NOvA in 10 Minutes

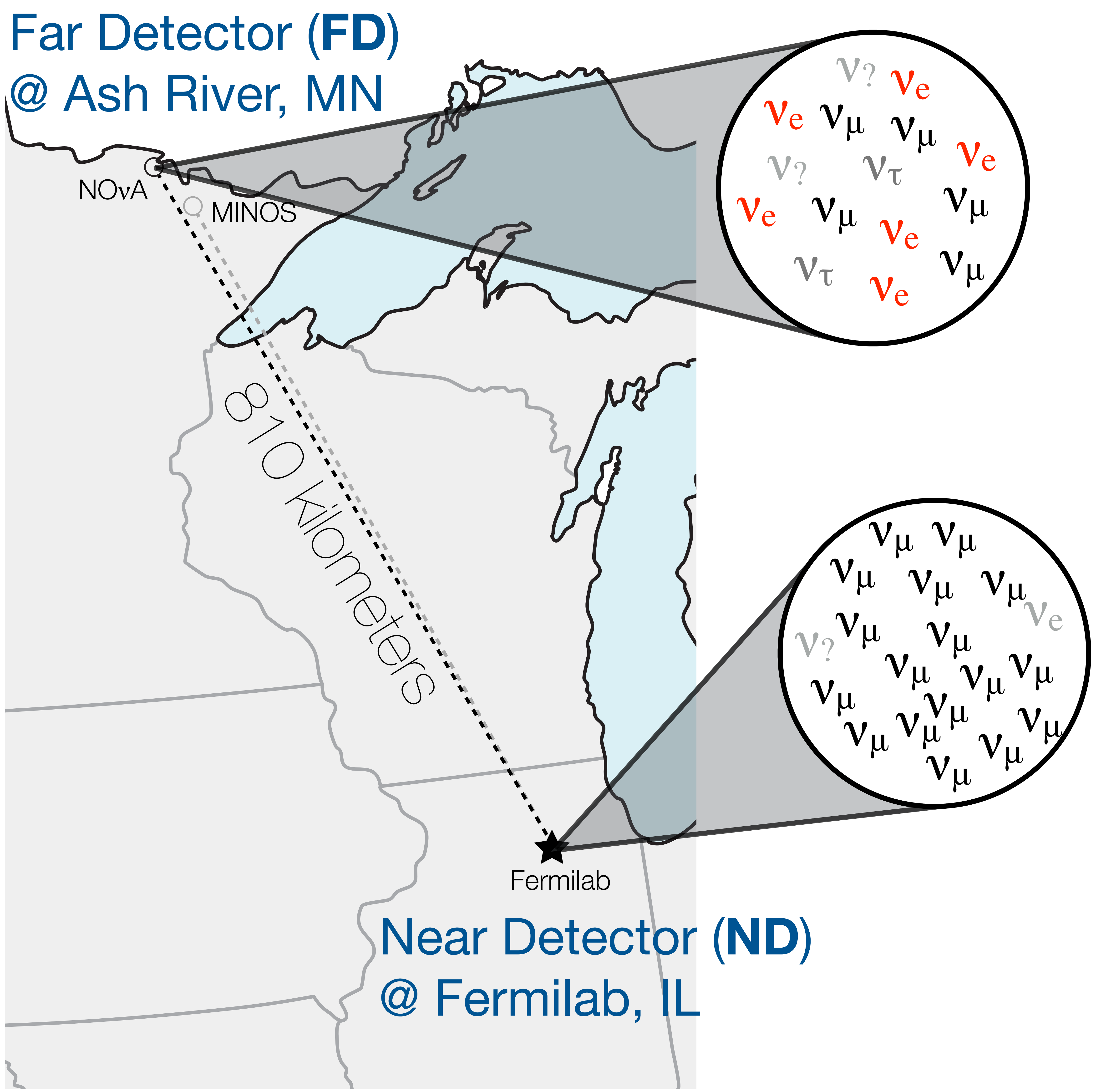
Fan Gao (University of Pittsburgh)
for the NOvA Collaboration

New Perspectives 2021 (Virtual)
August 19, 2021

The NOvA Experiment

NuMI Off-axis ν_e Appearance

- NOvA is a long-baseline neutrino oscillation experiment
- NuMI beam at Fermilab
  — Neutrino mode (ν_μ) and antineutrino mode ($\bar{\nu}_\mu$)
- Two functionally-identical tracking calorimeter detectors
  — Liquid scintillator
  — Off-axis by 14.6 mrad
  — Separated by ~810 km
- Measure oscillations through 4 channels:
  $\nu_\mu \to \nu_\mu, \nu_\mu \to \nu_e, \bar{\nu}_\mu \to \bar{\nu}_\mu, \bar{\nu}_\mu \to \bar{\nu}_e$



Neutrino Oscillations

- As neutrinos propagate, they change from one flavor to another.

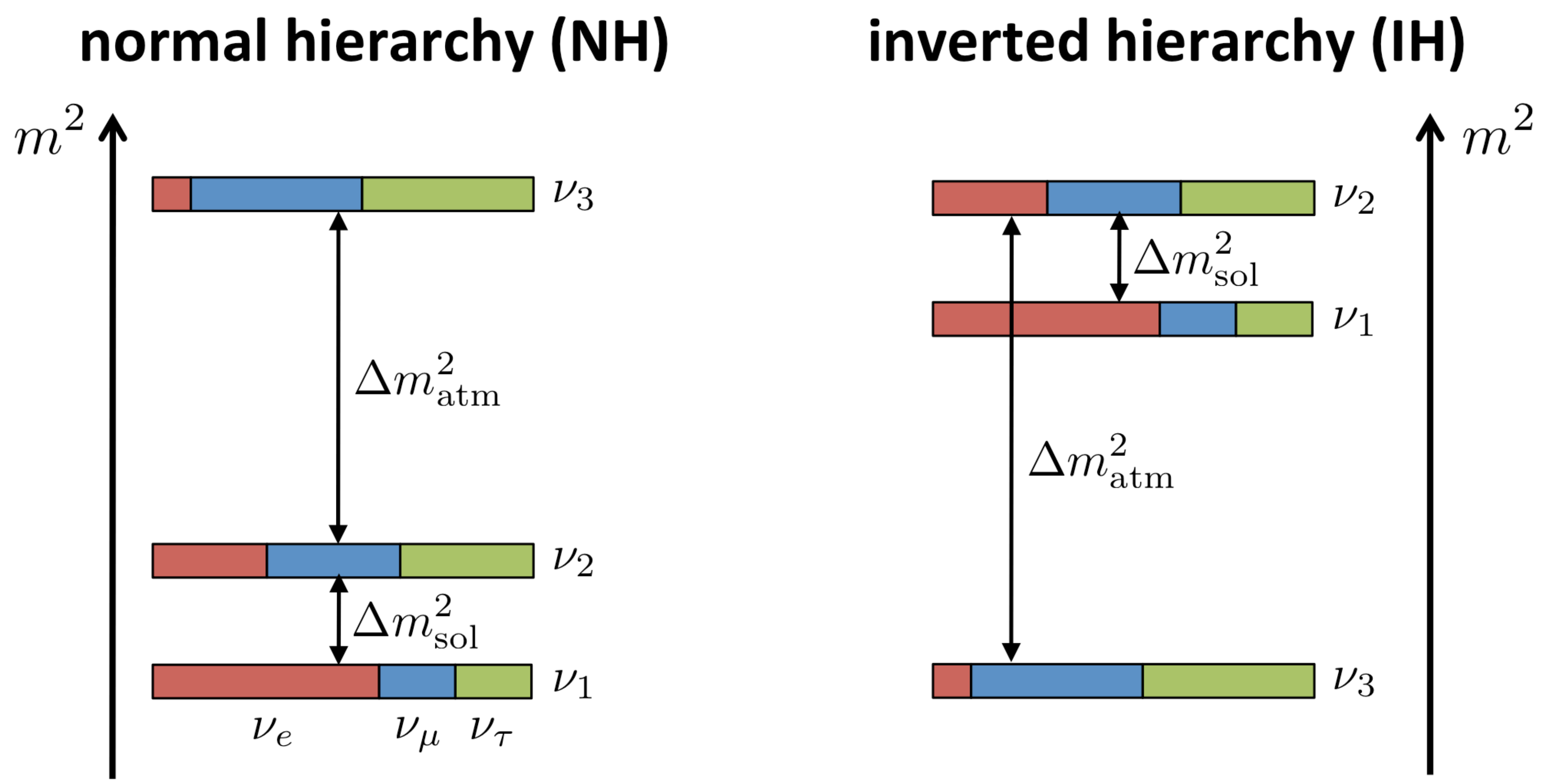
- $$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{R(\theta_{23}) \cdot R(\theta_{13}, \delta_{CP}) \cdot R(\theta_{12})}_{\text{Mixing matrix (PMNS Matrix)}} \left.\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}\right\} \text{Mass squared differences } \Delta m^2_{21}, \Delta m^2_{32}$$

- Neutrino oscillation experiments use neutrino beams propagating in matter (through earth). Oscillation probabilities in matter also depend on unknown sign of Δm^2 term.

NOvA Primary Physics Goals

- Is the neutrino mass hierarchy normal or inverted?

- The determination of θ_{23}
  - Is θ_{23} mixing maximal (ν_μ-ν_τ symmetry)?
  - If not, what is the octant of θ_{23} ?



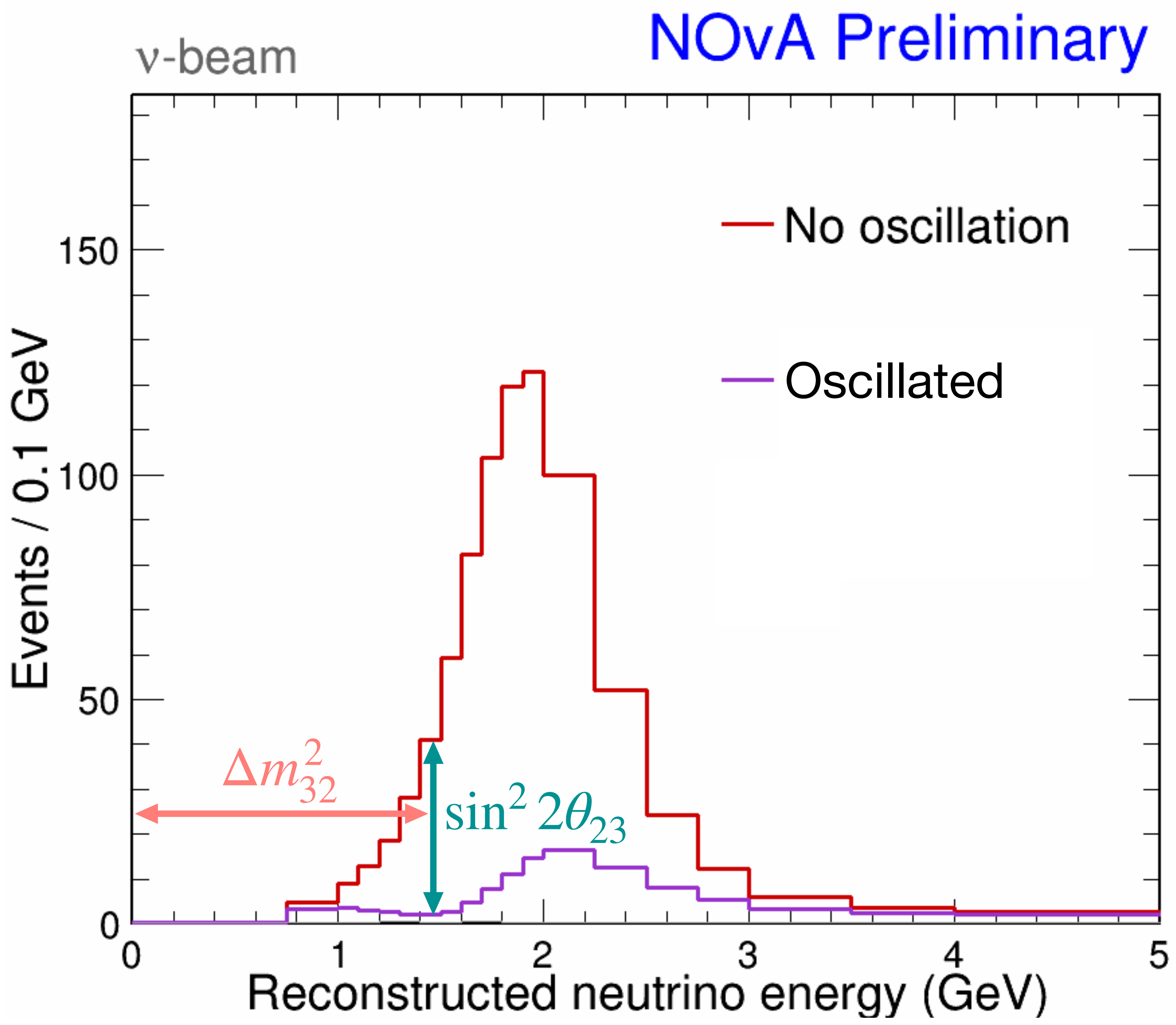
- The value of CP-violating phase $\delta_{\rm CP}$
  - Is CP violated in the neutrino sector (ν-$\bar{\nu}$ asymmetry)?

$\nu_\mu \rightarrow \nu_\mu$ Disappearance

- $P(\nu_\mu \rightarrow \nu_\mu / \bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$ depends on θ_{23} and $|\Delta m^2_{32}|$

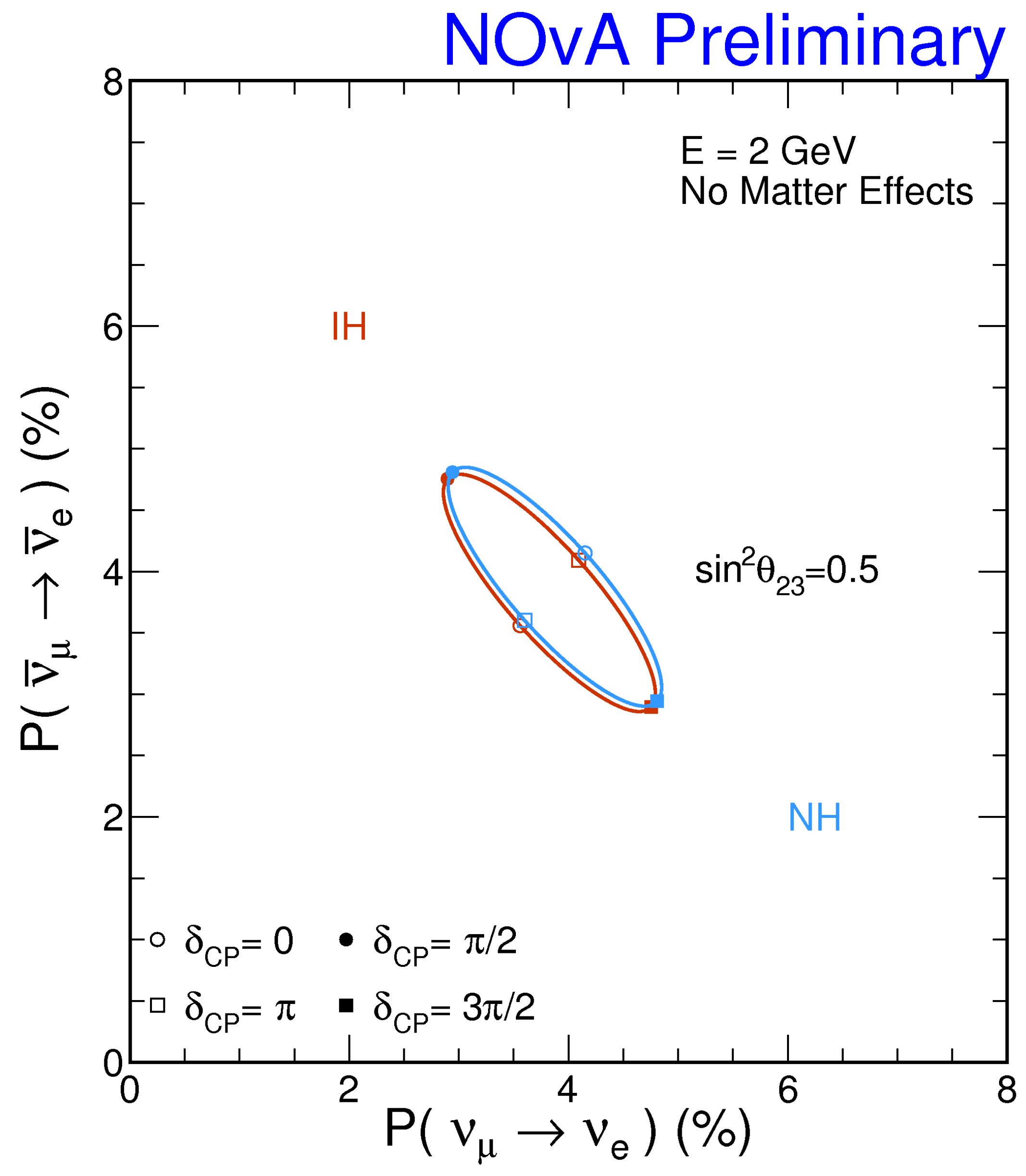
- Compare the oscillated spectrum with the unoscillated prediction
  - Oscillation "dip" location $\rightarrow |\Delta m^2_{32}|$
  - Oscillation "dip" amplitude $\rightarrow \sin^2 2\theta_{23}$

➡ Precise measurement on $\sin^2 2\theta_{23}$ and $|\Delta m^2_{32}|$

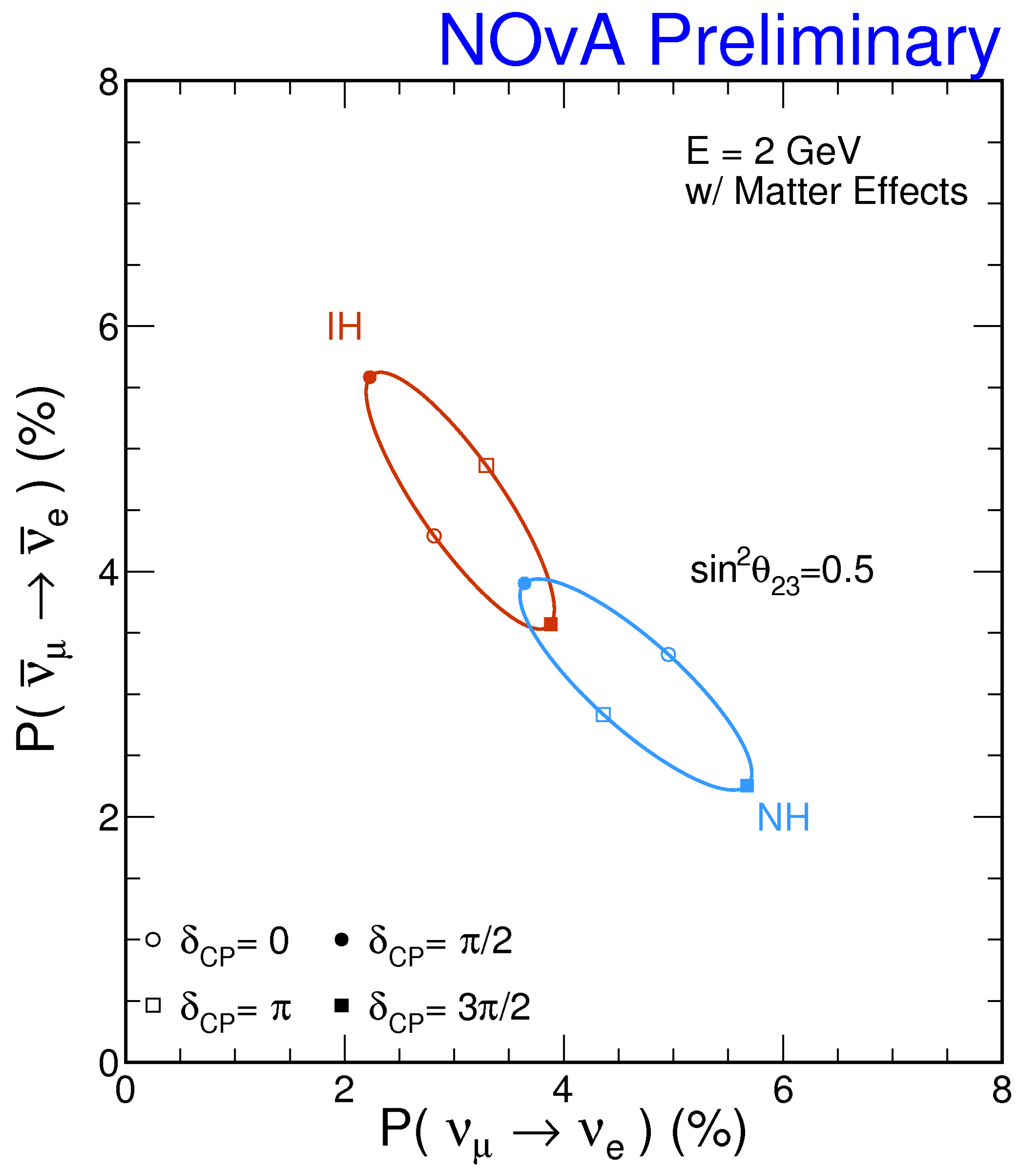


$\nu_\mu \rightarrow \nu_e$ Appearance

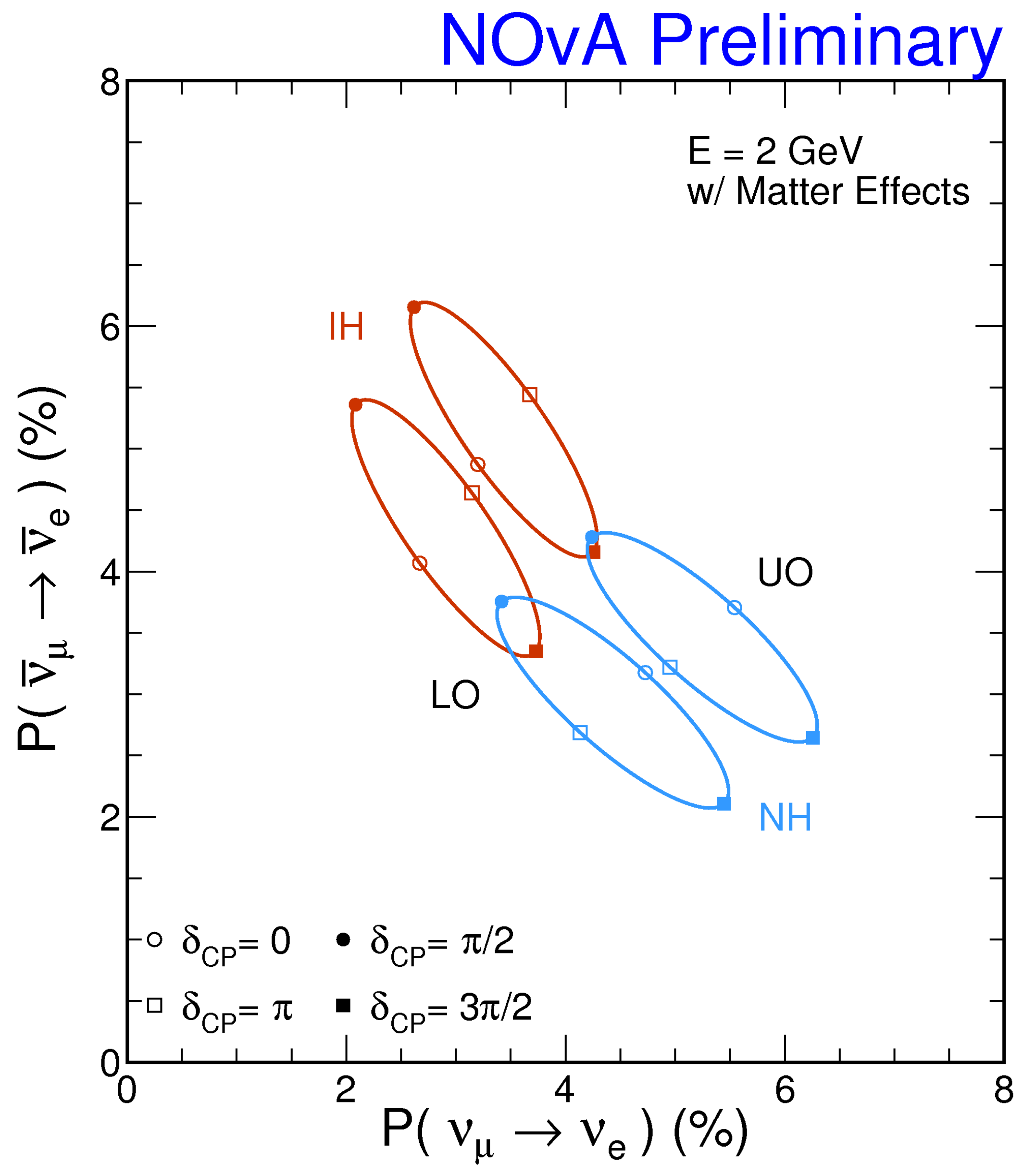
- $P(\nu_\mu \rightarrow \nu_e/\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ depends on every oscillation parameters, primarily on θ_{23}, Δm^2_{32} and δ_{CP}
- Compare the neutrino and antineutrino oscillations



- maximal mixing
- oscillations in vacuum



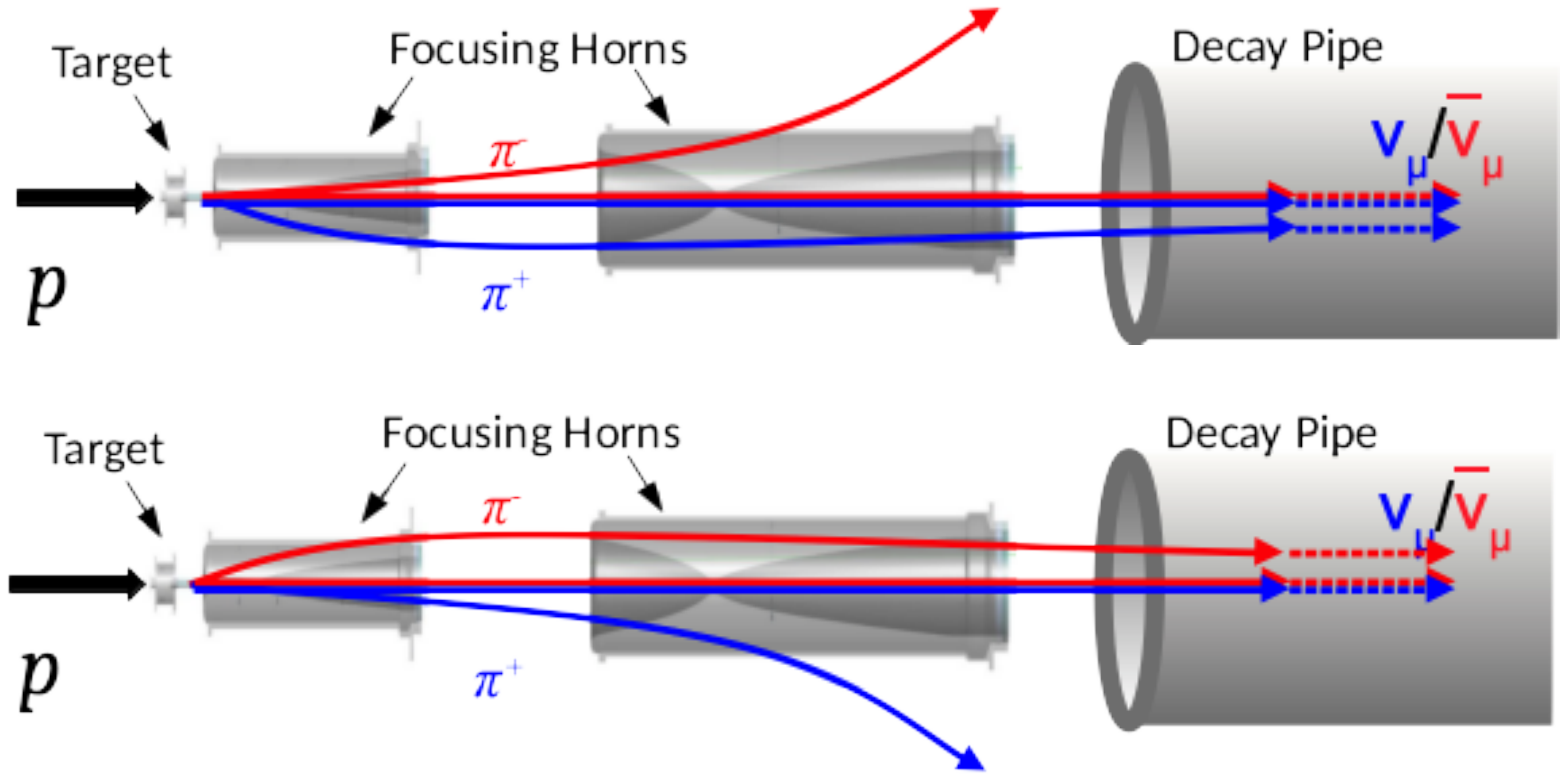
- maximal mixing
- oscillations in matter



- non-maximal mixing
- oscillations in matter

The NuMI Beamline

Neutrinos at the Main Injector



- Two running configurations:

  Neutrino mode (ν_μ) and antineutrino mode ($\bar{\nu}_\mu$)

- Small contamination:

  Wrong sign and $\nu_e/\bar{\nu}_e$

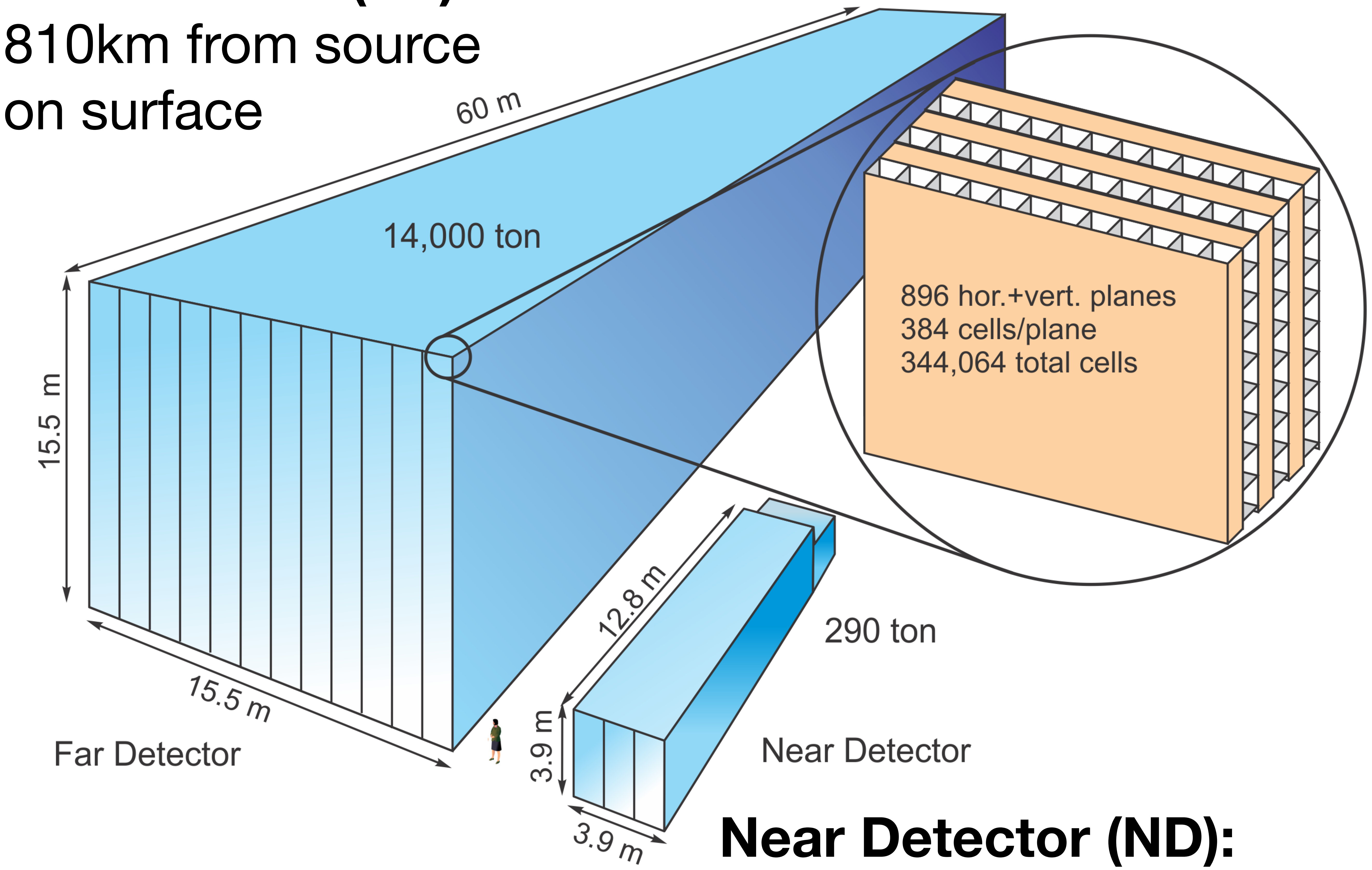
Analysis dataset used in this talk

- Neutrino mode: 13.6×10^{20} POT (Proton on Target)
- Antineutrino mode: 12.5×10^{20} POT

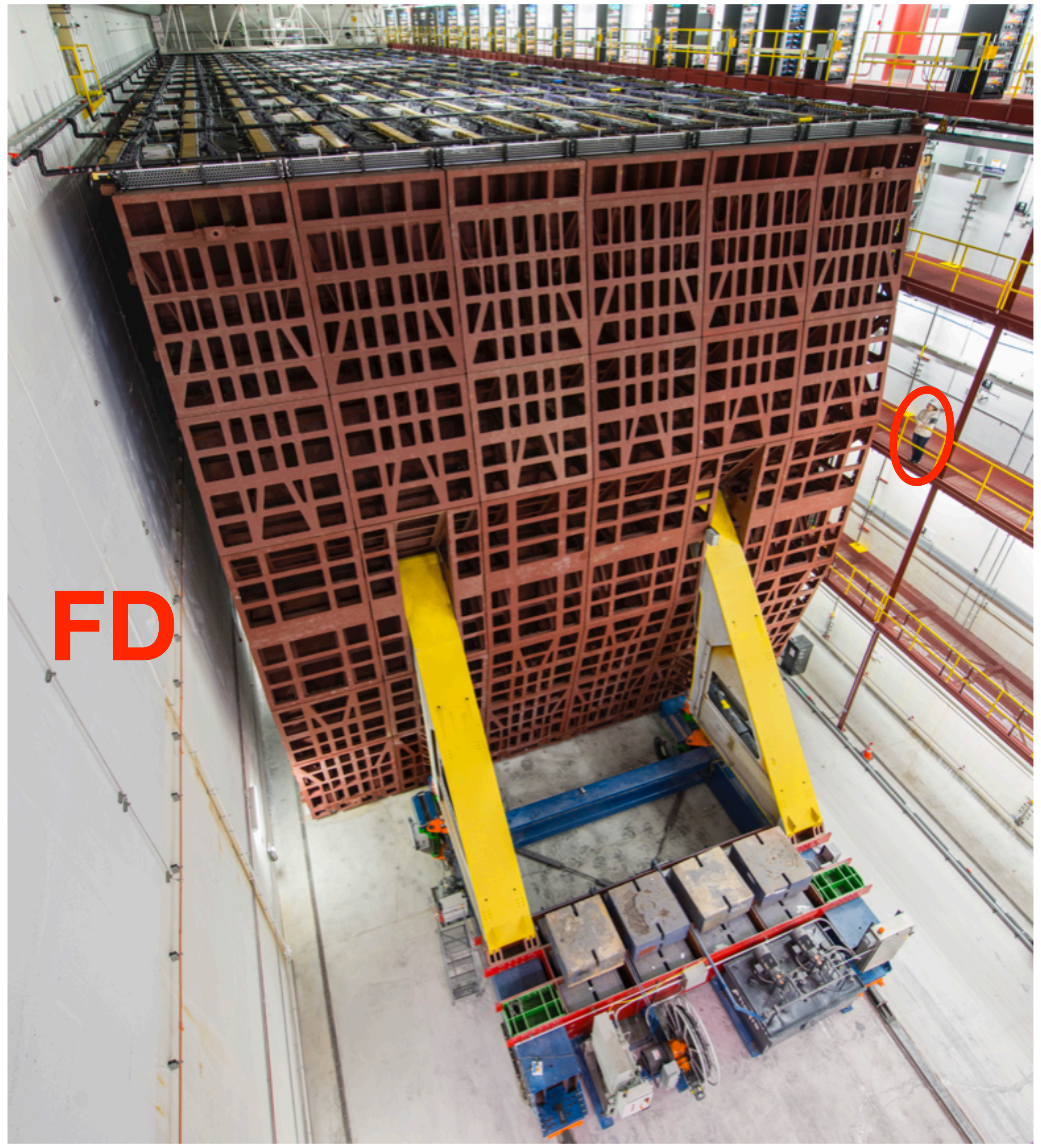
(2014 - 2020)

The NOvA Detectors

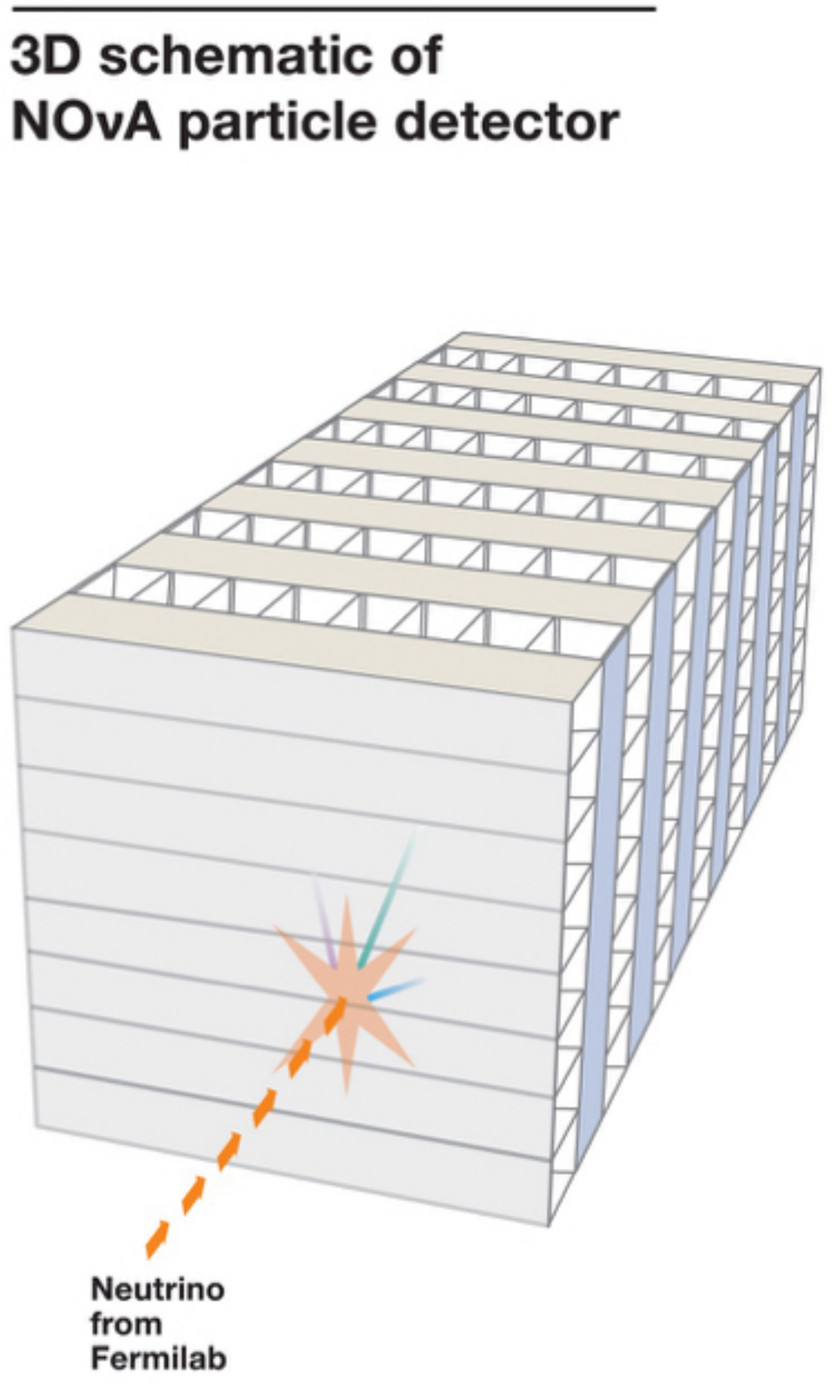
Far Detector (FD):
810km from source
on surface

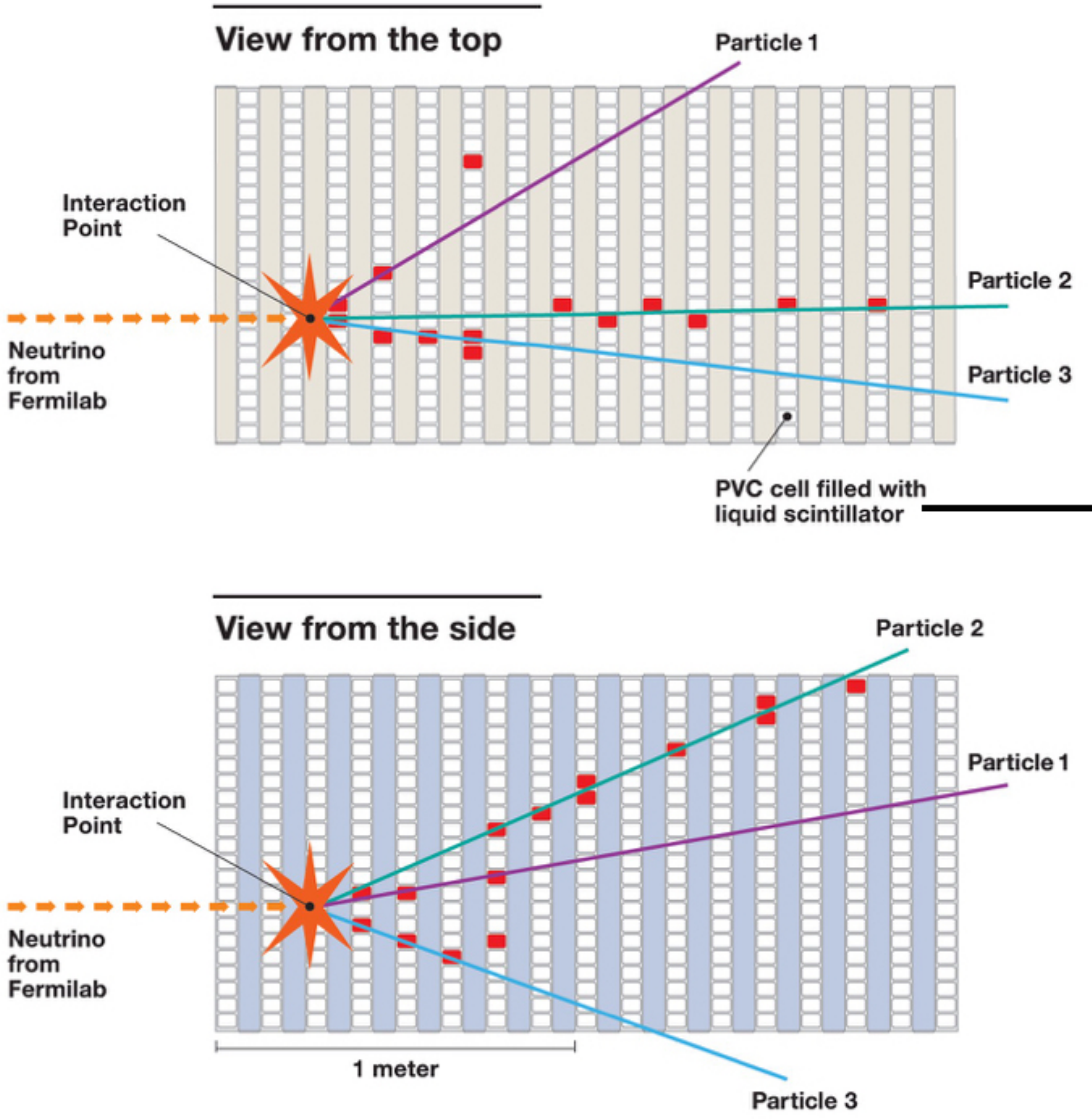


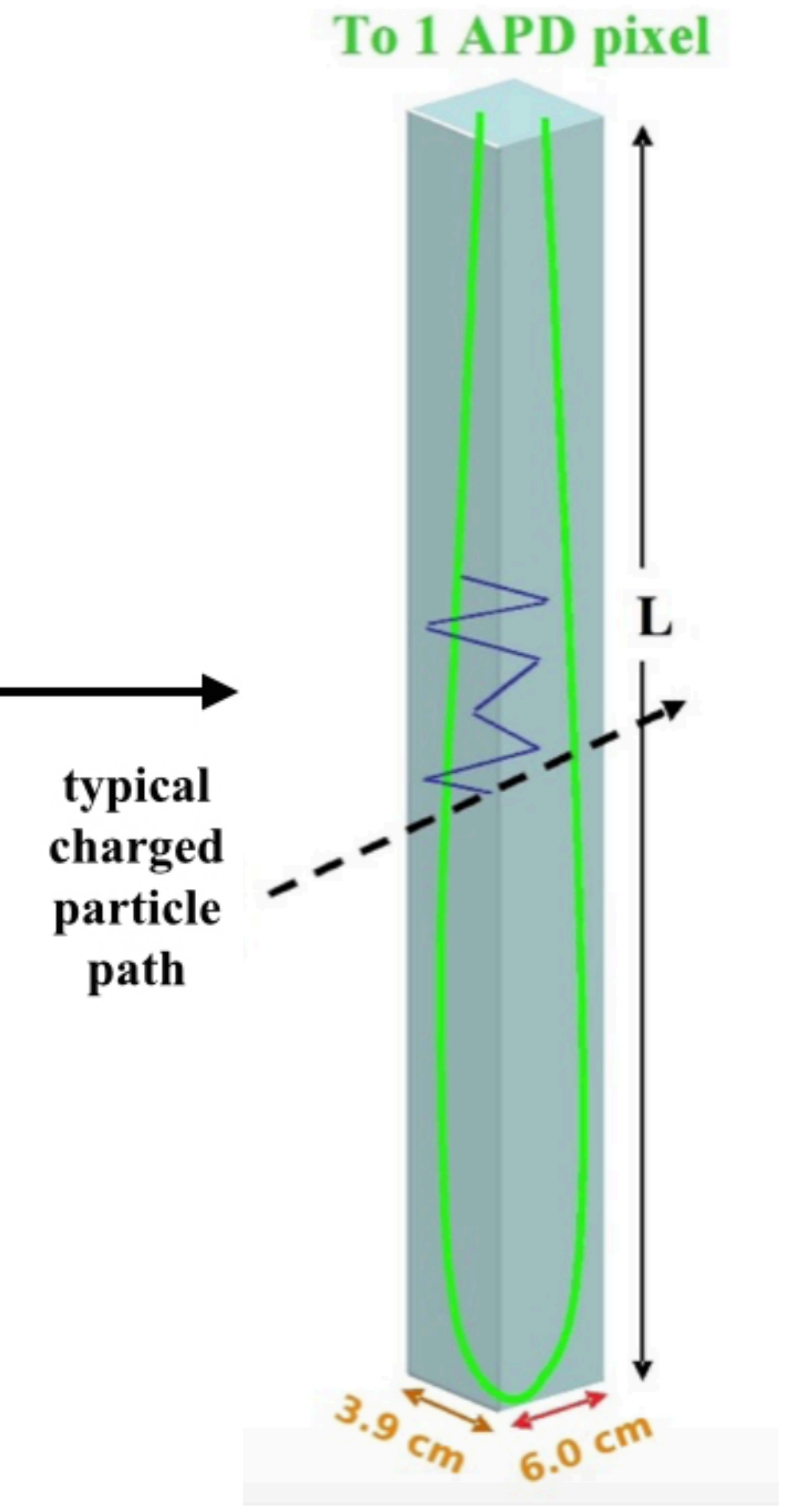
Near Detector (ND):
1km from source
100m underground

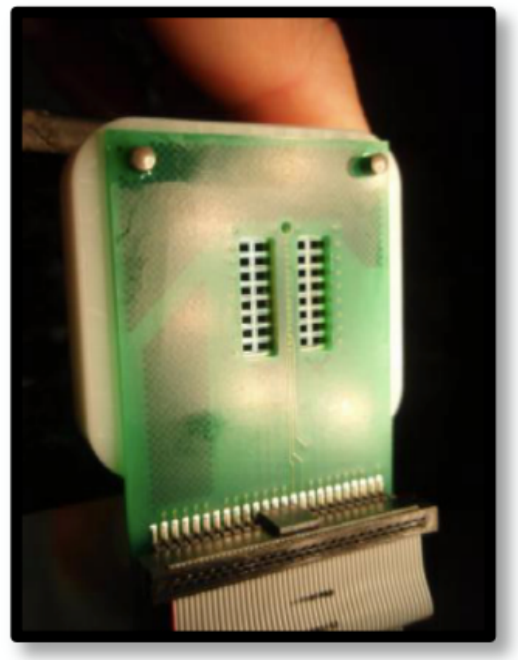


The NOvA Detectors



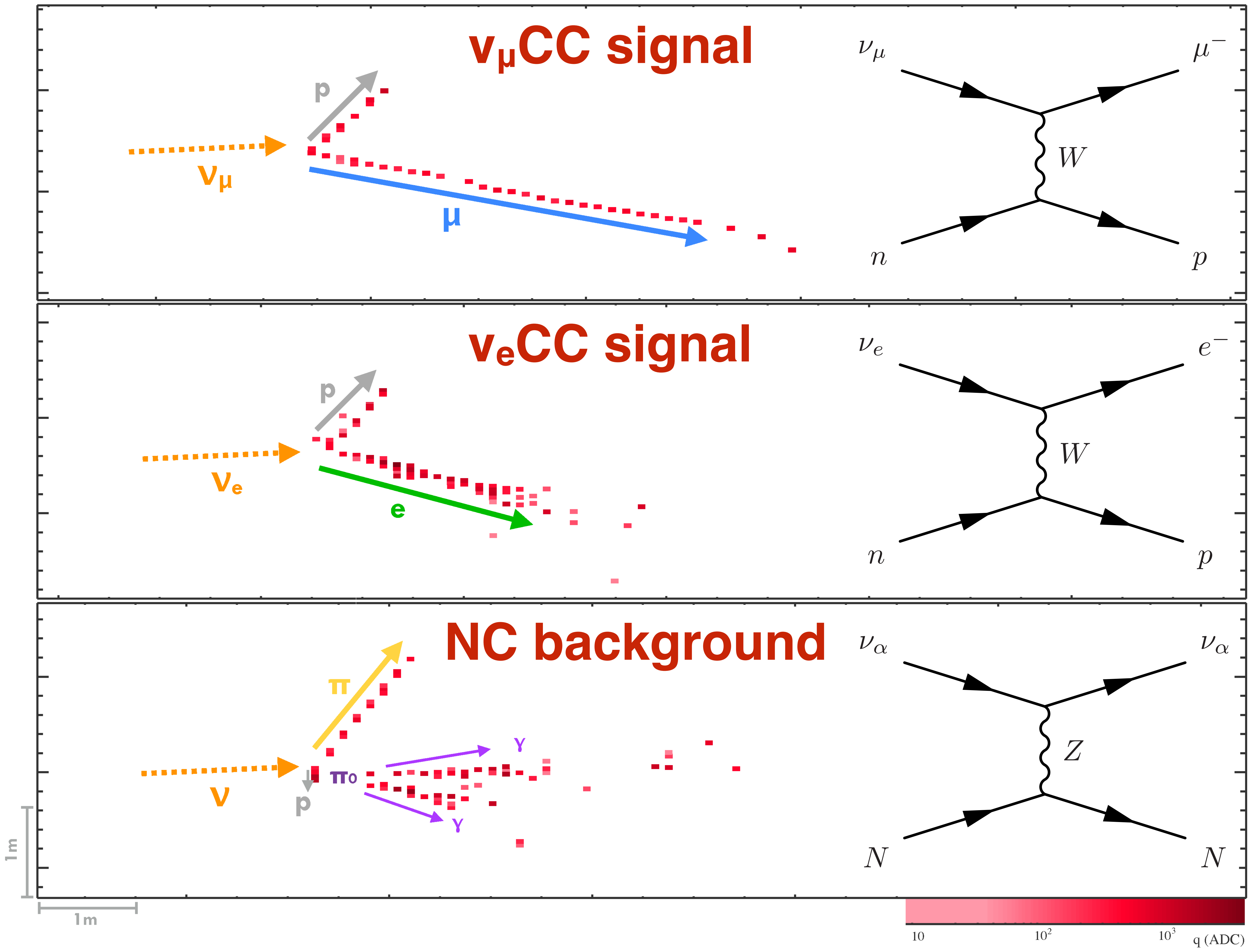






- PVC plastic cells are filled with liquid scintillator oil and arranged into planes. Layers alternate in orthogonal views for 3D reconstruction (top view and side view).
- Each of the cells contains one loop of wavelength-shifting fiber. Light is produced when charged particles pass through the cells and read out by avalanche photo-diode (APD).

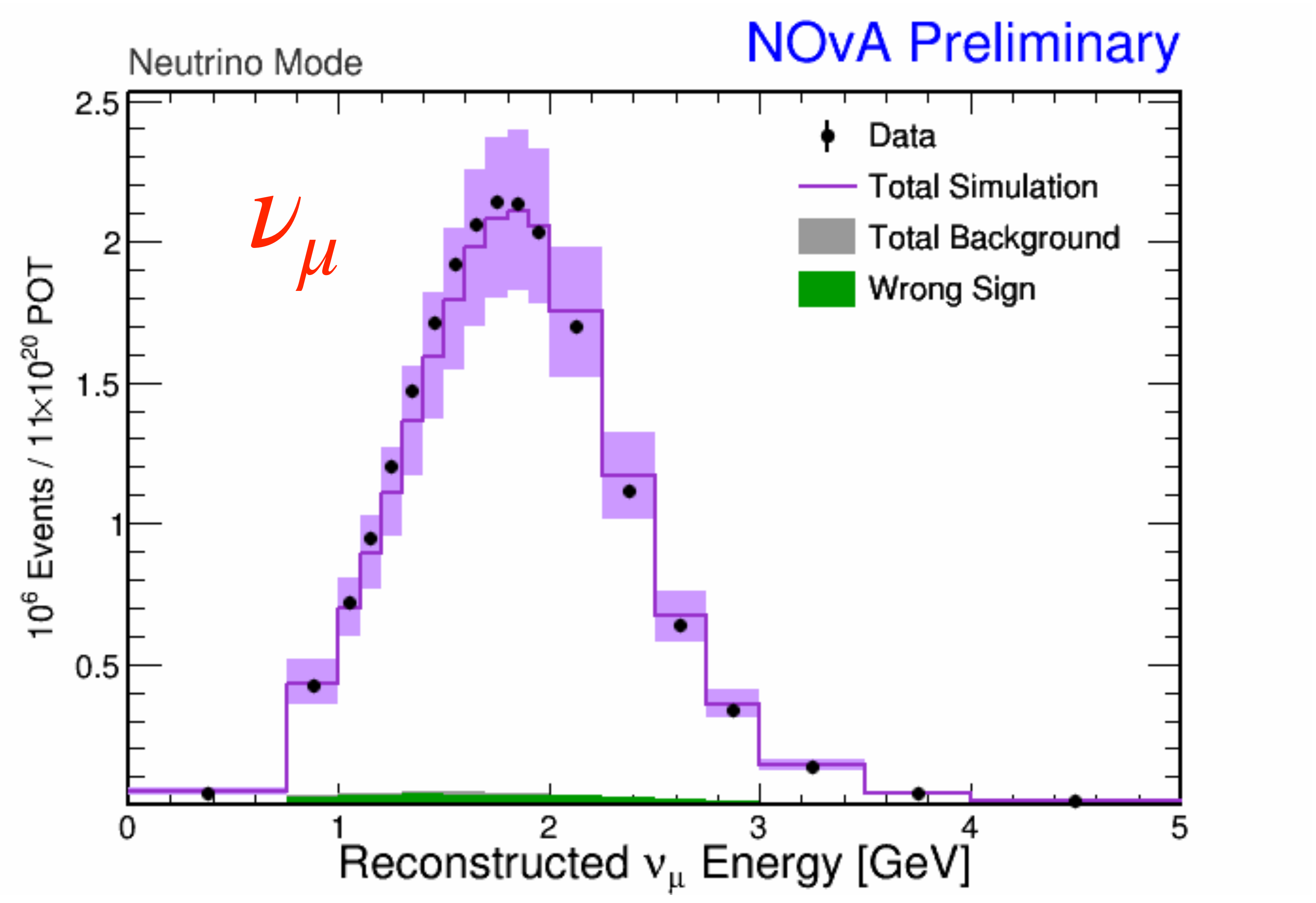
Identifying Neutrino Events



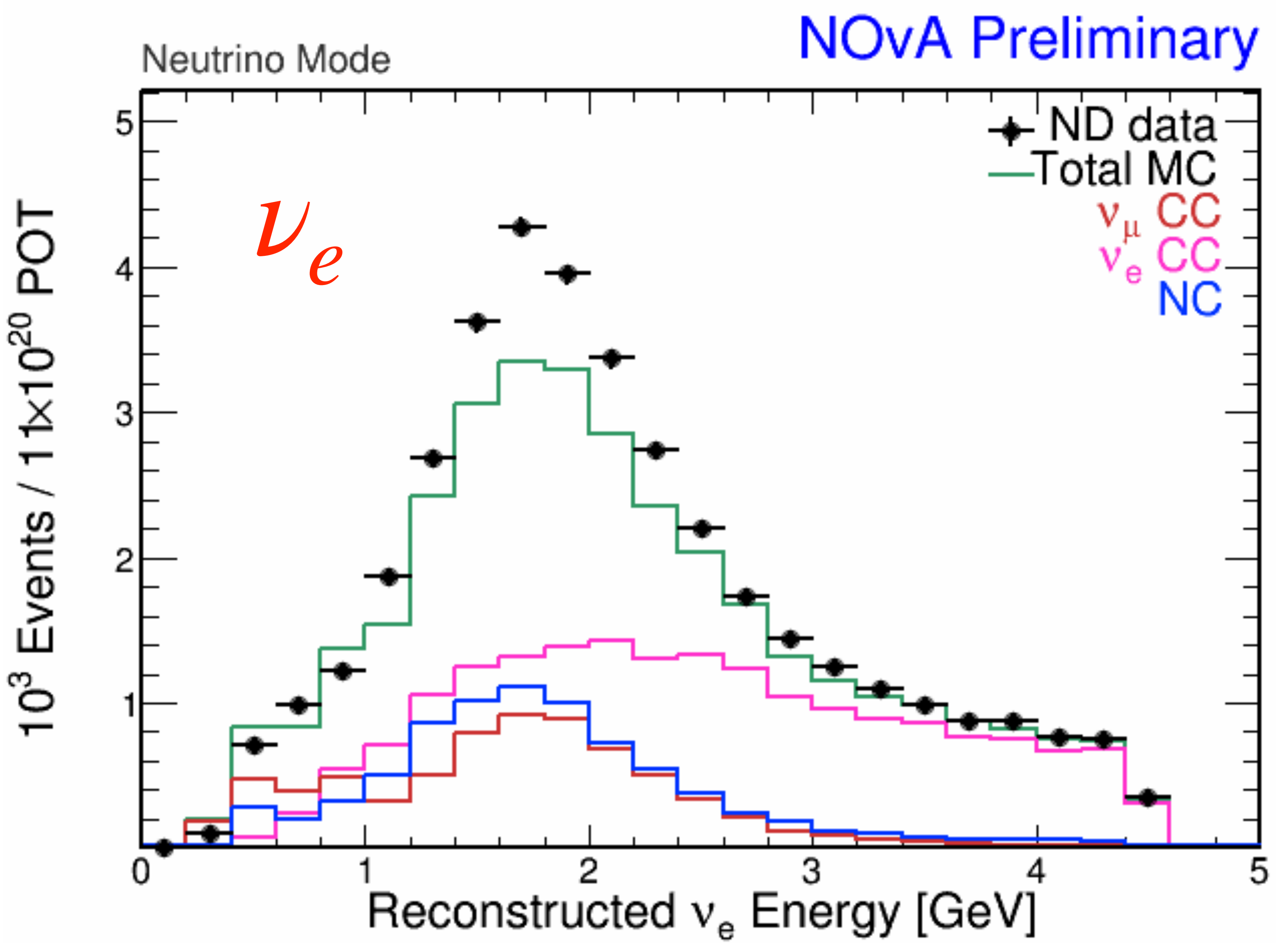
- Neutrino event identification is done using a **Convolutional Neural Network** (CNN) in NOvA, which is a deep-learning technique from computer vision.
- Convolutions are applied to images of the events, which are trained to identify particular features (tracks, vertex, showers, etc). Output of this process is a score by category.
- Cosmic rays are rejected using Boosted Decision Trees (BDTs).

The Near Detector Spectra

- ND and FD are functionally identical. They share similar systematic uncertainties, particularly on neutrino cross-section and flux.
- Extrapolating high statistics ND data to predict FD spectra can significantly reduce systematic uncertainties correlated between two detectors.

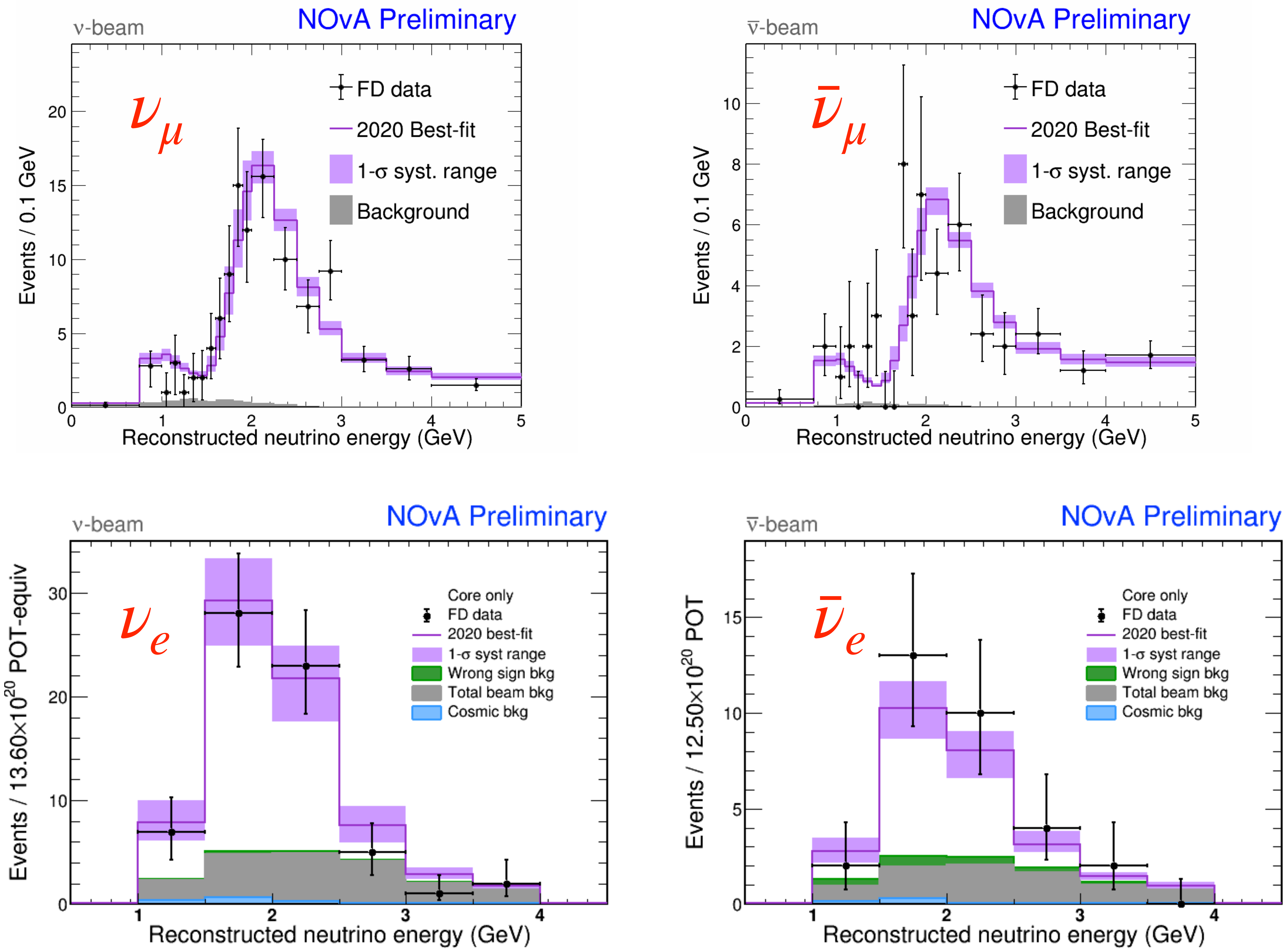


ND ν_μ-like samples are used to predict FD ν_μ and ν_e **signal** spectra.



ND ν_e-like samples are used to predict FD ν_e **background**.

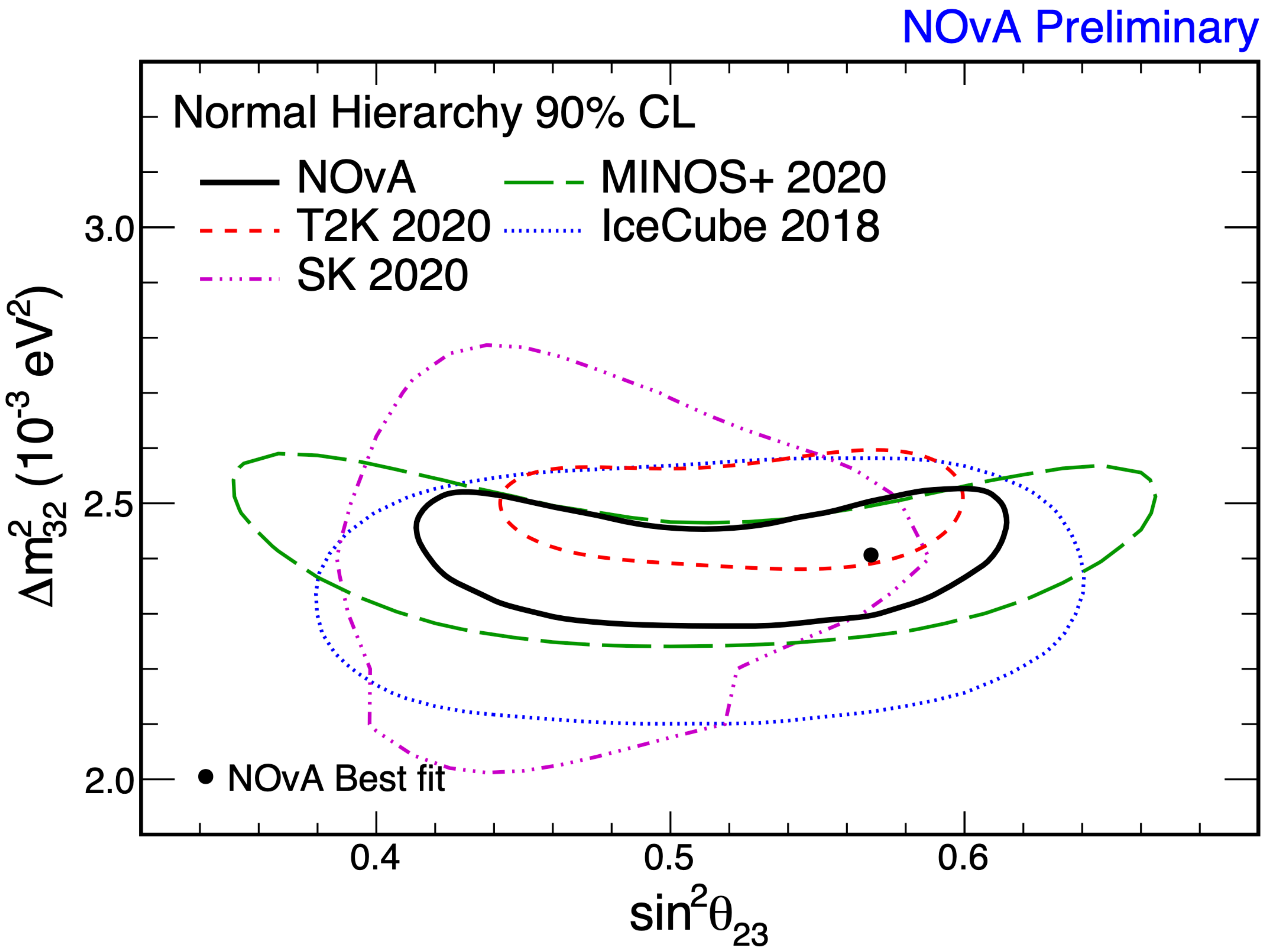
The Far Detector Data



	ν_μ	$\bar{\nu}_\mu$
Observed	211	105
Prediction	222.3	105.4
Background	8.2	2.1

	ν_e	$\bar{\nu}_e$
Observed	82	33
Prediction	85.8	33.2
Background	26.8	14.0

Results (θ_{23} , Δm^2_{32})



Best fit:

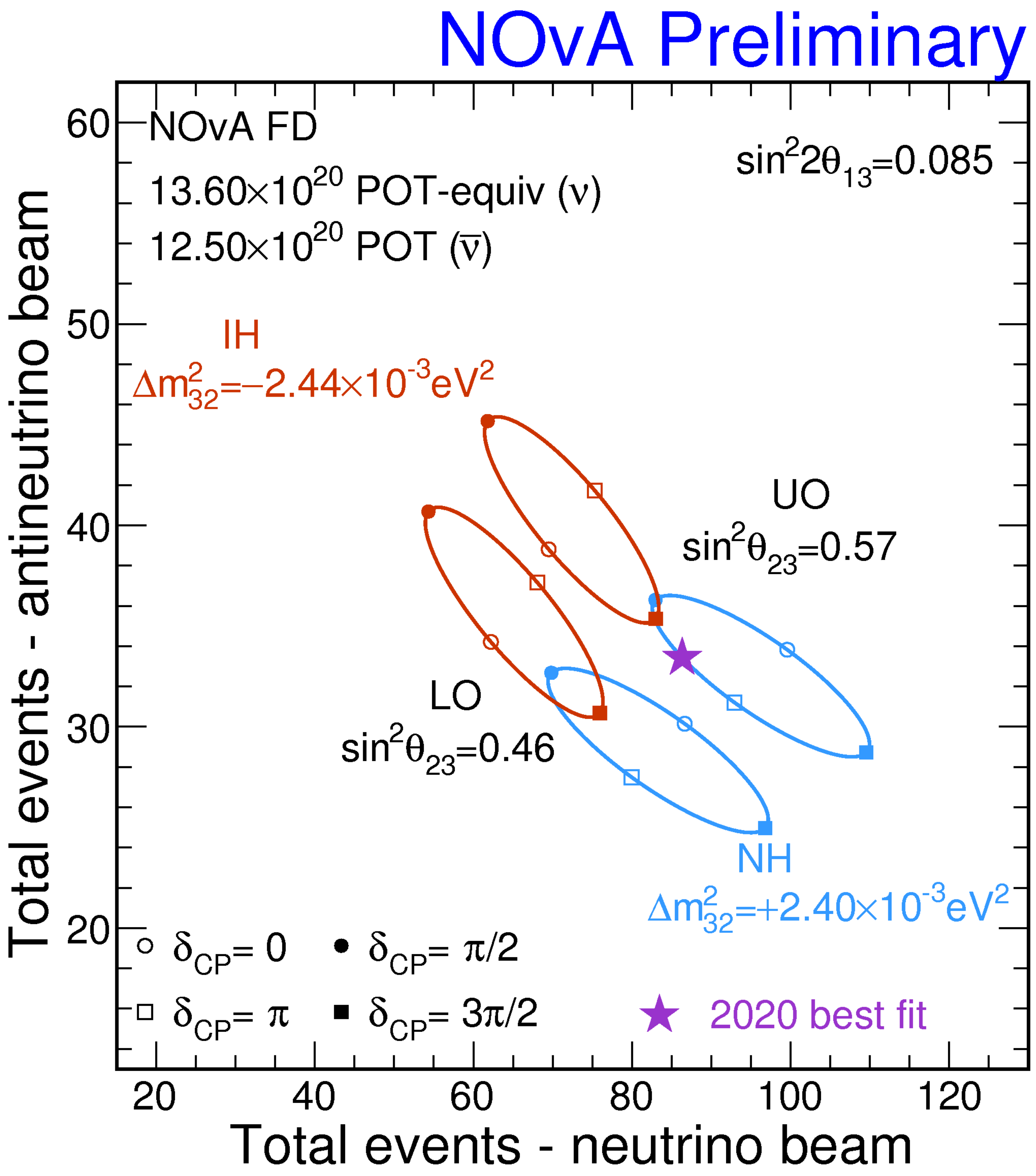
Normal hierarchy

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

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

- Precision measurements of Δm^2_{32} (3%) and $\sin^2\theta_{23}$ (6%)
- Lower octant ($\sin^2\theta_{23} < 0.5$) disfavored at 1.2σ

$\nu_e/\bar{\nu}_e$ Appearance Results



Best fit:

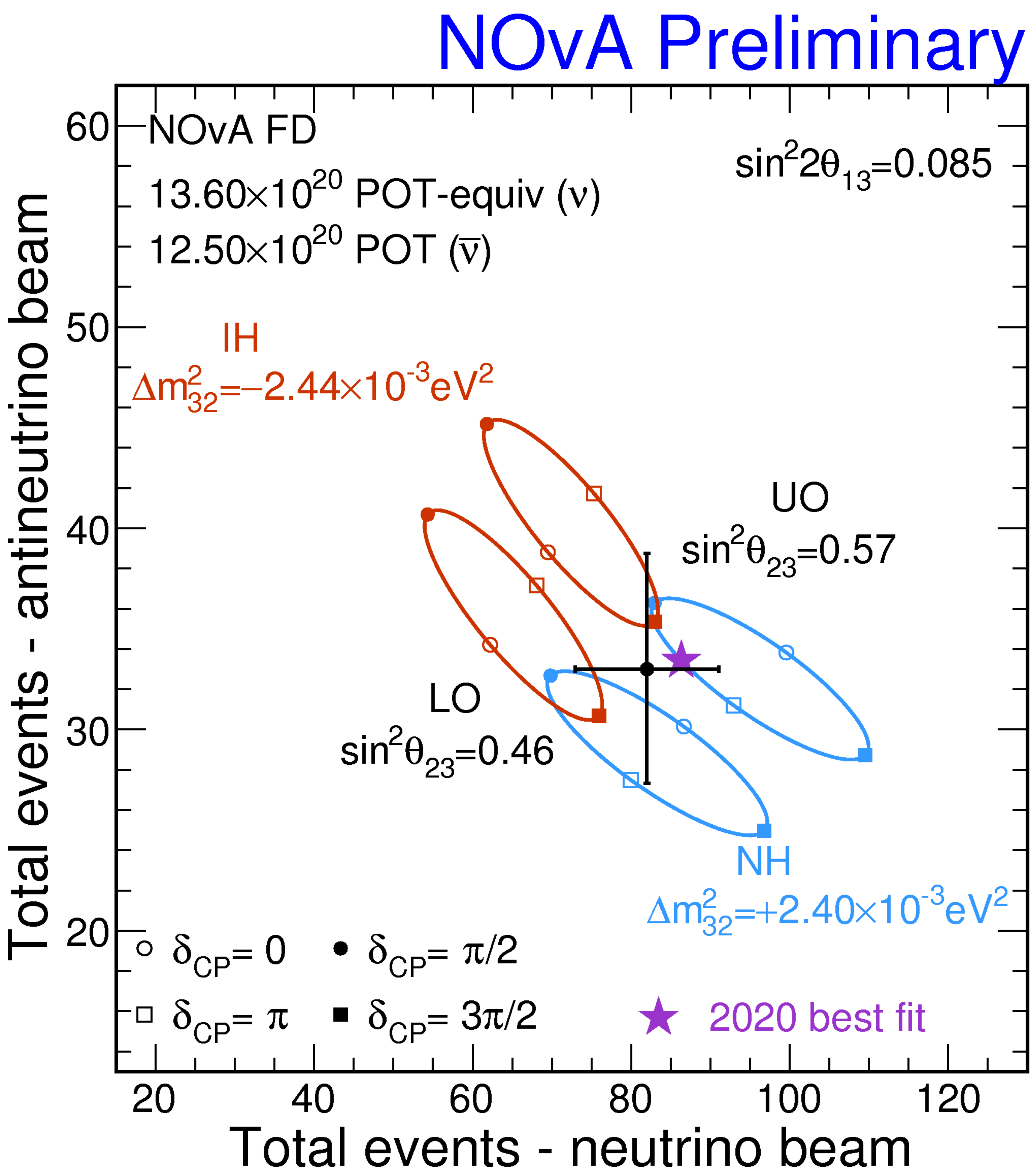
Normal hierarchy

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

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

$\delta_{\mathrm{CP}} = 0.82\pi$

$\nu_e/\bar{\nu}_e$ Appearance Results



Best fit:

Normal hierarchy

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

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

$\delta_{\mathrm{CP}} = 0.82\pi$

Observe no strong asymmetry between ν_e and $\bar{\nu}_e$ appearance rates

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

Disfavor NH $\delta_{\mathrm{CP}} = 3\pi/2$ at ~ 2σ

Looking Ahead

- NOvA is expected to run through 2026, to reach ~50% neutrino and ~50% antineutrino data with a projected total exposure 60-70 $\times$ 10^{20} POT.
- With full dataset and upgraded beam, we predict:
  - 3σ hierarchy sensitivity for 30-50% of δ values.
  - 5σ hierarchy sensitivity in the most favorable case.
  - ~2σ sensitivity of CP violation.
- Plan to use results of our test beam experiment to address some of the largest systematic uncertainties in NOvA.

More NOvA Topics

Cross-section measurements / Sterile neutrino searches / Cosmic ray physics and exotics …

Further reading

New Perspectives

Harry Hausner: Maximizing NOvA's Sensitivity to Sterile Neutrinos using Covariance Matrices

Michael Dolce: Fitting NOvA cross-section parameters with Markov Chain Monte Carlo

Chatura Kuruppu: Status of the muon neutrino charged-current coherent pion production in the NOvA near detector

Akshay Chatla: Context Enriched Prong CNN performance studies in NOvA

Sebastian Sanchez-Falero: Status of the muon neutrino charged-current mesonless cross section measurement in the NOvA near detector

54th Users Meeting

Talks

Erika Catano-Mur: NOvA 3-Flavor oscillation results

Wenjie Wu: NOvA cross-section measurements

Posters

Akshay Chatla: Context Enriched Prong CNN Performance Studies in NOvA

Cullen Sullivan, Mark Messier, Ashley Back: Investigating Improvements to the NOvA Event Selection Efficiency for Events in the Mass-hierarchy-sensitive Energy Range

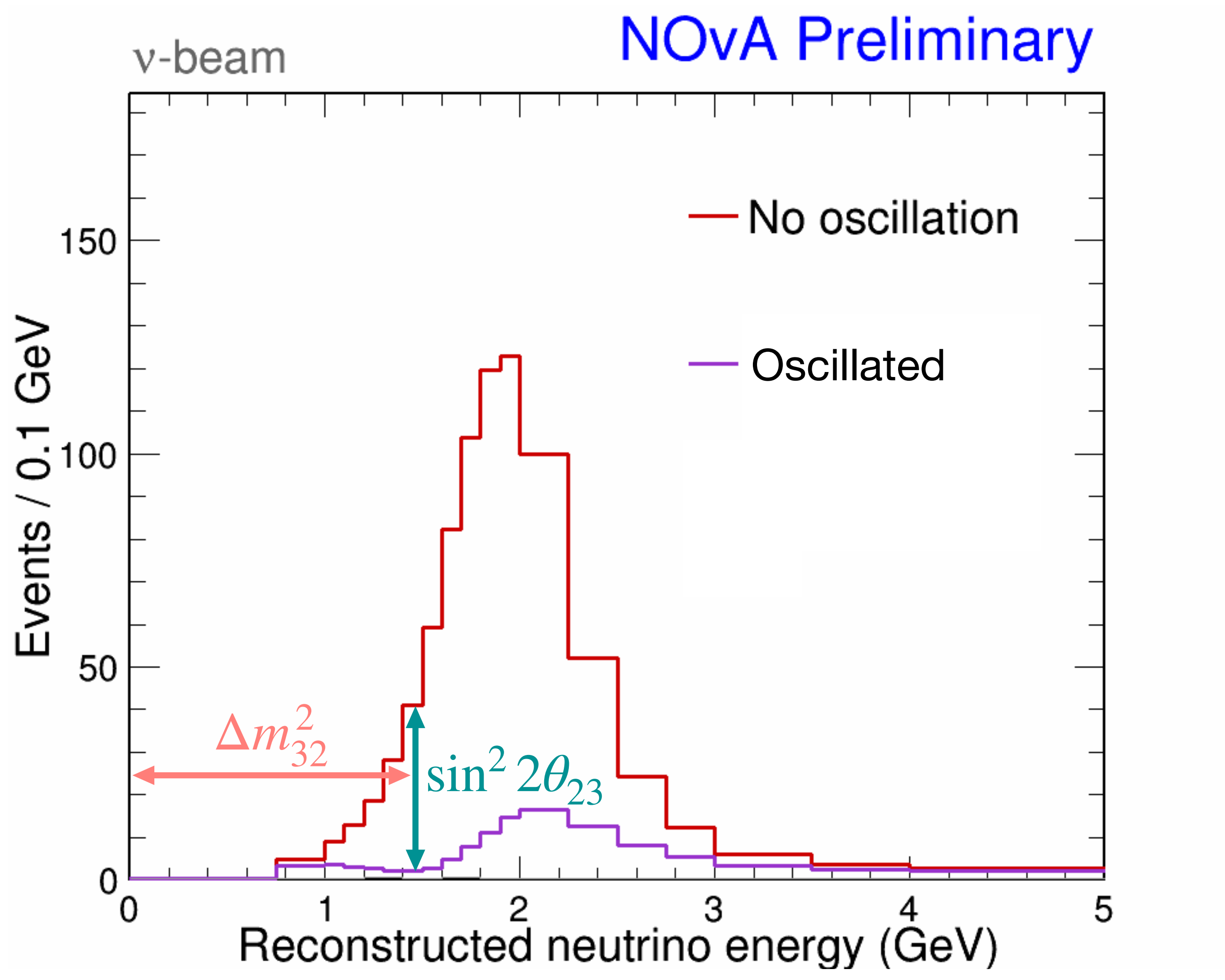
Miranda Elkins: NOvA's Latest 3-Flavor Neutrino Oscillation Results

Sebastian Sanchez-Falero: Status of the Muon Neutrino Charged-Current Zero Mesons Cross Section Measurement in the NOvA Near Detector

Thank you!

Backup

NOvA Physics Goals



ν_μ Disappearance

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

→ precise measurement on $\sin^2 2\theta_{23}$ and $|\Delta m^2_{32}|$

ν_e Appearance

$$P(\nu_\mu \to \nu_e / \bar{\nu}_\mu \to \bar{\nu}_e) \approx \left|\sqrt{P_{\mathrm{atm}}}e^{-i(\Delta_{32}+\delta_{\mathrm{CP}})} + \sqrt{P_{\mathrm{sol}}}\right|^2$$

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

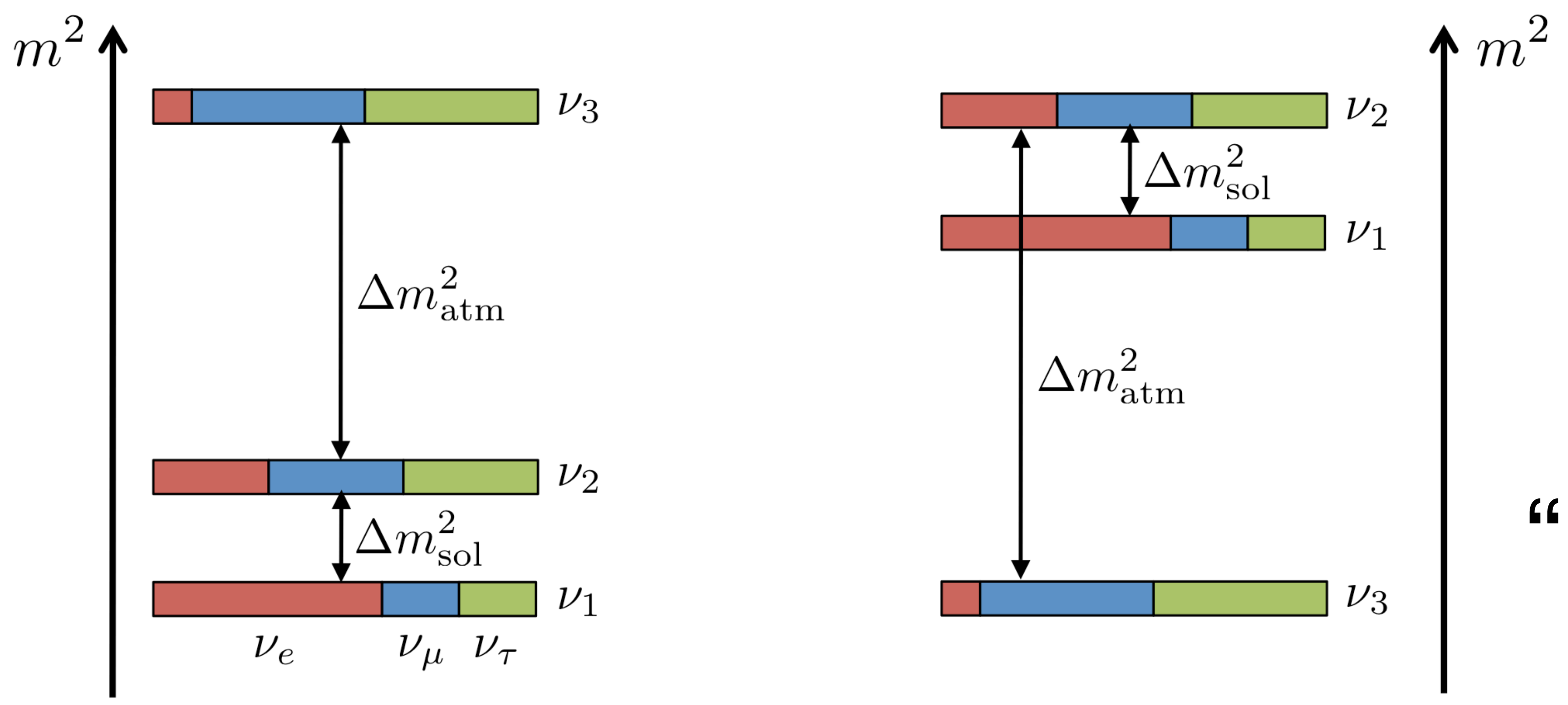
$\Delta P_{\nu\bar{\nu}} \propto \sin\delta_{\mathrm{CP}}$

$\delta_{\mathrm{CP}} = ?$ ③

$$\sqrt{P_{\mathrm{atm}}} \equiv \sin\boxed{\theta_{23}}\sin 2\theta_{13}\frac{\sin(\boxed{\Delta_{31} - aL})}{\boxed{\Delta_{31} - aL}}\Delta_{31}$$ (in matter)

$$\sqrt{P_{\mathrm{sol}}} \equiv \cos\boxed{\theta_{23}}\cos\theta_{13}\sin 2\theta_{12}\sin\Delta_{21}$$

normal hierarchy (NH) **inverted hierarchy (IH)**



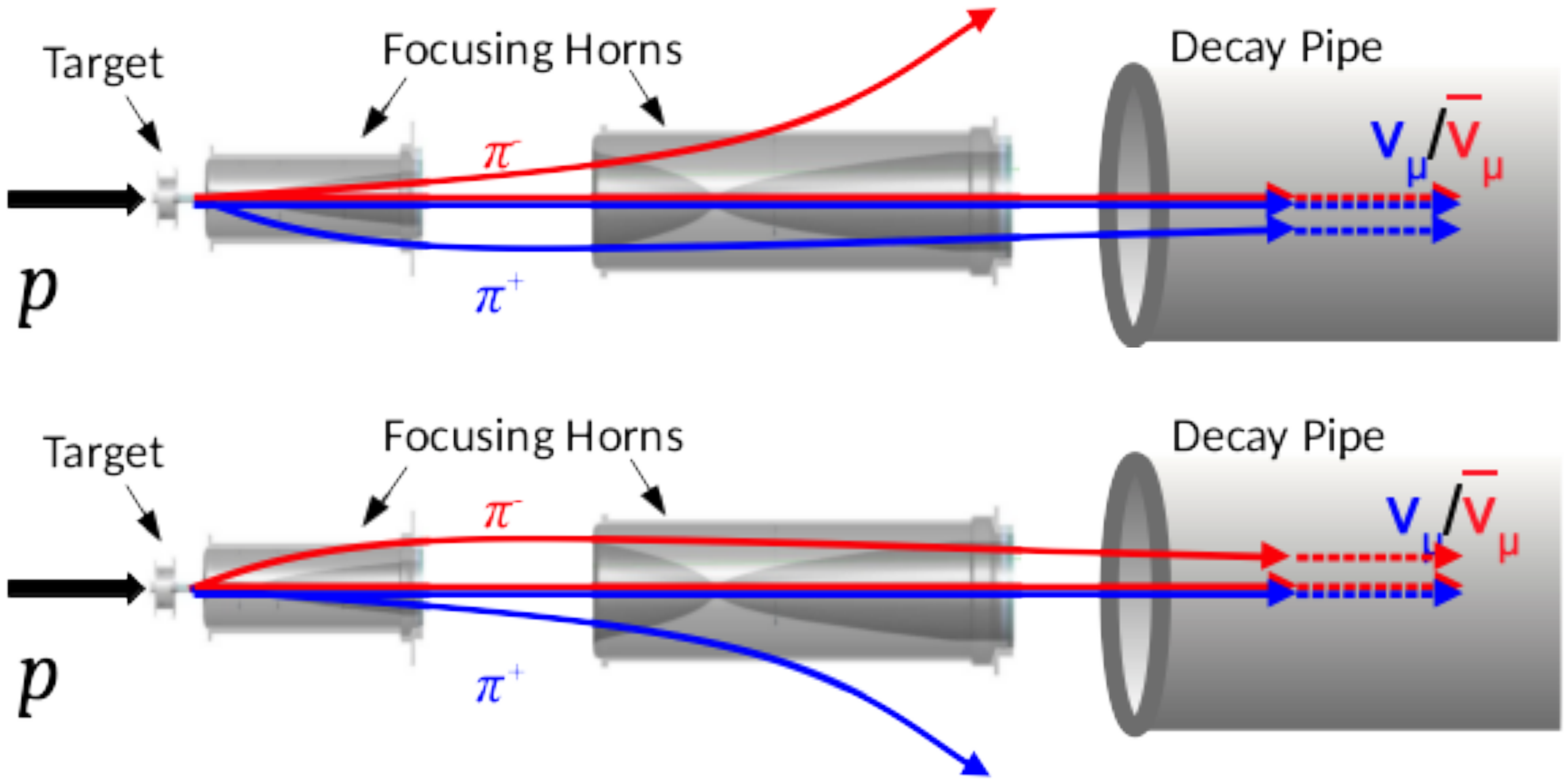
① Is the mass hierarchy "normal" or "inverted" ?

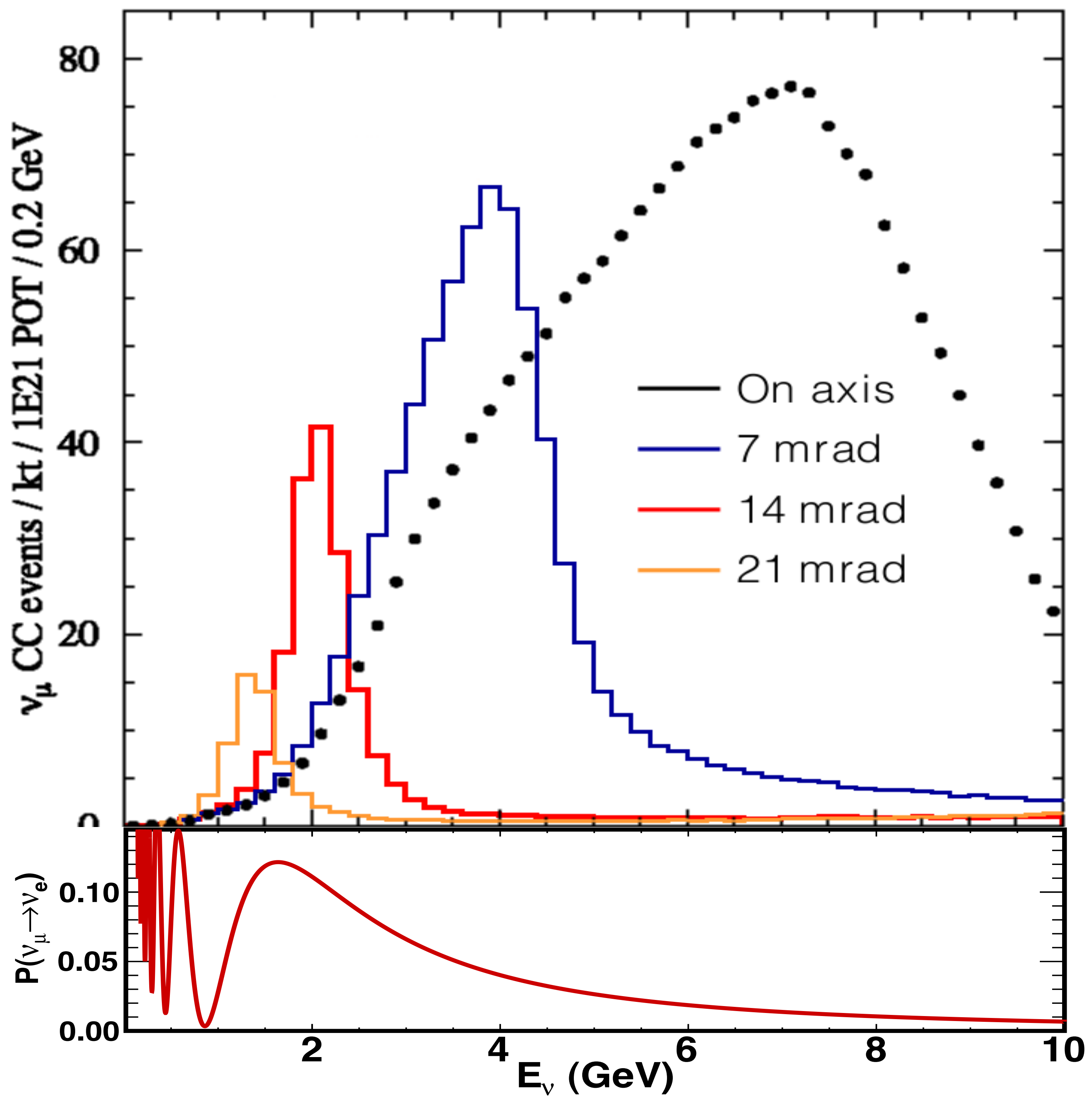
② Is θ_{23} >, <, = 45° ?

ν_3=

The NuMI Beamline

***Neu**trinos at the **M**ain **I**njector*





- Two running configurations:

  Neutrino mode (ν_μ) and antineutrino mode ($\bar{\nu}_\mu$)

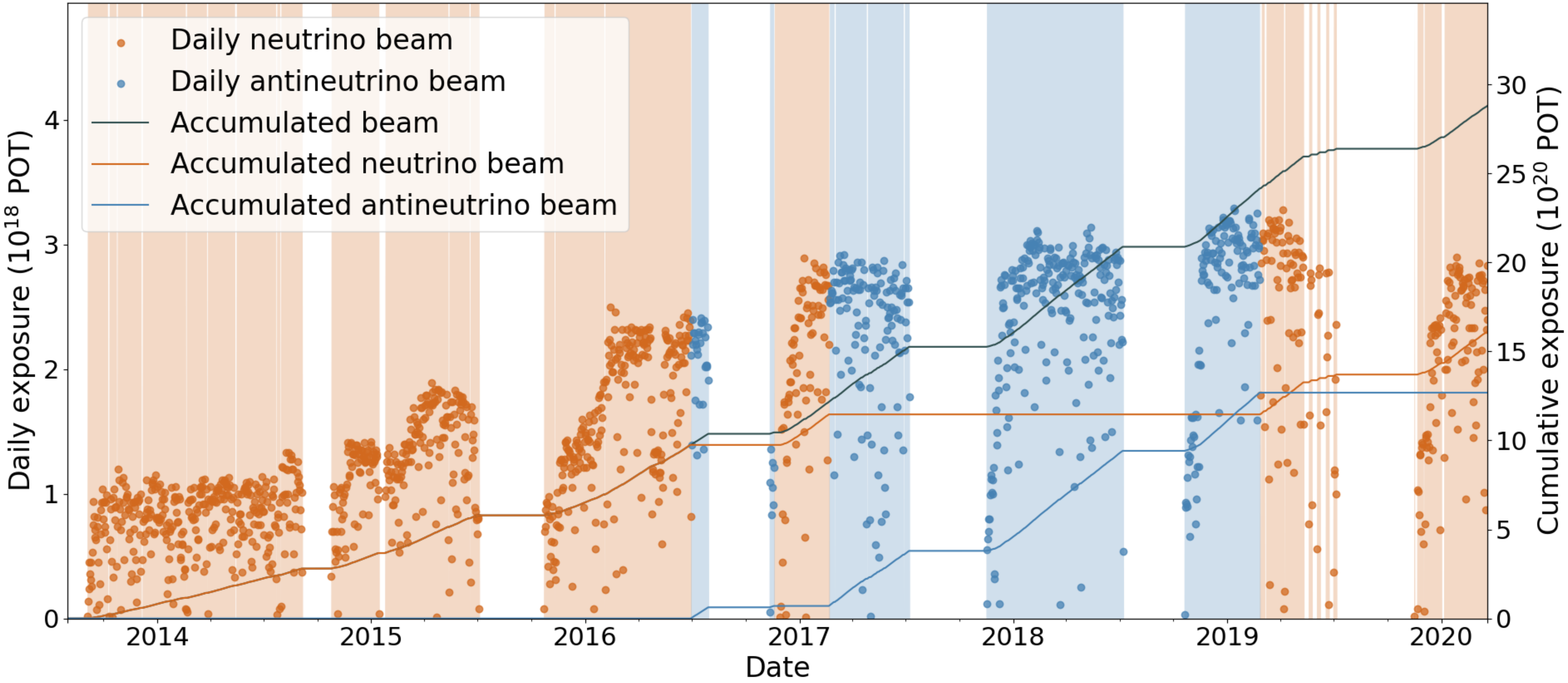
- Small contamination:

  Wrong sign and $\nu_e/\bar{\nu}_e$

14.6 mrad off-axis:

- Neutrino beam is narrowly peaked at ~2 GeV near oscillation maximum
- Reduce neutral-current backgrounds

The Beam Exposure

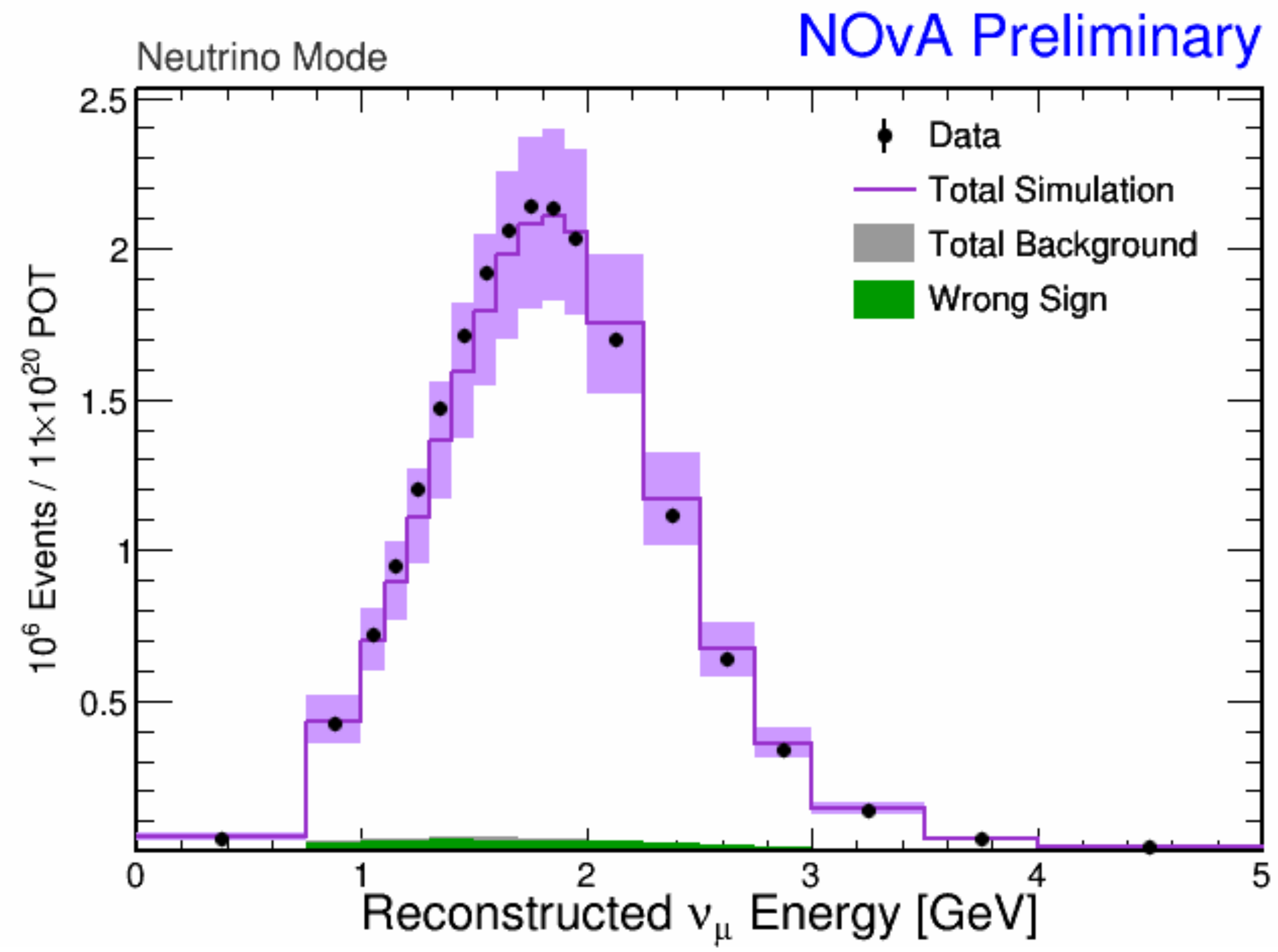


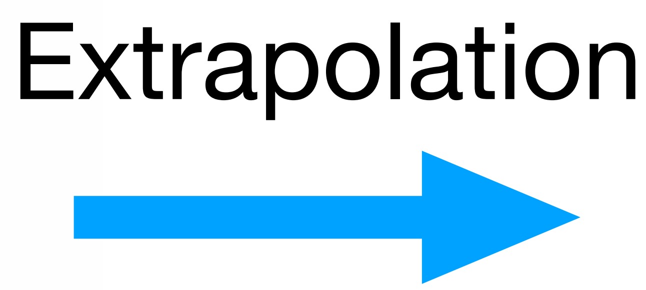
- Most powerful neutrino beam in the world — Peaks > 800 kW
- Currently taking data in Neutrino Mode

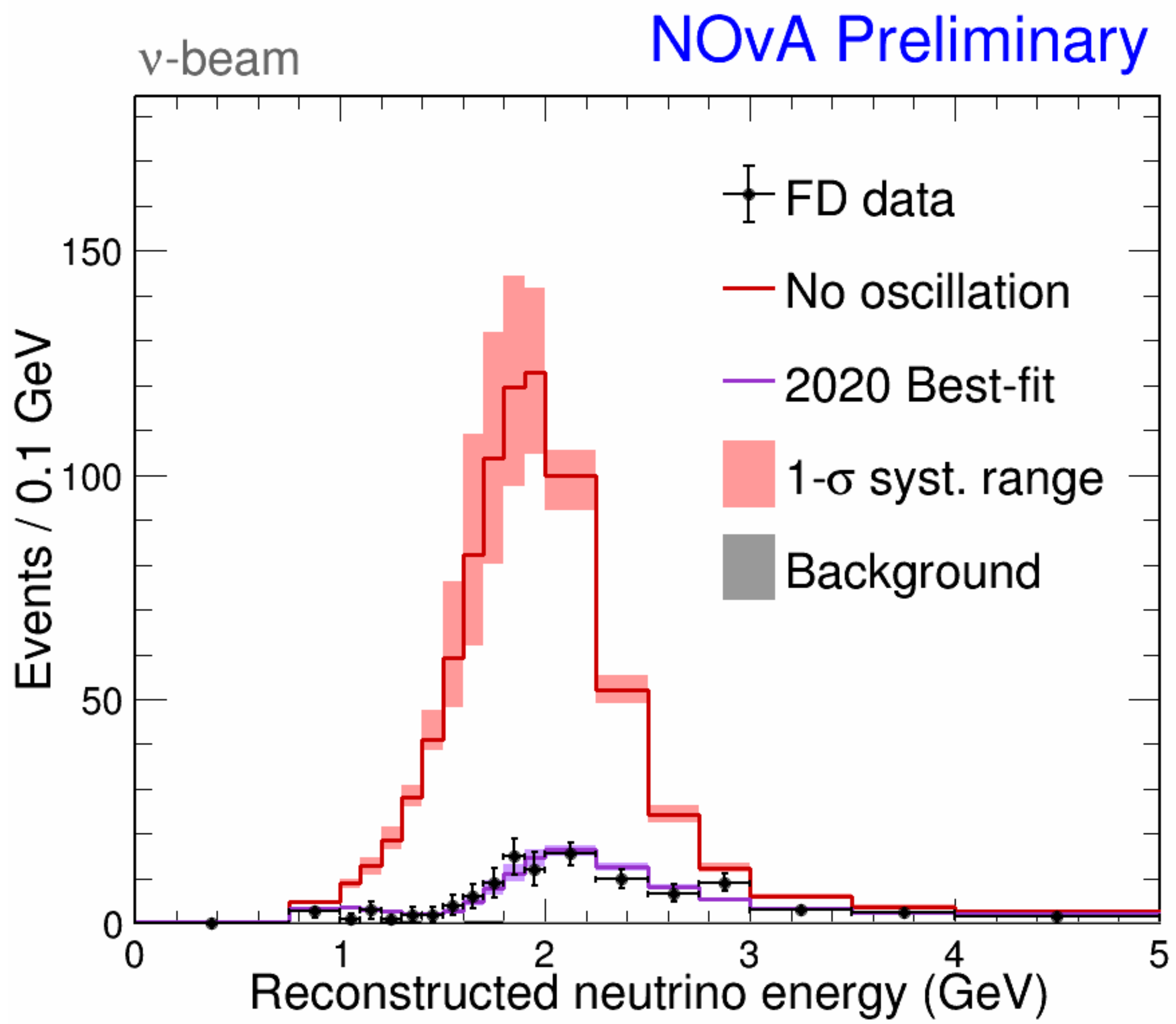
- Neutrino mode: 13.6×10^{20} POT
- Antineutrino mode: 12.5×10^{20} POT

(2014 - 2020)

ND to FD Extrapolation



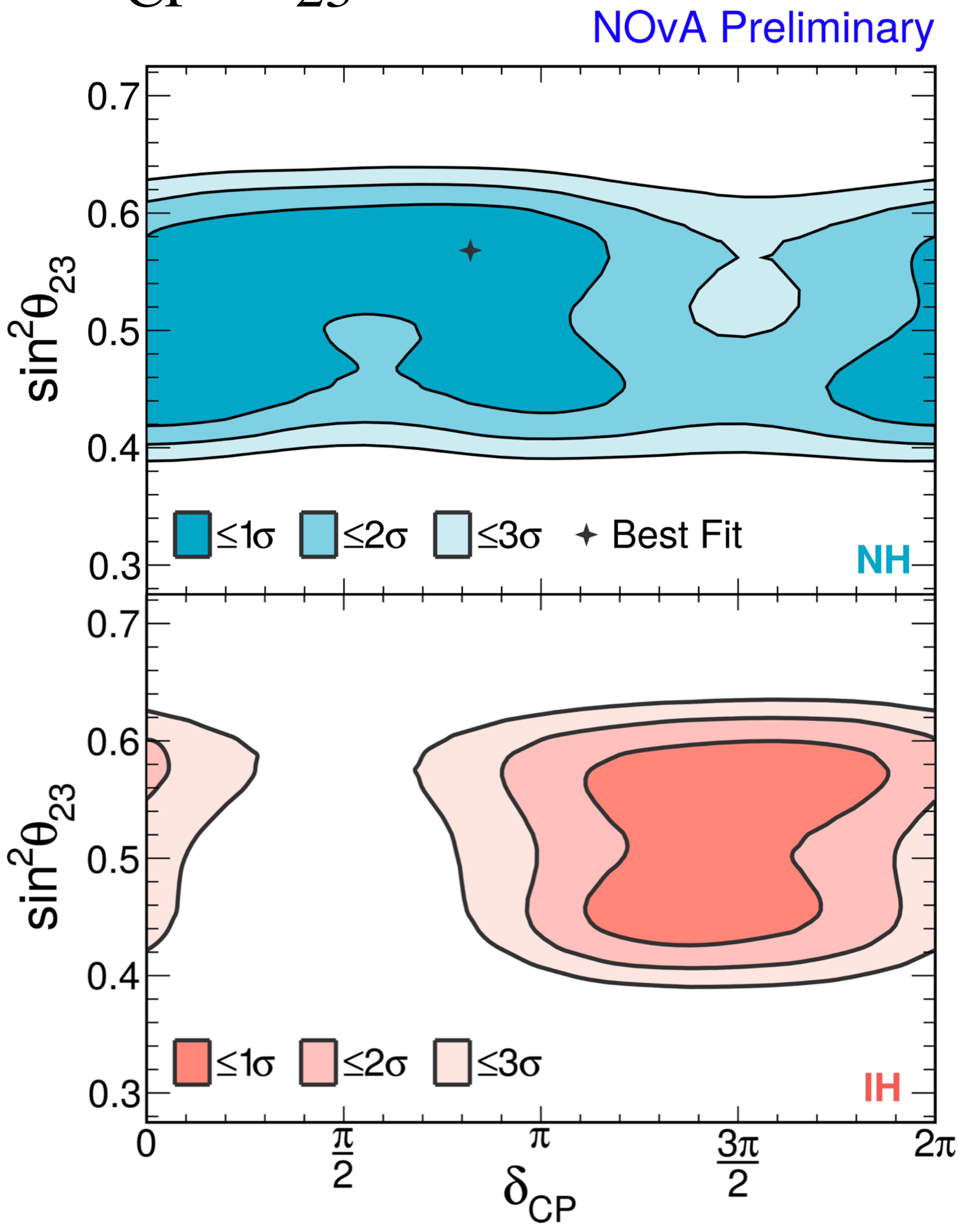




- Extrapolating high statistics ND data to predict FD spectra.

— Observe data-MC differences at the ND, which can be used to correct the FD prediction.
— Significantly reduce systematic uncertainties correlated between two detectors.

Results (δ_{CP} , θ_{23})



Best fit:

Normal hierarchy

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

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

$\delta_{CP} = 0.82\pi$

The NOvA Test Beam

- A scaled-down 30-ton NOvA detector
- Analyzes tagged charged particles from a tertiary beamline (protons, pions, muons, electrons and kaons) in the 0.2-2.0 GeV momentum range
- Results could address some of the largest systematic uncertainties in NOvA