RECENT NOvA NEUTRINO OSCILLATION MEASUREMENTS & PROSPECTS

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21st Rencontres du Vietnam, ICISE

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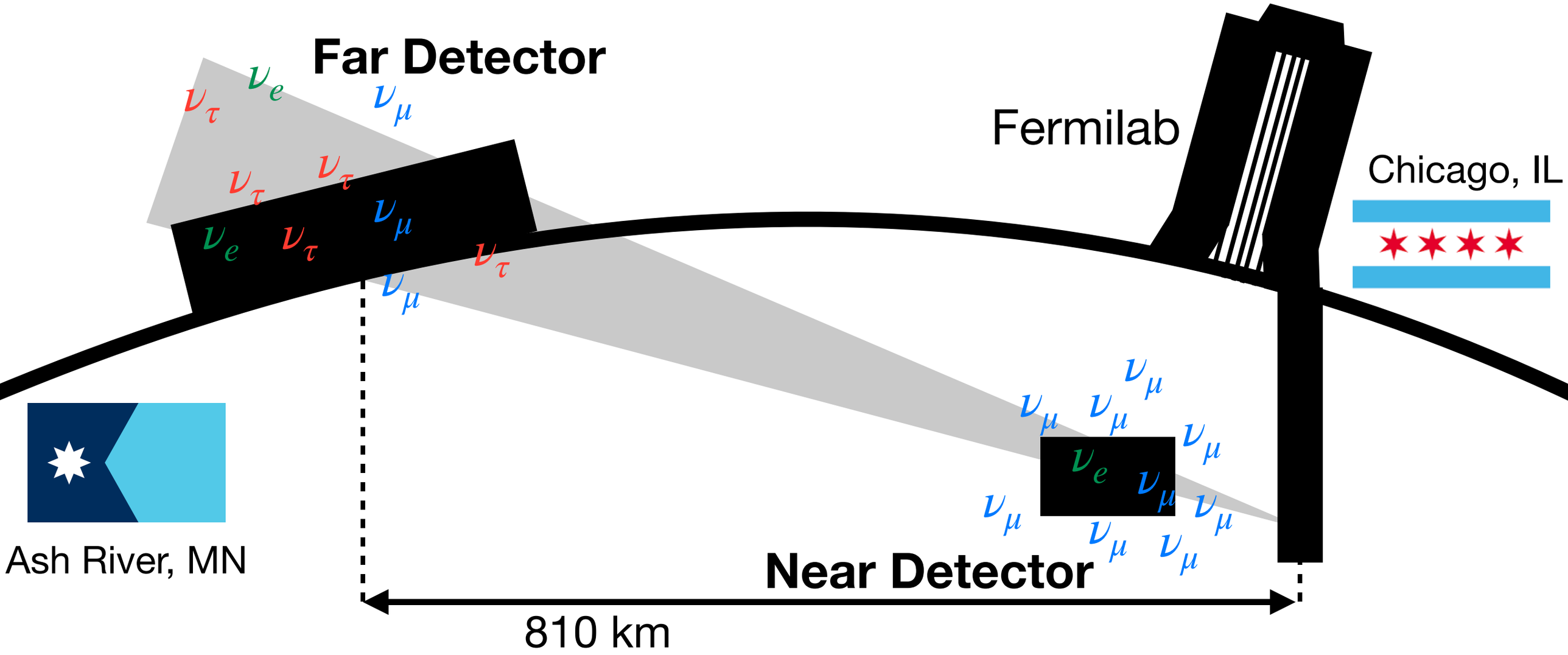
NOvA Experimental Setup

- 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 is to** study 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.



Questions that NOvA can help to answer…

- Long-baseline neutrino oscillation experiment.
  - NuMI **neutrino beam** at Fermilab.
  - **Near detector** to measure beam before oscillations.
  - **Far detector** measures the oscillated spectrum.

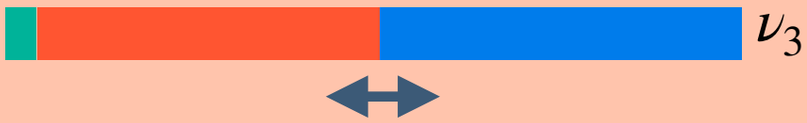
- **Primary goal is to** study 3-flavour oscillations via:
  - $\nu_\mu \rightarrow \nu_\mu$, $\nu_\mu \rightarrow \nu_e$
  - $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

- Other goals include:
  - Search for sterile neutrinos.
  - Neutrino cross sections.
  - Supernova neutrinos.
  - Cosmic ray physics.

Is the neutrino **mass ordering normal** or **inverted**?

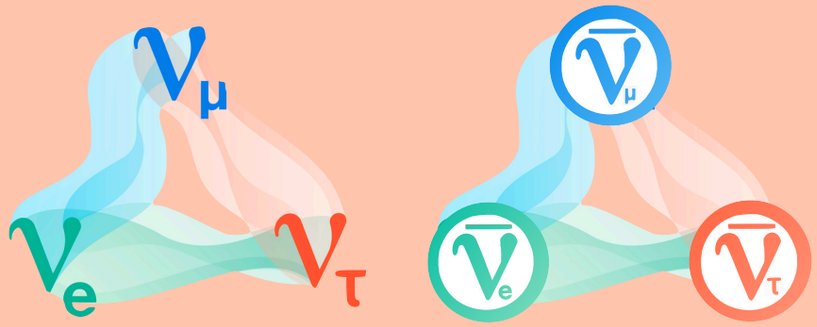
$|\Delta m^2_{32}|$?

Is there a **symmetry** between μ and τ flavours?



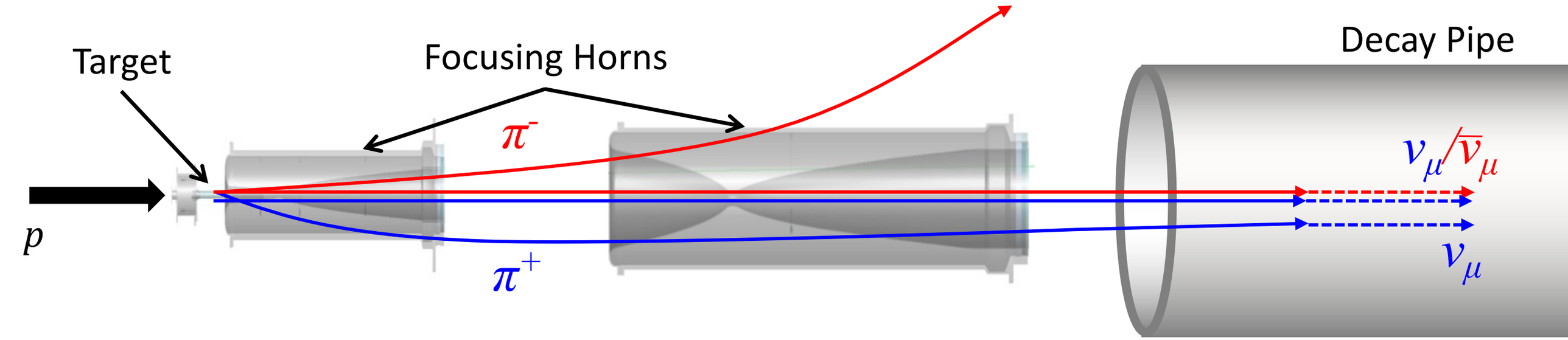
θ_{23}?

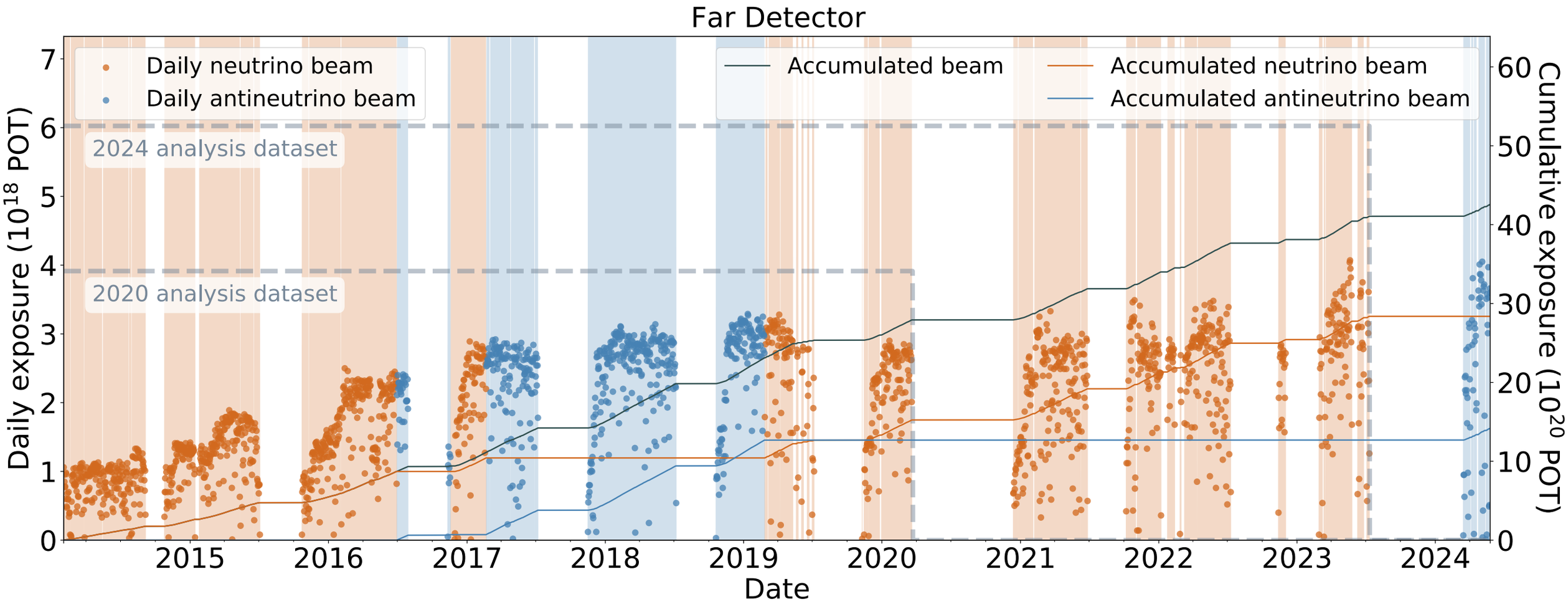
Do neutrinos **violate CP symmetry**?



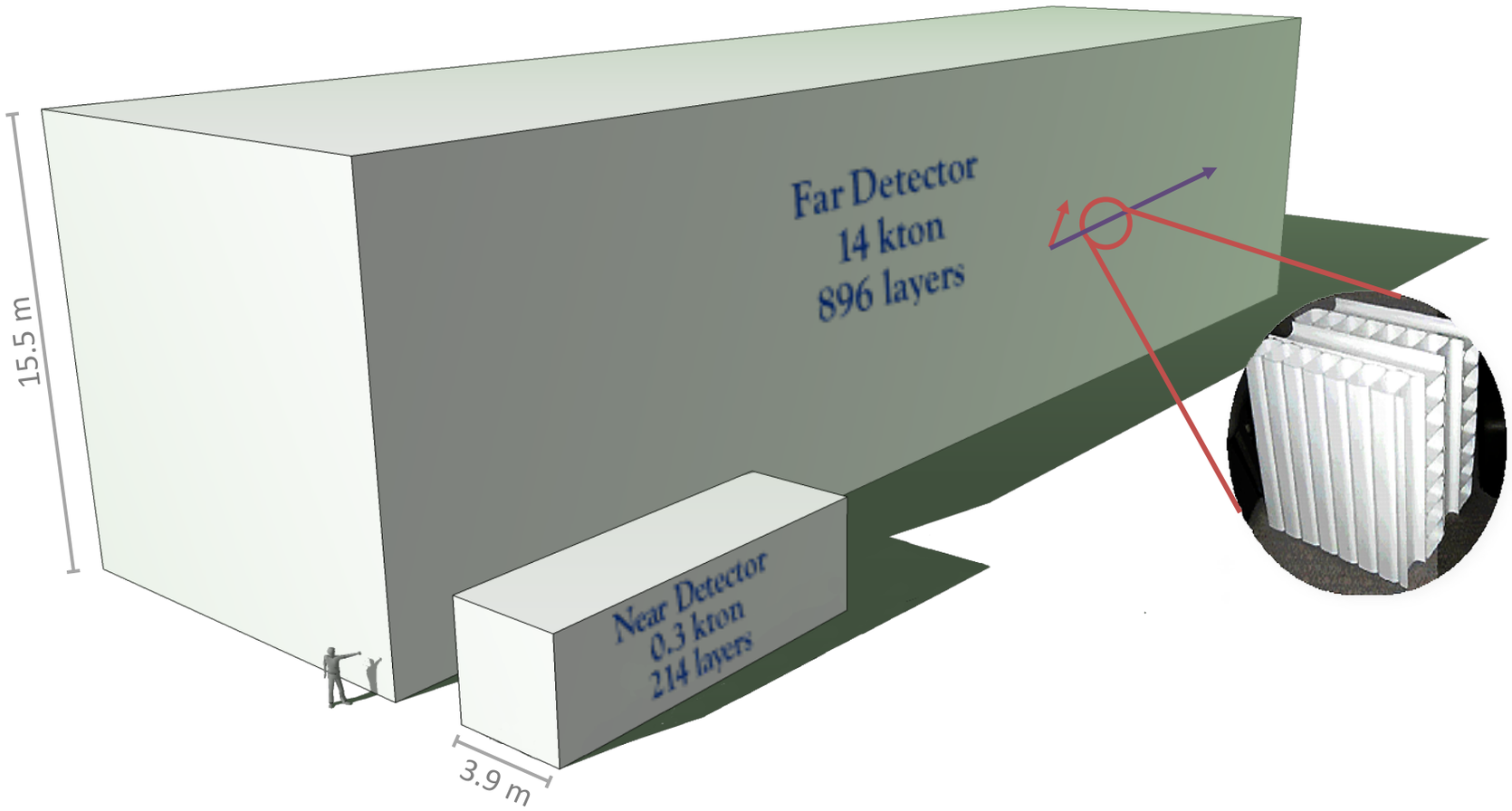
δ_{CP}?

How We Make Neutrinos: NuMI Beam



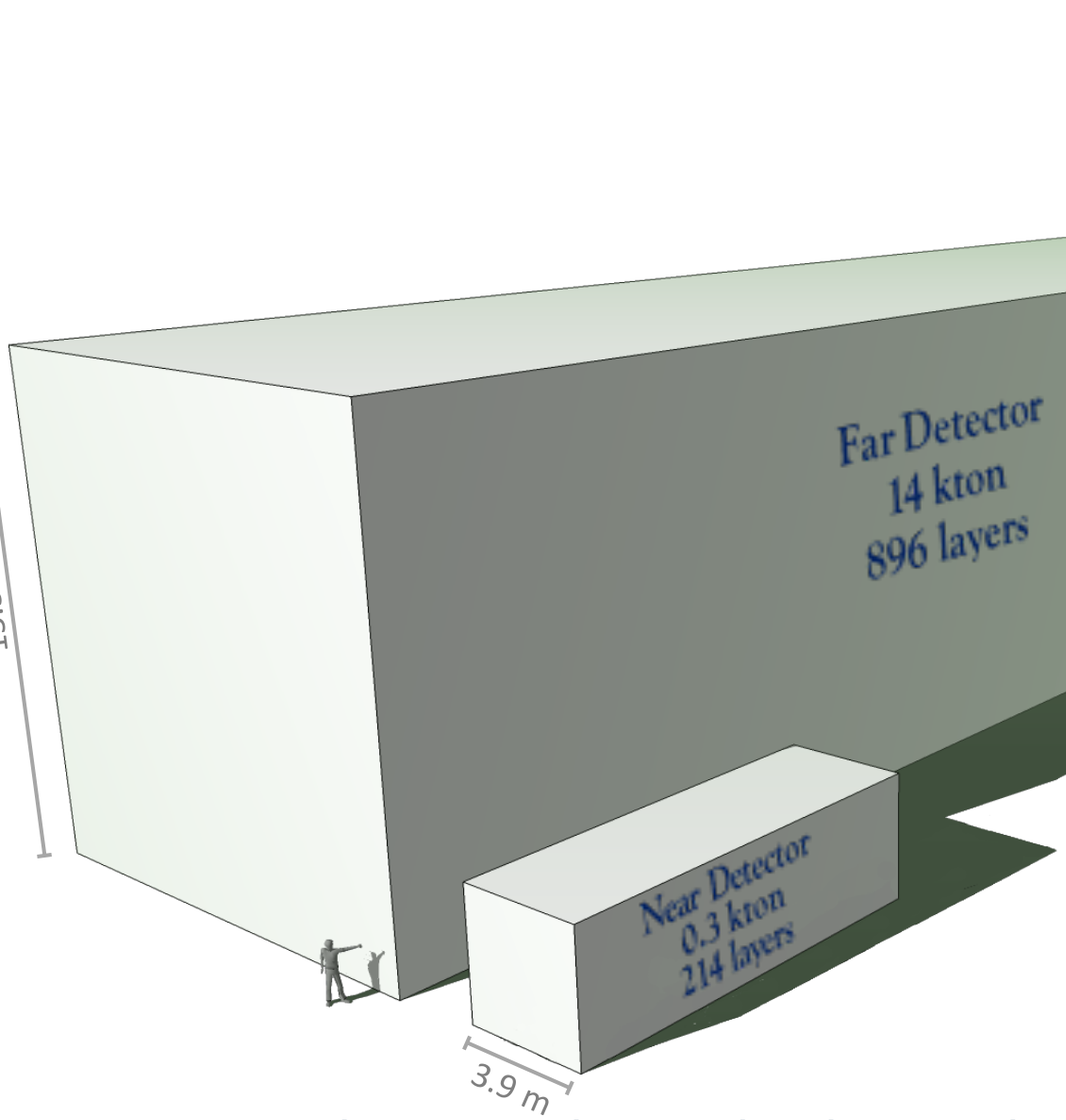


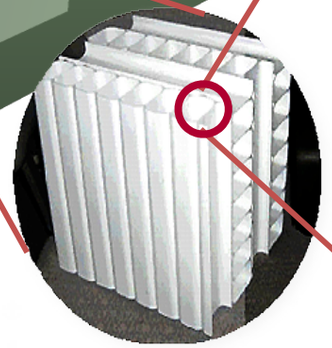
The NOvA Detectors

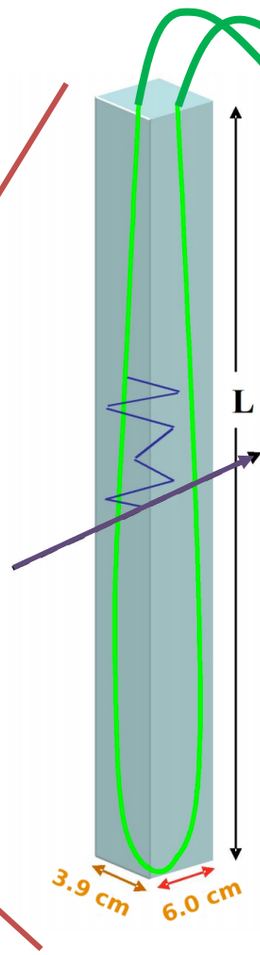


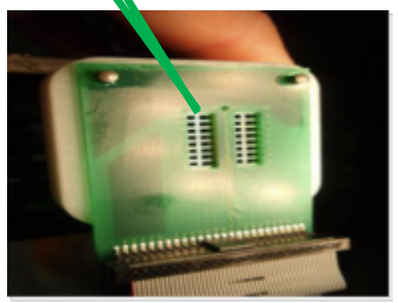
- Both are large, (FD 60 m long).
- Functionally identical: consist of extruded PVC cells filled with 11 million litres of liquid scintillator.
- Arranged in alternating directions for 3D reconstruction.

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.

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

Mostly unchanged!

Analysis Strategy

Particle ID

Reconstruction

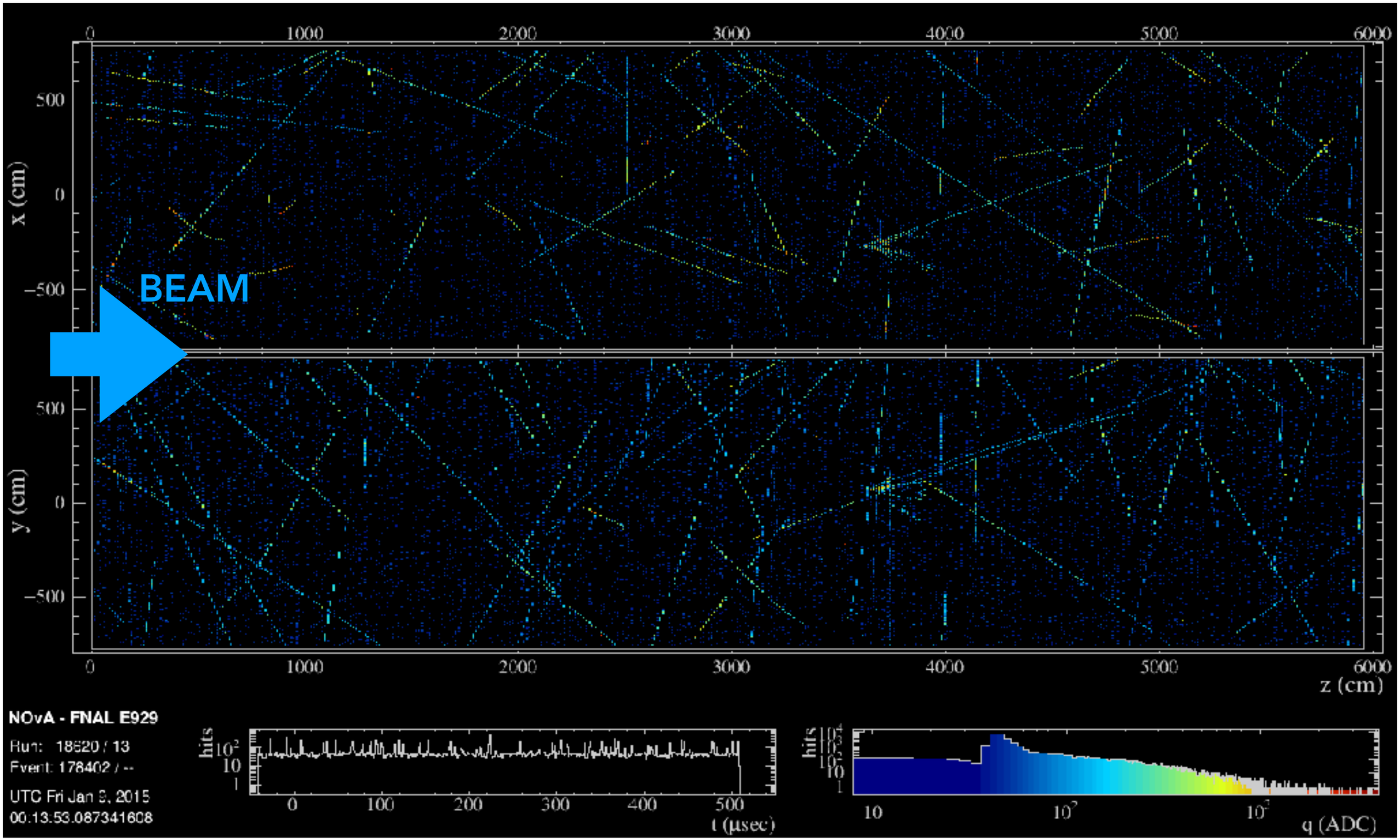
Observe flavour change as a function of energy over a long distance while mitigating uncertainties on neutrino flux, cross sections and detector response.

Extrapolation

Models

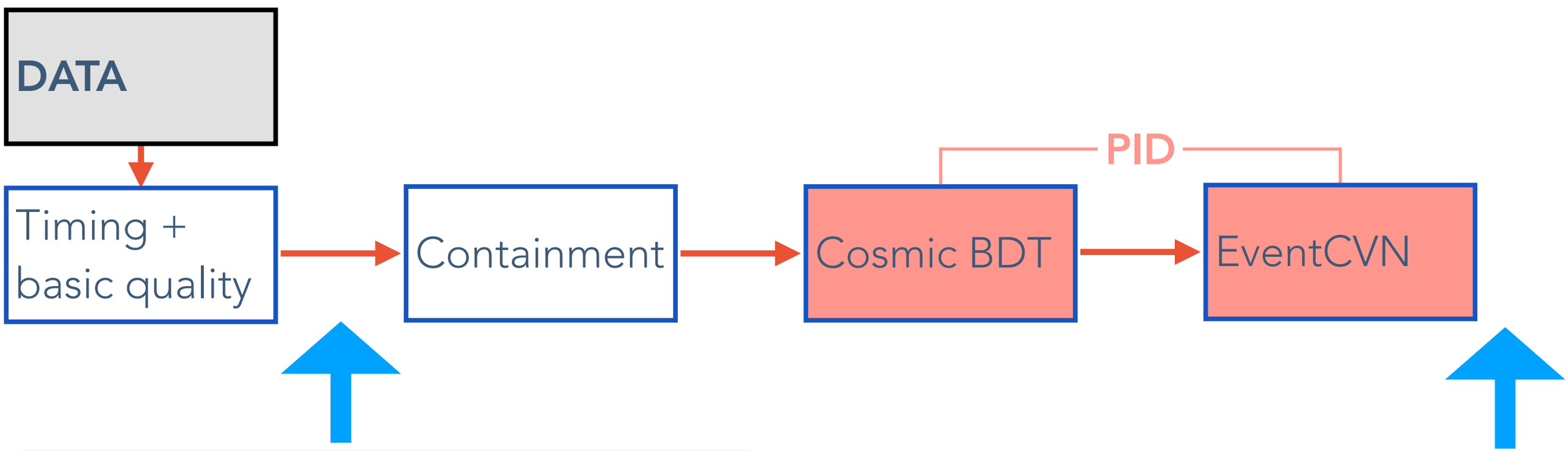
Improved!

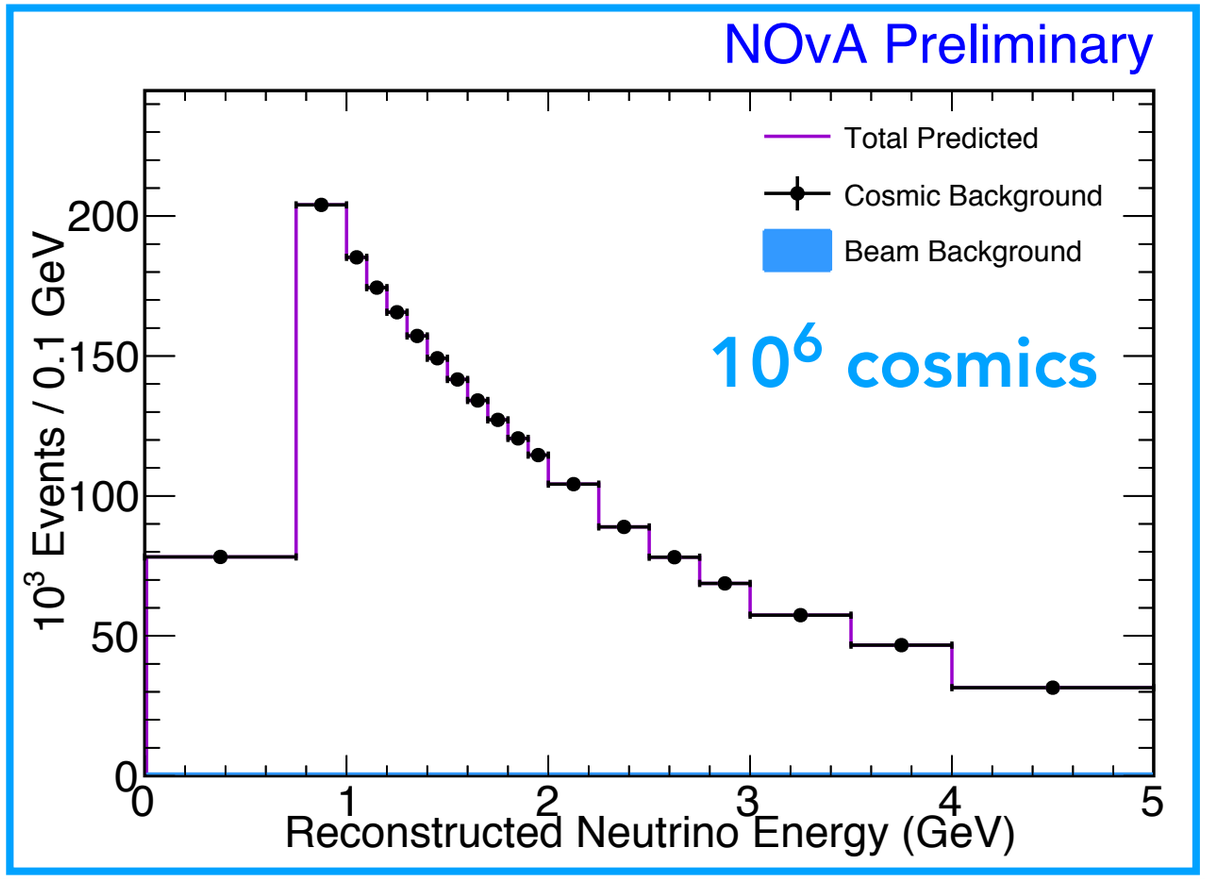
Selection: Cosmic Rejection

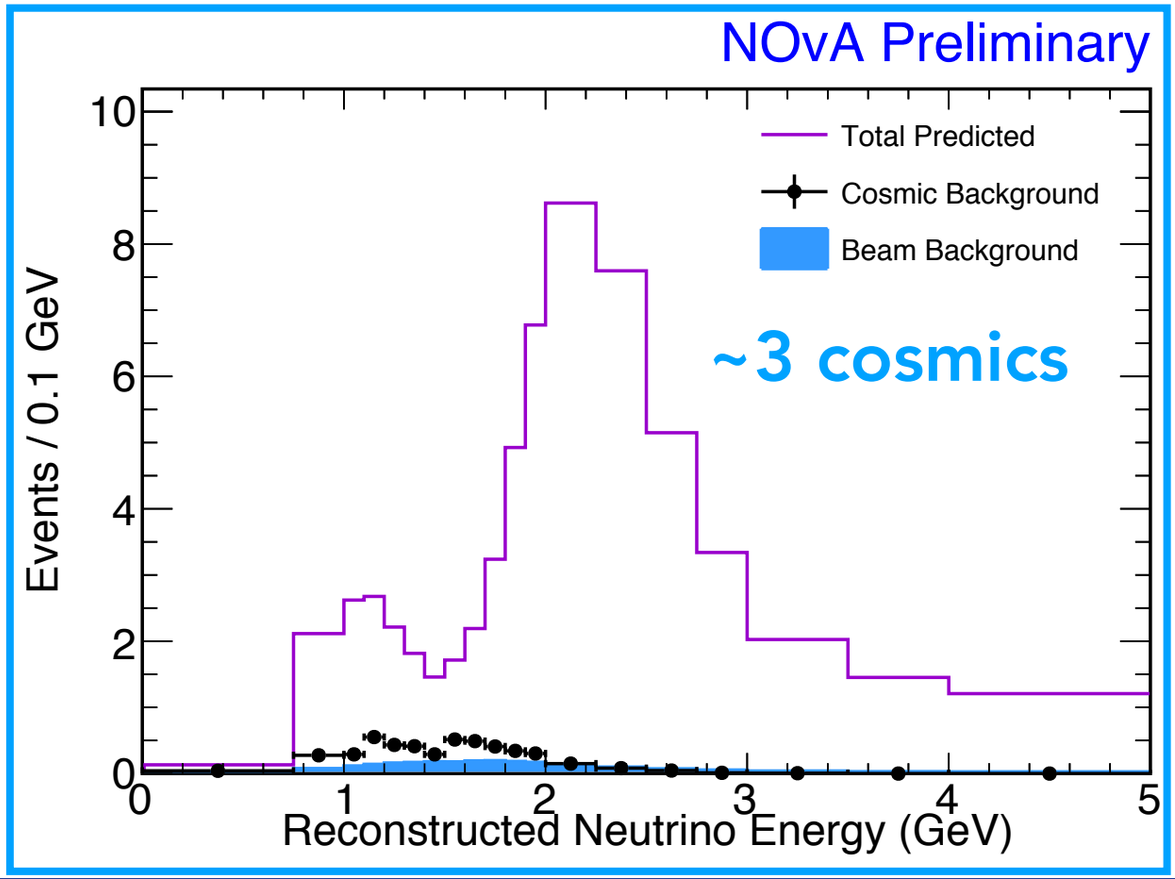


Cosmic rejection critical for FD: 11 billion cosmic rays/day

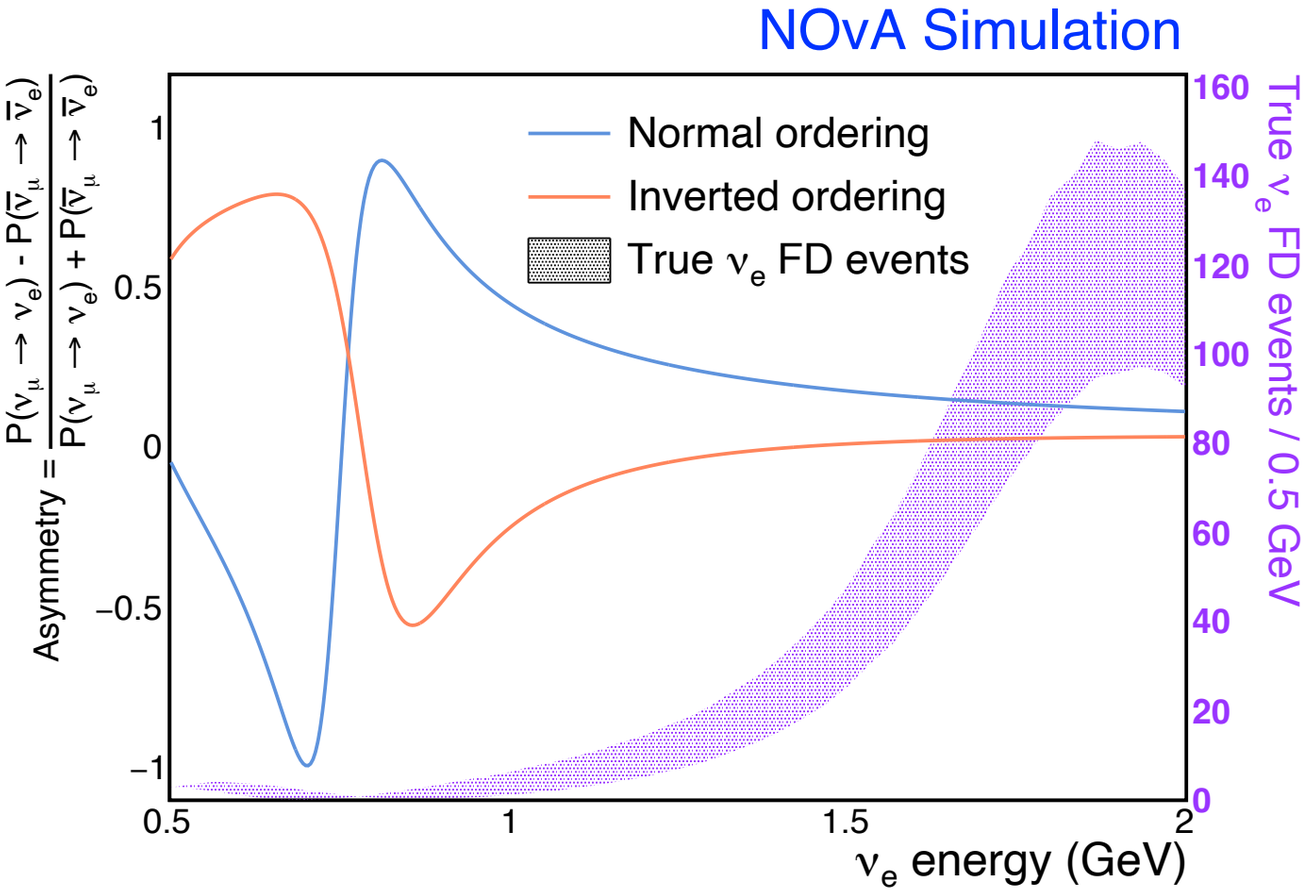
Selection: ν_μ

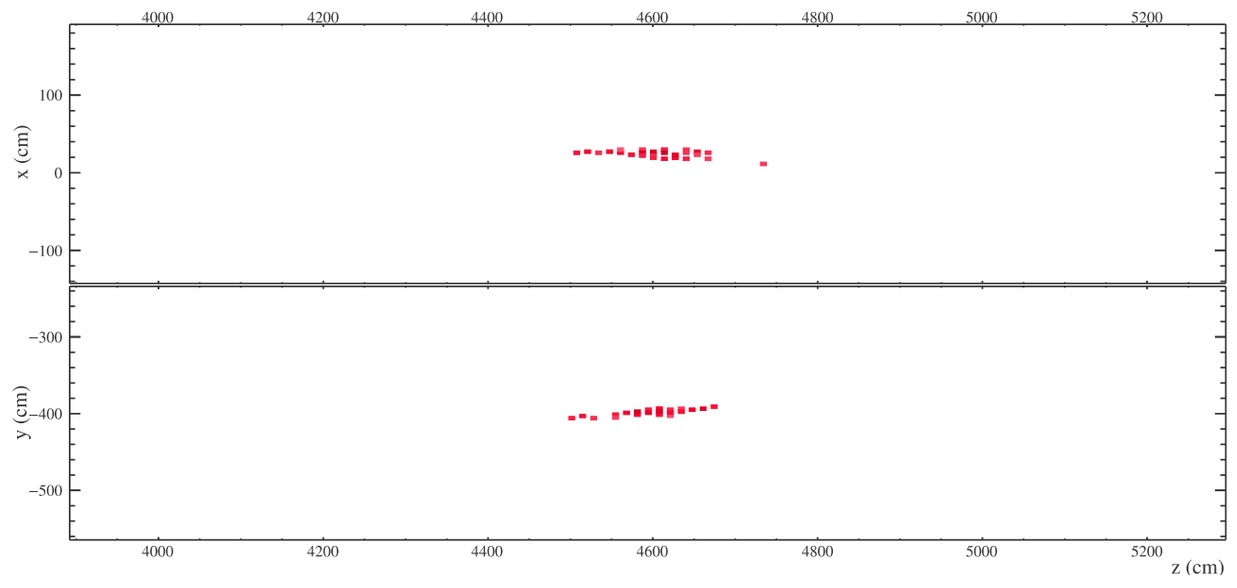






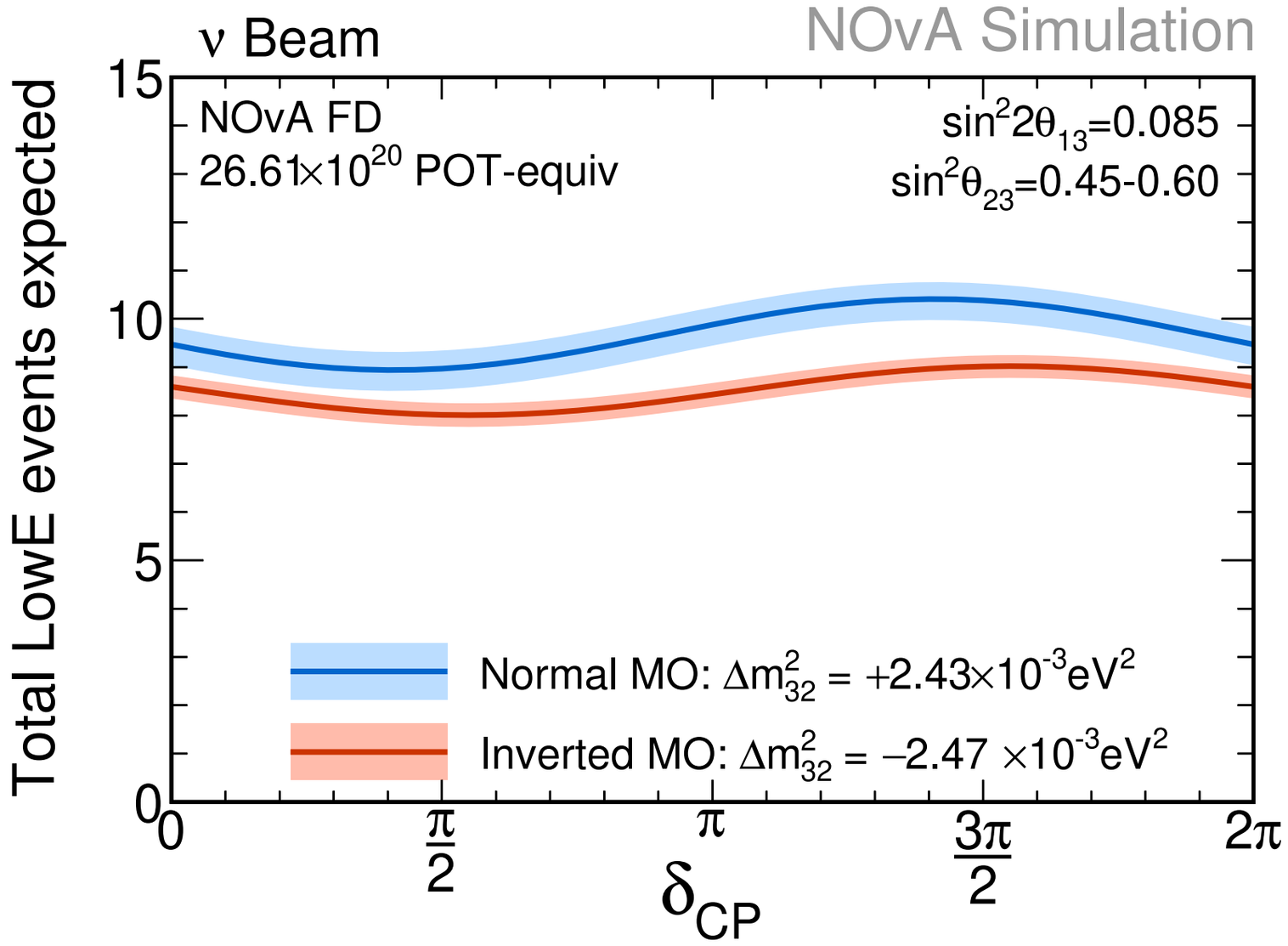
Expanding ν_e Candidate Selection





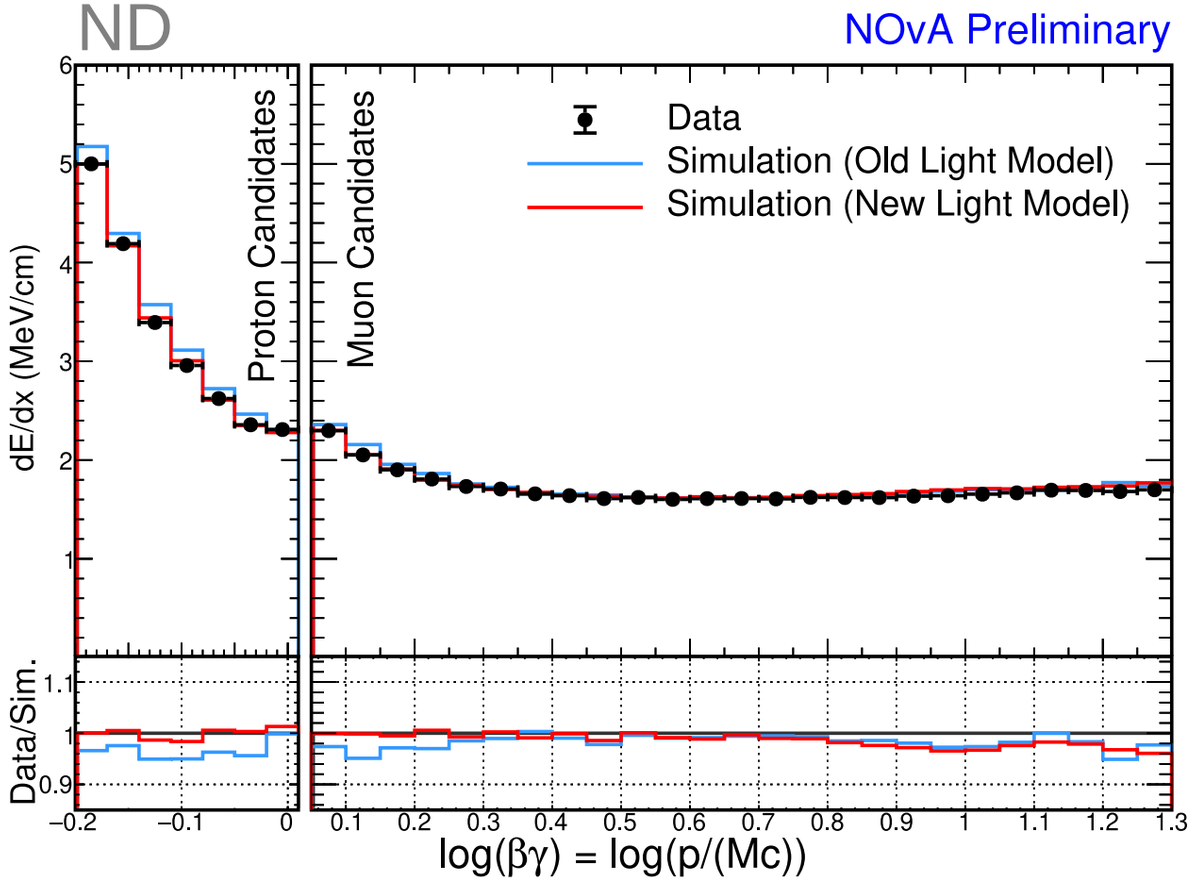
- For NOvA's energy range and baseline the effect of the mass ordering is largest at lower energies in the range.
- Challenging for NOvA - predicted number of events in this region is small.
- Pursuing these events with a new BDT classifier.

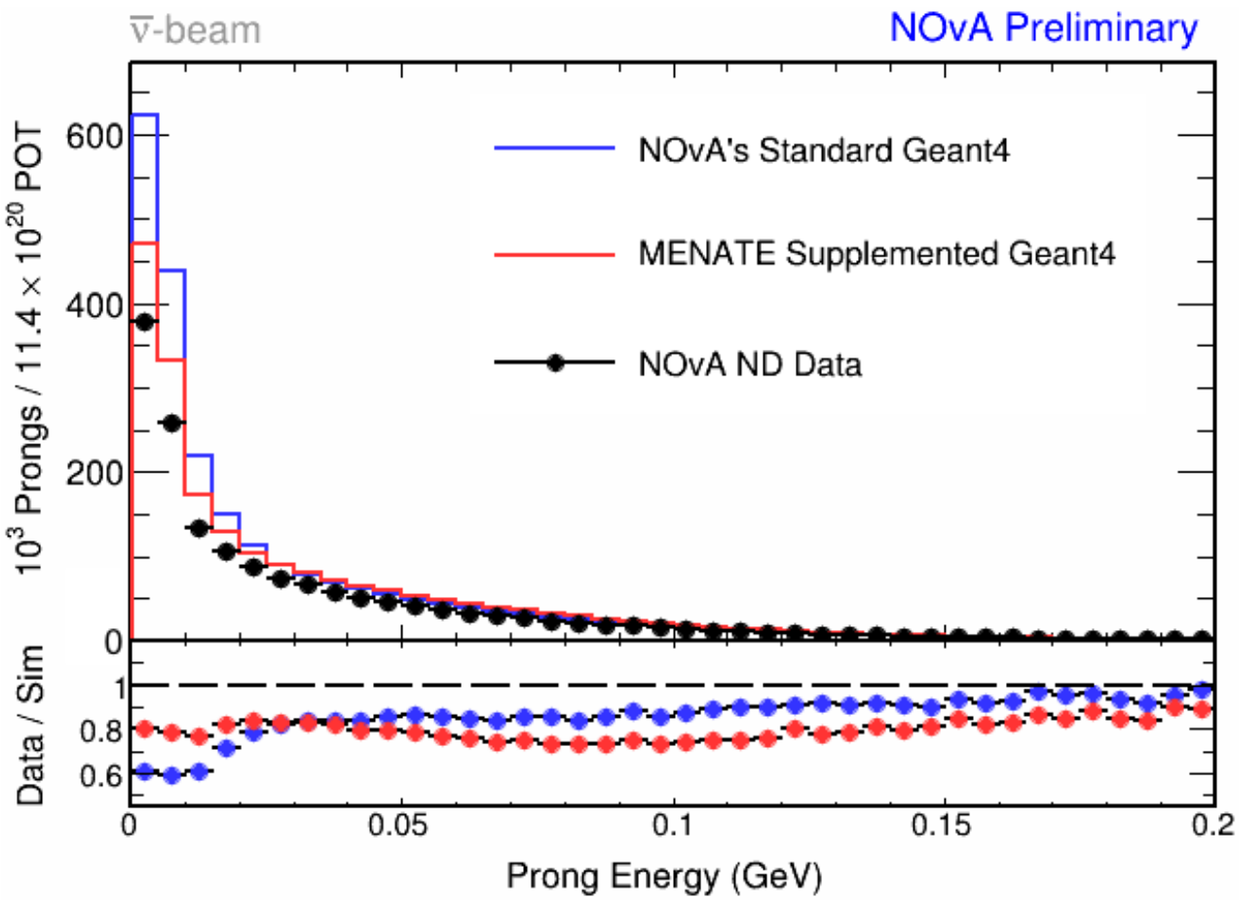
Expanding ν_e Candidate Selection



- Good separation in some regions.
- Only have sufficient statistics in the neutrino beam mode sample. Analogous sample in antineutrino beam mode is currently too small.
- Provides increase in sensitivity to the mass ordering of ~ few %.

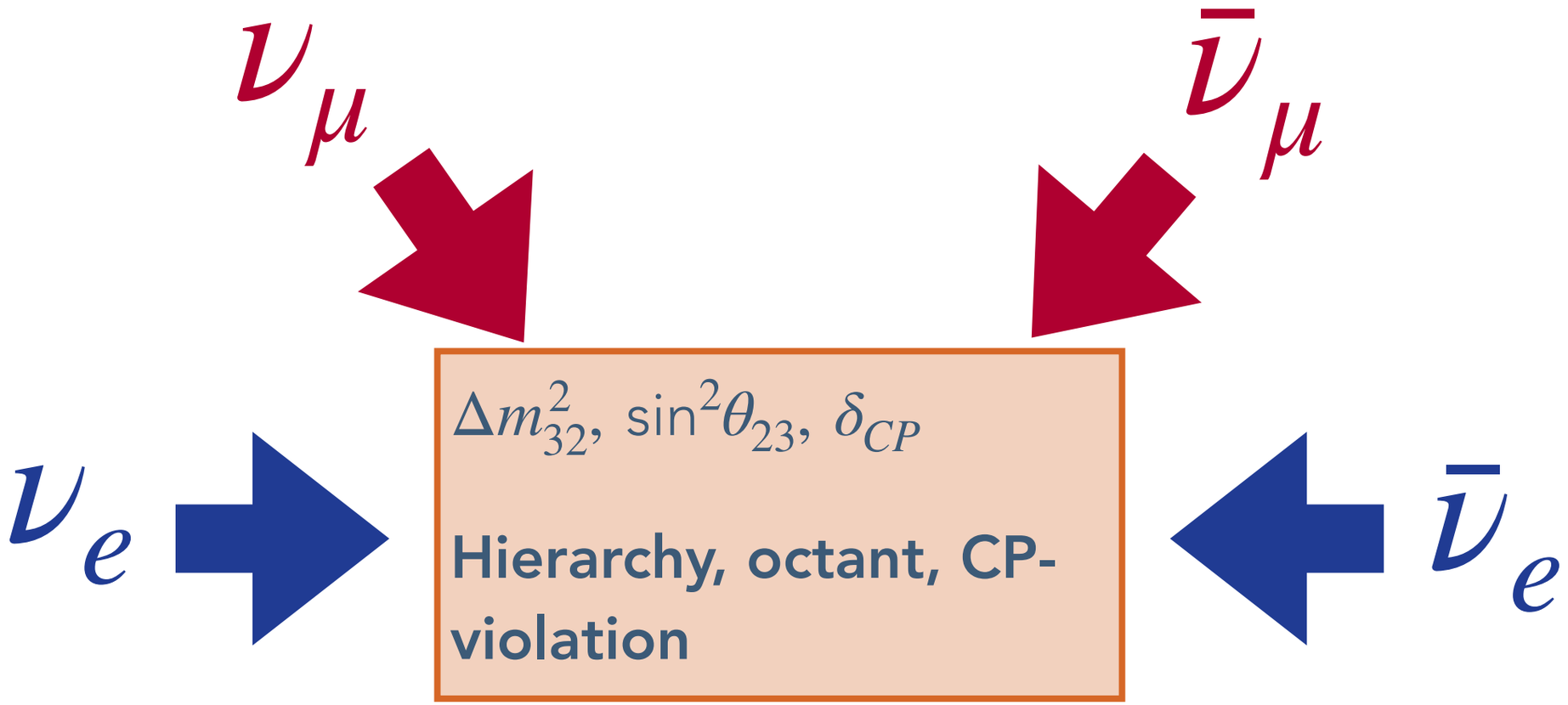
Detector Characterisation





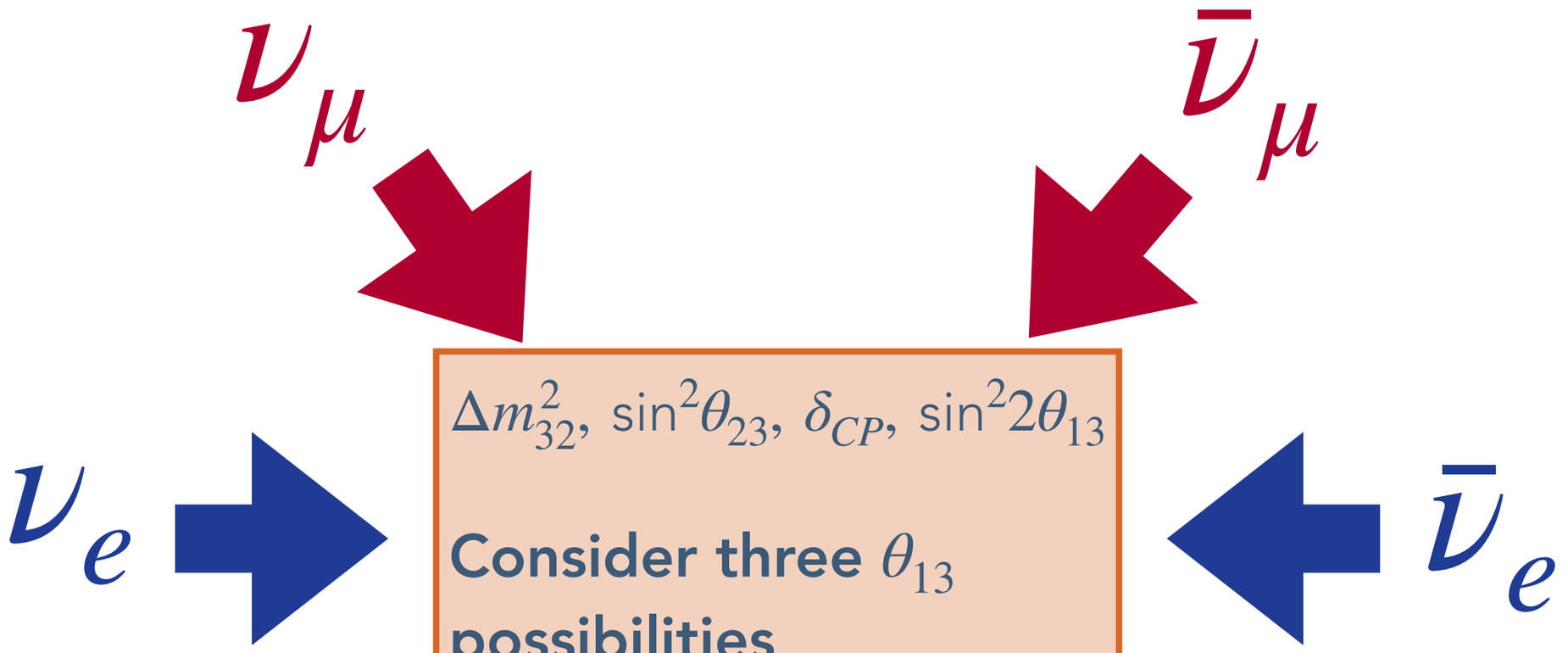
- Improved model of light production in the mineral oil (scintillation and Cherenkov) in both detectors.
- Dedicated bench measurements and studies of stopping proton and muon candidates in data.
- Difference between MENATE and default GEANT4.10.4 used to motivate a systematic uncertainty.
- In future analyses MENATE will become part of our nominal simulation.

Oscillation Fit



- All results come from a joint fit to neutrinos + antineutrinos, electron + muon.
- Other PMNS parameters are constrained by PDG **with one exception**.
- Poisson log-likelihood ratio, systematics ~60 nuisance parameters.
- Bayesian approach using Markov Chain Monte Carlo to sample posterior probability distribution and build credible intervals.

Oscillation Fit



θ_{13} unconstrained

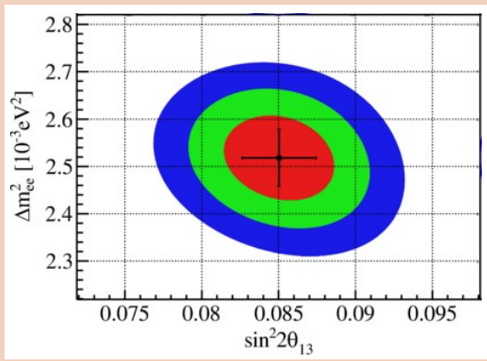
(NOvA only)

Daya Bay 1D θ_{13} constraint

($\sin^2 2\theta_{13} = 0.0851 \pm 0.0024$)

Daya Bay 2D $(\Delta m^2_{32}, \theta_{13})$ constraint

(PRL 130, 161802)



Results

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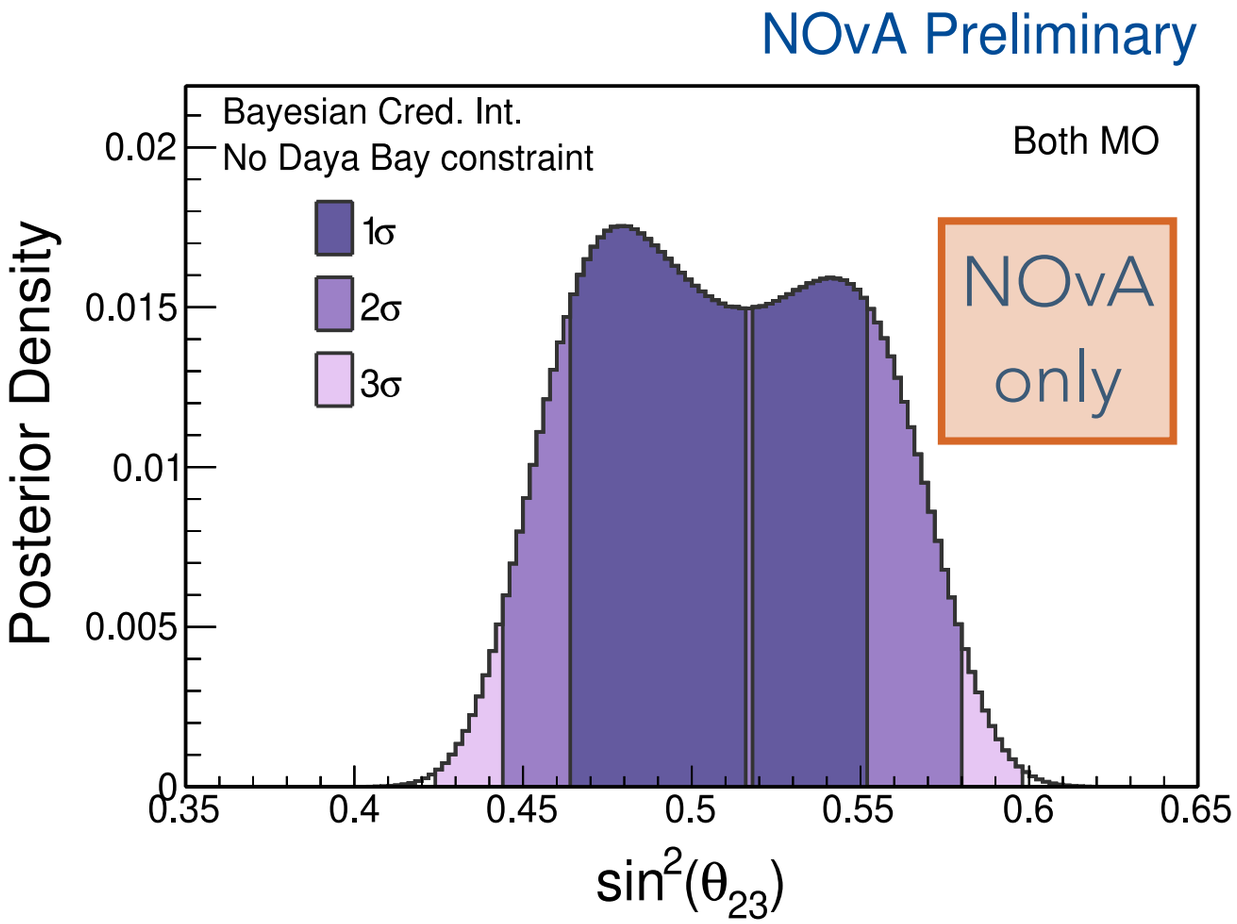
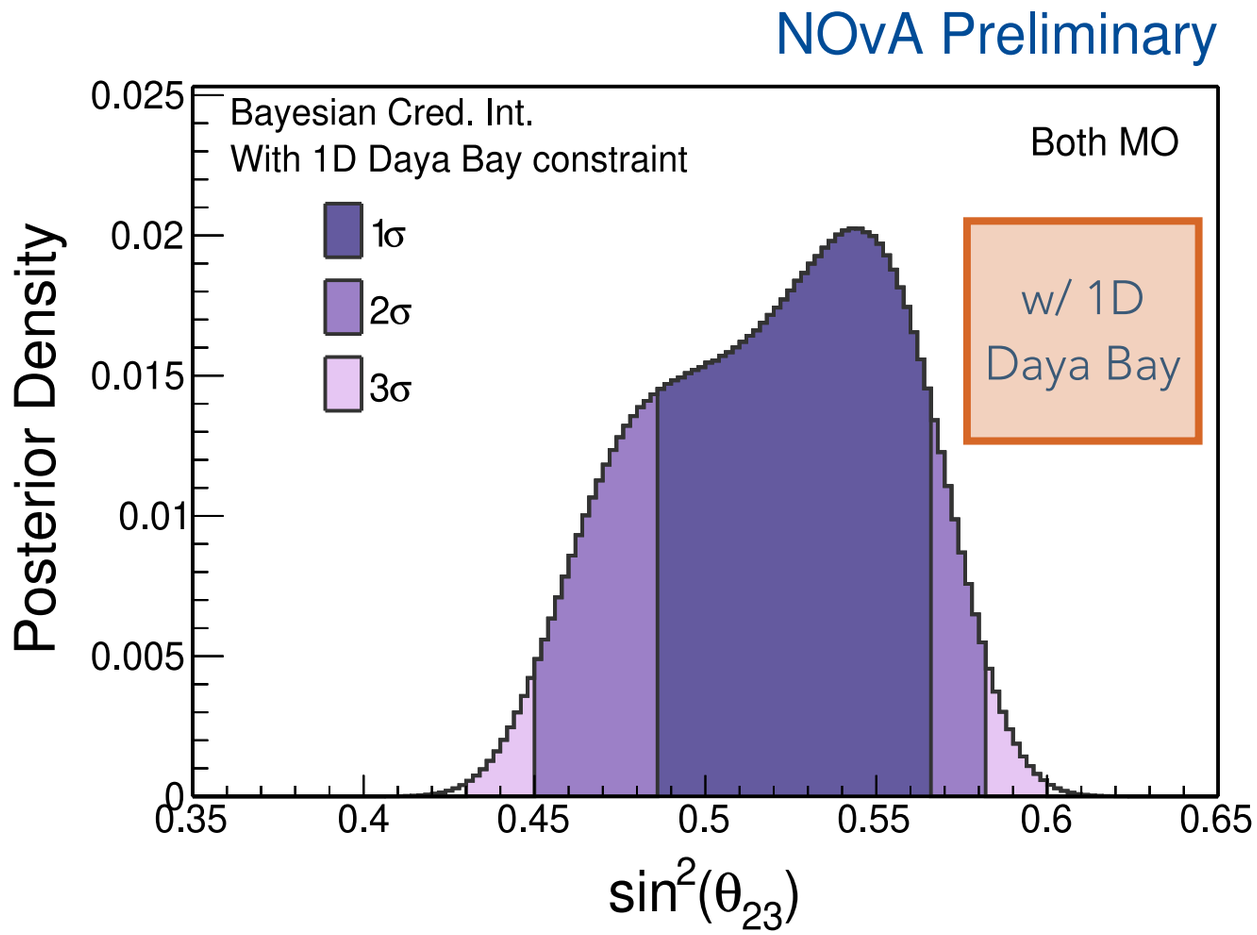
$\nu_2 - \nu_3$ Sector

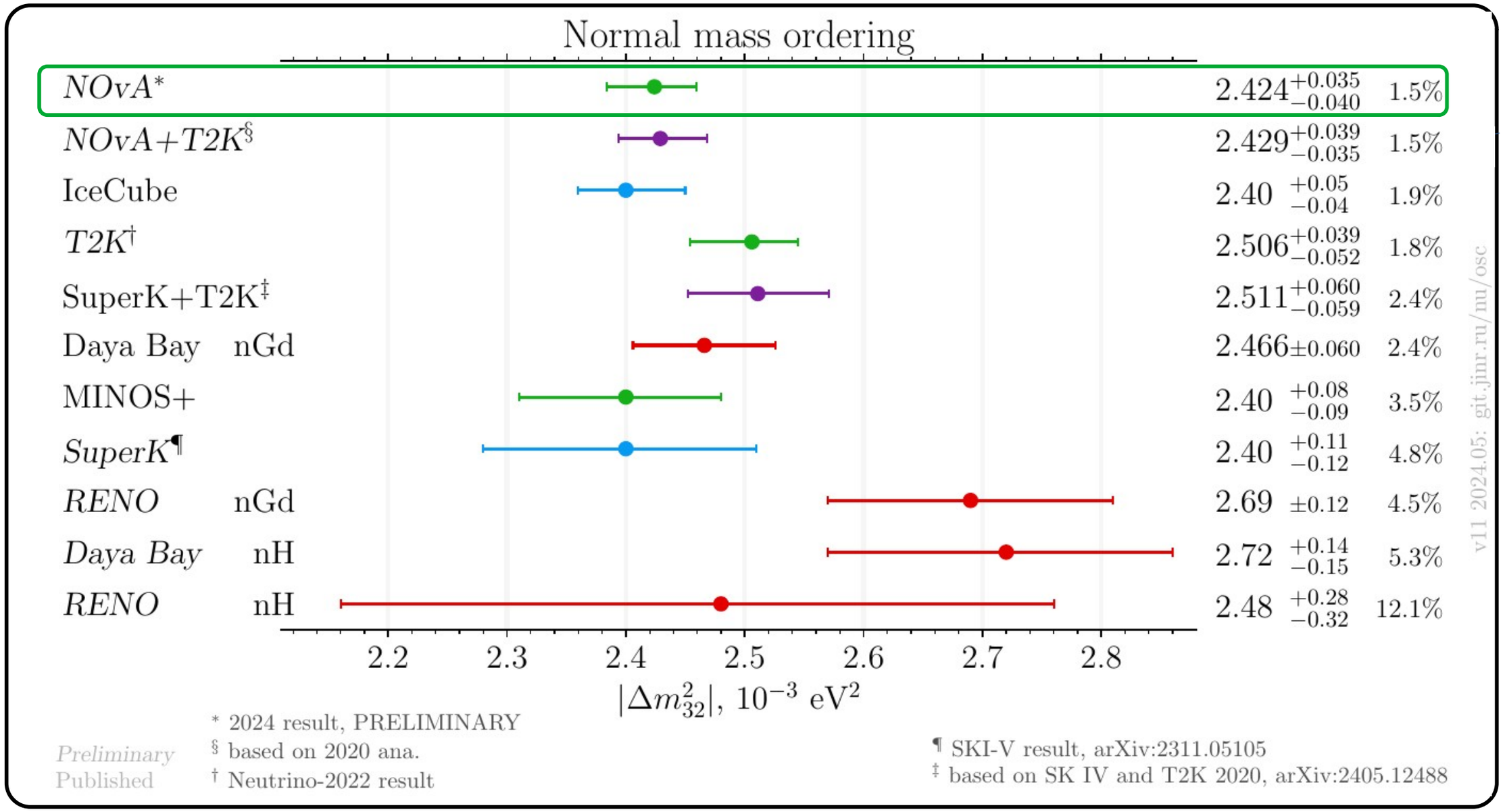




Maximal mixing is allowed at $< 1\sigma$ in both cases.

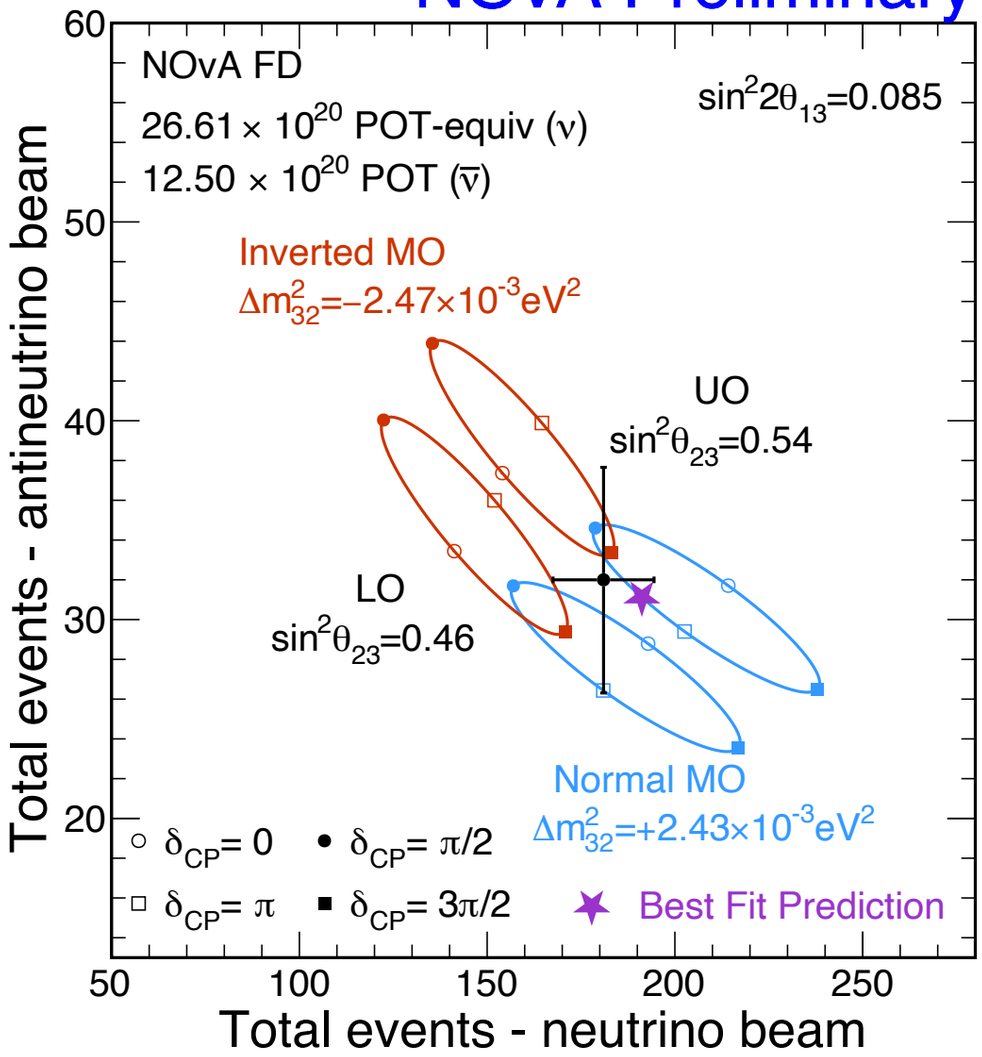
Mild upper octant preference w/ 1D constraint (Bayes Factor 2.2, 69% odds).

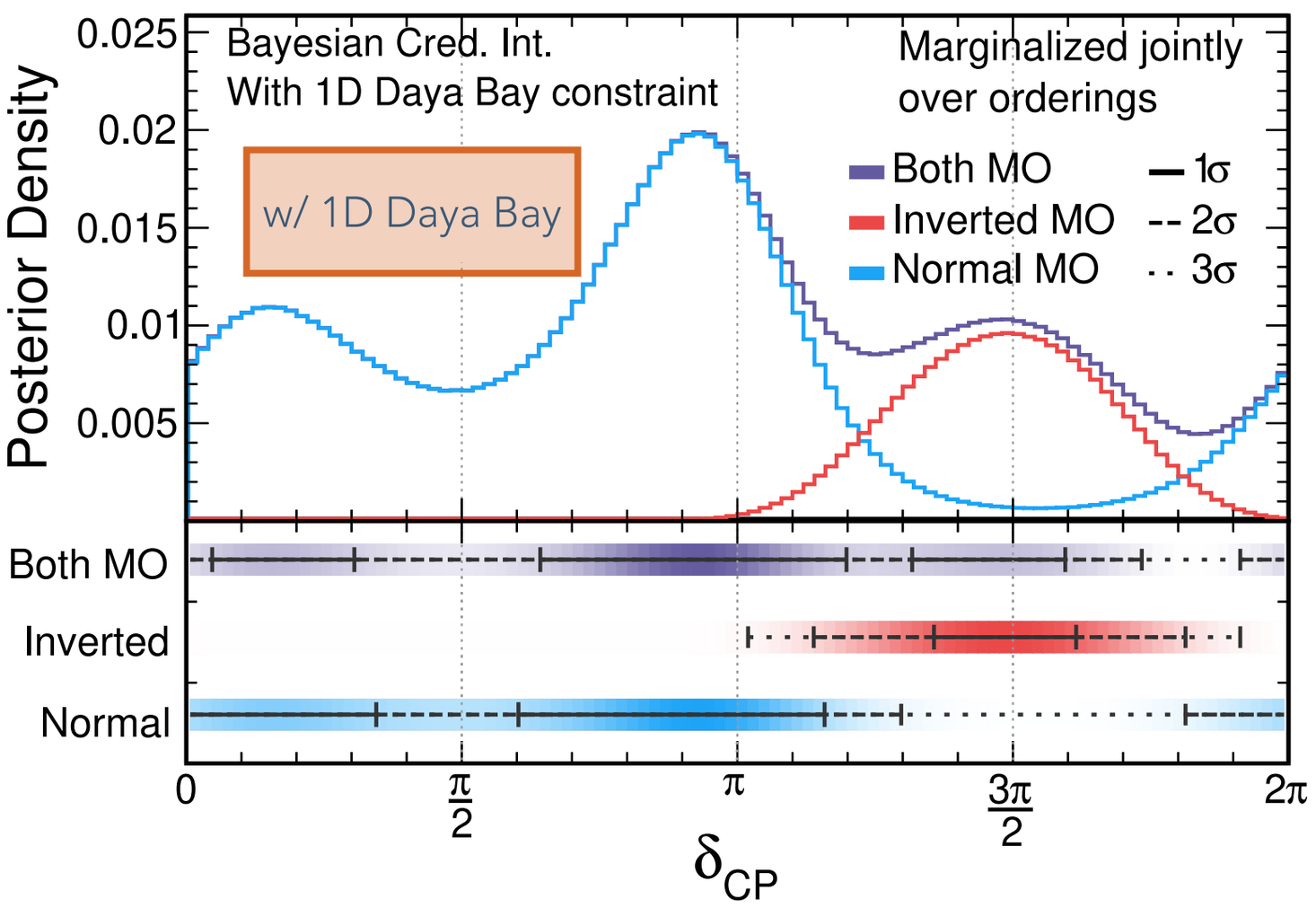
$\nu_2 - \nu_3$ Sector



Most precise single experiment measurement of Δm^2_{32}.

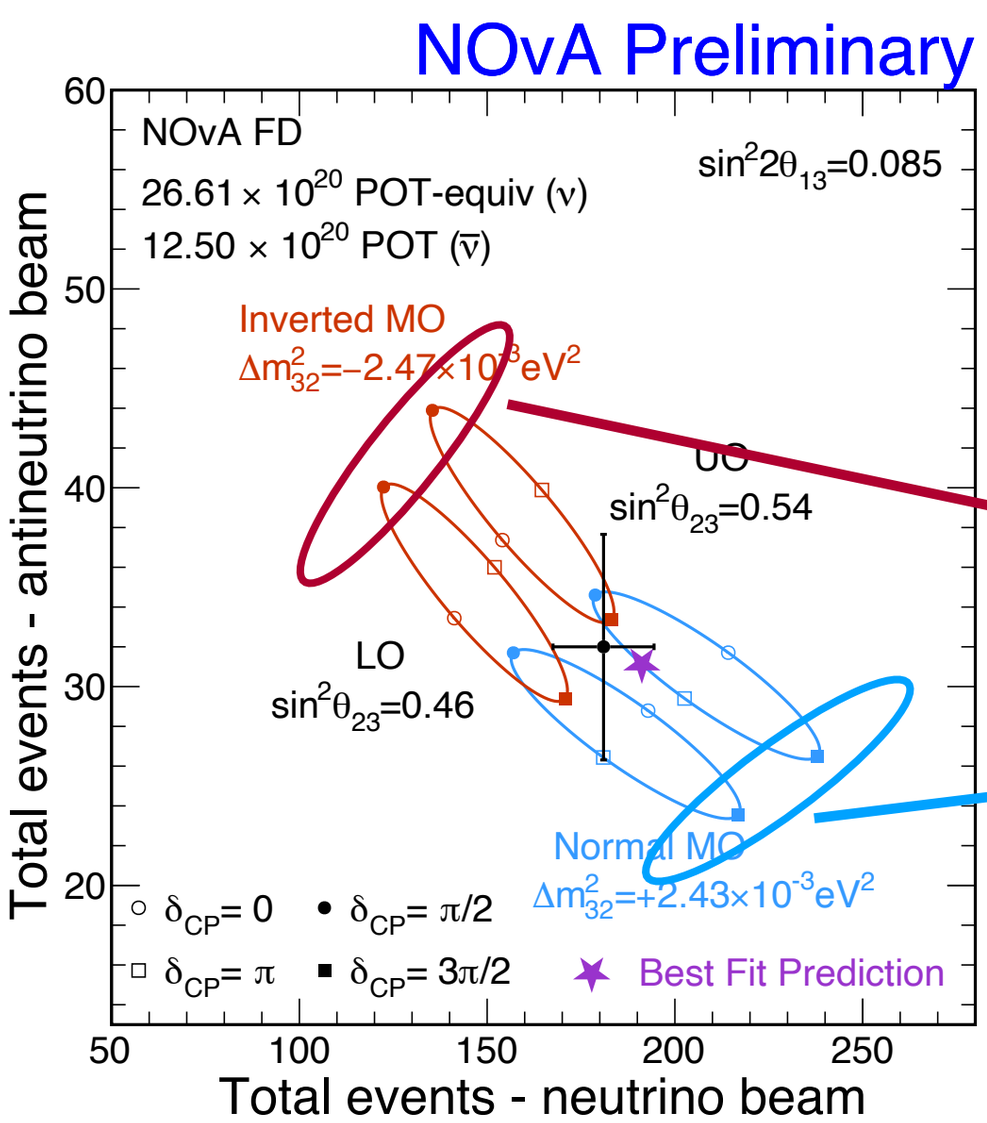
Mass Ordering with δ_{CP}

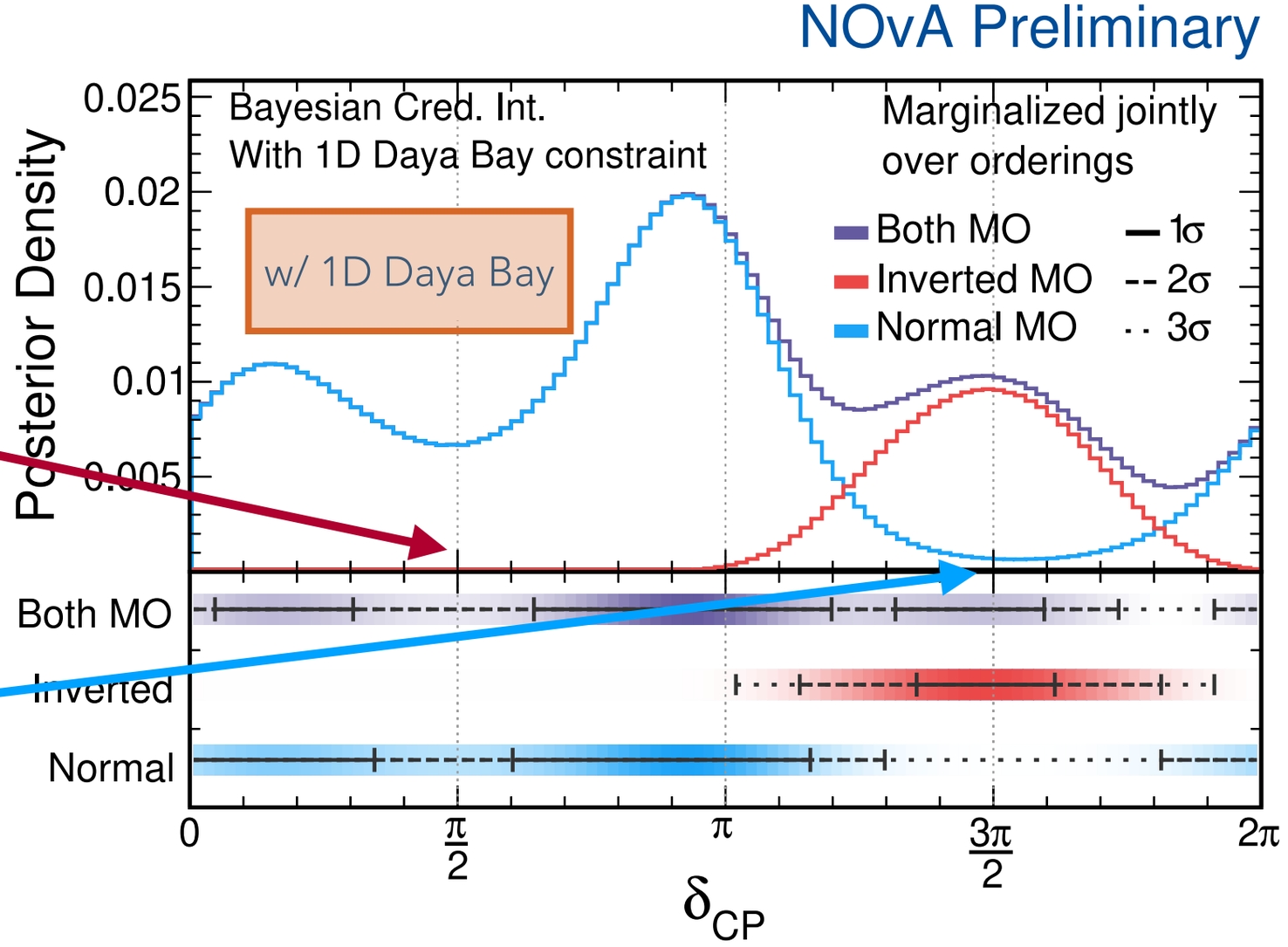




- No strong asymmetry in the rates of appearance of ν_e and $\bar{\nu}_e$.

Mass Ordering with δ_{CP}



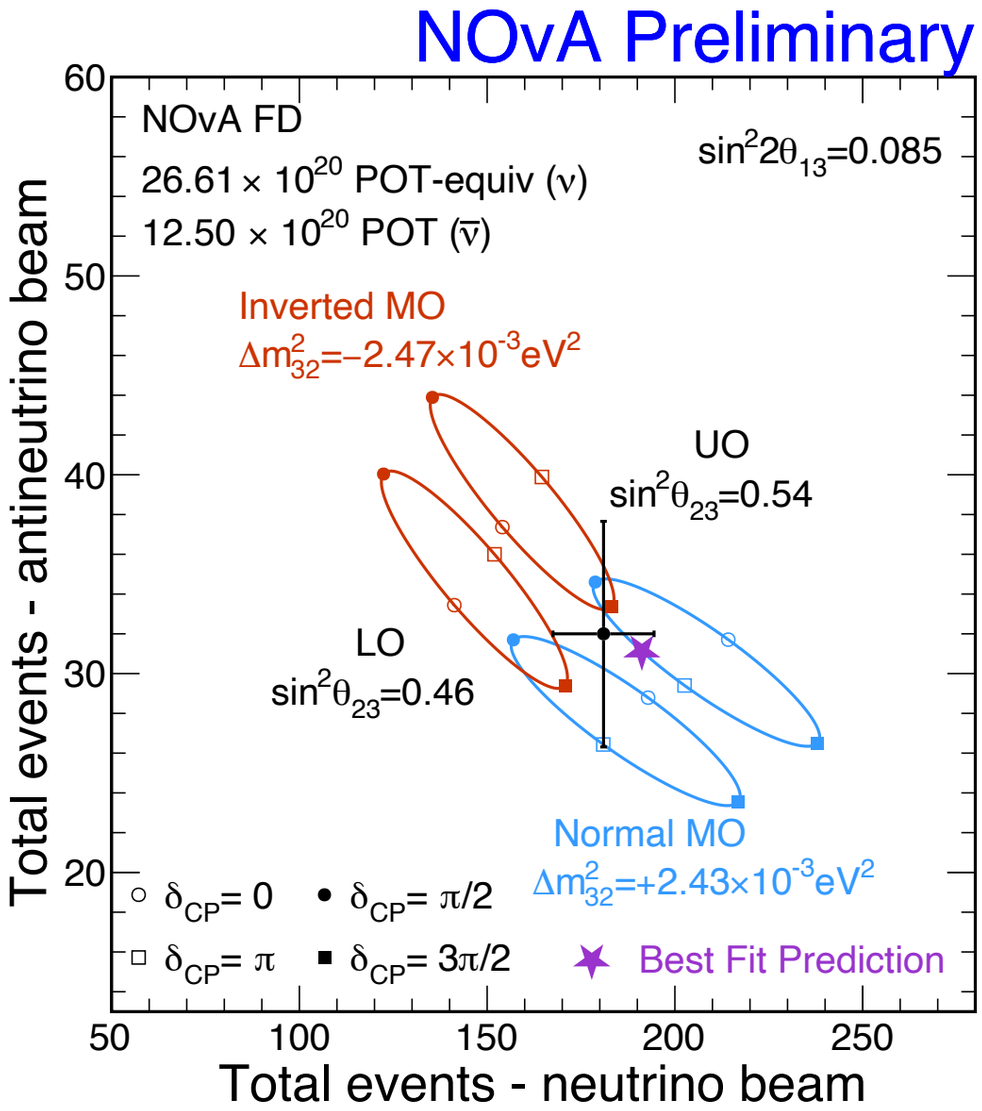


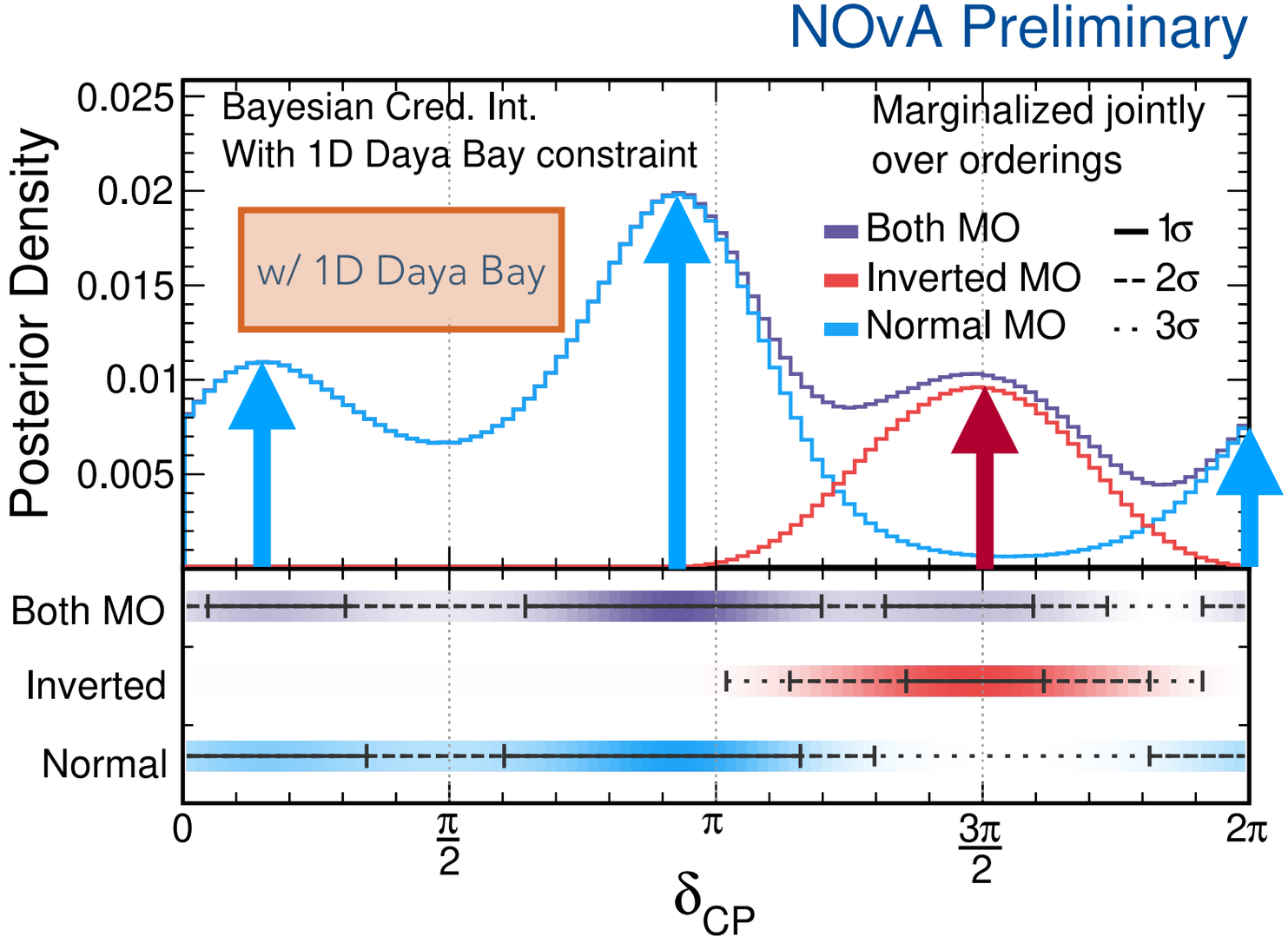
- No strong asymmetry in the rates of appearance of ν_e and $\bar{\nu}_e$.
- Disfavour ordering-δ_{CP} combinations which would produce asymmetry.

Exclude IO $\delta_{CP} = \frac{\pi}{2}$ at $> 3\sigma$

Disfavour NO $\delta_{CP} = \frac{3\pi}{2}$ at $\sim 2\sigma$

Mass Ordering with δ_{CP}

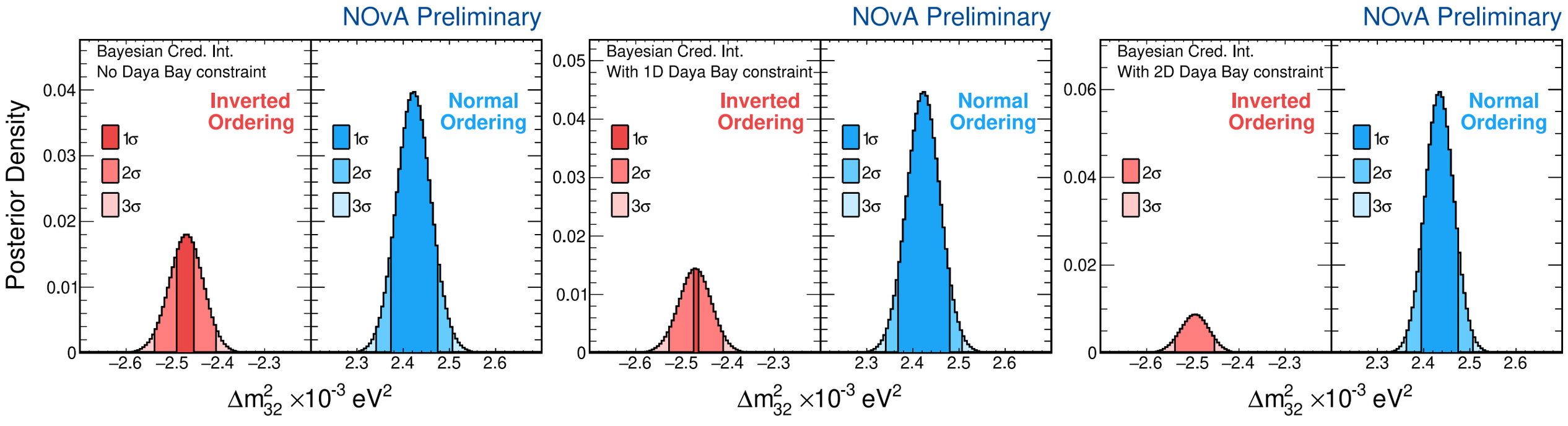




- No strong asymmetry in the rates of appearance of ν_e and $\bar{\nu}_e$.
- Disfavour ordering-δ_{CP} combinations which would produce asymmetry.

Prefer:
Normal ordering with Bayes Factor 3.2, 76% odds (frequentist significance 1.4σ).

Mass Ordering with δ_{CP}



θ_{13} **unconstrained** (NOvA only)	**Daya Bay 1D θ_{13} constraint**	**Daya Bay 2D $(\Delta m^2_{32}, \theta_{13})$ constraint**
BF: 2.2, 69% odds	BF: 3.2, 76% odds (1.4σ*)	BF: 6.9, 87% odds (1.6σ*)

Mass ordering preference is strengthened by the application of the reactor constraint. Expected: Phys. Rev. D 72: 013009, 2005

*Frequentist significance.

Summary

- First new 3 flavour neutrino oscillation result from NOvA since 2020:
  - Doubled neutrino-mode dataset and have analysed 10 years of neutrino and antineutrino data.
  - Updated simulation including improved light response model and neutron propagation uncertainty.
  - Expanded our selection with a new low-energy electron neutrino candidate sample.
  - The **most precise single experiment measurement of Δm^2_{32} (1.5%)**.
  - Data favours a region where **matter and CP violation effects are degenerate**.

- Strong synergy with reactor measurements:
  - Constraint on θ_{13} enhances upper octant preference (69% odds).
  - Constraint on Δm^2_{32} enhances normal ordering preference (87% odds).

- Additional data from current and upcoming oscillation experiments will help to untangle degeneracies.

Questions?

Back-up

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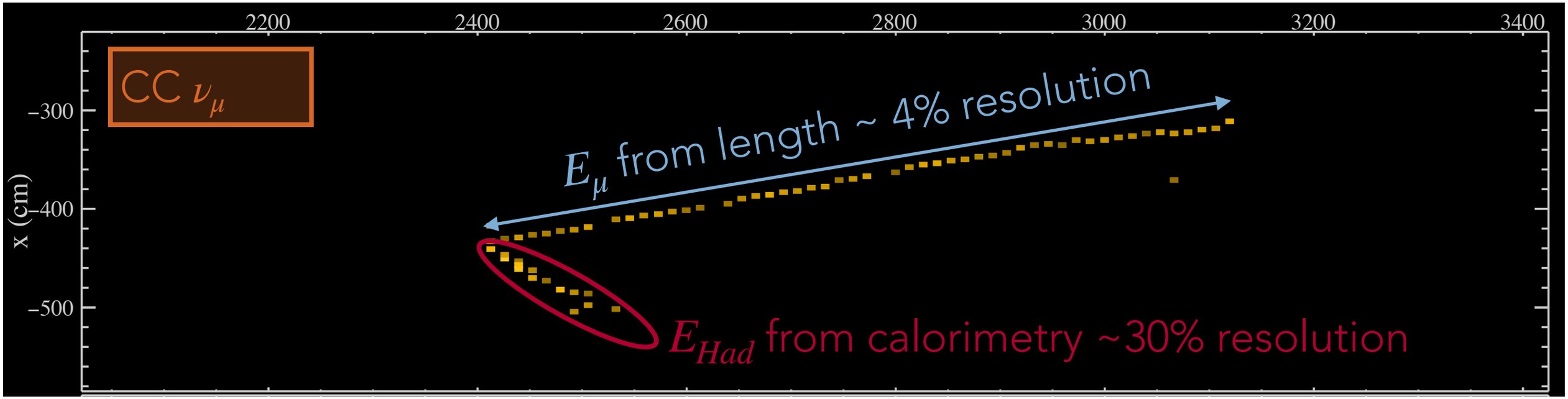
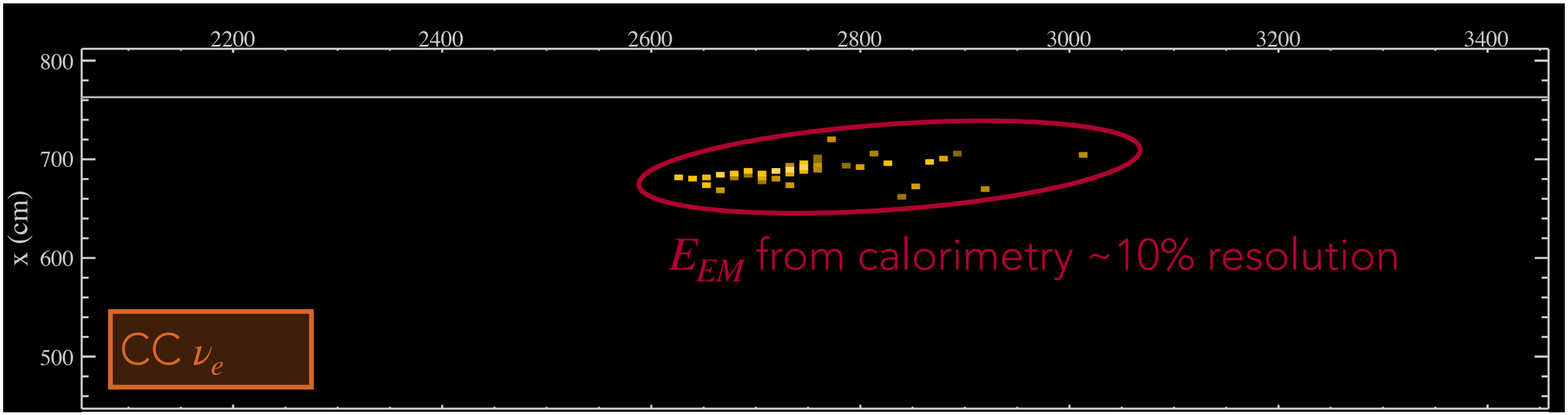
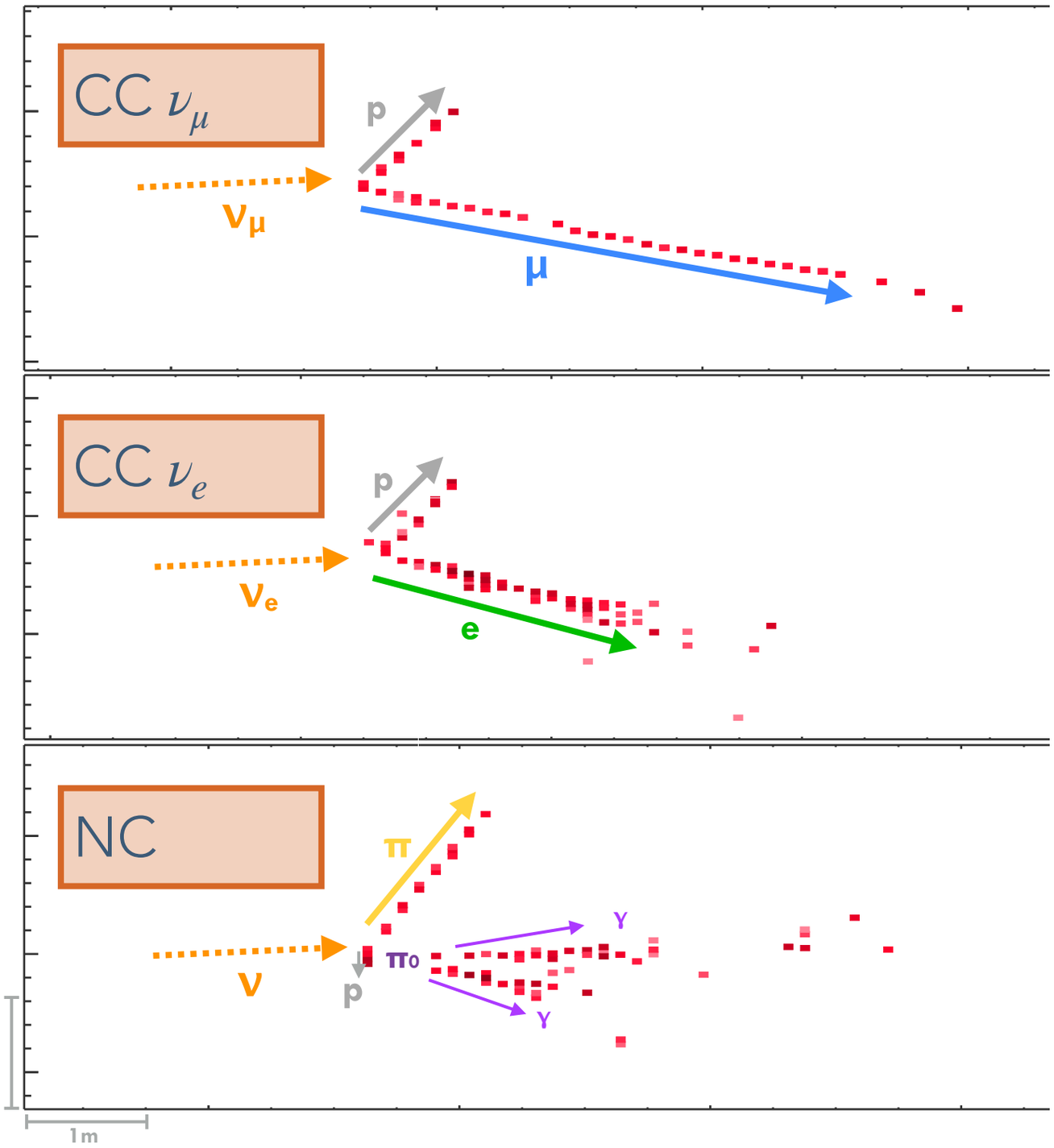
Energy Reconstruction



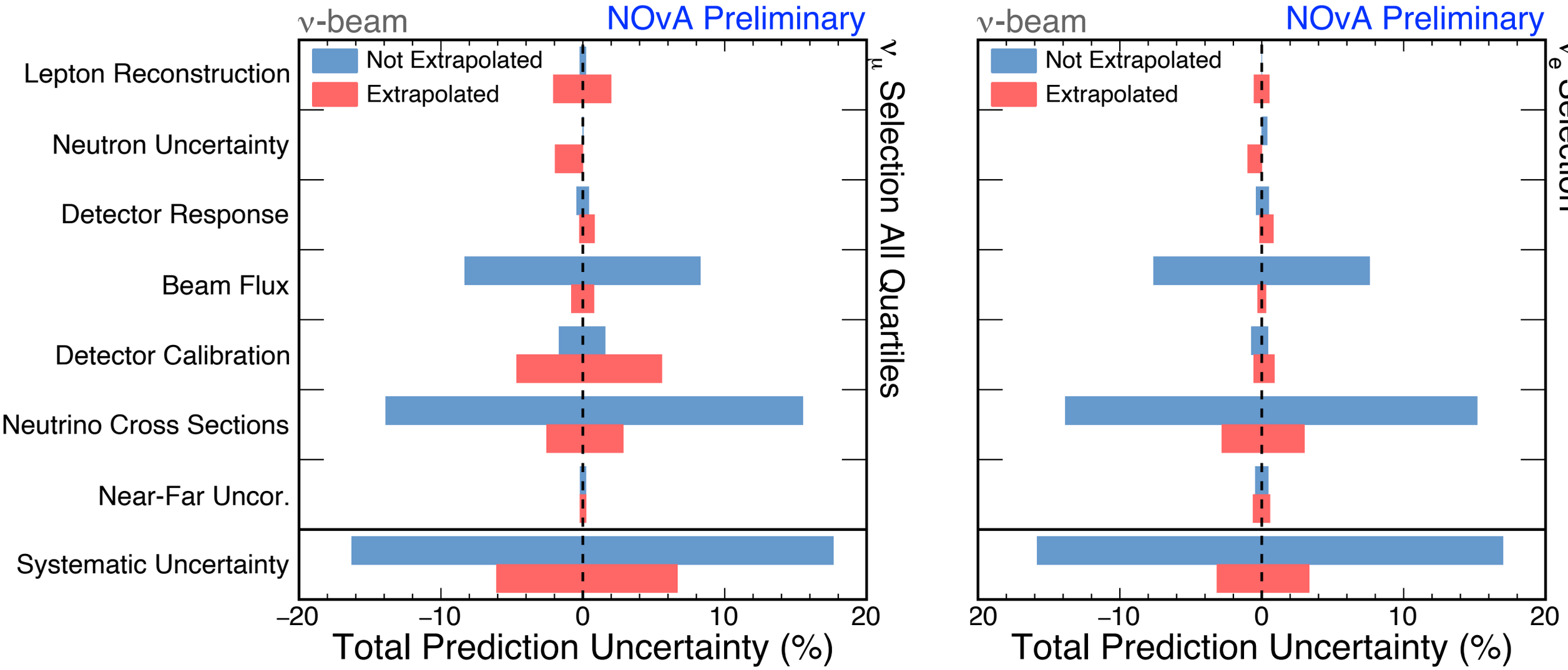


Selecting & Identifying Neutrinos



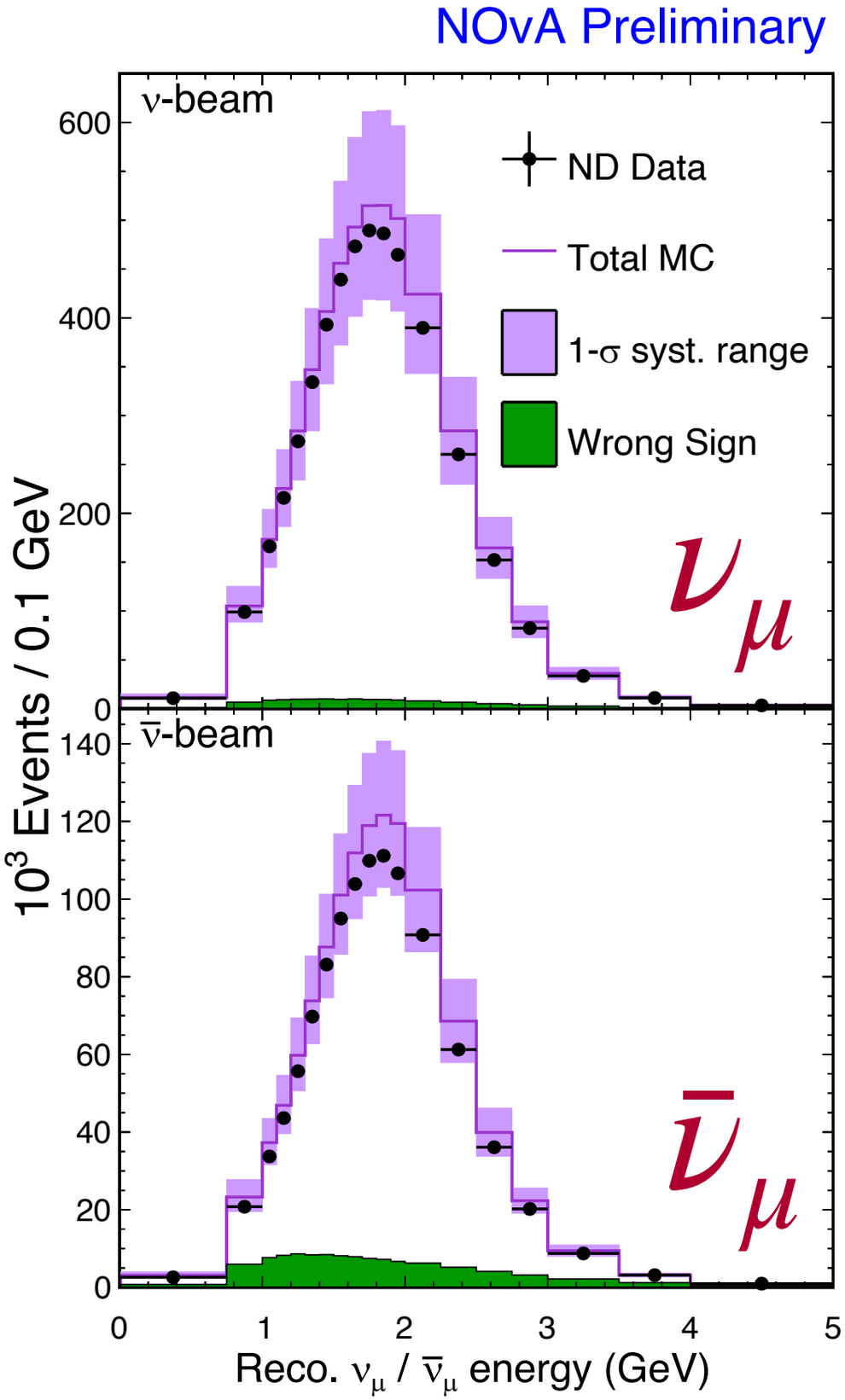
- Use **convolutional neural network** technique from deep learning.
  - NOvA was first HEP experiment to use CNN for PID.
- Successive layers of "feature maps":
  - Create many variants of original image which enhance different features.
  - Variations which are best for enhancing most important features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

Impact of Systematic Uncertainty



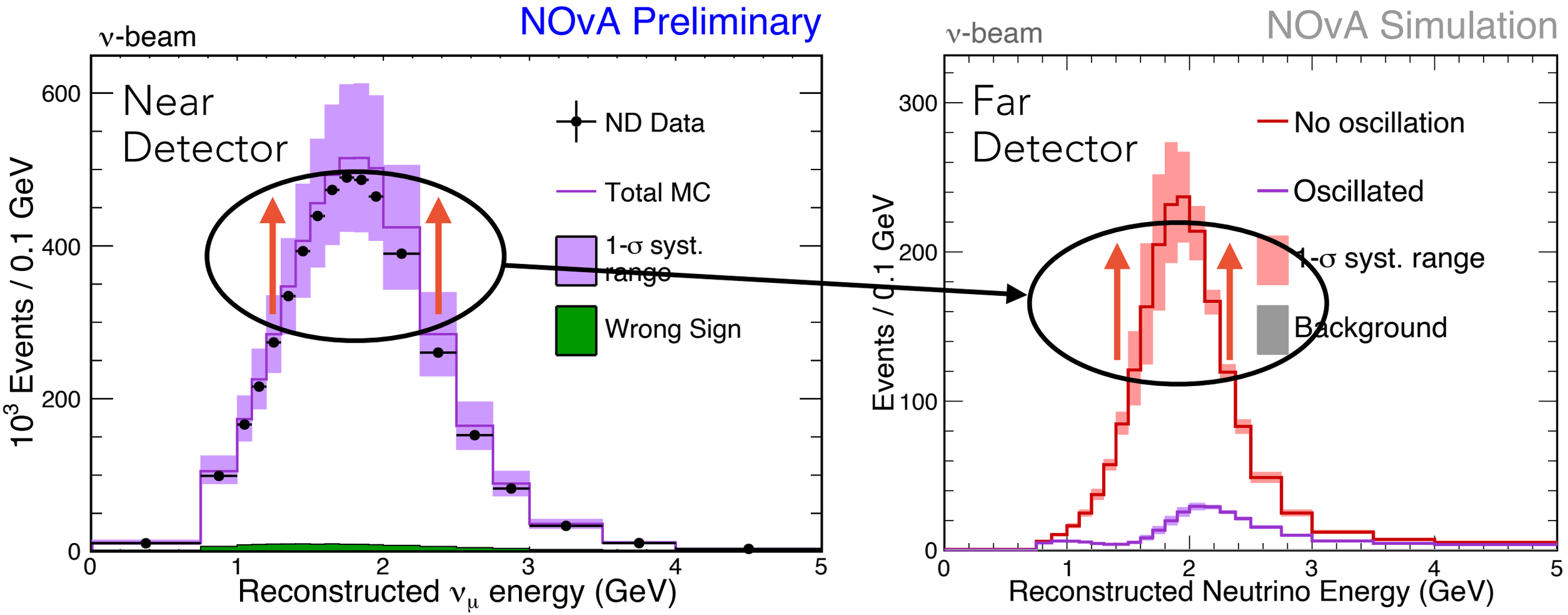
- Overall systematic reduction is 10 to 15 percentage points.
- Systematics related to neutron propagation and detector response are now subdominant.

Near Detector, ν_μ



- 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 ν_μ and the ν_e signal spectra at the Far Detector.
- Appearing ν_e's are still ν_μ's at the Near Detector.

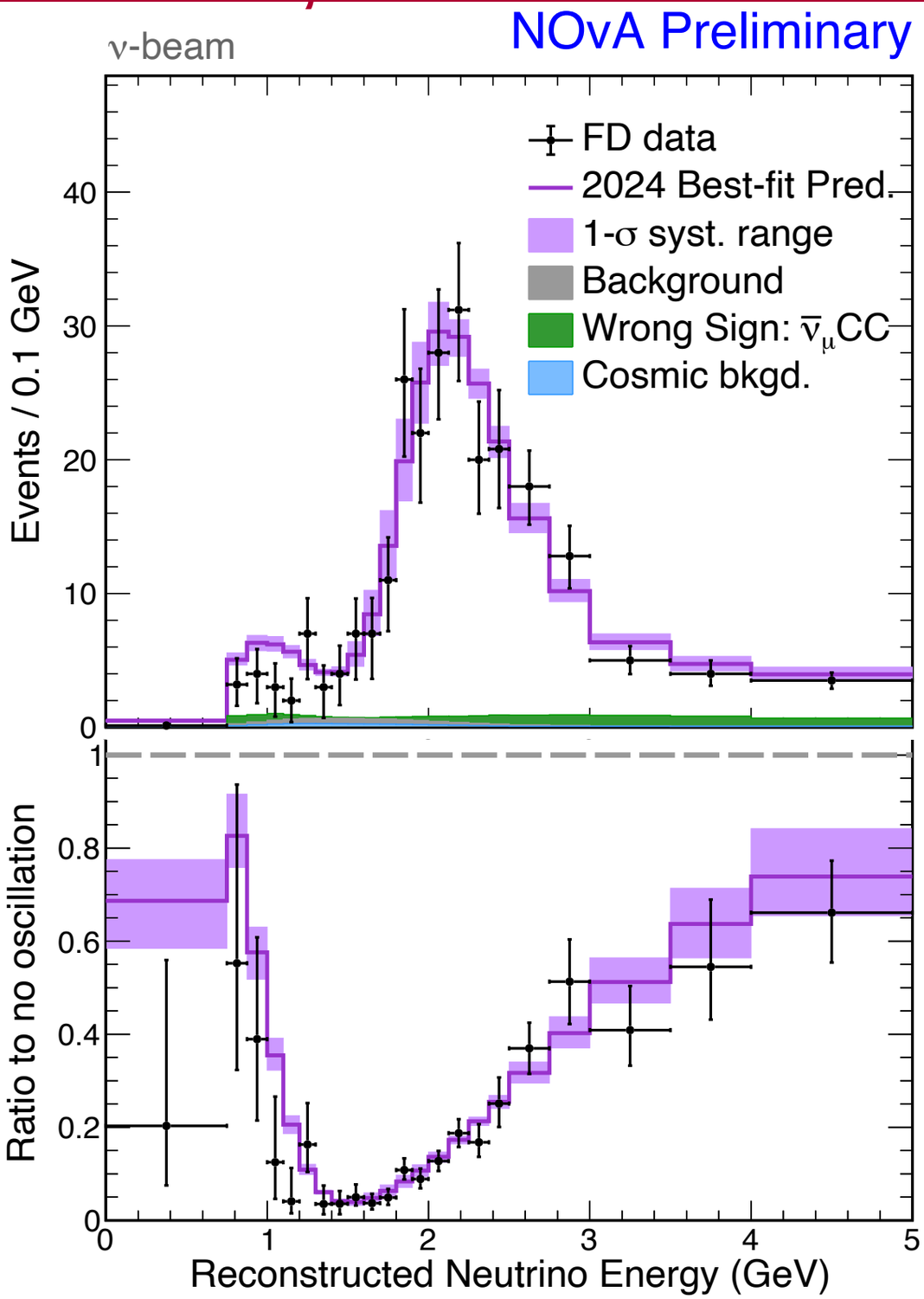
Extrapolation



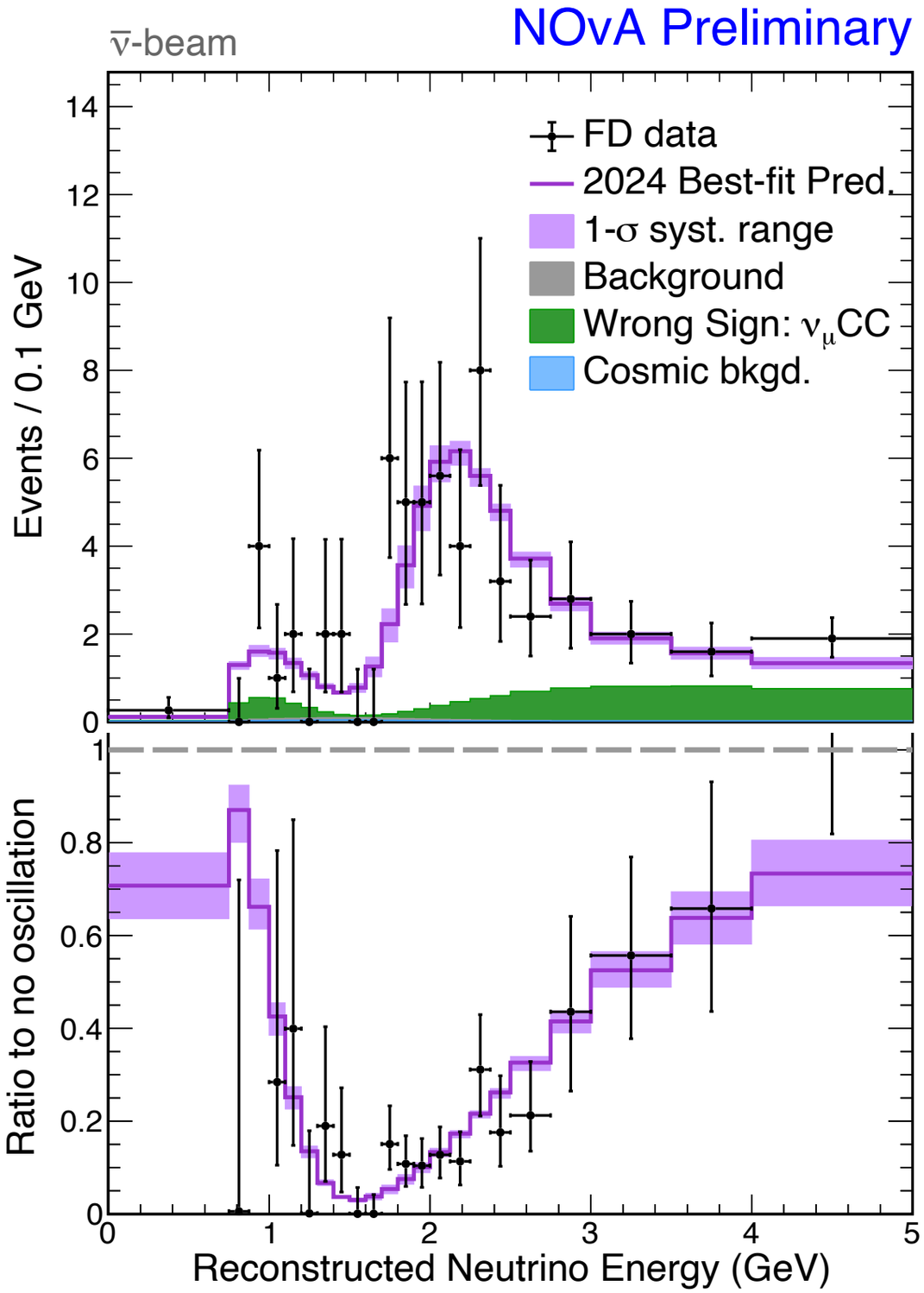
- Observe data-MC differences at the ND, use them to modify the FD MC.

- Significantly reduces the impact of uncertainties correlated between detectors.
  - Especially effective at rate effects like the flux (7% to 0.3%).

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

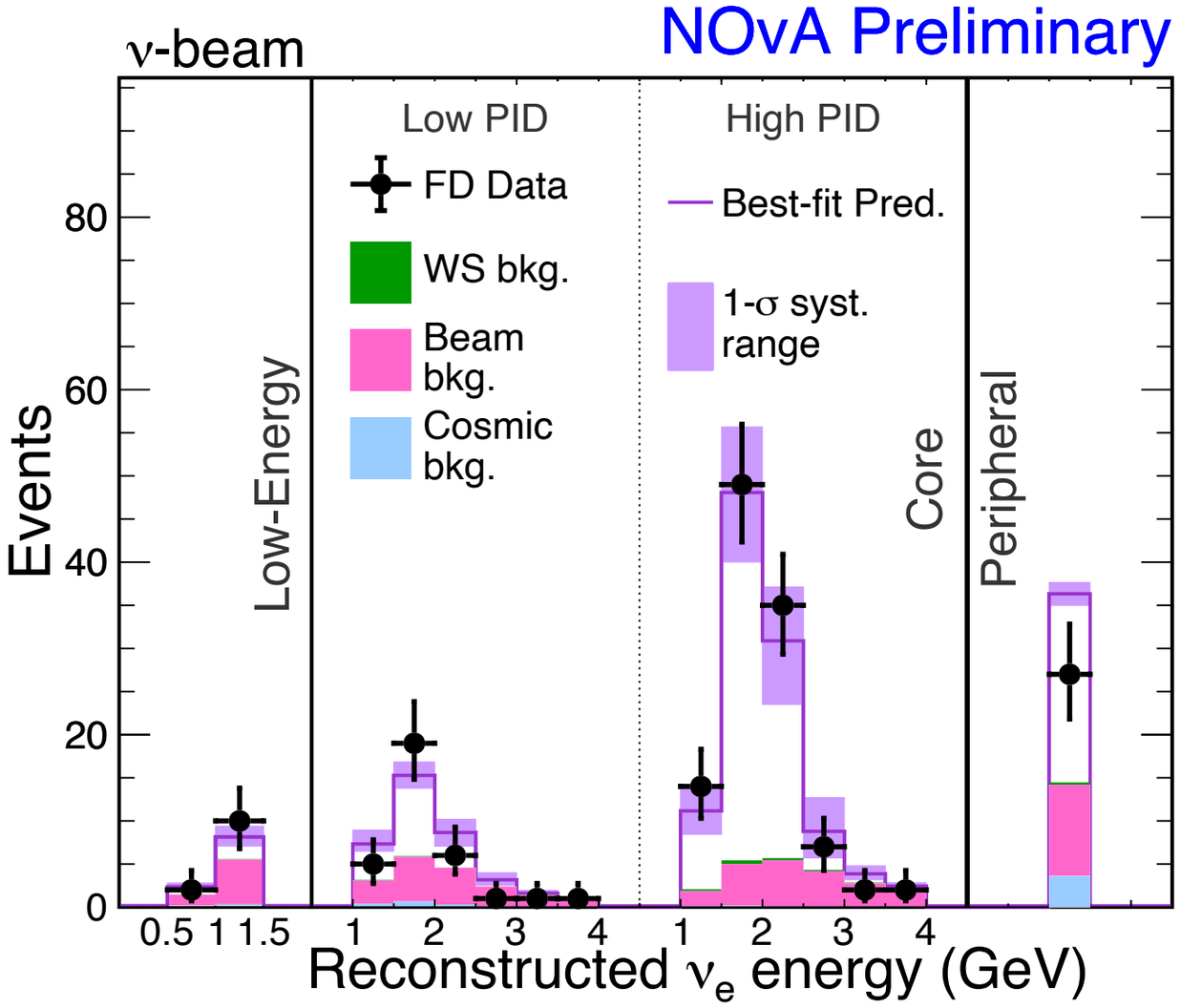


384 events, 11.3 background

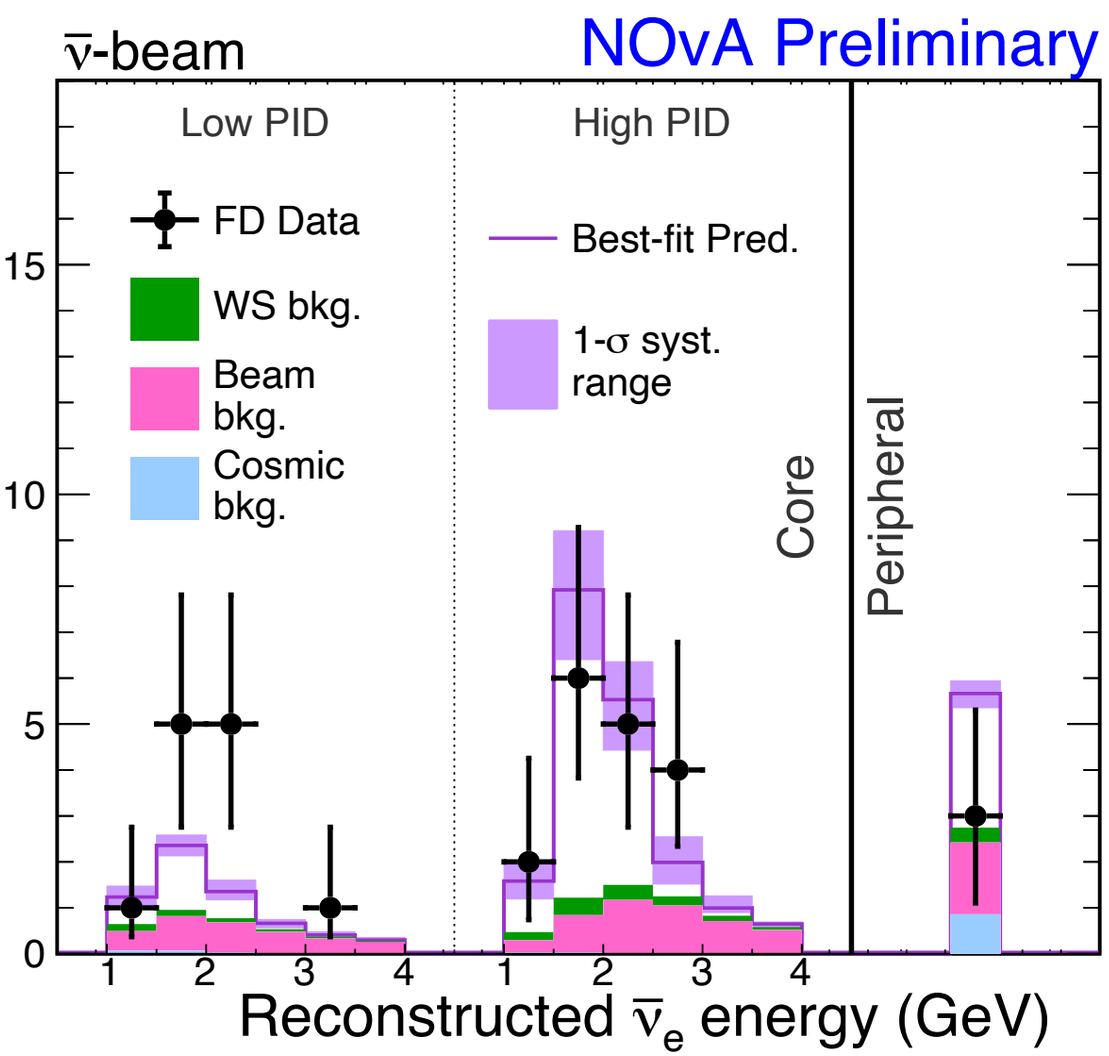


106 events, 1.7 background

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

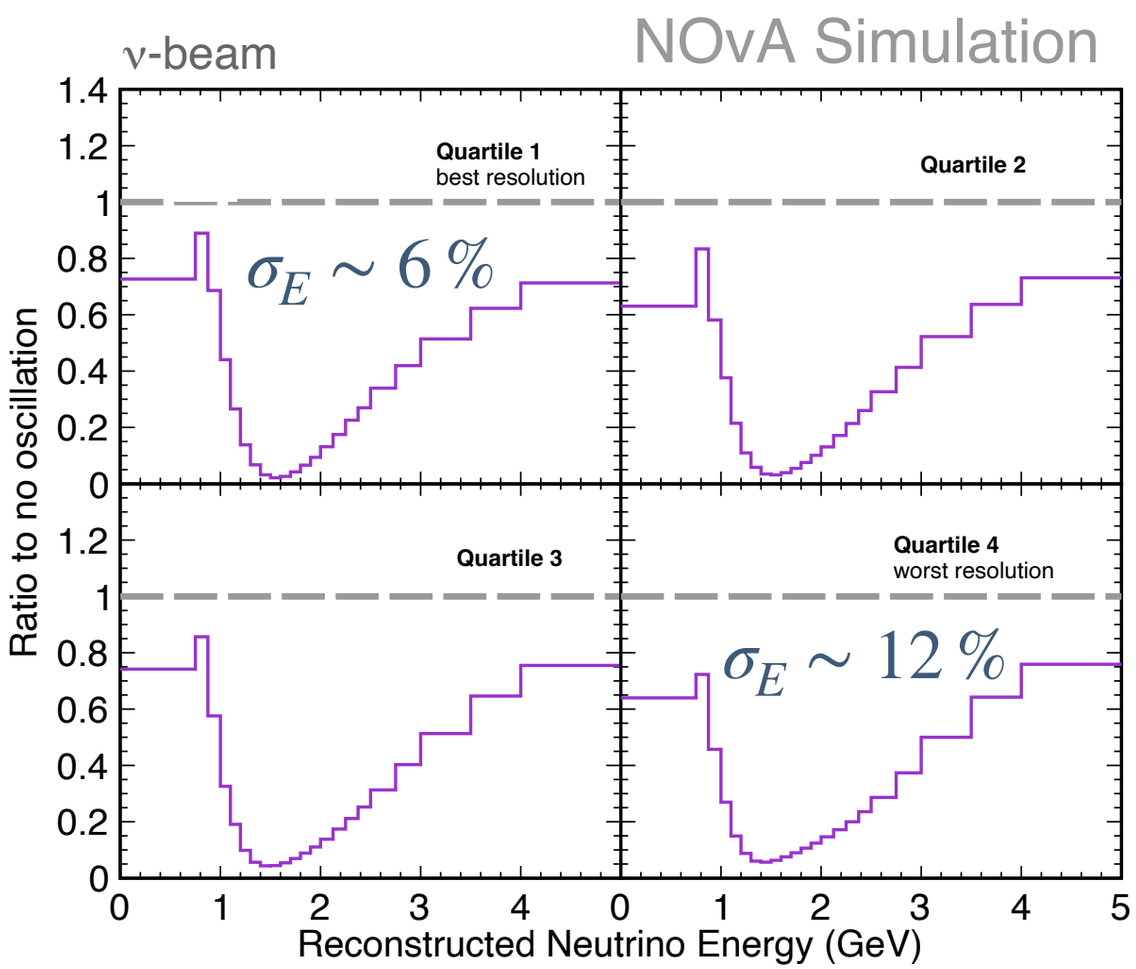


Total Observed	181	Range
Total Prediction	186.2	119-250
Wrong-sign	1.8	0.6-1.7
Beam Bkgd.	53.7	
Cosmic Bkgd.	6.2	
Total Bkgd.	61.7	61-63



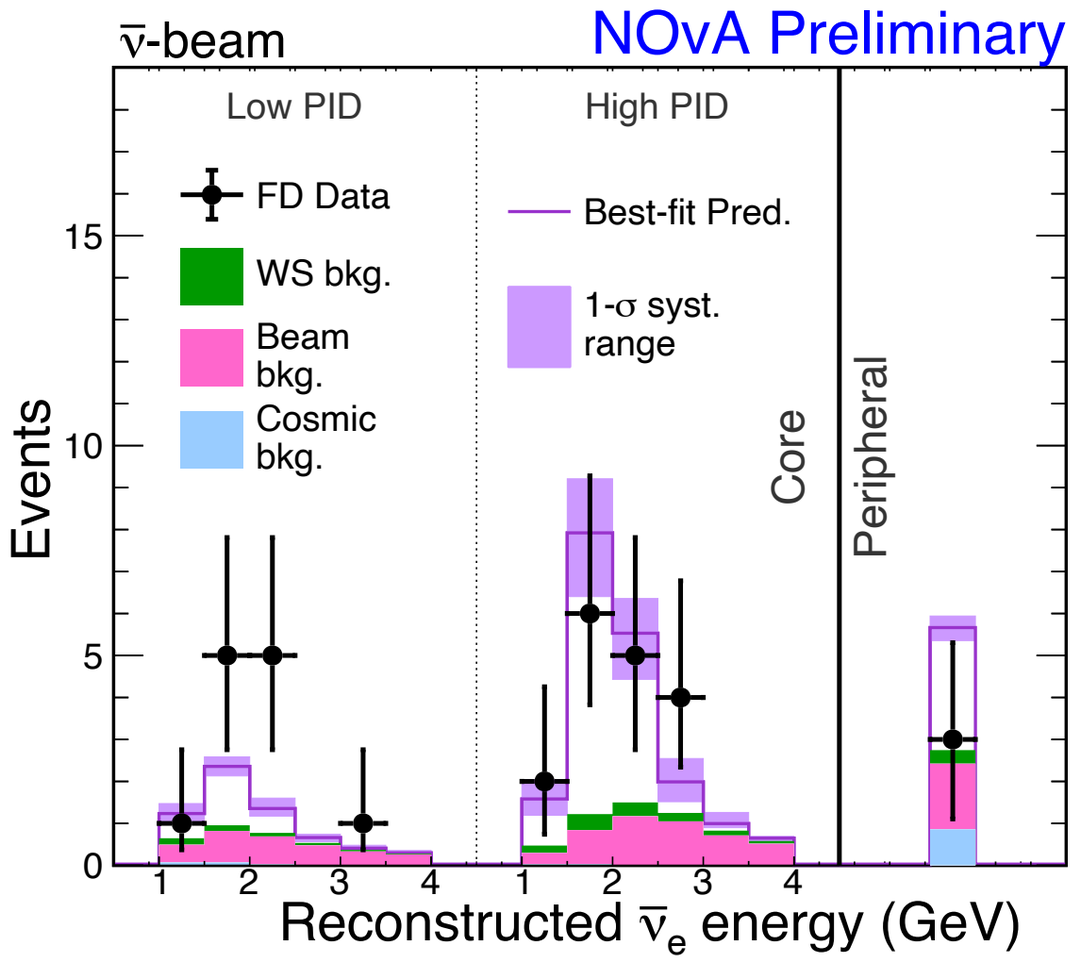
Total Observed	32	Range
Total Prediction	30.4	28-38
Wrong-sign	2.1	1.0-3.2
Beam Bkgd.	9.0	
Cosmic Bkgd.	1.1	
Total Bkgd.	12.2	11-13

Improving Sensitivity to Oscillations



ν_μ

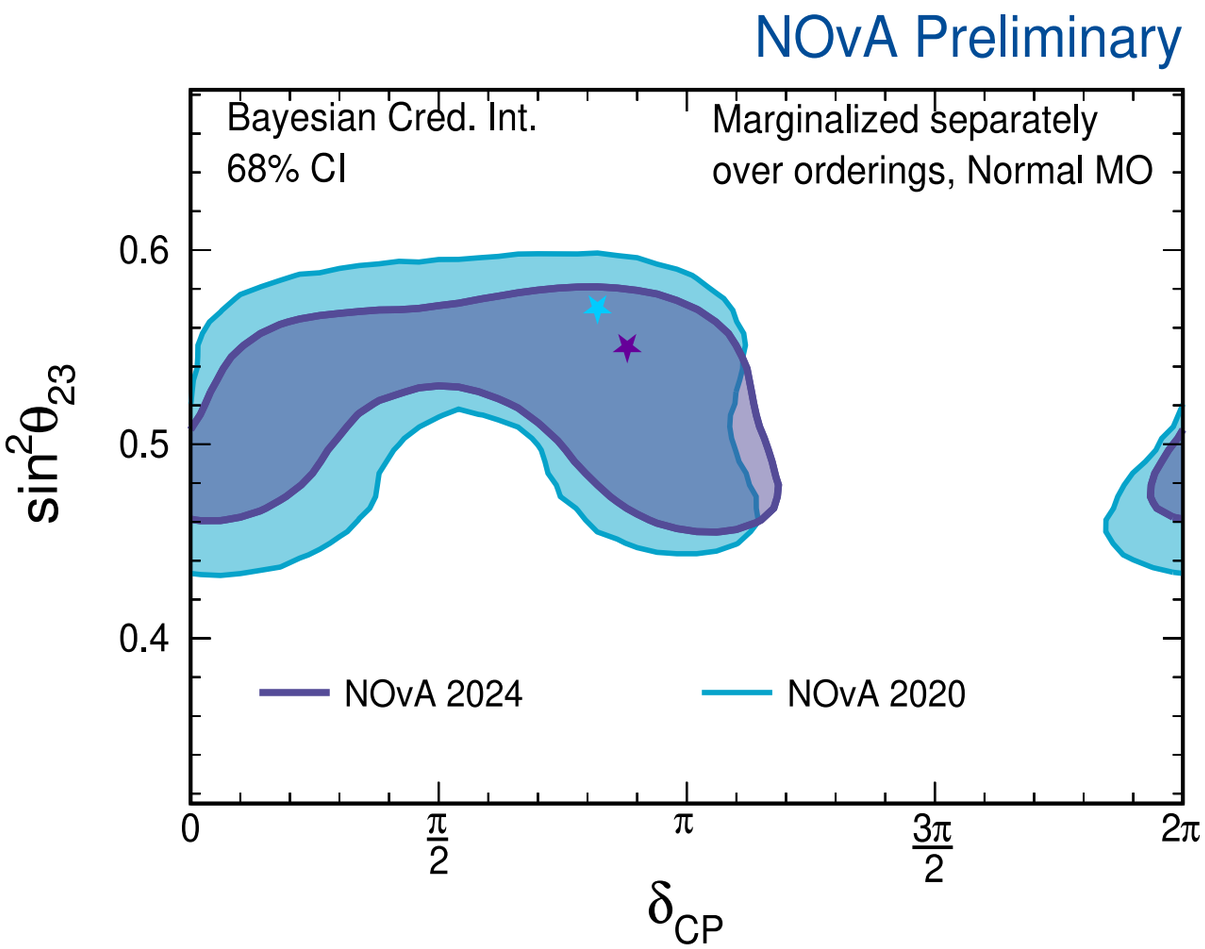
- Sensitivity depends primarily on the shape of the energy spectrum.
- Bin by energy resolution: bins of hadronic energy fraction.

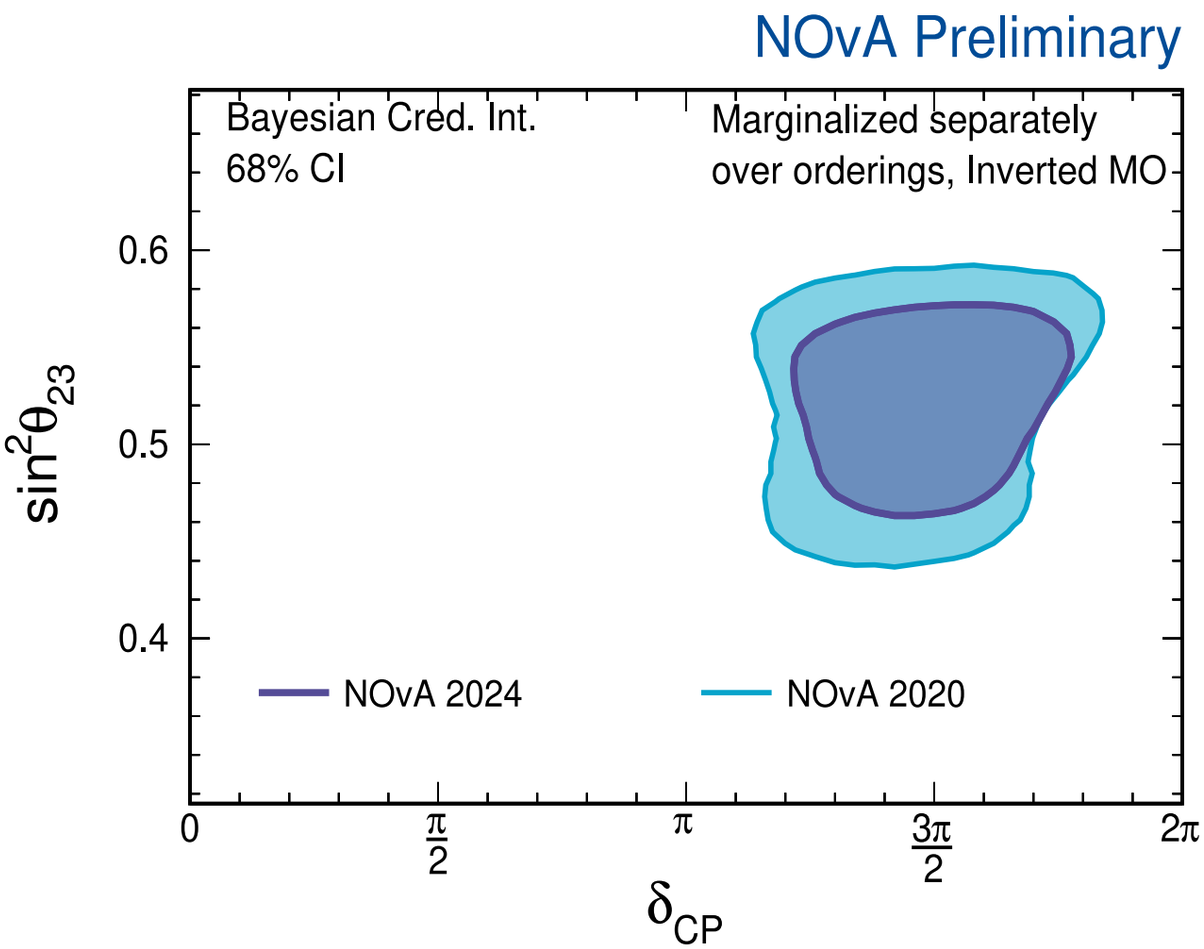


ν_e

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

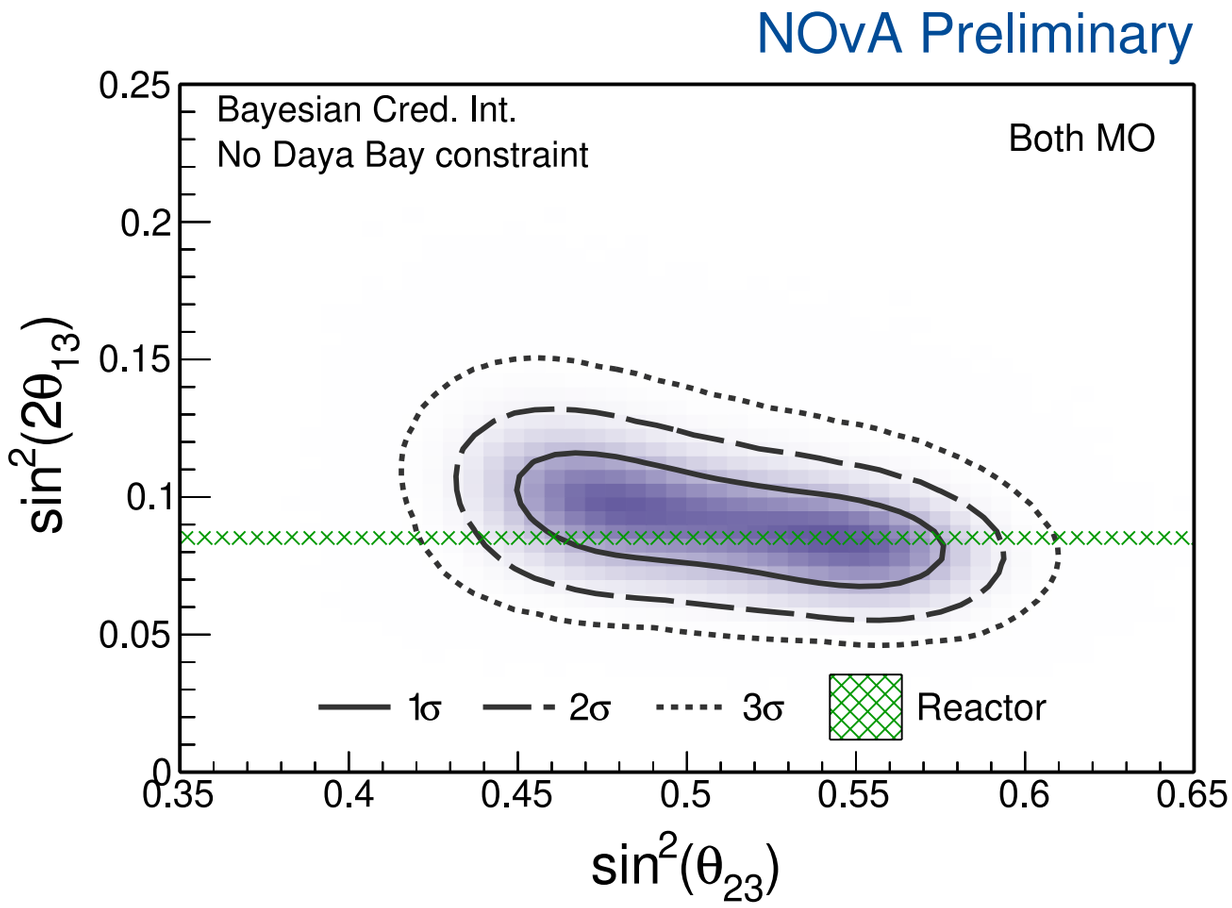
Mass Ordering with θ_{23} & δ_{CP}

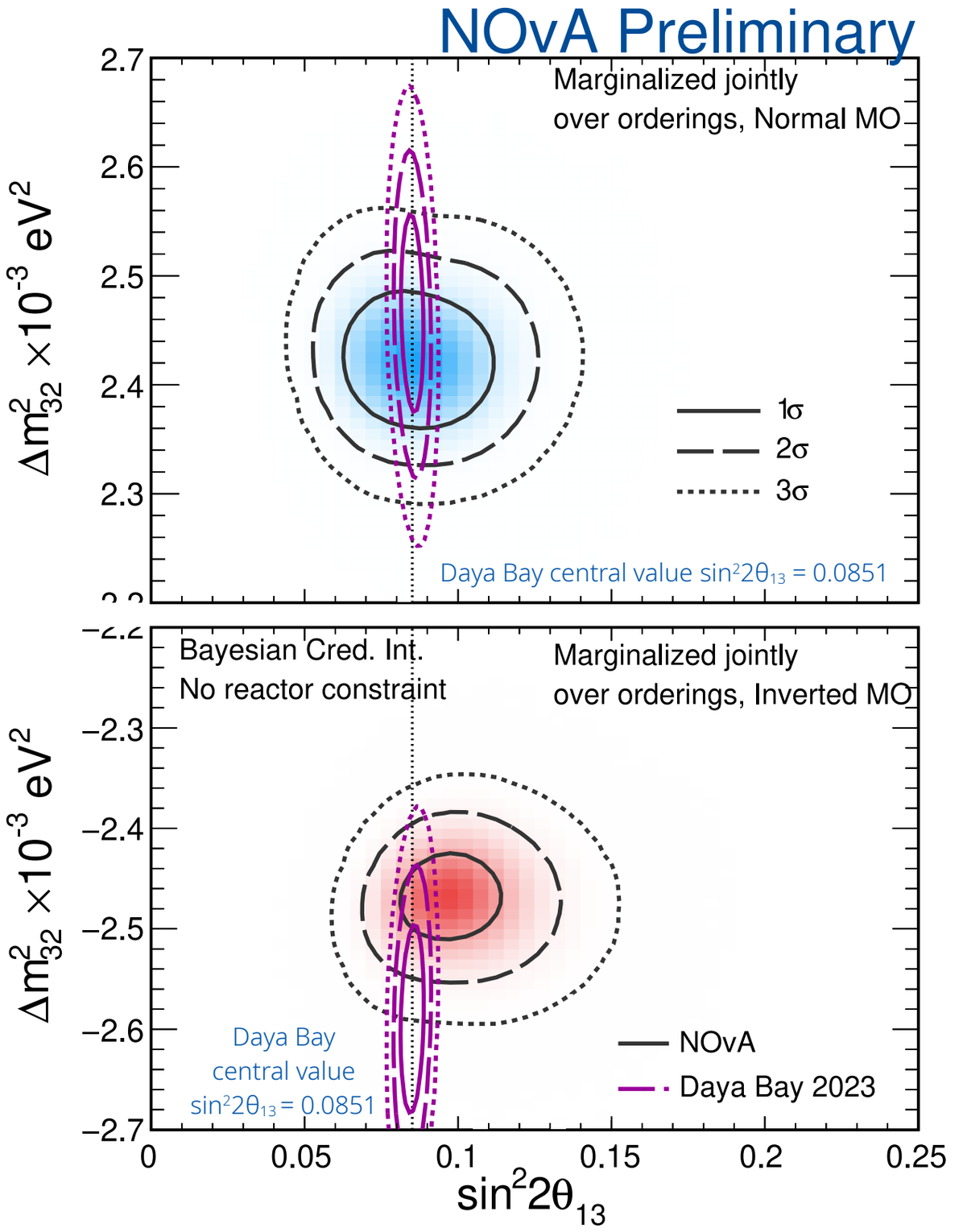




- Consistency with previous result (*different reactor constraints used).
- Tighter contours almost everywhere.

Daya Bay / NOvA Correlations





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