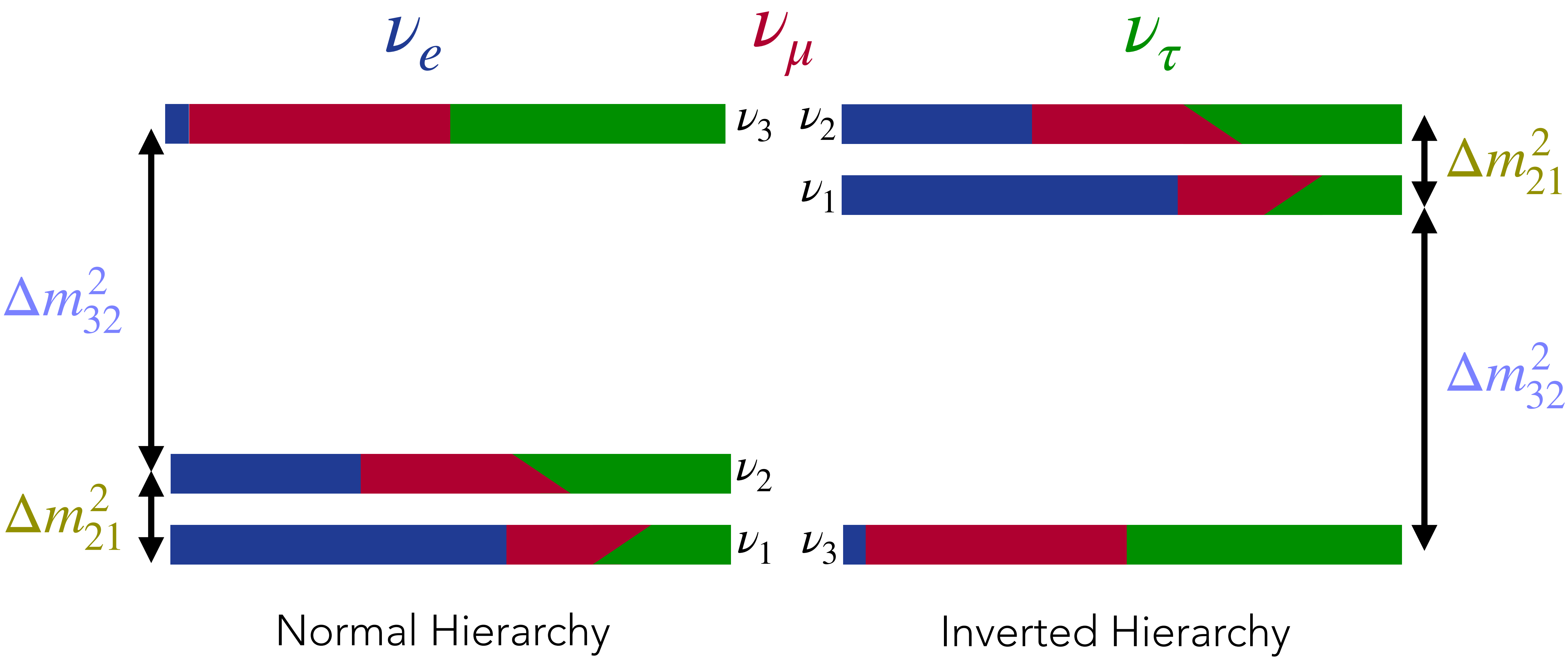

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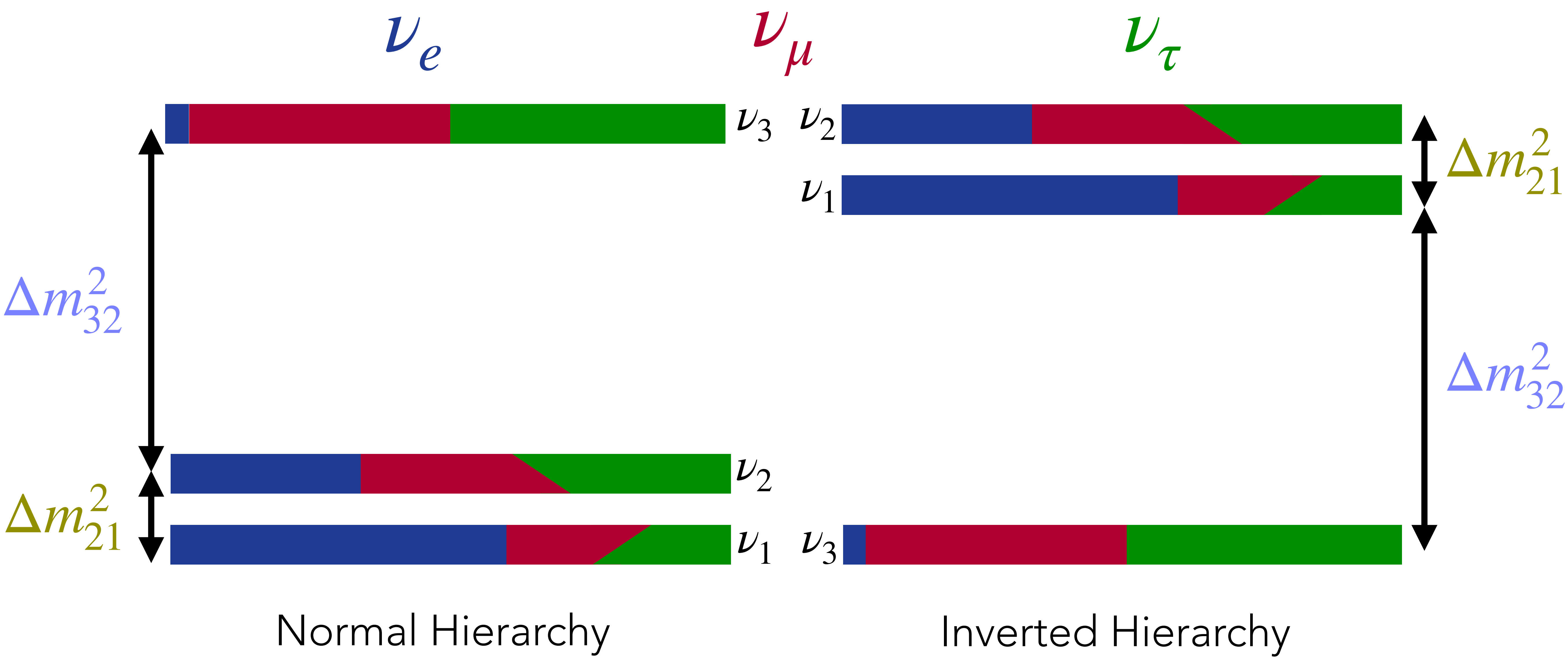

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- $\nu_\mu \rightarrow \nu_e$ depends on:
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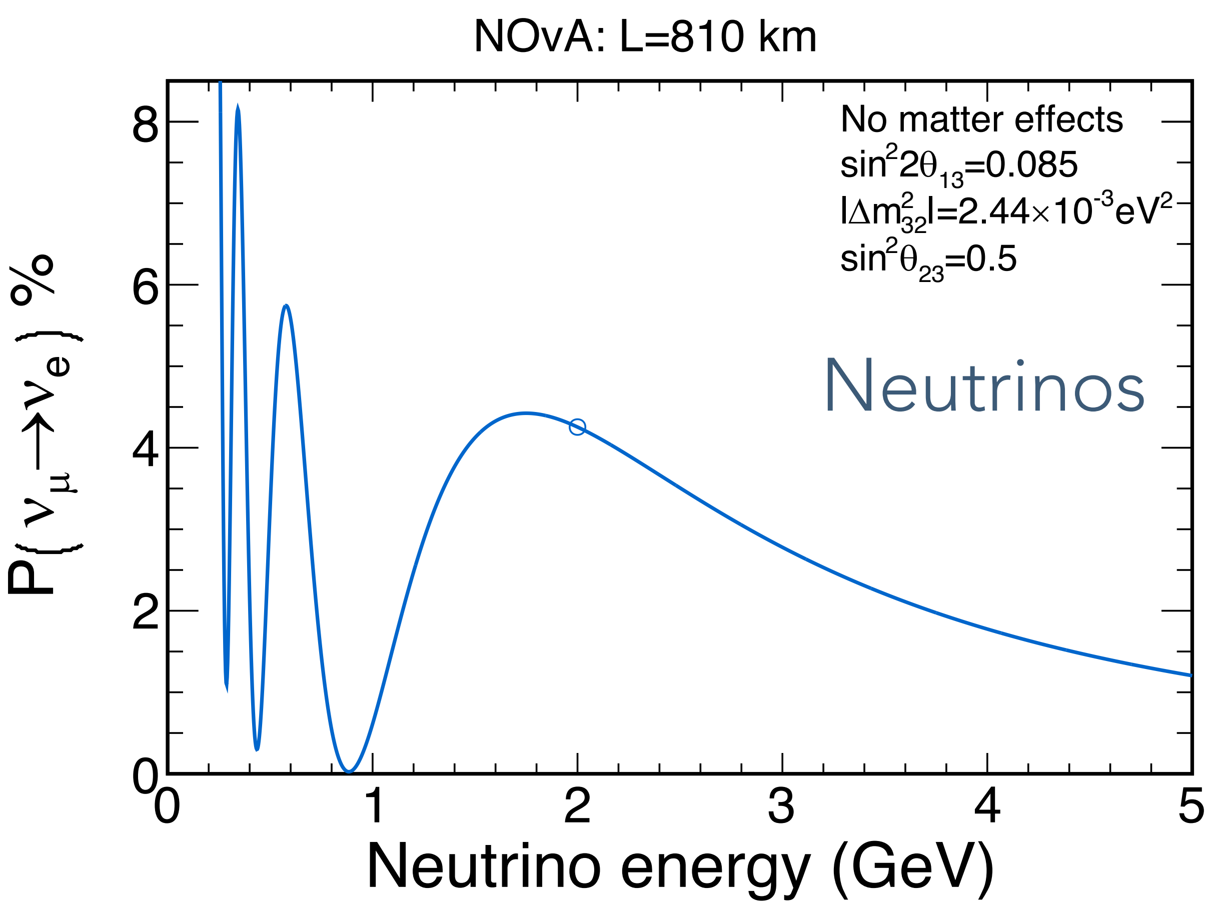
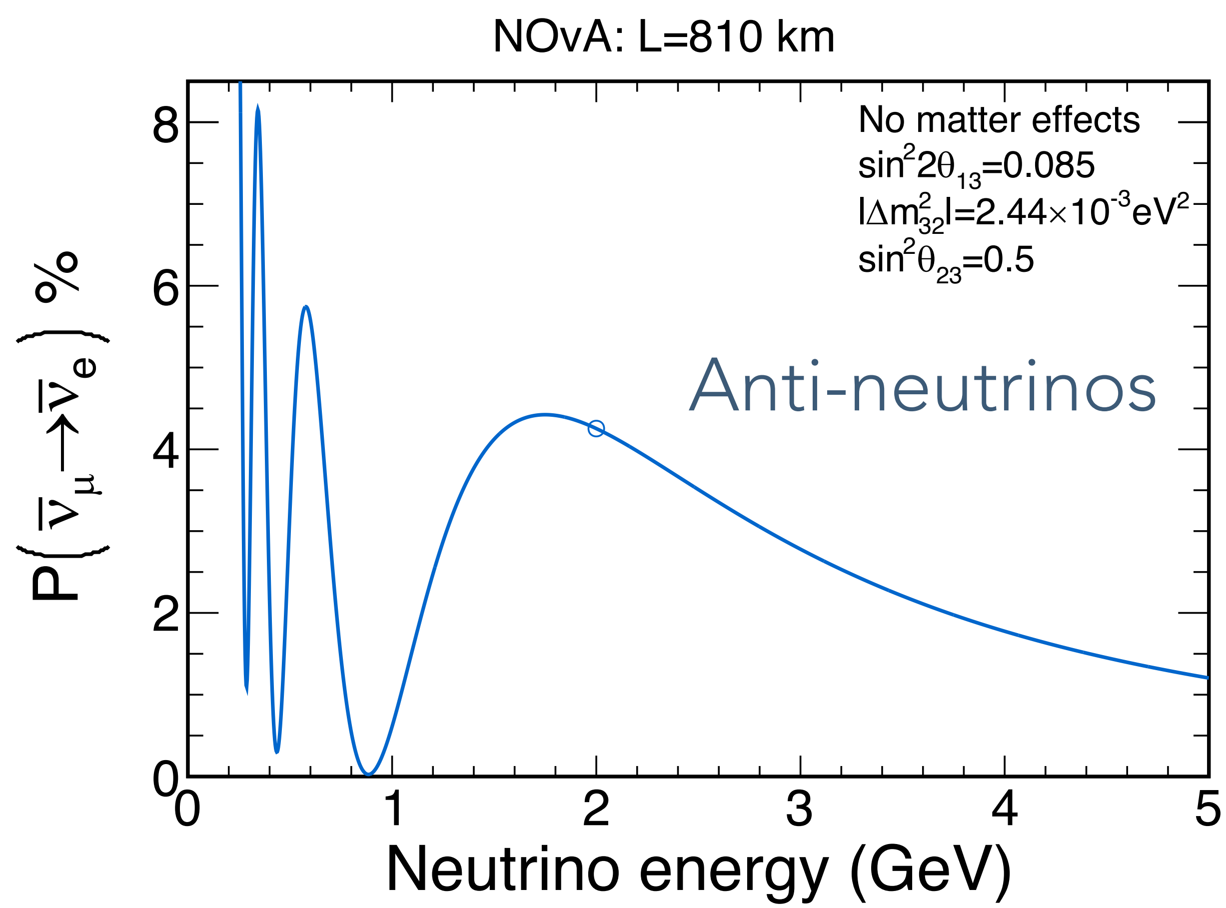
  - CP phase: $\delta_{CP}$.

$$P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)?$$



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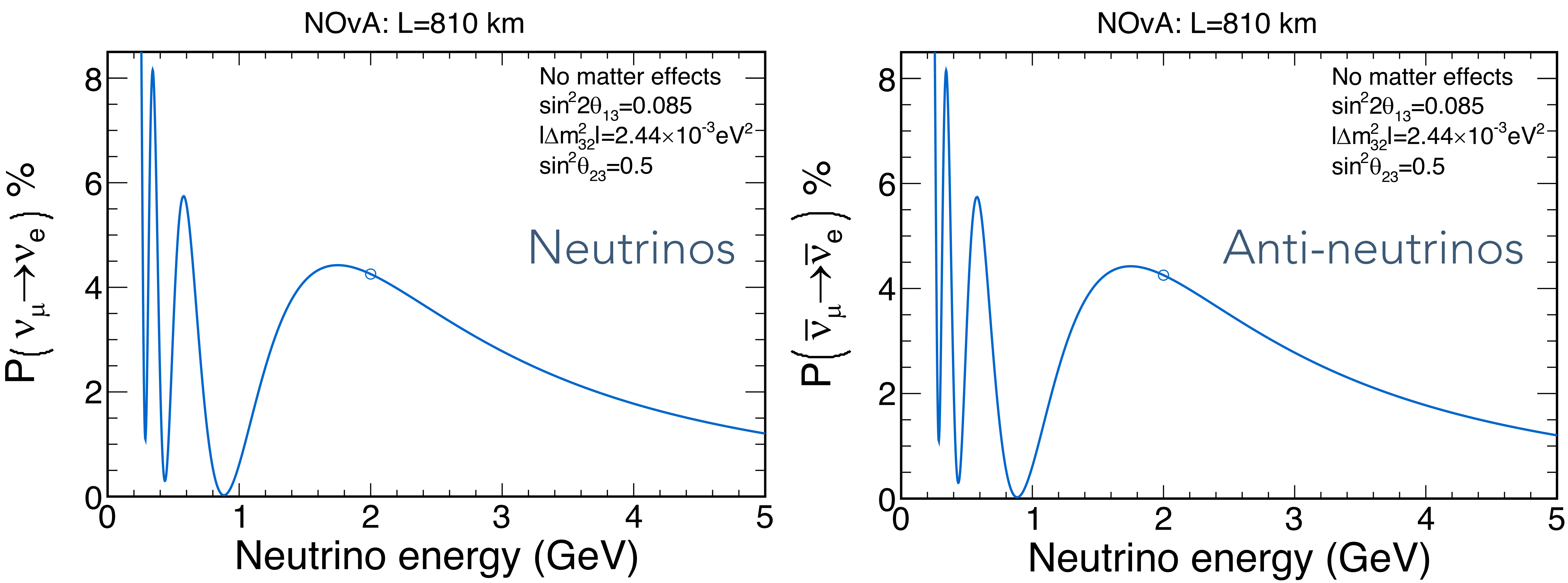
**CP conserved**



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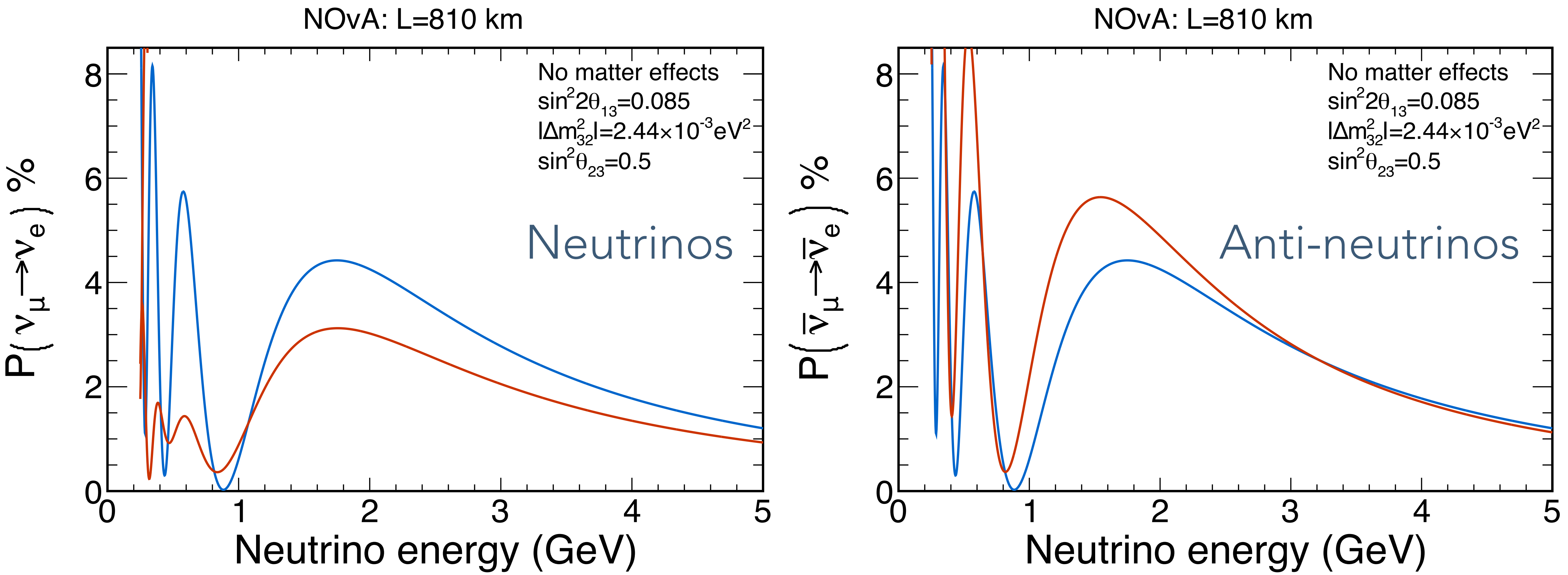
**CP conserved**

$\delta_{CP} = \pi/2$



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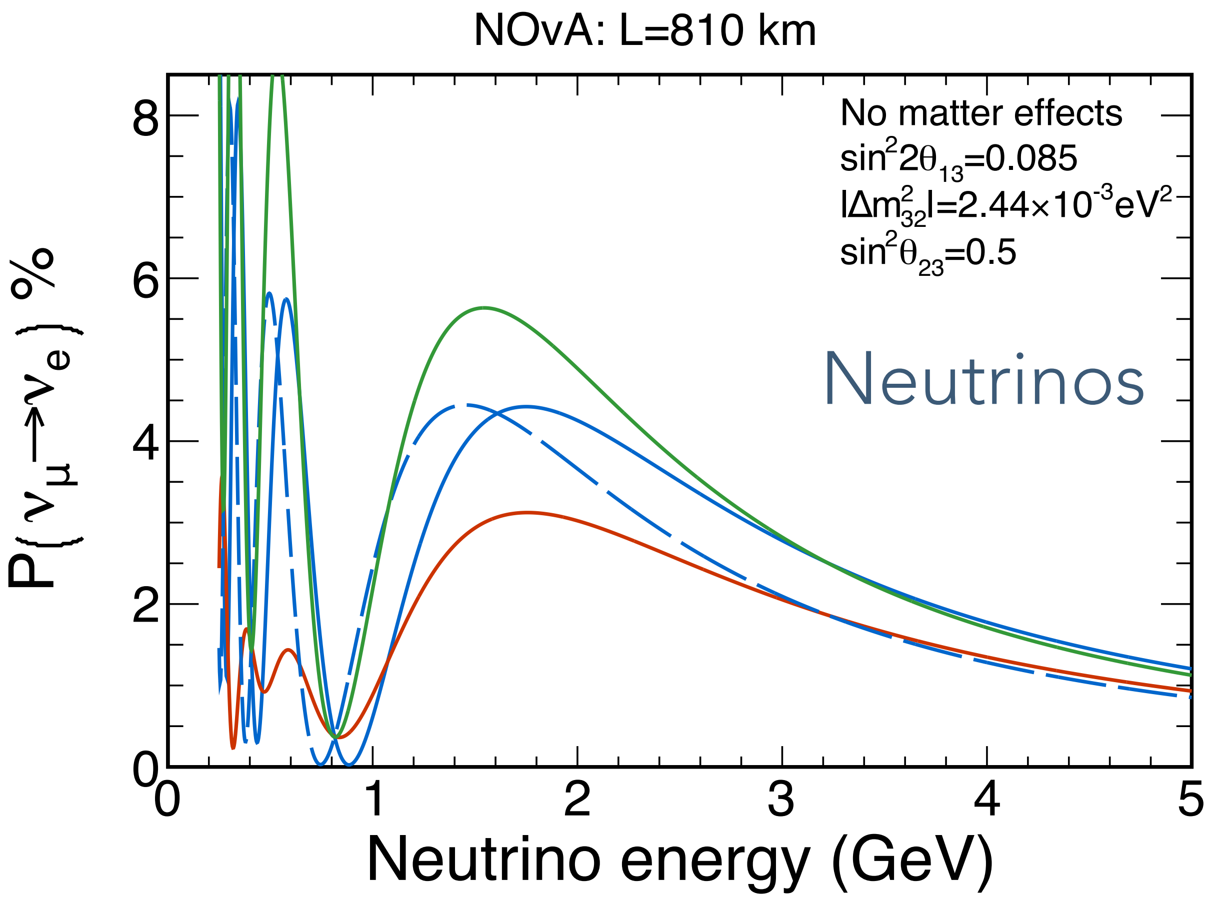
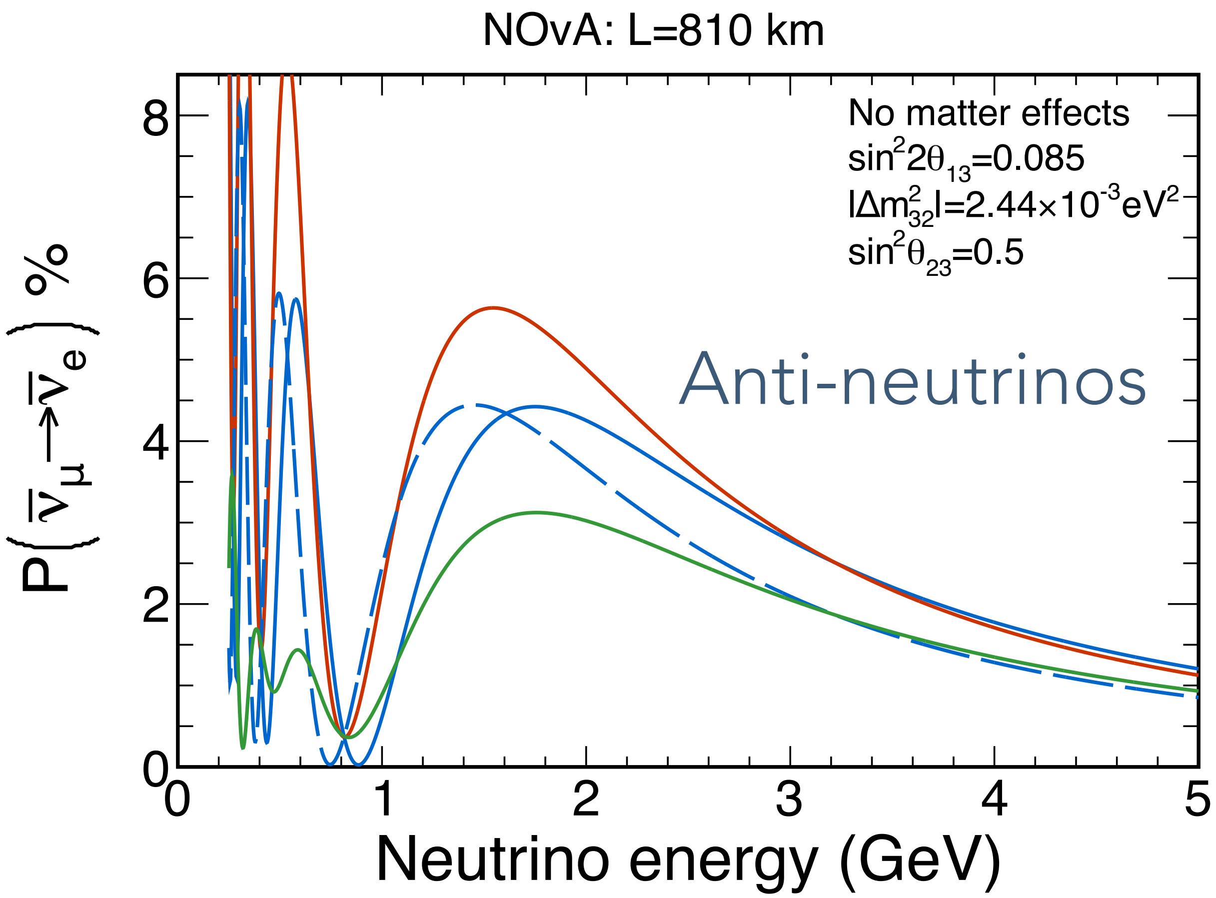
**CP conserved**

$\delta_{CP} = \pi/2$ $\delta_{CP} = 3\pi/2$



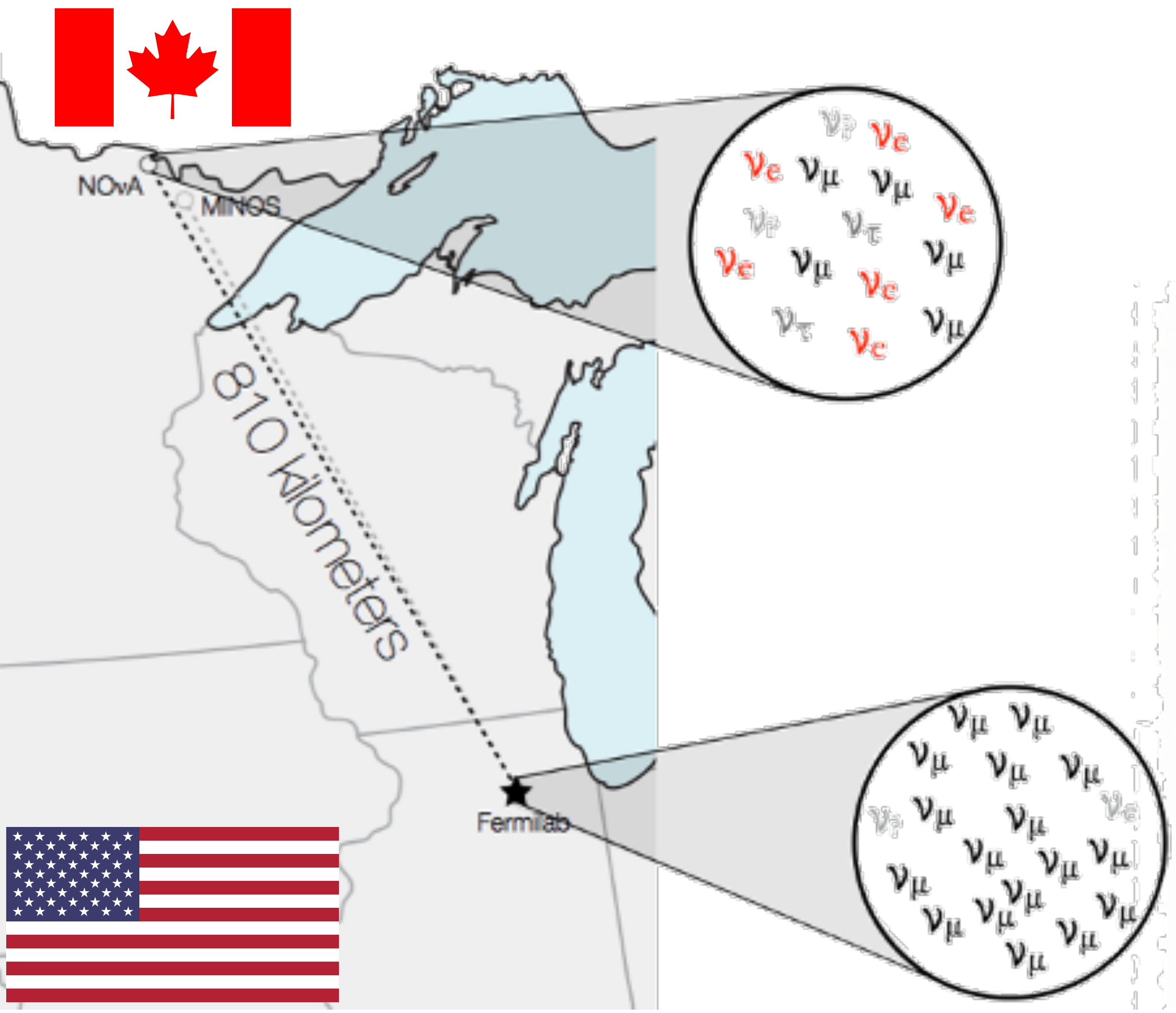
# Mini-Summary

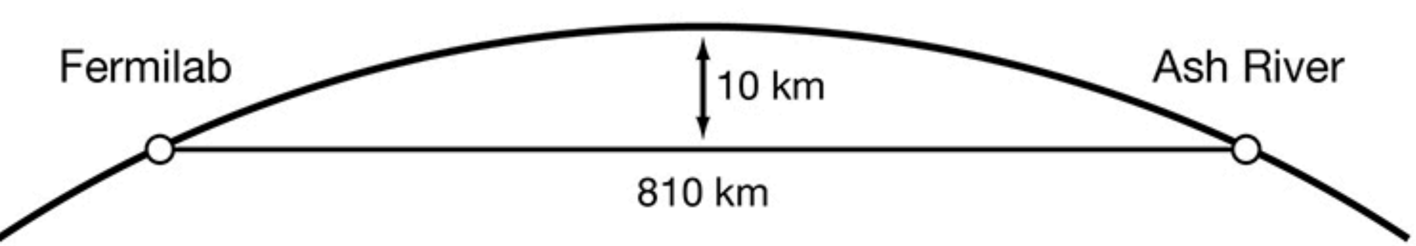
- Neutrinos are well worth studying!
- There are 7 parameters governing 3-flavour oscillation.
- NOvA is interested in 3.
- Make measurements by measuring muon neutrino disappearance probabilities and electron neutrino appearance probabilities ($P(\nu_\mu \rightarrow \nu_e)$).

# NOvA Experimental Setup

Queen Mary University of London

# NOvA Overview




- Long-baseline neutrino oscillation experiment.
  - NuMI **neutrino beam** at Fermilab.
  - **Near detector** to measure beam before oscillations.
  - **Far detector** measures the oscillated spectrum.
- **Primary goal,** measurement of 3-flavour oscillations via:
  - $\nu_\mu \rightarrow \nu_\mu$ , $\nu_\mu \rightarrow \nu_e$
  - $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ , $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- Other goals include:
  - Search for sterile neutrinos.
  - Neutrino cross sections.
  - Supernova neutrinos.
  - Cosmic ray physics.

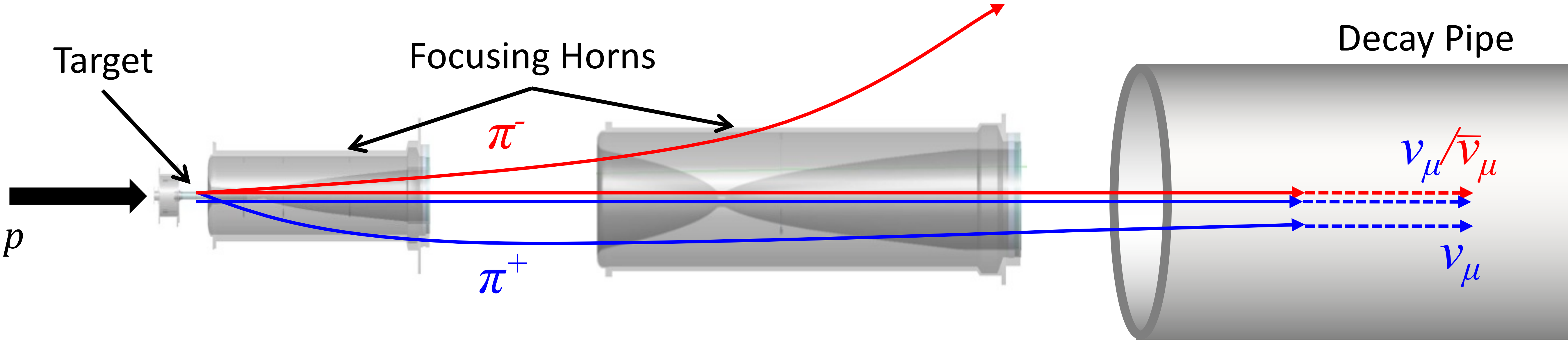
# The NOvA Collaboration

> 240 people, ~ 50 institutions, 7 countries

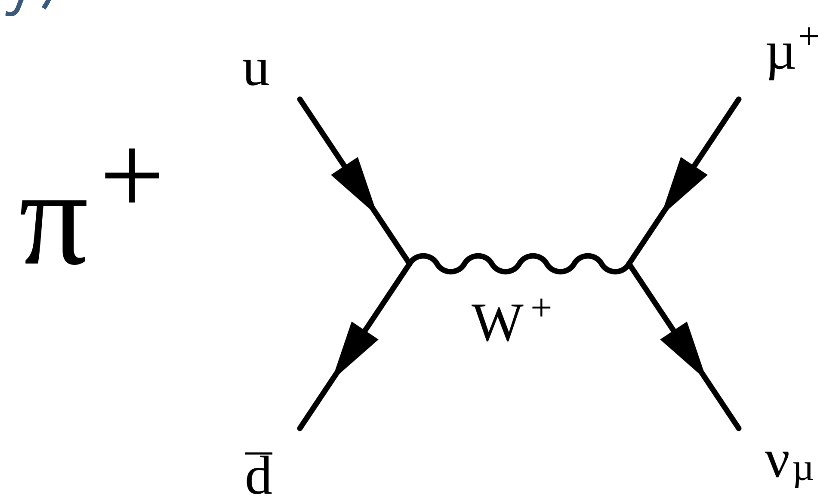
# The NOvA Collaboration

QMUL is one of the collaboration’s newest institutions.

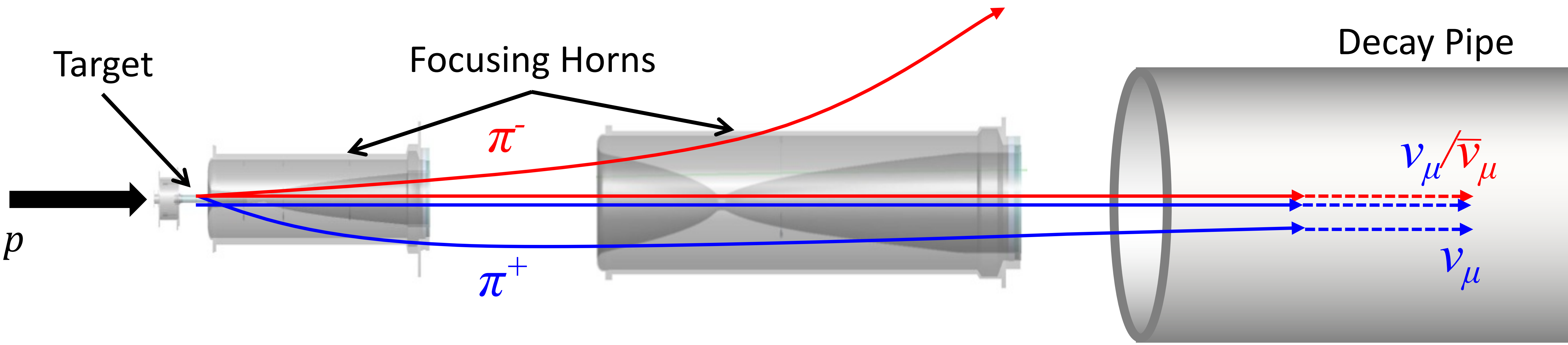
# How We Make Neutrinos: NuMI Beam



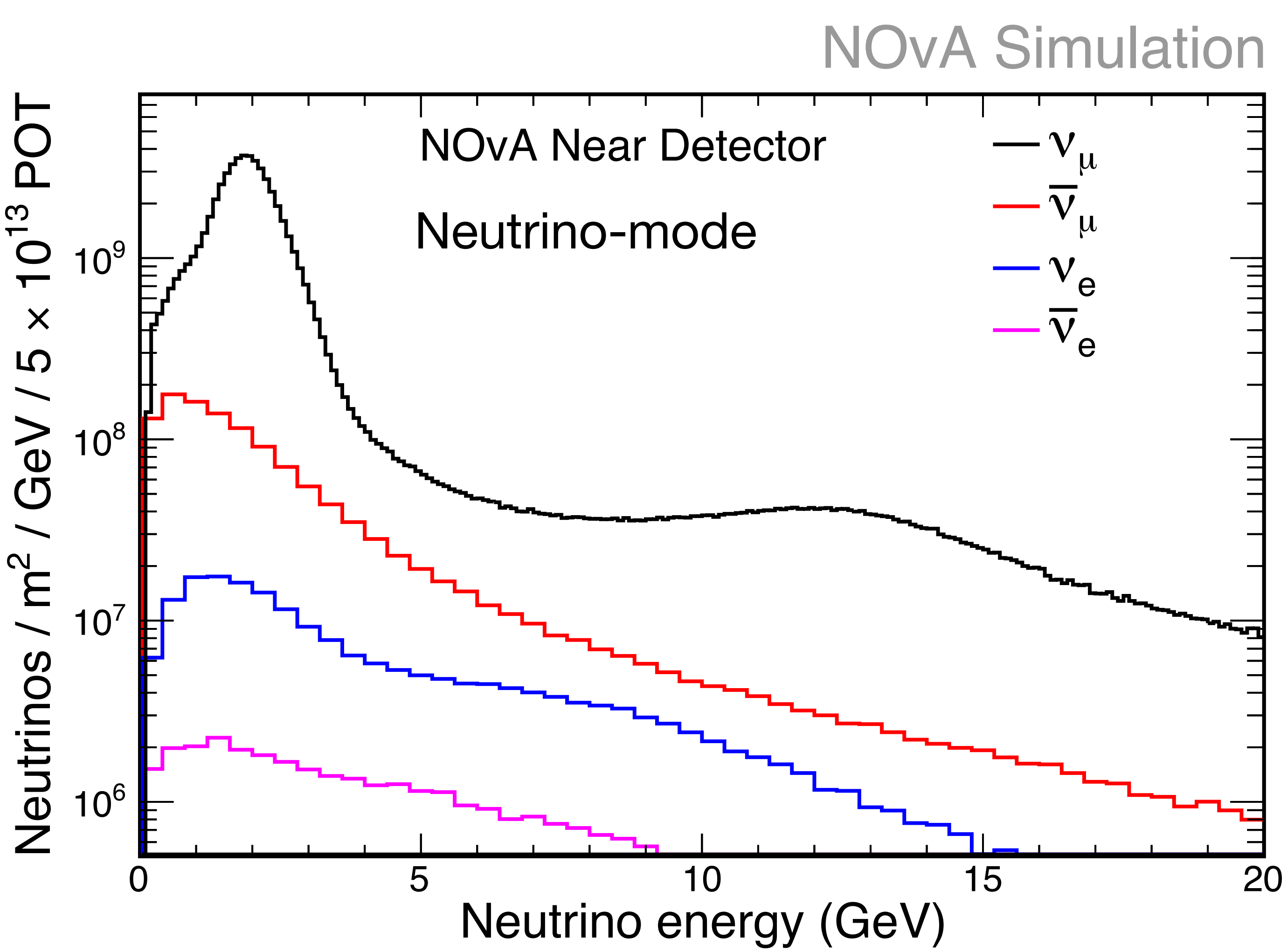

- 120 GeV protons from main injector onto graphite target.
- Spill every ~1.5 s, lasts 10 us.
- Hadron spray directed by focussing horns (± 200 kA, FHC/RHC).
- Pions decay (mostly) to muon/muon neutrino pairs.



# How We Make Neutrinos: NuMI Beam




- 14 mrad off axis, peak at 2 GeV.
- 96% pure $\nu_\mu$, 3% $\bar{\nu}_\mu$.
- ~1% $\nu_e + \bar{\nu}_e$



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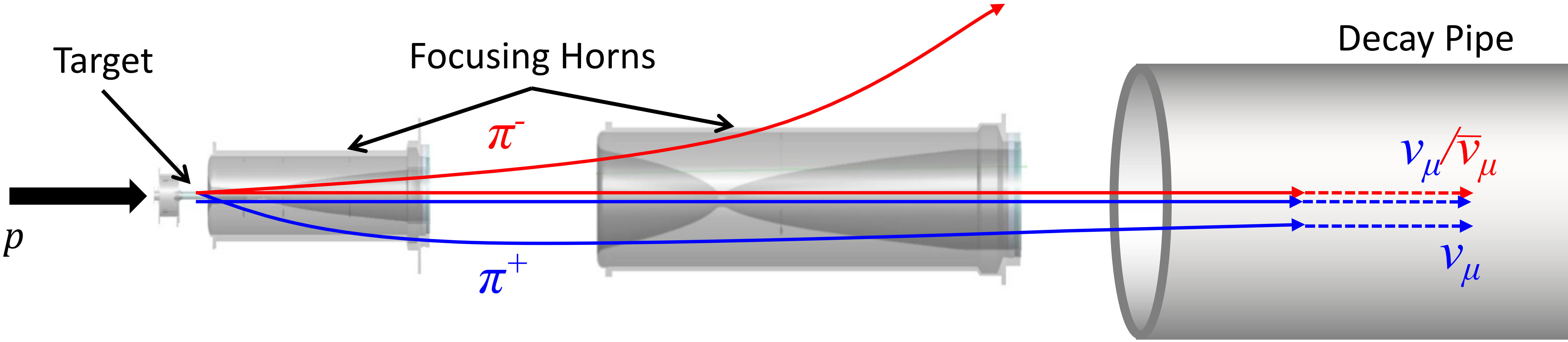
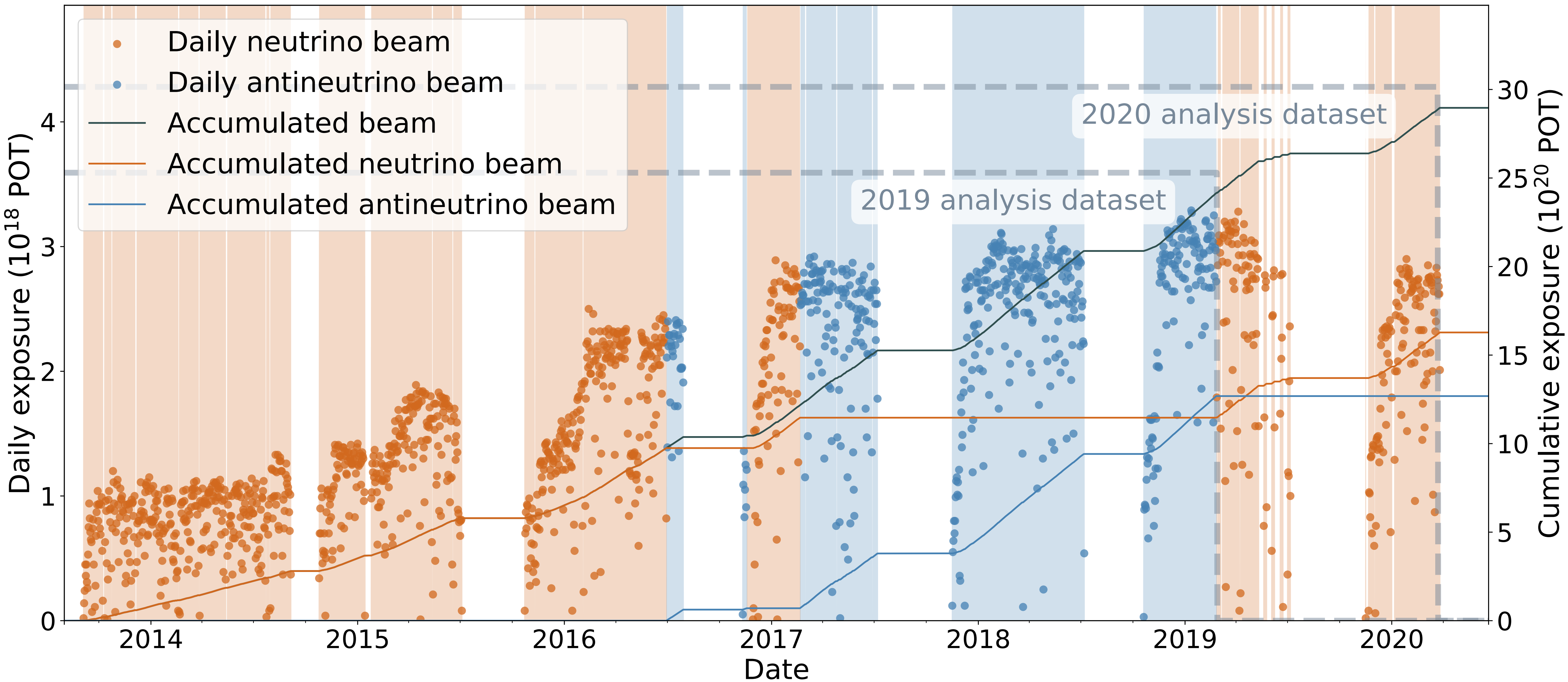
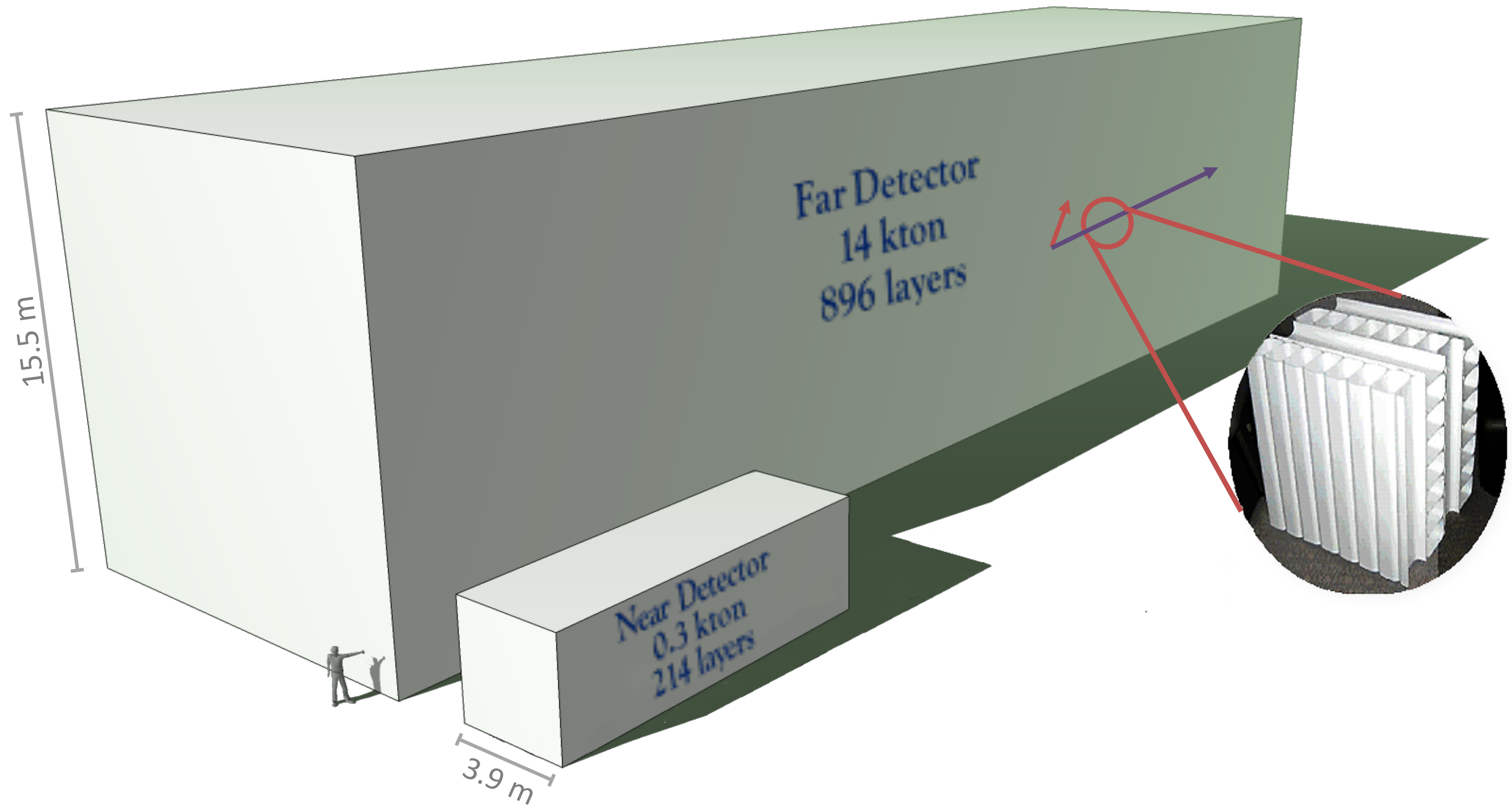


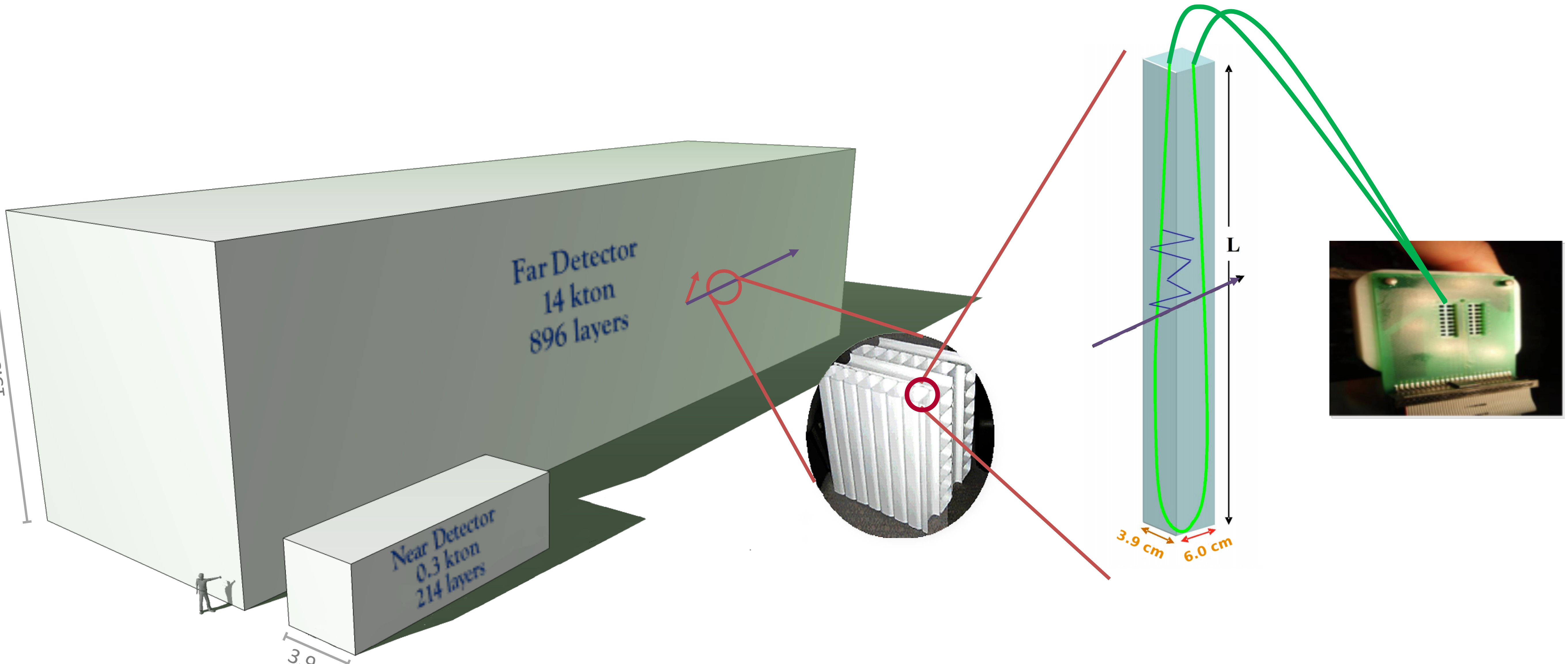



# The NOvA Detectors




- Both are large, (FD 60 m long).
- Functionally identical: consist of extruded PVC cells filled with 11 million litres of liquid scintillator.
- Arranged in alternating directions for 3D reconstruction.
- FD on surface, ND 100 m underground.

# The NOvA Detectors




- Light produced when charged particle passes through cells.
- The light is picked up by wavelength shifting fibre. Transported to an Avalanche PhotoDiode - light collected and amplified.
- Good timing resolution. ~ few ns.

# 2020 Analysis Methodology

# Analysis Strategy

Observe flavour change as a function of energy over a long distance while mitigating uncertainties on neutrino flux, cross sections and detector response.

# Analysis Strategy

Particle ID

Reconstruction

Observe flavour change as a function of energy over a long distance while mitigating uncertainties on neutrino flux, cross sections and detector response.

Extrapolation

Models

# Analysis Strategy

Particle ID

Reconstruction

Observe flavour change as a function of energy over a long distance while mitigating uncertainties on neutrino flux, cross sections and detector response.

Extrapolation

Models

**Updated for 2020**

# Analysis Strategy

Improved robustness to:

- Pile-up of multiple interactions.
- Detector variation over time.

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Observe flavour change as a function of energy over a long distance while mitigating uncertainties on neutrino flux, cross sections and detector response.

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**Updated for 2020**

# Analysis Strategy

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Reconstruction

Observe flavour change as a function of energy over a long distance while mitigating uncertainties on neutrino flux, cross sections and detector response.

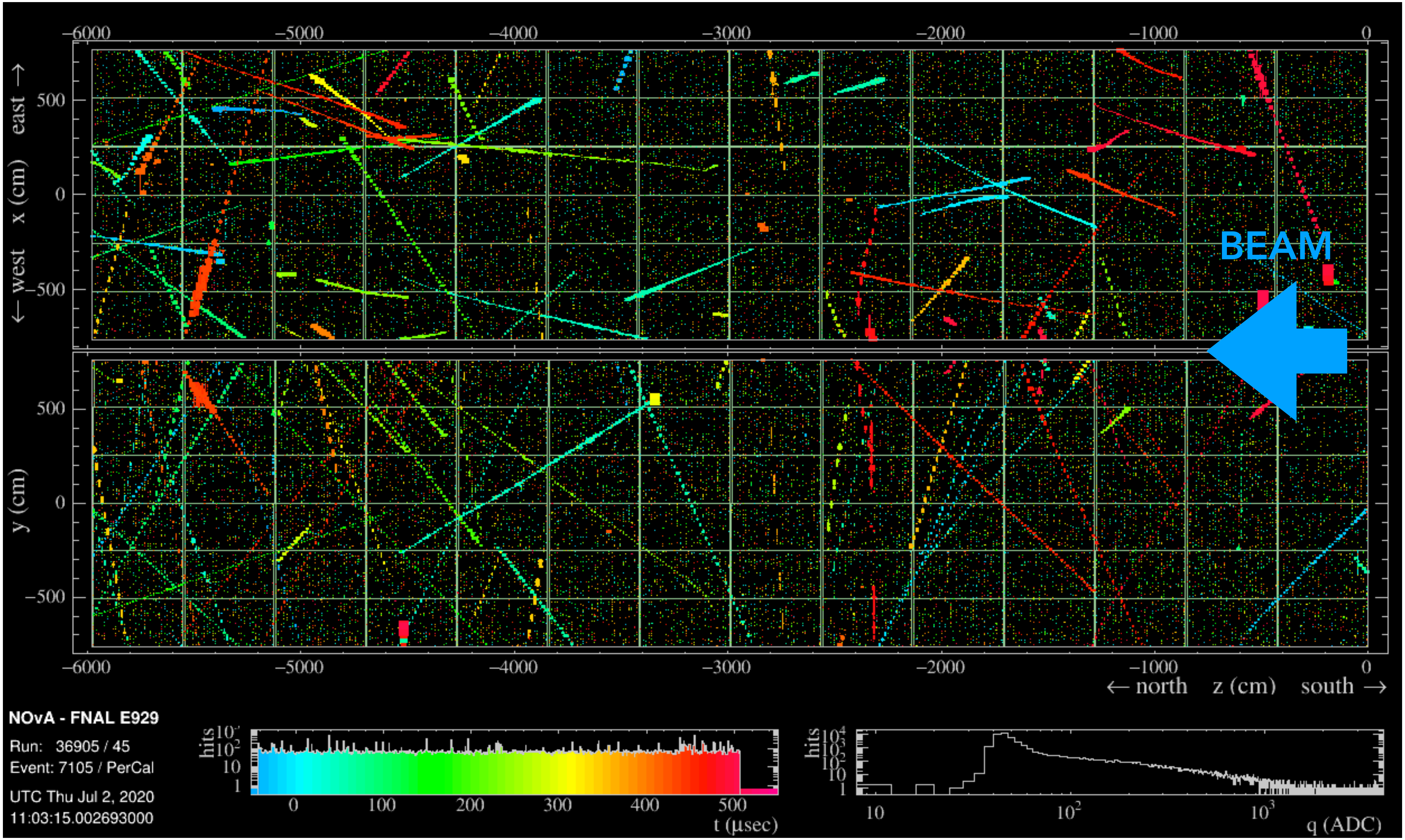
Extrapolation

Models

- New version of GEANT4.
- Updated geometry and light model.
- Updated cross-section model.

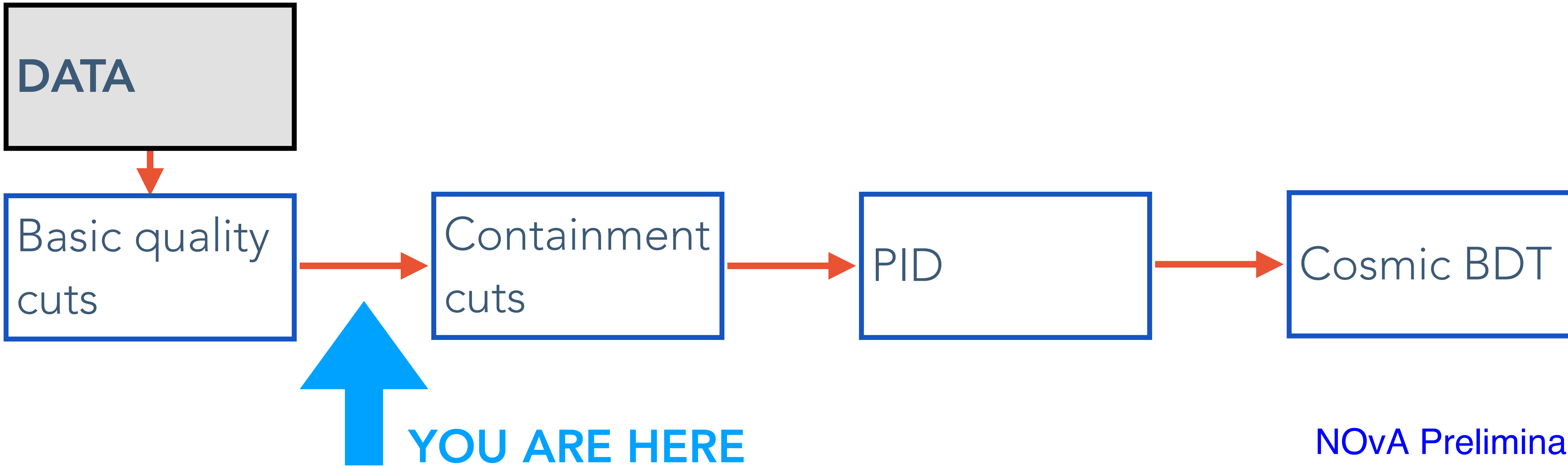
**Updated for 2020**

# Selection: Cosmic Rejection

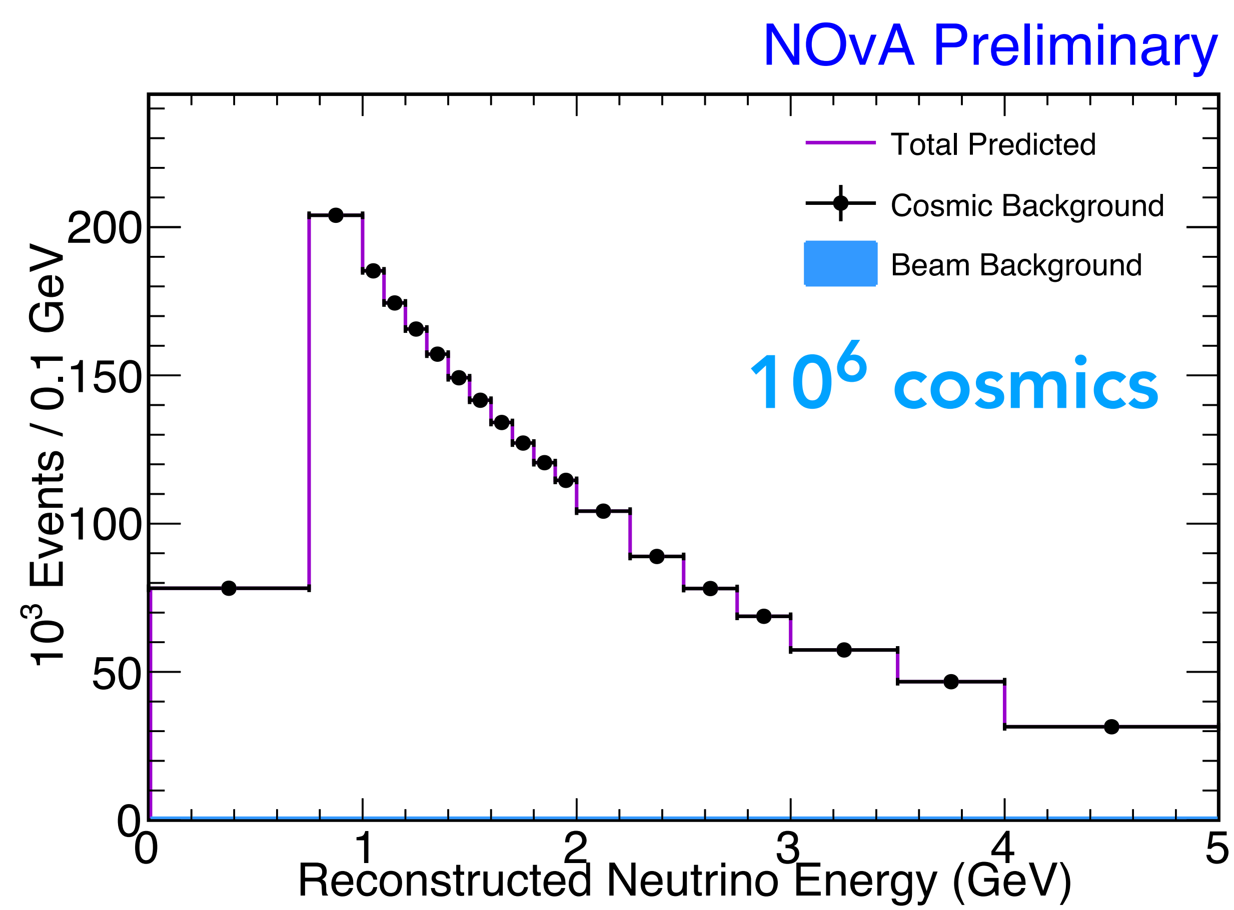



**Cosmic rejection critical for FD: 11 billion cosmic rays/day**

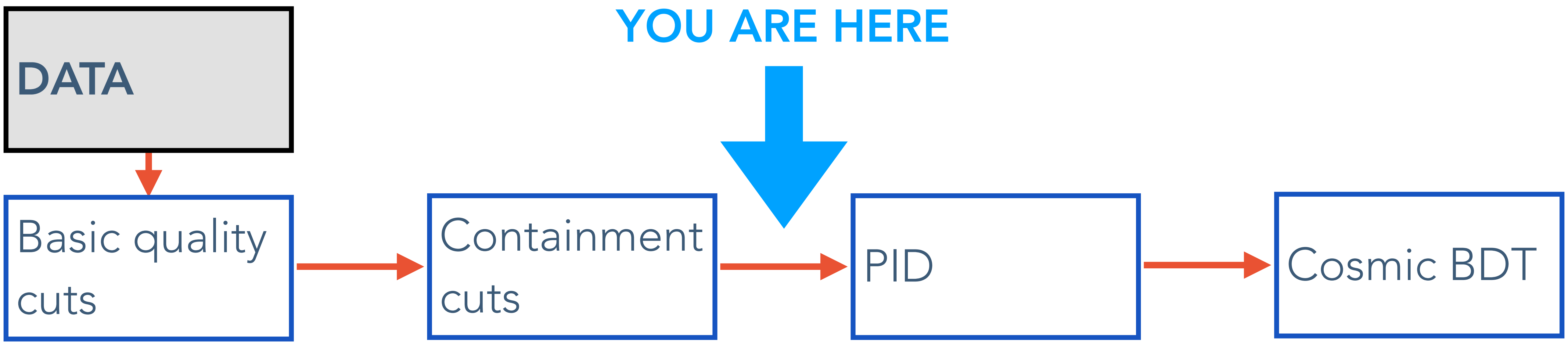
# Selection: $\nu_\mu$



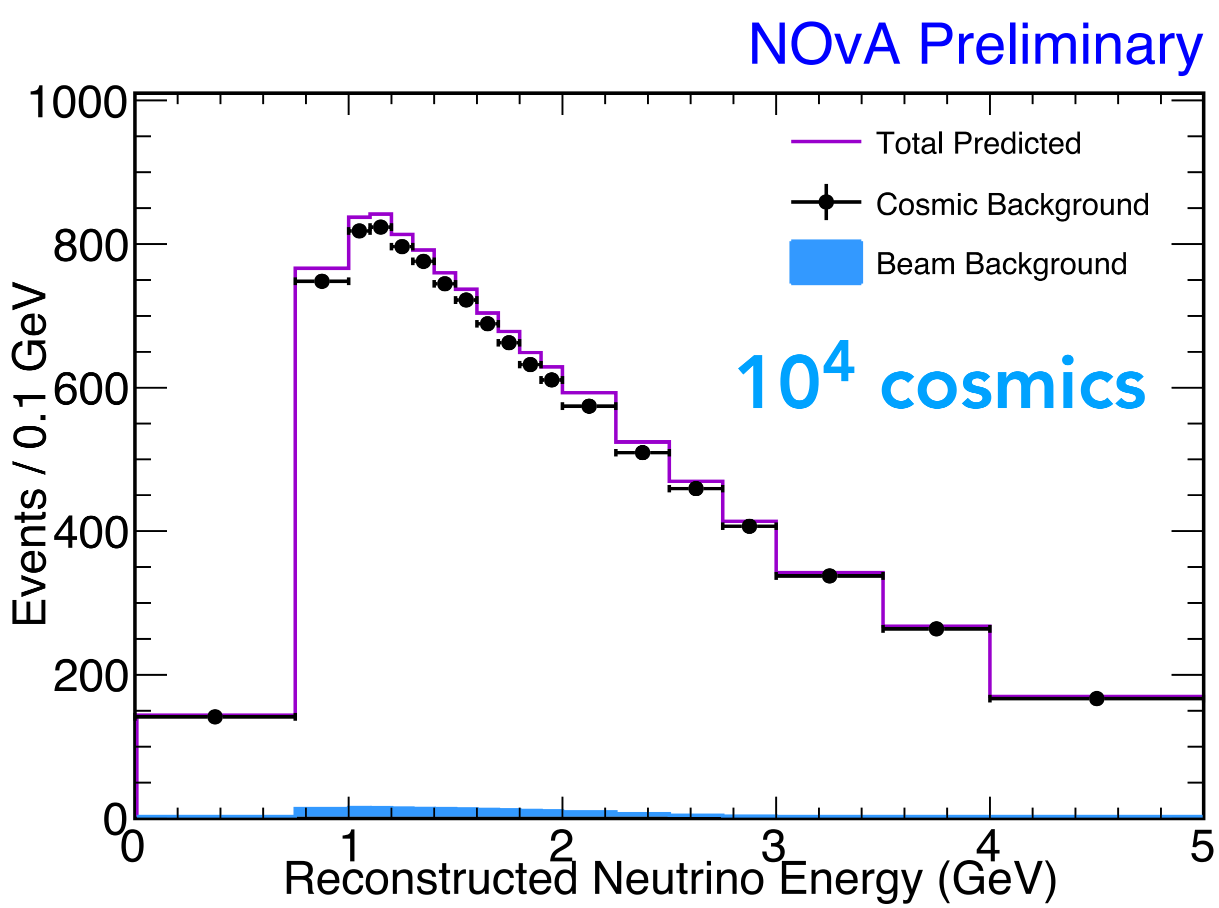

- Even with pulsed beam and excellent timing resolution, still a significant amount of cosmic background.
- Basic quality:
  - Number of hits, track angle, reasonable energy reconstructed.



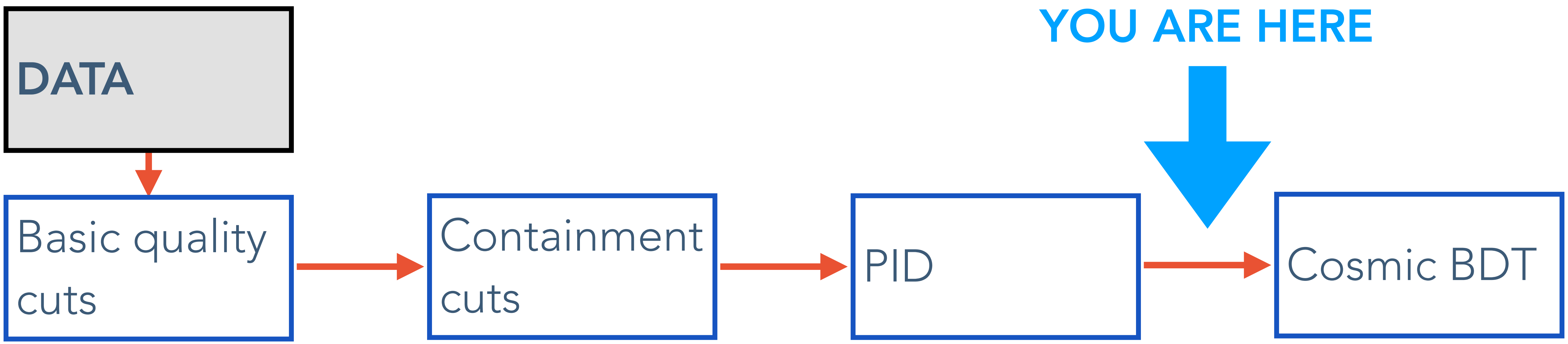
# Selection: $\nu_\mu$



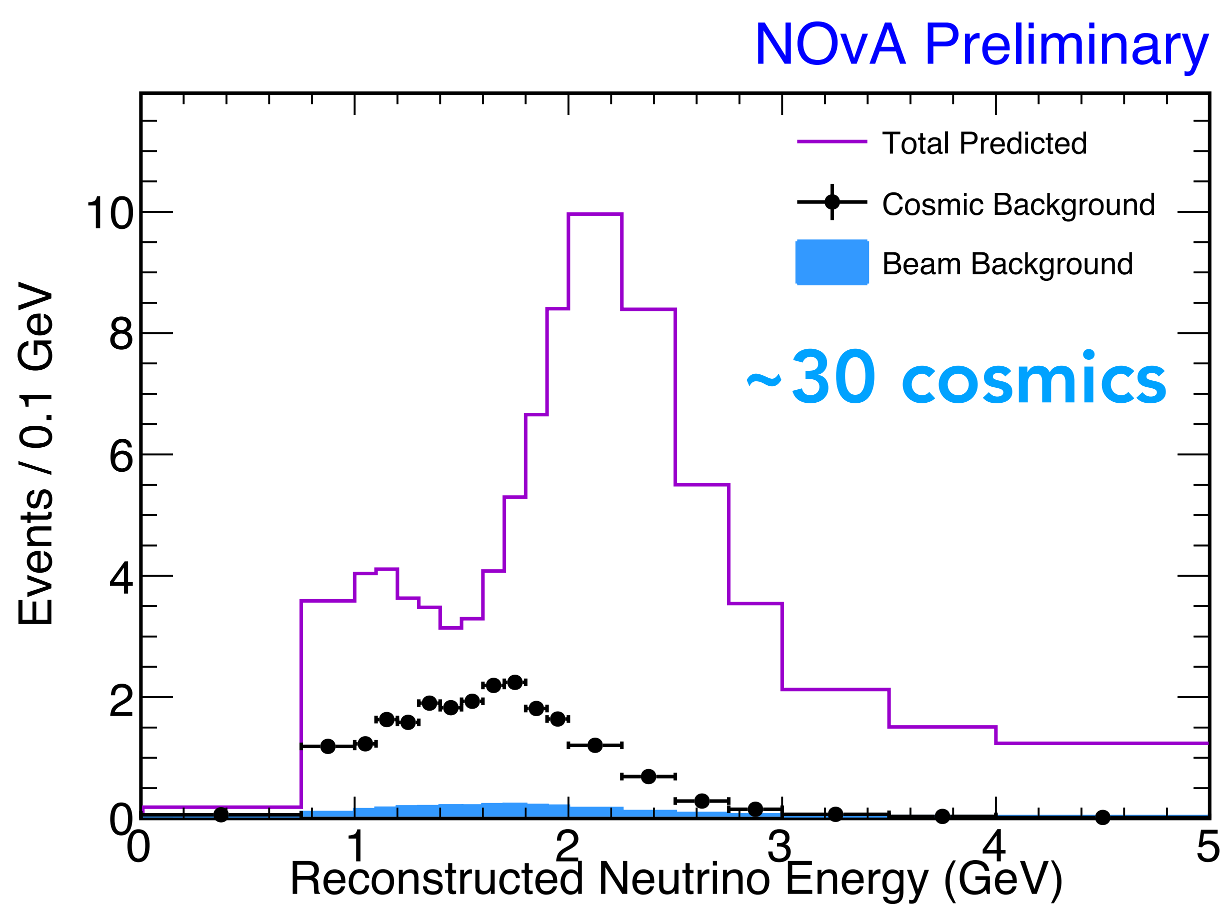

- Even with pulsed beam and excellent timing resolution, still a significant amount of cosmic background.
- Containment cuts:
  - Vertices in the fiducial volume.
  - Event contained within the detector.



# Selection: $\nu_\mu$




- Even with pulsed beam and excellent timing resolution, still a significant amount of cosmic background.
- PID:
  - Deep learning approach.



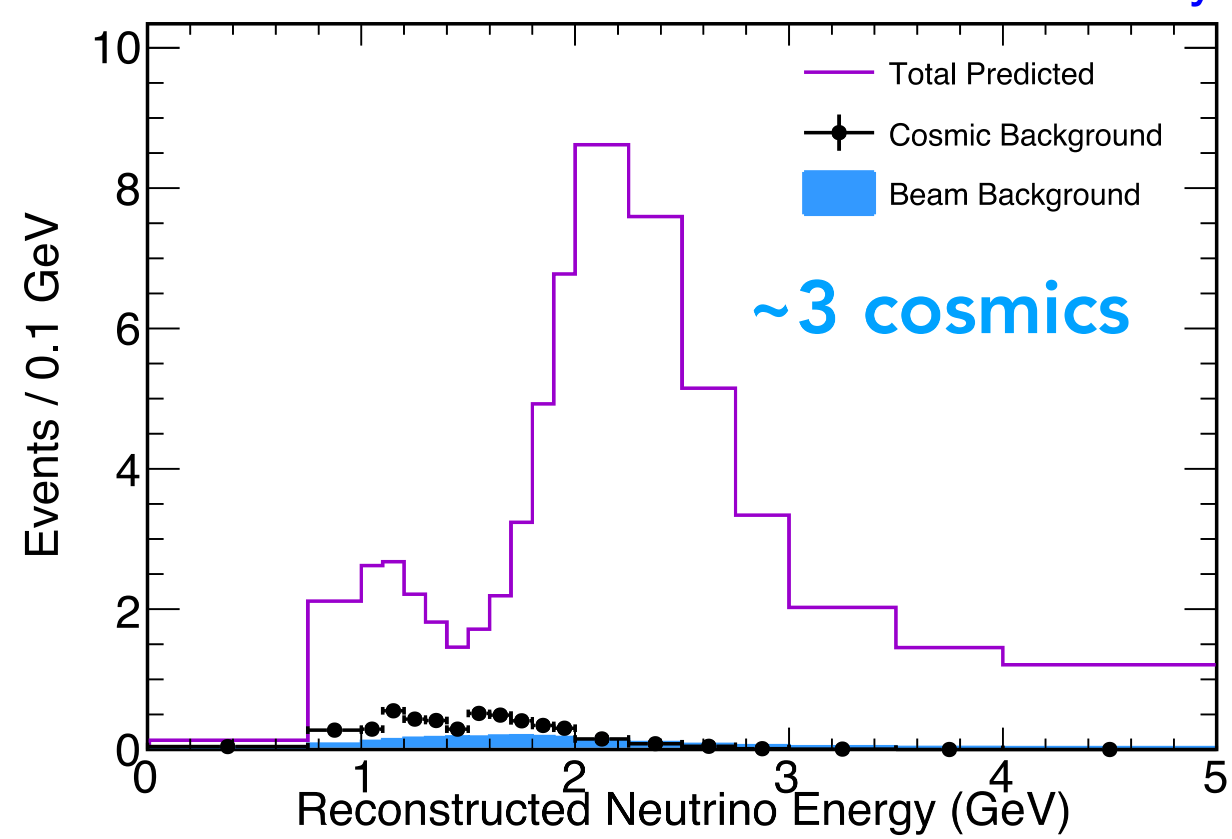
# Selection: $\nu_\mu$

DATA → Basic quality cuts → Containment cuts → PID → Cosmic BDT

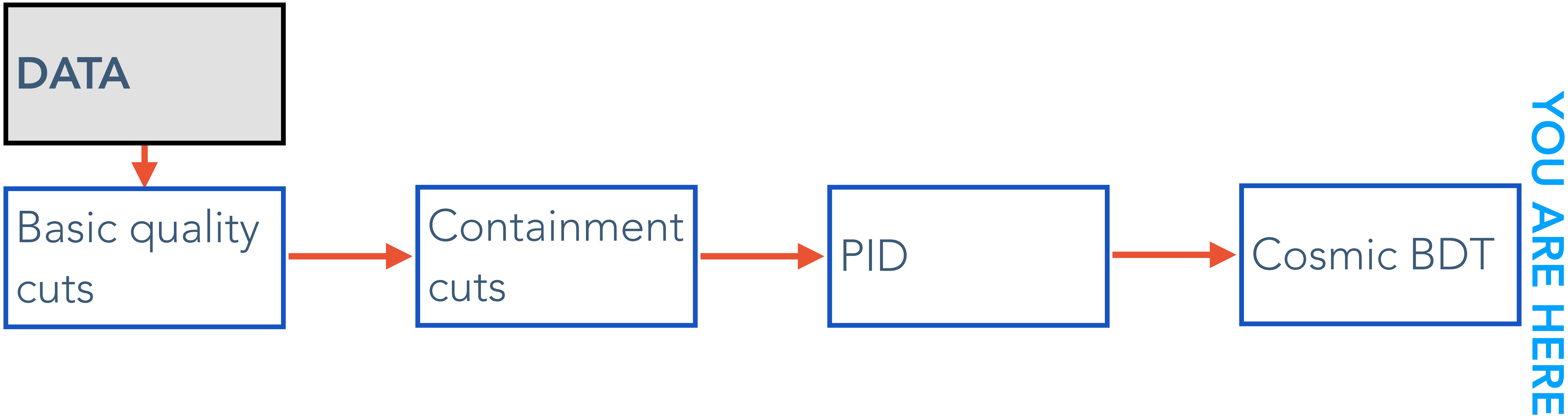
YOU ARE HERE

- Even with pulsed beam and excellent timing resolution, still a significant amount of cosmic background.

- Cosmic BDT:
  - Tuned to reject cosmic ray events.

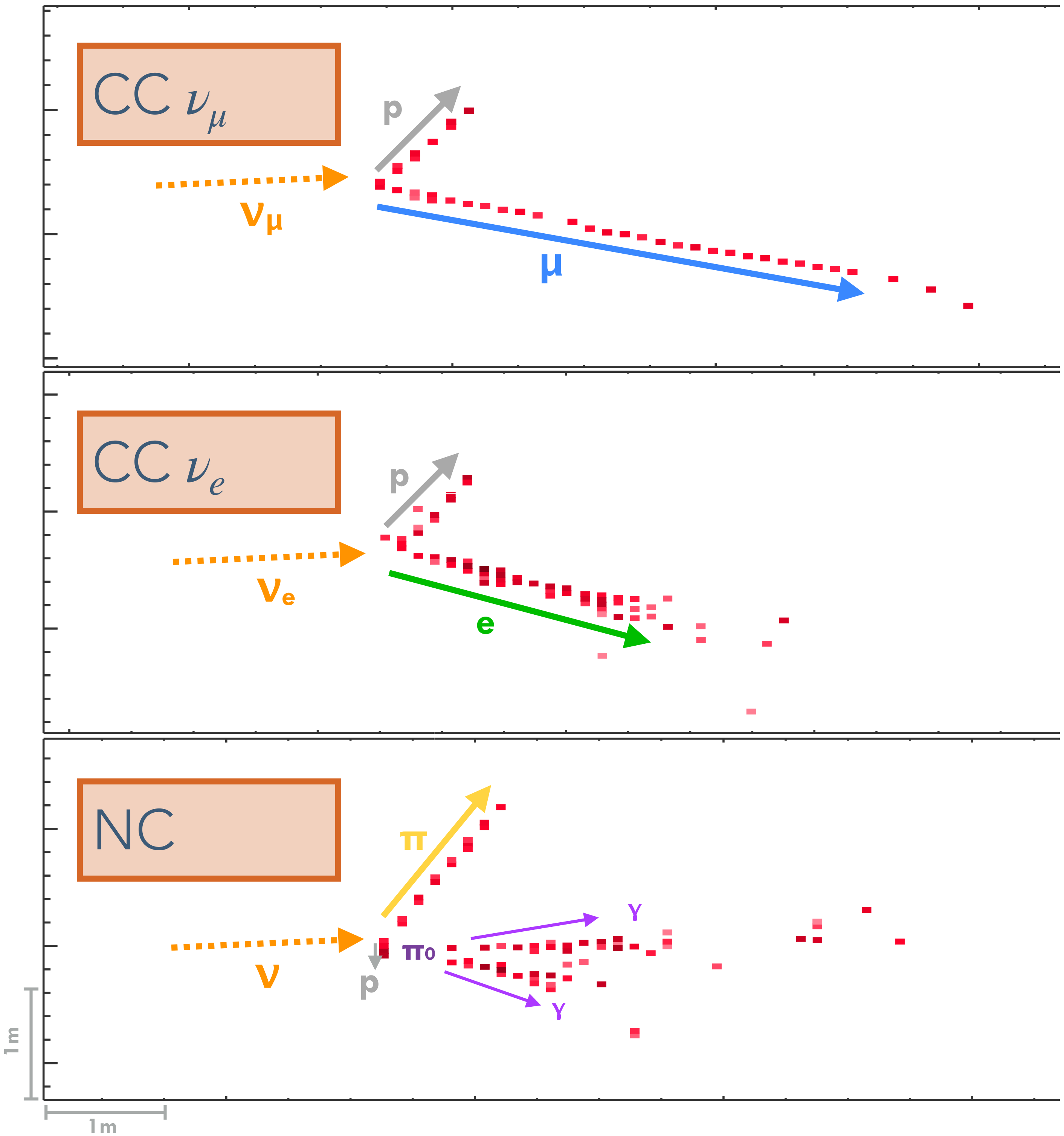


# Selection



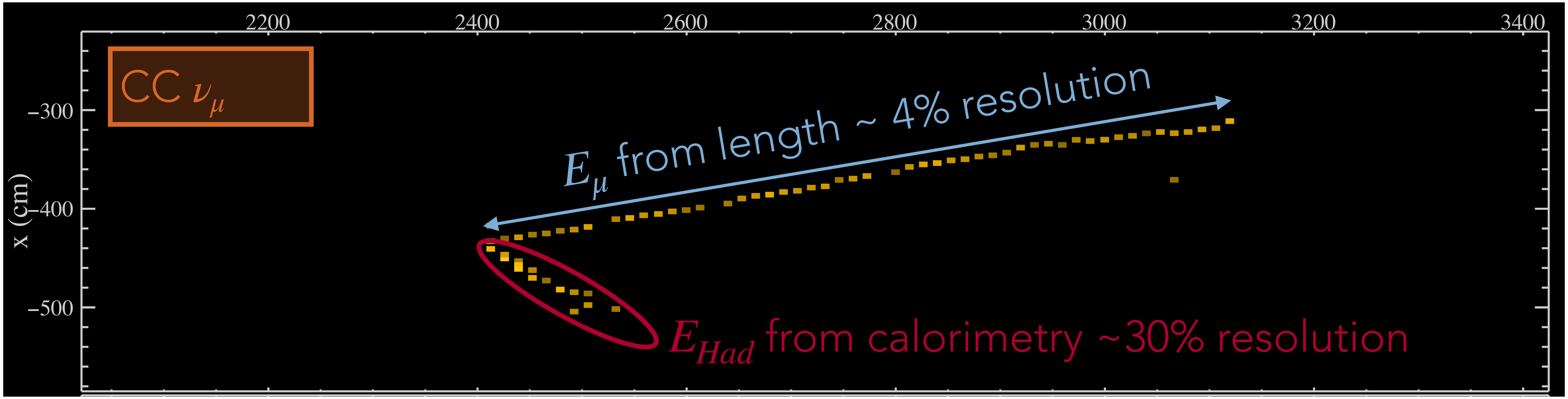

- Electron neutrino sample has second ‘peripheral’ sample containing high-confidence electron neutrino events close to detector walls.

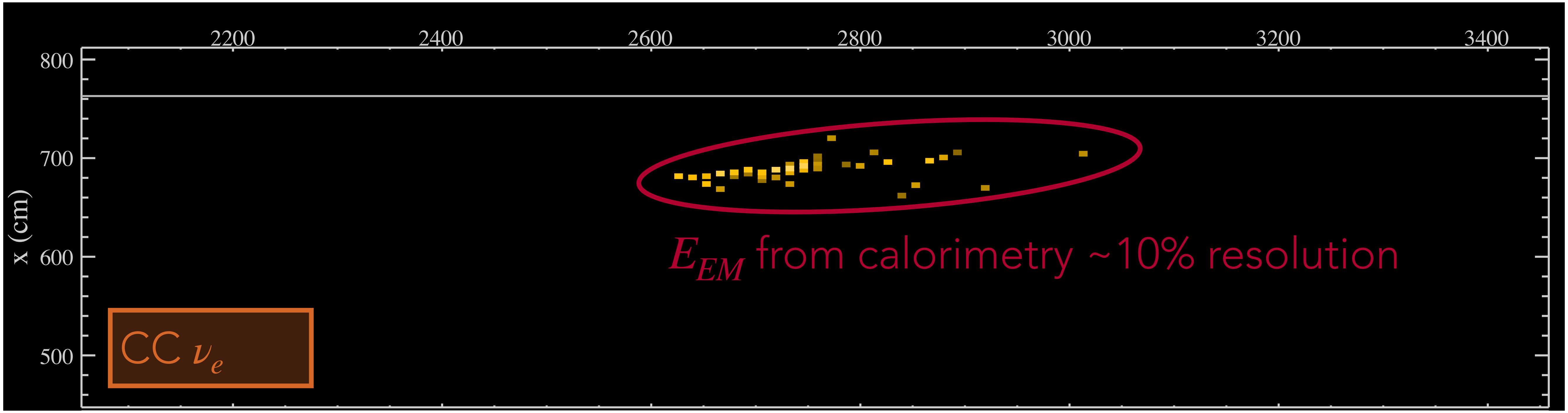
# Selecting & Identifying Neutrinos



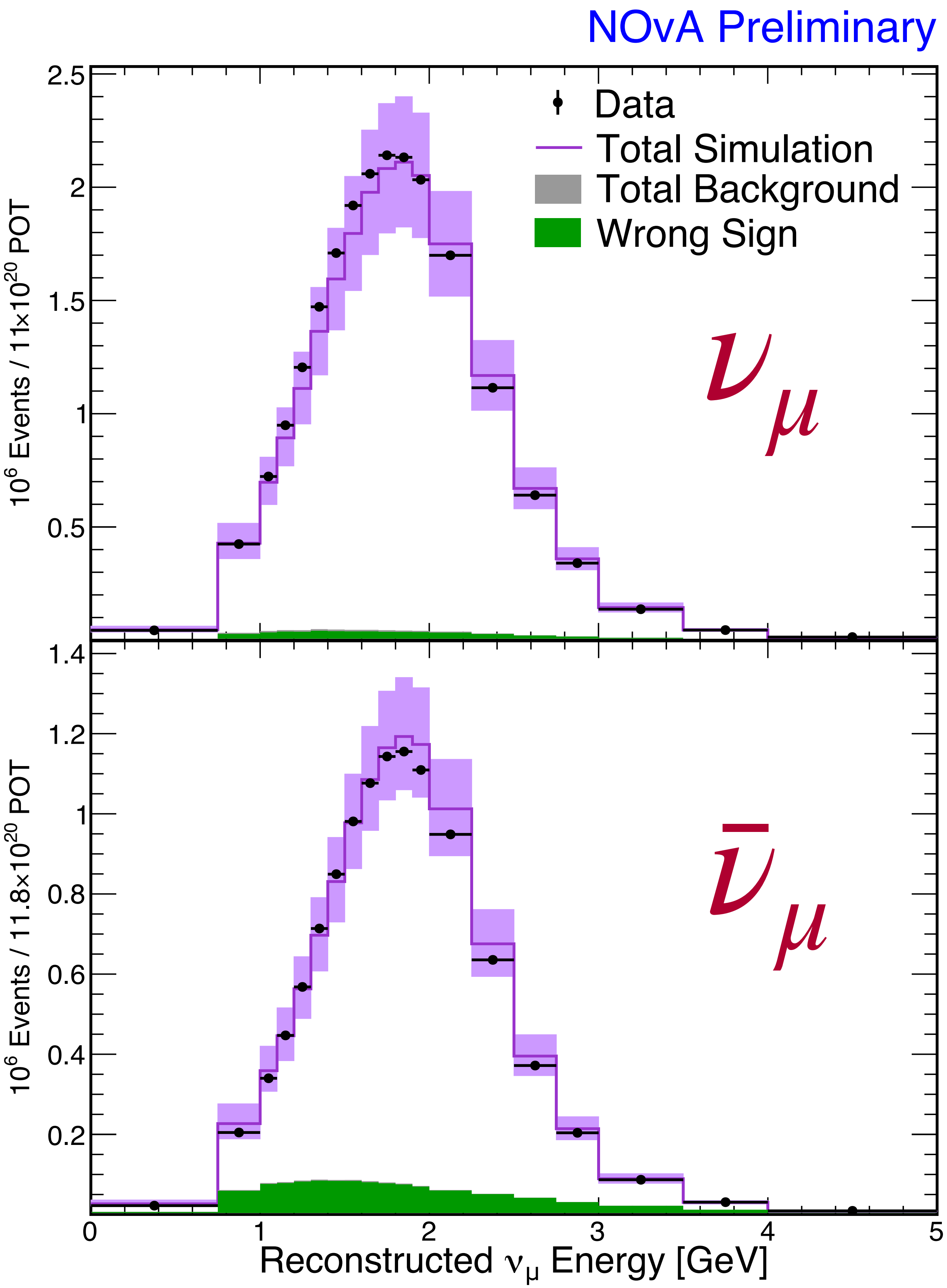

- Use **convolutional neural network** technique from deep learning.
  - NOvA was first HEP experiment to use CNN for PID.
- Successive layers of "feature maps":
  - Create many variants of original image which enhance different features.
  - Maps which are best for enhancing most important features for PID are learned.
  - Output is a **multi-label classifier.**
- **Improvement in sensitivity equivalent to 30% more exposure.**

# Energy Reconstruction



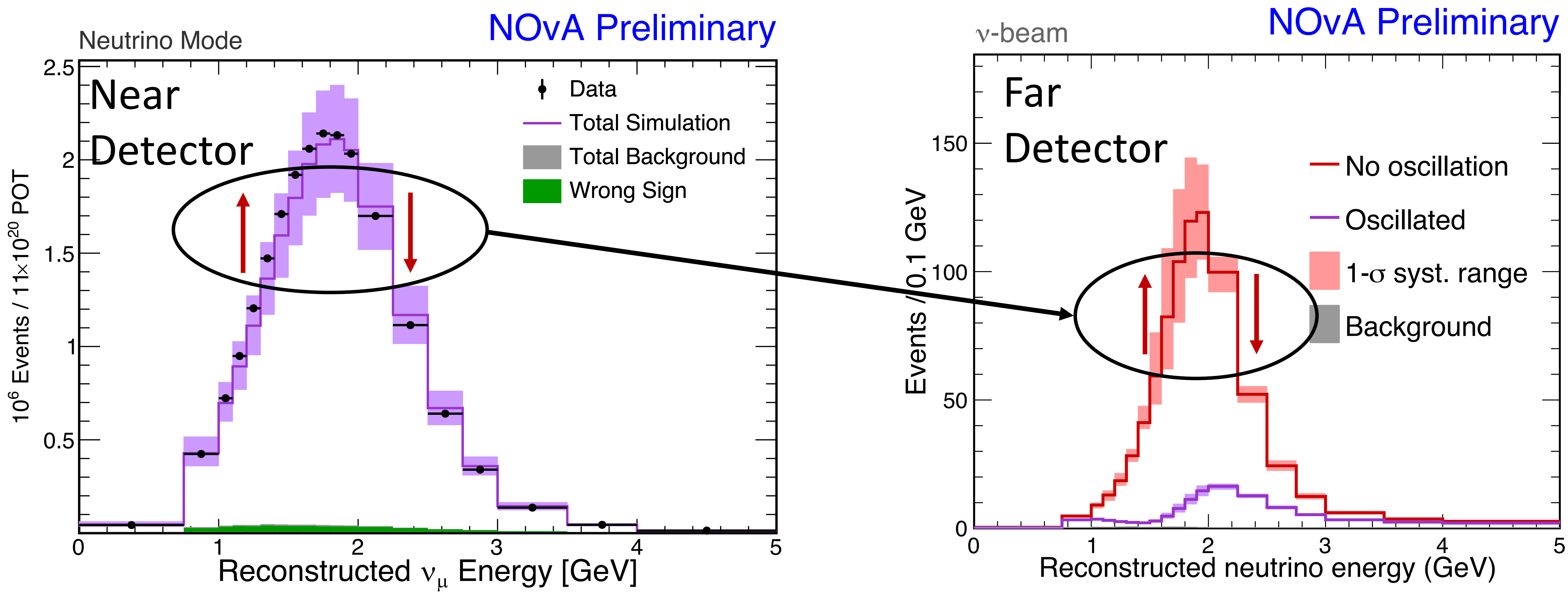



# Near Detector, $\nu_\mu$



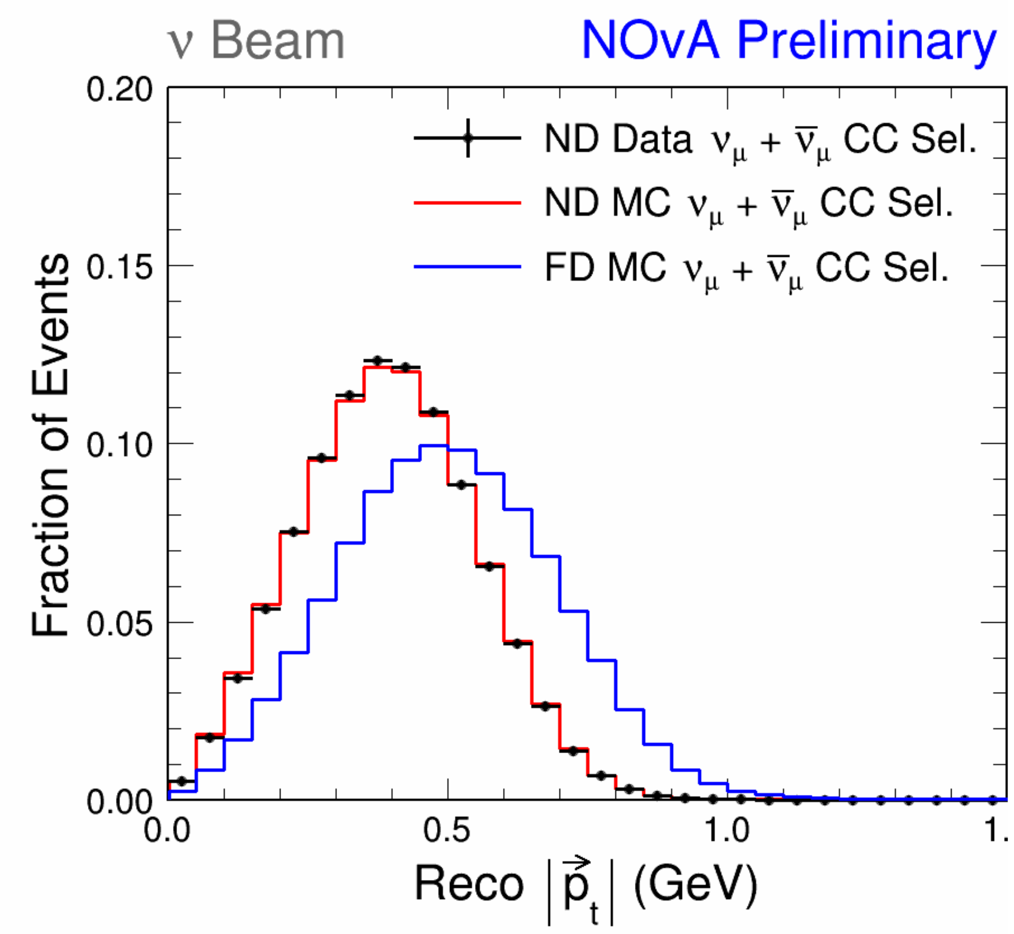

- Band around MC shows the large impact of flux and cross-section uncertainties when using a single detector.
- Use samples as a data constraint on what we predict at the Far Detector.
- These samples are used to predict both the $\nu_\mu$ and the $\nu_e$ signal spectra at the Far Detector.
- Appearing $\nu_e$'s are still $\nu_\mu$'s at the Near Detector.

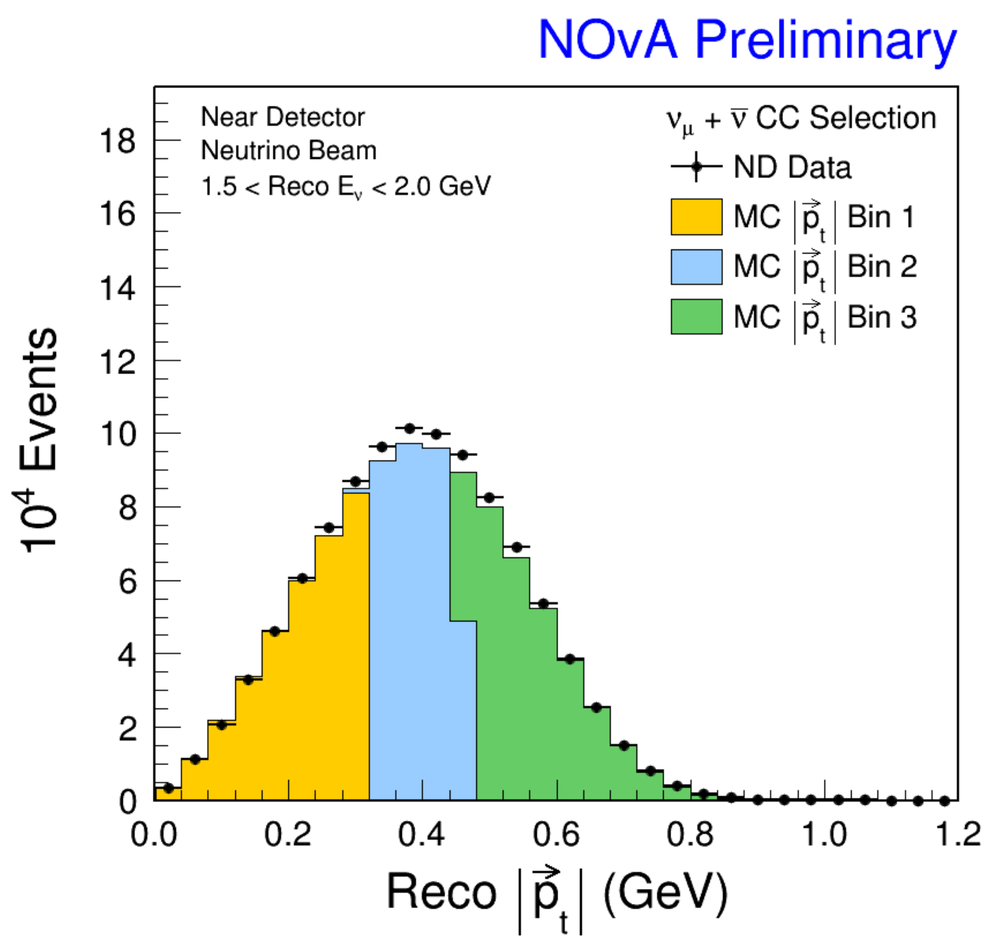
# Extrapolation

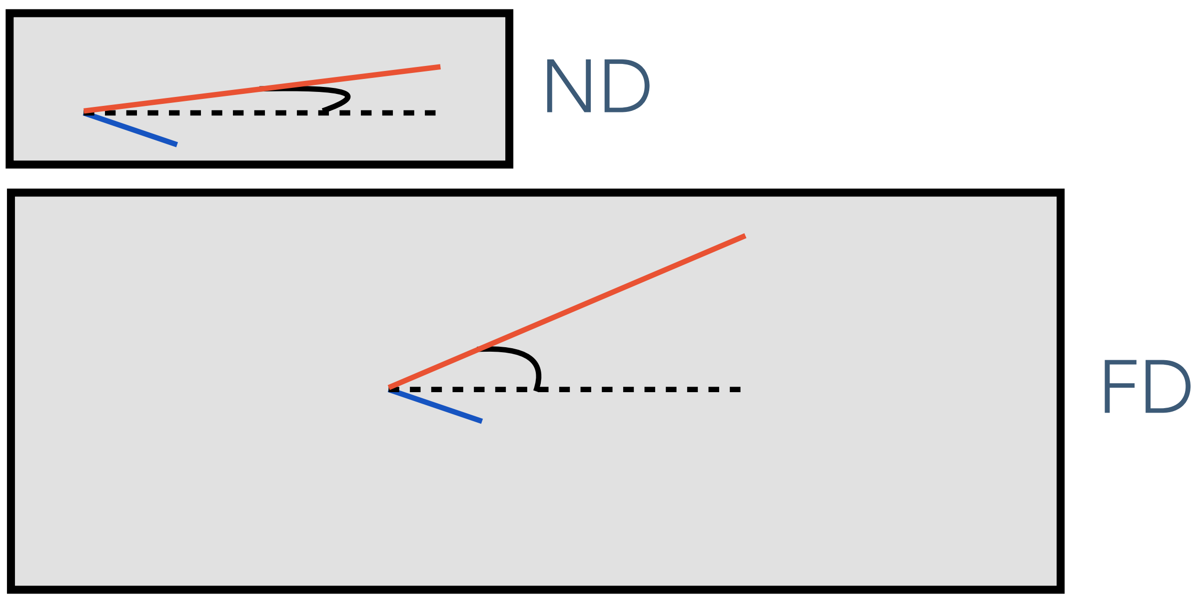



- Observe data-MC differences at the ND, use them to modify the FD MC.
- Significantly reduces the impact of uncertainties correlated between detectors.
  - Especially effective at rate effects like the flux (7% to 0.3%).

# Extrapolating Kinematics

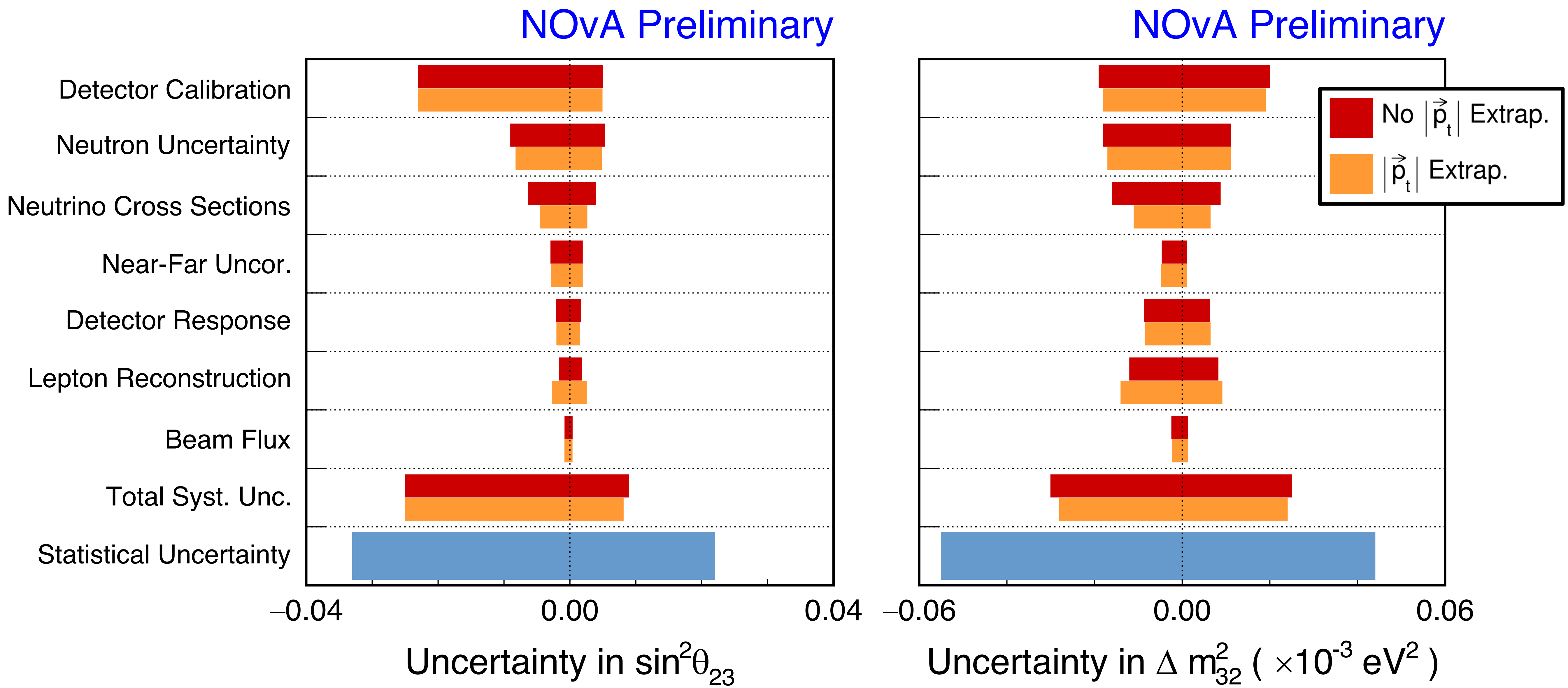


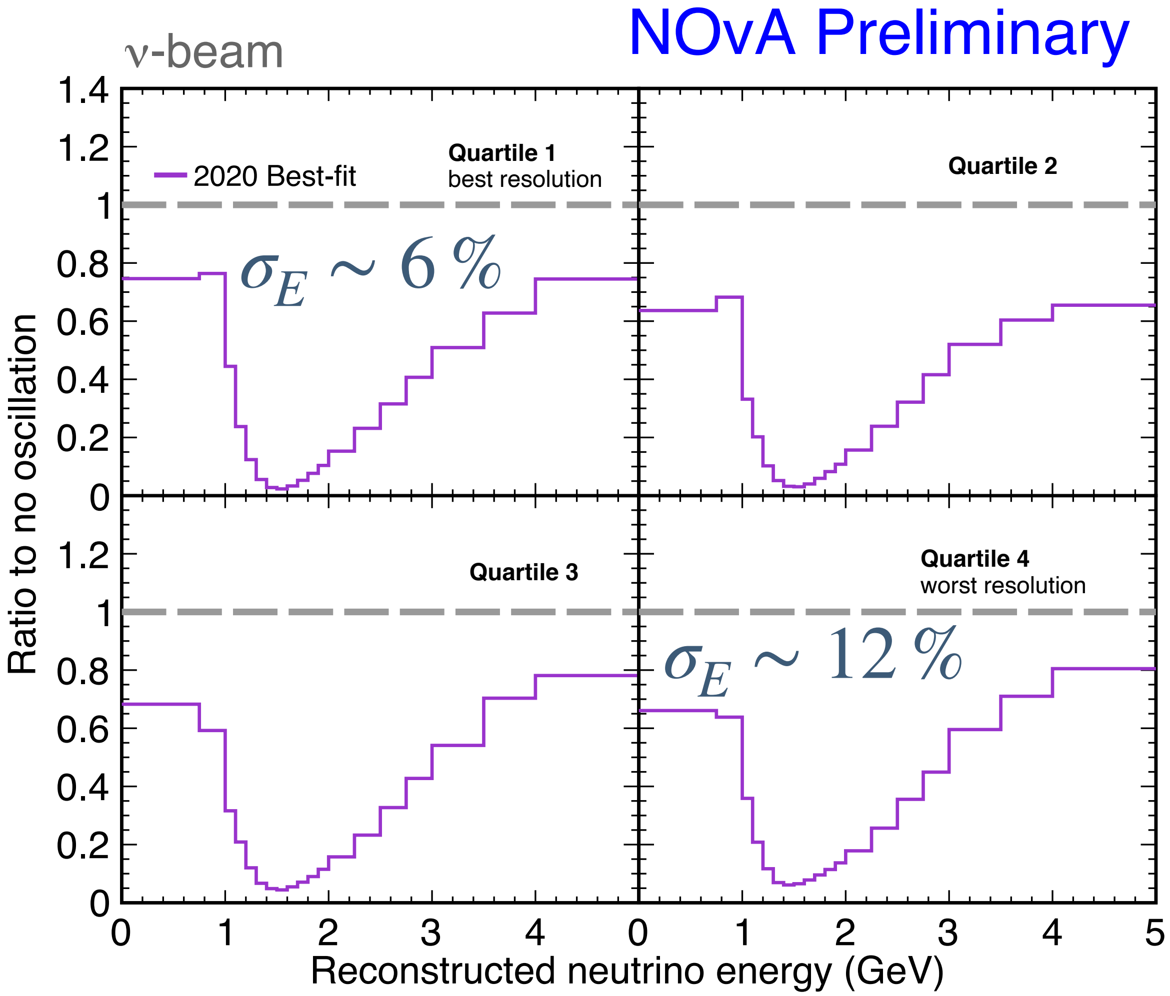

- Mitigate by extrapolating in bins of lepton transverse momentum, $p_t$.
- Split the ND sample into 3 bins of $p_t$, extrapolate each separately to the FD.
  - Effectively "rebalances" the kinematics to better match between the detectors.
  - Re-sum the $p_t$ bins before fitting.

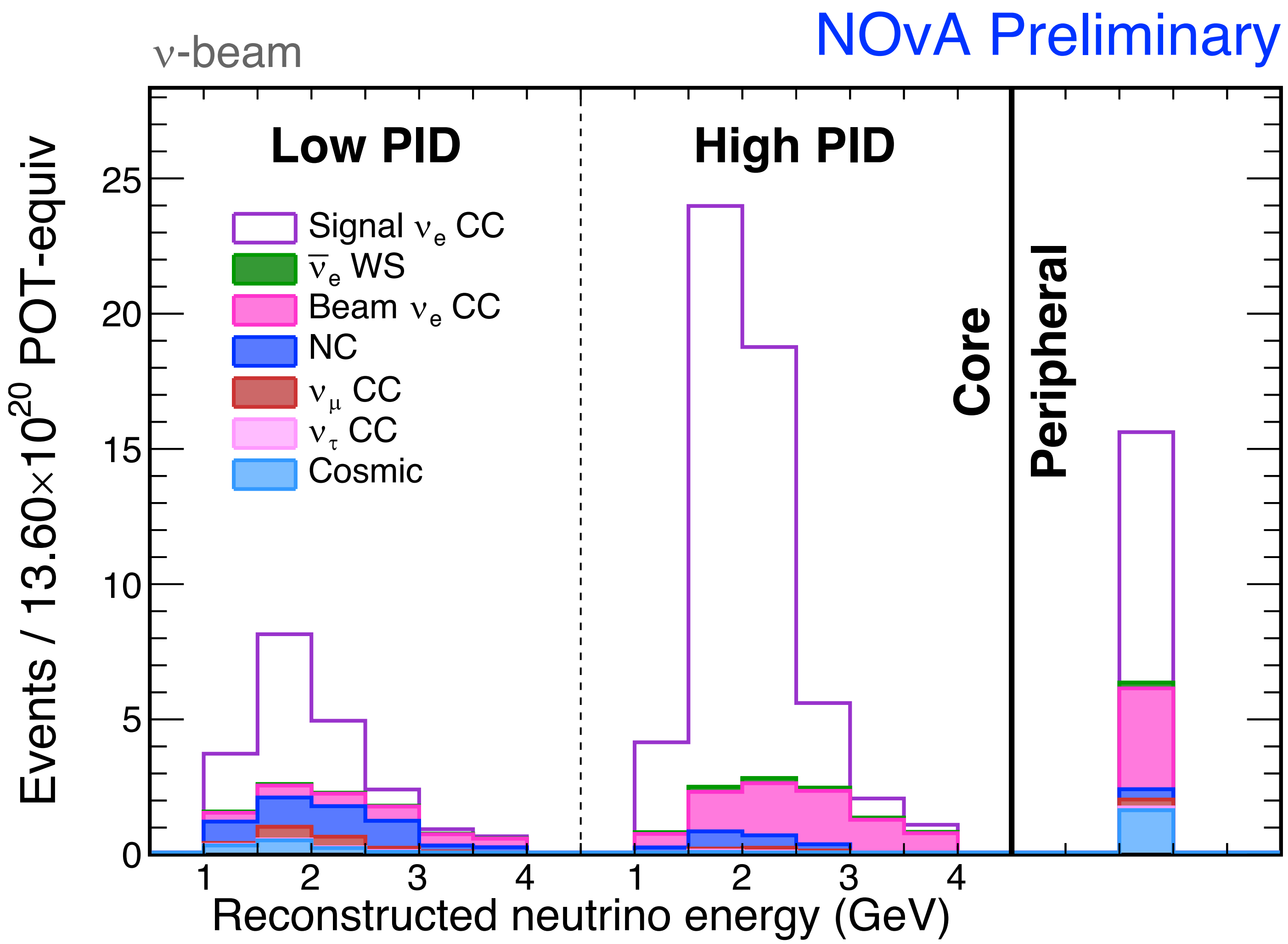
# Systematic Uncertainties with $p_t$ Extrapolation




- Overall systematic reduction is 5-10%.
- 30% reduction in cross-section uncertainties.
  - Reduces the size of systematics most likely to contain "unknown unknowns."
  - Slight increase in systematics on lepton reconstruction.

# Improving Sensitivity to Oscillations



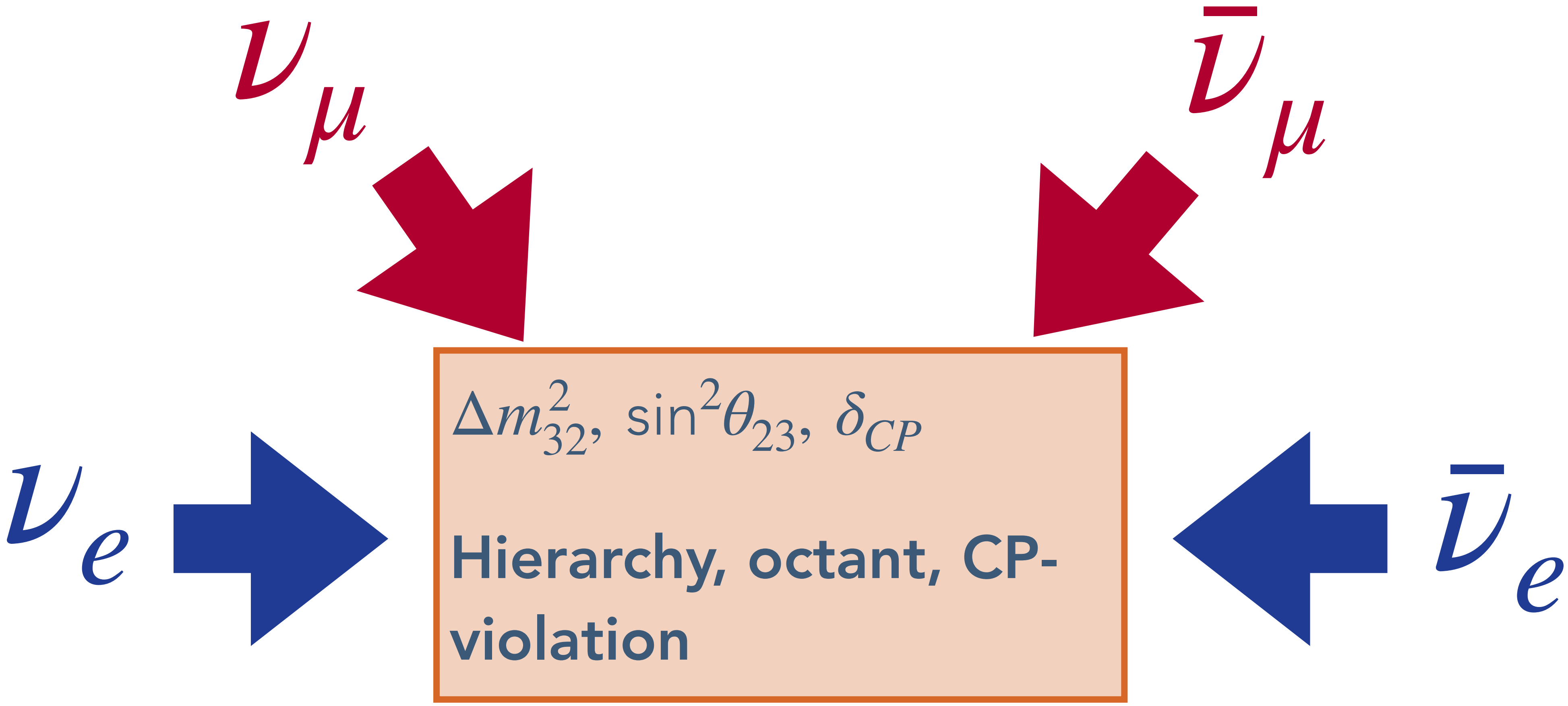

$\nu_\mu$

- Sensitivity depends primarily on the shape of the energy spectrum.
- Bin by energy resolution: bins of hadronic energy fraction.

$\nu_e$

- Sensitivity depends primarily on separating signal from background.
- Bin by purity: bin of low and high PID + peripheral.

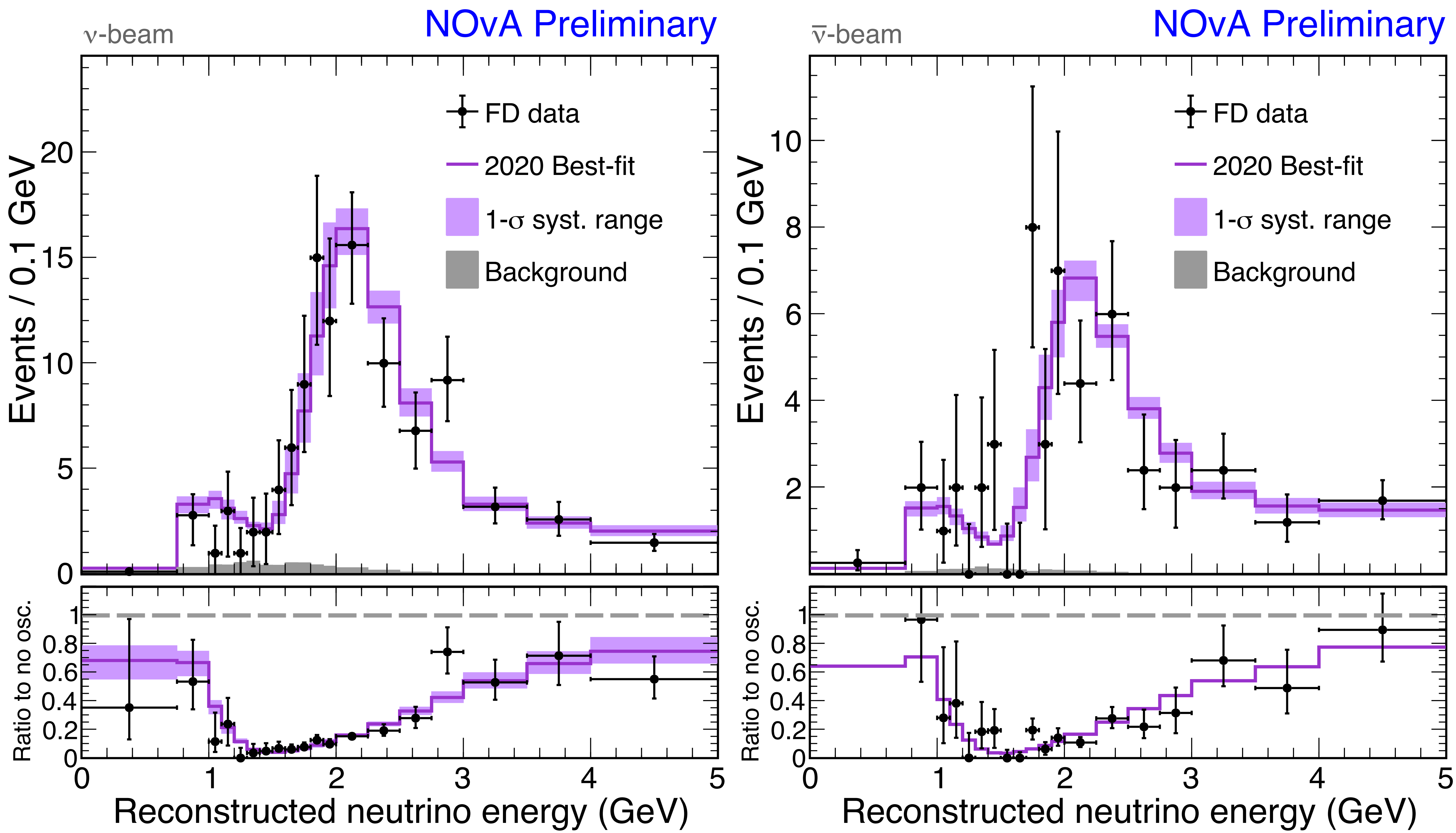
# Oscillation Fit




- All results come from a joint fit to neutrinos + antineutrinos, electron + muon.
- Other PMNS parameters are constrained by PDG.
- Minimisation of Poisson log-likelihood, systematics ~50 nuisance parameters.
- All confidence intervals and contours are Feldman-Cousins corrected to ensure proper coverage.

# Results: Neutrino 2020

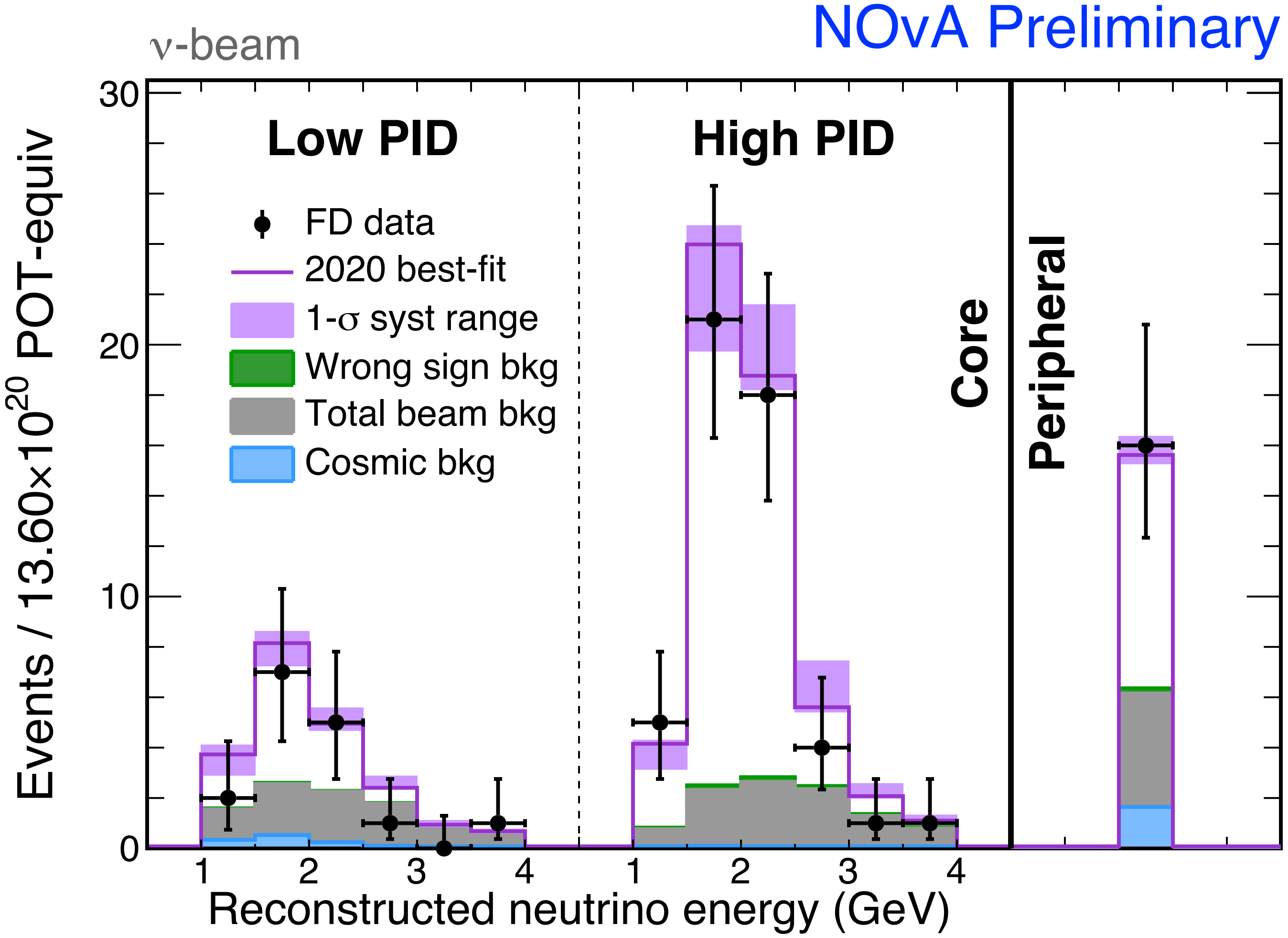
# $\nu_\mu$ and $\bar{\nu}_\mu$ Data at the Far Detector

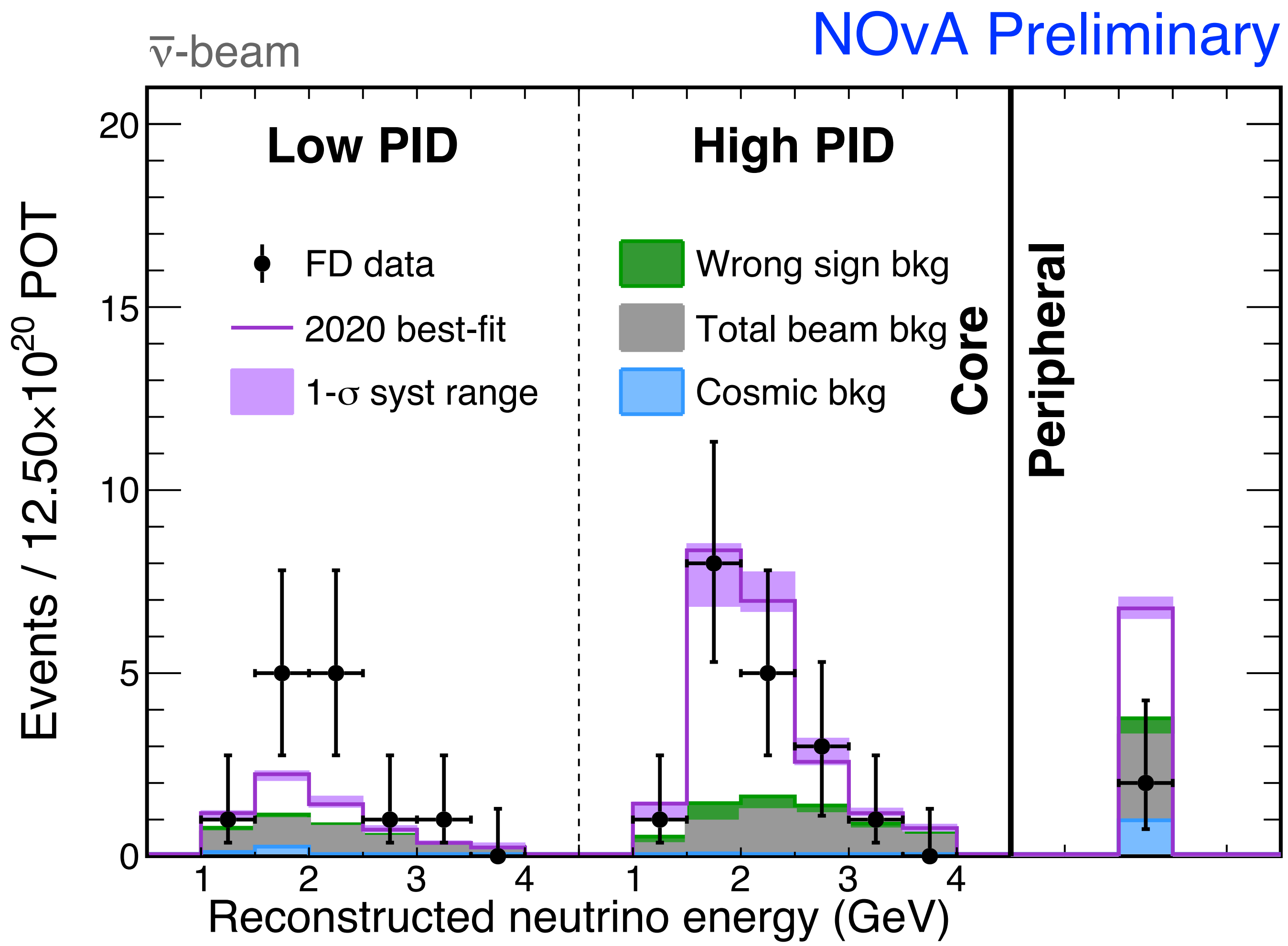



211 events, 8.2 background

105 events, 2.1 background

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



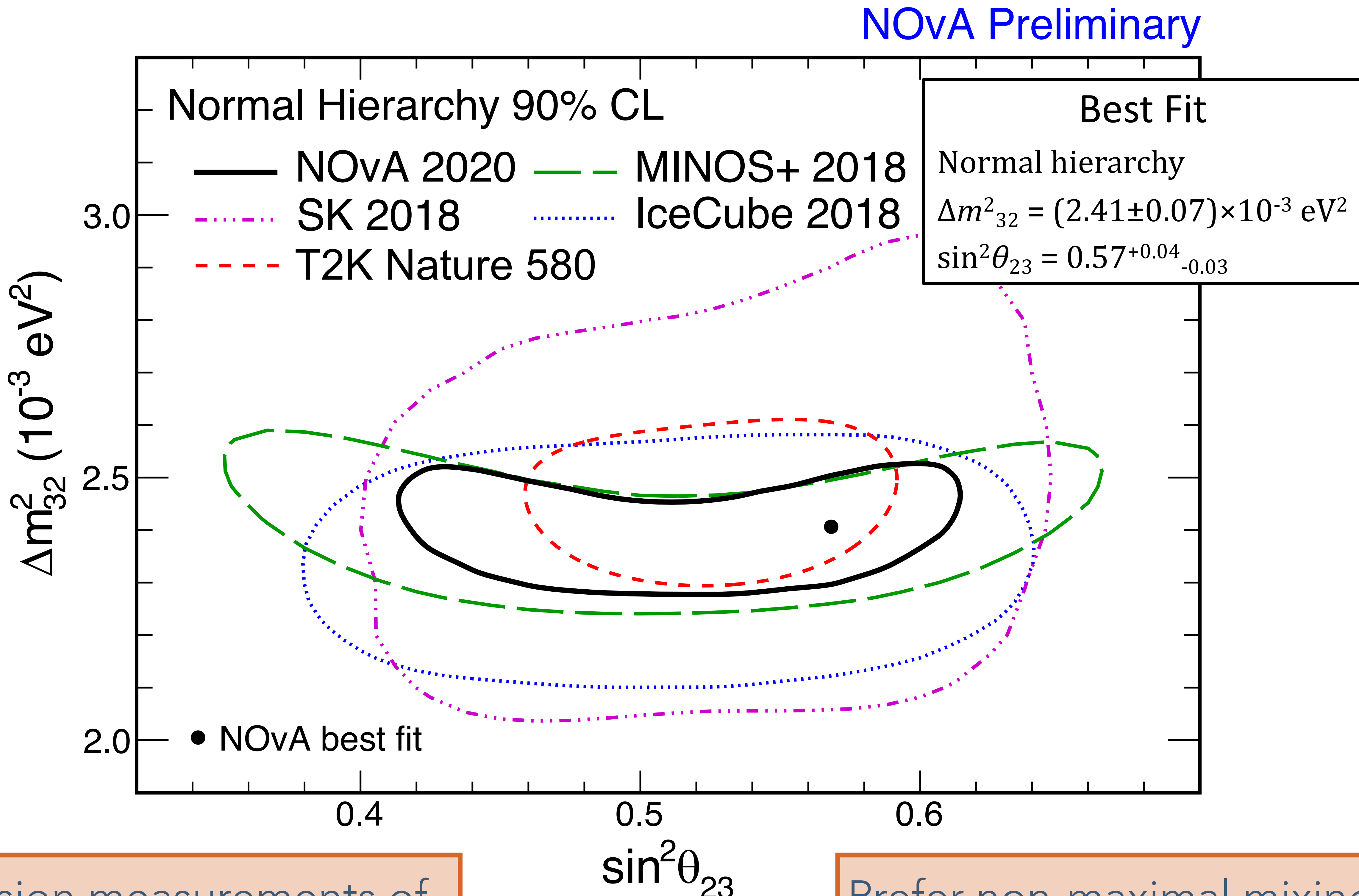




| Total Observed | 82 | Range |
|---|---|---|
| Total Prediction | 85.8 | 52-110 |
| Wrong-sign | 1.0 | 0.6-1.7 |
| Beam Bkgd. | 22.7 | |
| Cosmic Bkgd. | 3.1 | |
| Total Bkgd. | 26.8 | 26-28 |

| 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 |

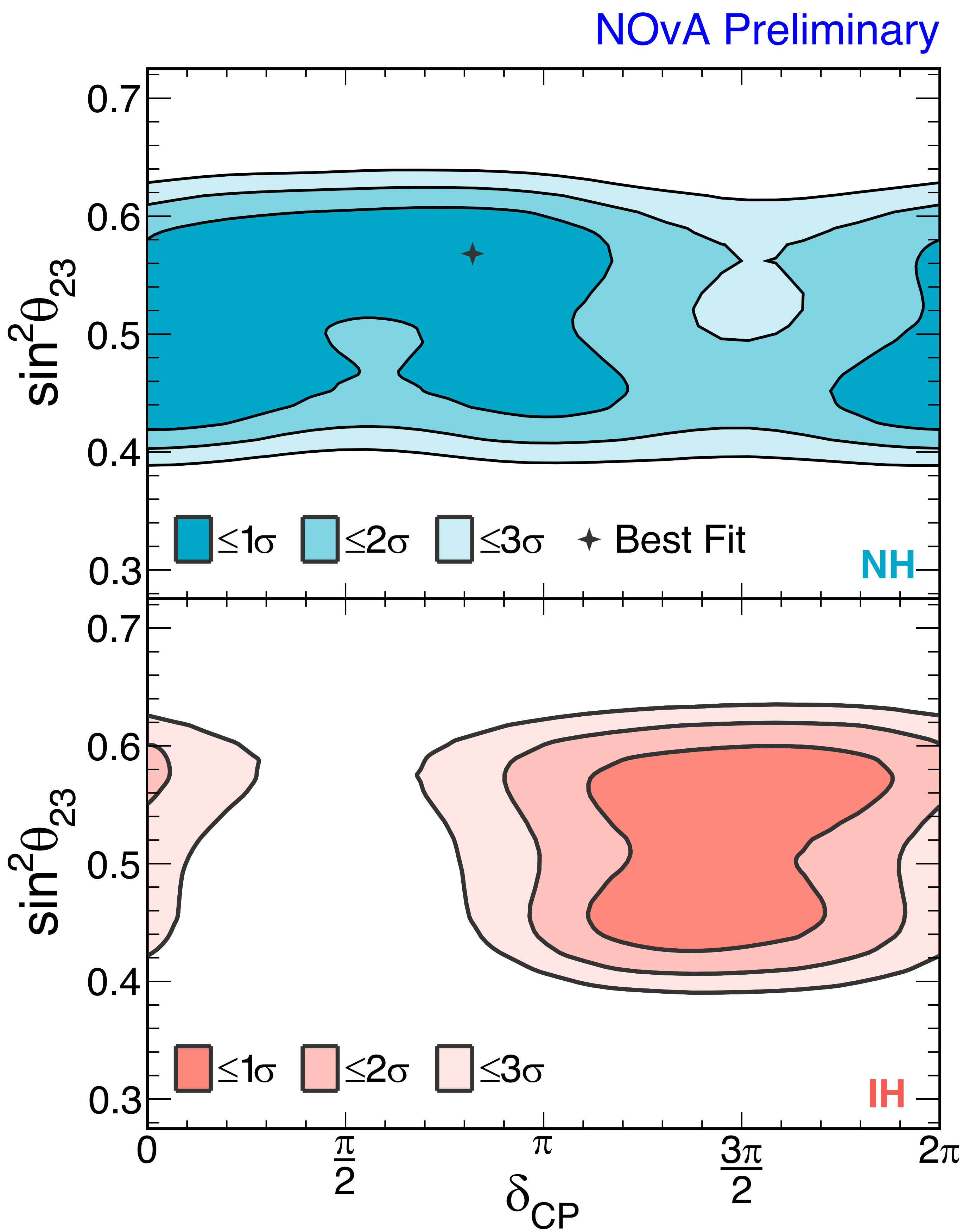
$>4\sigma$ of $\bar{\nu}_e$ appearance

# With Friends




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

Prefer non-maximal mixing by 1.1$\sigma$



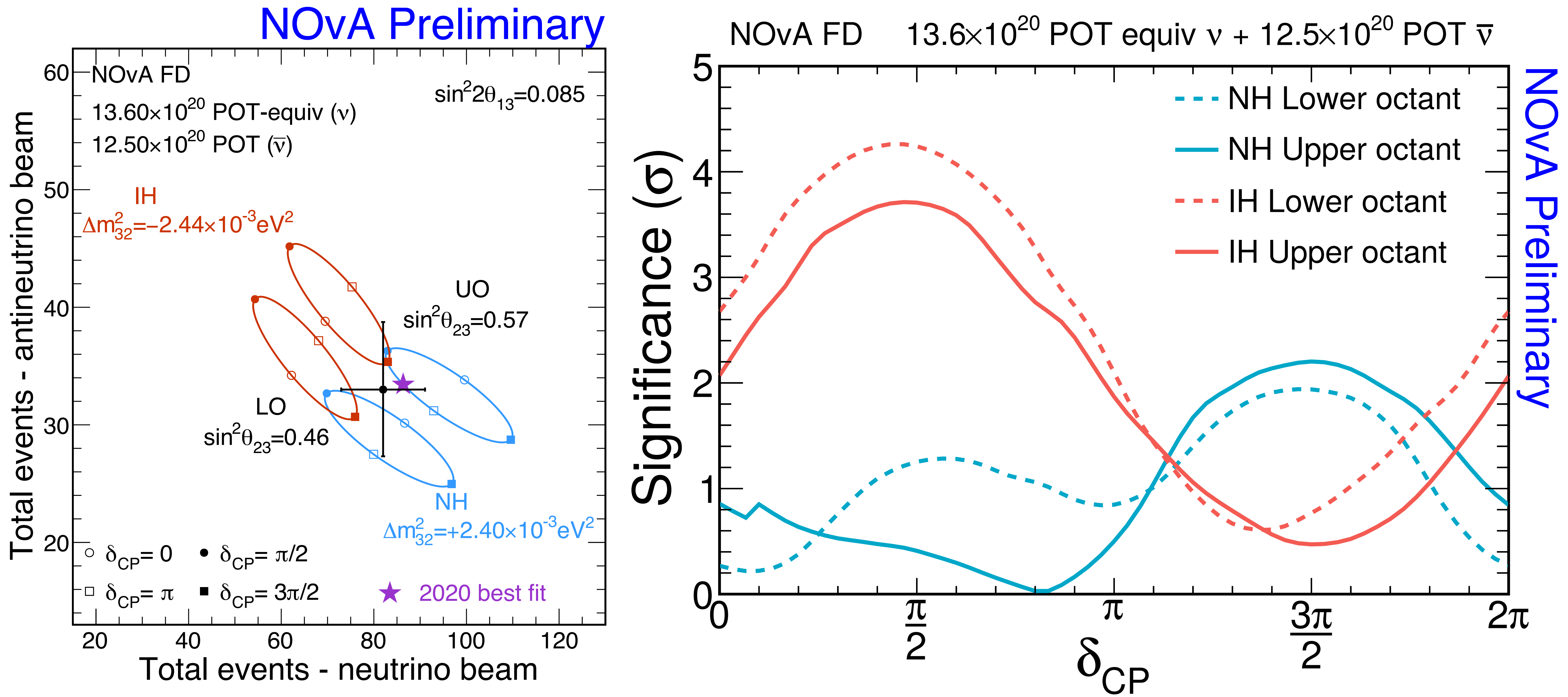

**Best Fit**

Normal hierarchy

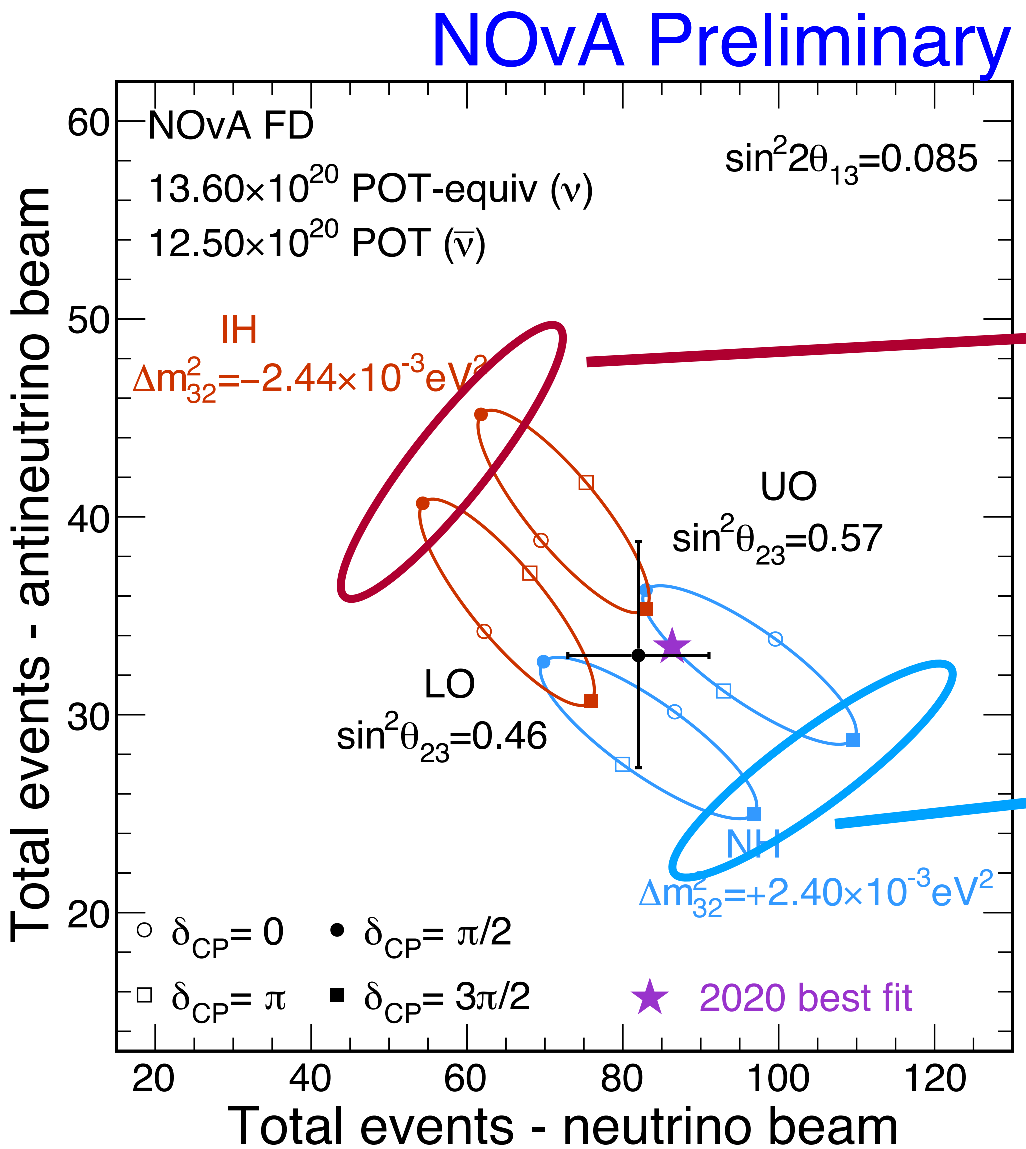
$\Delta m^2_{32} = (2.41 \pm 0.07) \times 10^{-3}\ \mathrm{eV}^2$

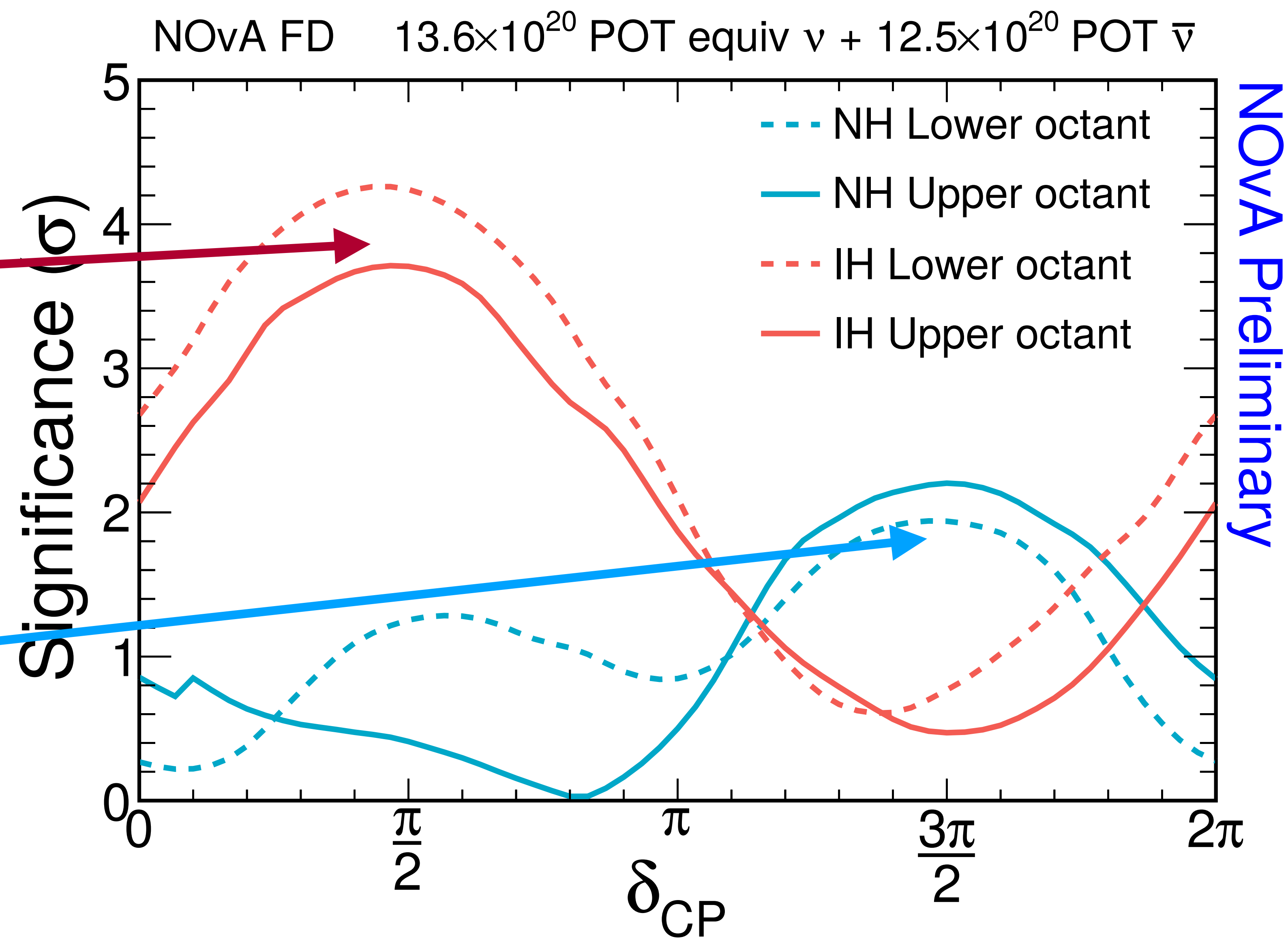
$\sin^2\theta_{23} = 0.57^{+0.04}_{-0.03}$

$\delta = 0.82\pi$




- No strong asymmetry in the rates of appearance of $\nu_e$ and $\bar{\nu}_e$.

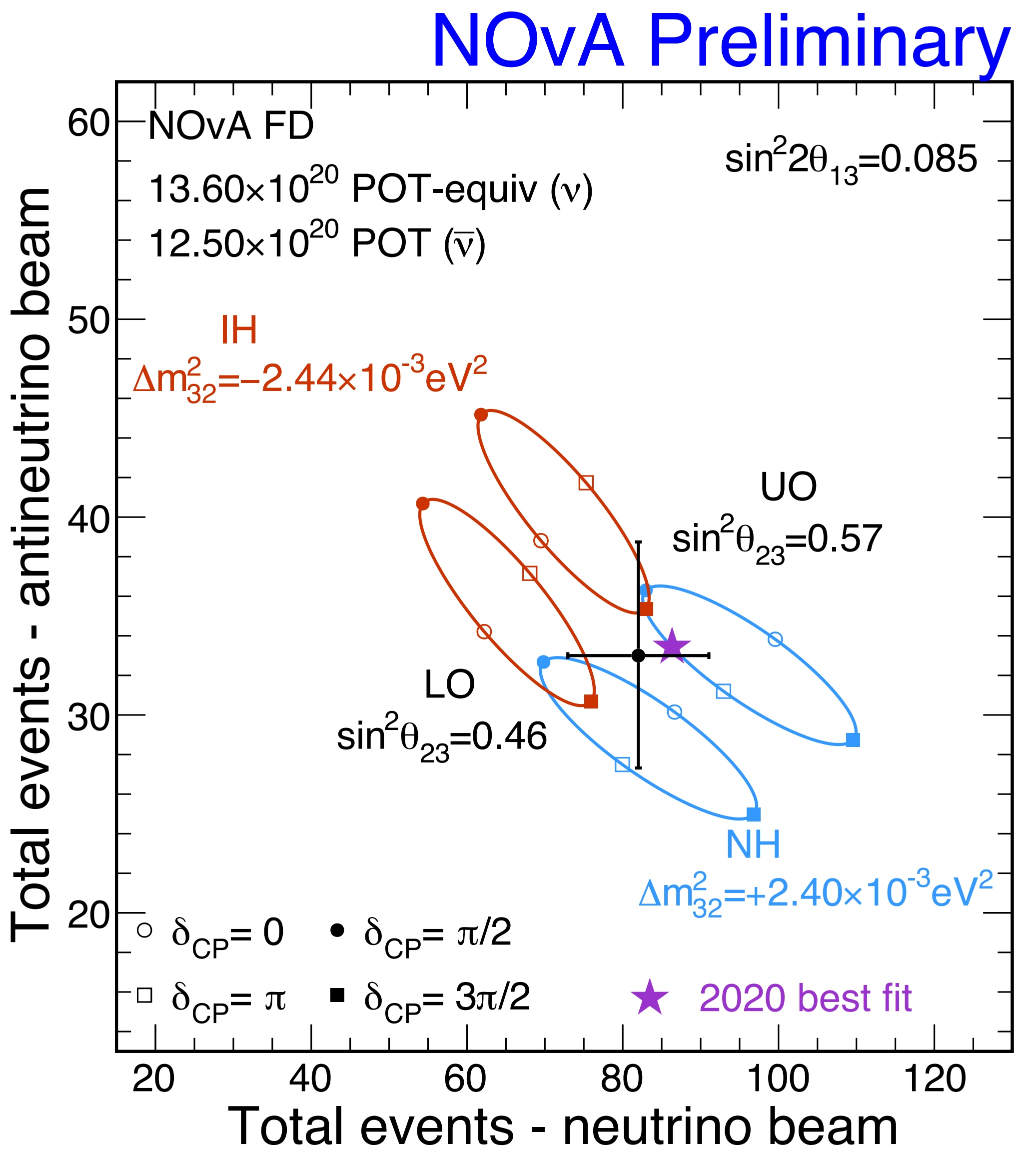


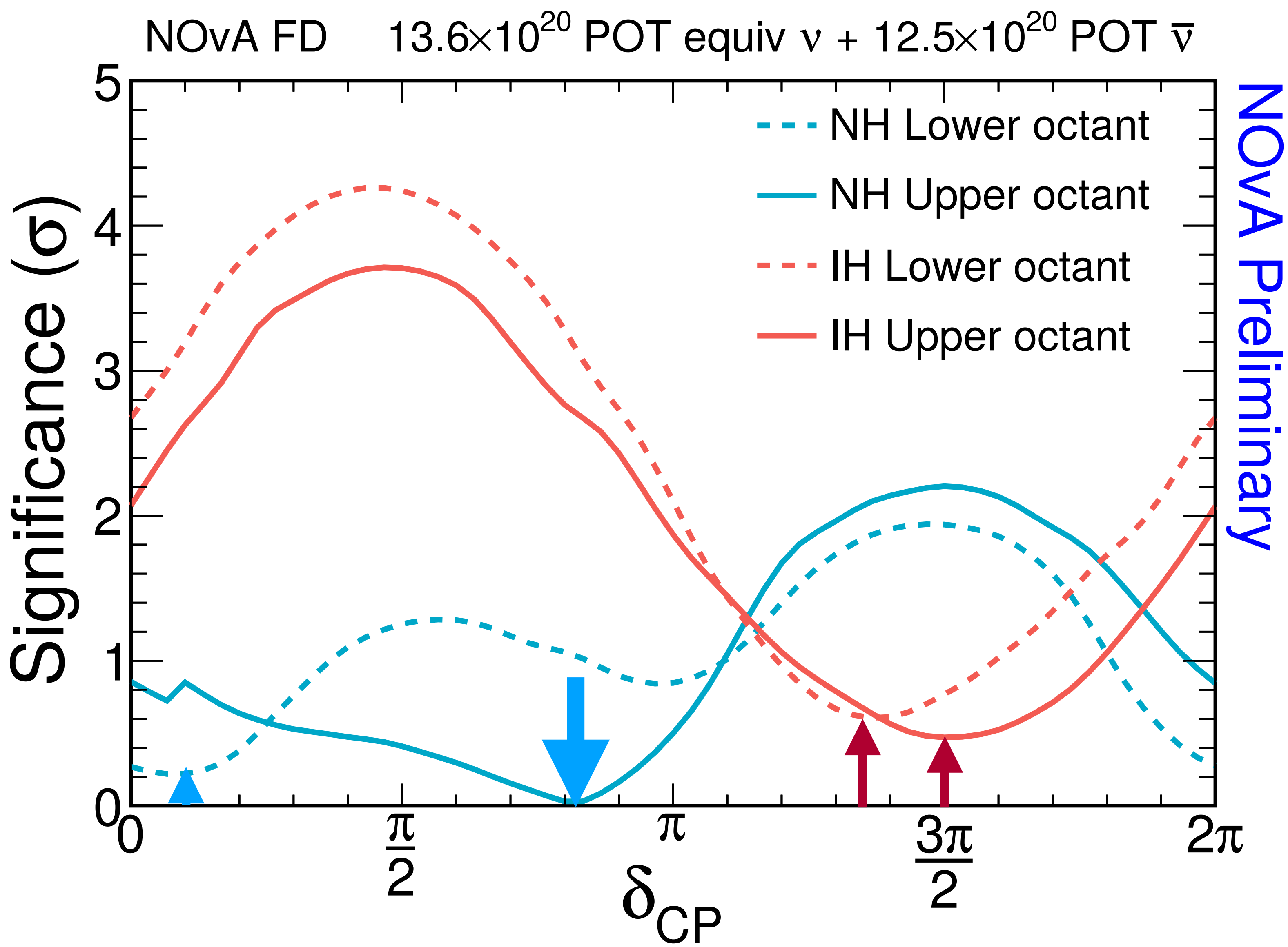




- No strong asymmetry in the rates of appearance of $\nu_e$ and $\bar{\nu}_e$.
- Disfavour hierarchy-$\delta_{CP}$ combinations which would produce asymmetry.

Exclude IH $\delta_{CP} = \dfrac{\pi}{2}$ at $> 3\sigma$

Disfavour NH $\delta_{CP} = \dfrac{3\pi}{2}$ at ~$2\sigma$




- No strong asymmetry in the rates of appearance of $\nu_e$ and $\bar{\nu}_e$.
- Disfavour hierarchy-$\delta_{CP}$ combinations which would produce asymmetry.

**Prefer:**

Normal Hierarchy at $1\sigma$

Upper Octant at $1.2\sigma$

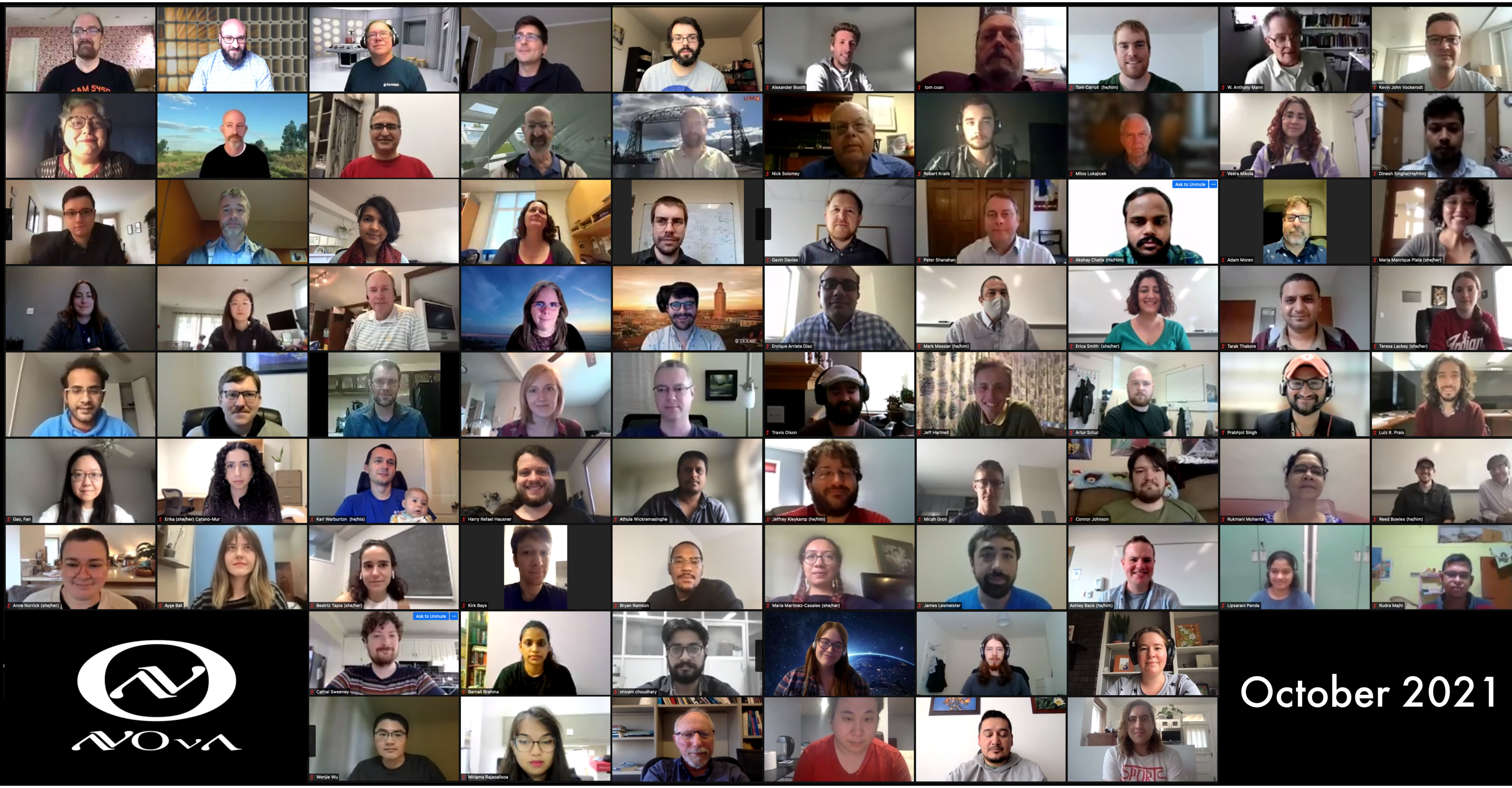
# Summary

- Recently opened the box on an updated neutrino oscillation analysis with:
  - 50% more neutrino beam data,
  - updated simulation and reconstruction, including a new cross-section model,
  - updated extrapolation which mitigates different detector acceptances.

- New 3-flavour oscillation results:
  - $\Delta m^2_{32} = (2.41 \pm 0.07) \times 10^{-3}\mathrm{eV}^2$
  - $\sin^2\theta_{23} = 0.57^{0.04}_{-0.03}$
  - exclude IH, $\delta_{CP} = \dfrac{\pi}{2}$ at $> 3\sigma$
  - disfavour NH, $\delta_{CP} = \dfrac{\pi}{2}$ at $\sim 2\sigma$

- In the future, joint fit with T2K - projected first result 2022.
  - Plan to reduce our largest systematic, those related to detector energy scale with the results of test beam experiment at FNAL (on-going).
  - Reach $3\sigma$ hierarchy sensitivity for 30-50% of $\delta_{CP}$ values, with full dataset and upgraded beam.

# Questions?

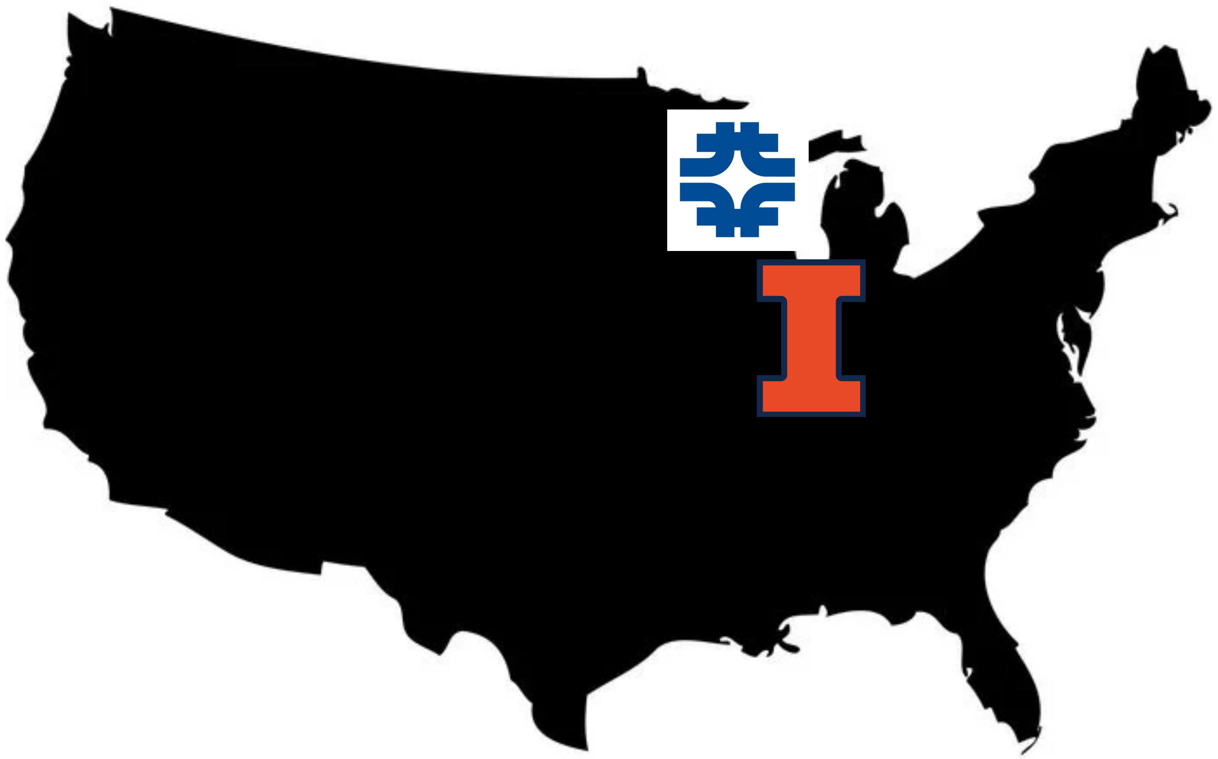


# Back-up

Queen Mary
University of London

NOvA

# A Bit About Me…




- PDRA at Queen Mary University of London.
- Collaborator in the NOvA & DUNE experiments.

# 3-flavour Neutrino Oscillations

$$P\left(\nu_\alpha \to \nu_\beta\right) \sim P\left(U(\theta_{23}, \theta_{13}, \delta, \theta_{12}), \Delta m^2_{21}, \Delta m^2_{32}, \Delta m^2_{31}, \frac{L}{E}\right)$$

**Hierarchy problem**

**3** mass splittings. → $\Delta m^2_{32}$ $\quad \Delta m^2_{31} \sim \Delta m^2_{32}$ $\quad \Delta m^2_{21}$

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

"Atmospheric" sector

"Reactor" sector

"Solar" sector

**3** angles, **1** complex phase. → $\theta_{23}$ $\quad \theta_{13}\ \delta$ $\quad \theta_{12}$

# 3-flavour Neutrino Oscillations

$$P\left(\nu_\alpha \to \nu_\beta\right) \sim P\left(U(\theta_{23}, \theta_{13}, \delta, \theta_{12}), \Delta m^2_{21}, \Delta m^2_{32}, \Delta m^2_{31}, \frac{L}{E}\right)$$

$\Delta m^2_{32} \approx 2 \times 10^{-3}\mathrm{eV}^2$ $\qquad$ $\Delta m^2_{31} \sim \Delta m^2_{32}$ $\qquad$ $\Delta m^2_{21} \approx +8 \times 10^{-5}\mathrm{eV}^2$

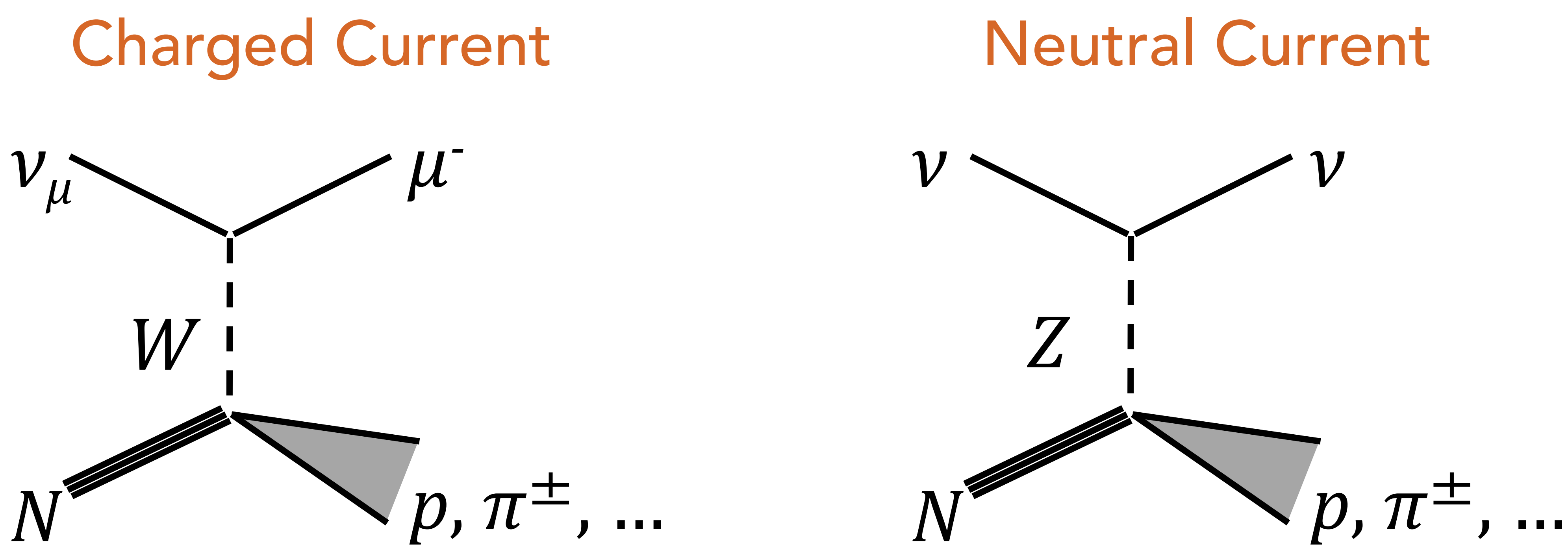
$\frac{L}{E} = 500\mathrm{km/GeV}$ $\qquad$ $\frac{L}{E} = 15000\mathrm{km/GeV}$

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

"Atmospheric" sector $\qquad$ "Reactor" sector $\qquad$ "Solar" sector

$\theta_{23}$ $\qquad$ $\theta_{13}$ $\delta$ $\qquad$ $\theta_{12}$

# How to Detect a Neutrino



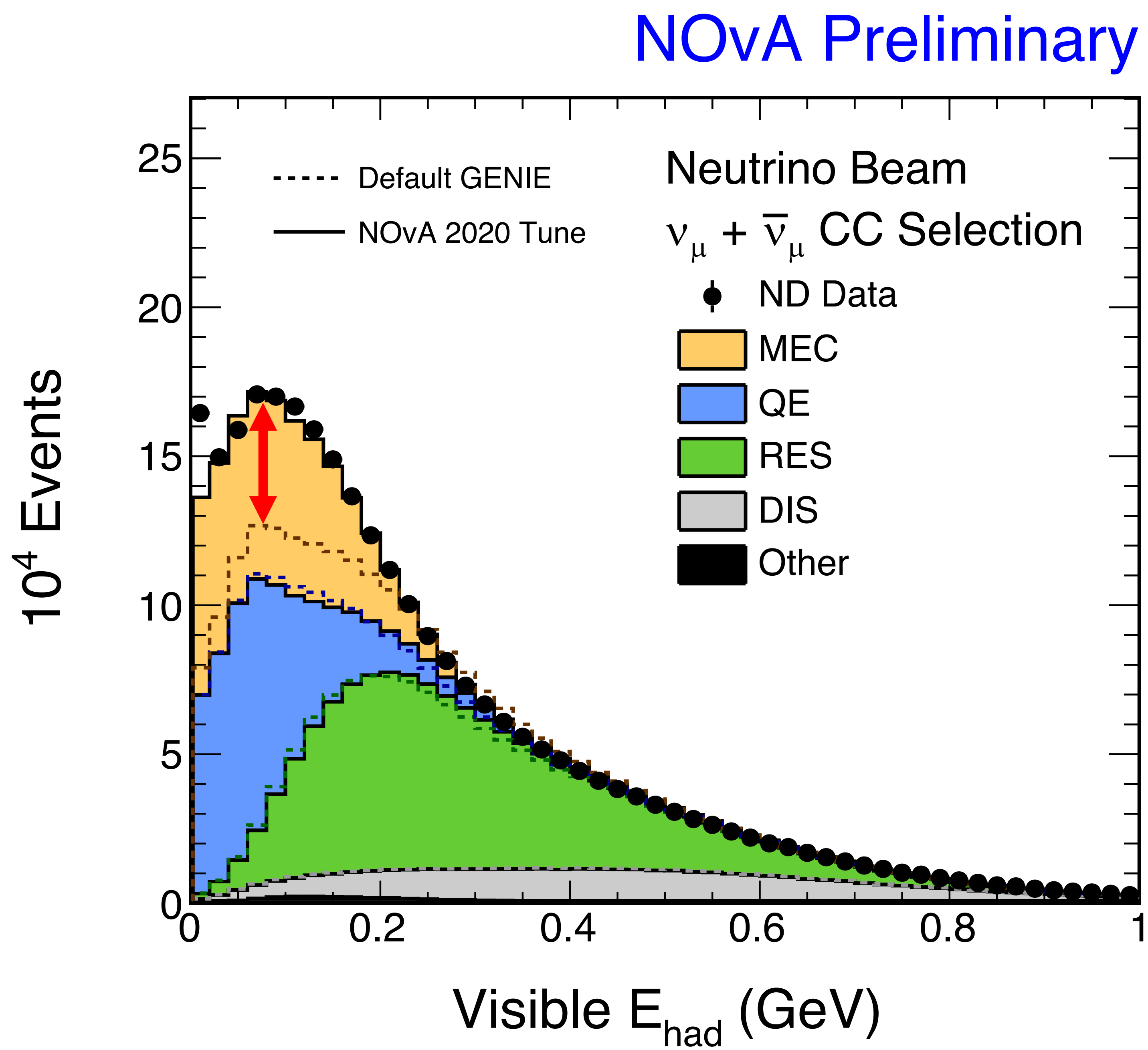

- Observe charged particles after a neutrino interacts with a nucleus.

- Lepton:
  - $\nu_\mu$ CC $\rightarrow \mu^-$, $\nu_e$CC $\rightarrow e^-$.
  - NC, no visible lepton.

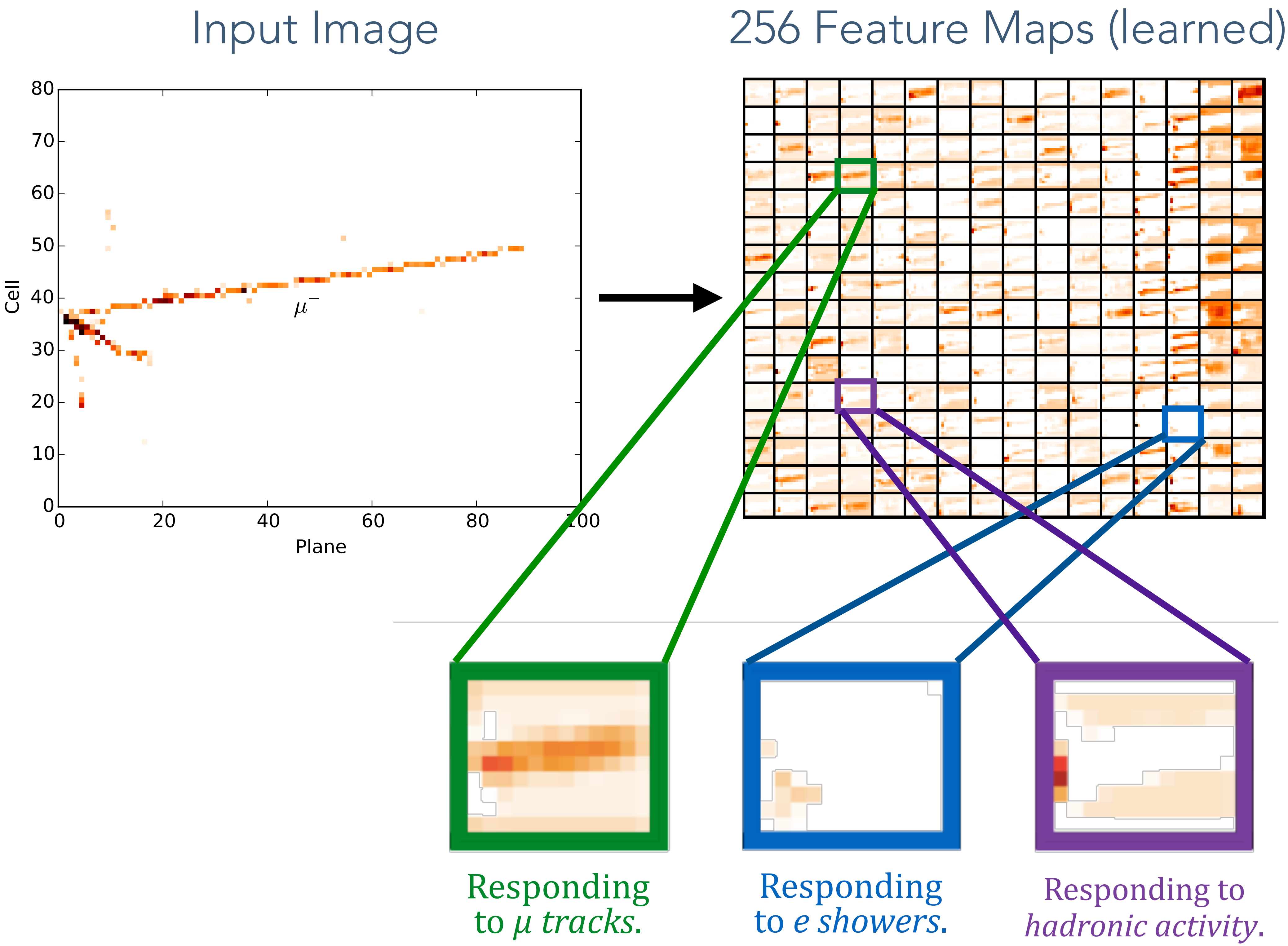
- Hadronic shower:
  - May contain protons, one or more $\pi^\pm$, etc.
  - May have EM components from $\pi^0 \rightarrow \gamma\gamma$

# Neutrino Interaction Model

- Understanding of neutrino interactions is constantly evolving.
- Upgrade to GENIE 3.0.6, gives freedom to chose the models.
- Even with many updated models, some custom tuning required.
  - **FSI**: tuned using external pion scattering data.
  - **MEC/Multi-nucleon**: tuned to NOvA ND data.

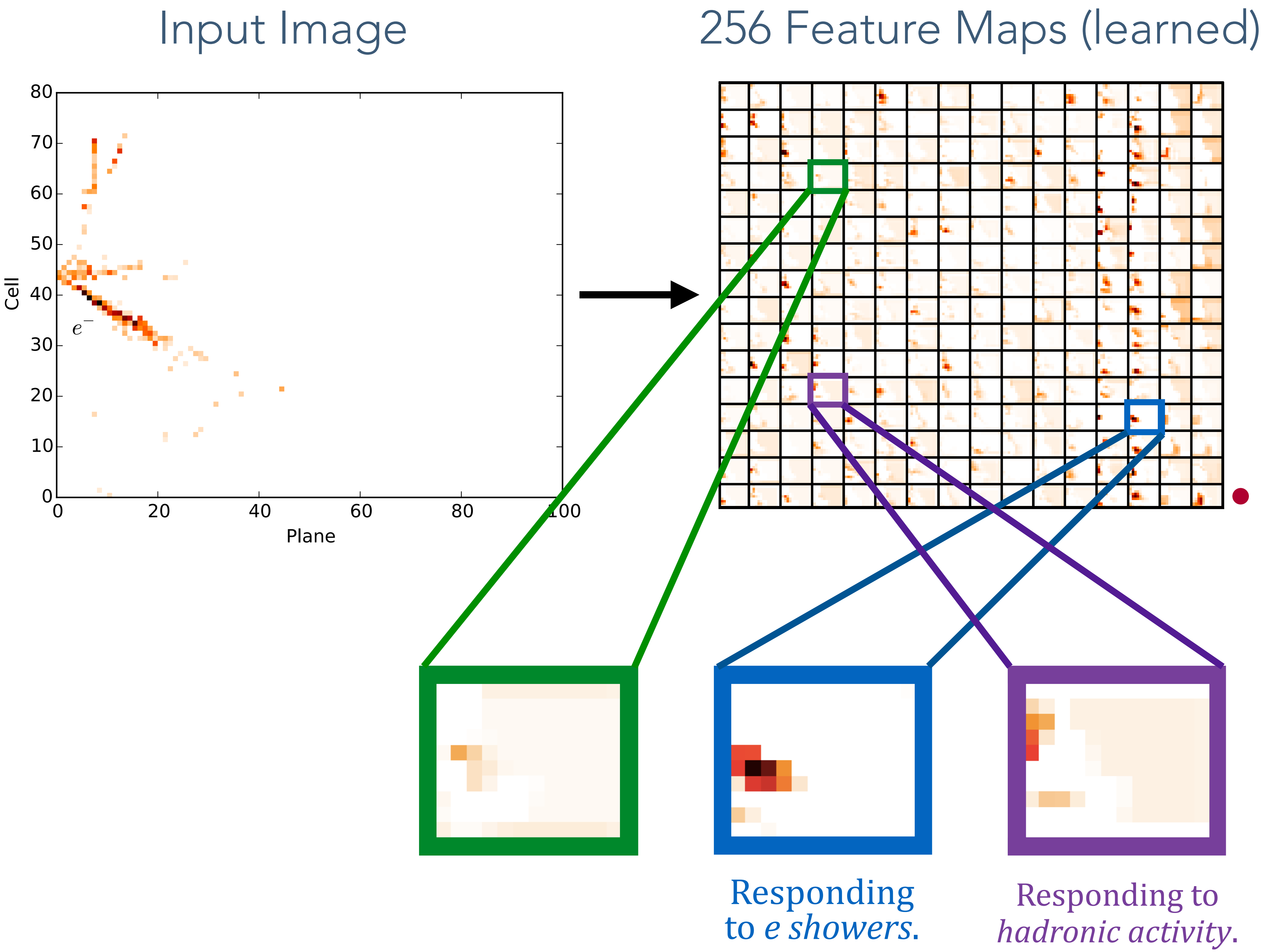


# Convolutional Neural Network




- Relative to prior selection:
  - $\nu_\mu$: ~90% efficient, 99% bkg. rejection.
  - $\nu_e$: ~80% efficient, 80% bkg. rejection.
- Improvement in sensitivity equivalent to 30% more exposure.

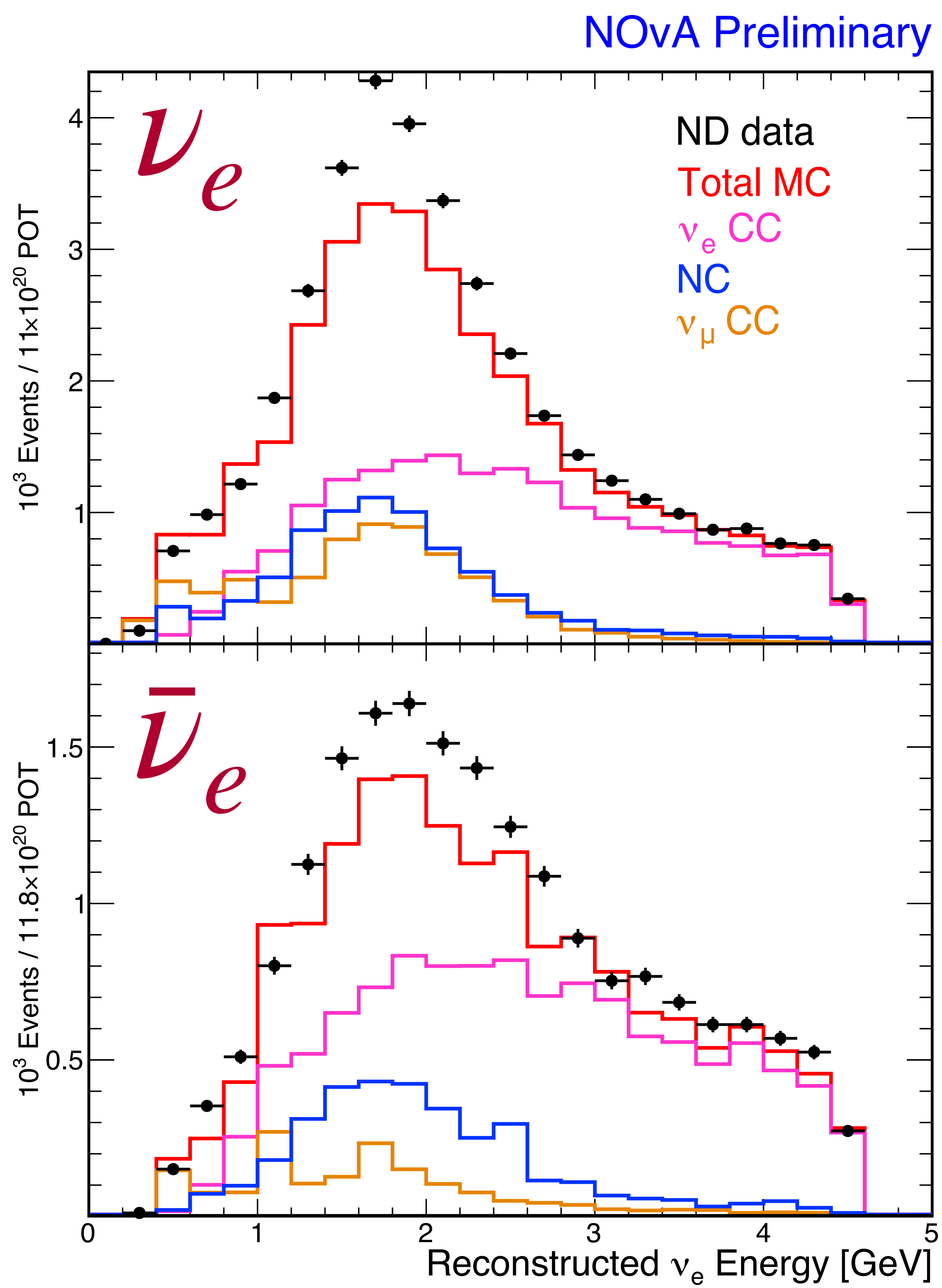
# Convolutional Neural Network




- Relative to prior selection:
  - $\nu_\mu$: ~90% efficient, 99% bkg. rejection.
  - $\nu_e$: ~80% efficient, 80% bkg. rejection.
- Improvement in sensitivity equivalent to 30% more exposure.

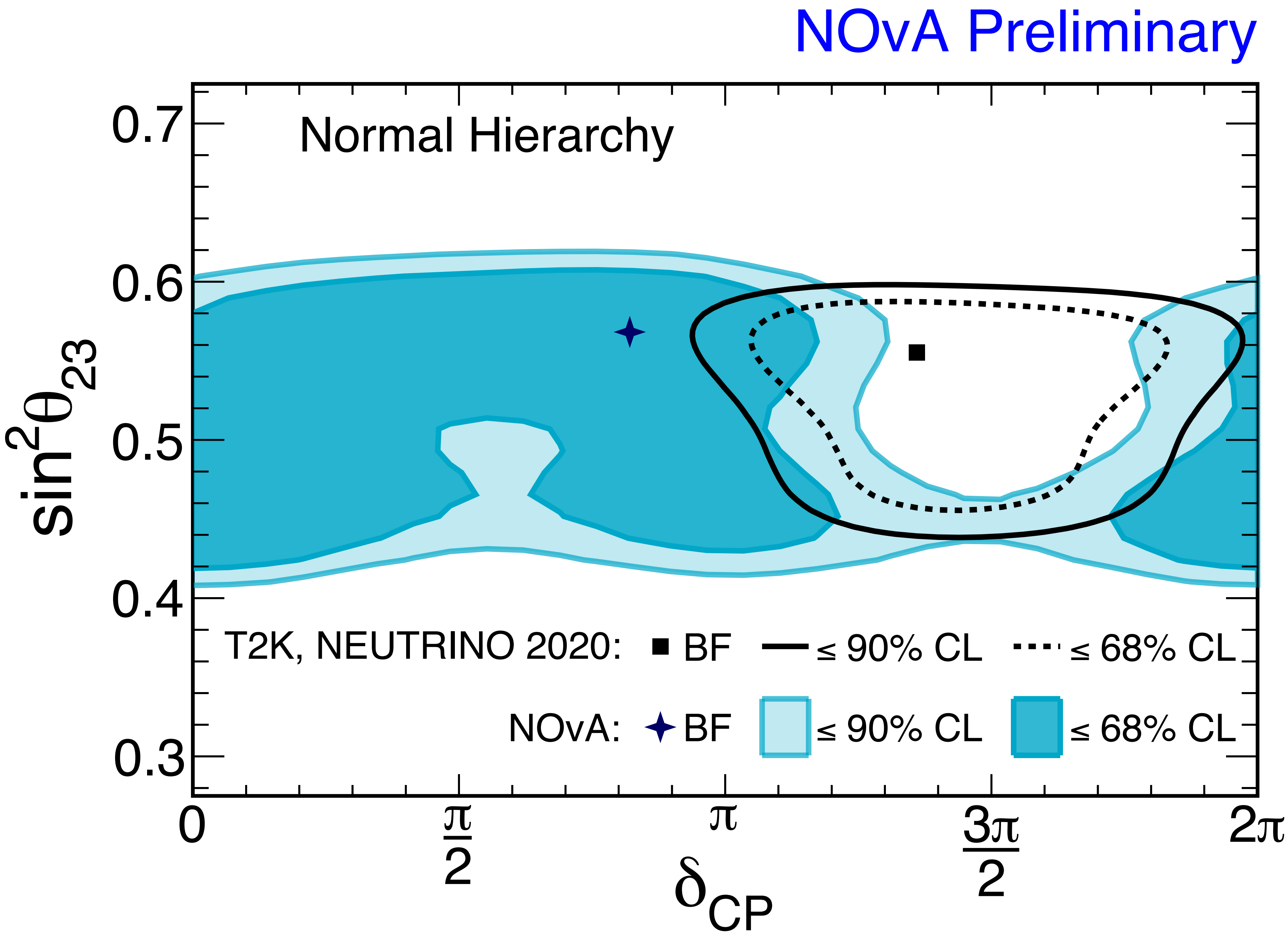
# Near Detector, $\nu_e$-like

- Near Detector $\nu_e$-like spectrum contains background to the appearing $\nu_e$'s at the FD.
- Largest background is irreducible $\nu_e$ / $\bar{\nu}_e$ flux component.
- Use this sample to predict the background to $\nu_e$ appearance.



# The Future

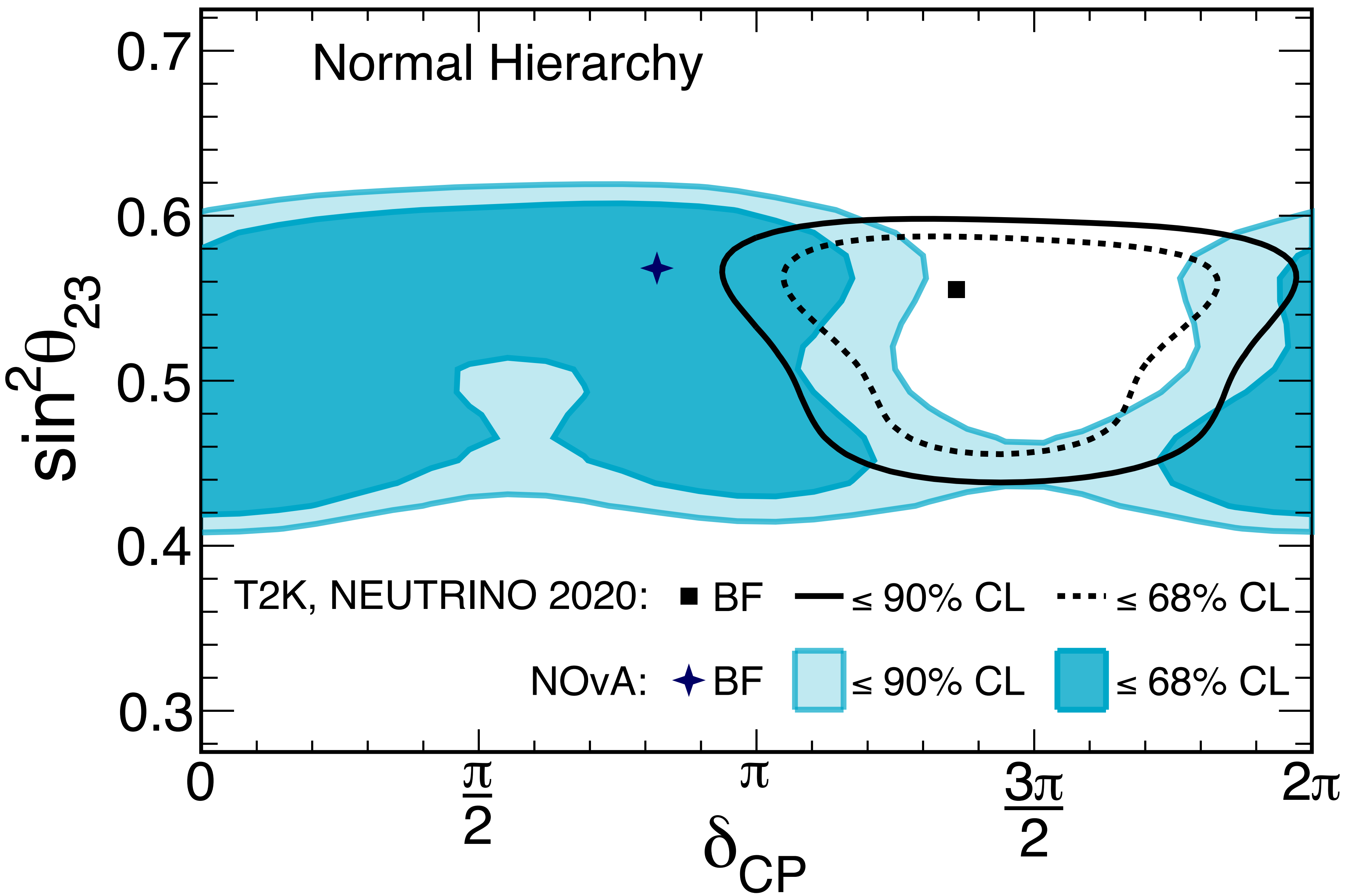
# NOvA & T2K



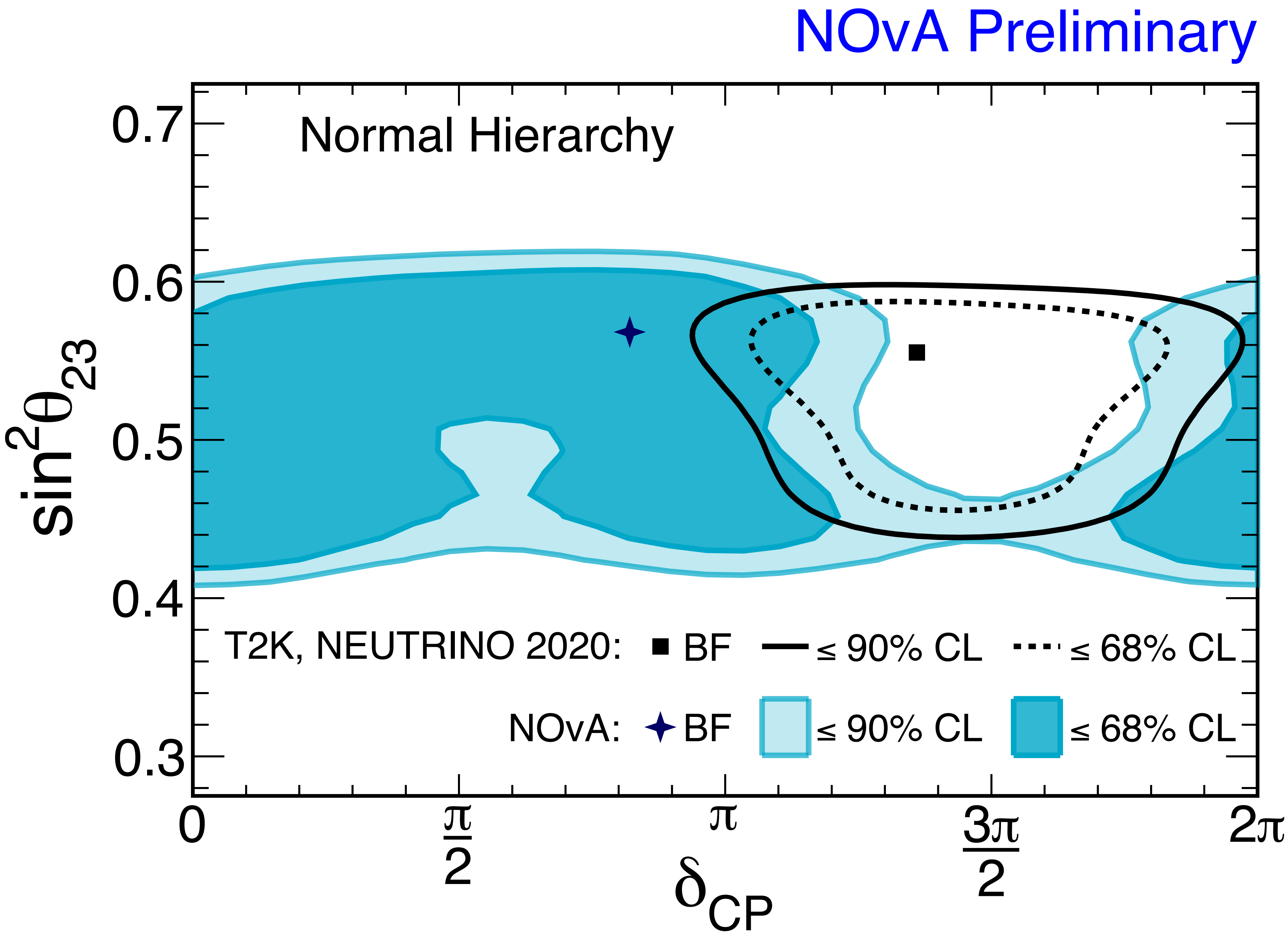

- Some tension with T2K's preferred region.
- T2K observes an asymmetry in their $\nu_e$ and $\bar{\nu}_e$ appearance.

# NOvA-T2K Joint Analysis

NOvA Preliminary

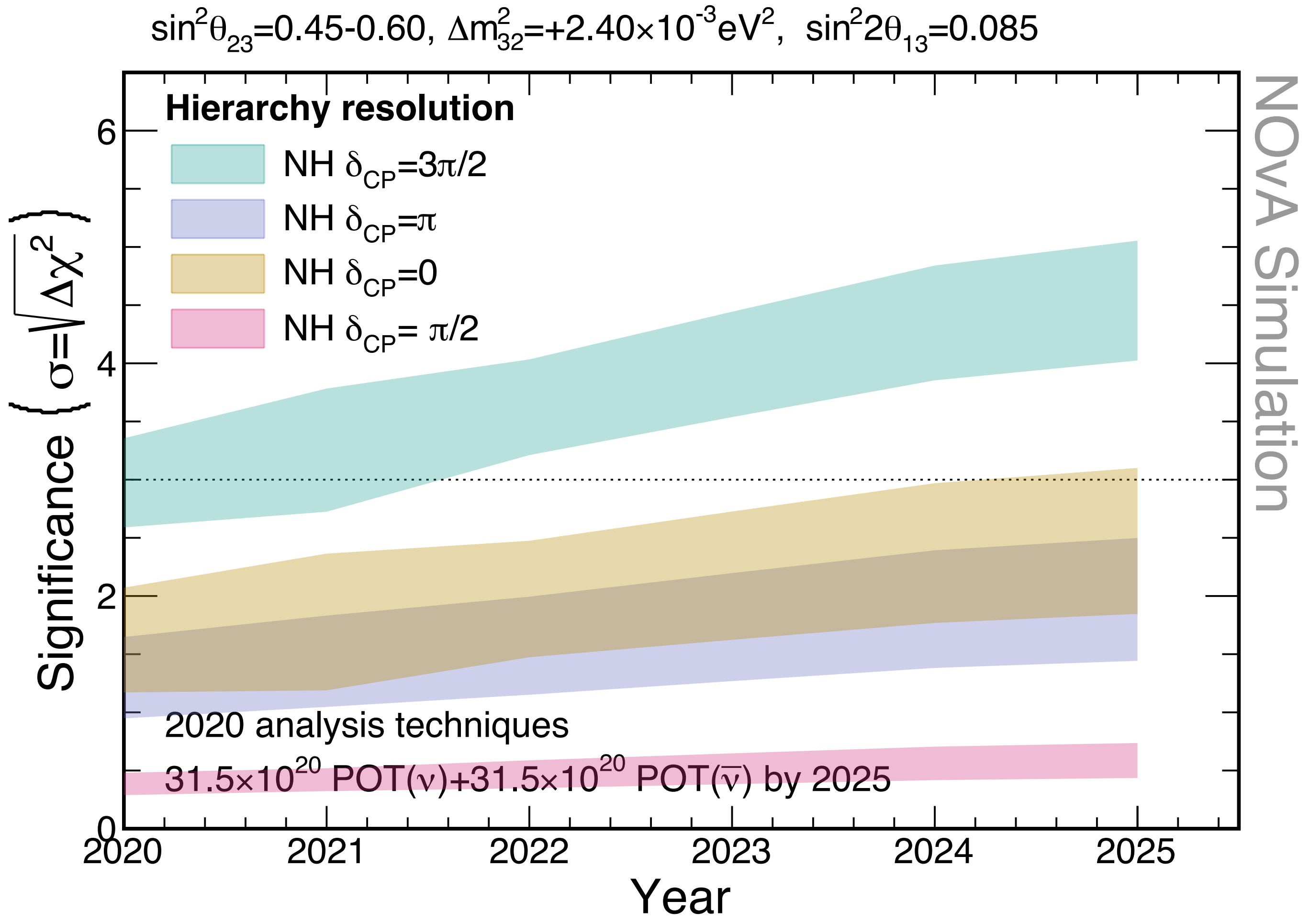


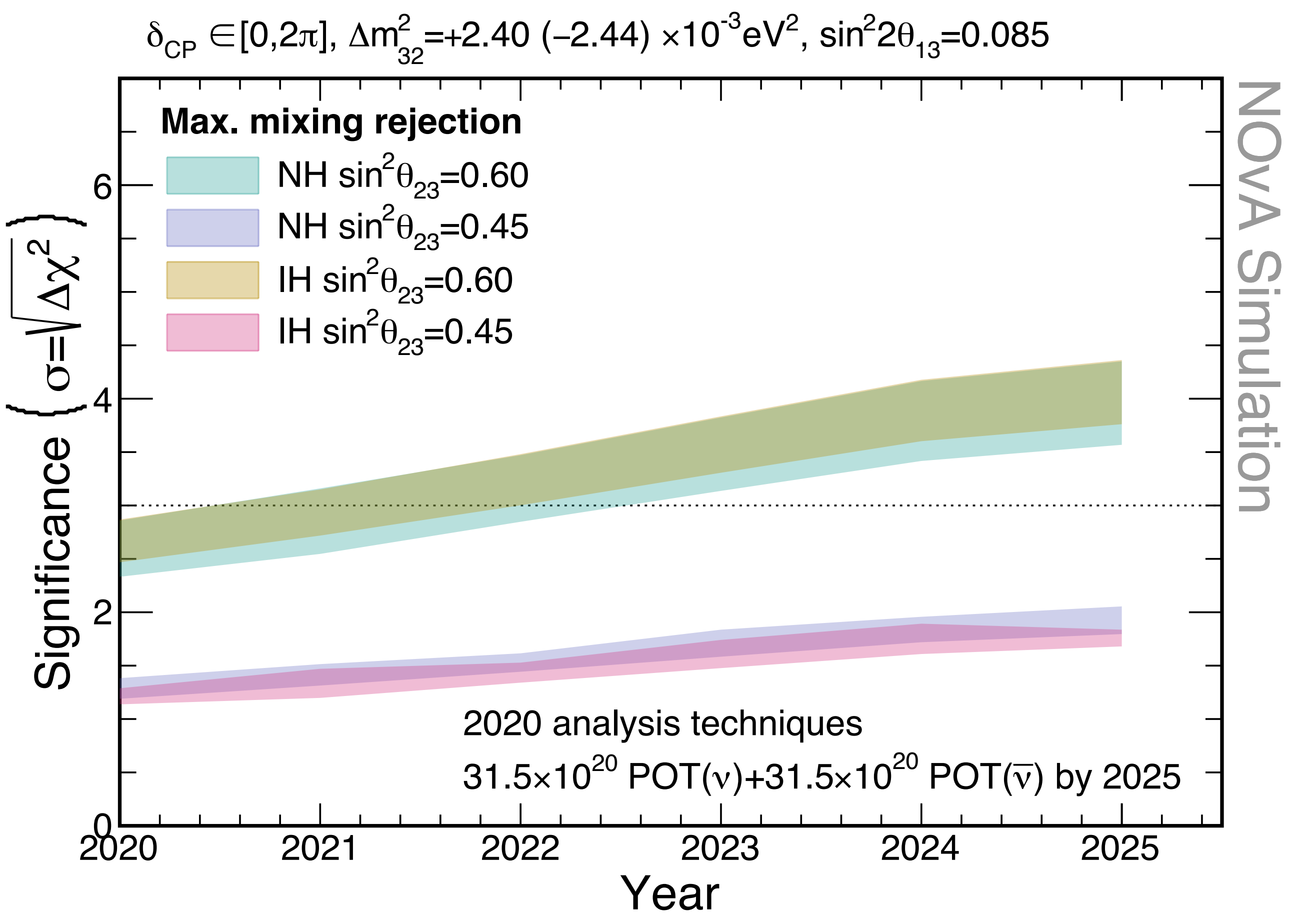

# NOvA-T2K Joint Analysis




- A joint analysis is planned which will entail:
  - A joint fit using the complete likelihoods of each experiment.
  - Full detailed energy reconstruction / smearing.
  - Correlating systematics that have a similar impact on both experiments.

# Future Sensitivities




## If nature is kind:

- $\sim 3\sigma$ sensitivity to mass hierarchy.
- $>3\sigma$ sensitivity to rejection of maximal mixing.