NOvA Results and Prospects

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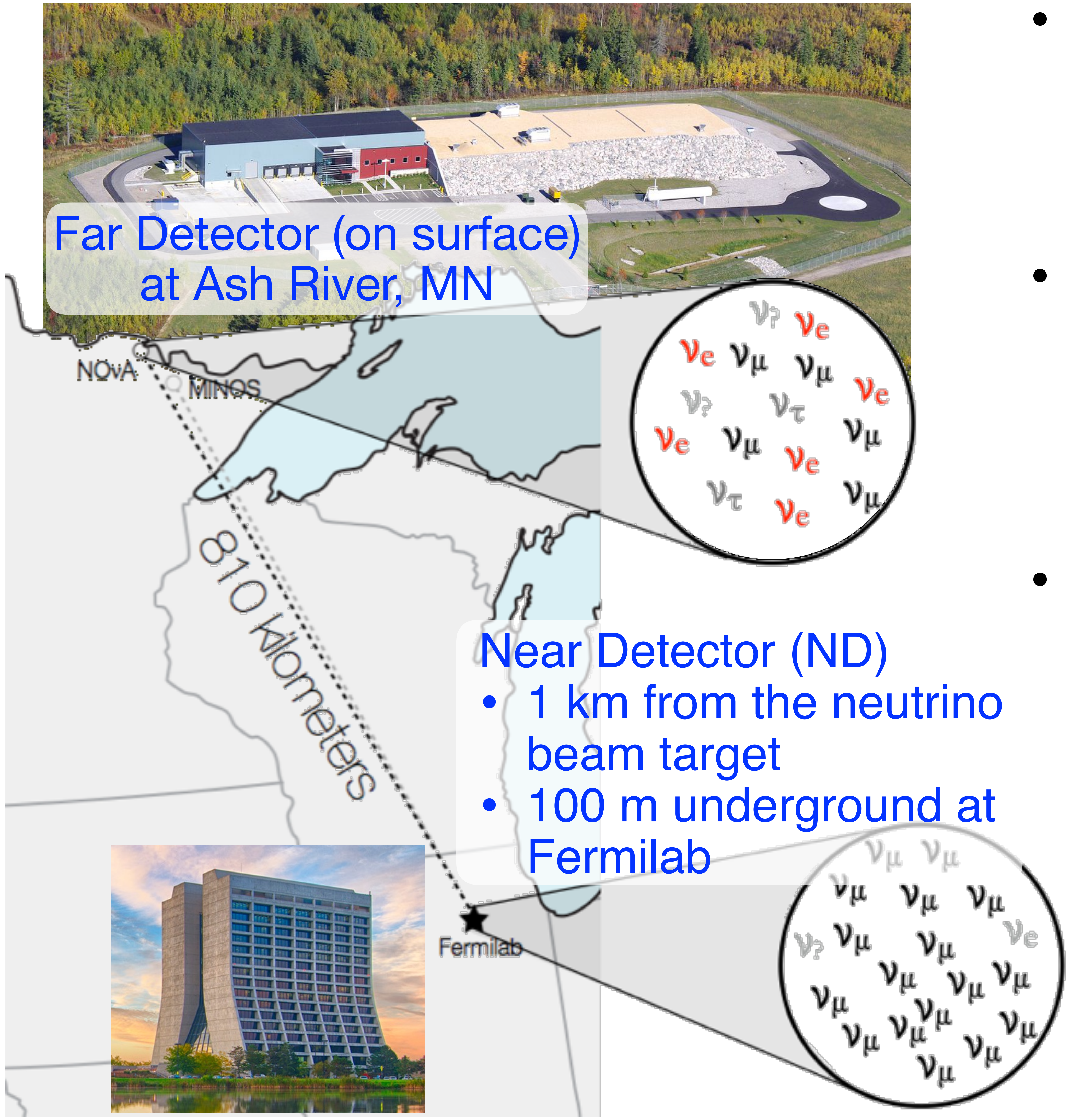
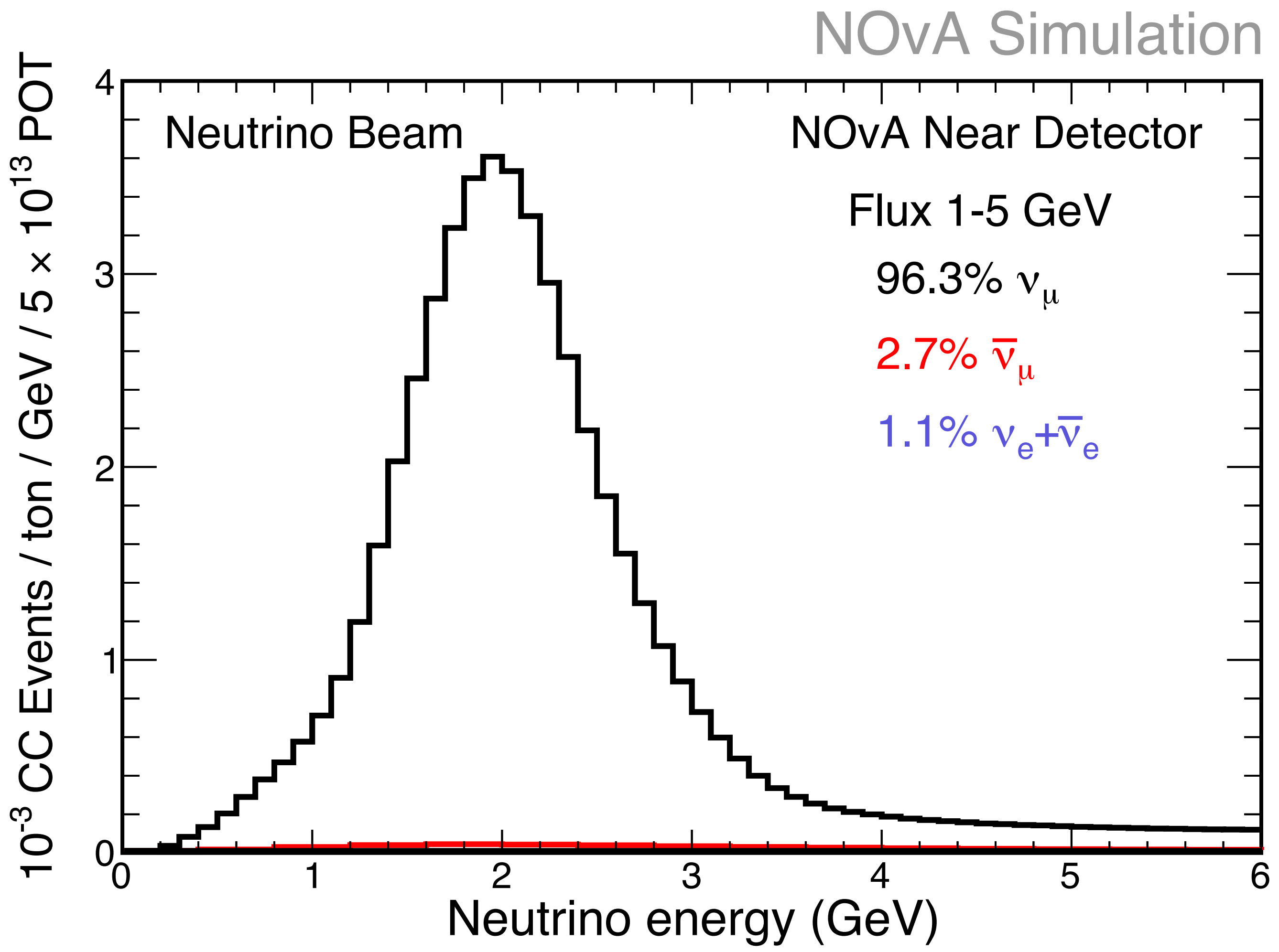
Lake Louise Winter Institute

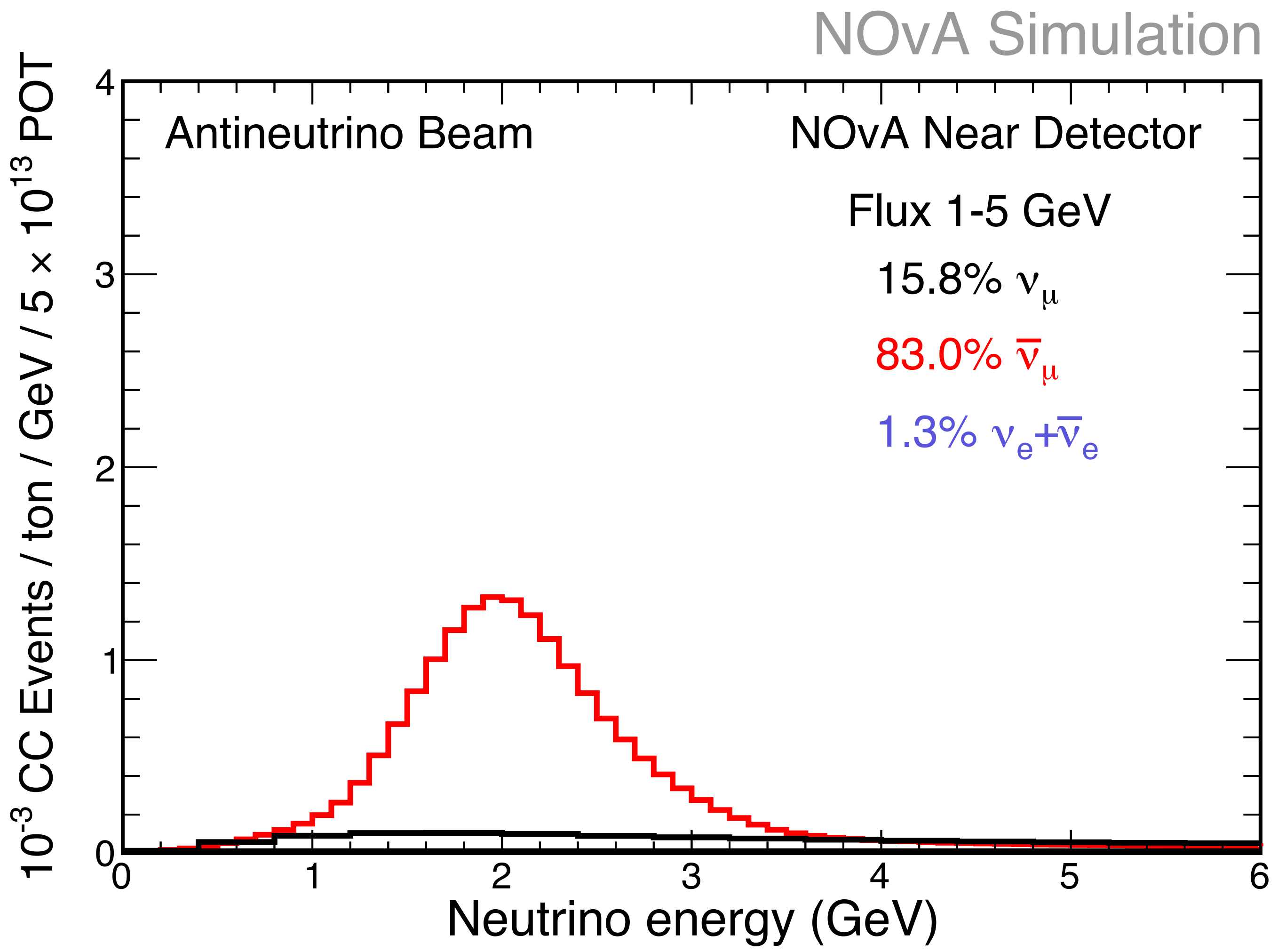
February 22nd, 2024

NOvA: NuMI Off-Axis ν_e Appearance Experiment

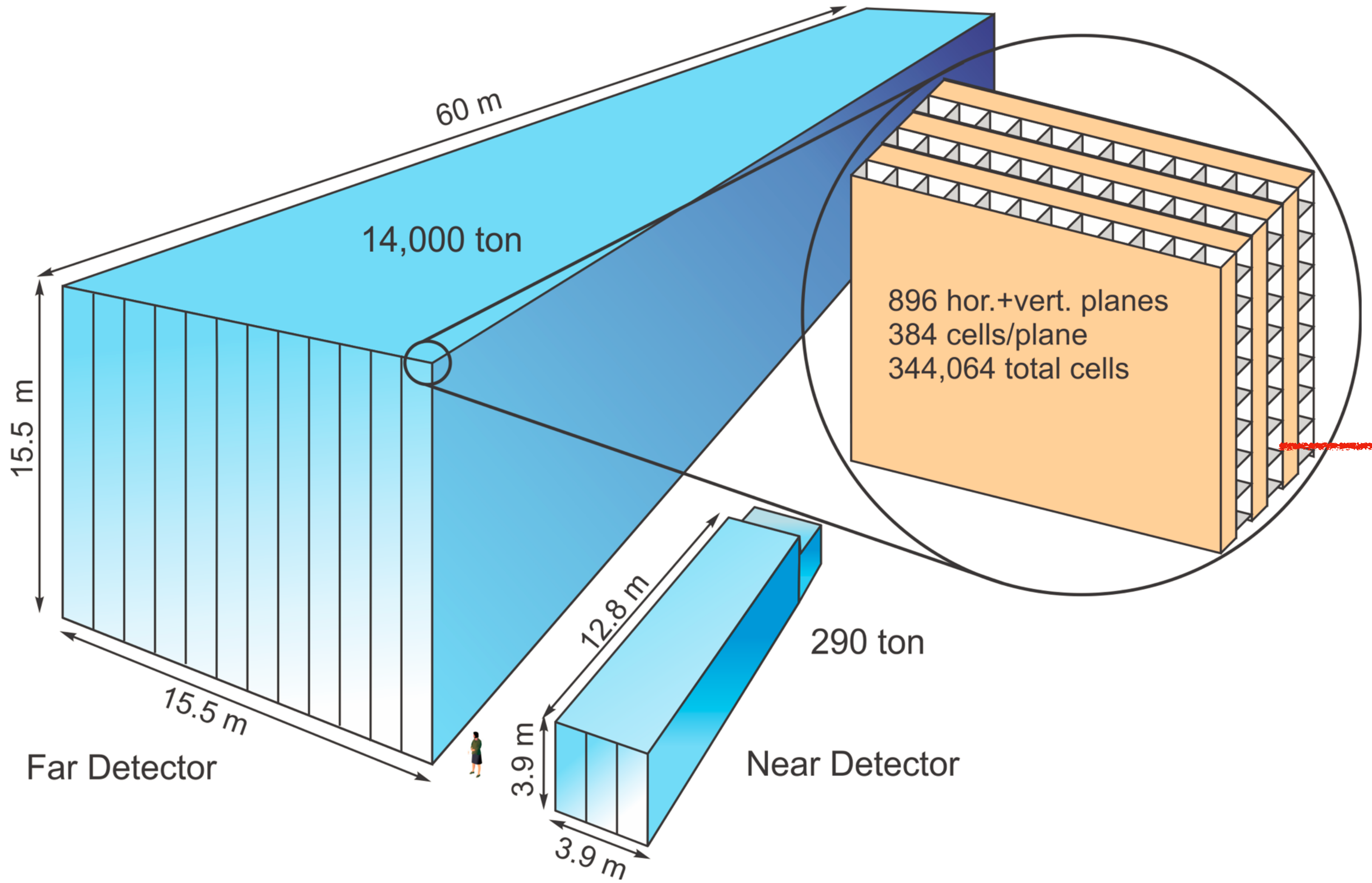


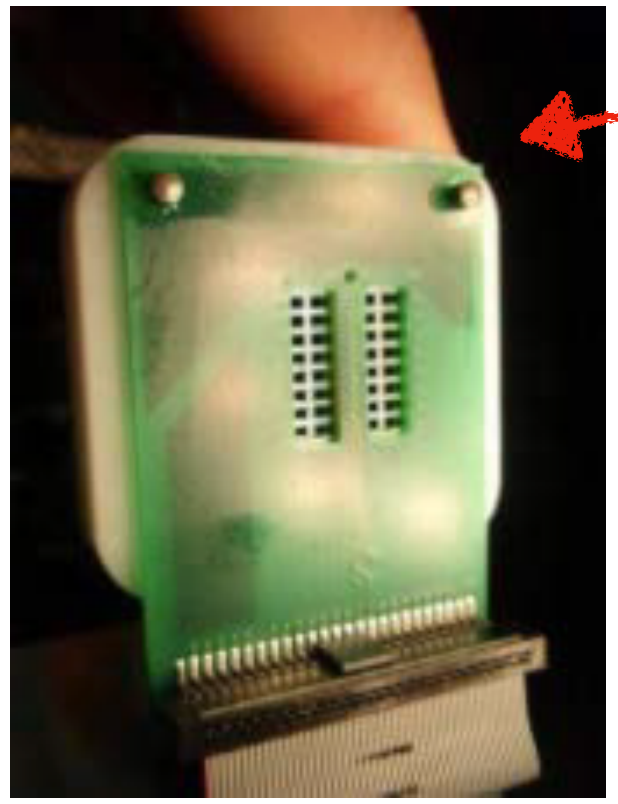
- NOvA is an accelerator-based neutrino experiment
  - Longest baseline in operation (810 km), large matter effect, sensitive to mass ordering
- Muon neutrino beam (NuMI) at Fermilab
  - Two configurations: neutrino mode and antineutrino mode
  - Power record 954 kW in 2023
- ~14 mrad off-axis, narrow-band beam around oscillation max.

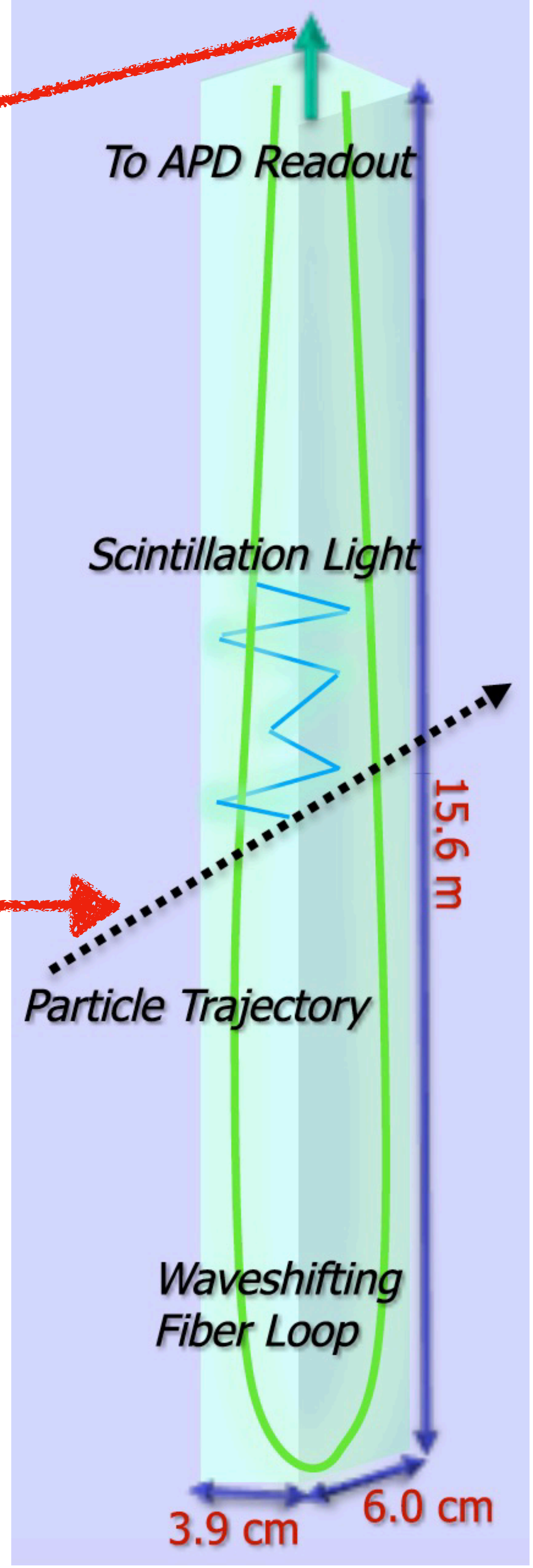




NOvA Detectors

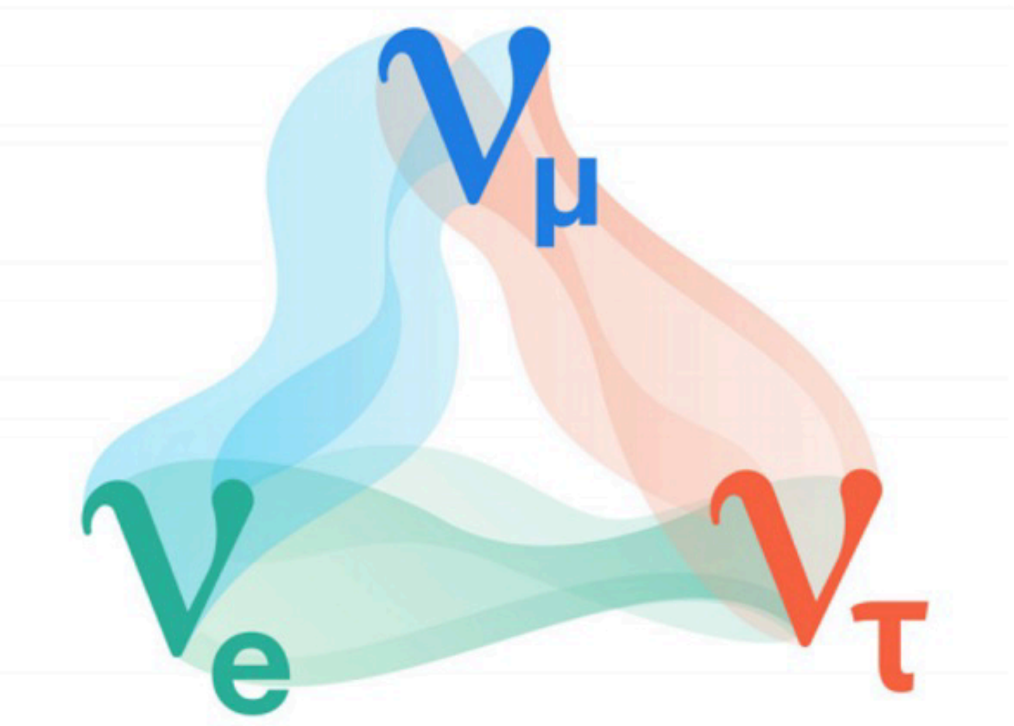






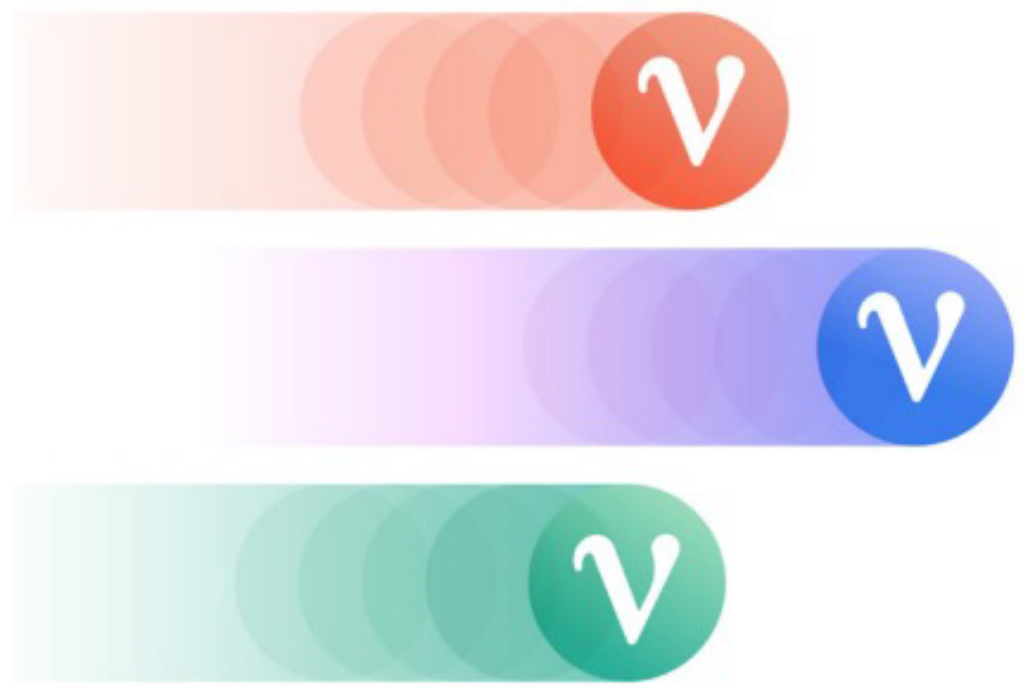
- FD and ND are functionally identical to minimize systematics
- Detectors composed of highly reflective extruded PVC cells filled with liquid scintillator. Alternating horizontal and vertical layers provide 3D views of the events
- Scintillation light captured and routed to APDs via wavelength shifting fibers

Neutrino oscillations



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\mathrm{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mixing Matrix



Flavor Eigenstates

Mass Eigenstates

$$U_{\mathrm{PMNS}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$c_{ij} = \cos\theta_{ij}$$
$$s_{ij} = \sin\theta_{ij}$$

$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$

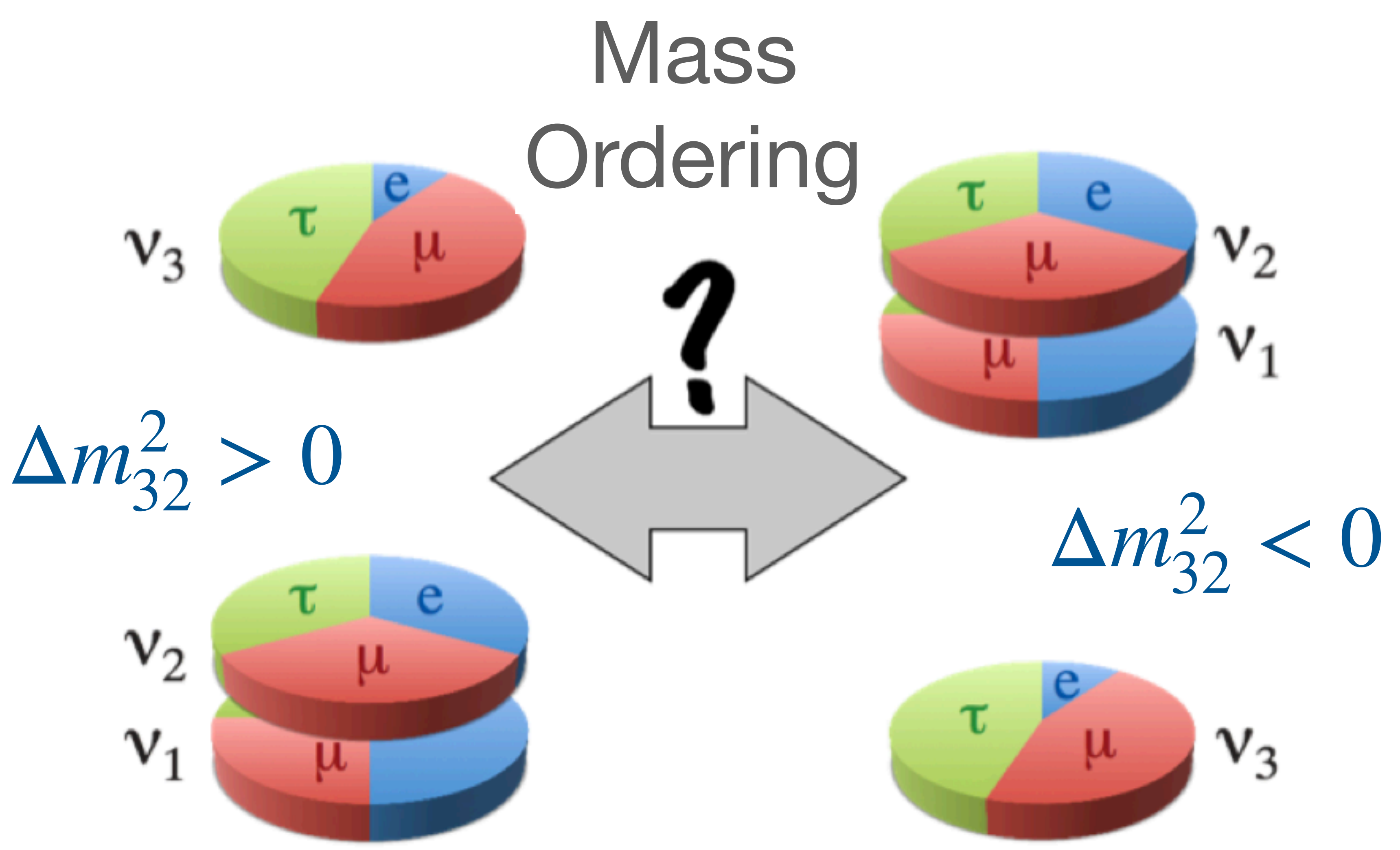
$$P(\nu_\alpha \to \nu_\beta) \sim \sin^2(2\theta)\sin^2\left(\frac{\Delta m_{ij}^2 L}{4E}\right)$$

The probability of flavor change depends on
L: travel distance (baseline)
E: neutrino energy

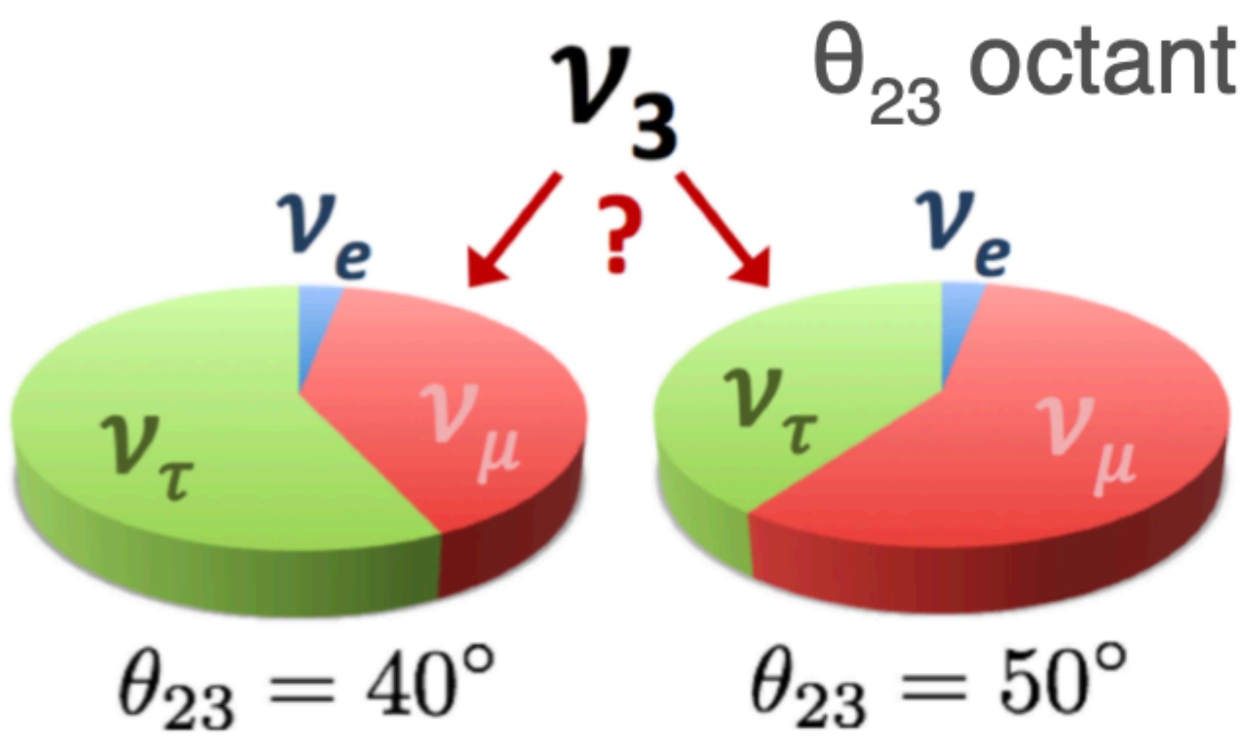
NOvA Physics Program

Addresses open questions:

- Sign of Δm^2_{32}: normal or inverted ordering?
- Value of θ_{23}: maximal mixing or (ν_μ/ν_τ asymmetry)?
- Is there CP violation in the lepton sector?



Using $\nu_\mu \to \nu_e$ and $\nu_\mu \to \nu_\mu$ and antineutrino oscillations



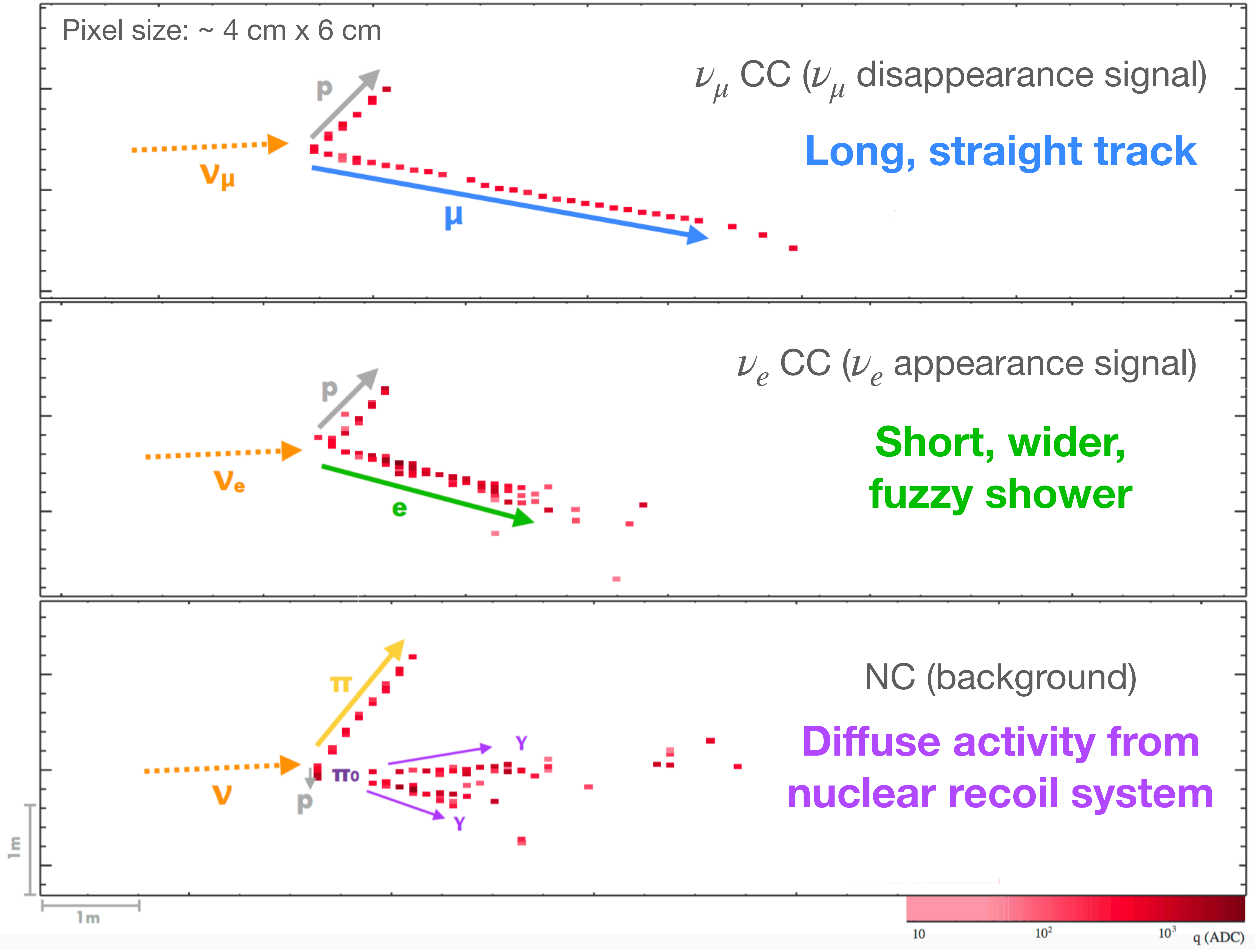
Broad physics program:

- Neutrino-nucleus cross-section measurements
- Search for sterile neutrinos, NSI
- Astrophysics and BSM: Multi-muon air showers, **And MORE!**

$\delta_{CP} = ?$

Event Identification and Selection

- Implemented a convolutional neural network (CNN) in the "image recognition" style to identify neutrino interactions
  - ν_e CC, ν_μ CC, NC, cosmics
- The statistical power of CVN is equivalent to 30% more exposure than previous methods
- Before CVN to ID events
  - Events are contained
  - Reject cosmic rays with CNN and BDTs

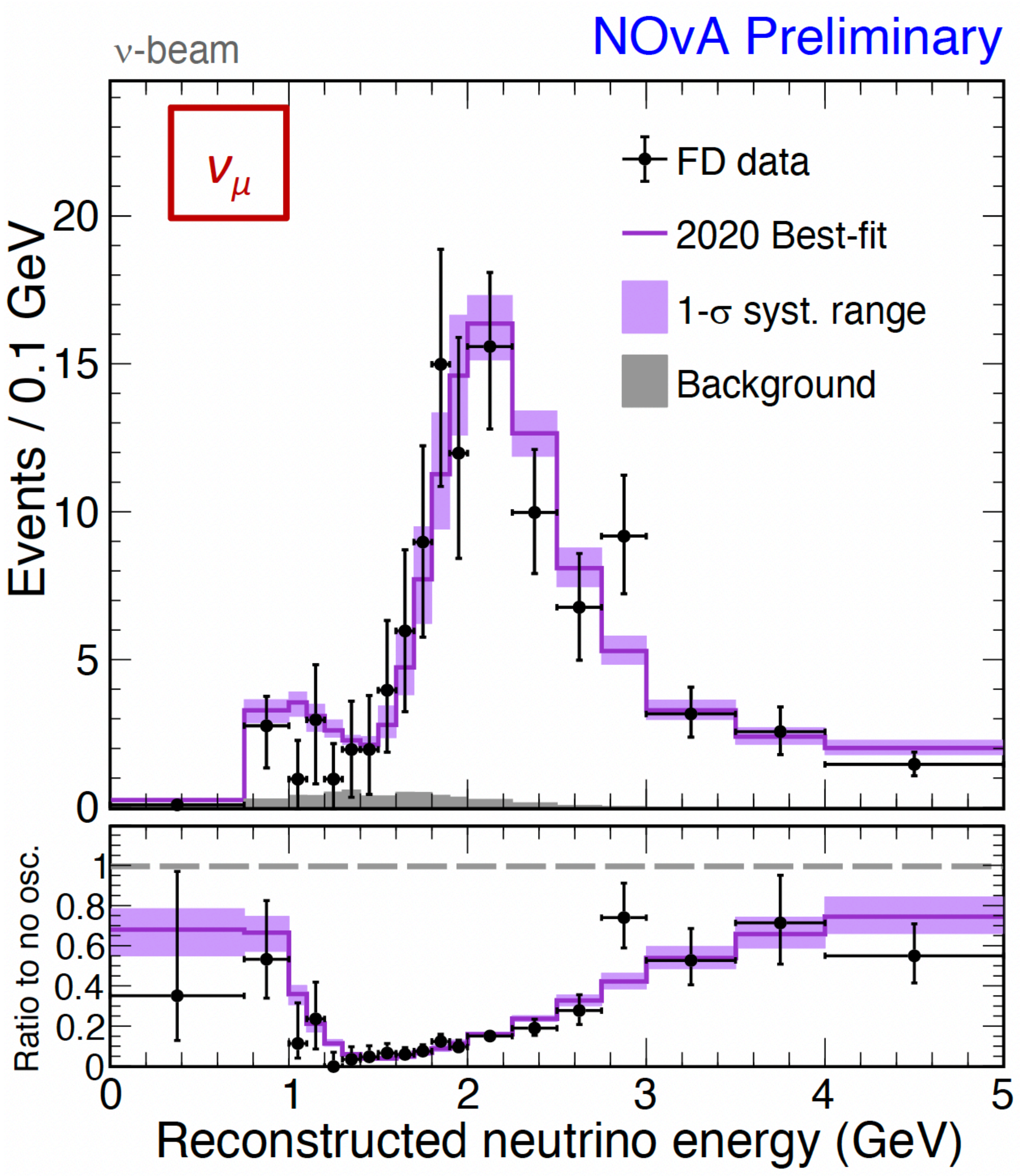


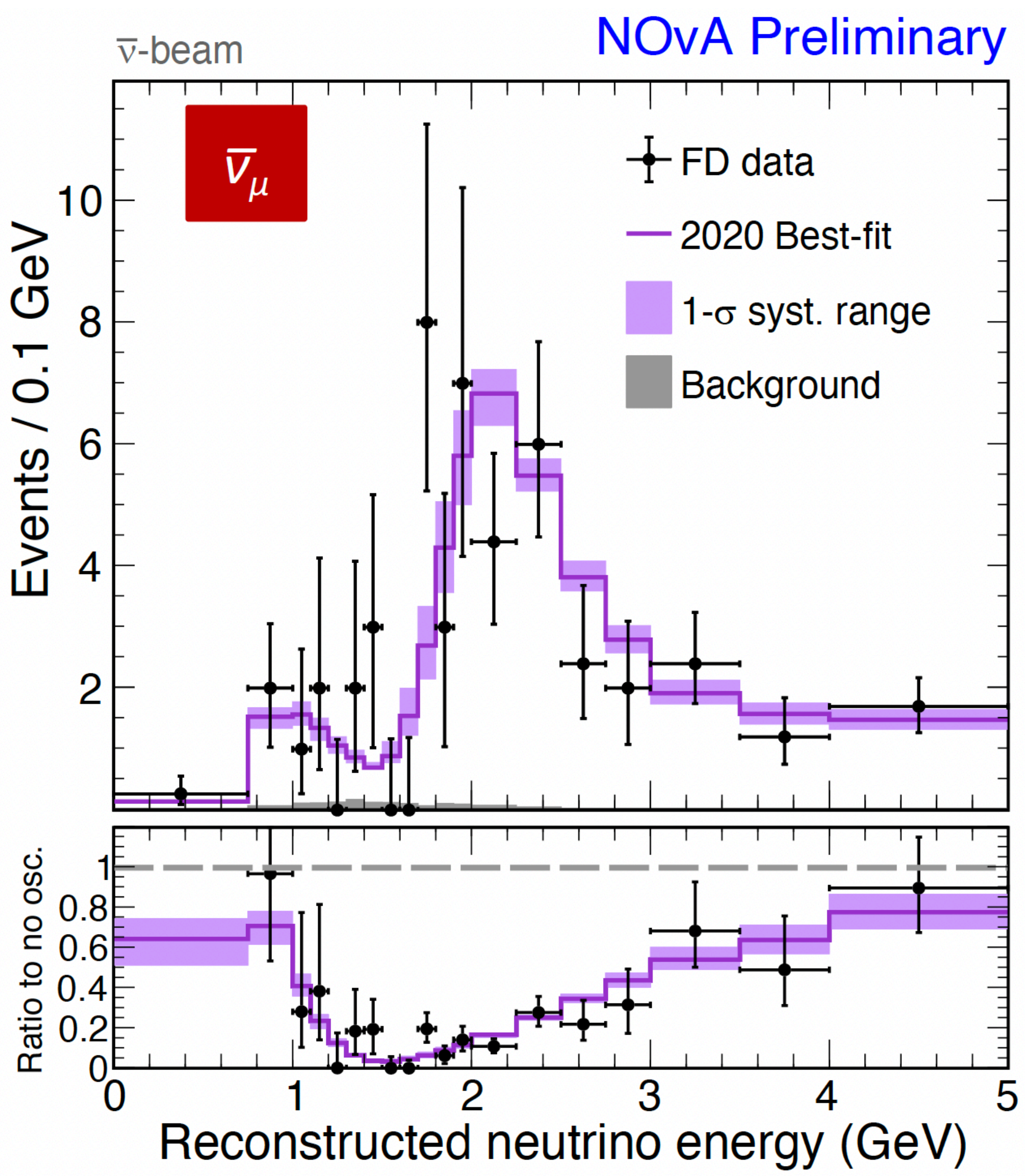
J. Inst. **11**, P09001 (2016)

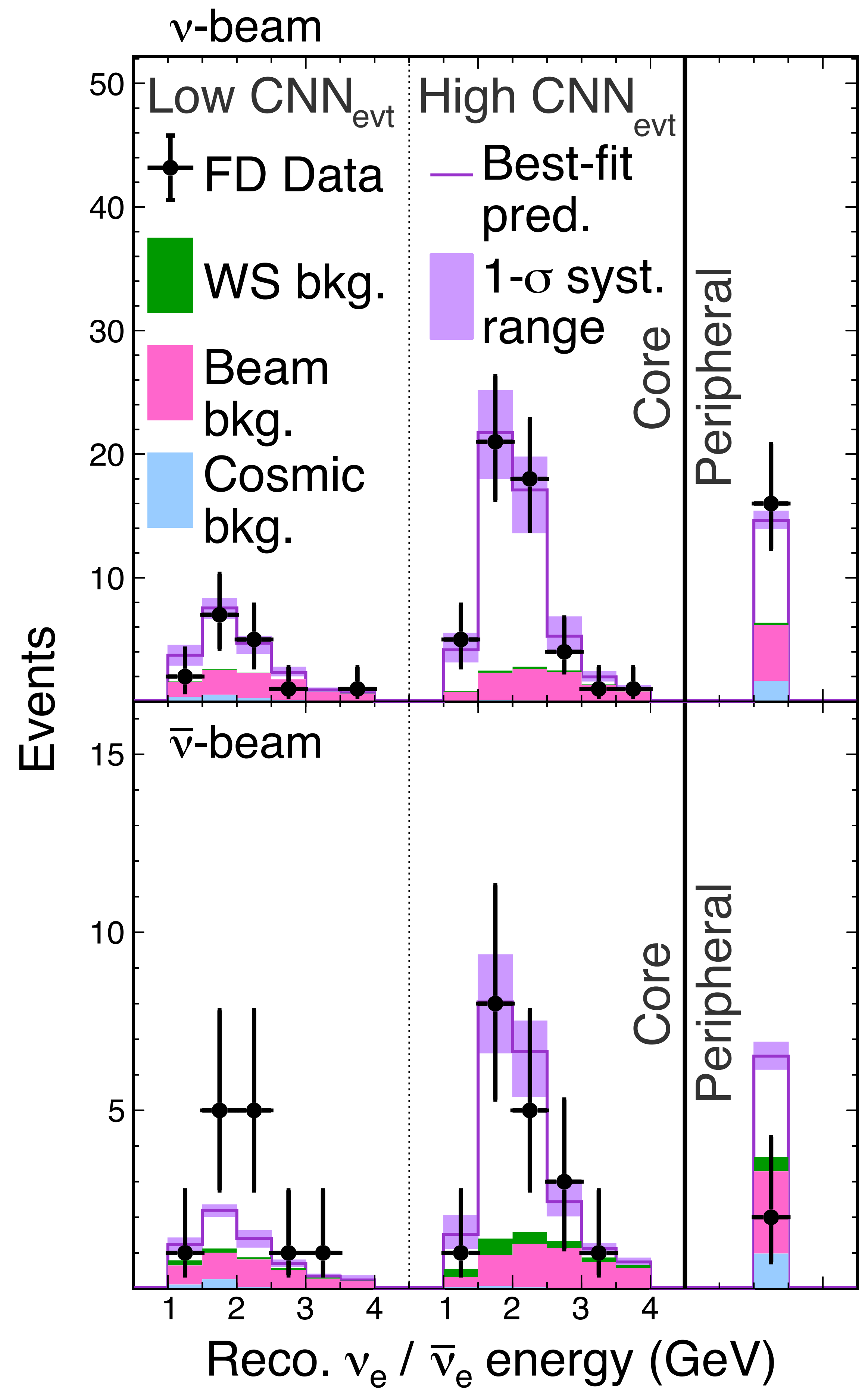
Selected Neutrinos

	Total Obs.	Best fit	Signal	BG
ν_e	82	85.8	59±2.5	26.8±1.7
$\bar{\nu}_e$	33	33.2	19.2±0.7	14.0±1.0

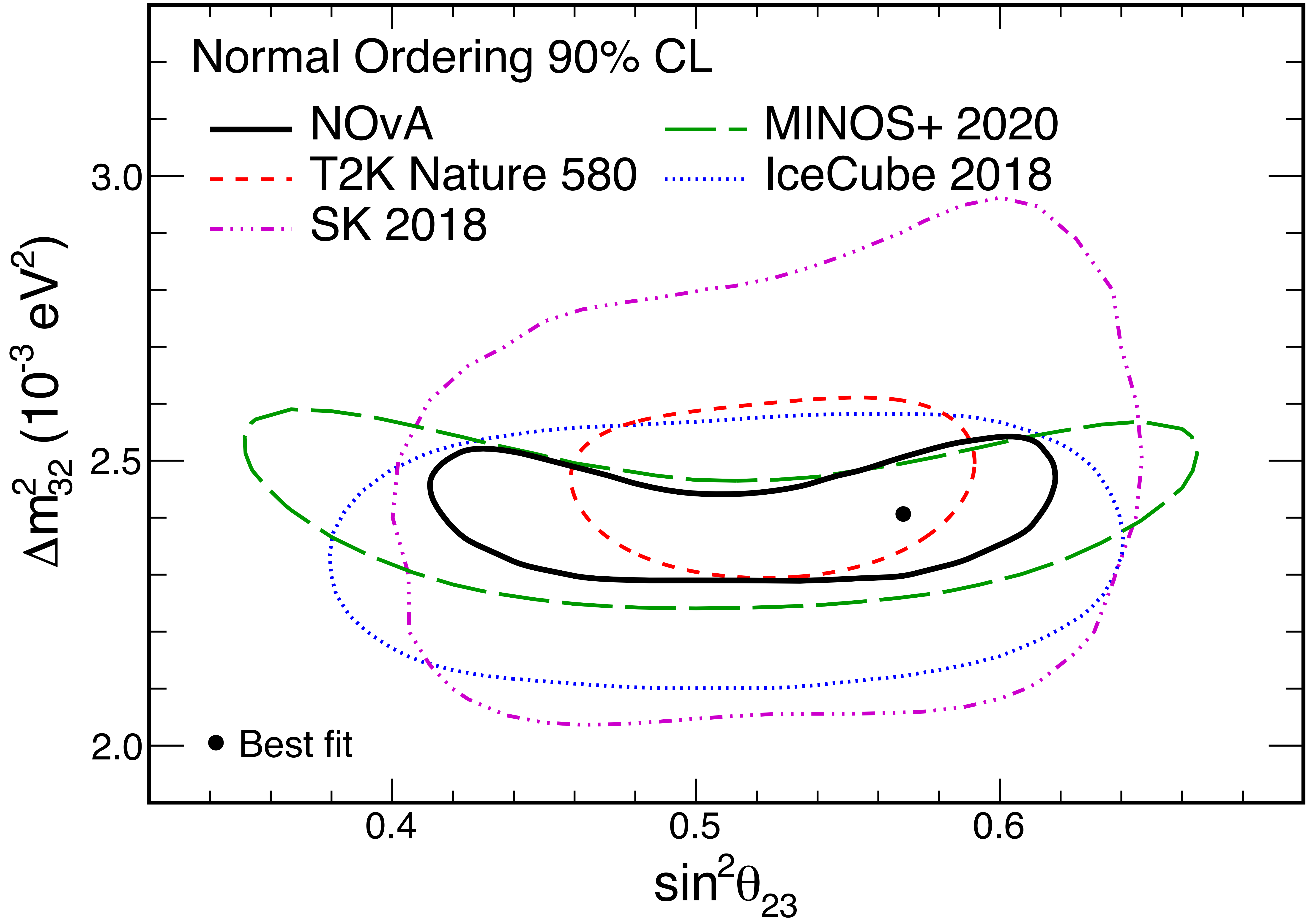
	Total Obs.	Best fit	Signal	BG
ν_μ	211	222.3	214±14	8.2±1.9
$\bar{\nu}_\mu$	105	105.4	103±7	2.1±0.7







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



$\sin^2 2\theta_{13}$ is constrained from PDG avg. of reactor data

Best fit is NO (1σ significance)

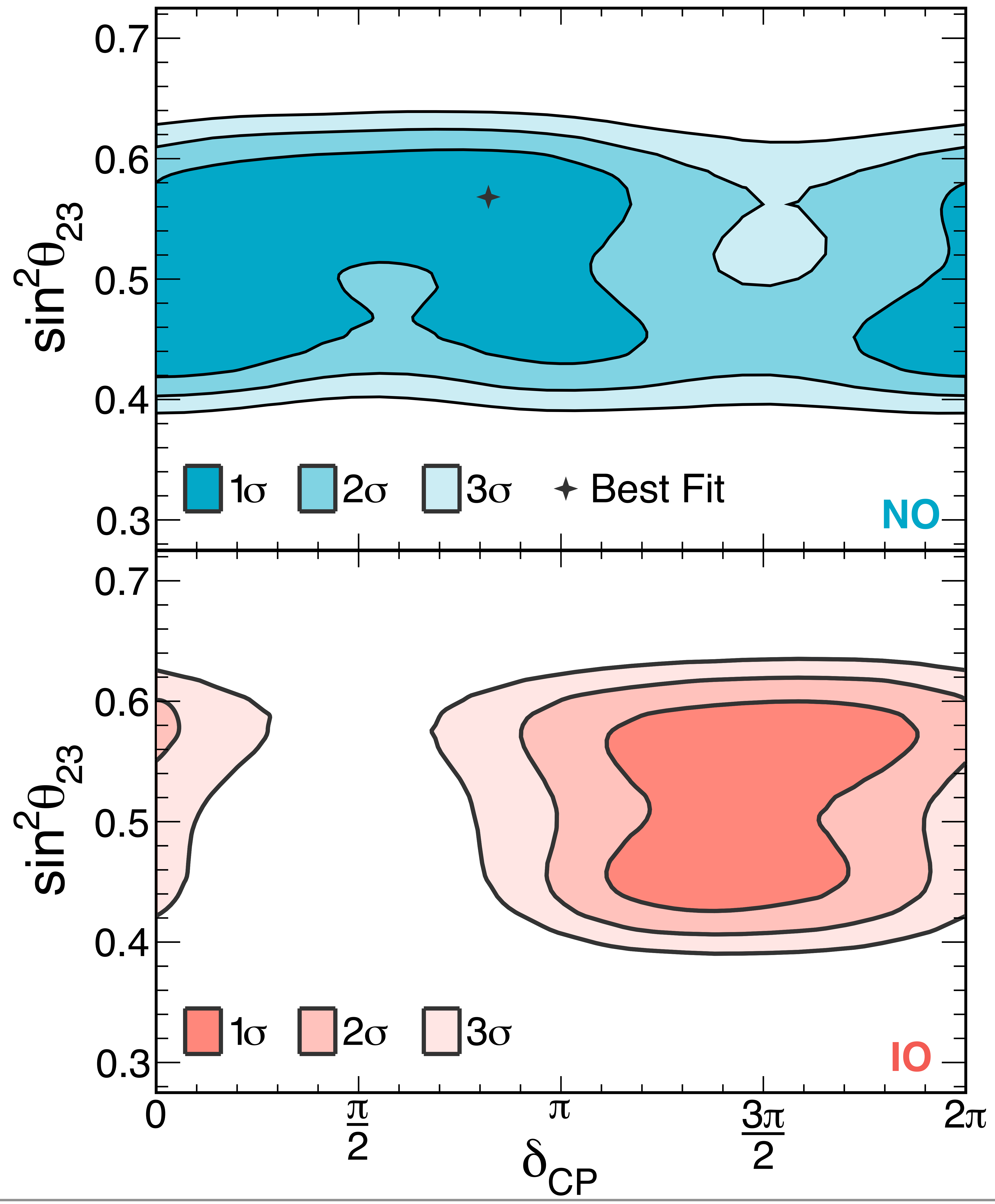
- $\Delta m^2_{32} = (2.41 \pm 0.07) \times 10^{-3}\ \mathrm{eV}^2$
- $\sin^2\theta_{23} = 0.57^{+0.03}_{-0.04}$

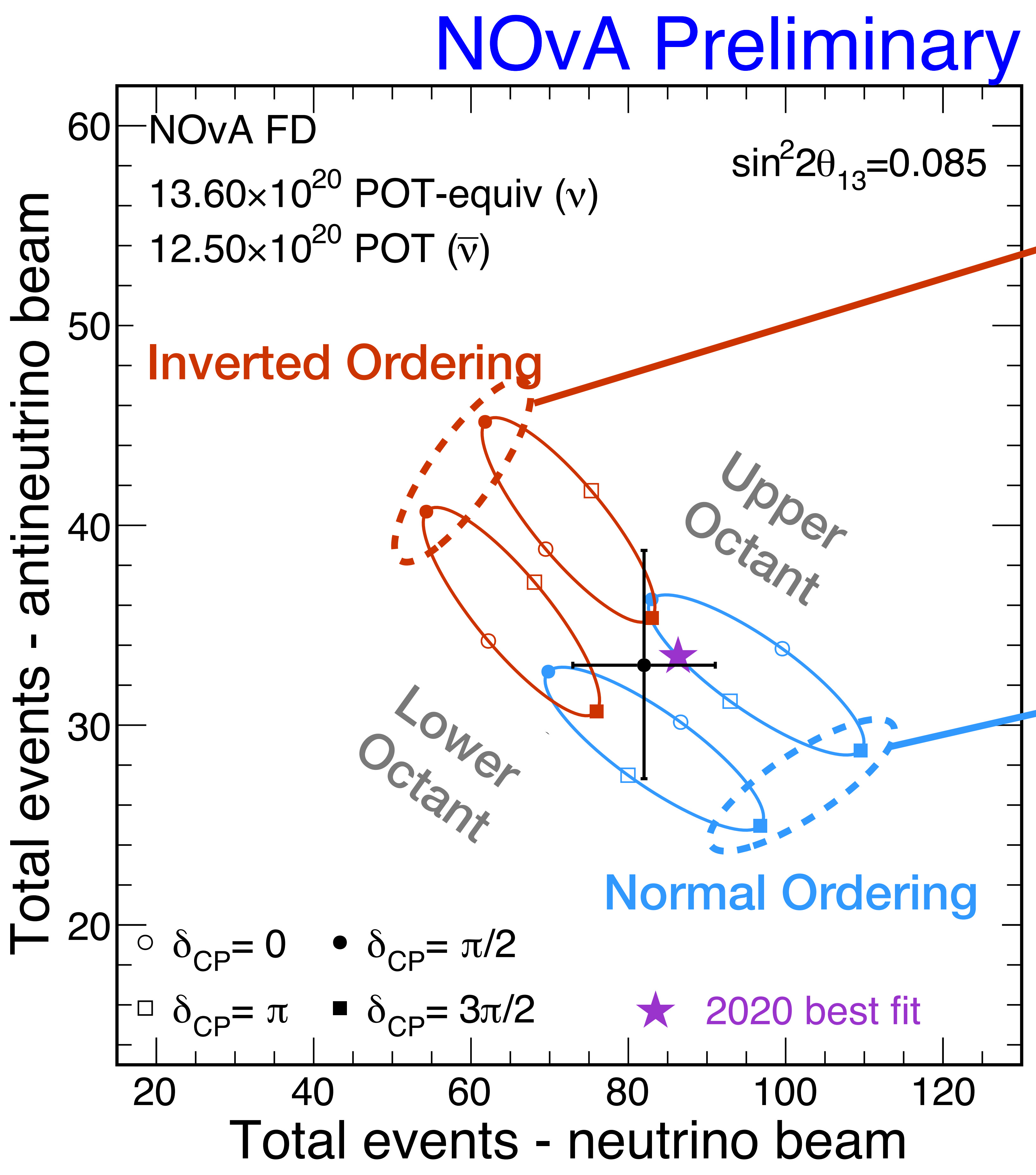
Prefer upper octant of ($\theta_{23} > 45°$) by 1.2σ

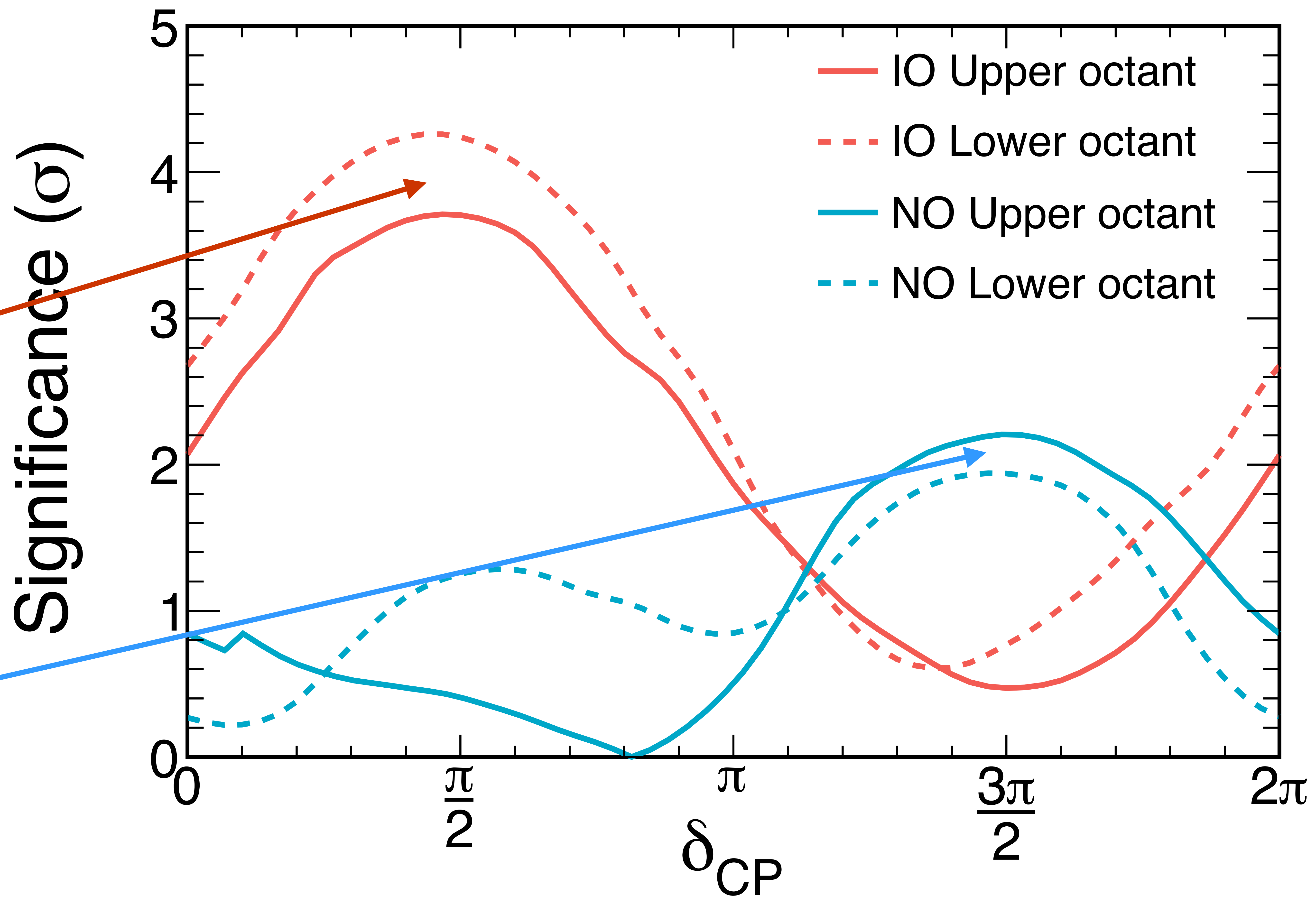
Phys. Rev. D **106**, 032004 (2022)

Best fit is NO

- $\Delta m^2_{32} = (2.41 \pm 0.07) \times 10^{-3}\ \mathrm{eV}^2$
- $\sin^2\theta_{23} = 0.57^{+0.03}_{-0.04}$
- $\delta_{CP} = 0.82^{+0.27}_{-0.87}\ \pi$





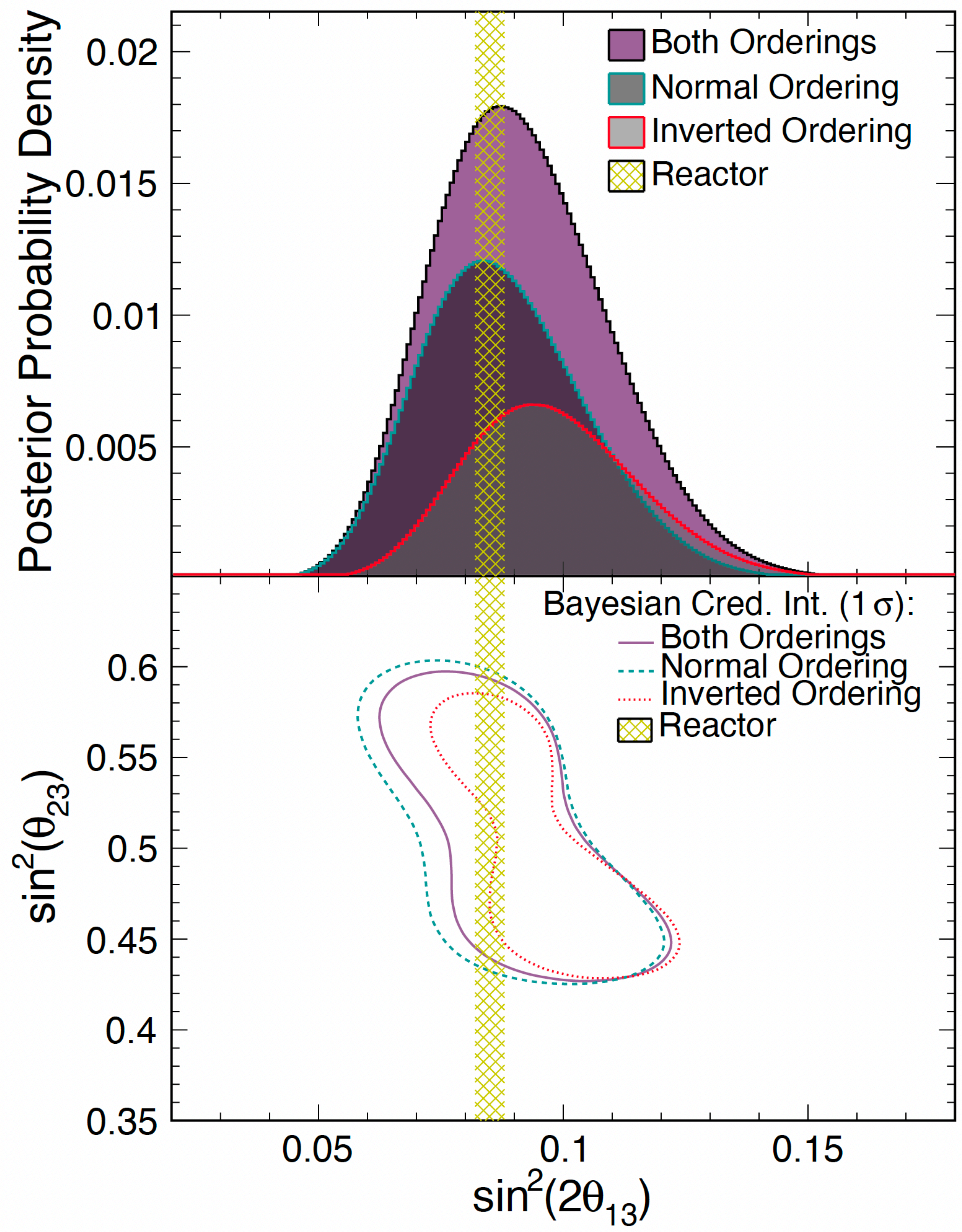


We observe no strong $\nu_e/\bar{\nu}_e$ asymmetry

- IO: $\delta_{CP} = \pi/2$ disfavored at > 3σ
- NO: $\delta_{CP} = 3\pi/2$ disfavored at > 2σ

Alternative statistical approach

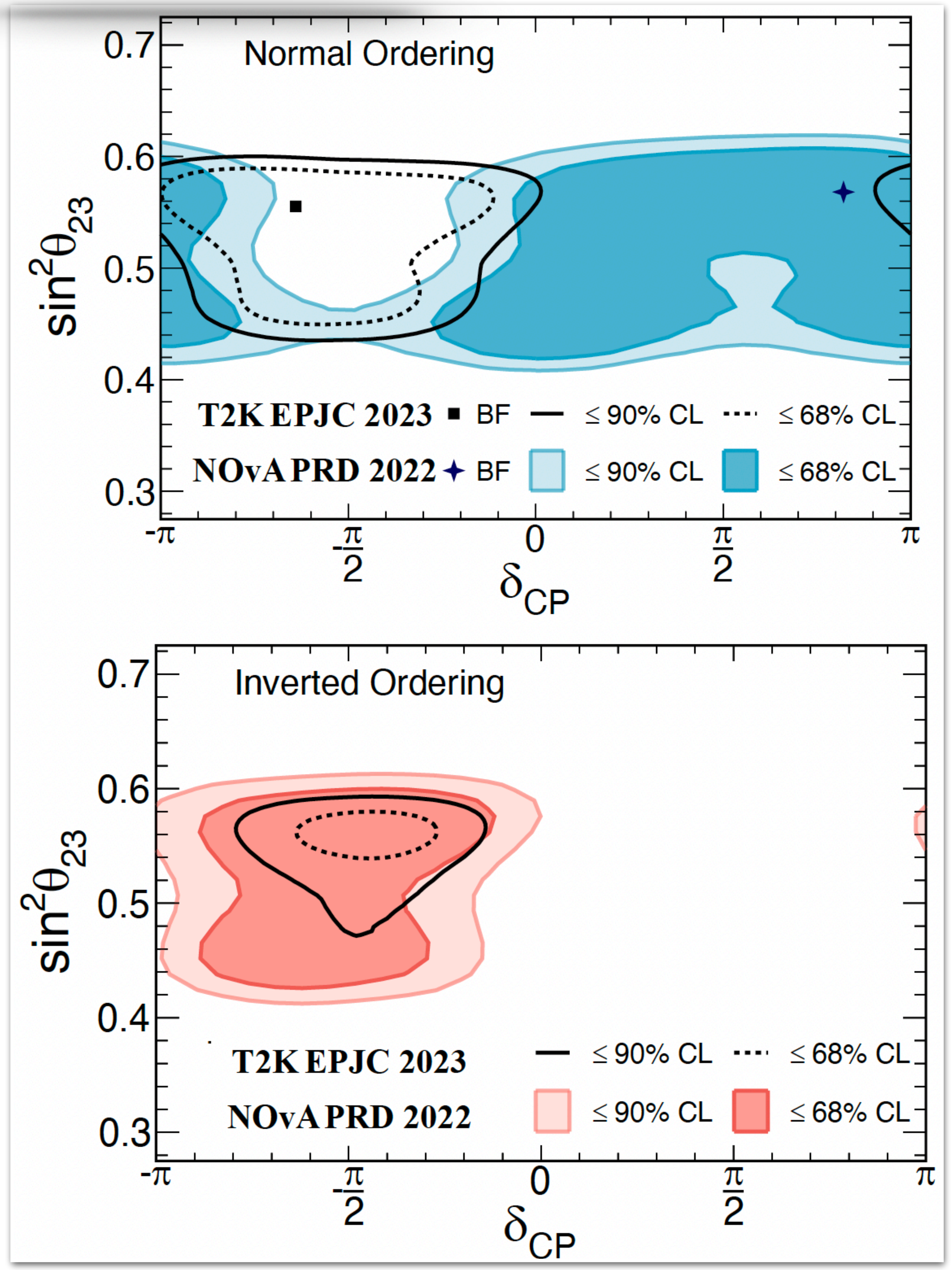
- Based on Bayesian Markov Chain Monte Carlo
- Conclusions are consistent with the frequentist results, preference for the normal ordering and upper octant
- Extend our inferences to θ_{13} for the first time
  - $0.071 \leq \sin^2 2\theta_{13} \leq 0.107$
  - consistent with reactor experiments



arXiv:2311.07835

NOvA-T2K

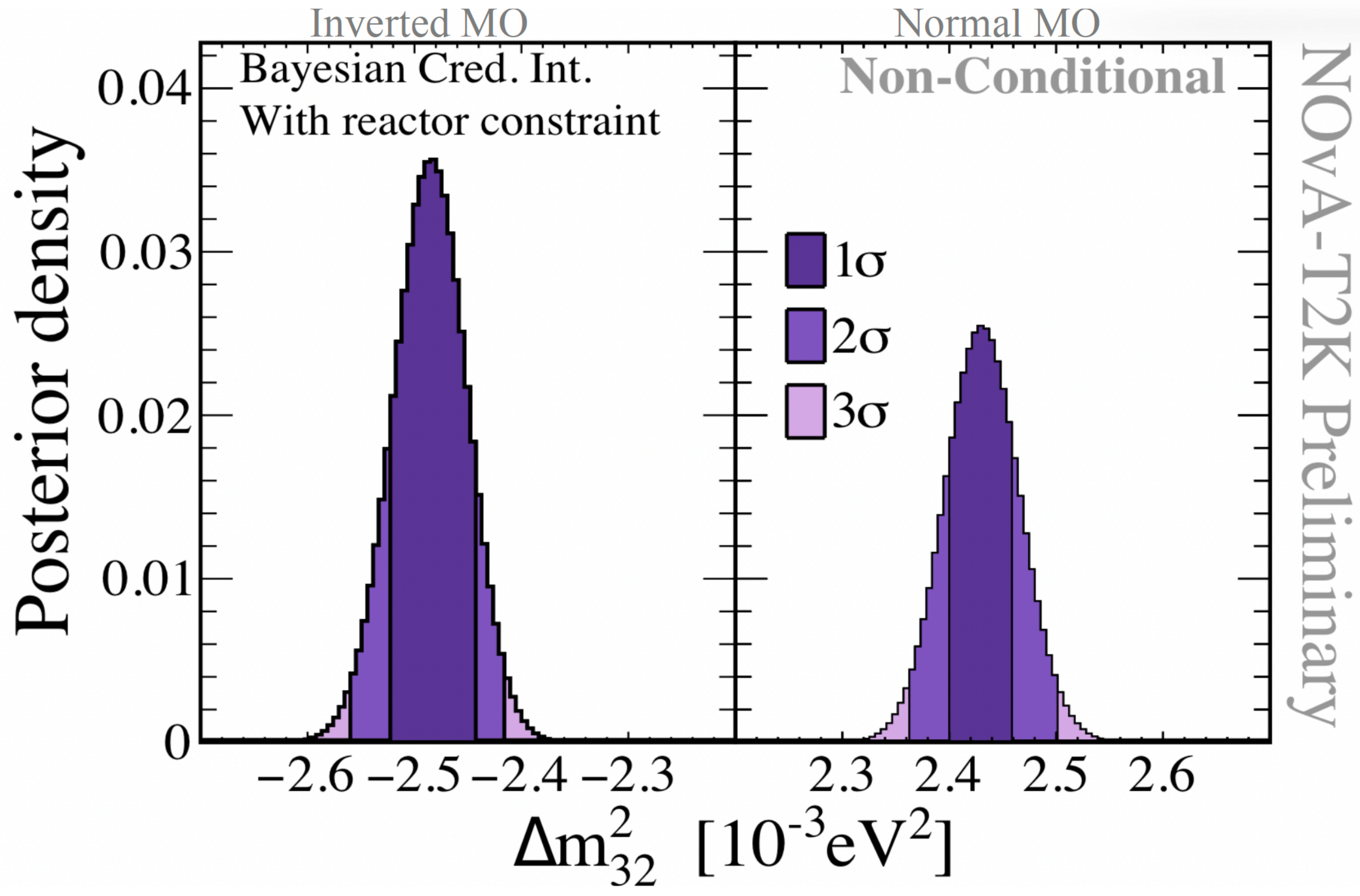
Why joint fit?

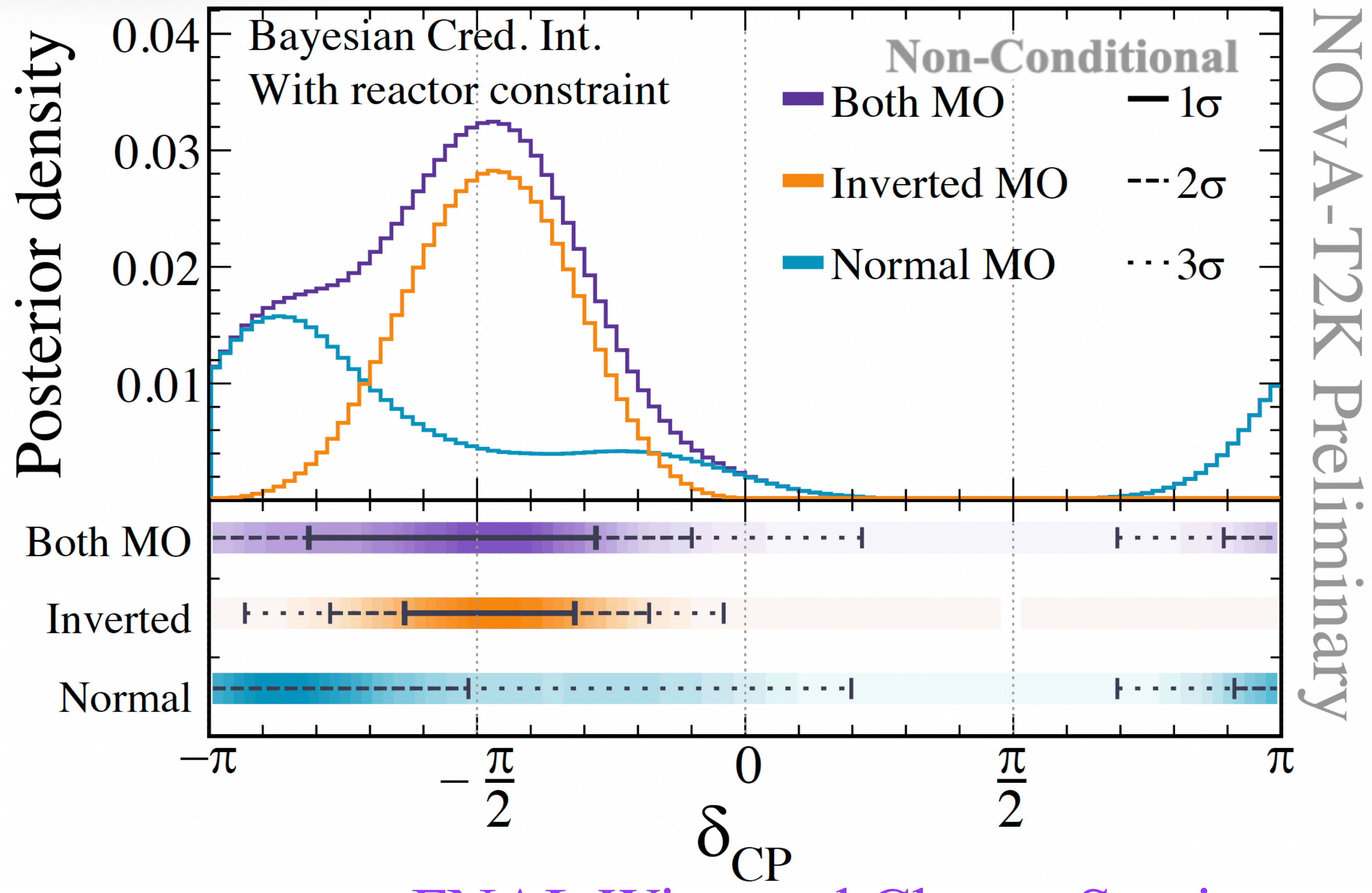


Results from NOvA and T2K from 2020 datasets

- The complementarity between the experiments (different baselines, beam energies, detector technologies) provides the power to break the degeneracies
  - Very strong constraint on $|\Delta m^2_{32}|$
  - Weak preference for the IO
    - Adding constraints from Daya Bay reverses the ordering preference to NO
  - CP conserving values for the IO fall outside the 3σ range
  - $\delta_{CP} = \pi/2$ lies outside 3σ credible interval for both mass ordering

Joint fit results





FNAL Wine and Cheese Seminar

More results since last year

FHC ν_e CC inclusive: Phys. Rev. Lett. 130, 051802 (2023)

Open Access

Measurement of the ν_e-Nucleus Charged-Current Double-Differential Cross Section at $\langle E_\nu \rangle = 2.4\ \mathrm{GeV}$ Using NOvA

M. A. Acero *et al.* (NOvA Collaboration)
Phys. Rev. Lett. **130**, 051802 – Published 3 February 2023

FHC ν_μ CC inclusive: Phys. Rev. D 107, 052011 (2023)

Open Access

Measurement of the double-differential muon-neutrino charged-current inclusive cross section in the NOvA near detector

M. A. Acero *et al.* (NOvA Collaboration)
Phys. Rev. D **107**, 052011 – Published 27 March 2023

FHC CC π^0 production: Phys. Rev. D 107, 112008 (2023)

Open Access

Measurement of ν_μ charged-current inclusive π^0 production in the NOvA near detector

M. A. Acero *et al.* (NOvA Collaboration)
Phys. Rev. D **107**, 112008 – Published 23 June 2023

FHC ν_μ CC 2p2h measurement: FNAL Wine and Cheese Seminar

Exploring 2p2h signatures in muon-neutrino charged-current measurements at NOvA.

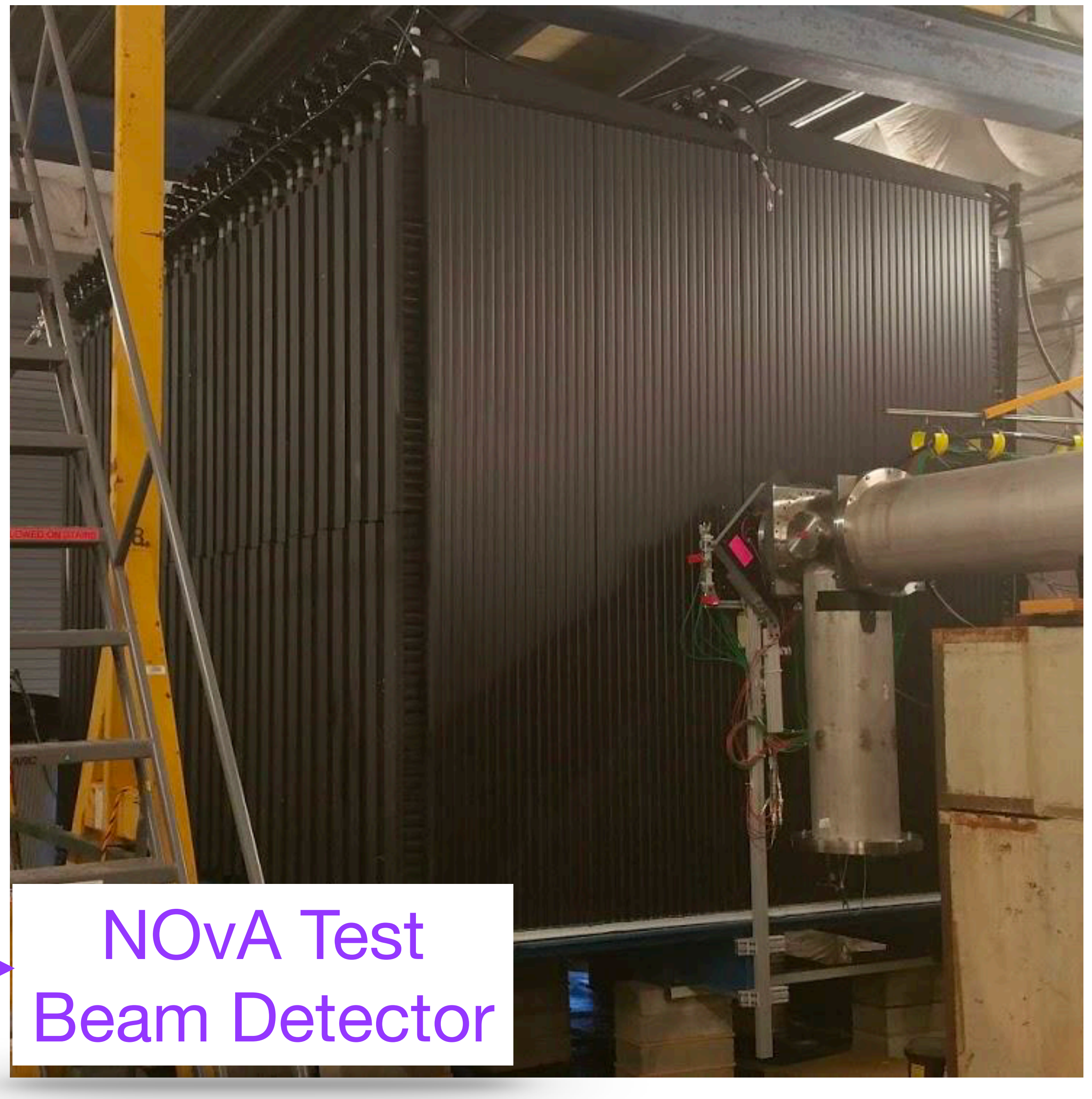
Friday Feb 2, 2024, 4:00 PM → 5:00 PM US/Central

And More Results On the Way!

Stay tuned …

Summary and Prospects

- We present the updated neutrino oscillation measurements using different statistical methods
  - $\Delta m^2_{32} = (2.41 \pm 0.07) \times 10^{-3}\ \text{eV}^2$
  - $\sin^2\theta_{23} = 0.57^{+0.03}_{-0.04}$
  - Excluded IO, $\delta_{CP} = \pi/2$ at $> 3\sigma$
  - Excluded NO, $\delta_{CP} = 3\pi/2$ at $> 2\sigma$
- NOvA-T2K joint analysis demonstrates simultaneously compatibility with both datasets
  - The working group is actively exploring the scope for the next steps with more data collected
- Looking ahead
  - Next analysis will have increasing sensitivity with ~2x neutrino data and improved systematics/reconstruction
  - We expect to reach 3σ mass ordering sensitivity for 30-50% of δ_{CP} values, with the full dataset and an upgraded beam
  - Plan to reduce our largest systematics related to detector energy scale, with the test beam program

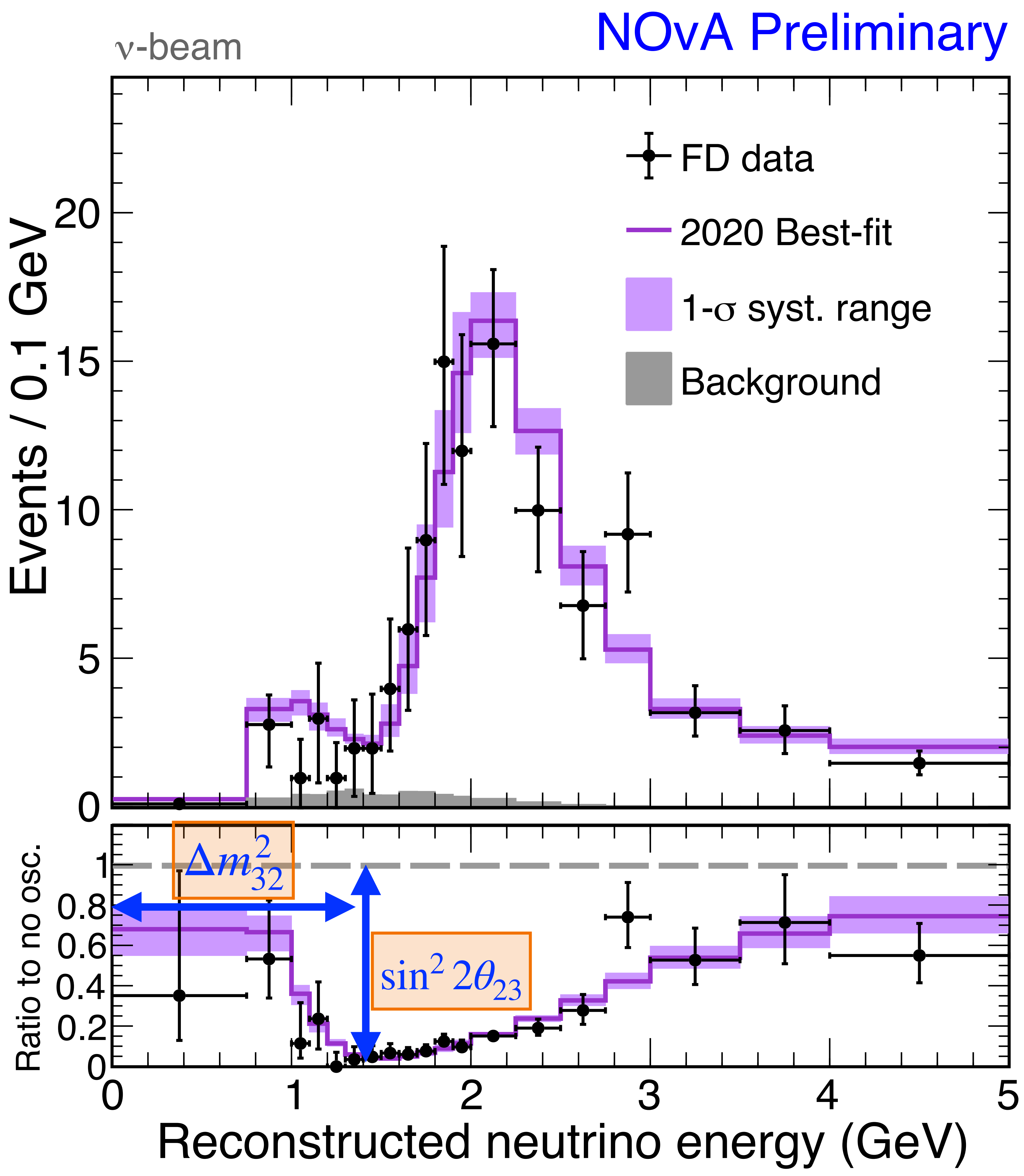


NOvA at UCI

Backup

Muon neutrino disappearance

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

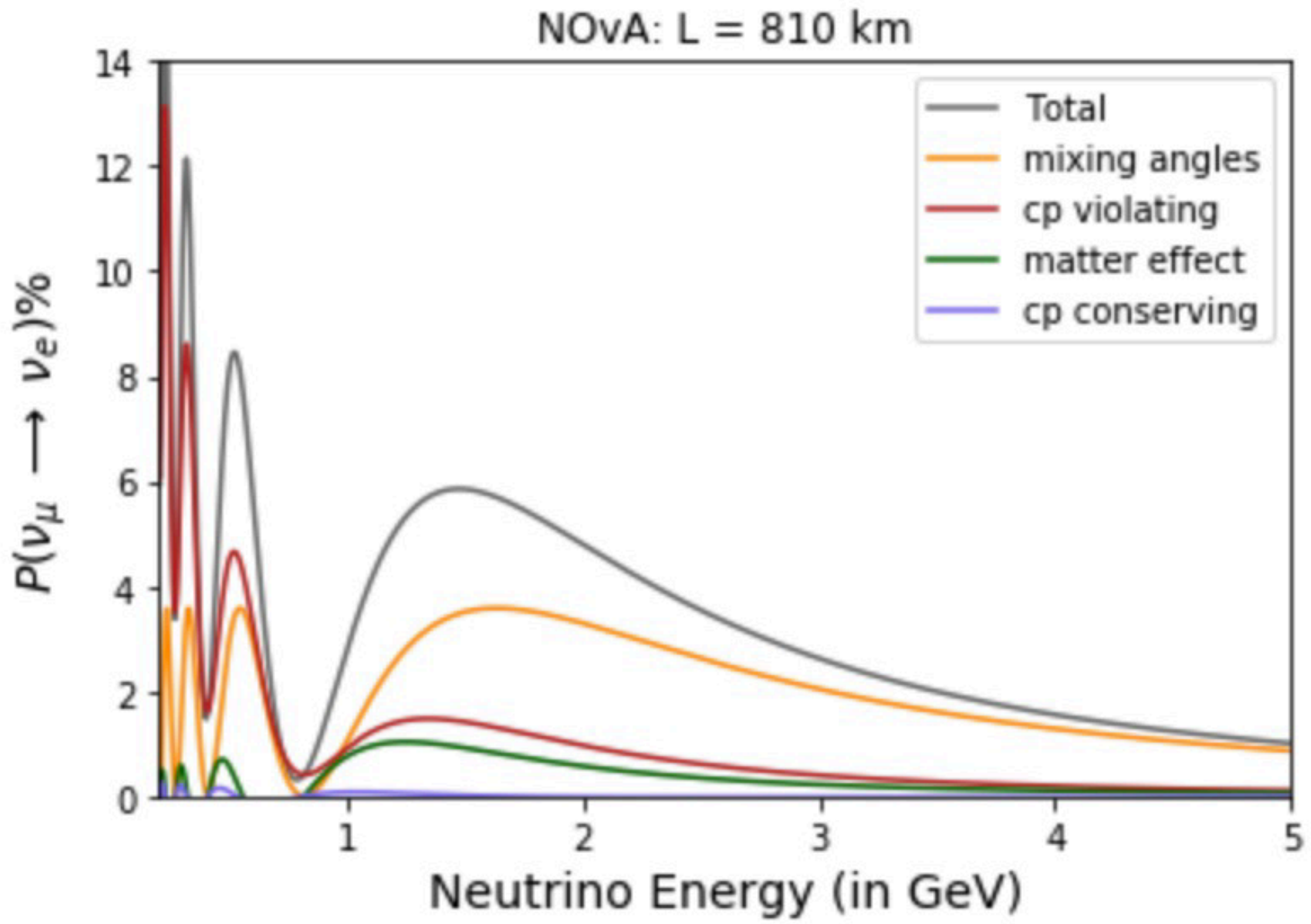


- Measure ν_μ ($\bar{\nu}_\mu$) survival probability with neutrino beam (anti-neutrino) beam.
- Provide high sensitivity to $\sin^2 2\theta_{23}$ and $|\Delta m^2_{32}|$.
- Is the θ_{23} mixing maximal (≷ 45°)?

Electron neutrino appearance

$$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2$$
$$+\sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}$$
$$\times\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}\pm\delta_{CP})$$
$$+\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2$$

$$a = \pm\frac{G_F N_e}{\sqrt{2}}$$



Complicated dependence on multiple parameters of interest.

$\sin^2 2\theta_{13}$ measured by reactor experiments

$|\Delta m^2_{32}|$ and $\sin^2\theta_{23}$ constrained by ν_μ disappearance

$P(\nu_\mu \rightarrow \nu_e)$ difference between $\Delta m^2_{31} > 0$ and $\Delta m^2_{31} < 0$ enlarged by matter effect

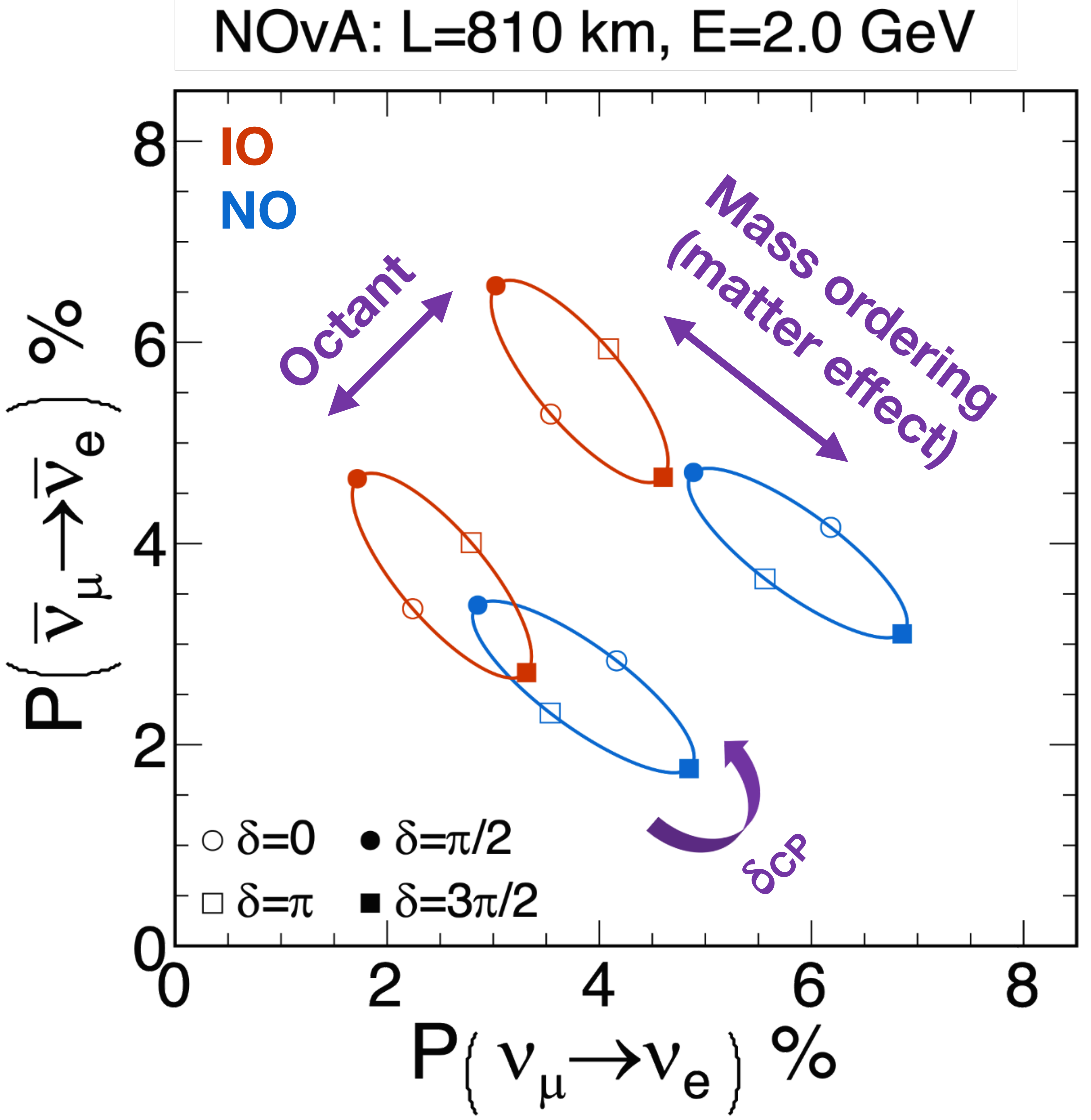
Long-baseline experiments

1. Inverted ordering gives a slight suppression in both.

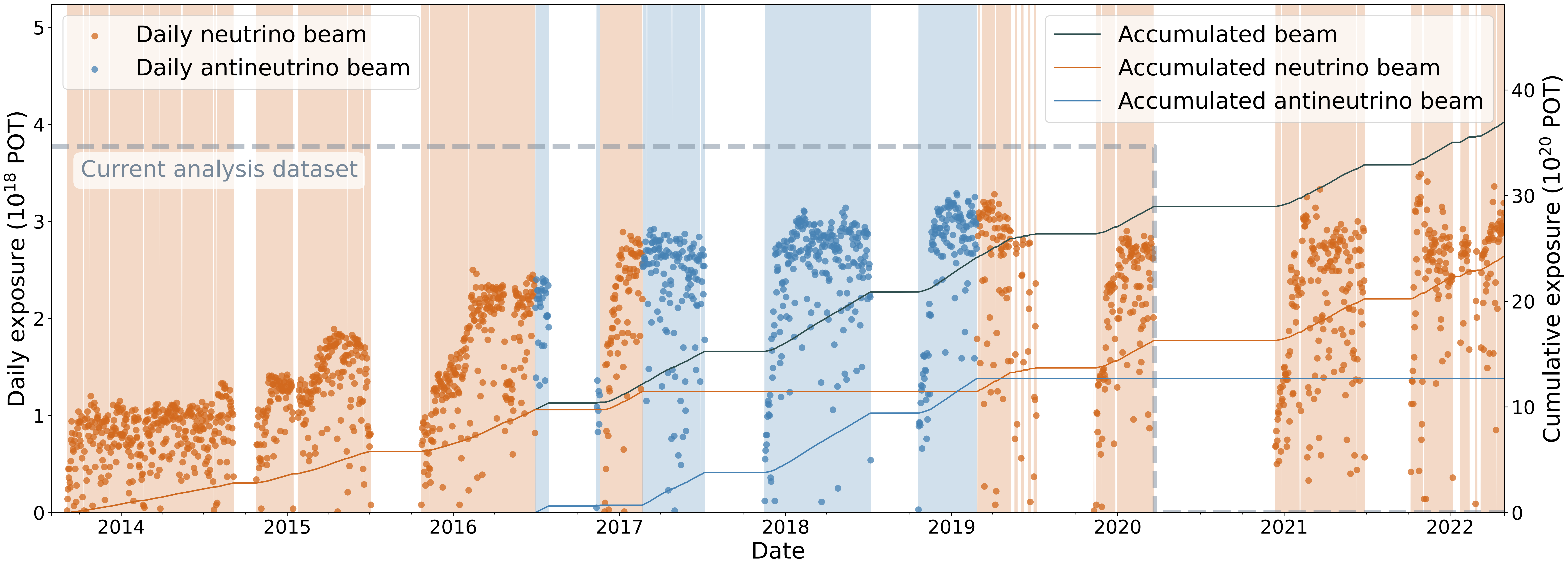
2. CP violating phase causes opposite effects in neutrinos and anti-neutrinos.

3. Matter effects also produce opposite effects in neutrinos and anti-neutrinos.

4. Impact of matter effect is proportional to baseline: longer baseline -> larger matter effect -> more sensitive to mass ordering.



NuMI beam



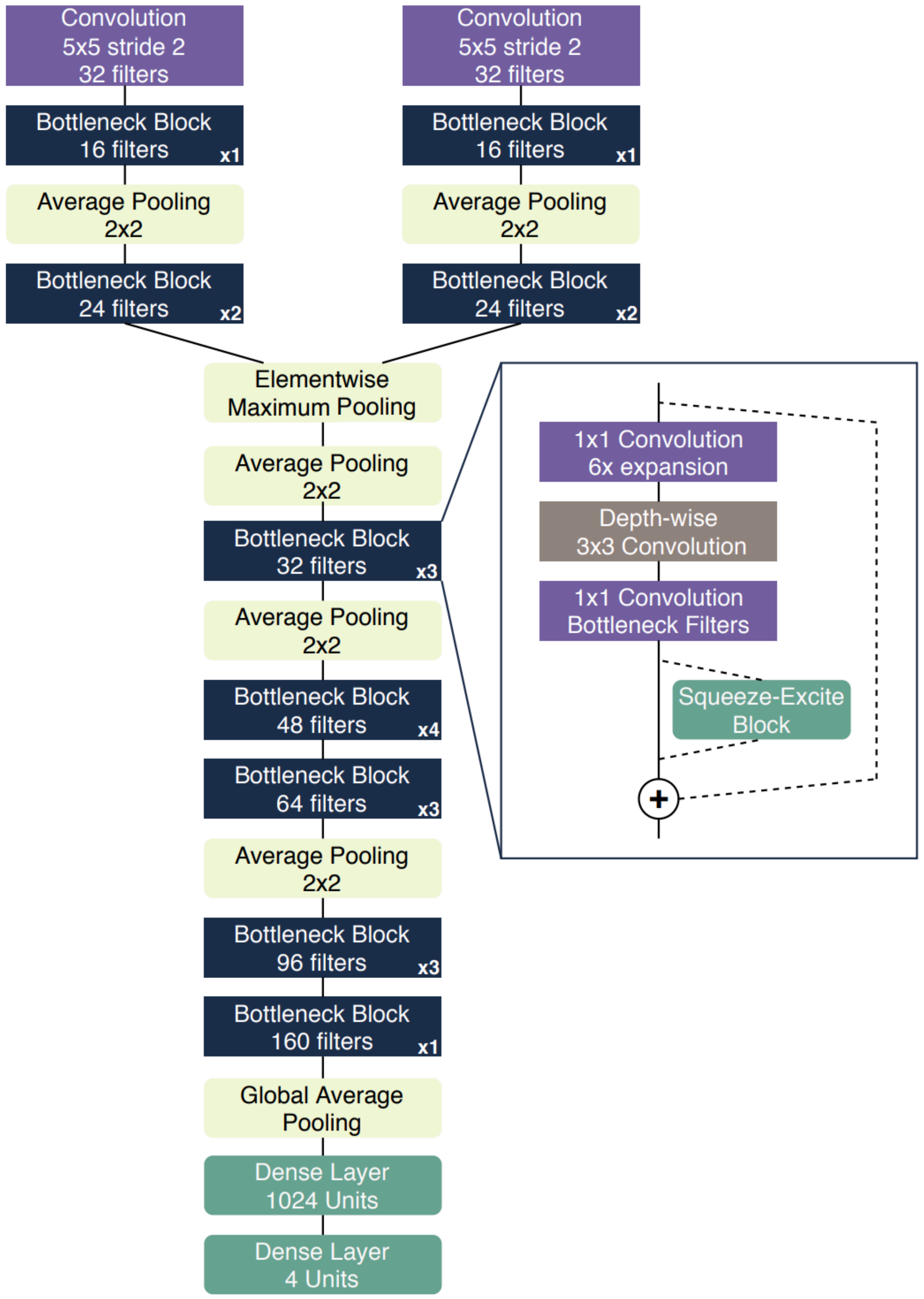
- Taking data since 2014, exceed 700 kW design goal since Jan 2017.
- New beamline components installed in 2022, power record 954 kW in 2023.

Current analysis utilizes

- FHC POT: 13.6×10^{20}
- RHC POT: 12.5×10^{20}

Deep-Learning based neutrino classifier

- NOvA is the first neutrino experiment using convolutional neural networks (CNN) for event reconstruction.
- CVN (convolutional visual network) is an event classifier which employs a Deep CNN in the “image recognition” style
  - ν_e CC, ν_μ CC, NC, cosmics.
- Two-tower CNN architecture learns from the top and side views independently.
- The statistical power of CVN is equivalent to 30% more exposure than previous methods.

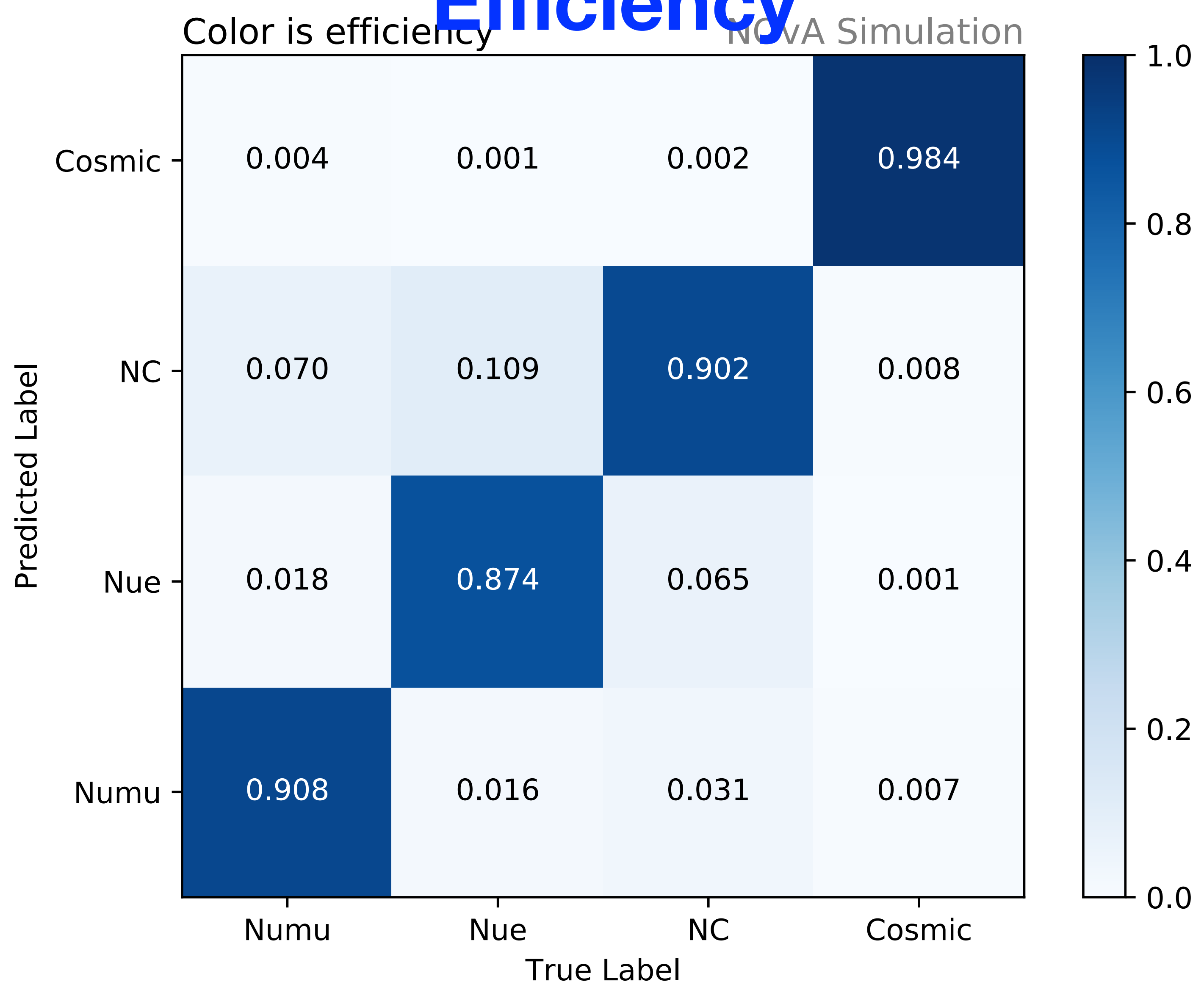


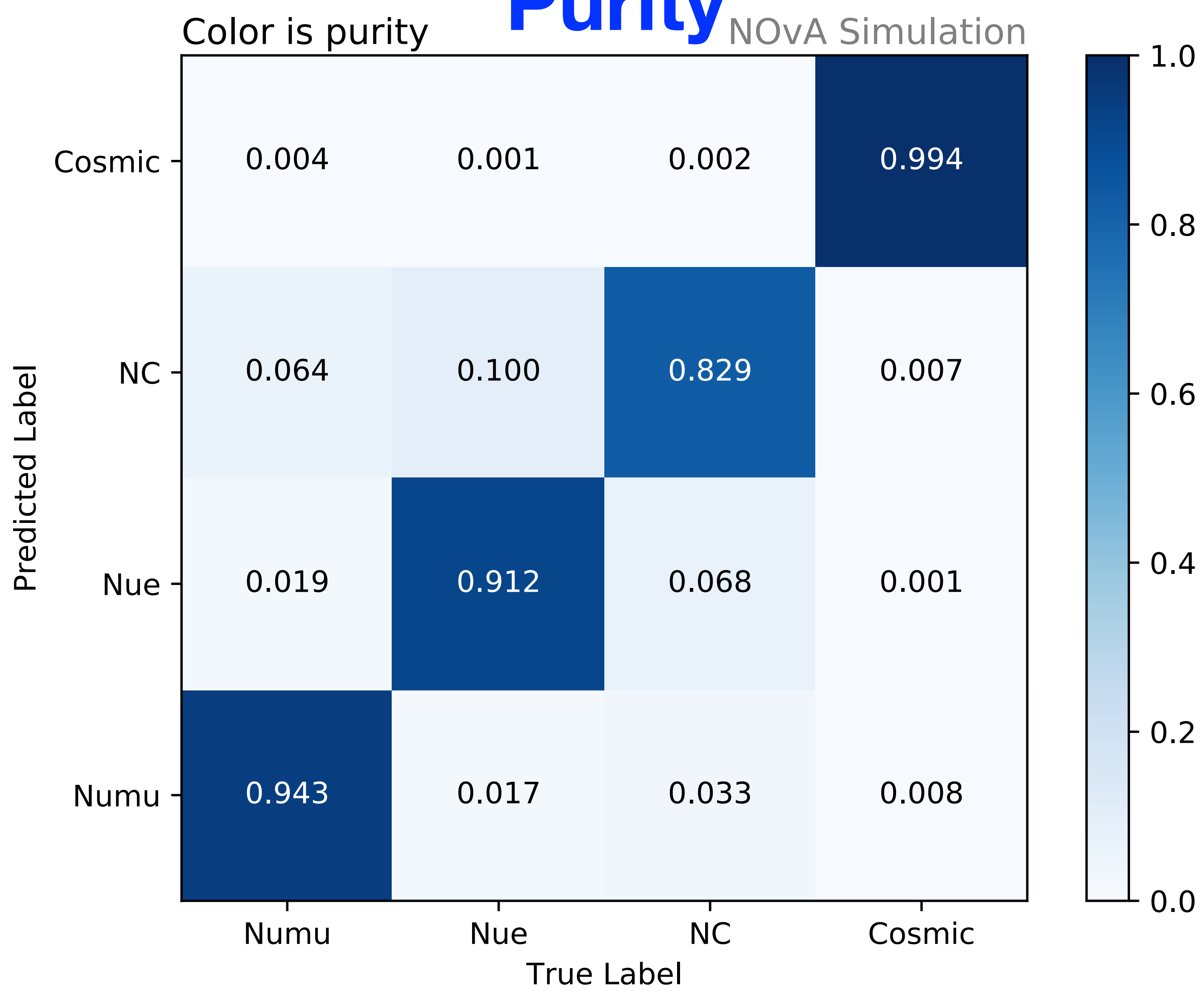
Deep-Learning based neutrino classifier

Confusion matrix

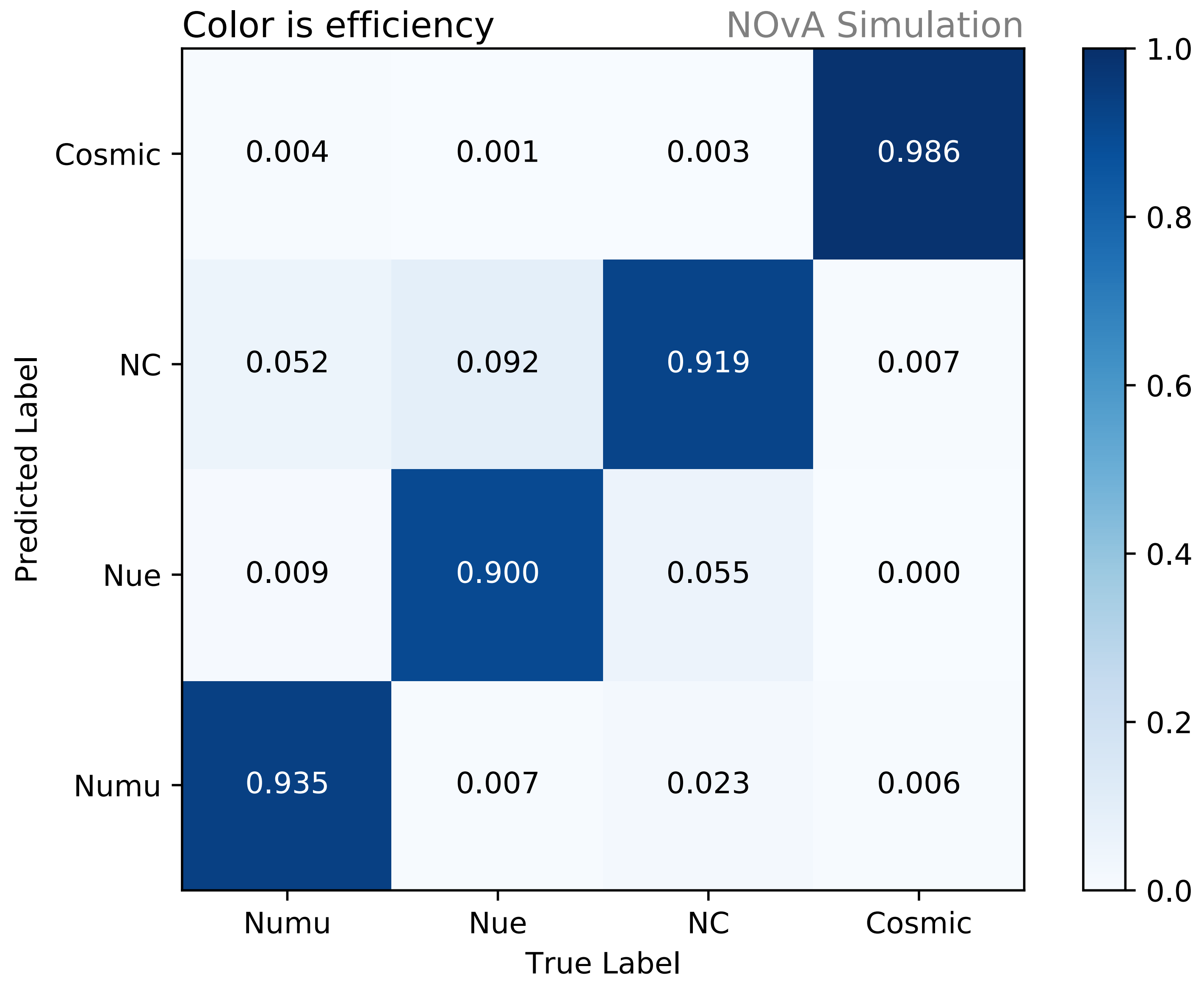
Efficiency **Purity**

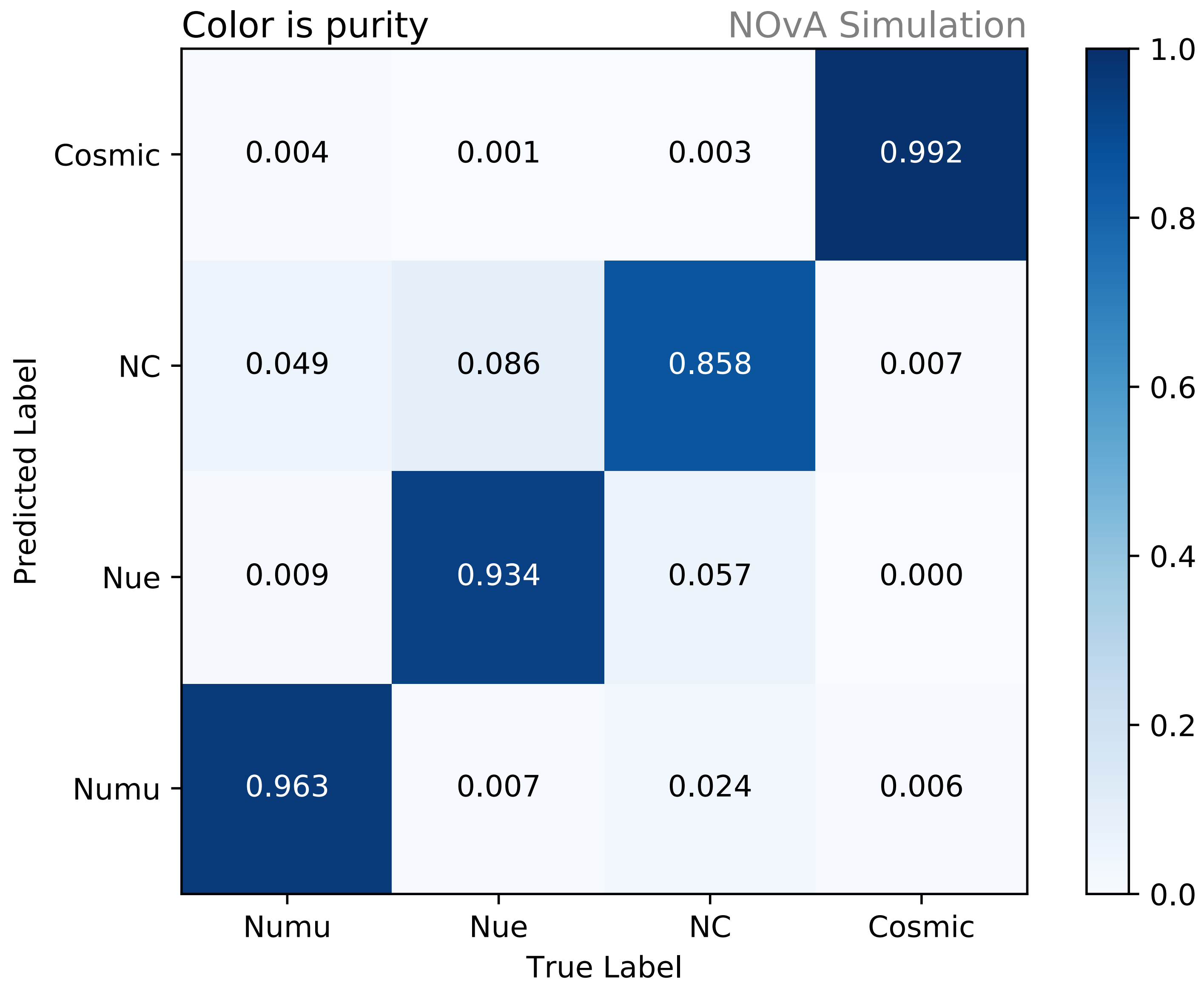
Neutrino beam mode





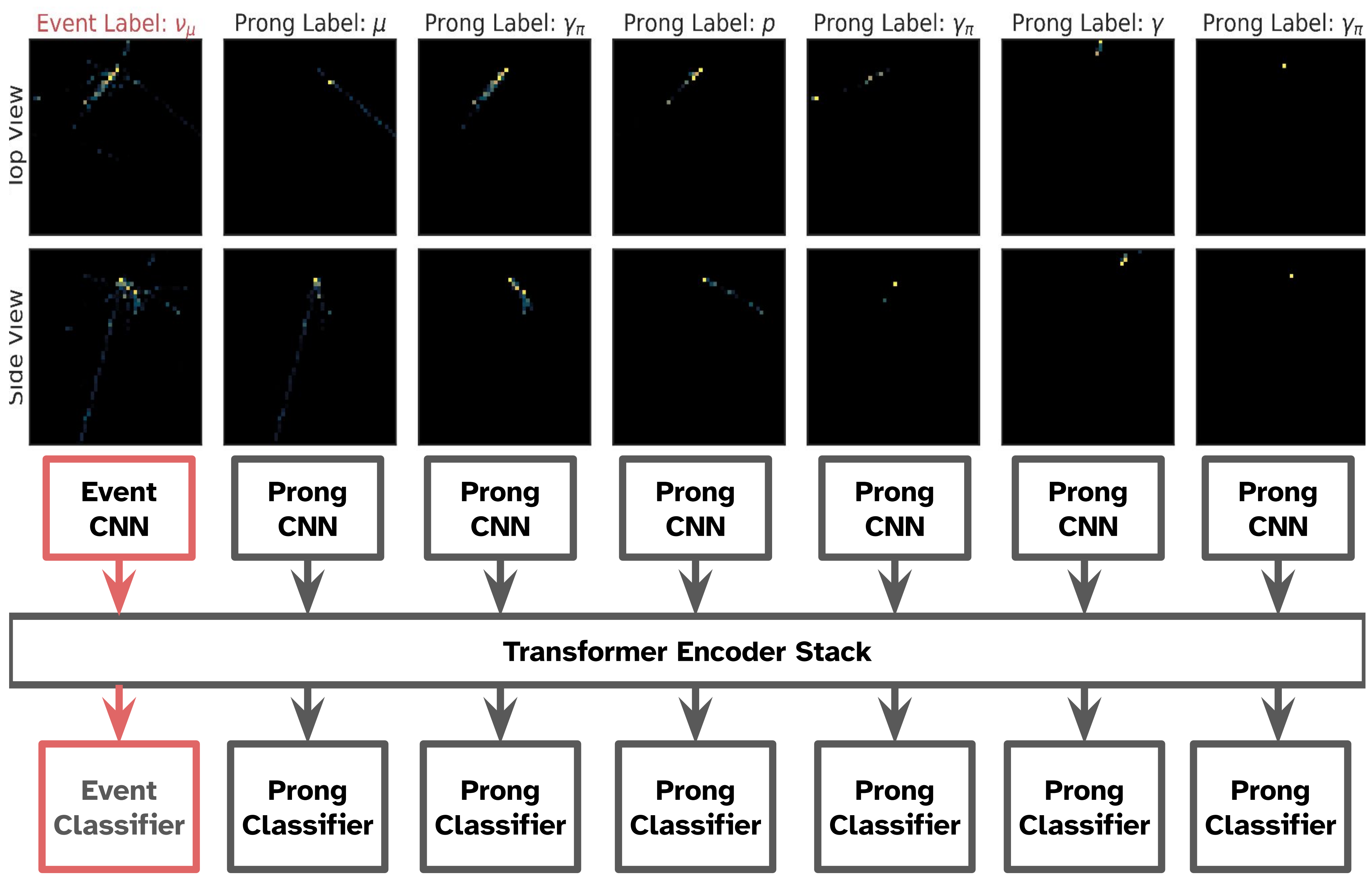
Anti-neutrino beam mode



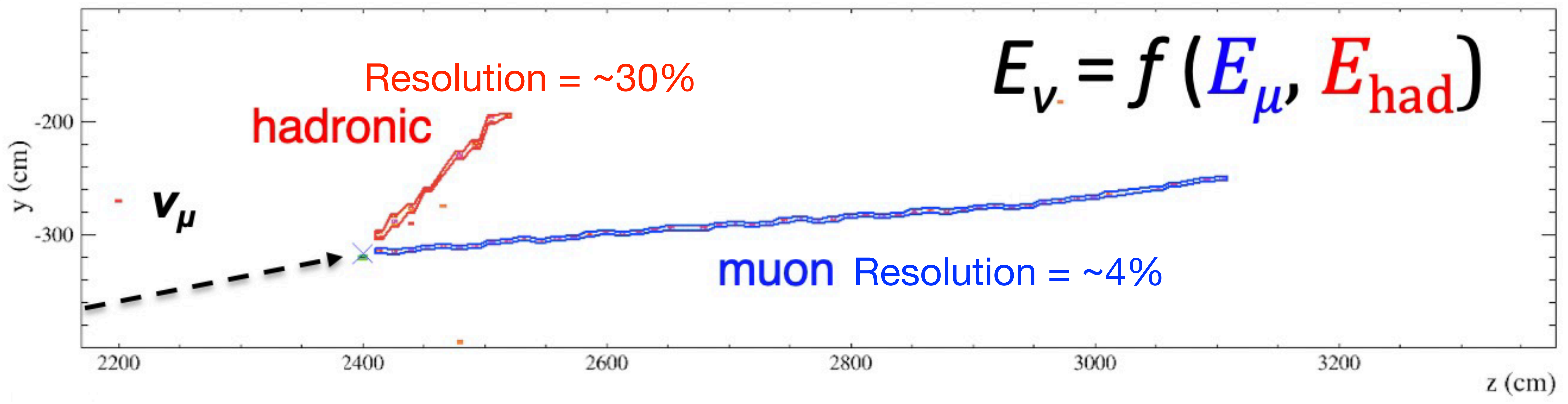


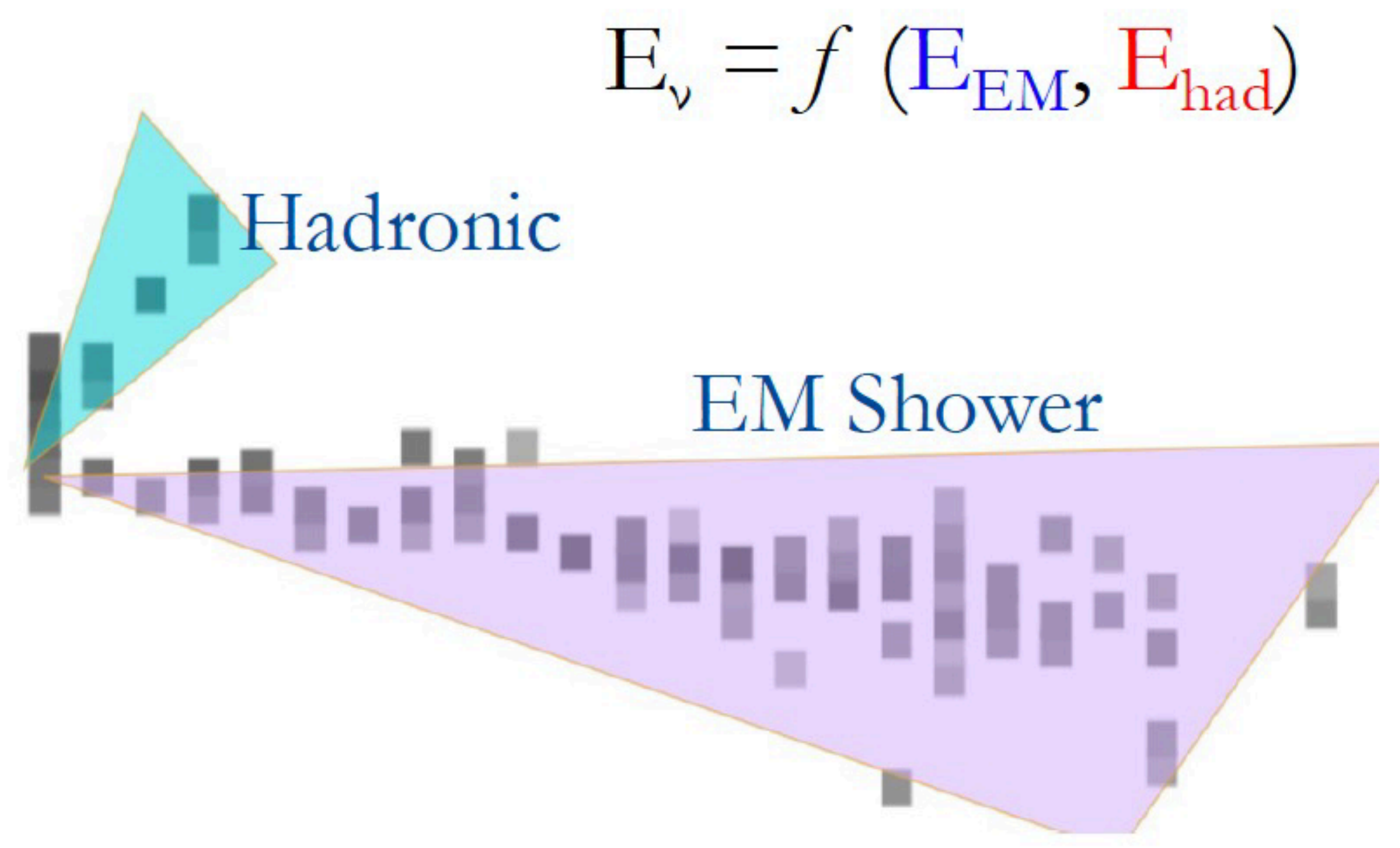
Deep-Learning based neutrino classifier

- NOvA is also exploring new deep learning algorithms to improve the interpretability, causality, and robustness of the data analysis.
- TransformerCVN, a novel NN that combines the spatial learning enabled by convolutions with the contextual learning enabled by attention, simultaneously classifies each event and reconstructs every individual particle's identity.
- TransformerCVN enables performing interpretability studies.

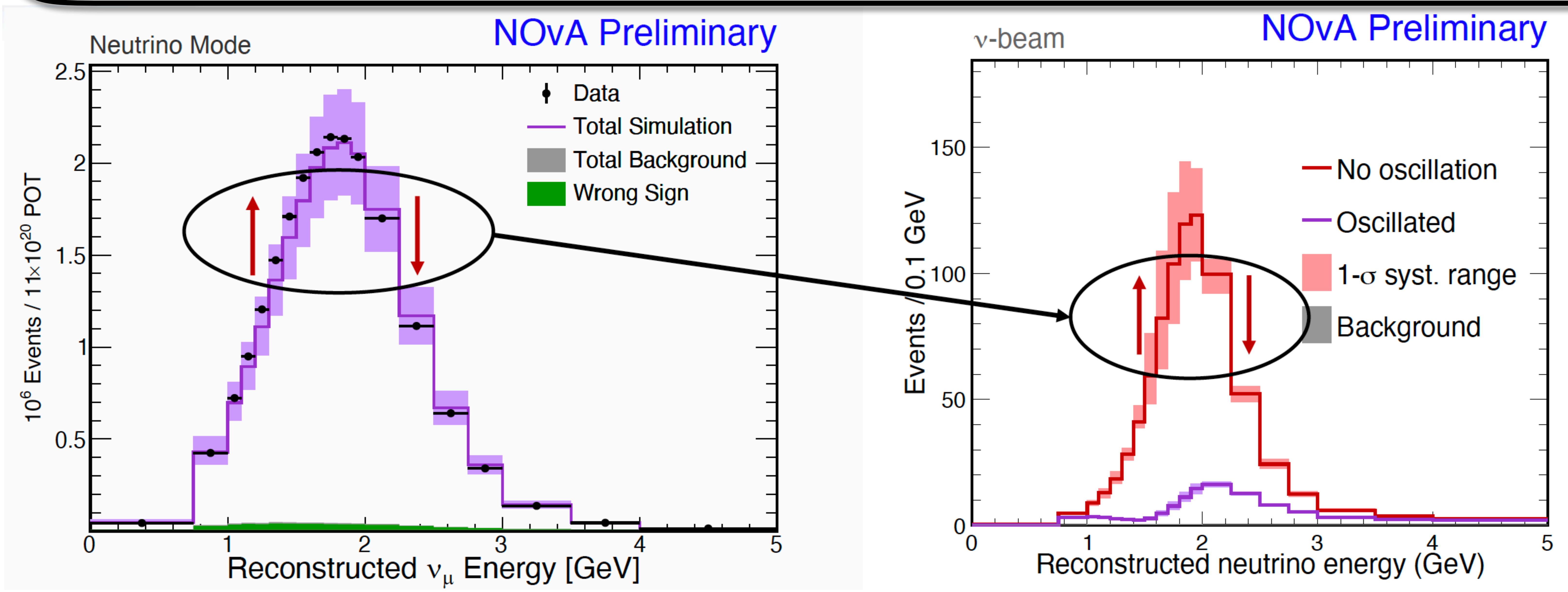


Energy reconstruction and extrapolation





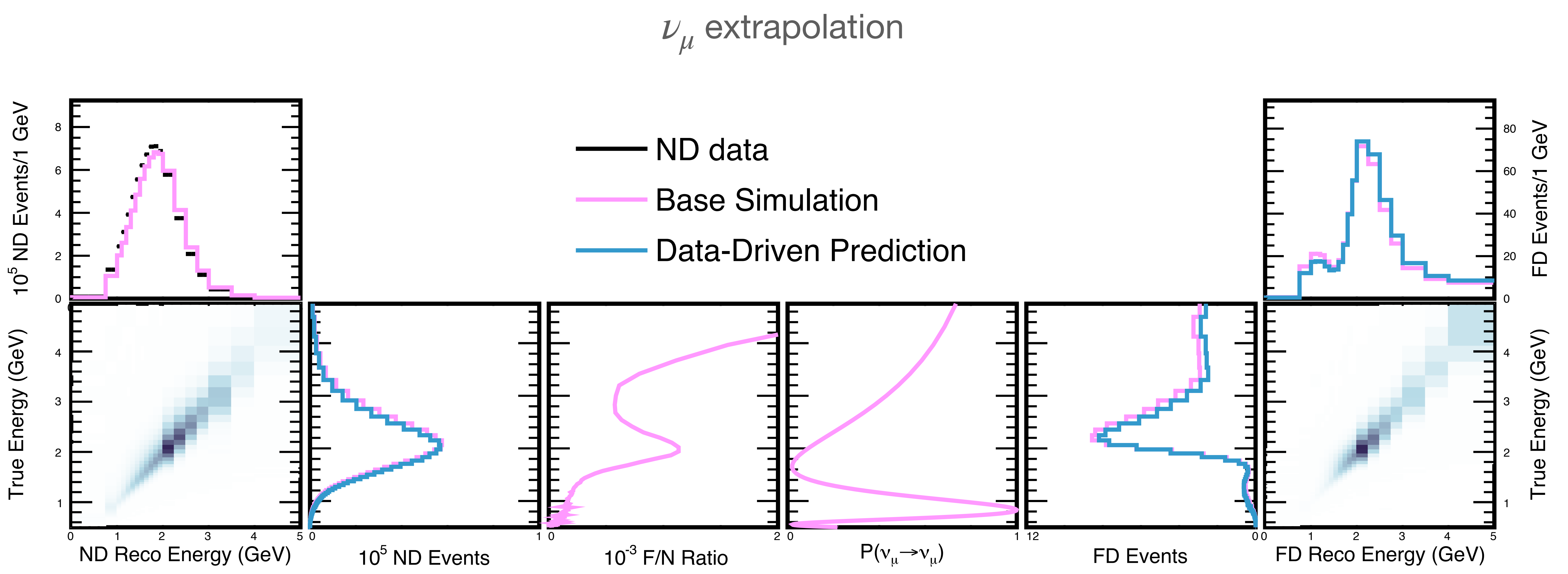
Overall resolution = ~11%

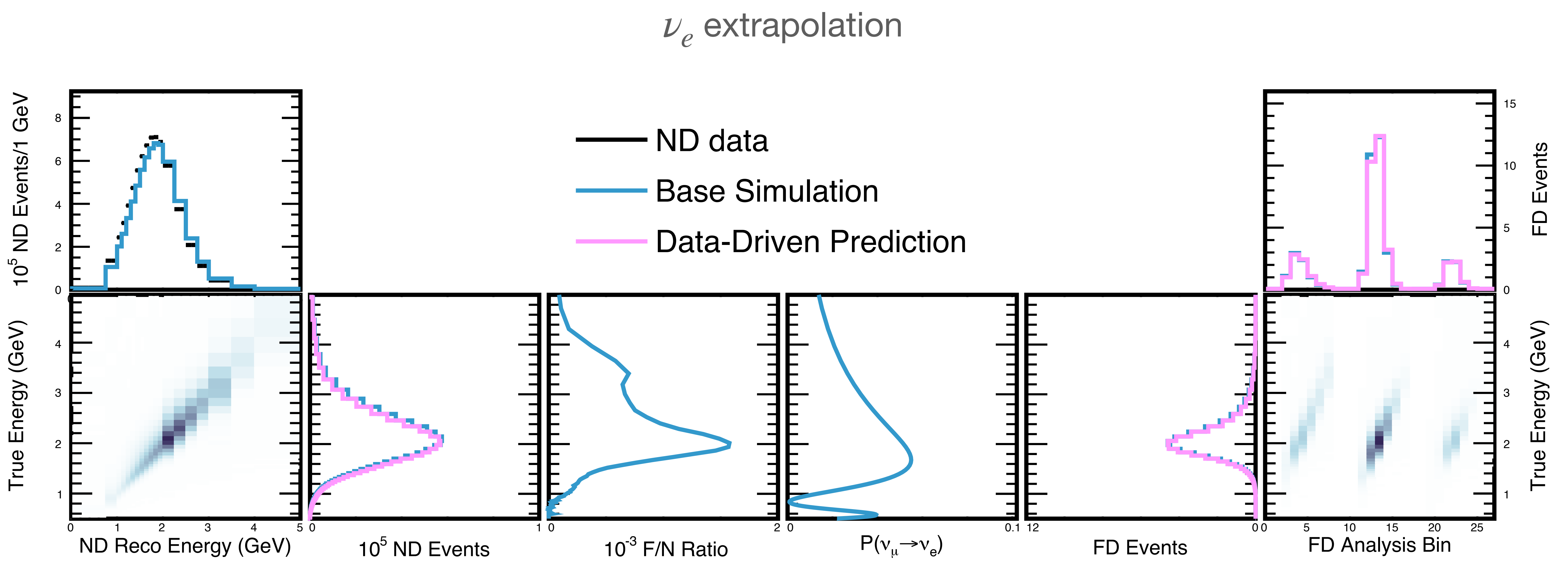


- Observed data-MC differences at ND, extrapolate them to modify the FD MC prediction (significantly reduce systematics).
- Systematic uncertainties determined in ND also extrapolated to FD.

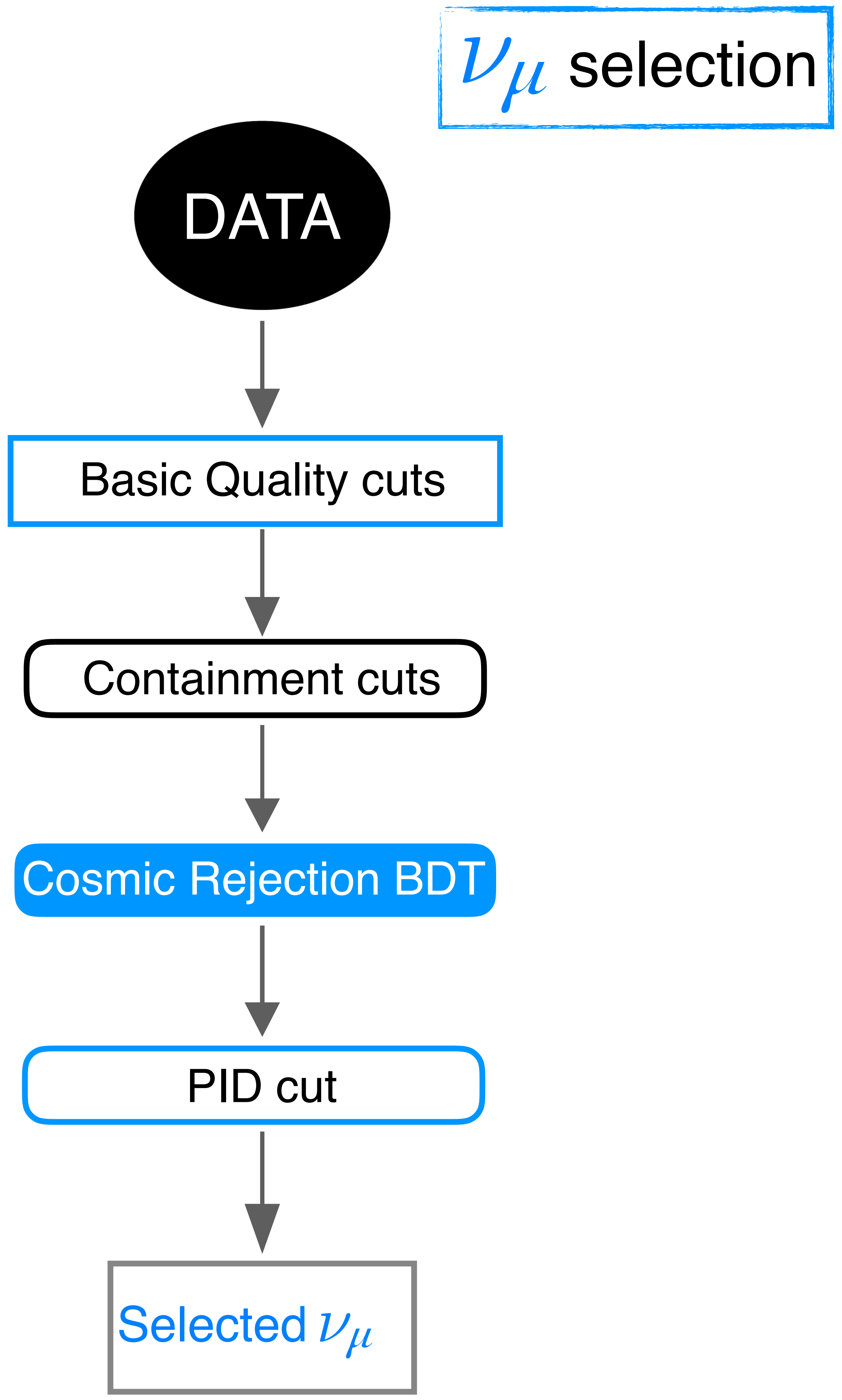
3-flavor oscillations

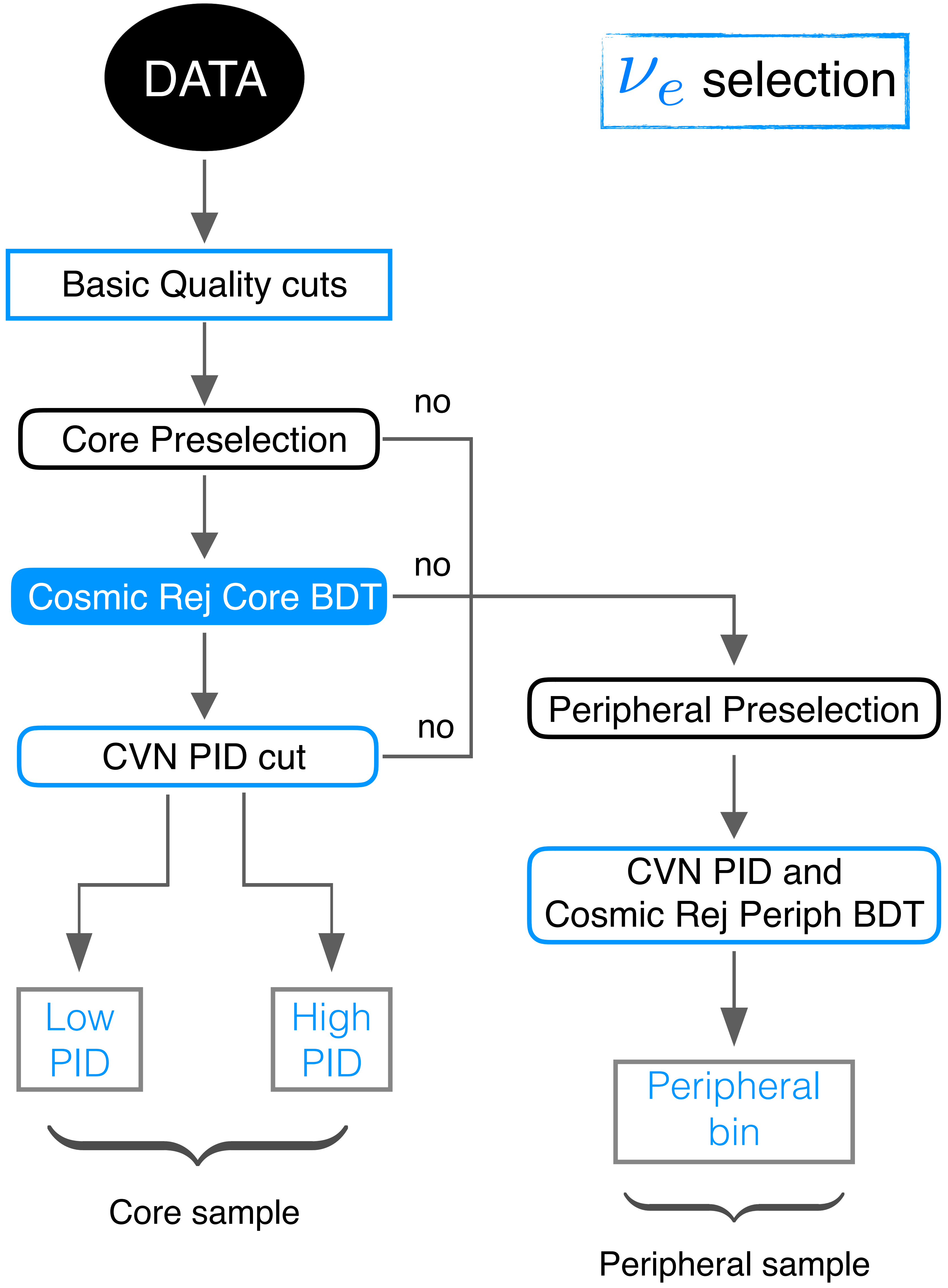
- Extrapolate the high statistics spectra observed at the Near Detector to see what you expect at the Far Detector
  - Including the "not ν_μ CC" BG
  - Estimate remaining cosmic BG from data adjacent to beam spill
  - Fit for both FHC/RHC, appearance/disappearance





Event selection





Systematics

- Systematics assessed by generating shifted sets of simulated data.
  - Can get slight improvements by extrapolating to FD in P_T bins (5-10% overall, 30% in xsec).
  - Still statistics dominated.