3-FLAVOUR OSCILLATION RESULTS FROM NOvA WITH 10 YEARS OF DATA

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RAL PPD Seminar Series
November 13th, 2024

Queen Mary
University of London

Neutrinos 101

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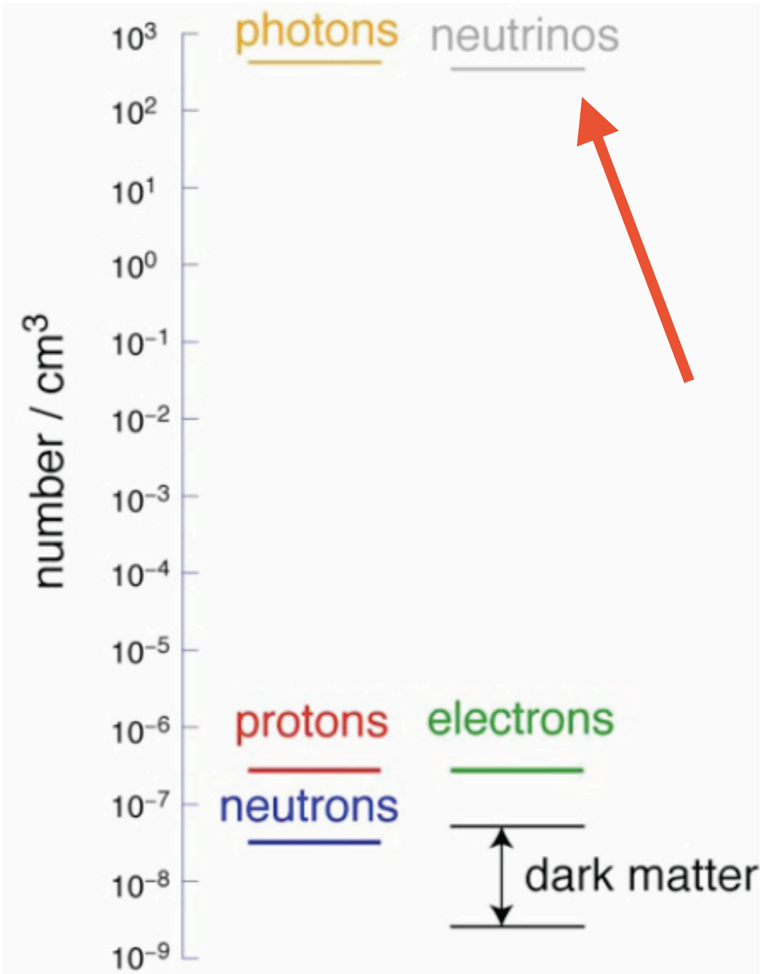
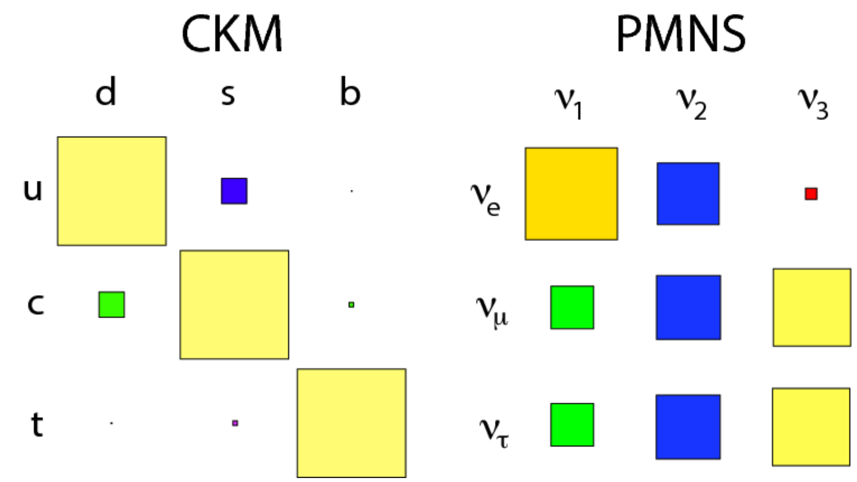
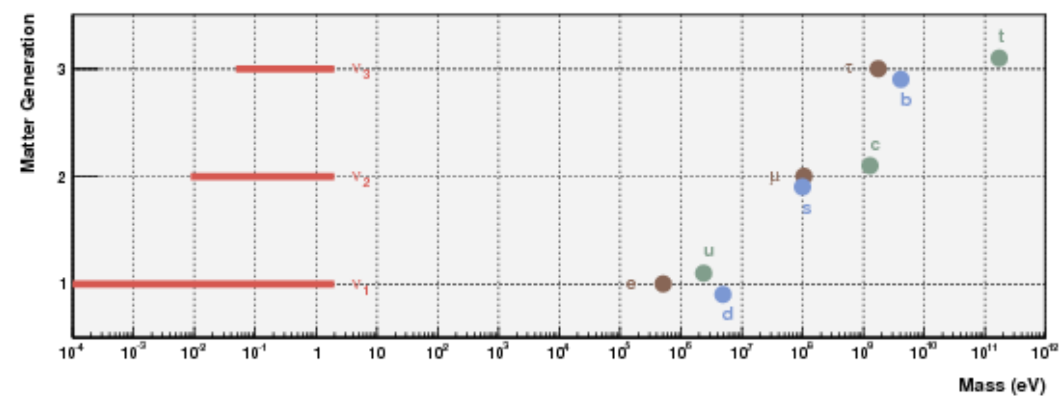
Why Study Neutrinos?







- 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!

Neutrino Oscillations 101

- Create in one flavour (ν_μ), but detect in another (ν_e).

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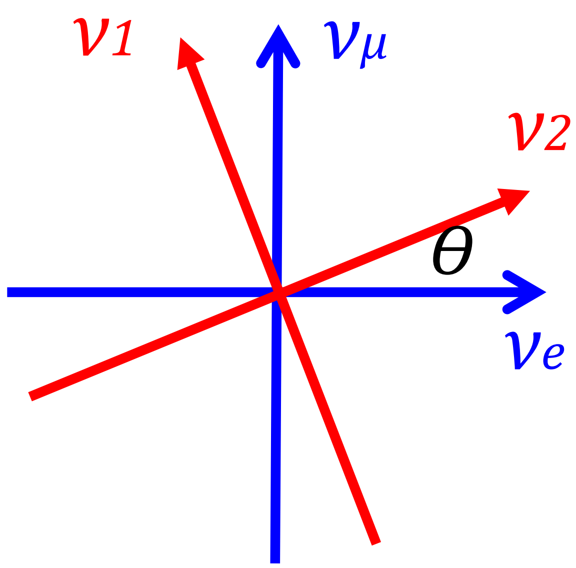
- Each flavour is a superposition of different masses.

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



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3 flavours →

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

3-flavour Neutrino Oscillations

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

ν_e ν_μ ν_τ

ν_1 ν_2 ν_3

PMNS matrix

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

3 angles, **1** complex phase.

3-flavour Neutrino Oscillations

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

ν_e ν_μ ν_τ

ν_1 ν_2 ν_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. → θ_{23} θ_{13} δ θ_{12}

3-flavour Neutrino Oscillations

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

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

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

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

"Atmospheric" sector	"Reactor" sector	"Solar" sector
θ_{23}	θ_{13} δ	θ_{12}

3 angles, **1** complex phase. →

3-flavour Neutrino Oscillations

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

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

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

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

"Atmospheric" sector — θ_{23}

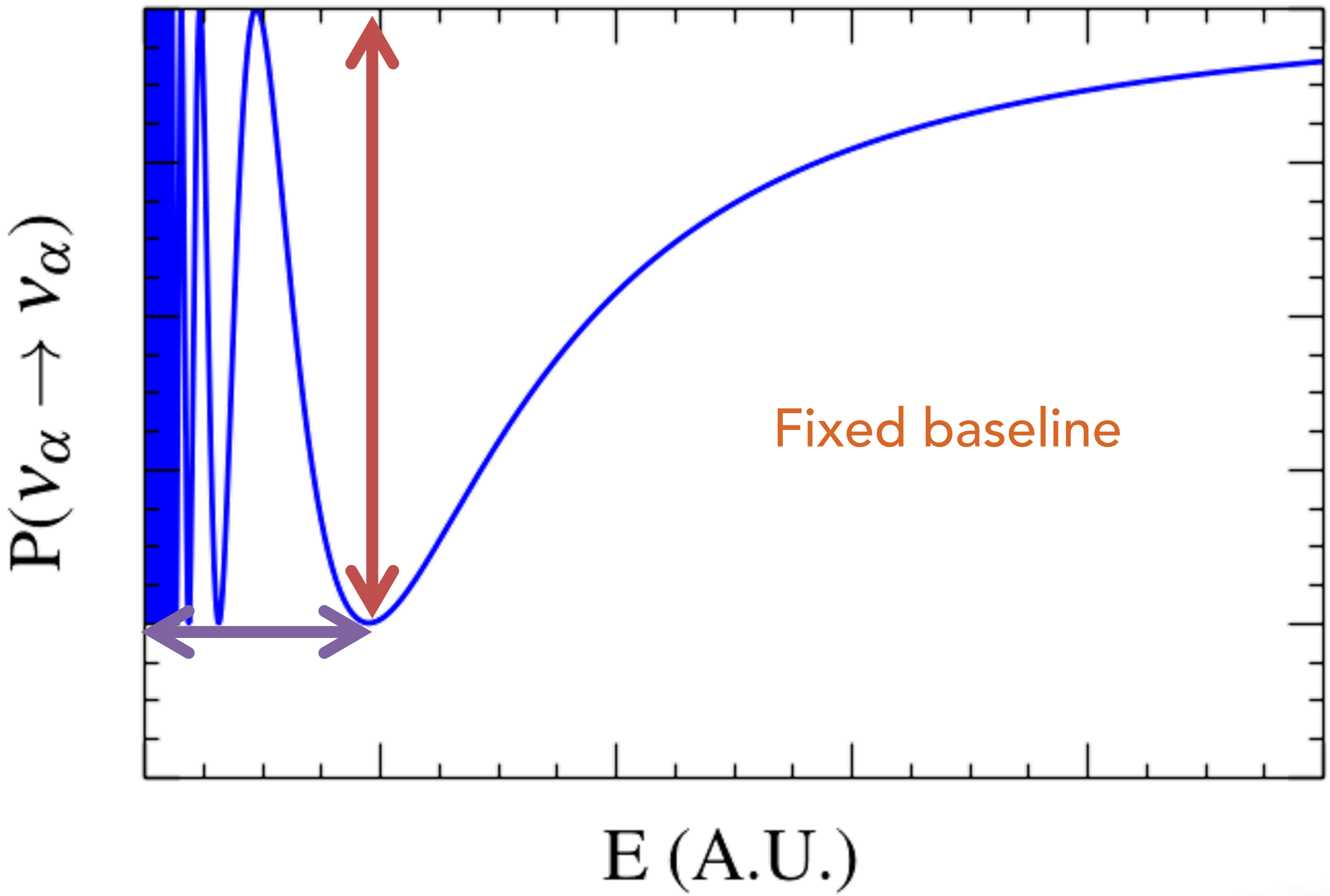
"Reactor" sector — θ_{13} δ

"Solar" sector — θ_{12}

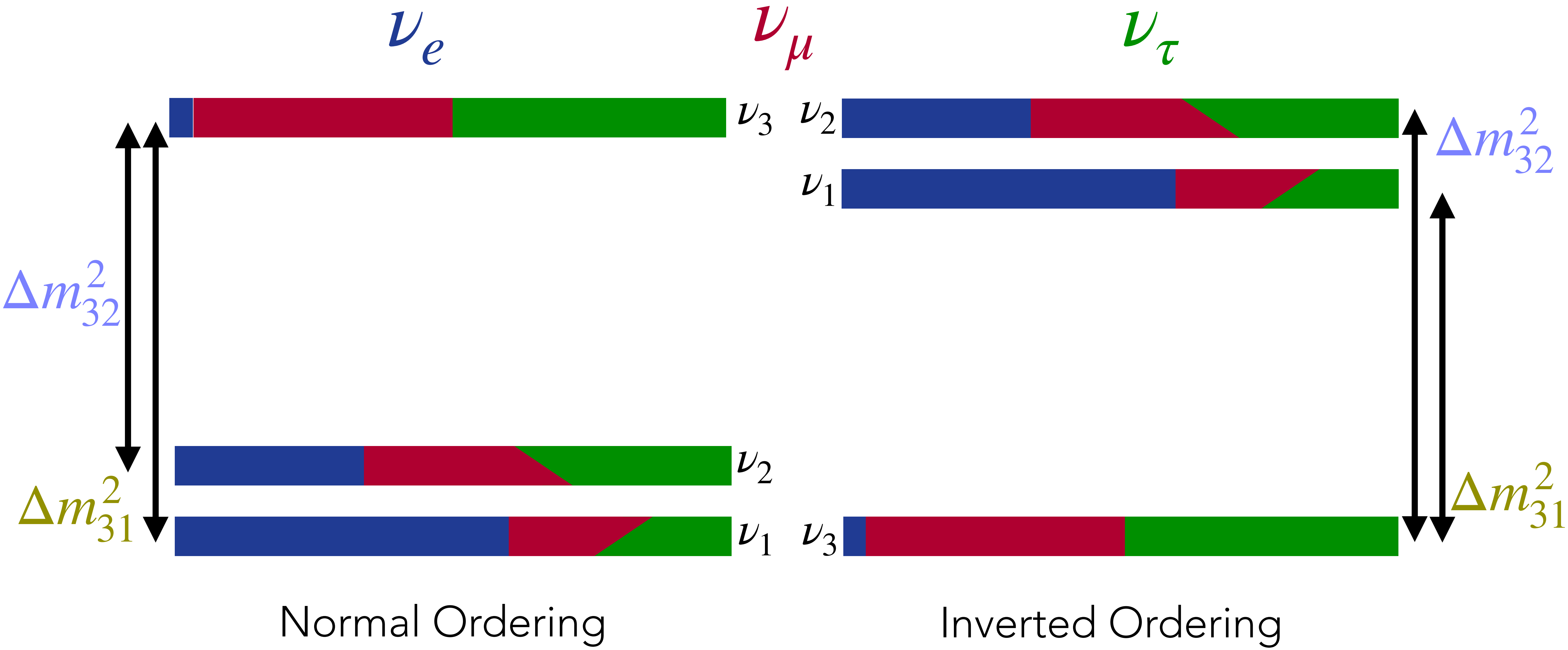
For given splitting, there is an L/E defining maximum (minimum) transition probability.

How to: Disappearance

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

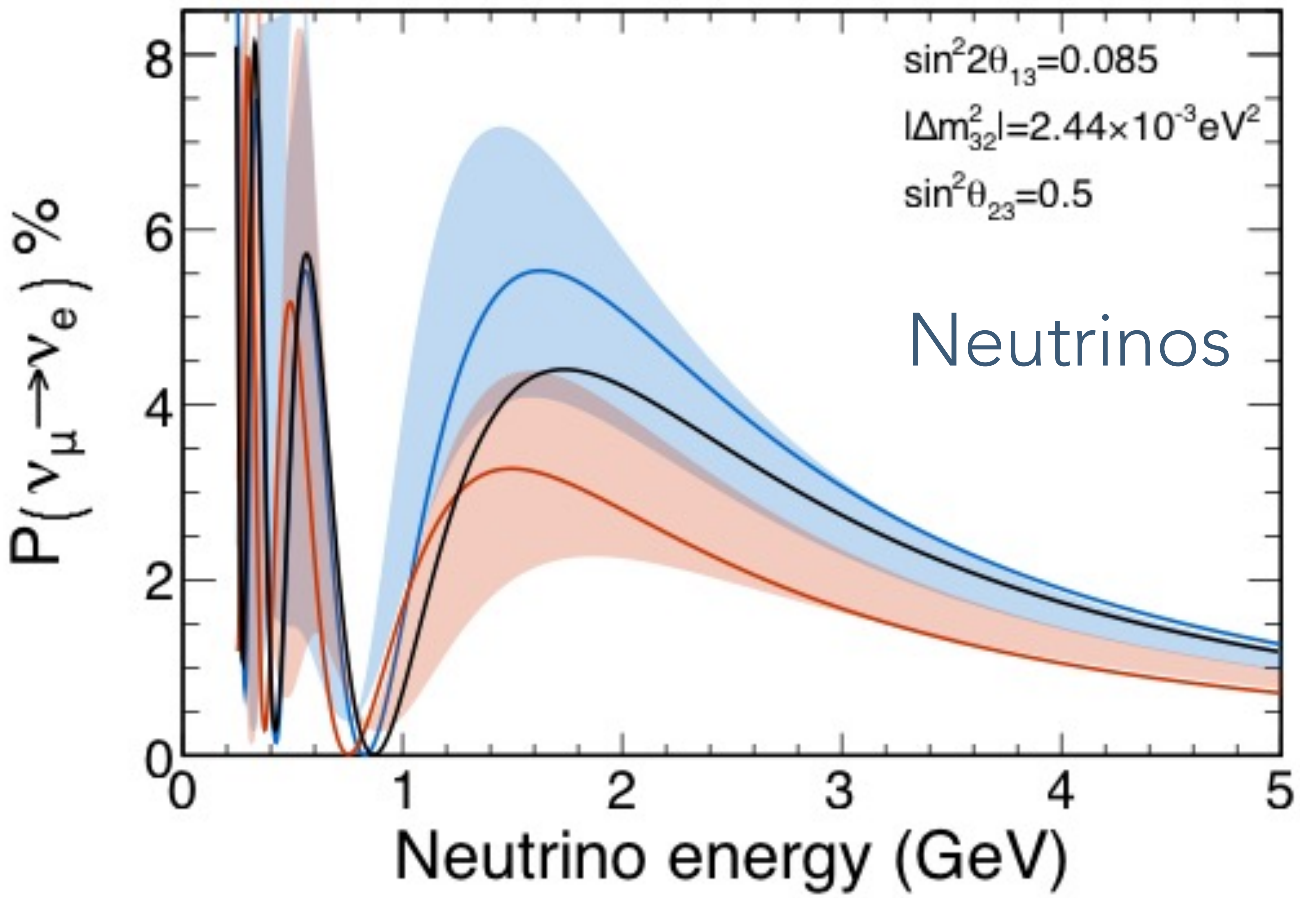


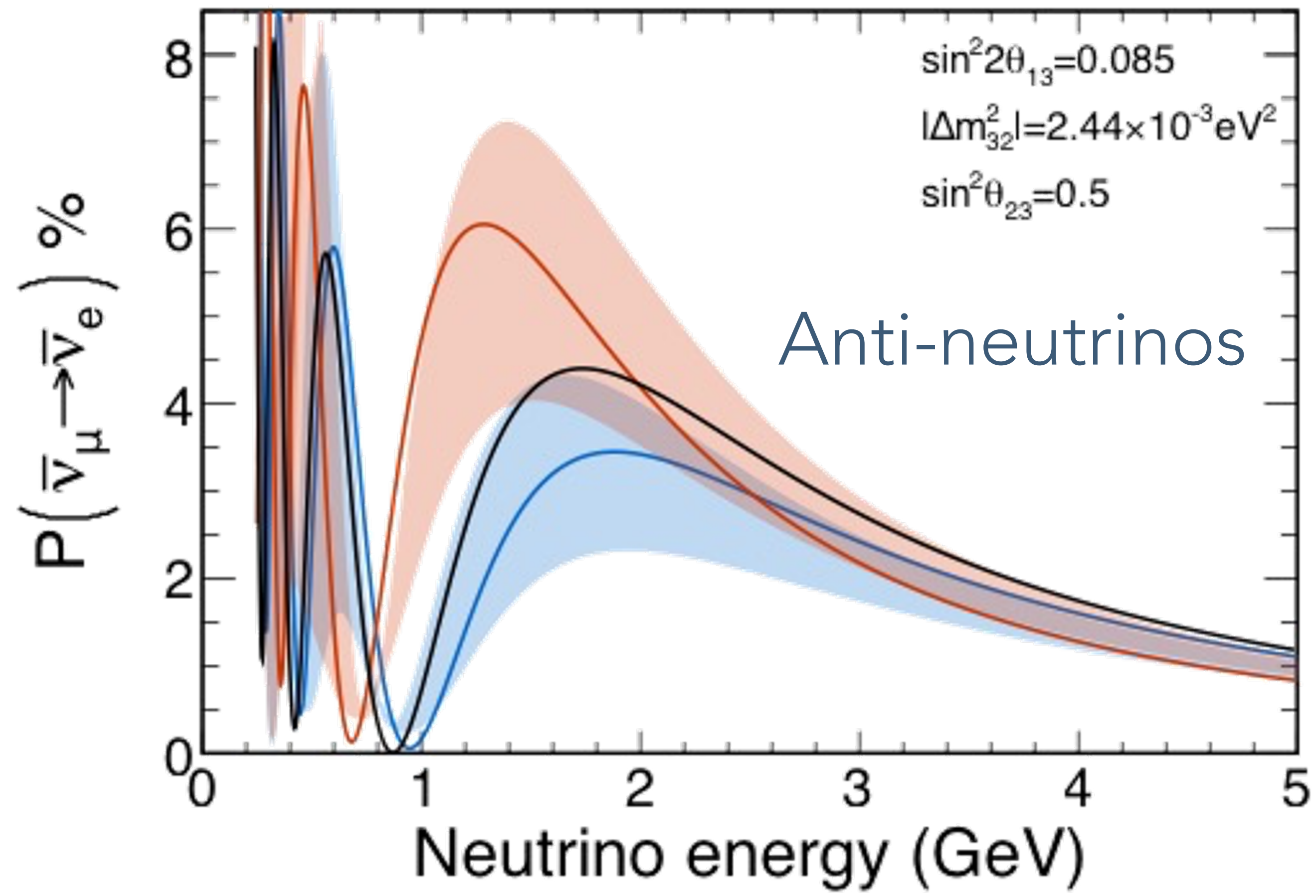
Mass Ordering & MSW Effect



- 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!



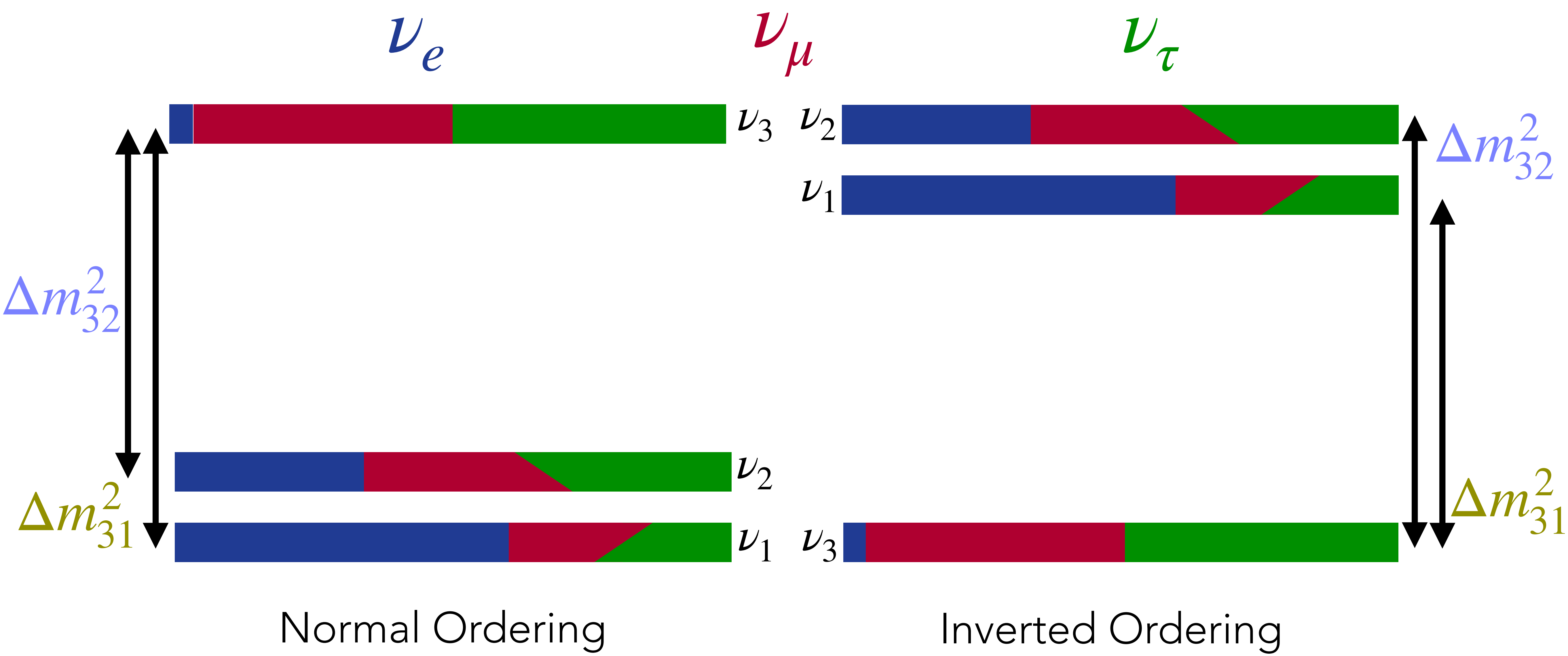


Normal Ordering **Vacuum** **Inverted Ordering**

- $\nu_\mu \rightarrow \nu_e$ enhanced in NO, suppressed in IO.
- $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ enhanced in IO, suppressed in NO.

Open Questions: Appearance

- $\nu_\mu \to \nu_e$ depends on:
  - Mass ordering and matter effects.
  - Octant of θ_{23}.
  - CP phase: δ_{CP}.



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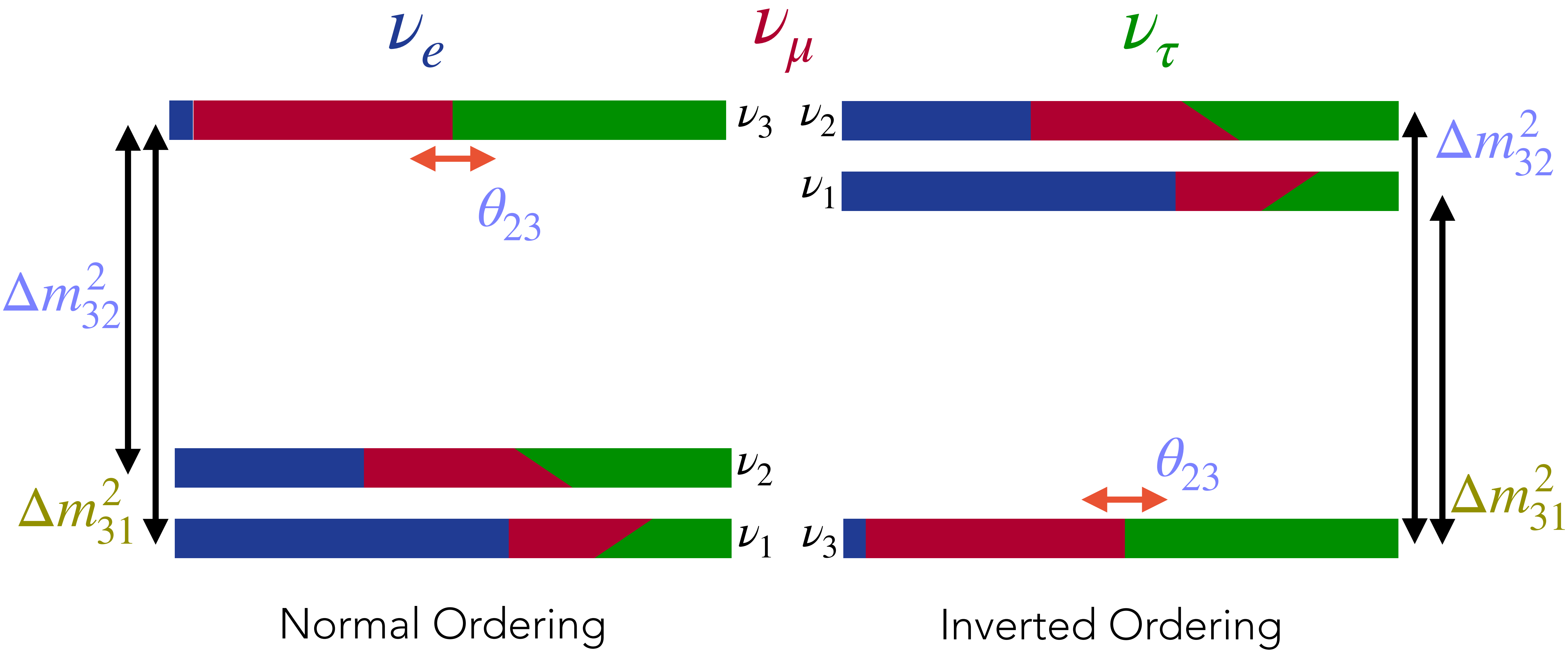
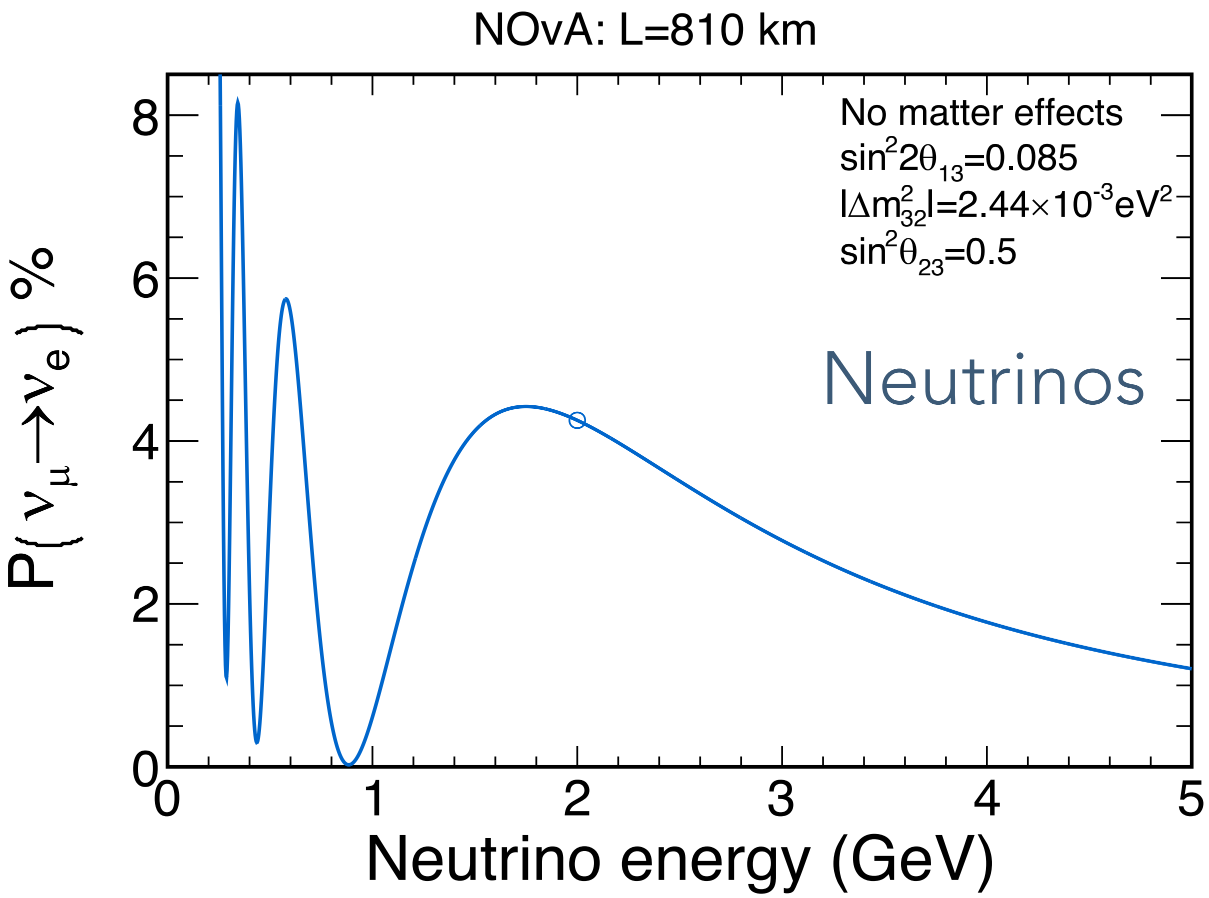
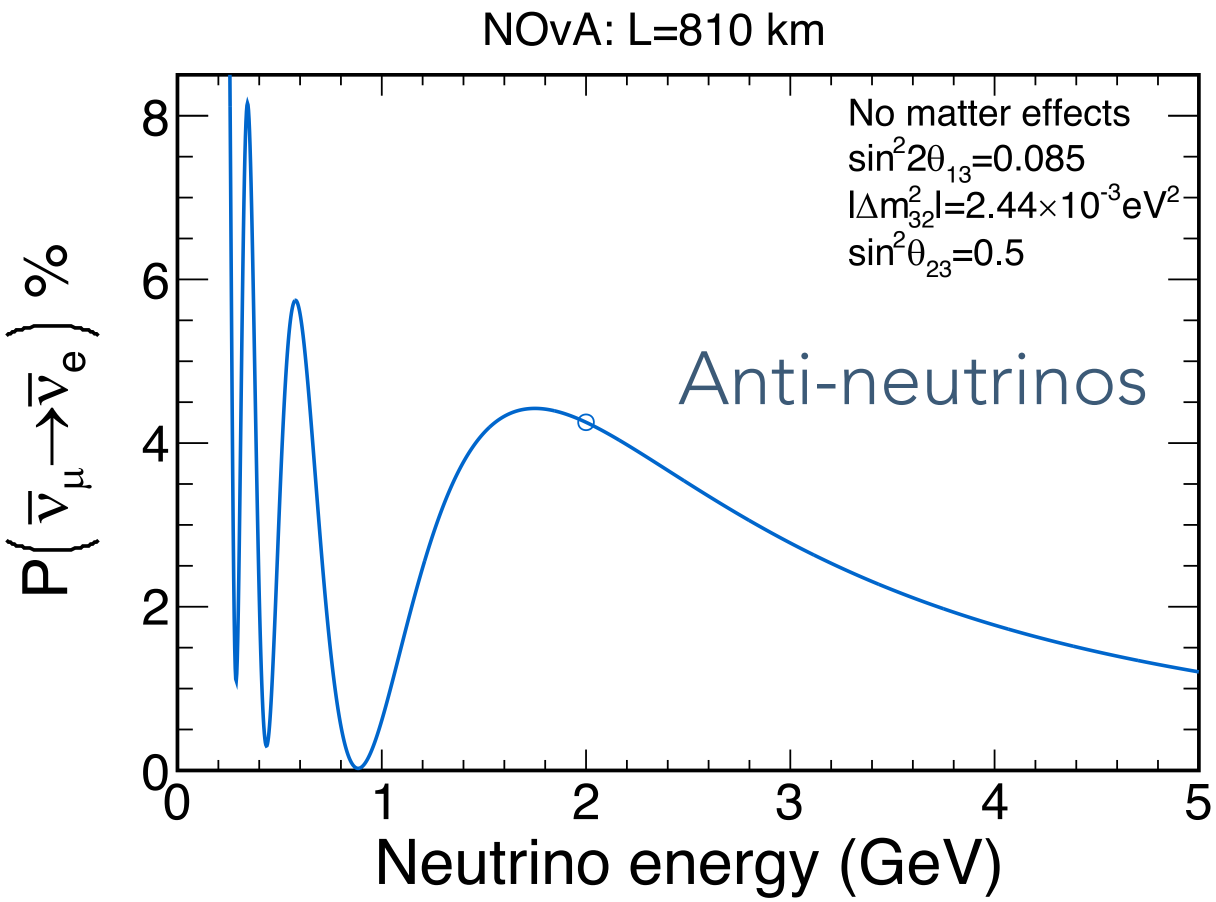


Open Questions: Appearance

- $\nu_\mu \rightarrow \nu_e$ depends on:
  - Mass ordering and matter effects.
  - Atmospheric parameters: $\sin^2(\theta_{23})$, Δm^2_{32}
  - CP phase: δ_{CP}.

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





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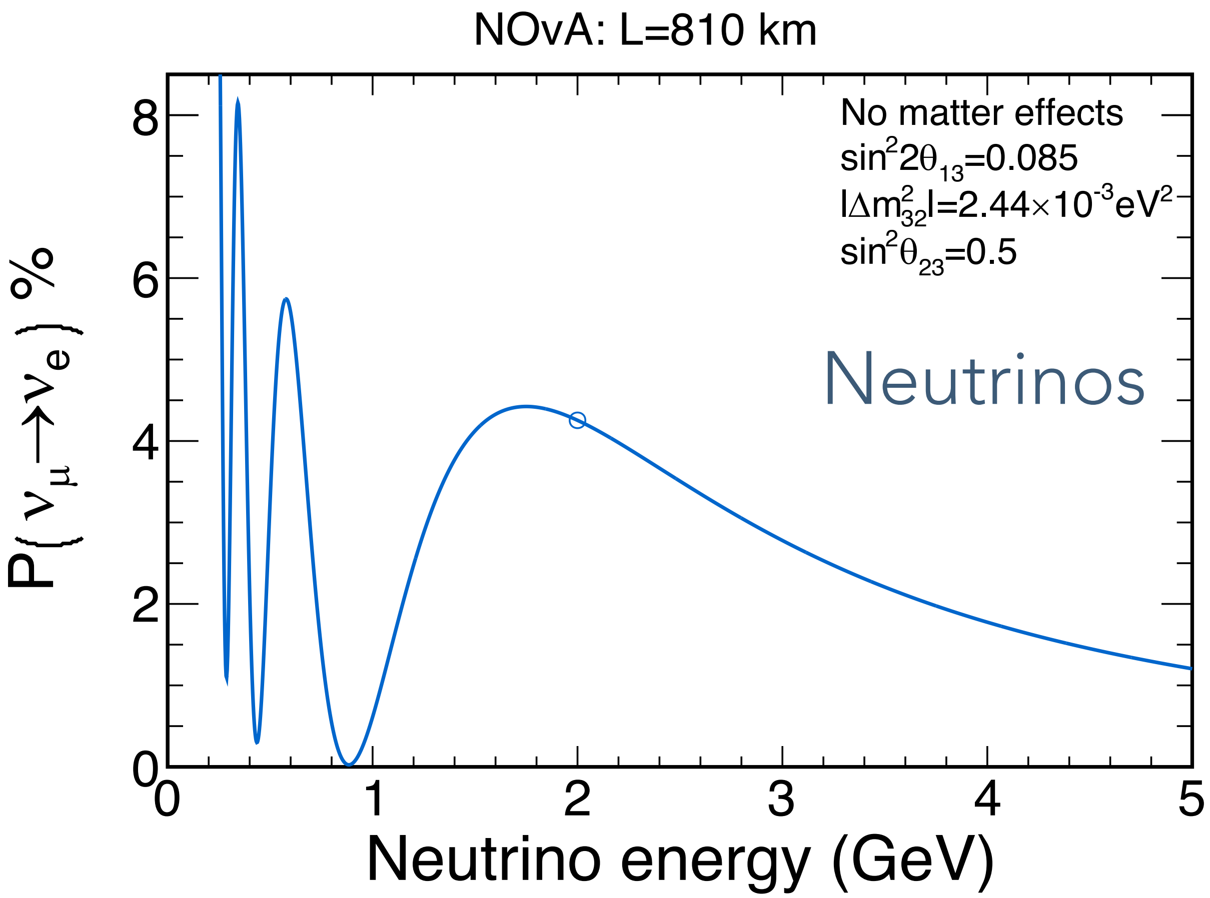
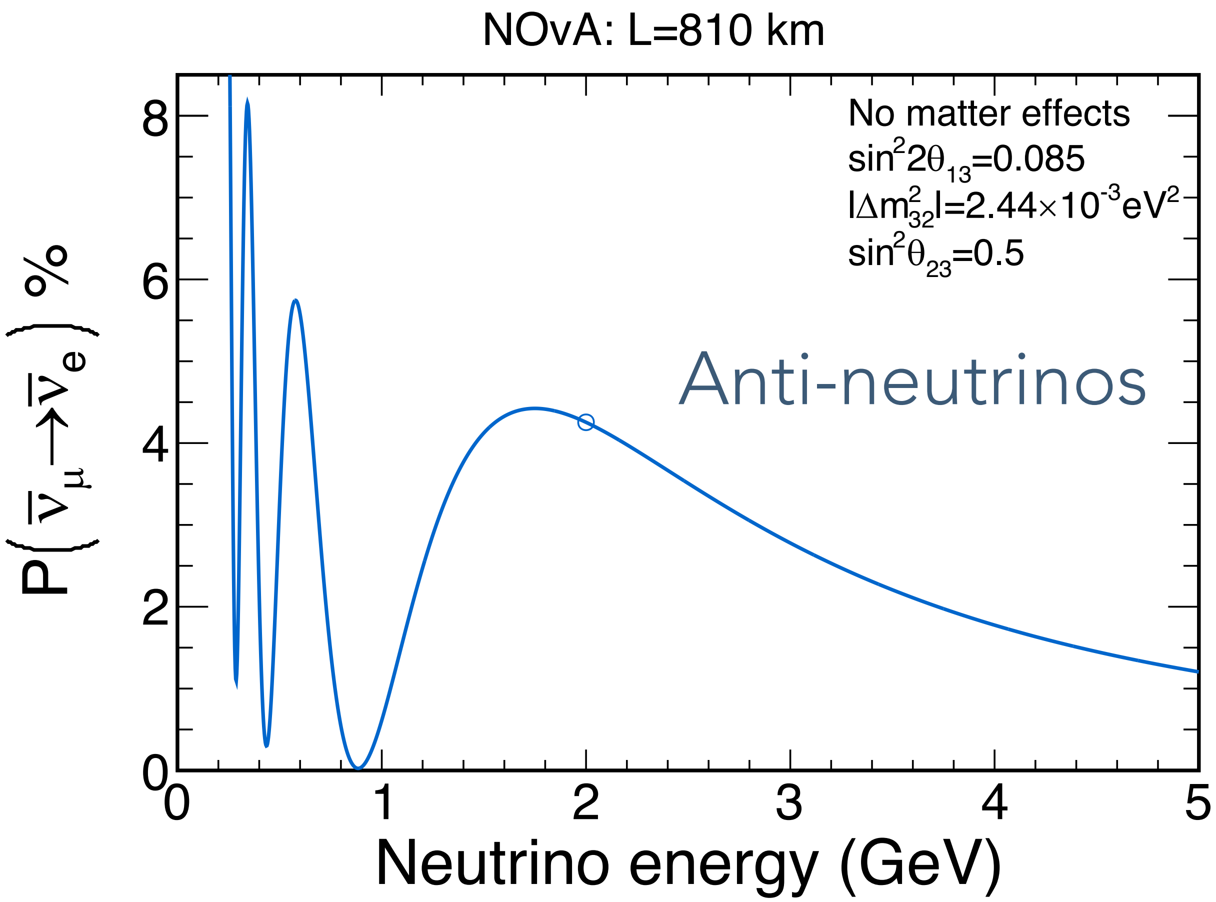
CP conserved





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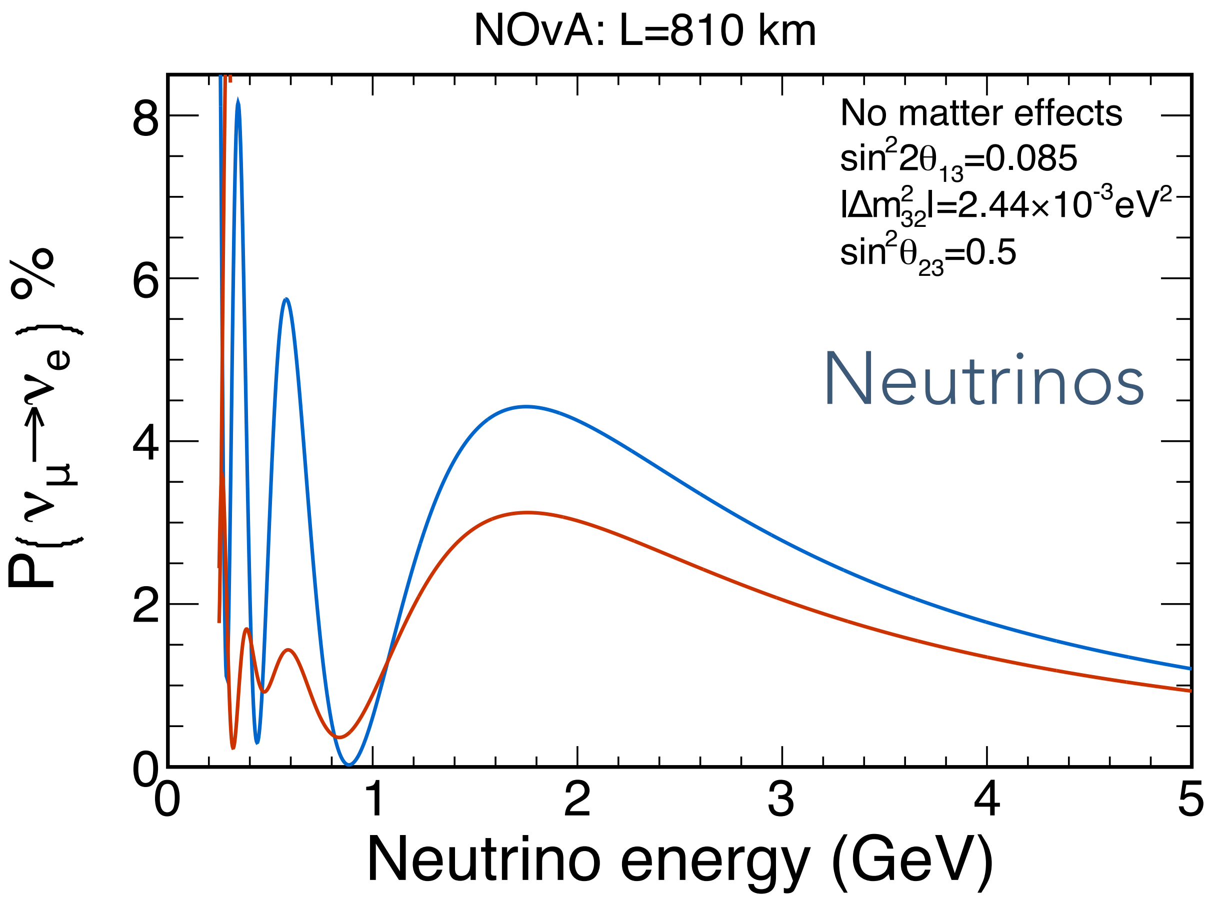
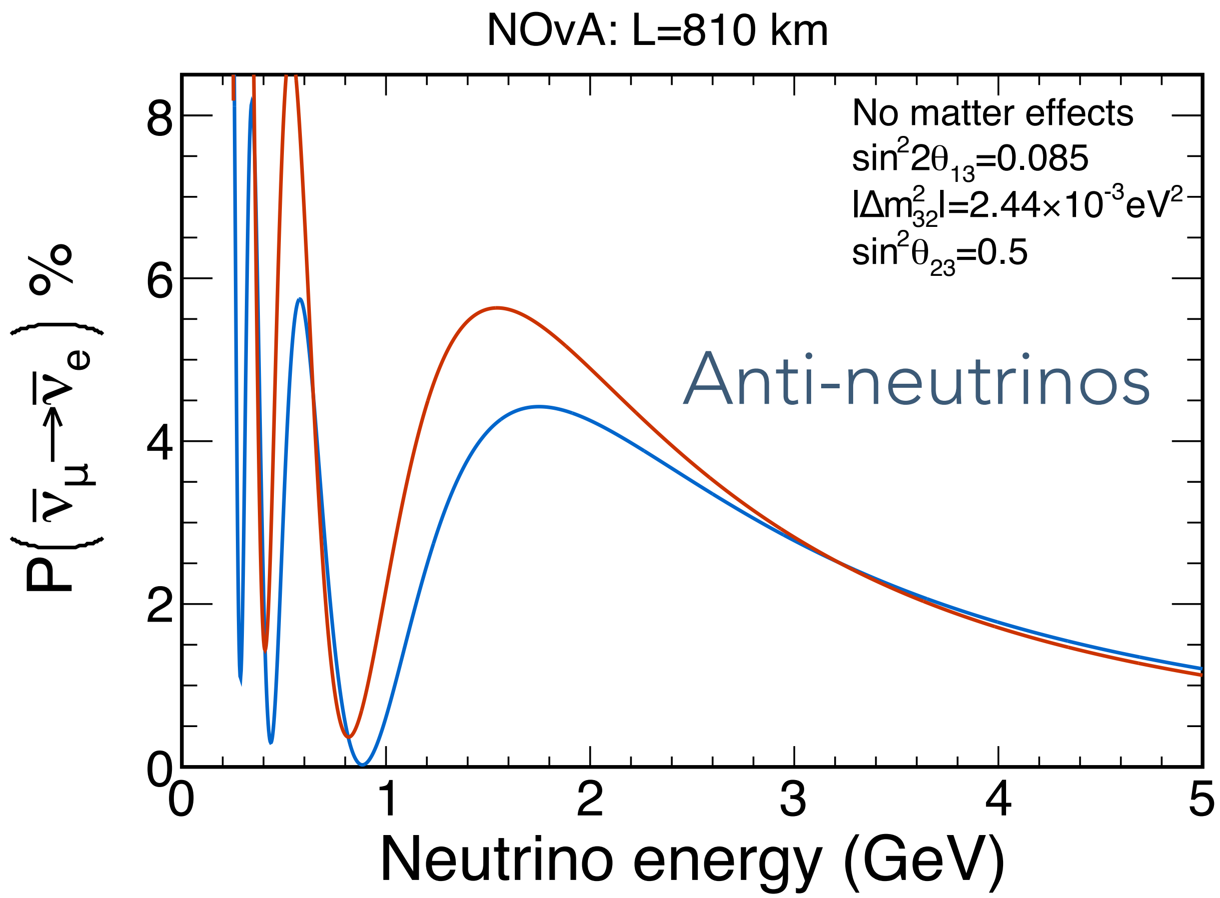
CP conserved

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





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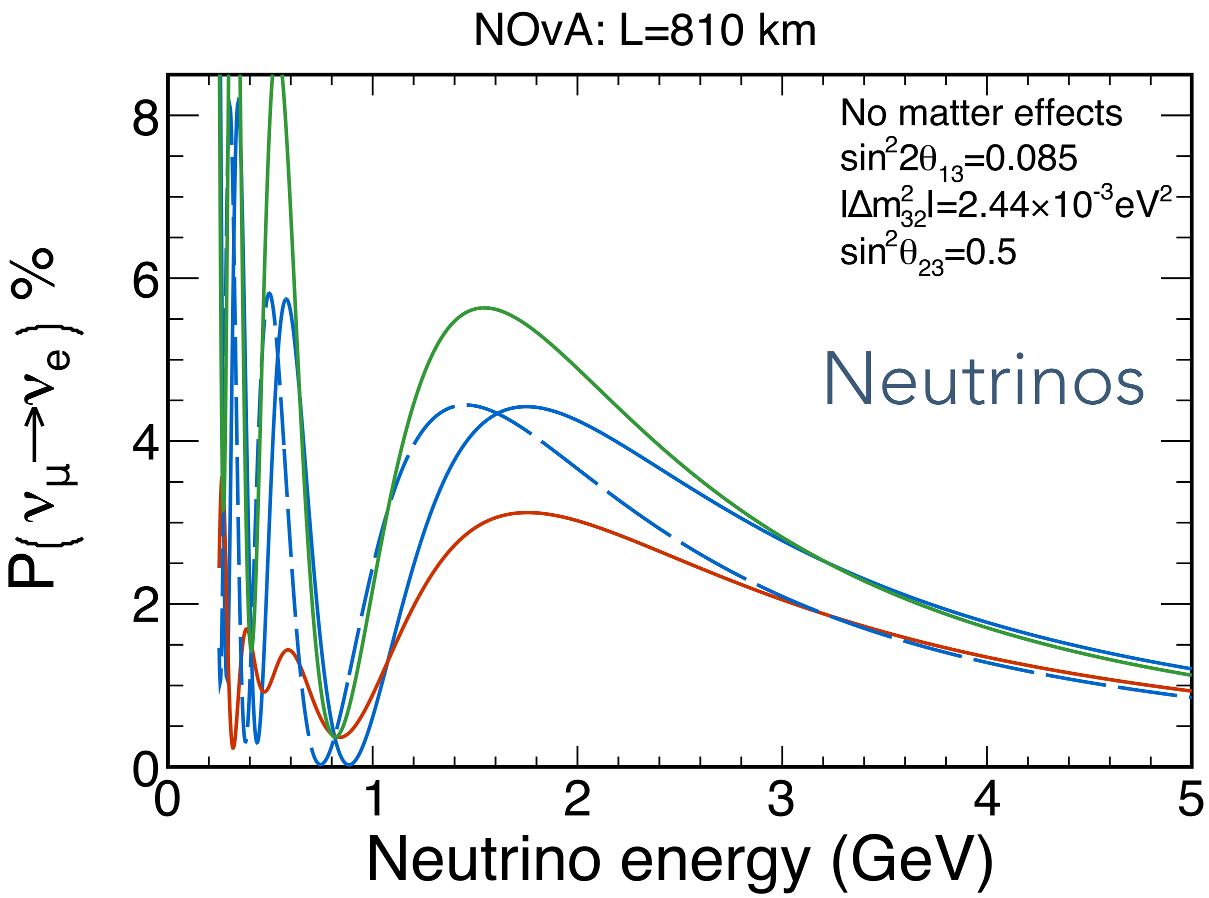
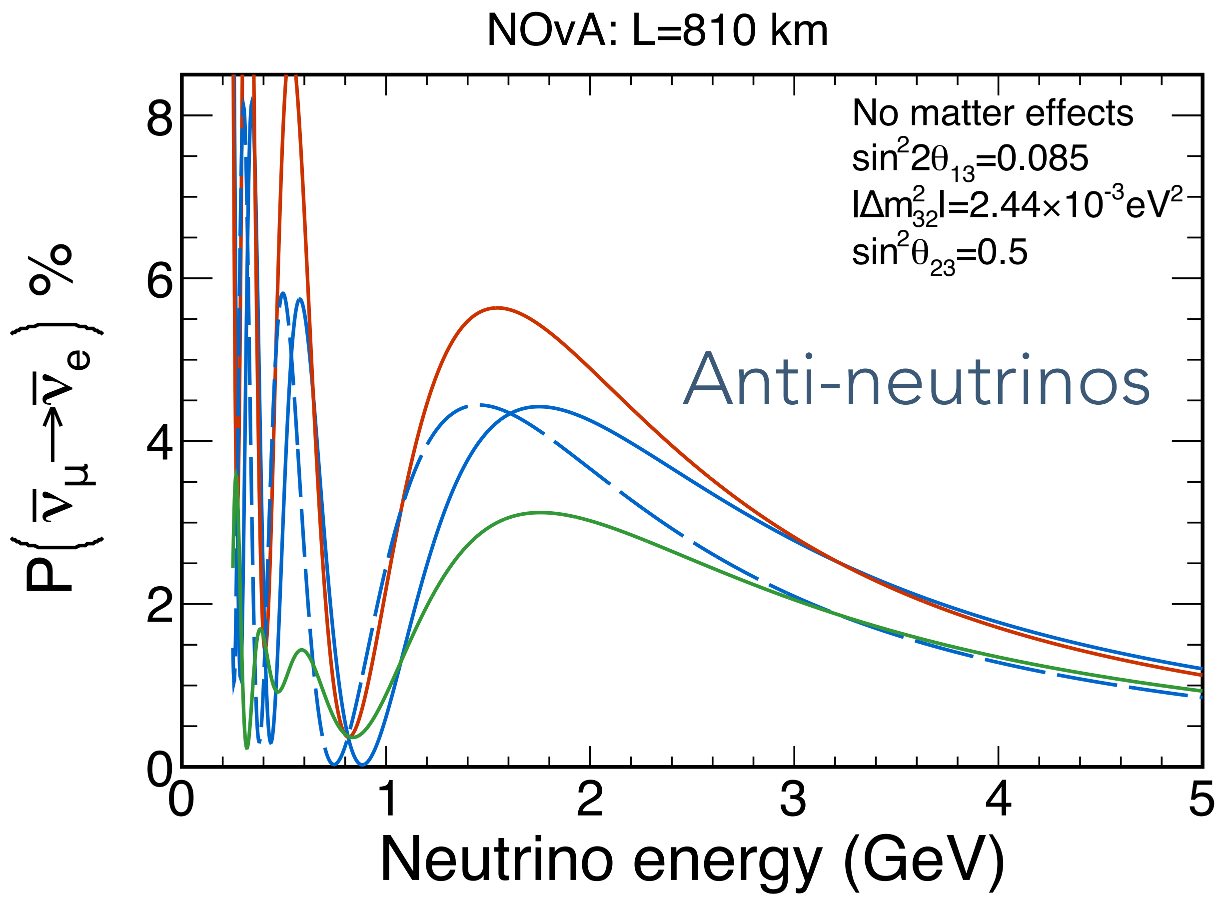
  - Mass ordering and matter effects.
  - Atmospheric parameters: $\sin^2(\theta_{23})$, Δm^2_{32}
  - CP phase: δ_{CP}.

CP conserved

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



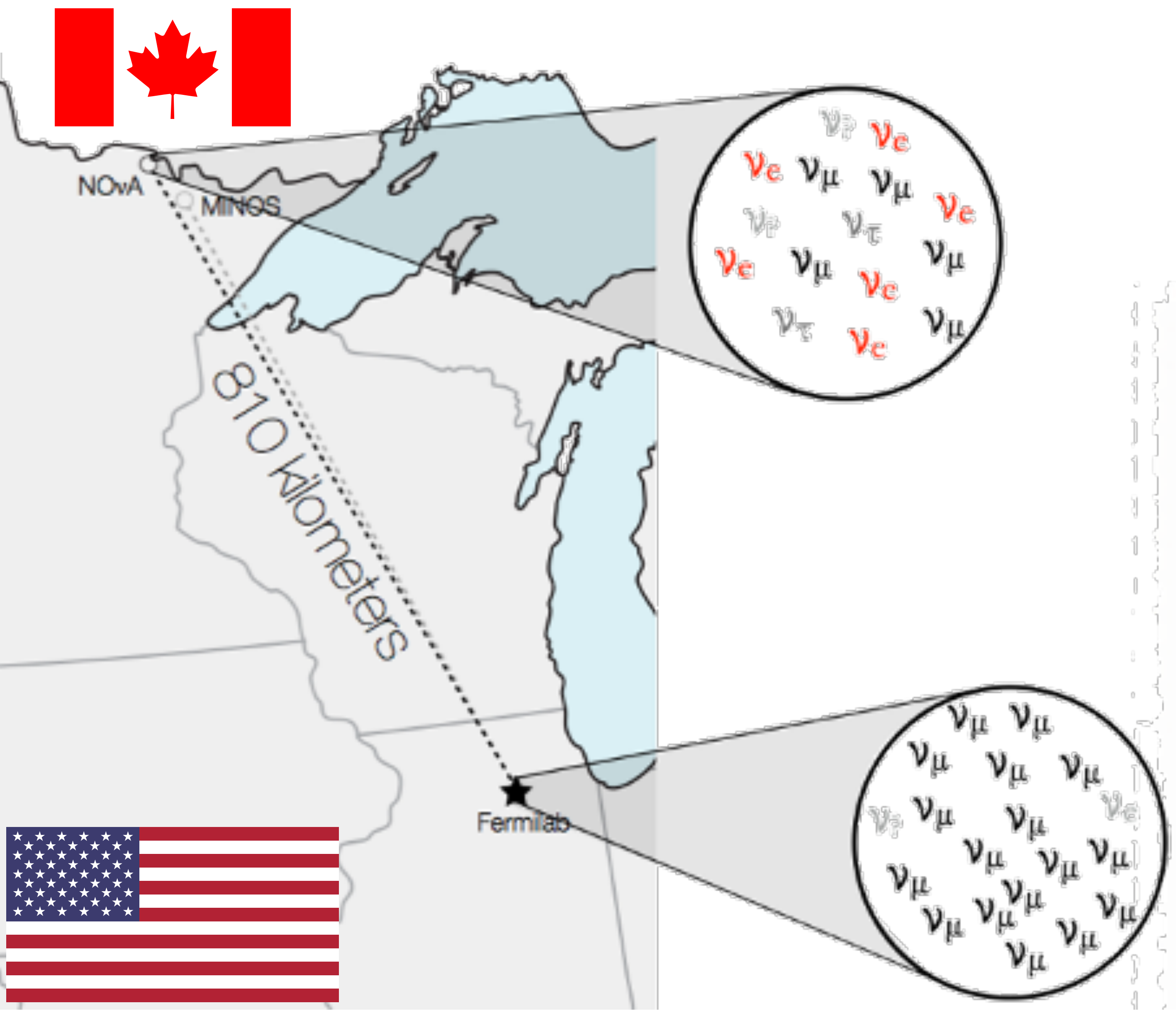


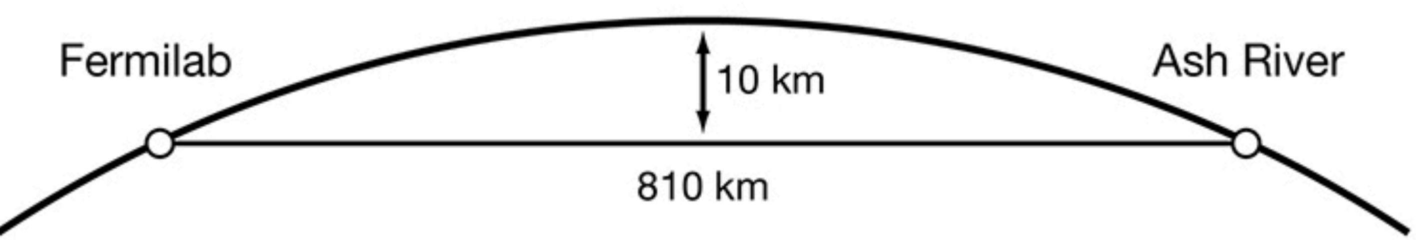
Mini-Summary

- 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 ($P(\nu_\mu \rightarrow \nu_\mu)$) and electron neutrino appearance probabilities ($P(\nu_\mu \rightarrow \nu_e)$).

NOvA Experimental Setup

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.

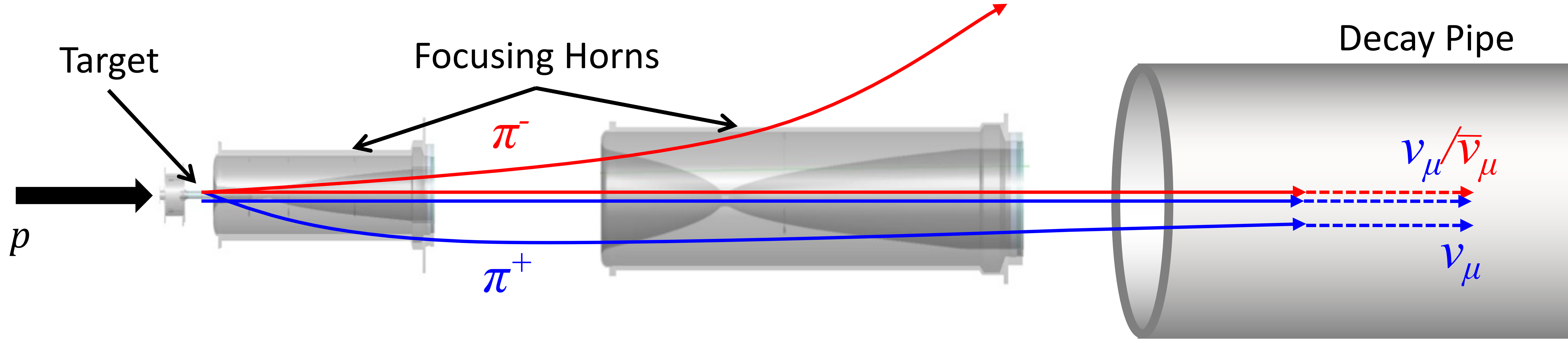
- **Primary goal,** measurement of 3-flavour oscillations via:
  - $\nu_\mu \to \nu_\mu$, $\nu_\mu \to \nu_e$
  - $\bar{\nu}_\mu \to \bar{\nu}_\mu$, $\bar{\nu}_\mu \to \bar{\nu}_e$

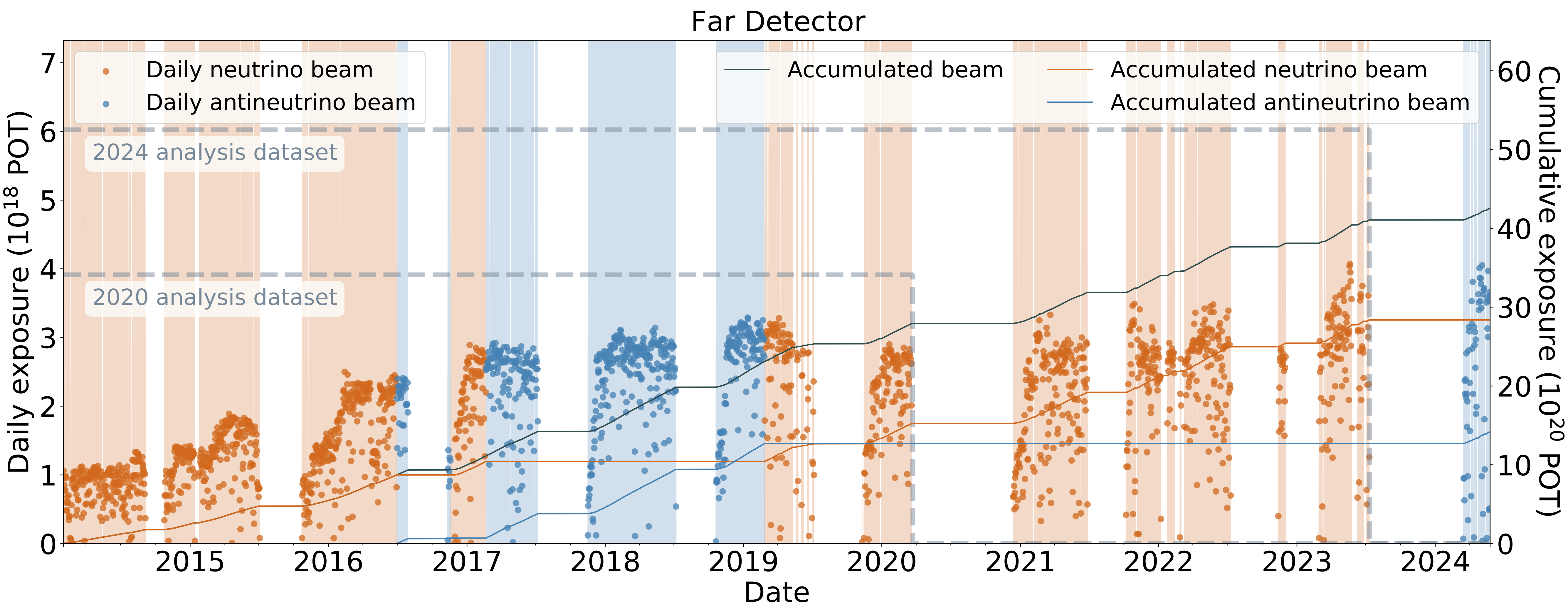
- Other goals include:
  - Search for sterile neutrinos.
  - Neutrino cross sections.
  - Supernova neutrinos.
  - Cosmic ray physics.

The NOvA Collaboration

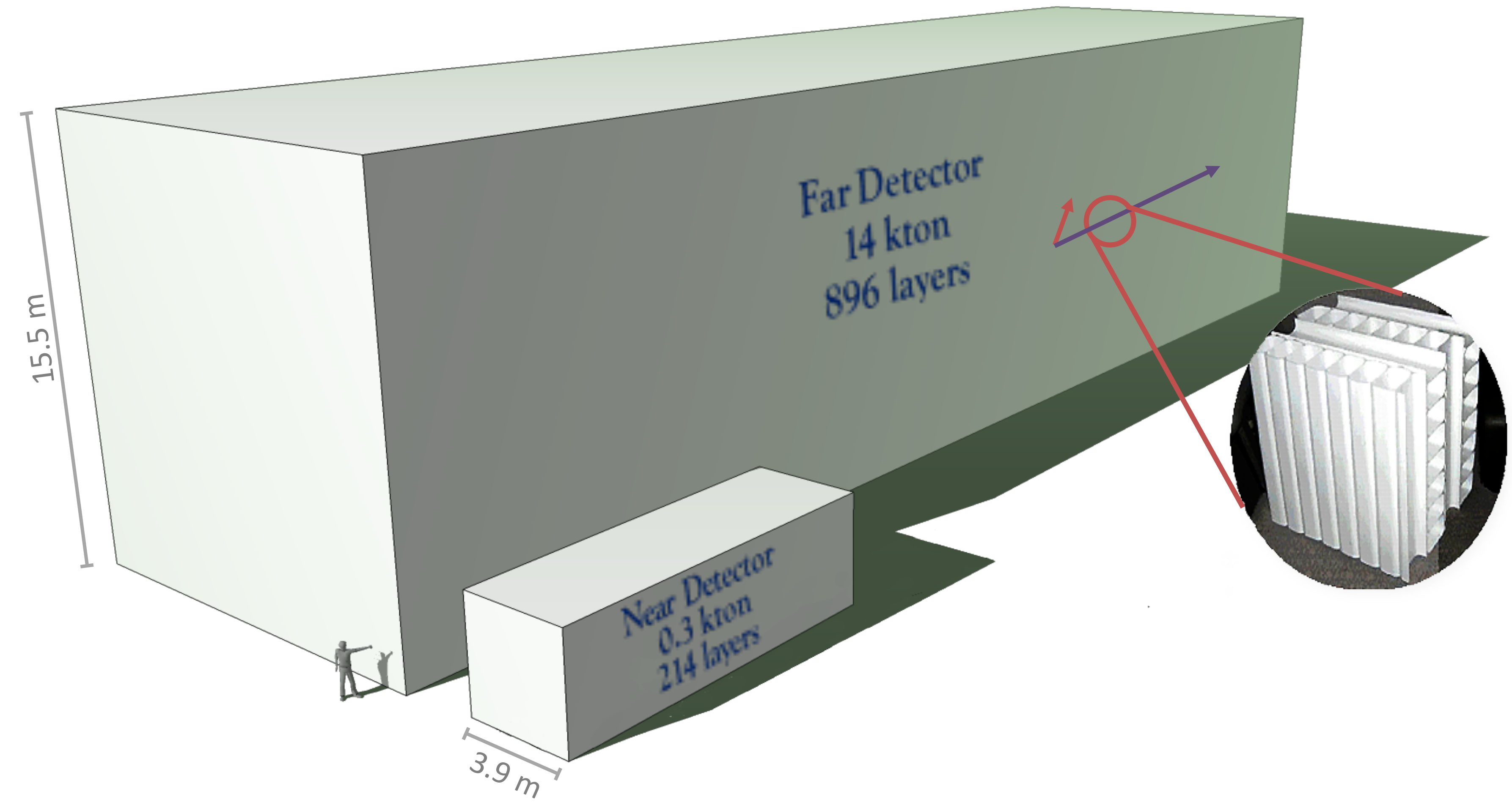
> 260 people, ~ 50 institutions, 8 countries

How We Make Neutrinos: NuMI Beam



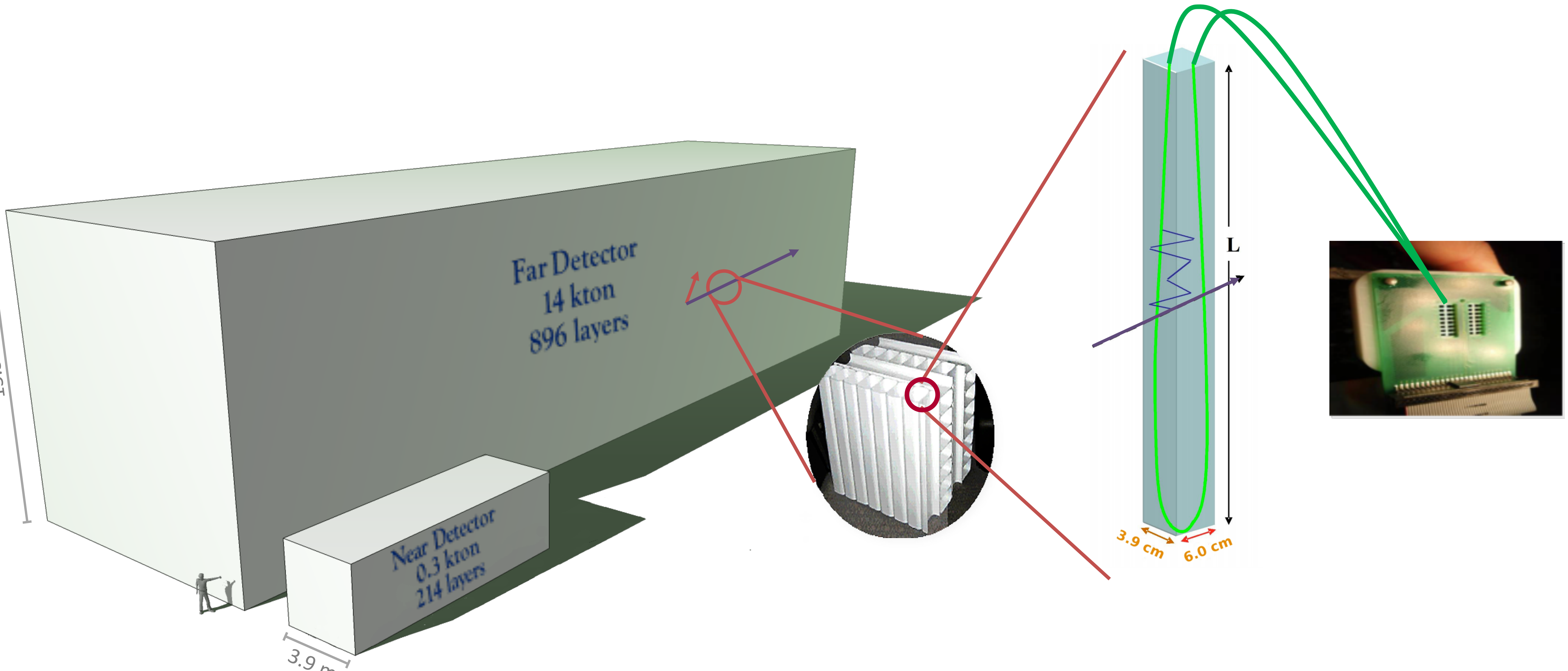


The NOvA Detectors



- 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 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

Mostly unchanged!

Analysis Strategy

Particle ID

Reconstruction

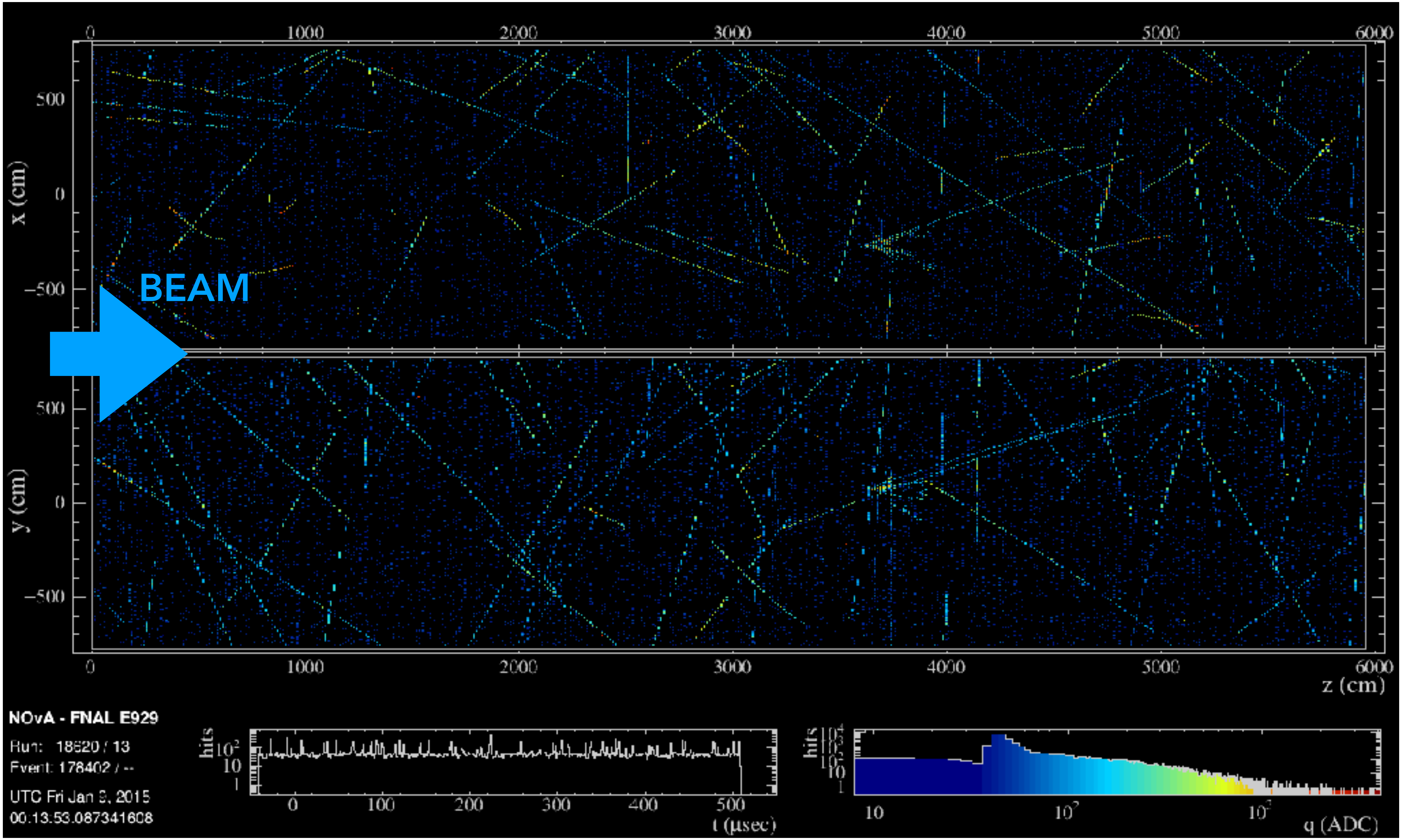
Observe flavour change as a function of energy over a long distance while mitigating uncertainties on neutrino flux, cross sections and detector response.

Extrapolation

Models

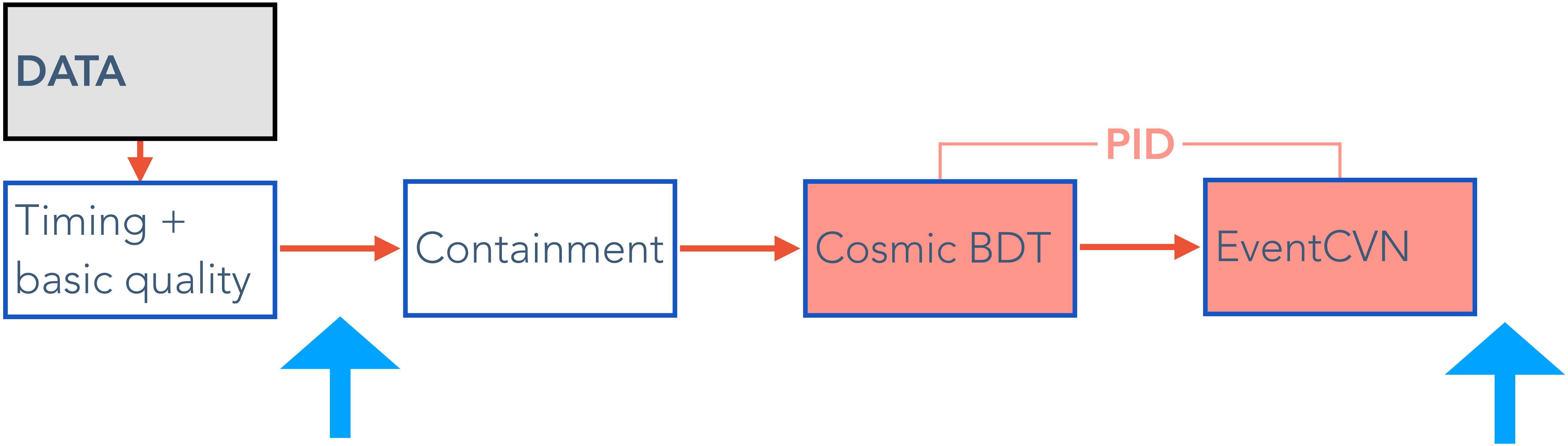
Improved!

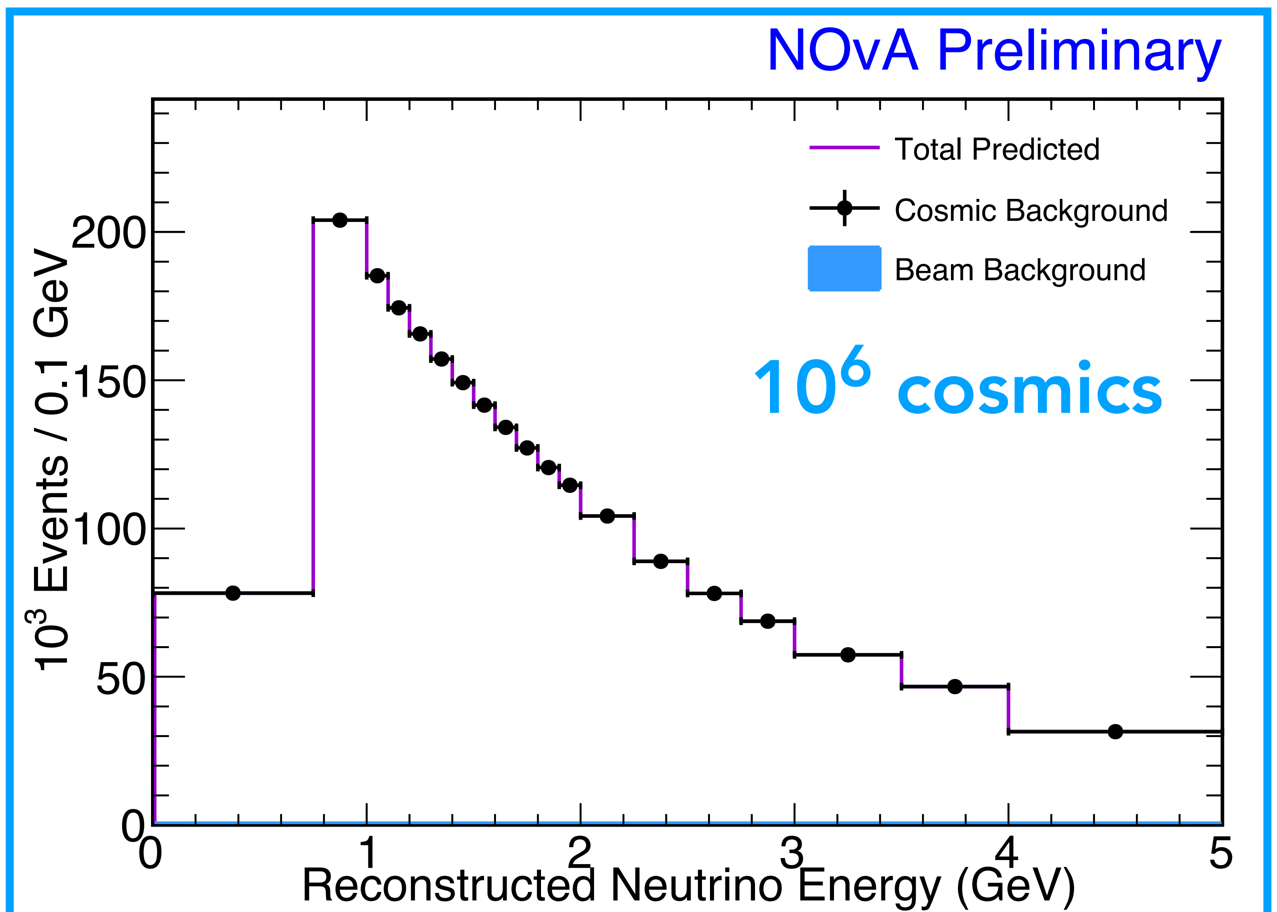
Selection: Cosmic Rejection

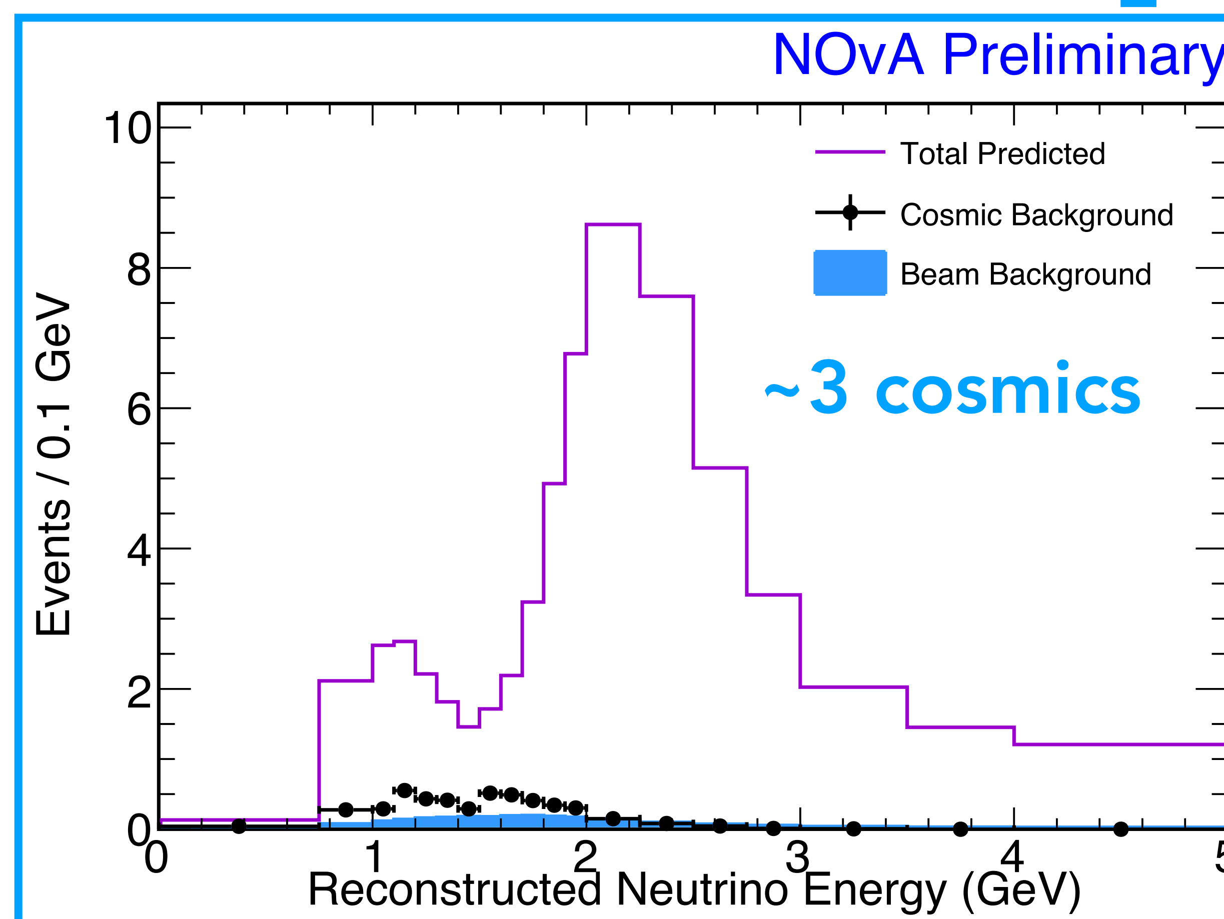


Cosmic rejection critical for FD: 11 billion cosmic rays/day

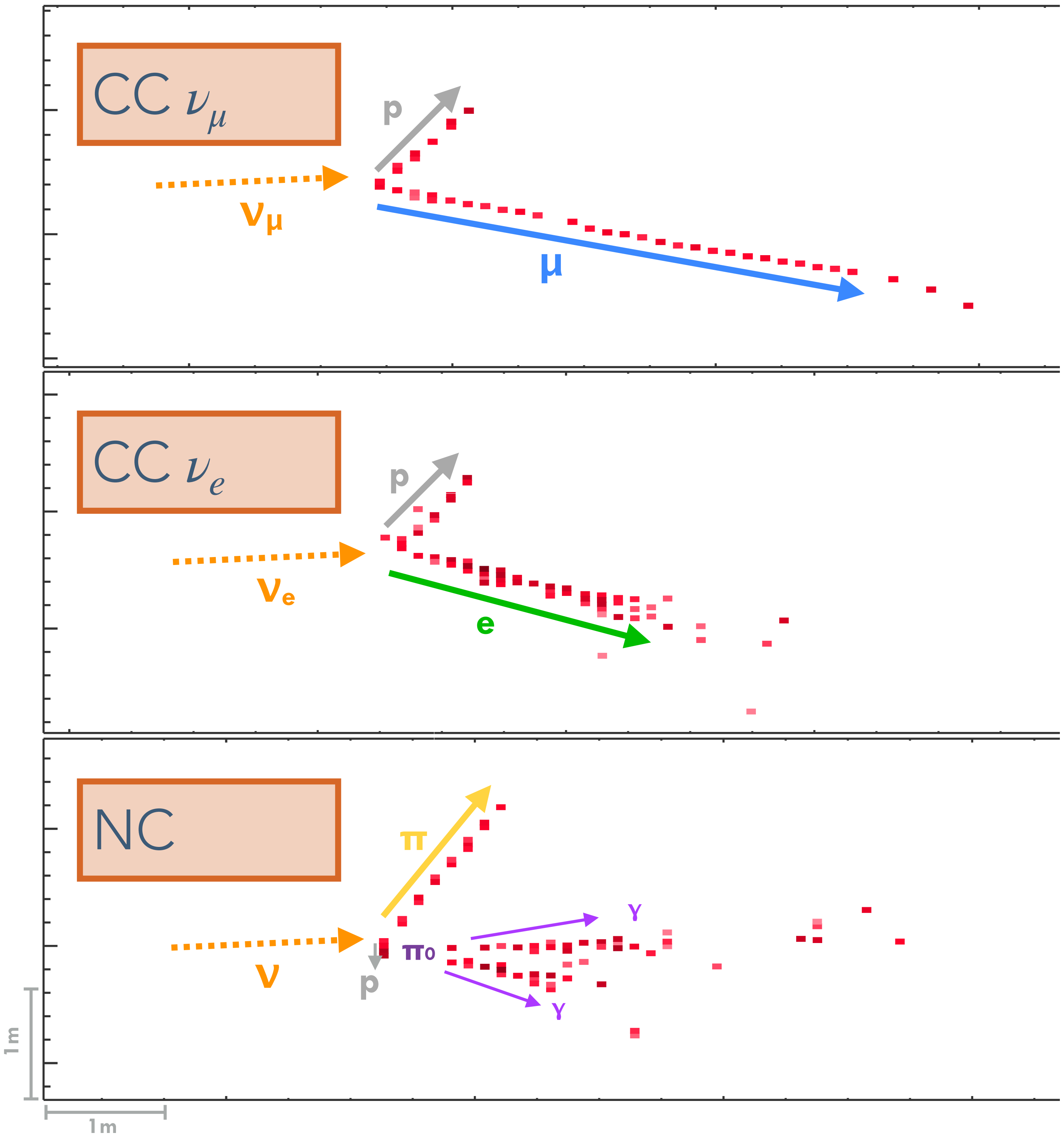
Selection: ν_μ





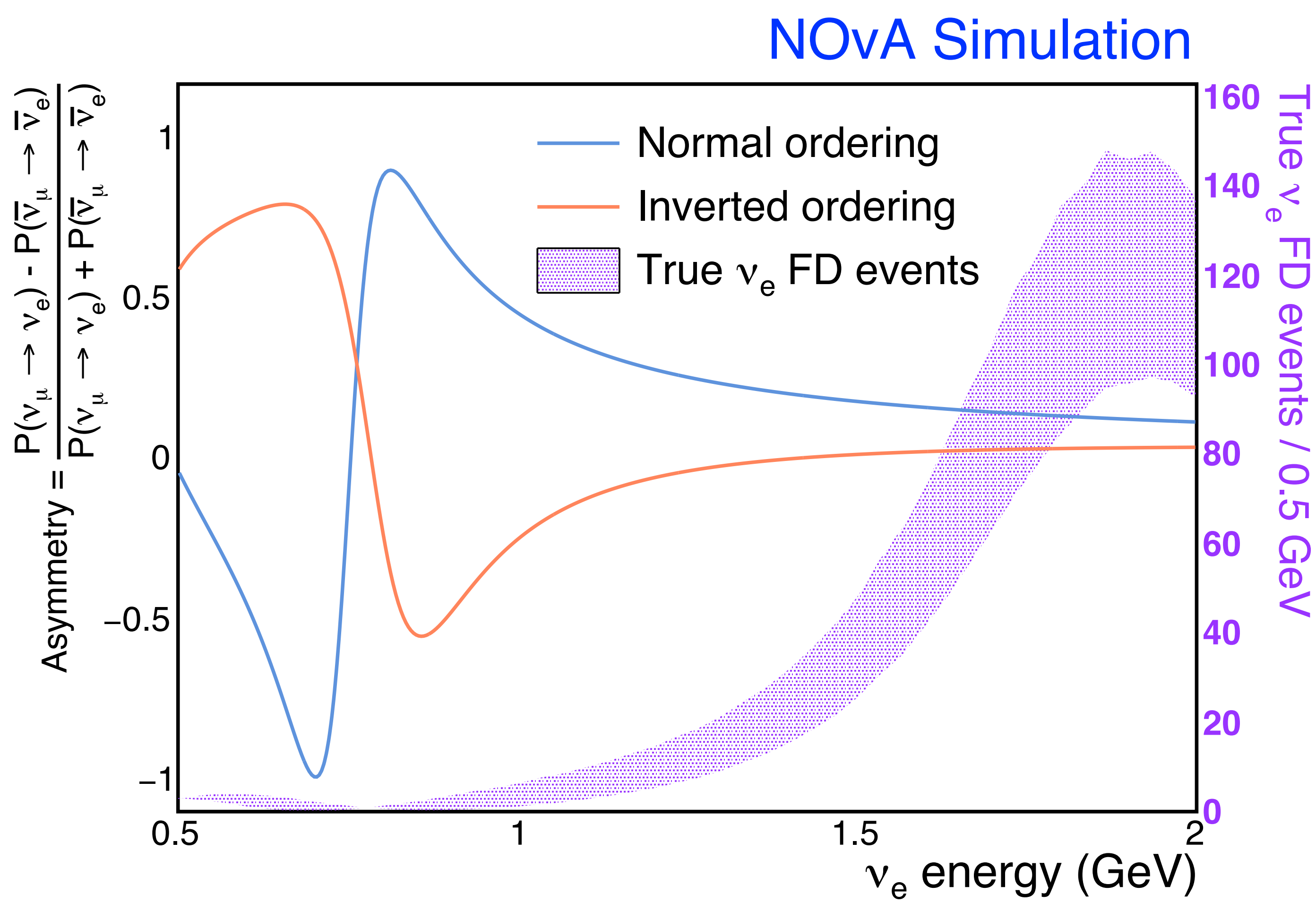


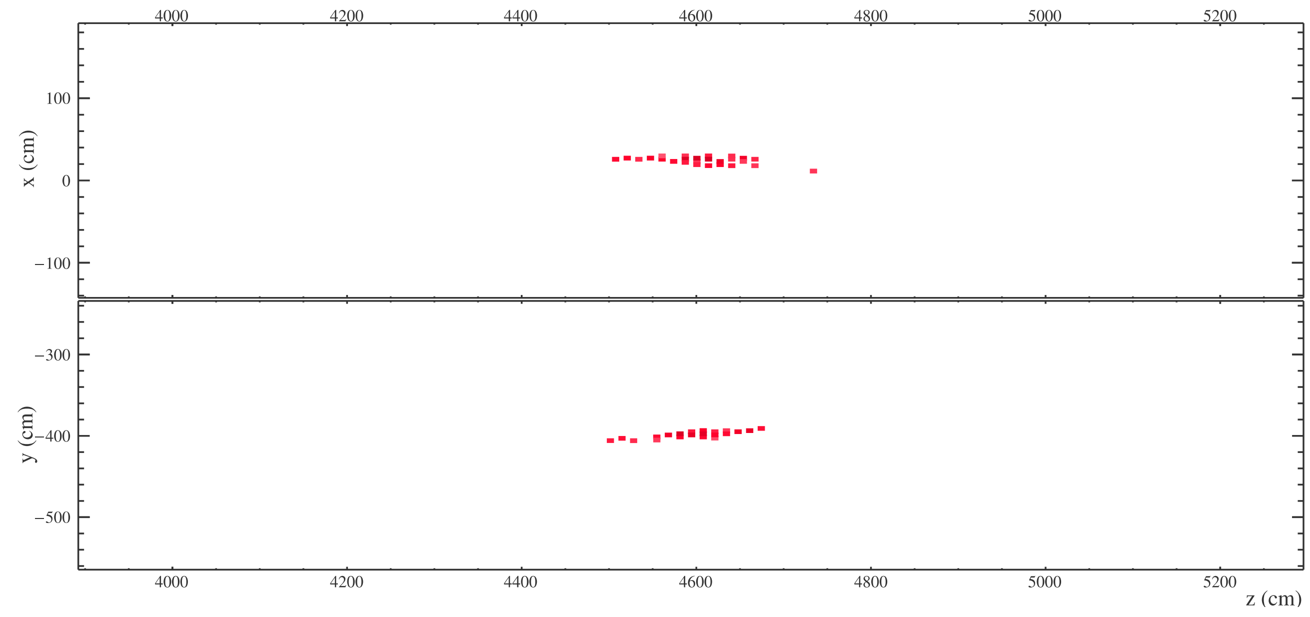
Selecting & Identifying Neutrinos



- 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.**

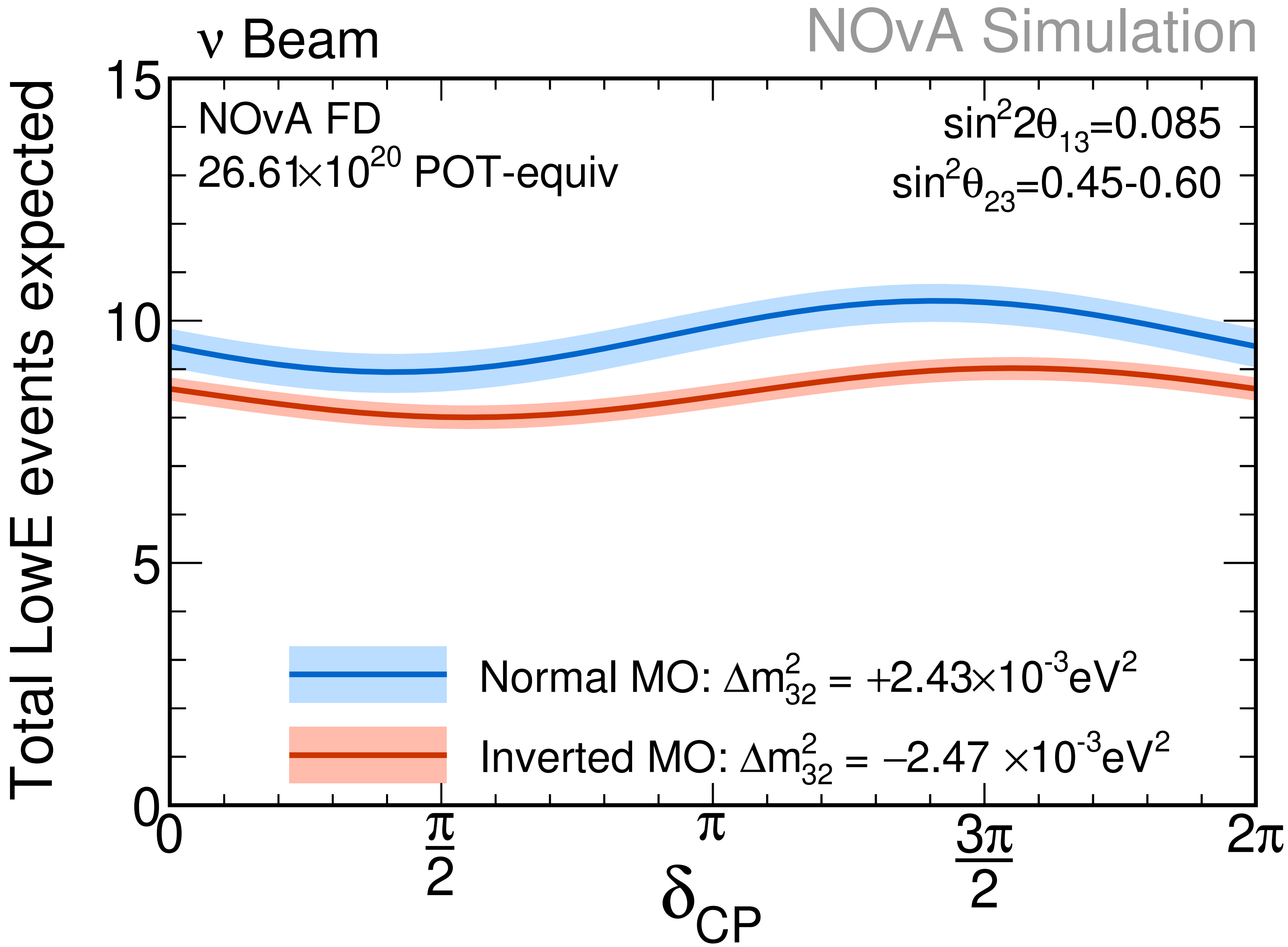
Expanding ν_e Candidate Selection





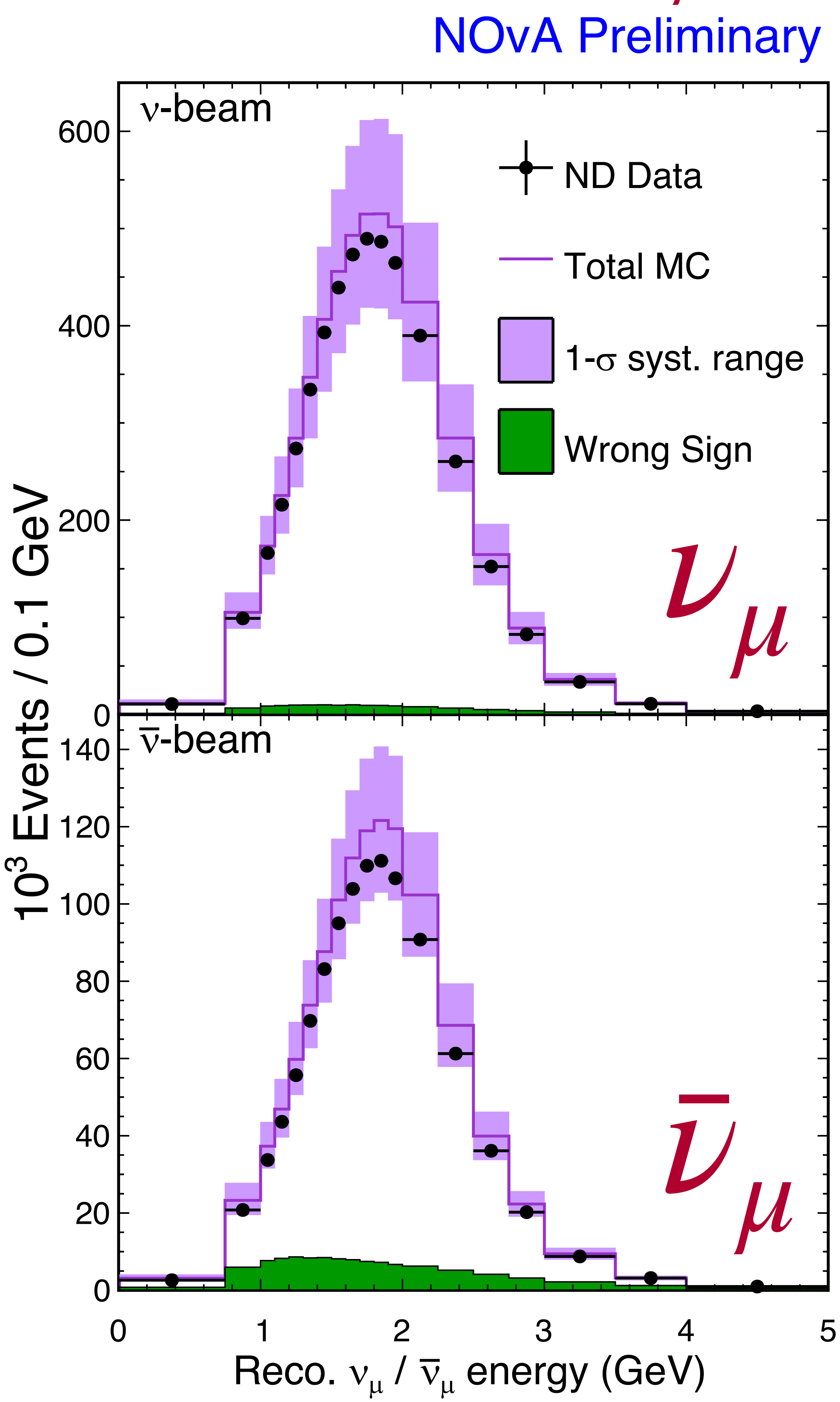
- For NOvA's energy range and baseline the effect of the mass ordering is largest at lower energies in the range.
- Challenging for NOvA - predicted number of events in this region is small.
- Pursuing these events with a new BDT classifier.

Expanding ν_e Candidate Selection



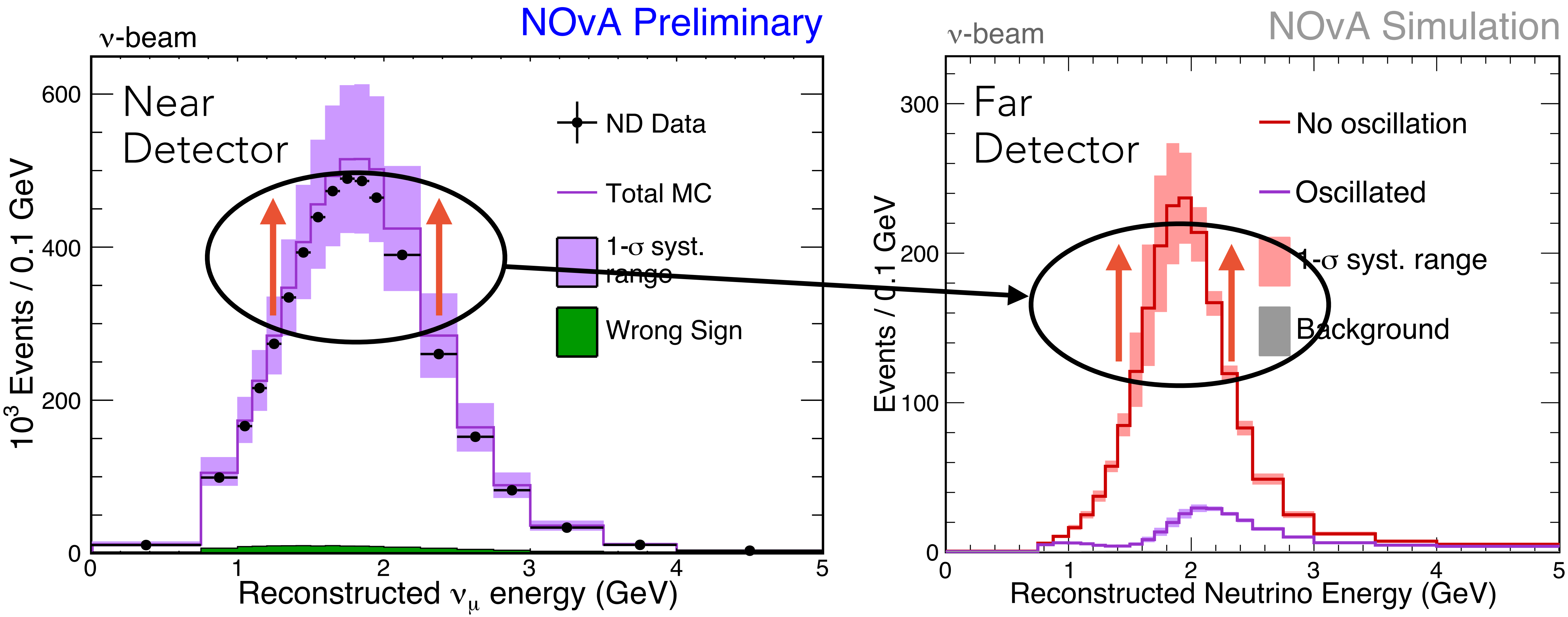
- Good separation in some regions.
- Only have sufficient statistics in the neutrino beam mode sample. Analogous sample in antineutrino beam mode is currently too small.
- Provides increase in sensitivity to the mass ordering of ~ few %.

Near Detector, ν_μ



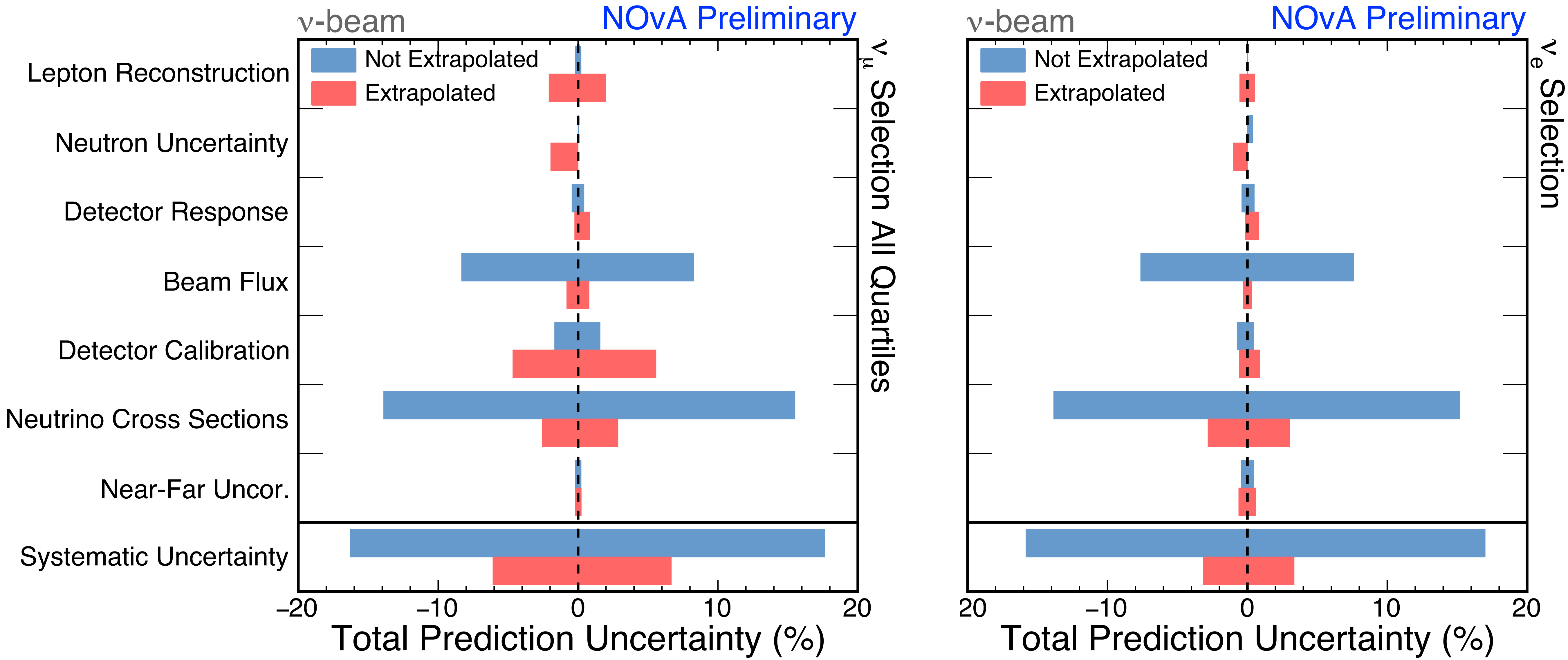
- Band around MC shows the large impact of flux and cross-section uncertainties when using a single detector.
- Use samples as a data constraint on what we predict at the Far Detector.
- These samples are used to predict both the ν_μ and the ν_e signal spectra at the Far Detector.
- Appearing ν_e's are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

Extrapolation



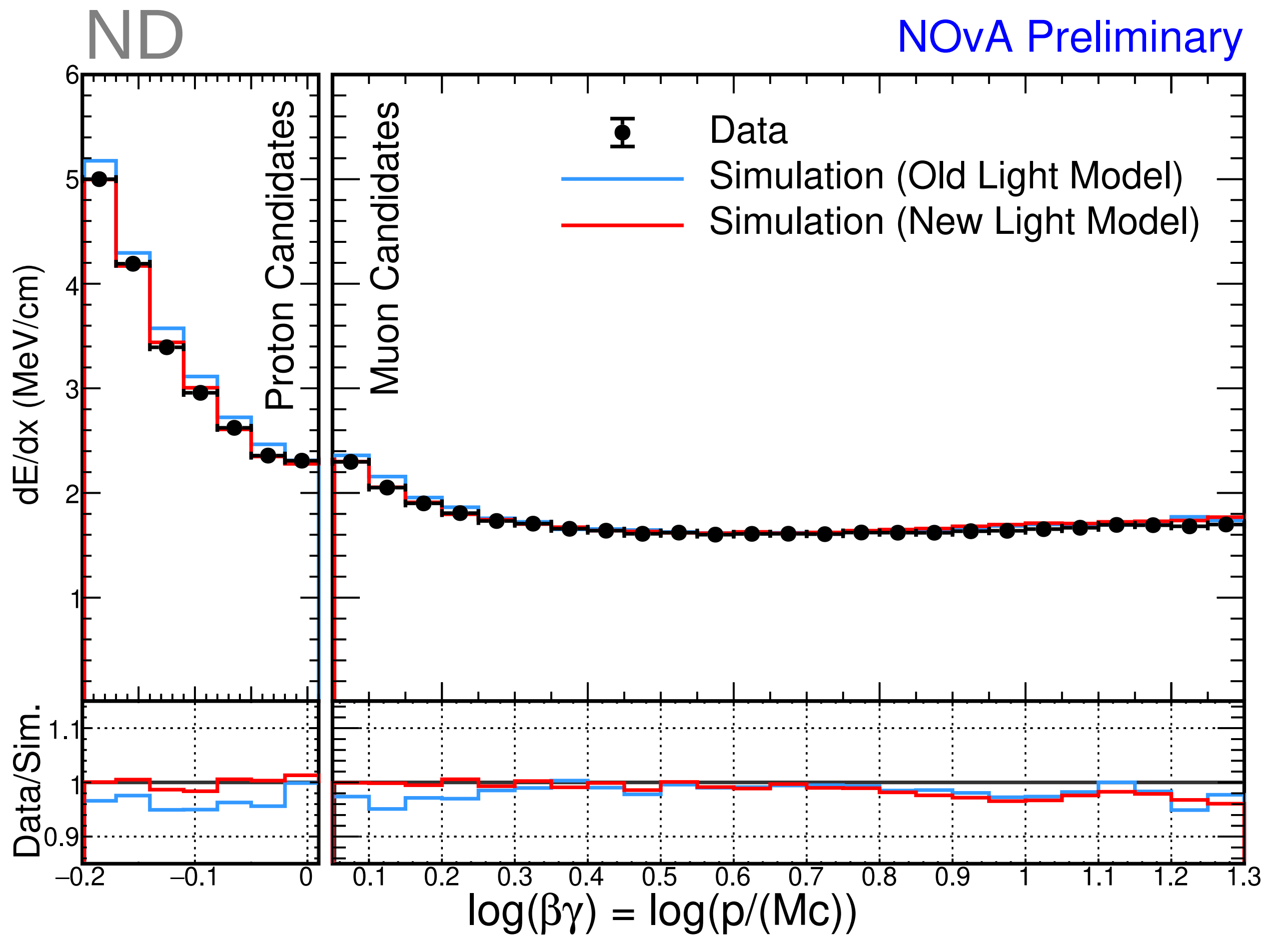
- Observe data-MC differences at the ND, use them to modify the FD MC.
- Significantly reduces the impact of uncertainties correlated between detectors.
  - Especially effective at rate effects like the flux (7% to 0.3%).

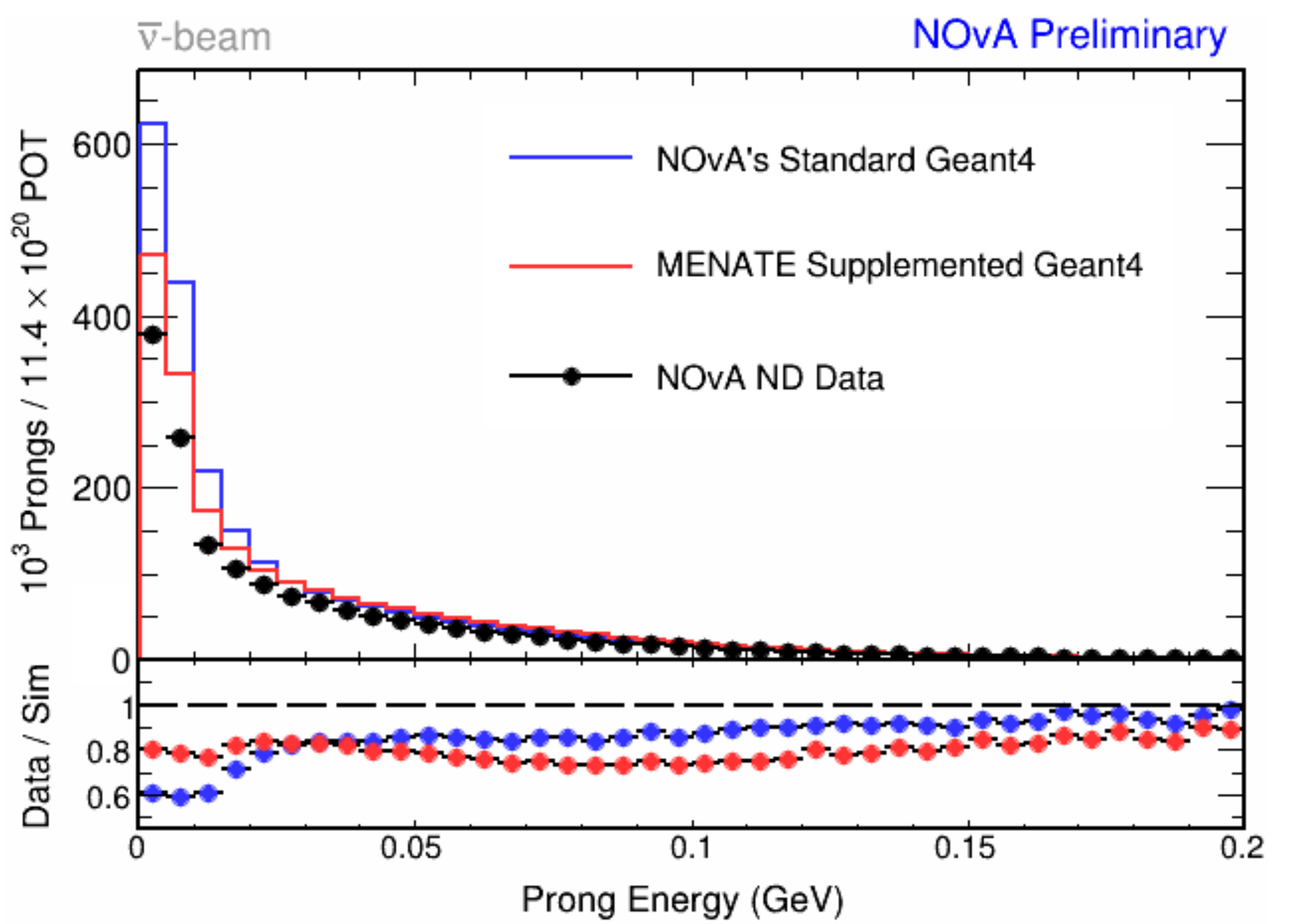
Impact of Systematic Uncertainty



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

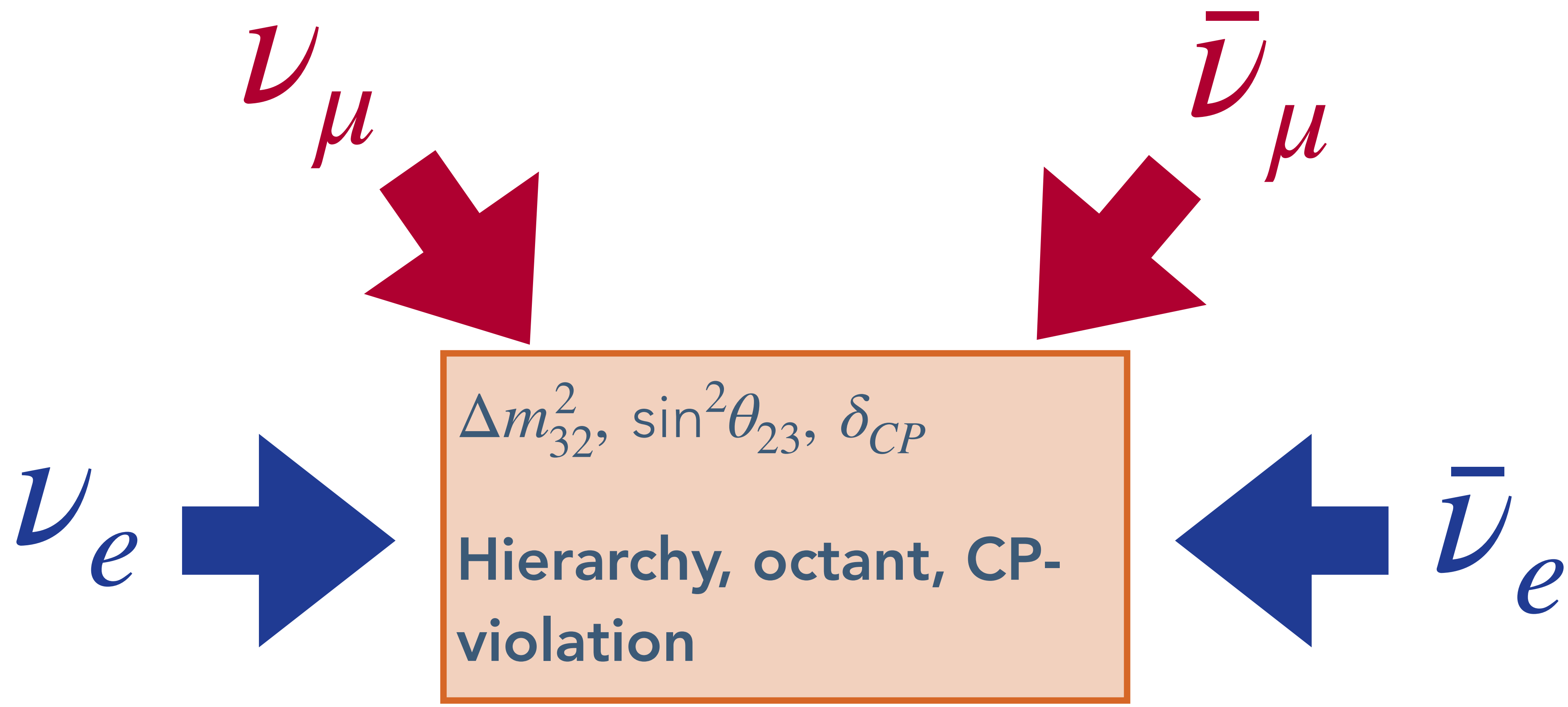
Detector Characterisation





- 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

ν_μ $\bar{\nu}_\mu$

Δm^2_{32}, $\sin^2\theta_{23}$, δ_{CP}, $\sin^2 2\theta_{13}$

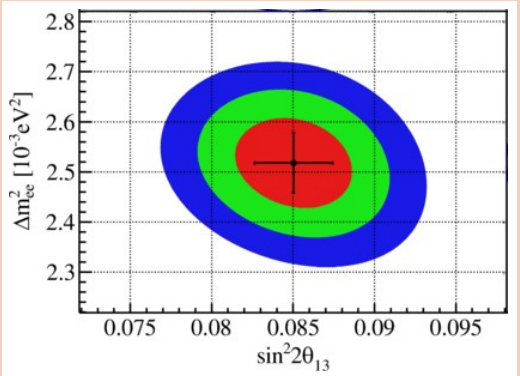
Consider three θ_{13} possibilities

ν_e $\bar{\nu}_e$

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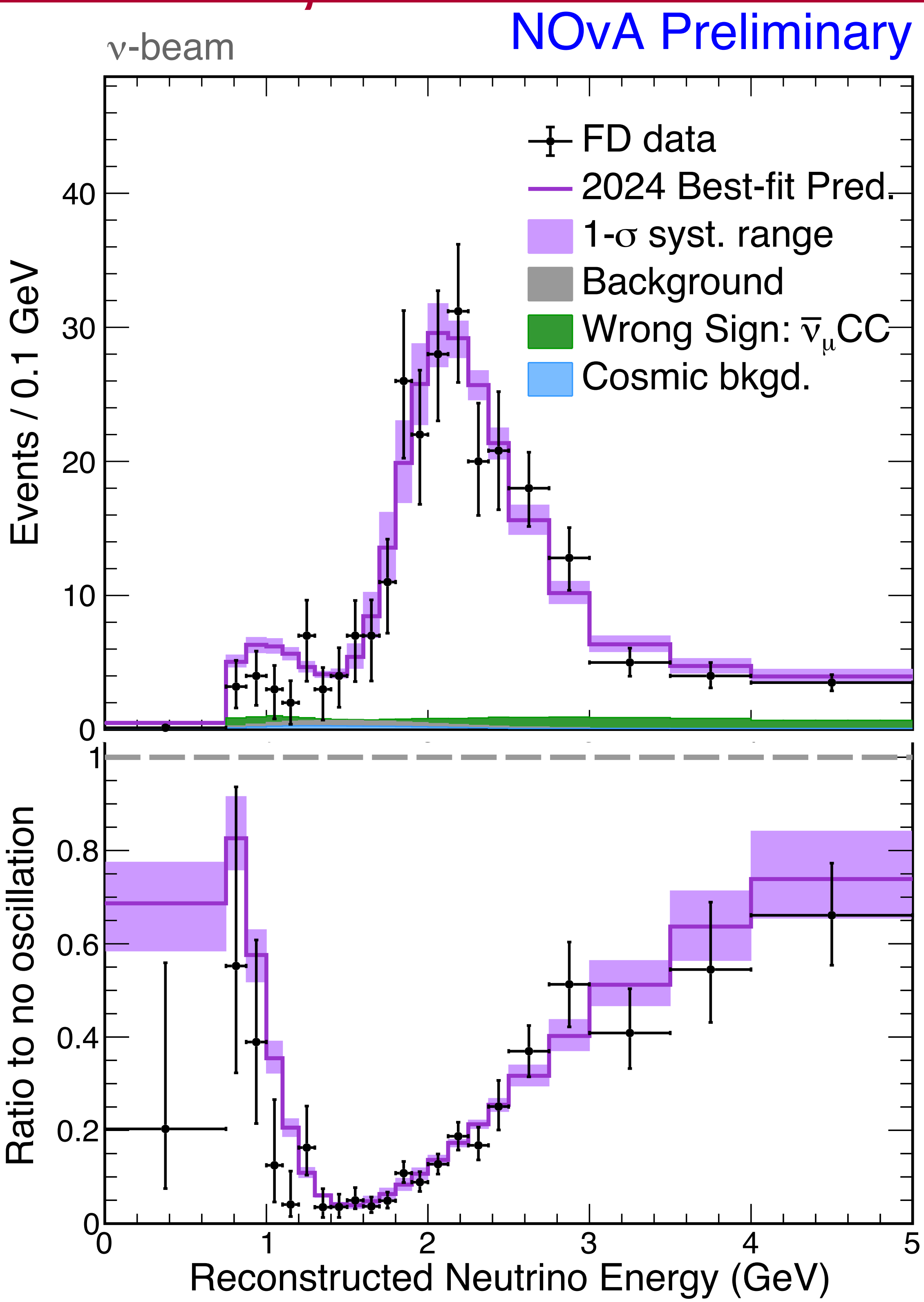
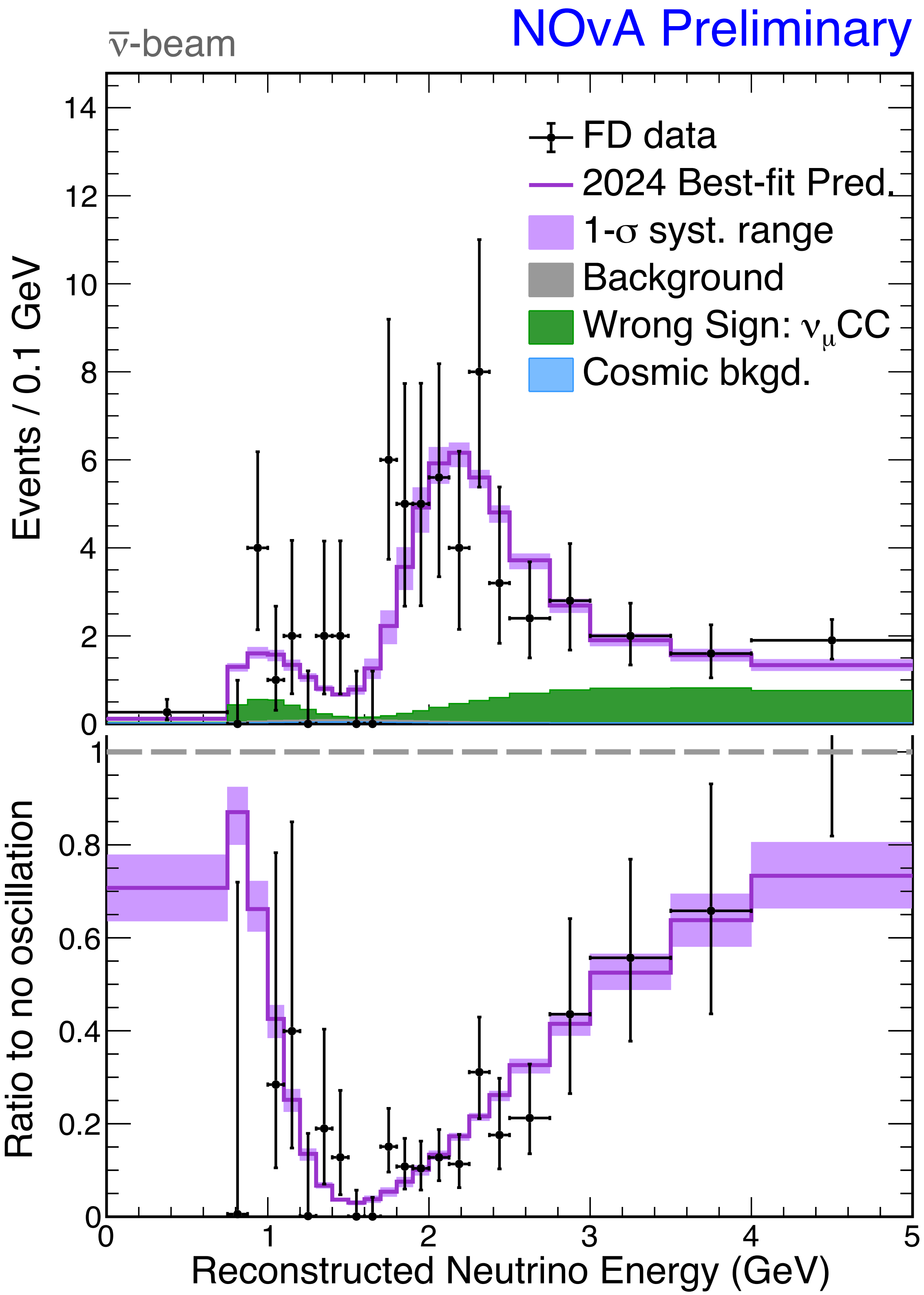
ν_μ and $\bar{\nu}_\mu$ Data at the Far Detector

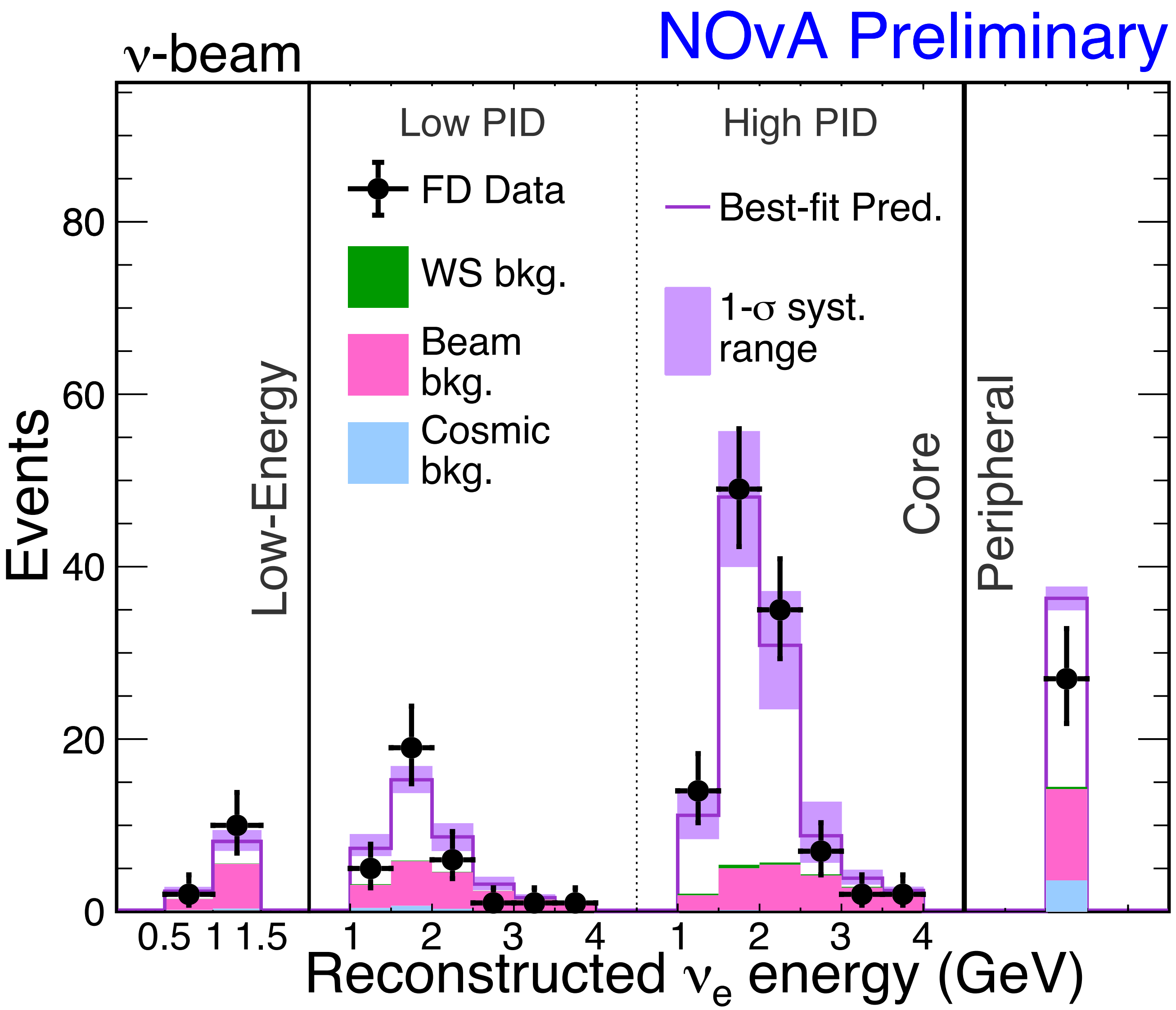


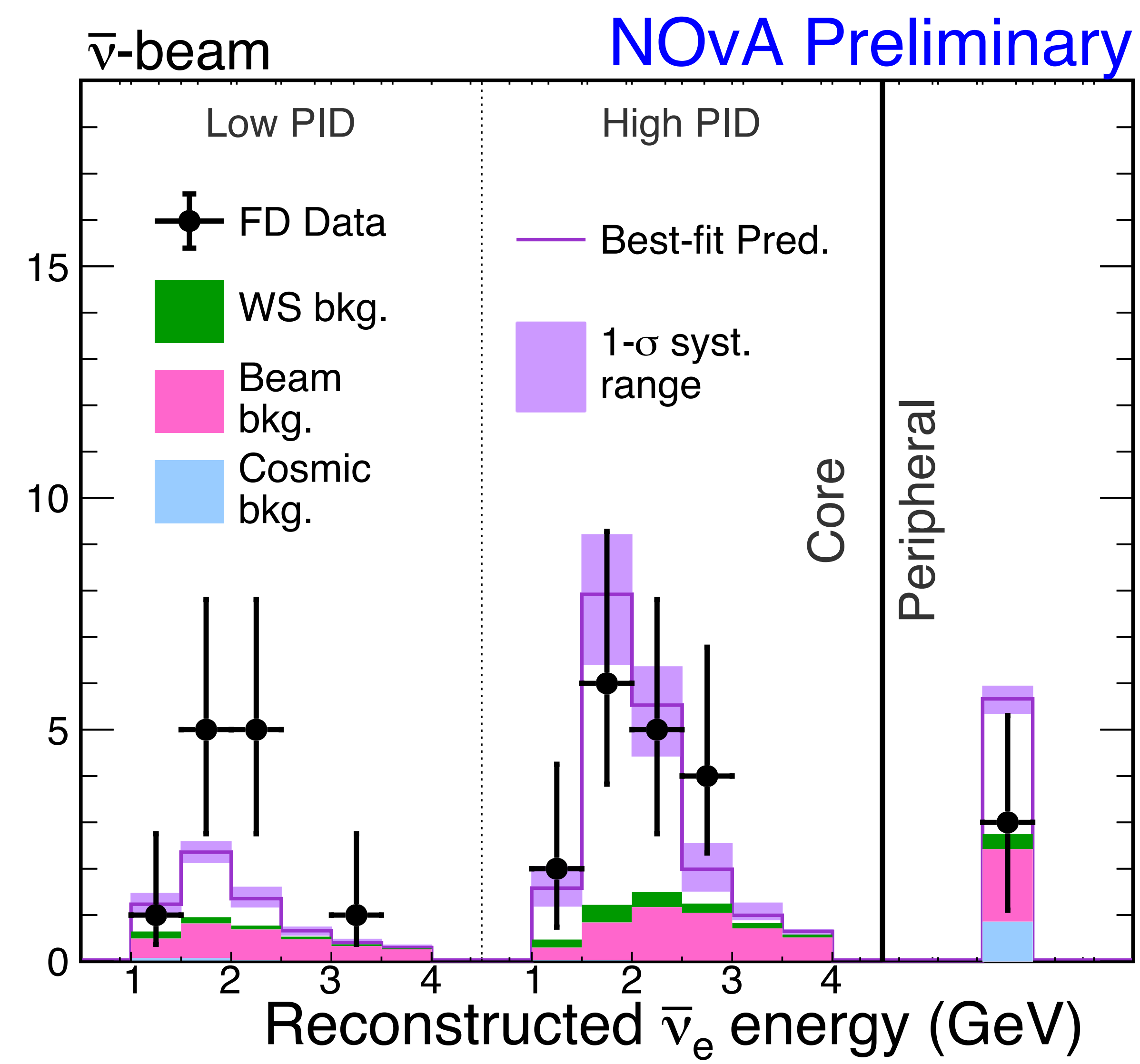
384 events, 11.3 background



106 events, 1.7 background

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

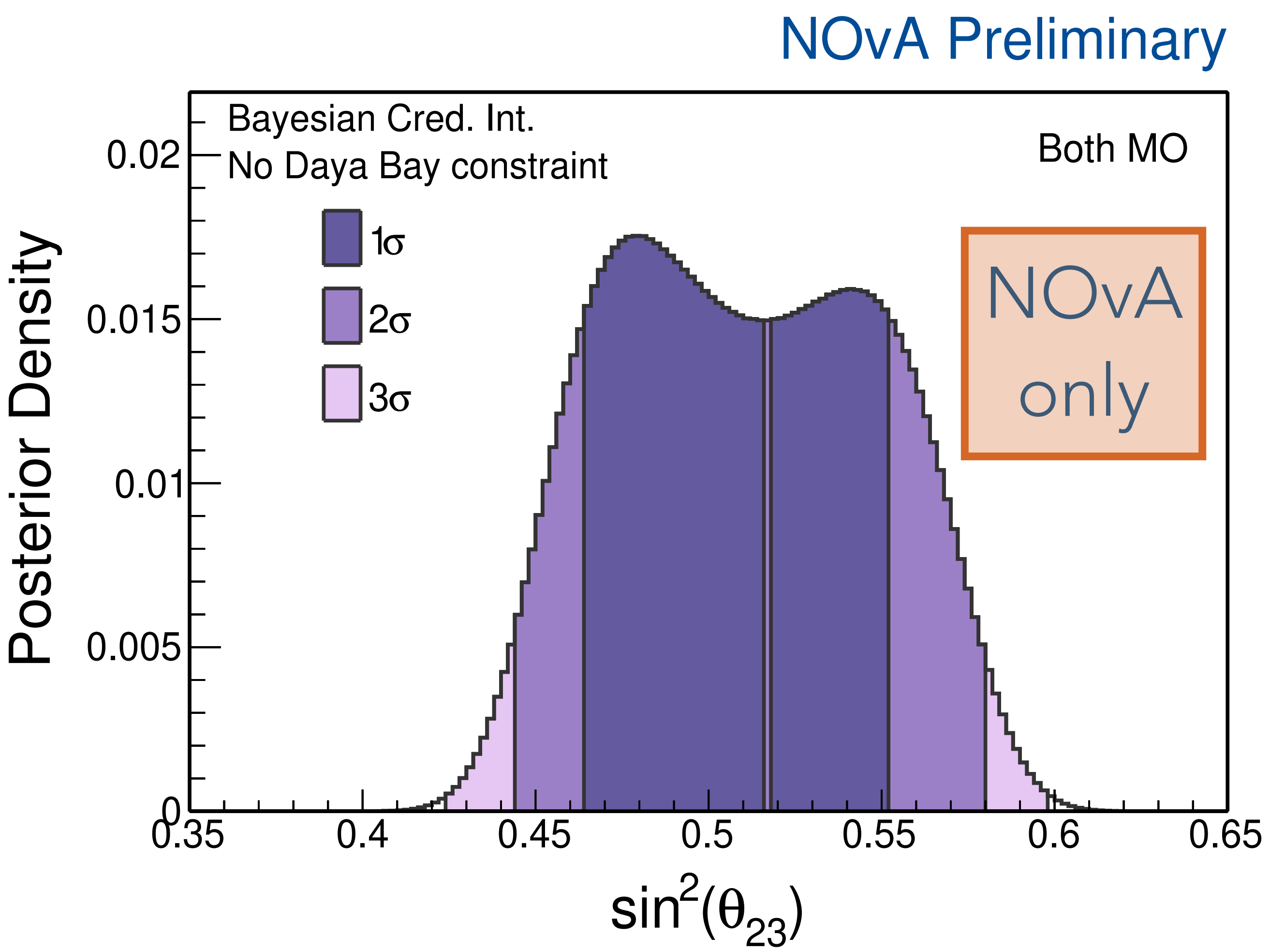


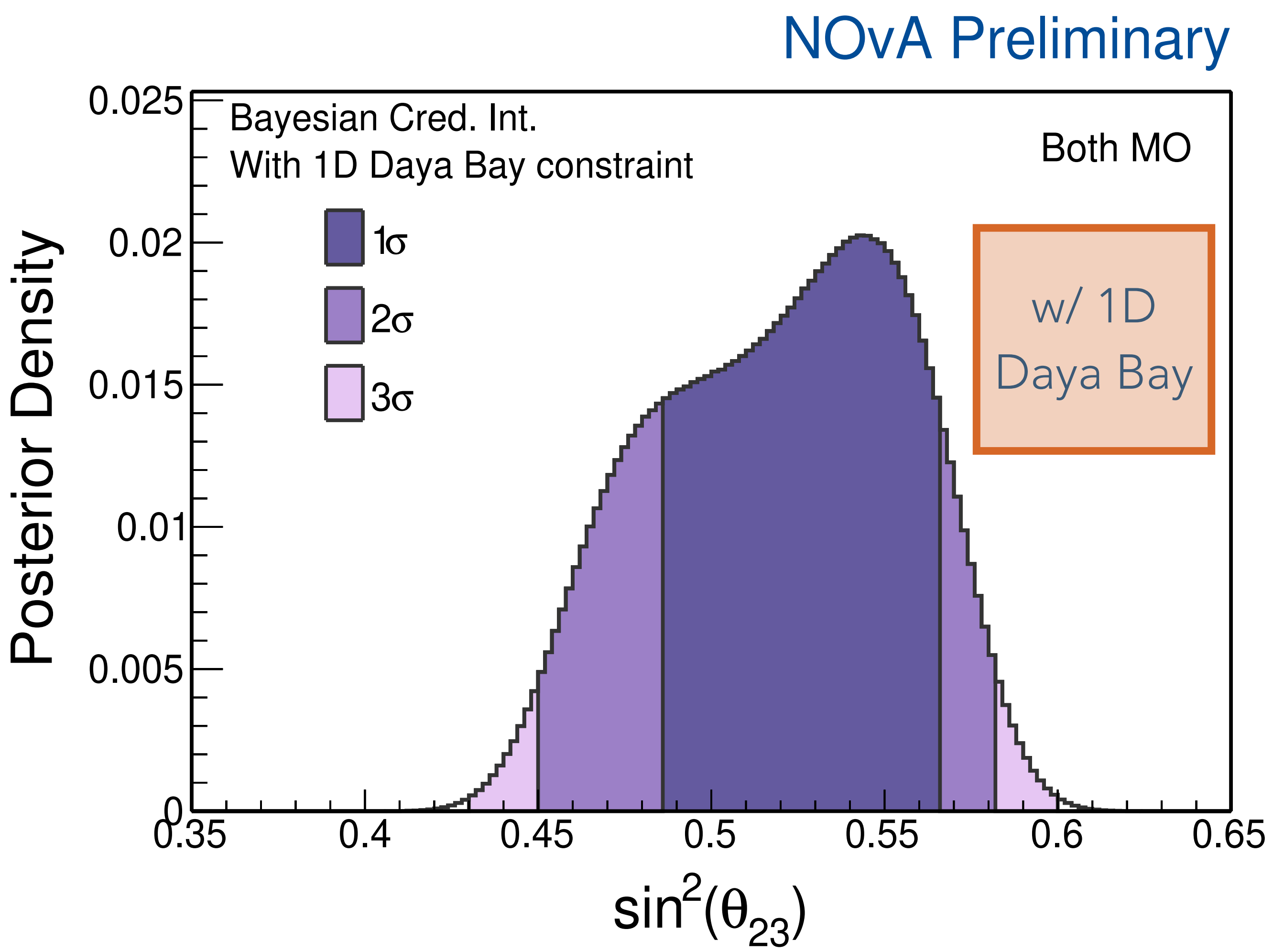


Total Observed	181	Range
Total Prediction	186.2	119-250
Wrong-sign	1.8	0.6-1.7
Beam Bkgd.	53.7	
Cosmic Bkgd.	6.2	
Total Bkgd.	61.7	61-63

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

$\nu_2 - \nu_3$ Sector

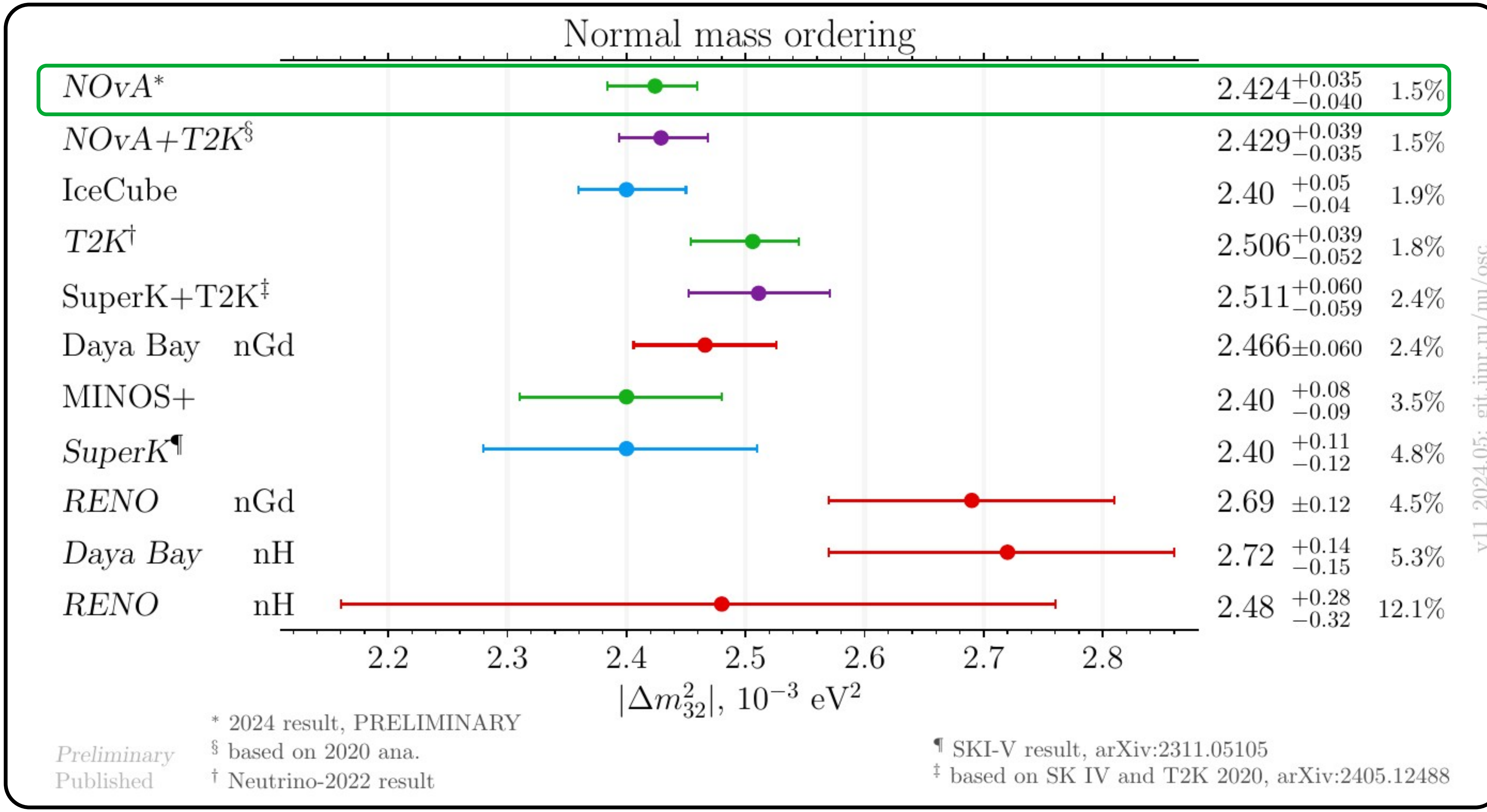




Maximal mixing is allowed at $< 1\sigma$ in both cases.

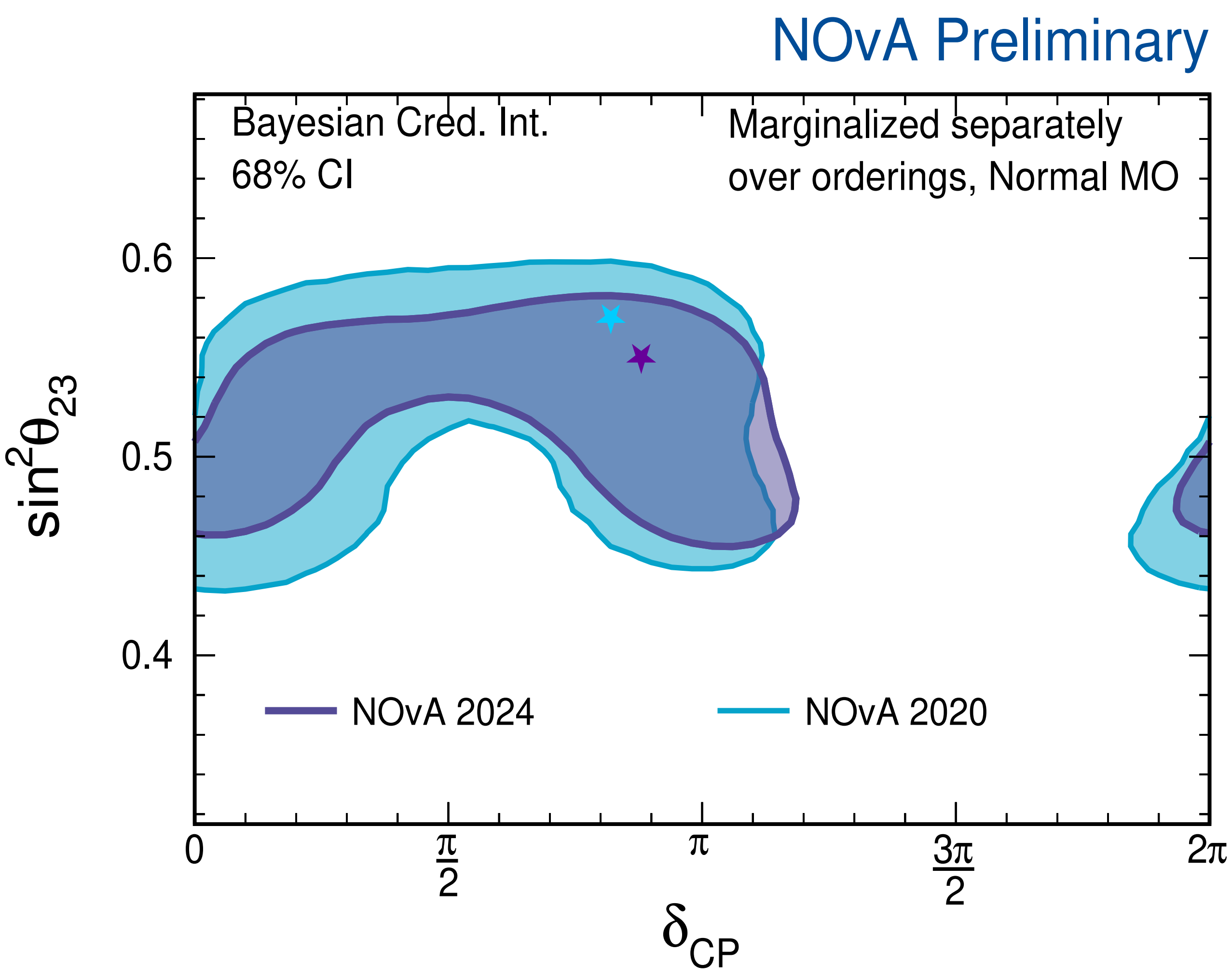
Mild upper octant preference w/ 1D constraint (Bayes Factor 2.2, 69% odds).

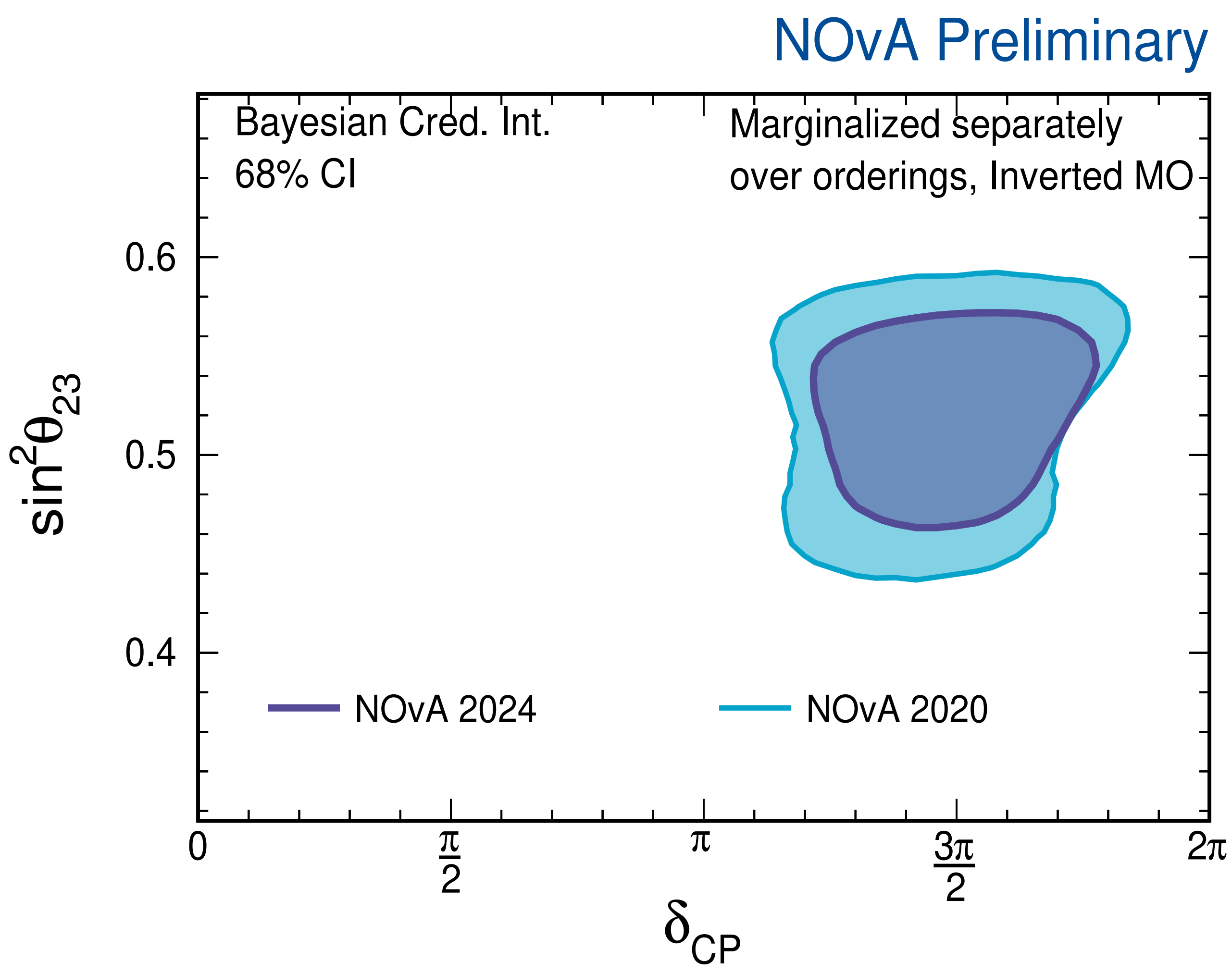
$\nu_2 - \nu_3$ Sector



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

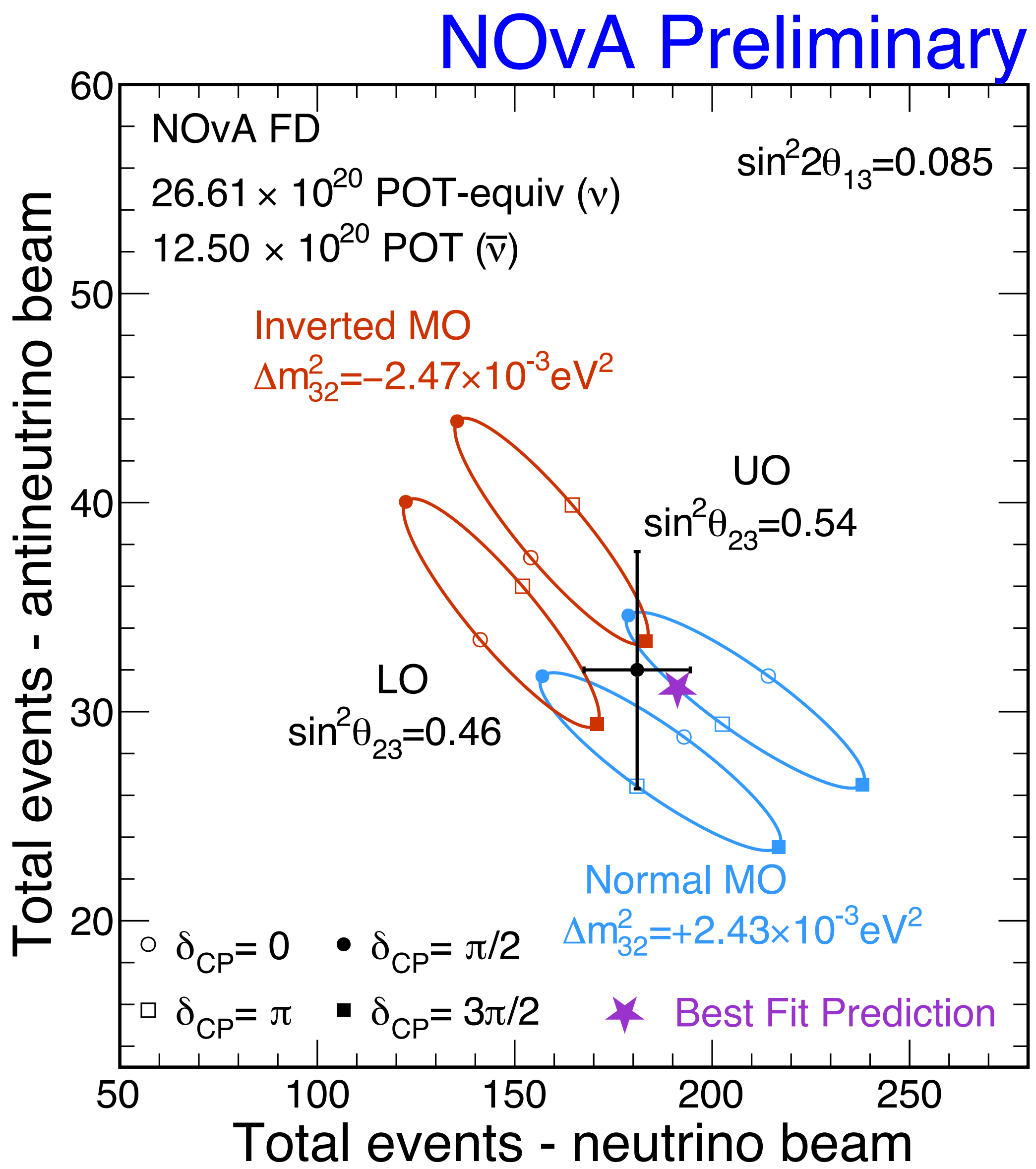
Mass Ordering with θ_{23} & δ_{CP}

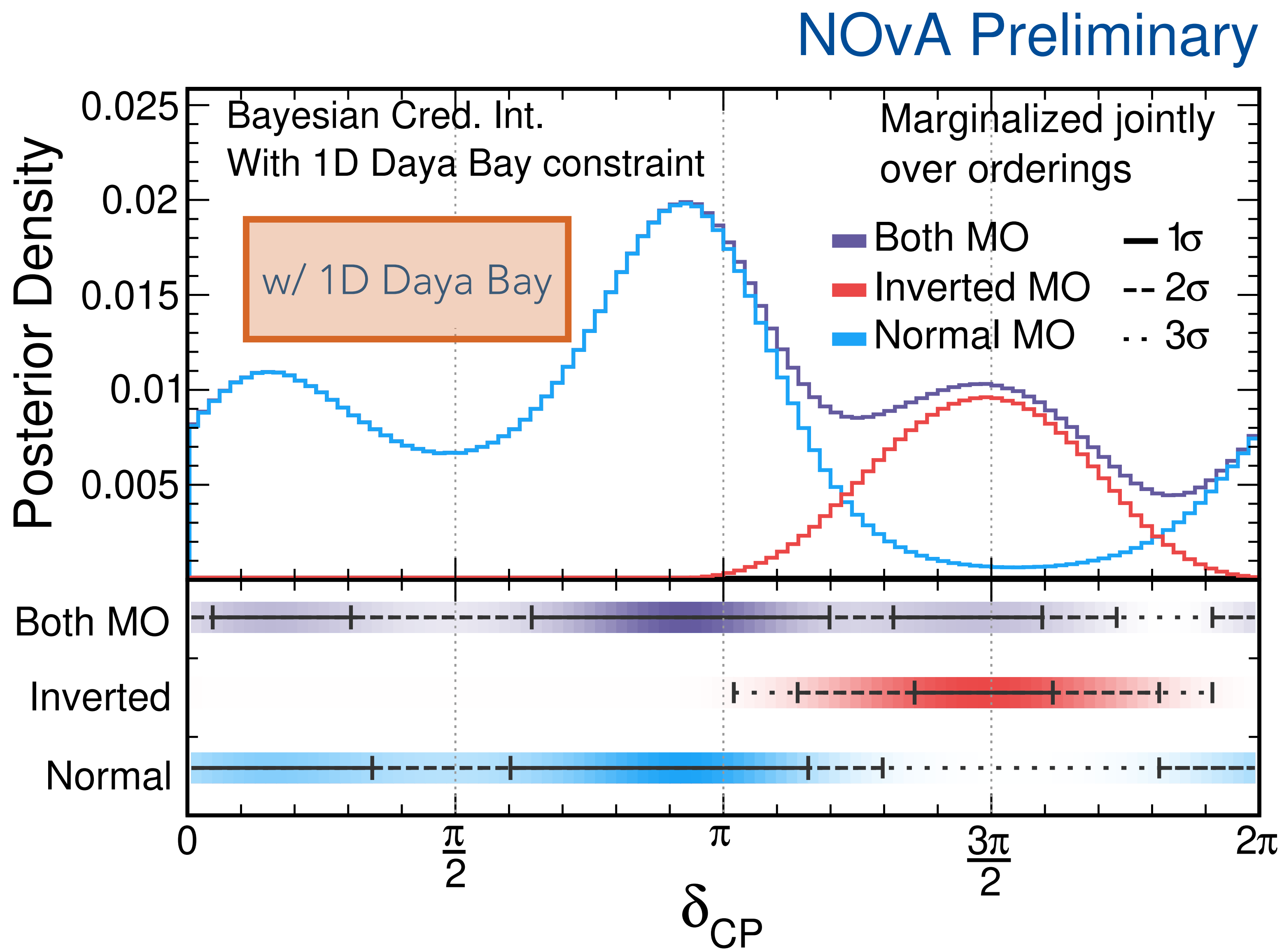




- Consistency with previous result (*different reactor constraints used).
- Tighter contours almost everywhere.

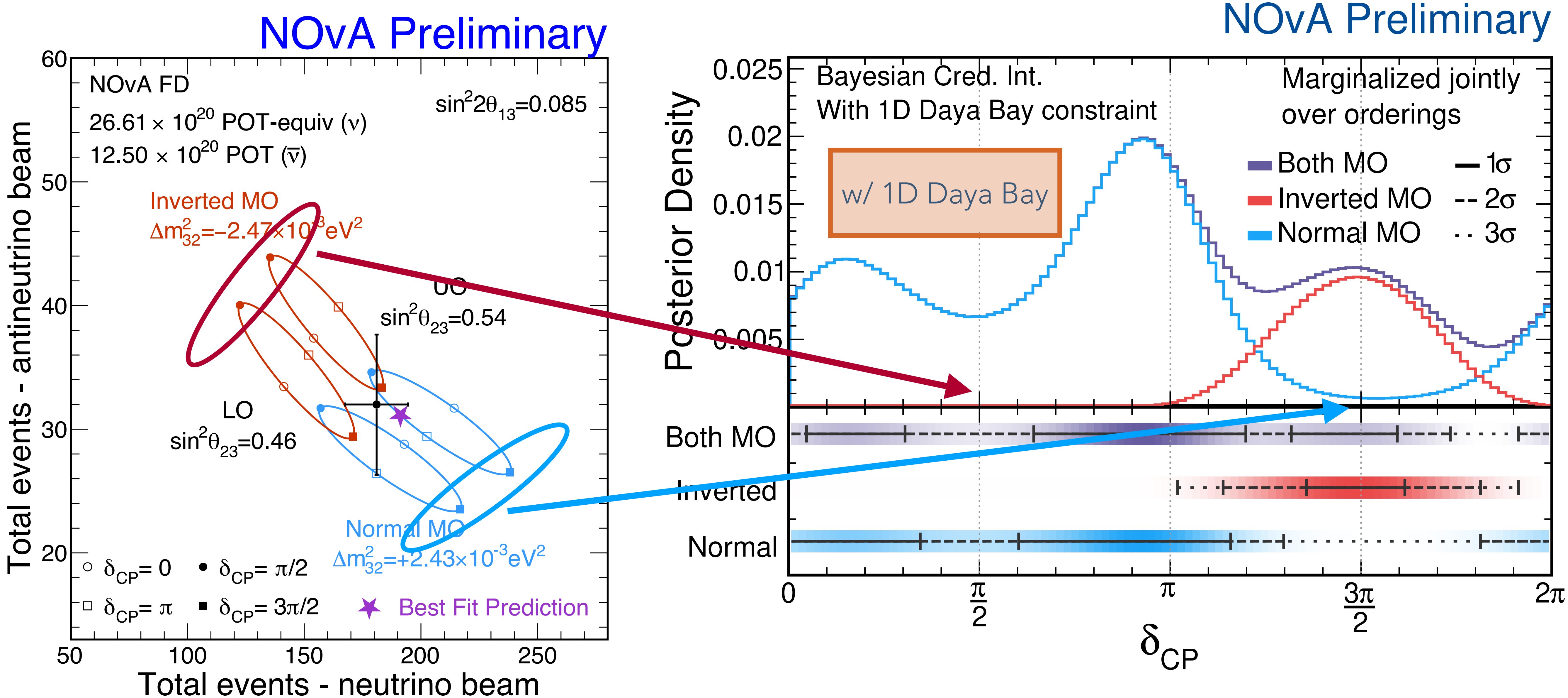
Mass Ordering with δ_{CP}





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

Mass Ordering with δ_{CP}

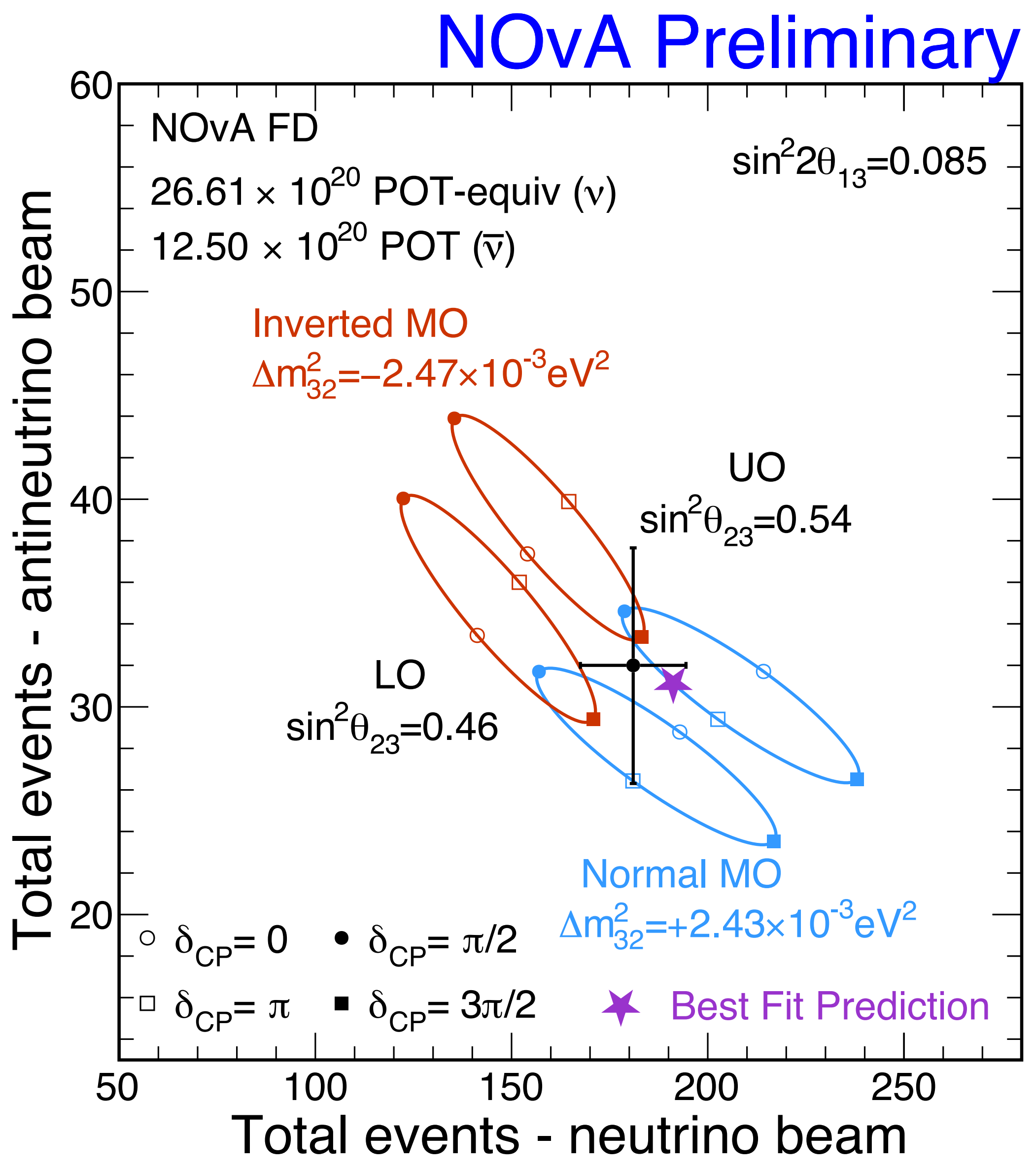


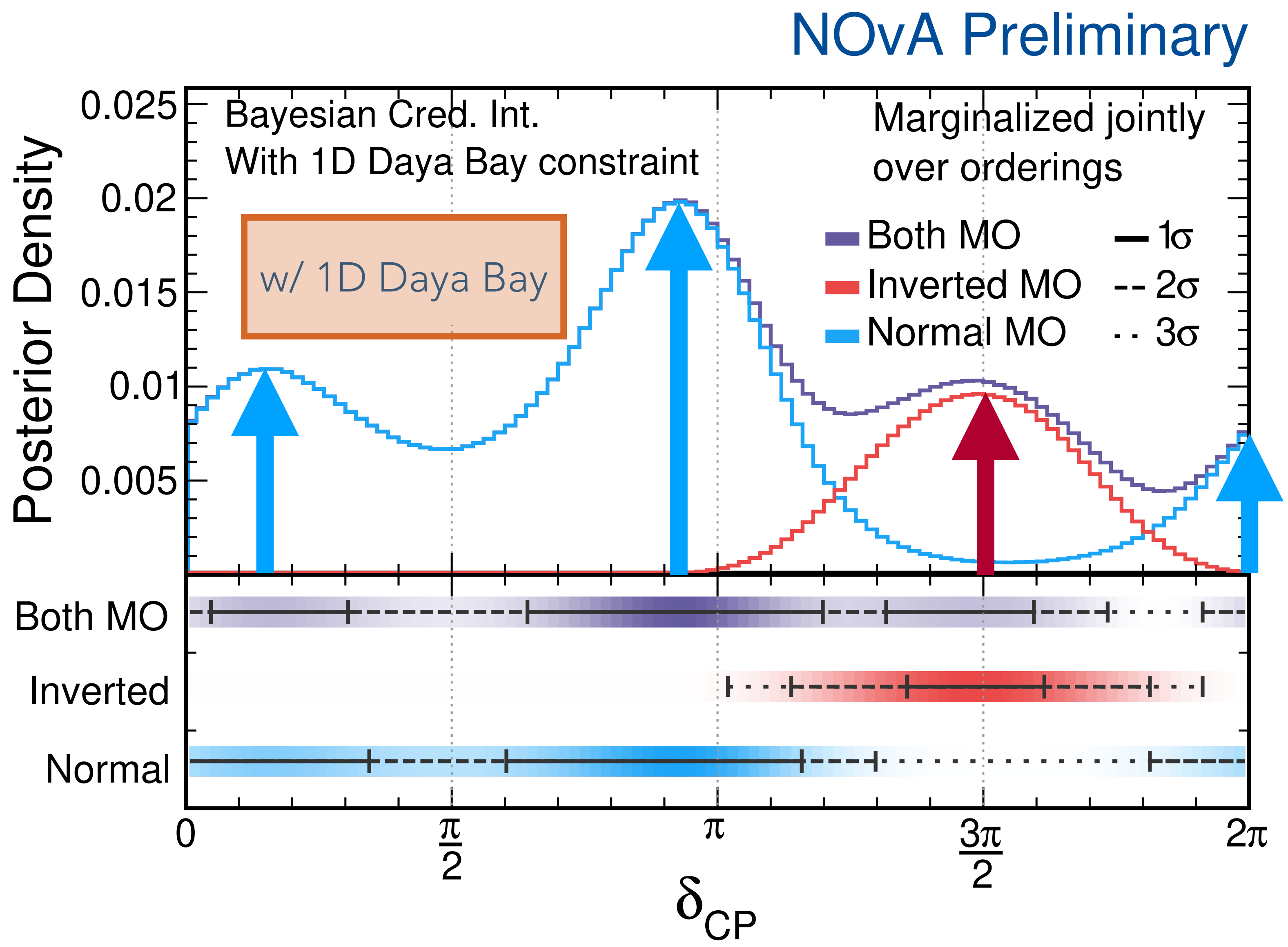
- No strong asymmetry in the rates of appearance of ν_e and $\bar{\nu}_e$.
- Disfavour ordering-δ_{CP} combinations which would produce asymmetry.

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

Disfavour NO $\delta_{CP} = \frac{3\pi}{2}$ at ~2σ

Mass Ordering with δ_{CP}

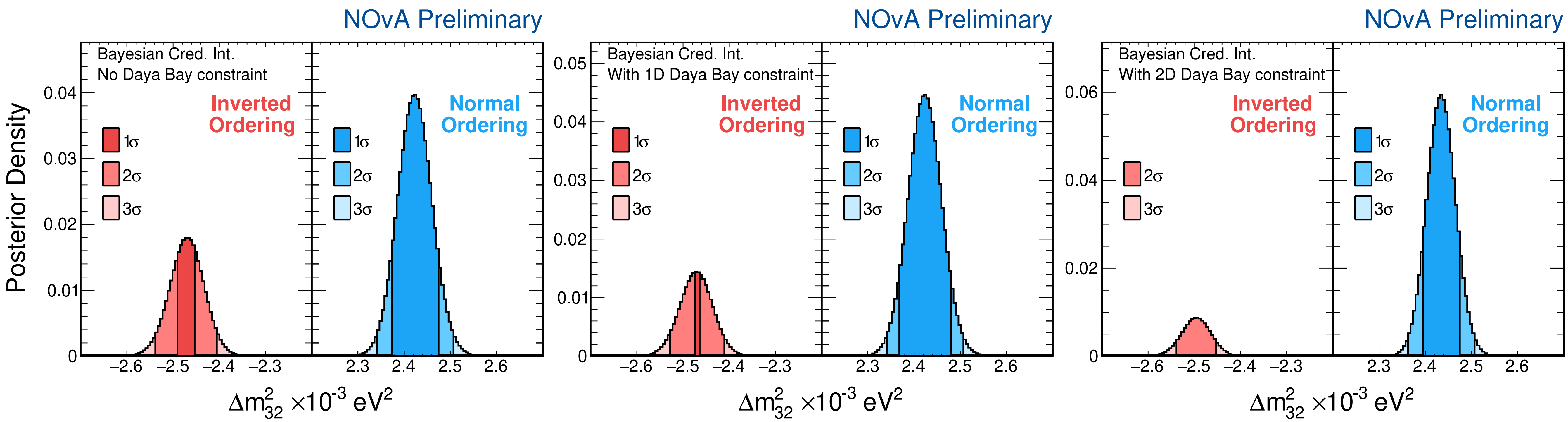




- No strong asymmetry in the rates of appearance of ν_e and $\bar{\nu}_e$.
- Disfavour ordering-δ_{CP} combinations which would produce asymmetry.

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

Mass Ordering with δ_{CP}



θ_{13} unconstrained
(NOvA only)
BF: 2.2, 69% odds

Daya Bay 1D θ_{13} constraint
BF: 3.2, 76% odds (1.4σ*)

Daya Bay 2D $(\Delta m^2_{32}, \theta_{13})$ constraint
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 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 with reactor measurements:
  - Constraint on θ_{13} enhances upper octant preference (69% odds).
  - Constraint on Δm^2_{32} enhances normal ordering preference (87% odds).

- Compelling future oscillation prospects for NOvA!
  - Collect as **many antineutrinos as we can** before 2027 - important for untangling degeneracies.
  - Analysis of **test beam data** on-going - reduce uncertainties related to detector energy scale.
  - NOvA & T2K are actively exploring the scope and timeline for the next steps to take joint fit work forward.

Questions?

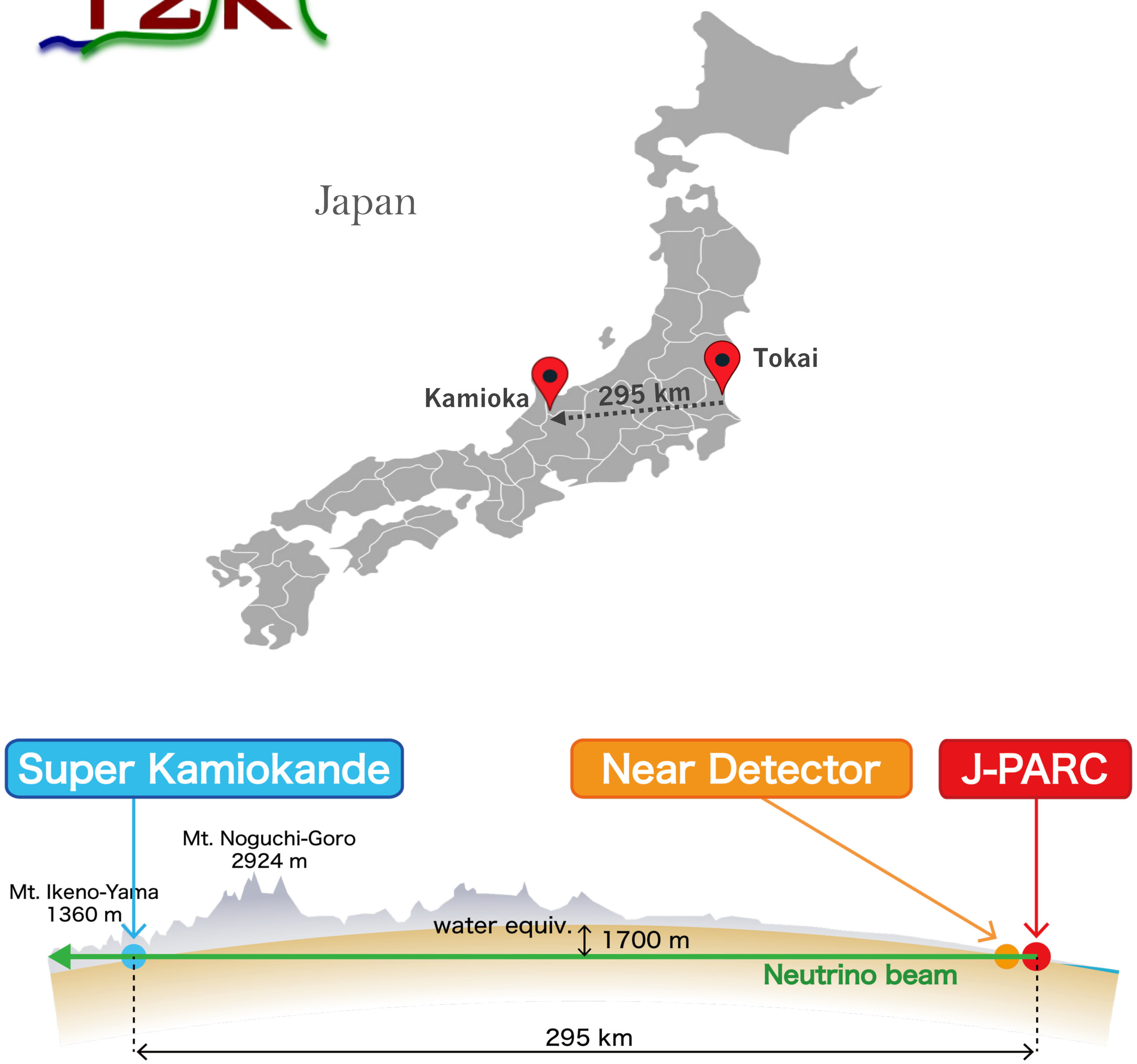
Back-up

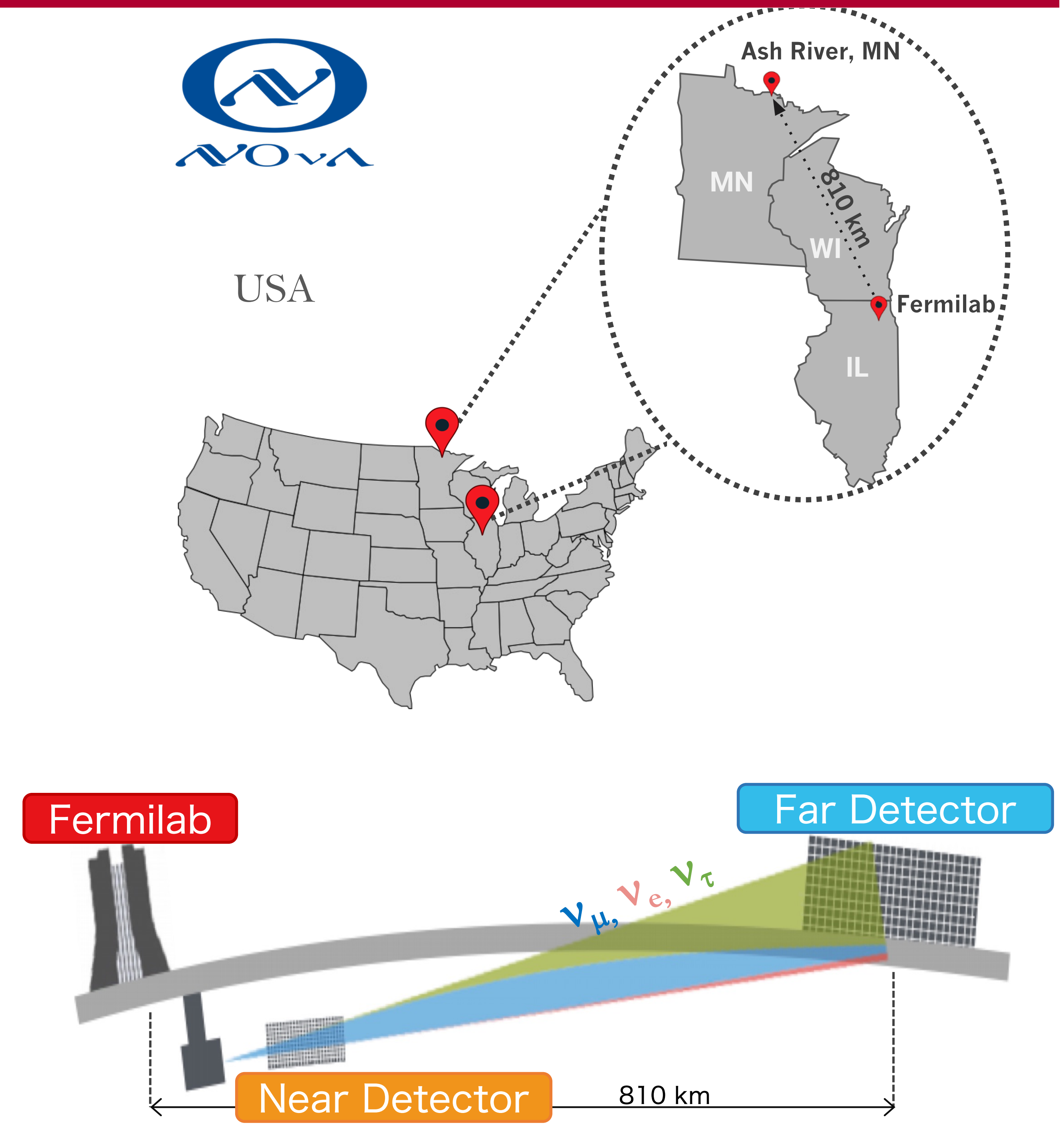
Queen Mary
University of London

T2K-NOvA Joint Fit

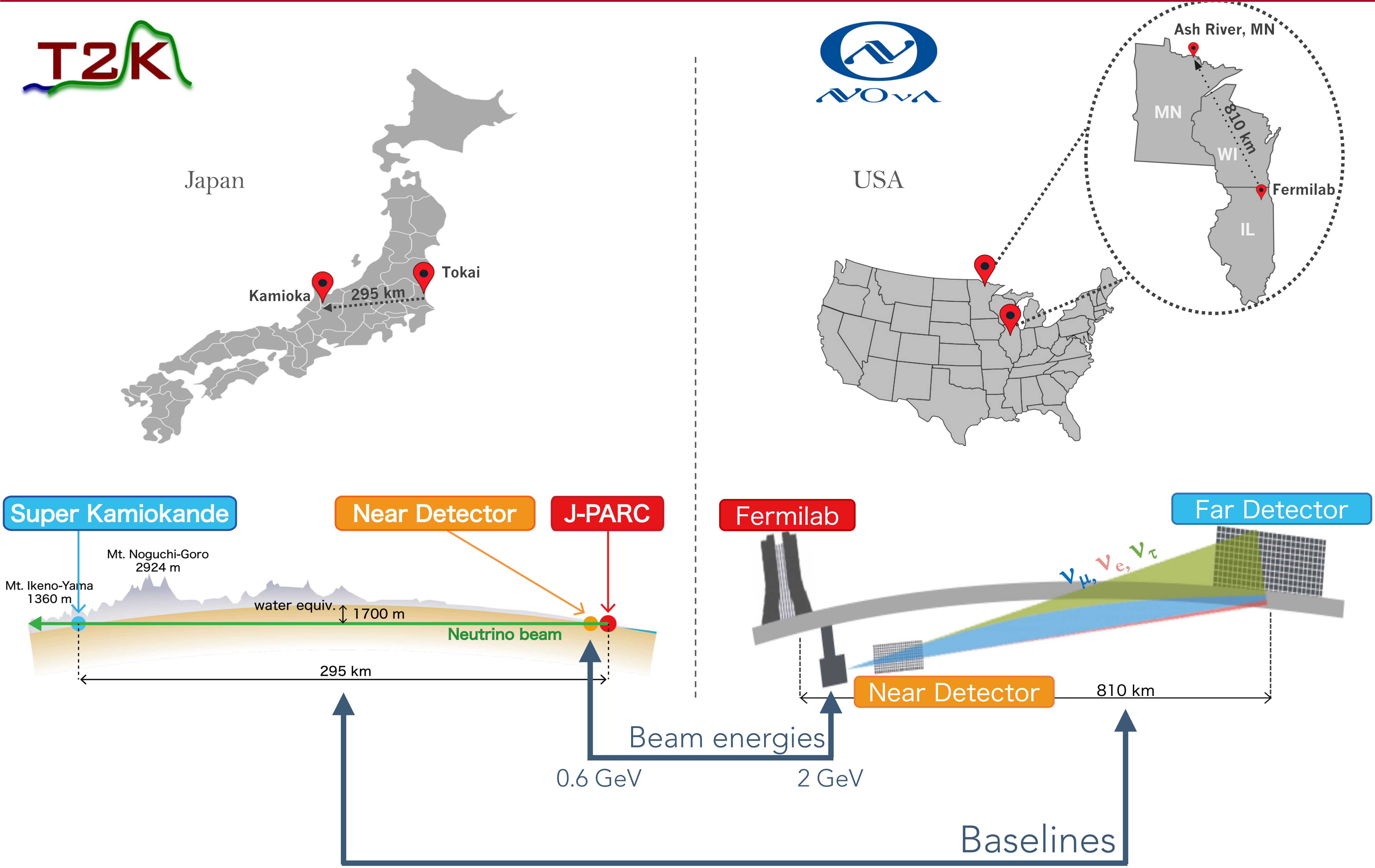
Queen Mary
University of London

Combining Long-baseline Experiments



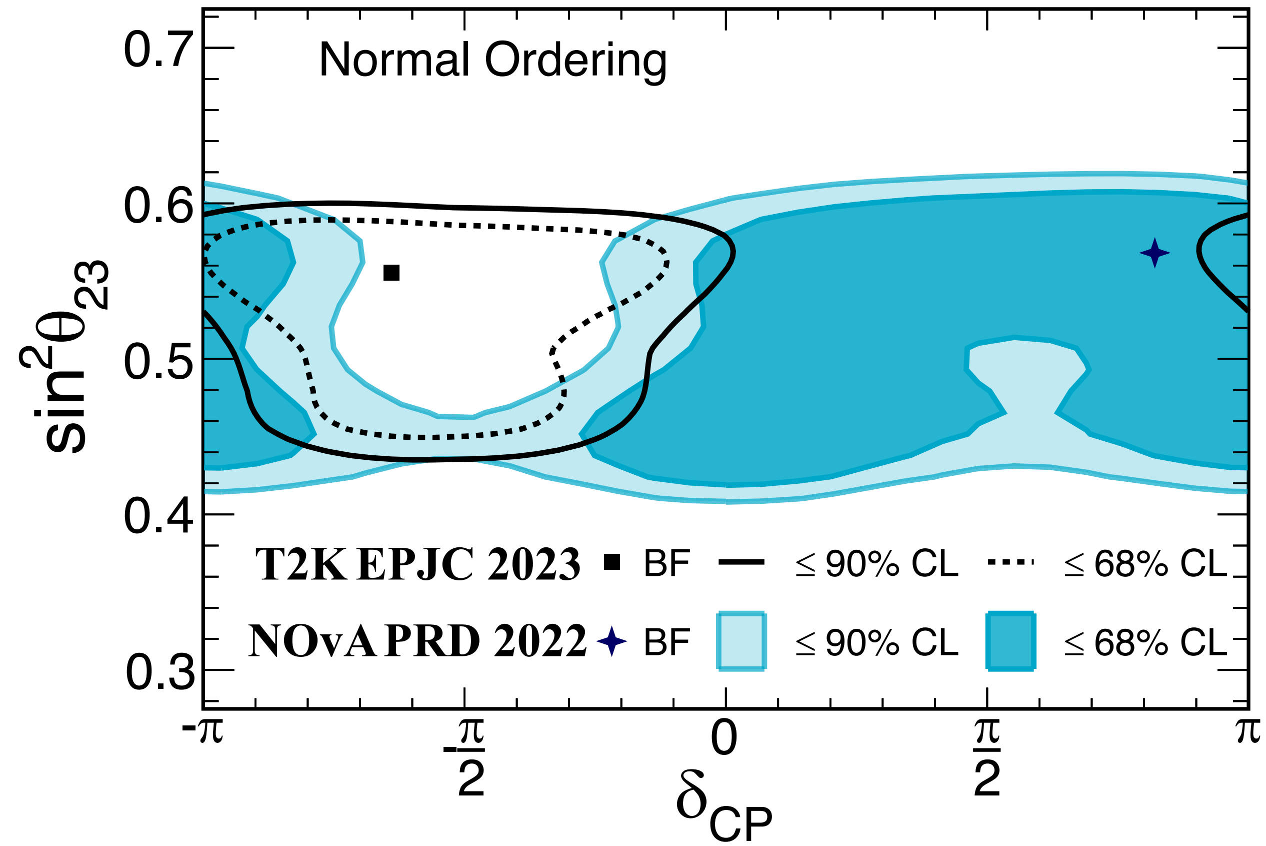


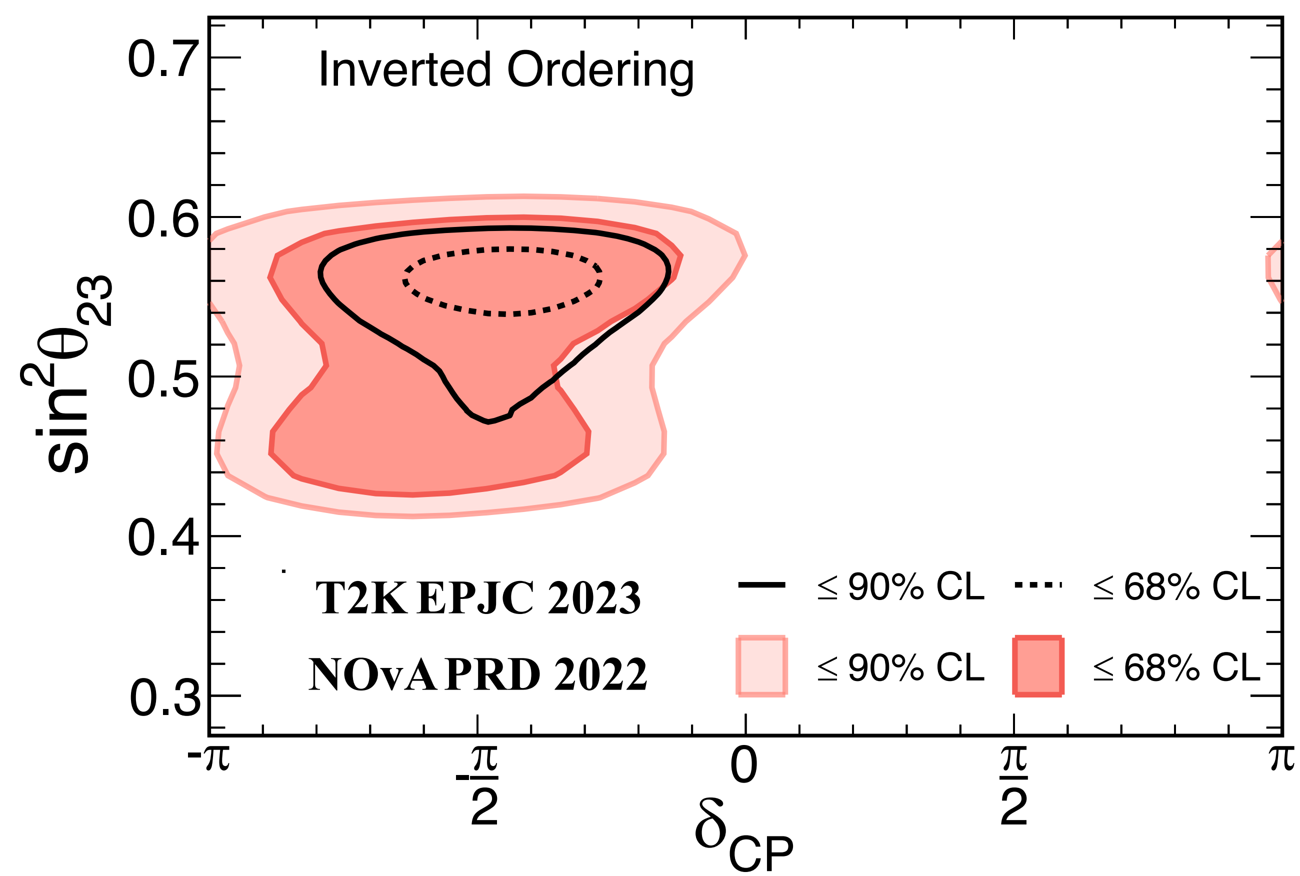
Combining Long-baseline Experiments



Why Combine T2K & NOvA?

- Complementarity between the two experiments provides the power to **break degeneracies**.
  - Joint Analysis probes different oscillation environments, lifting degeneracies of individual experiments.
- In-depth review of:
  - Models, systematic uncertainties and possible correlations.
  - Different analysis approaches driven by contrasting detector design.
- Full implementation of:
  - Energy reconstruction and detector response of both experiments.
  - Combined detailed likelihood of both experiments.
  - Consistent statical inference across full dimensions of phase space.





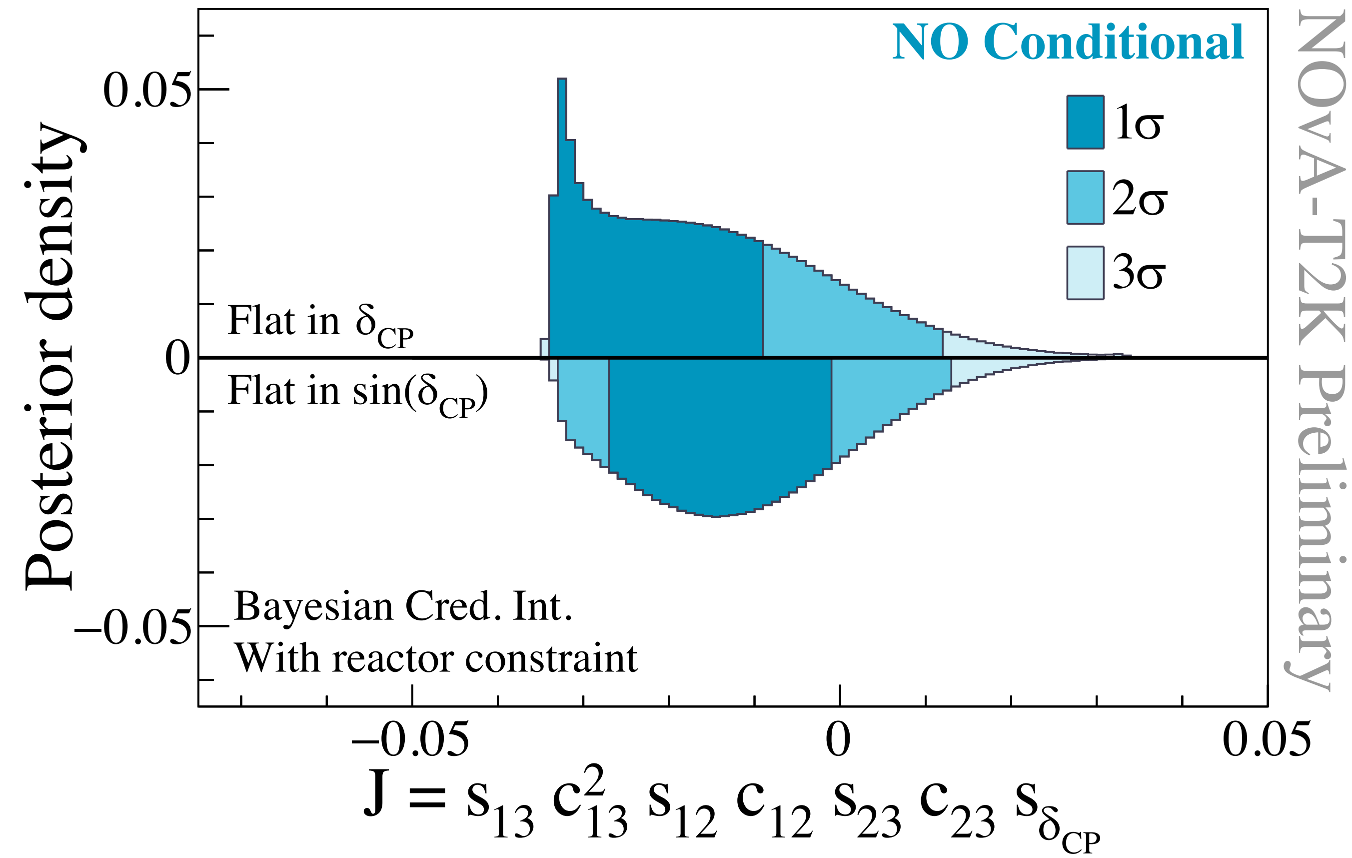
CP Violation

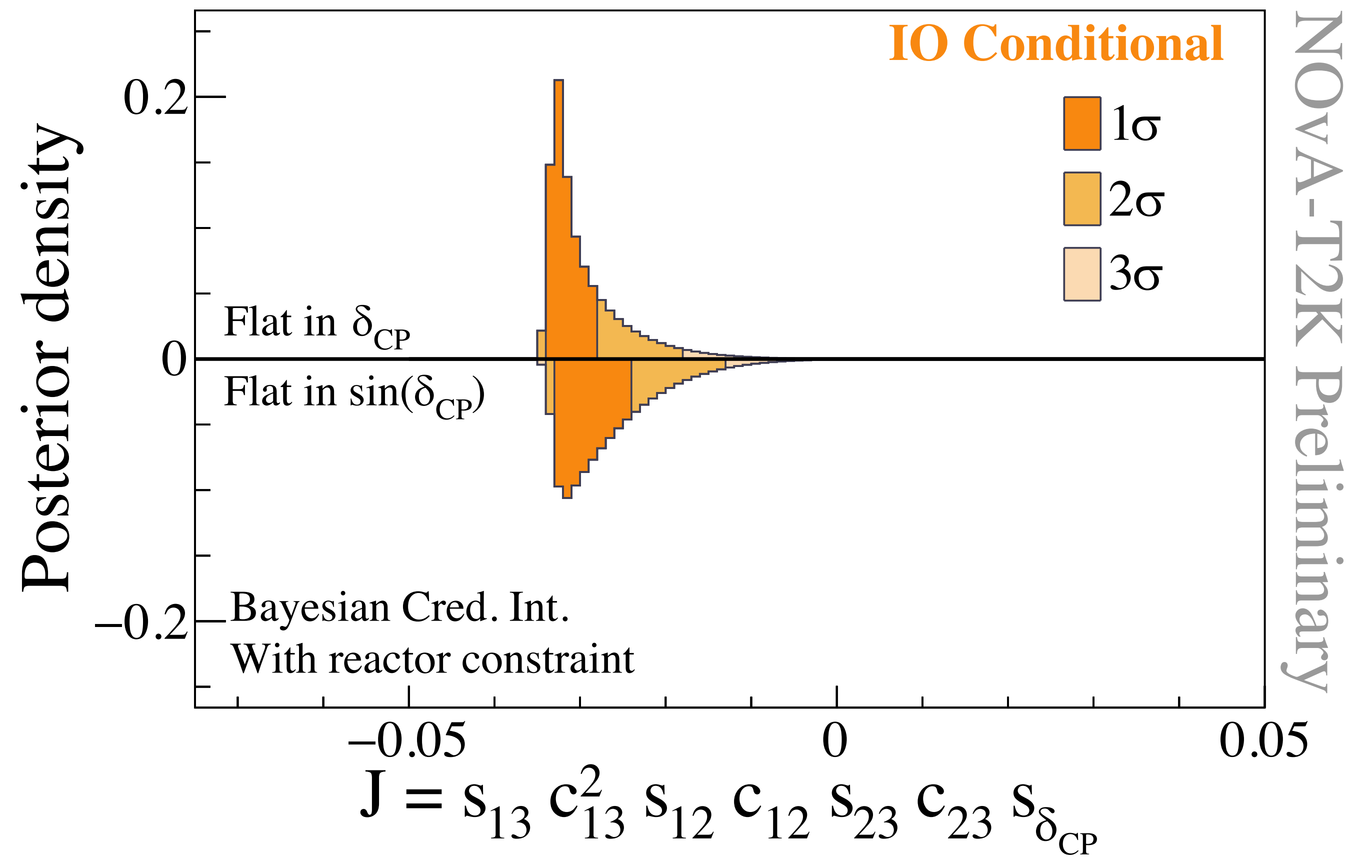
- Jarlskog-invariant is **parameterisation-independent*** way to measure CP violation.

$$J = \sin\theta_{13} cos^2\theta_{13} \sin\theta_{12} \cos\theta_{12} \sin\theta_{23} \cos\theta_{23} \sin\delta_{CP}$$

$J = 0$: CP conversed, $J \neq 0$: CP Violation

- $J = 0$ lies outside of the 3σ credible interval for the Inverted Ordering.
- For Normal Ordering, a considerably wider range of probable values for J.

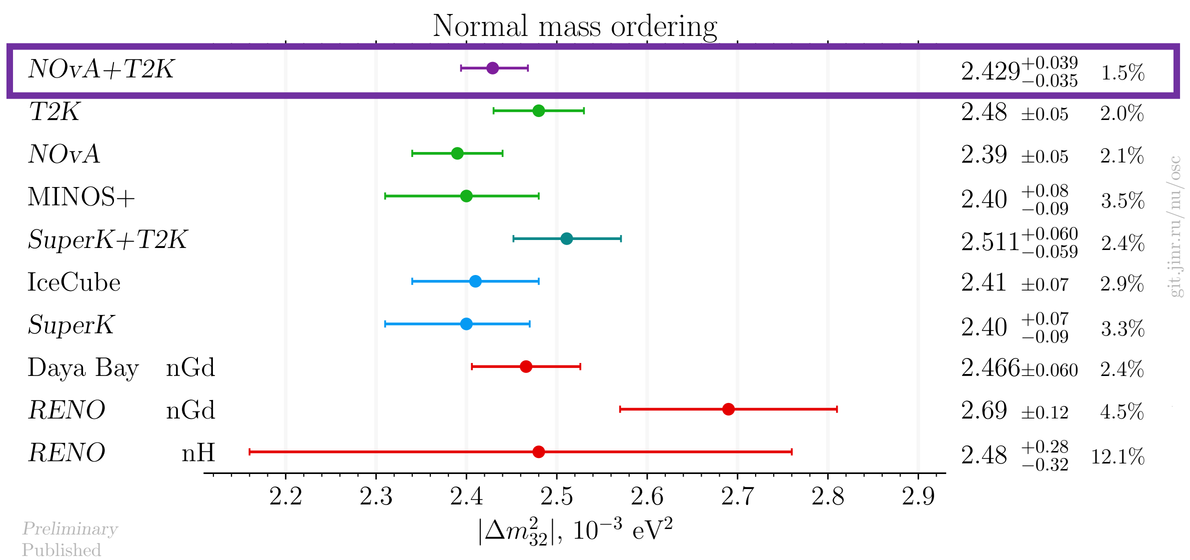


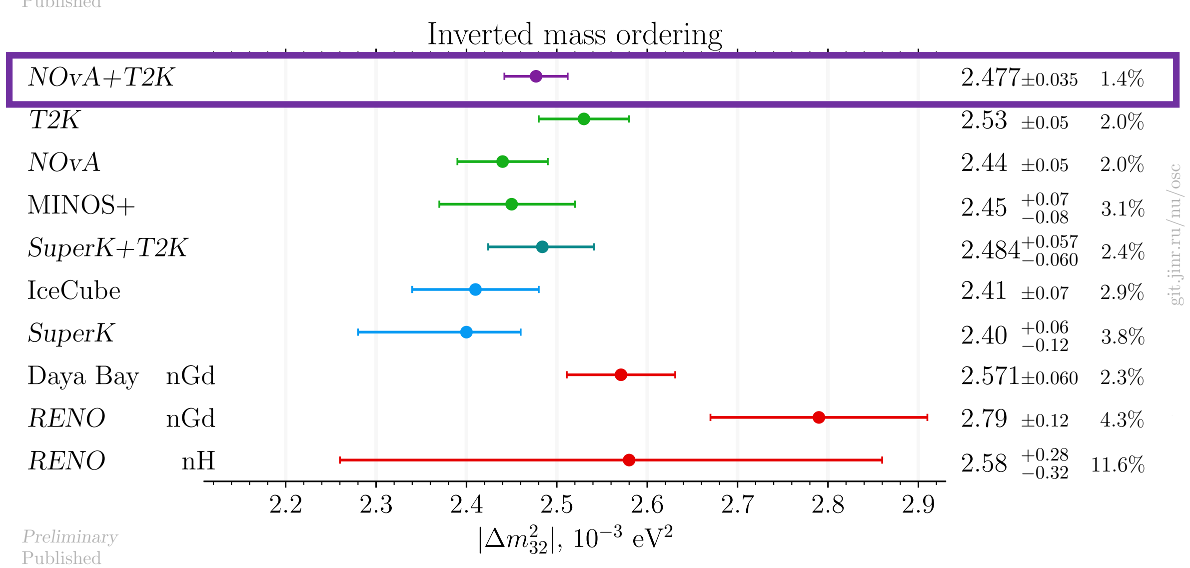


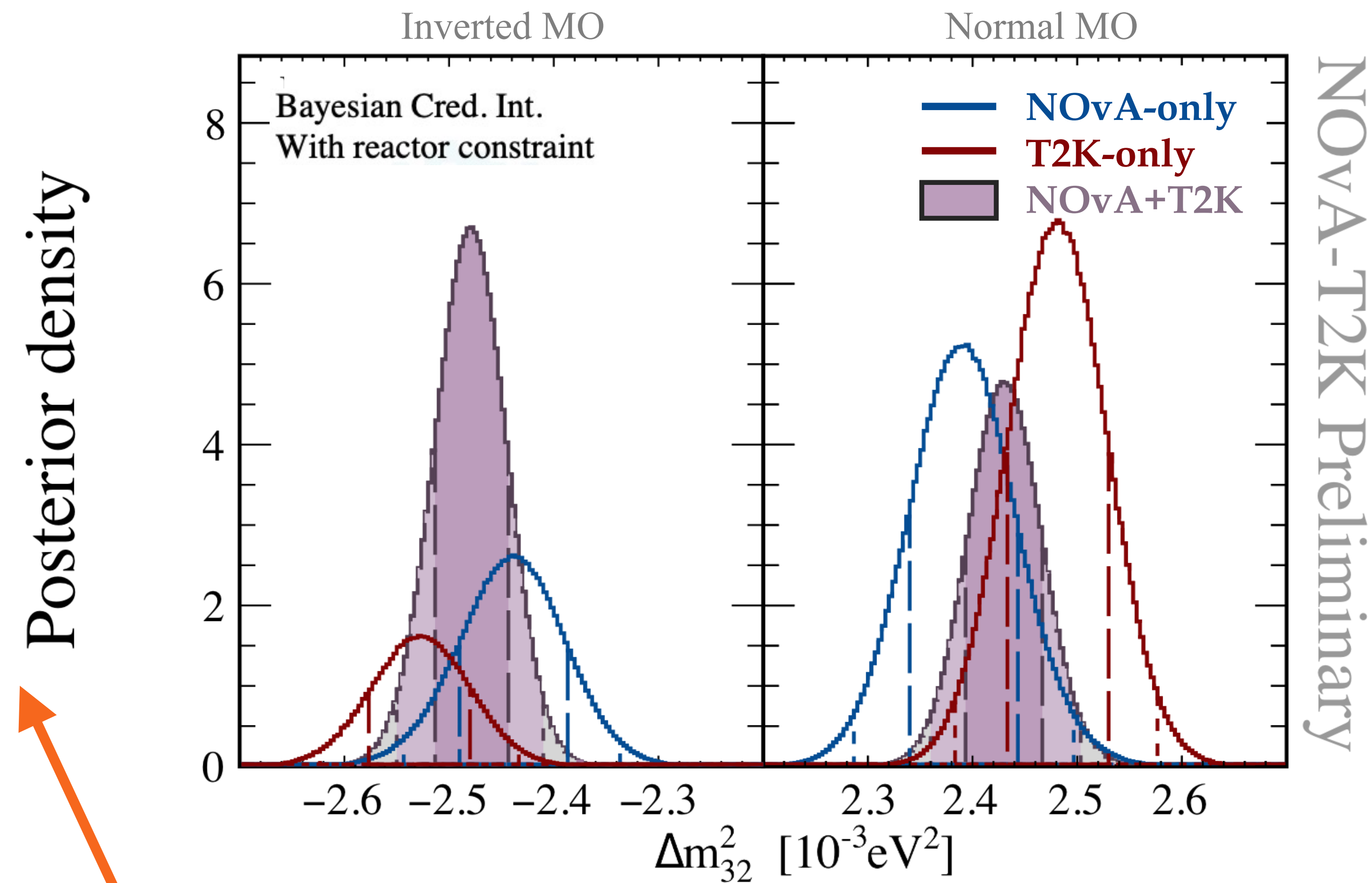
*Phys. Rev. D 100, 053004 (2019)

Δm^2_{32} & Mass Ordering

- Compare fraction of posterior density in each Mass Ordering.
- **Inverted ordering is weakly preferred** with a Bayes factor of 1.36 (IO/NO).

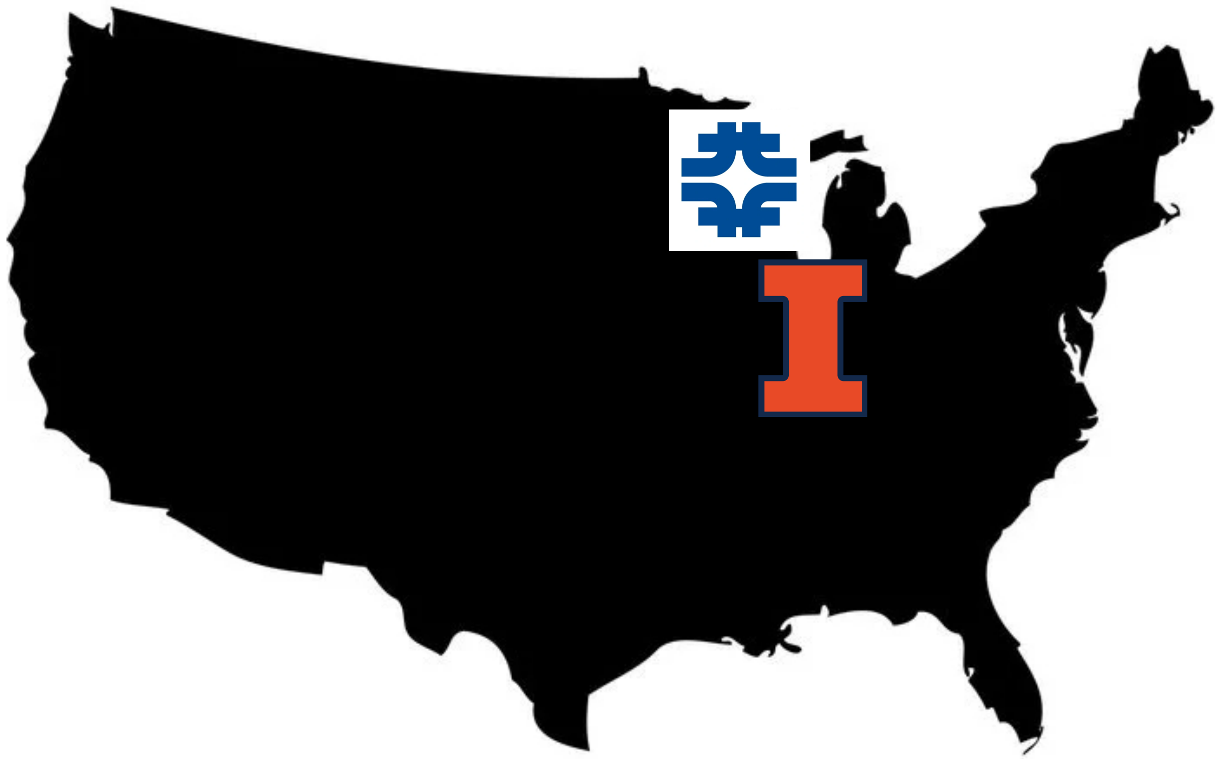


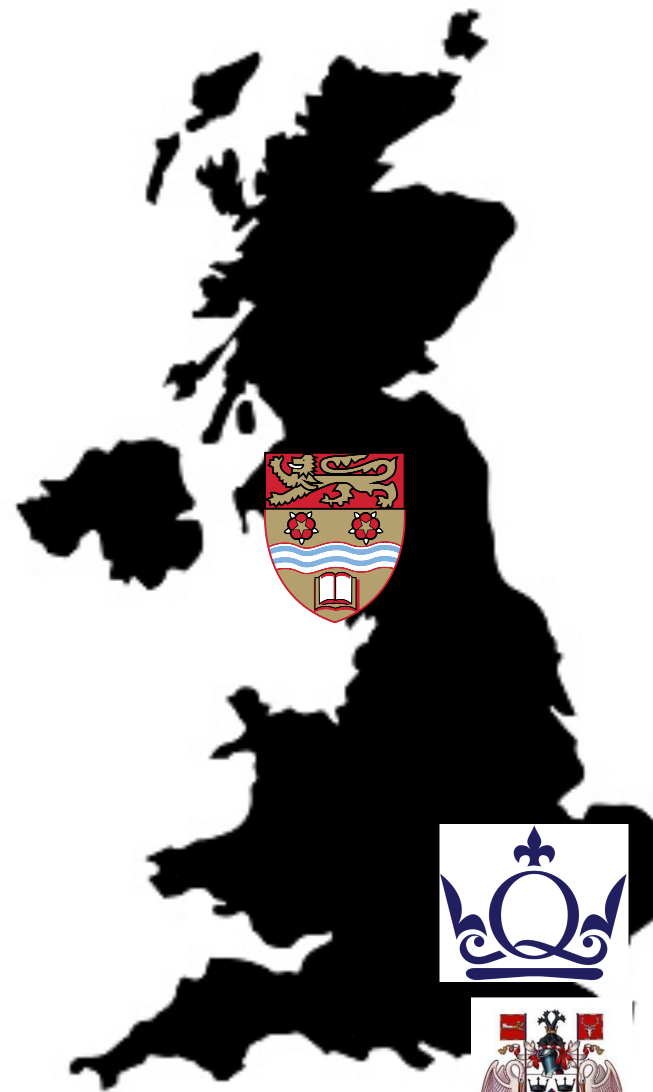


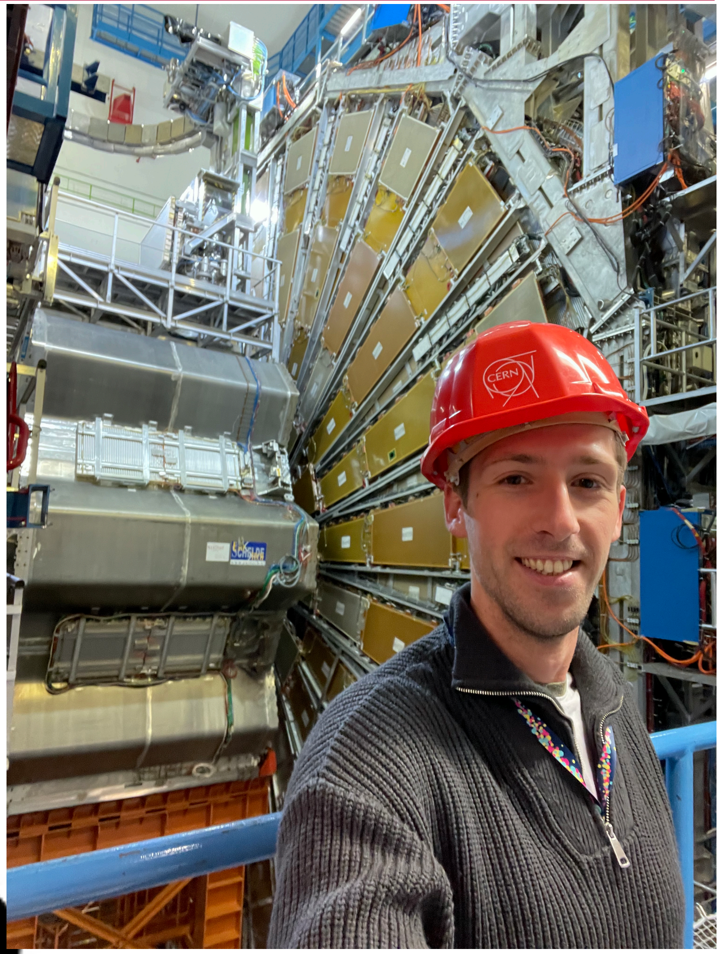


Smallest (equal*) uncertainty on $|\Delta m^2_{32}|$ as compared to other previous measurements.

A Bit About Me…





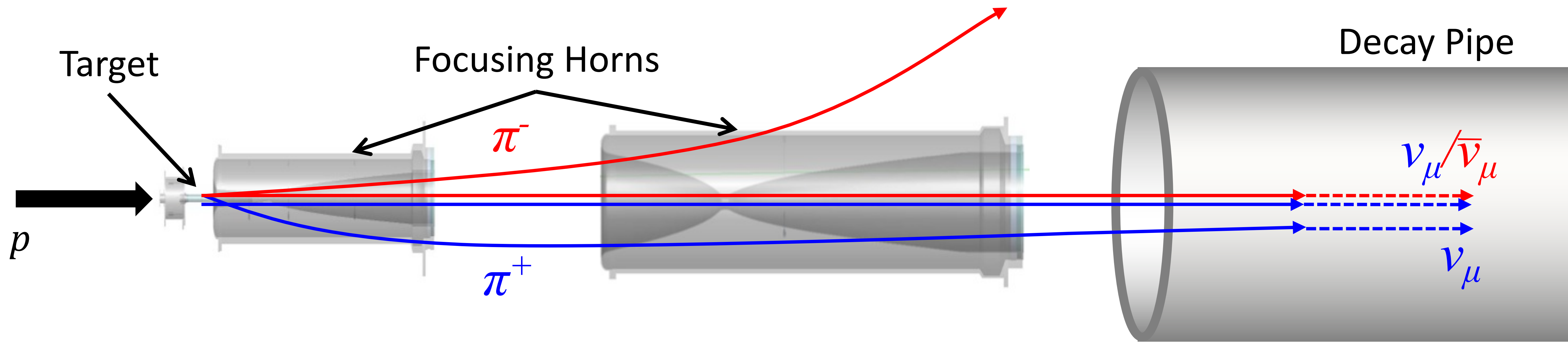


- PDRA at Queen Mary University of London.
- Collaborator in the NOvA & DUNE experiments.

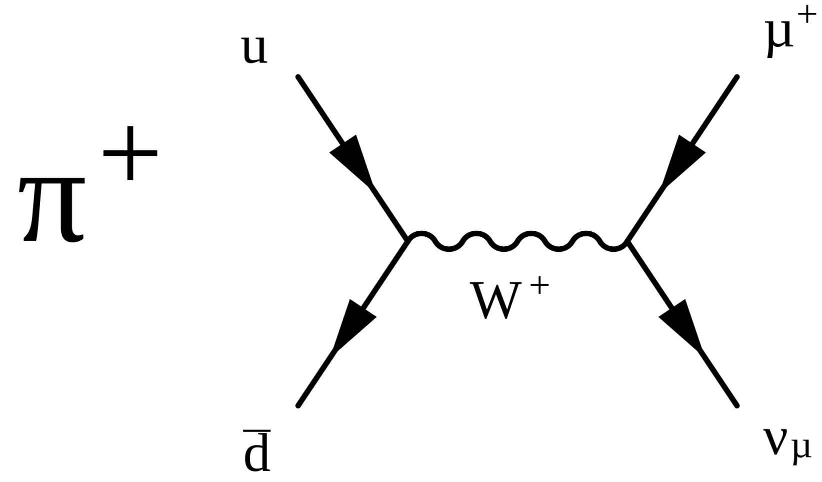
The NOvA Collaboration

QMUL is one of the collaboration's newest institutions.

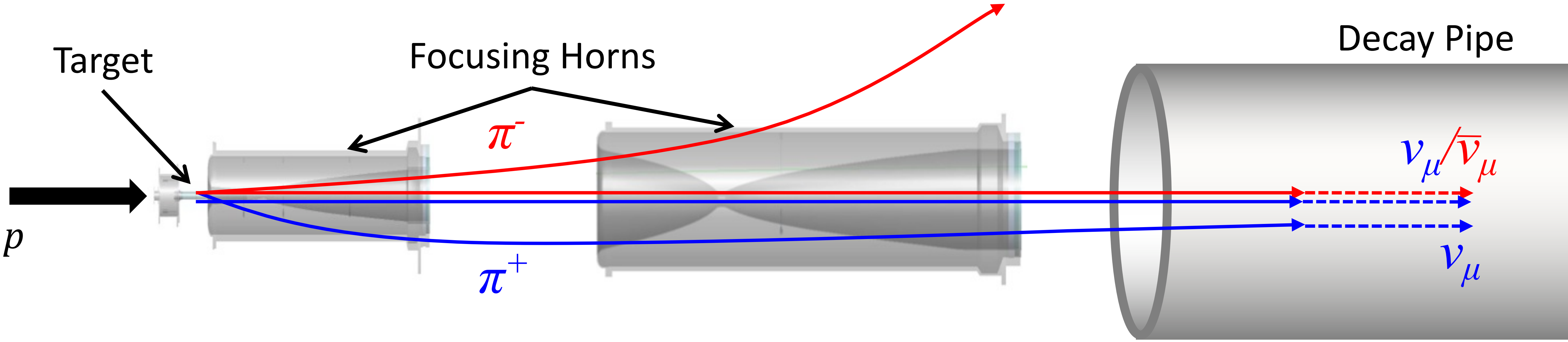
How We Make Neutrinos: NuMI Beam



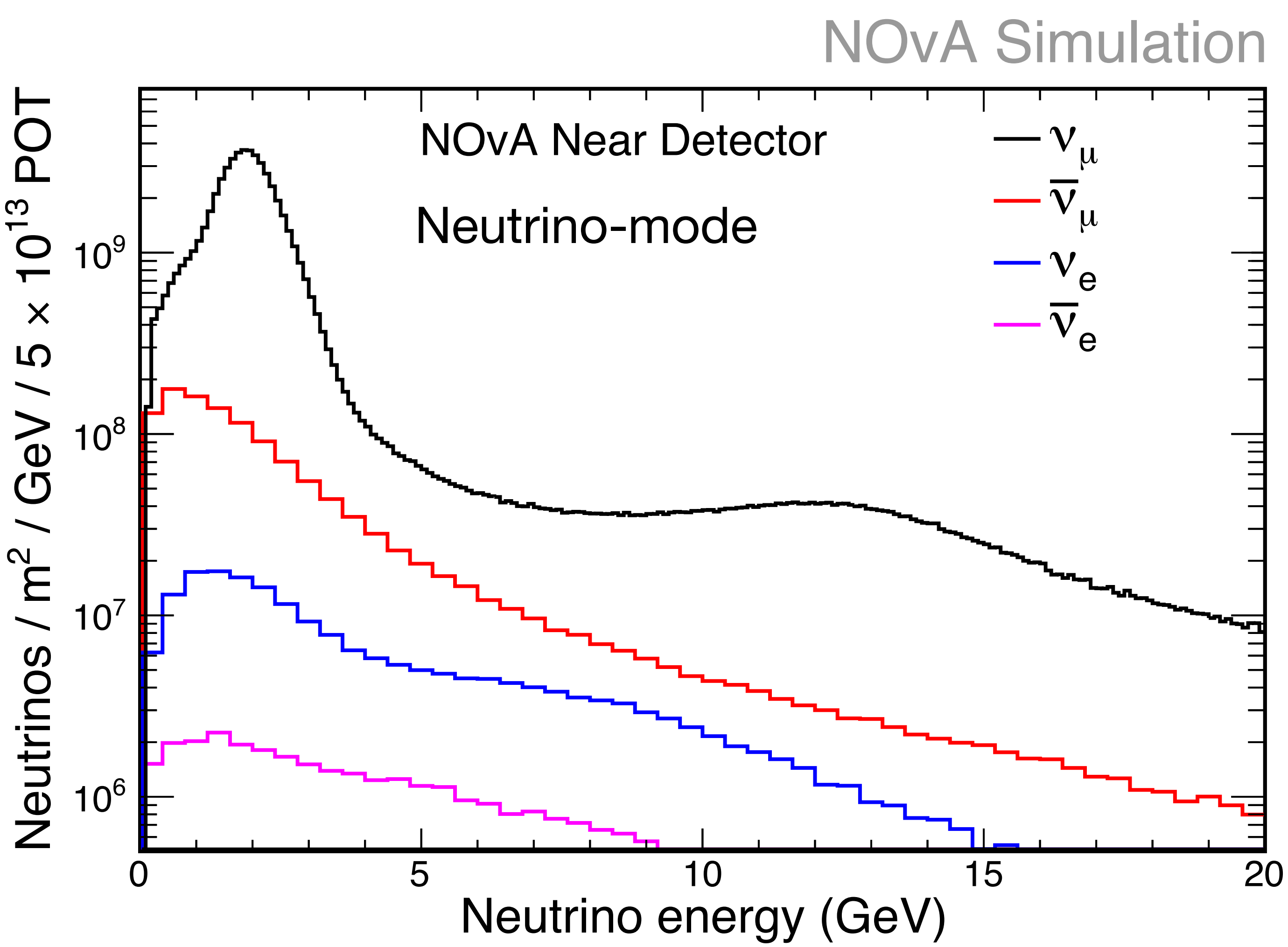
- 120 GeV protons from main injector onto graphite target.
- Spill every ~1.5 s, lasts 10 us.
- Hadron spray directed by focussing horns (± 200 kA, FHC/RHC).
- Pions decay (mostly) to muon/muon neutrino pairs.



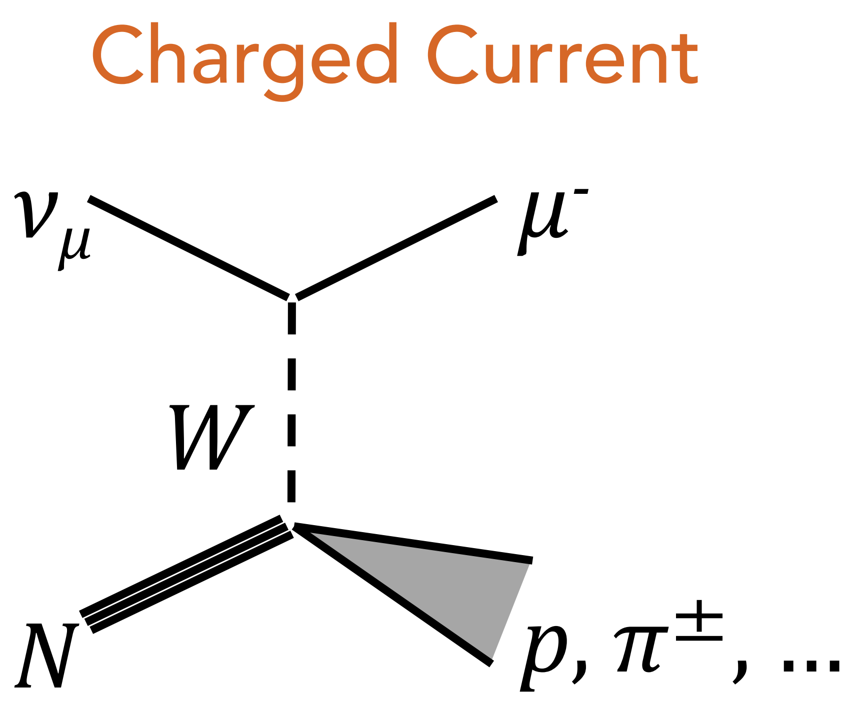
How We Make Neutrinos: NuMI Beam

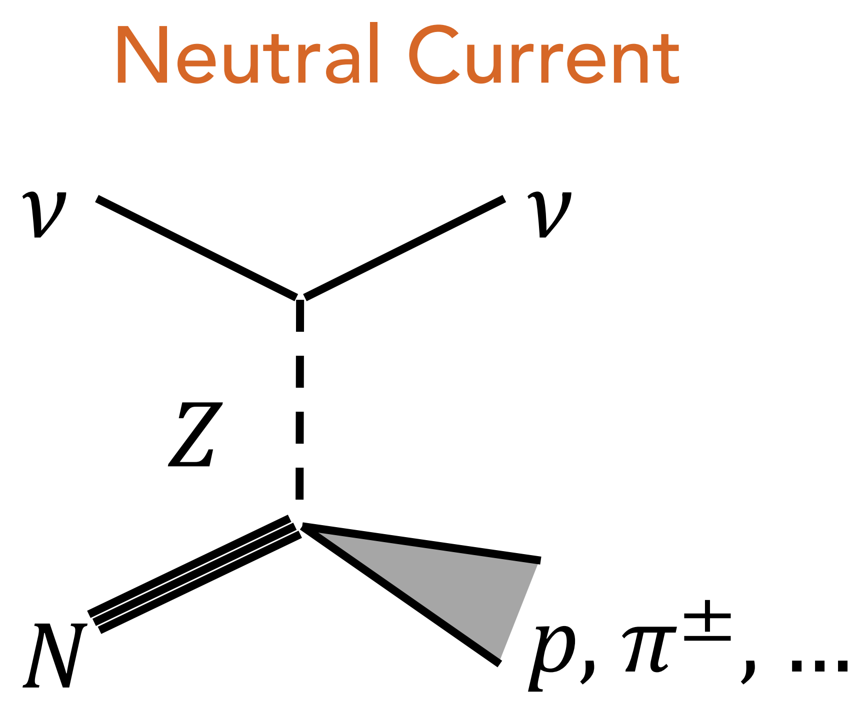


- 14 mrad off axis, peak at 2 GeV.
- 96% pure ν_μ, 3% $\bar{\nu}_\mu$.
- ~1% $\nu_e + \bar{\nu}_e$



How to Detect a Neutrino



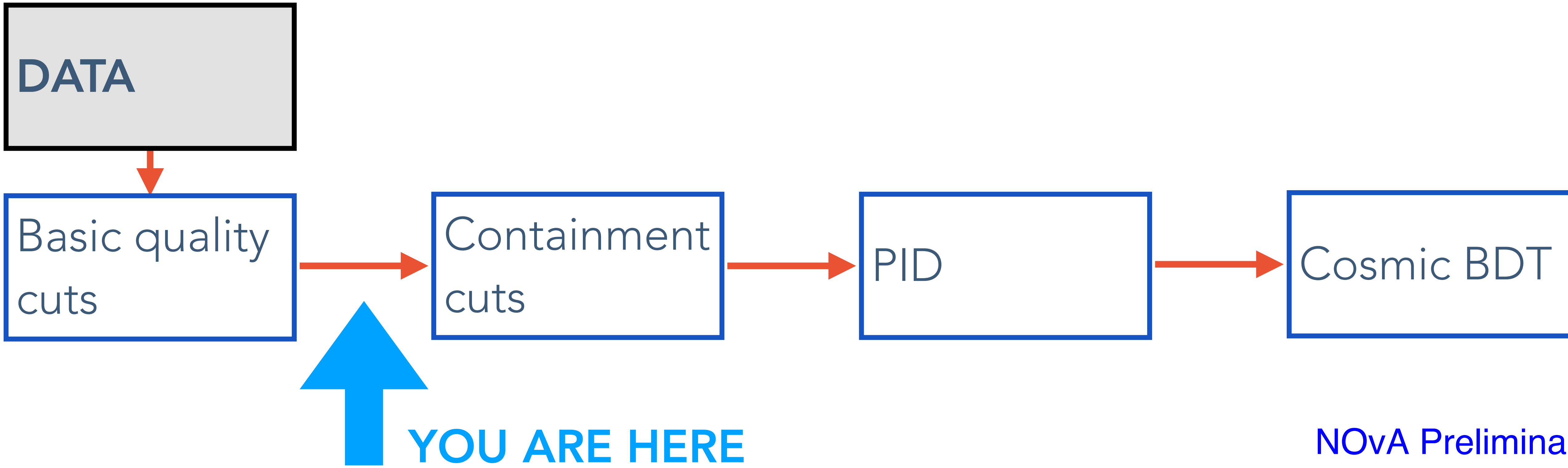


- Observe charged particles after a neutrino interacts with a nucleus.

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

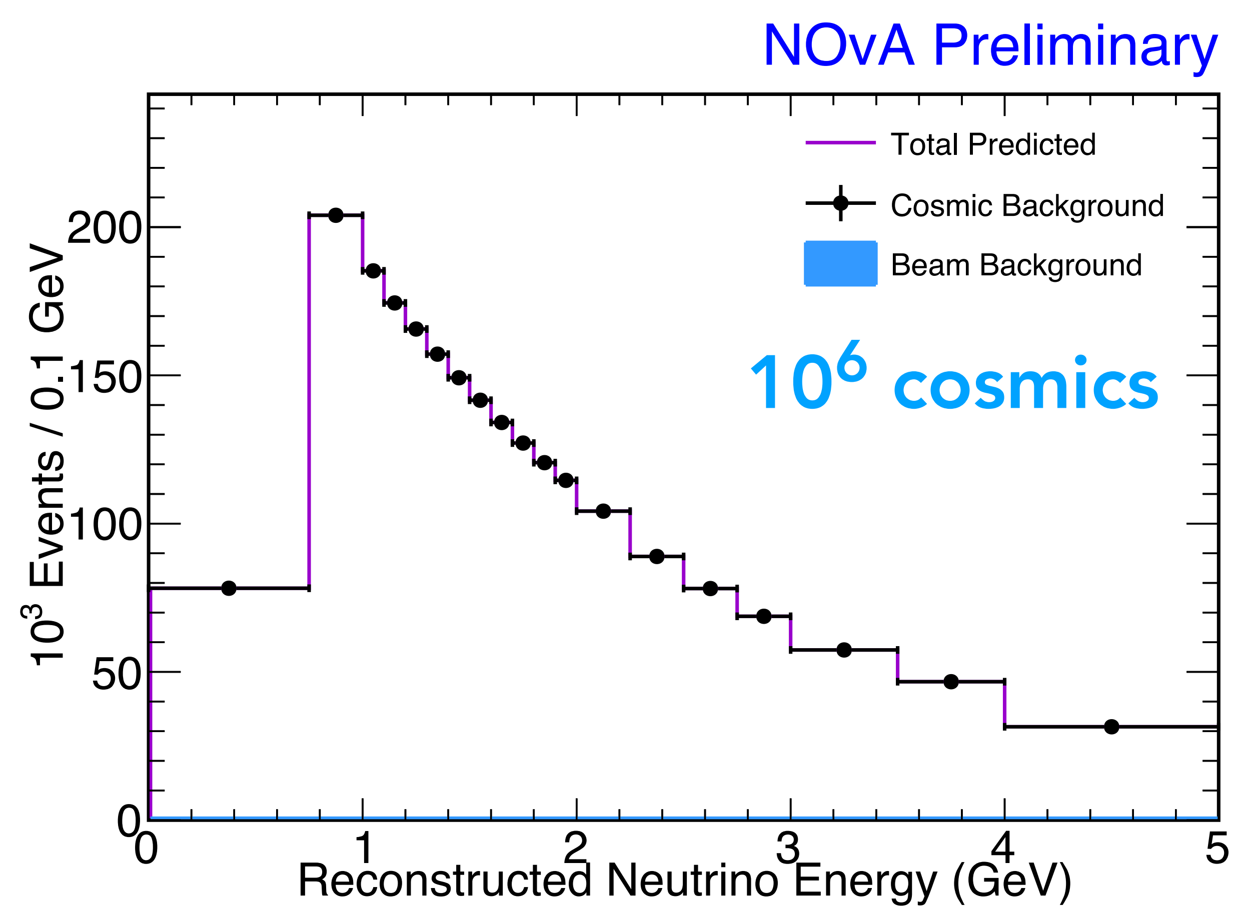
- Hadronic shower:
  - May contain protons, one or more $\pi^{\pm}$, etc.
  - May have EM components from $\pi^0 \rightarrow \gamma\gamma$

Selection: ν_μ

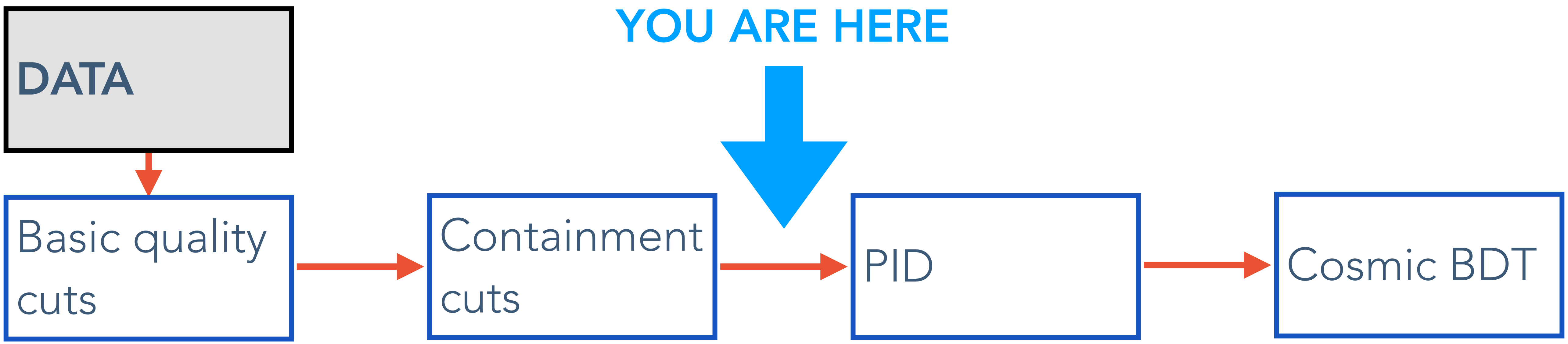


- Even with pulsed beam and excellent timing resolution, still a significant amount of cosmic background.

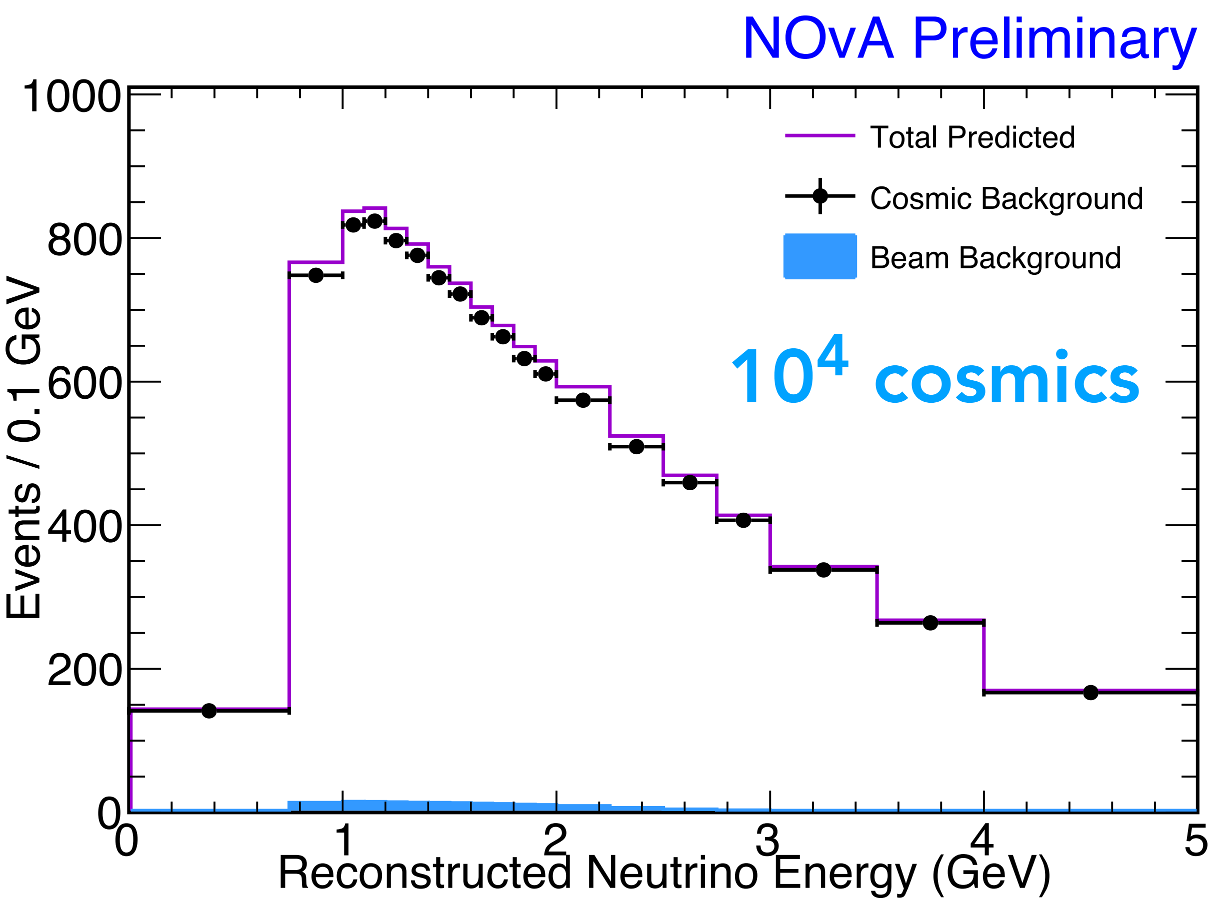
- Basic quality:
  - Number of hits, track angle, reasonable energy reconstructed.



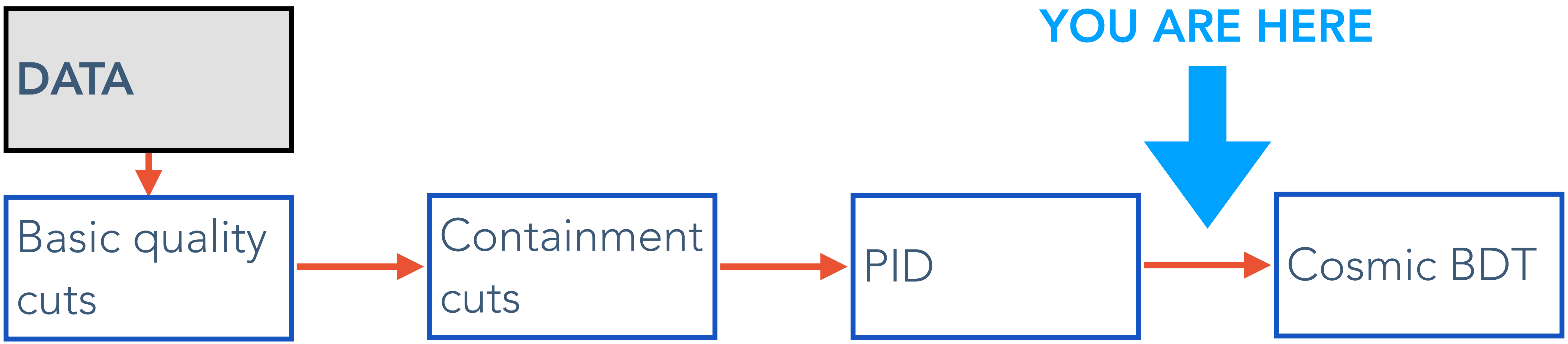
Selection: ν_μ



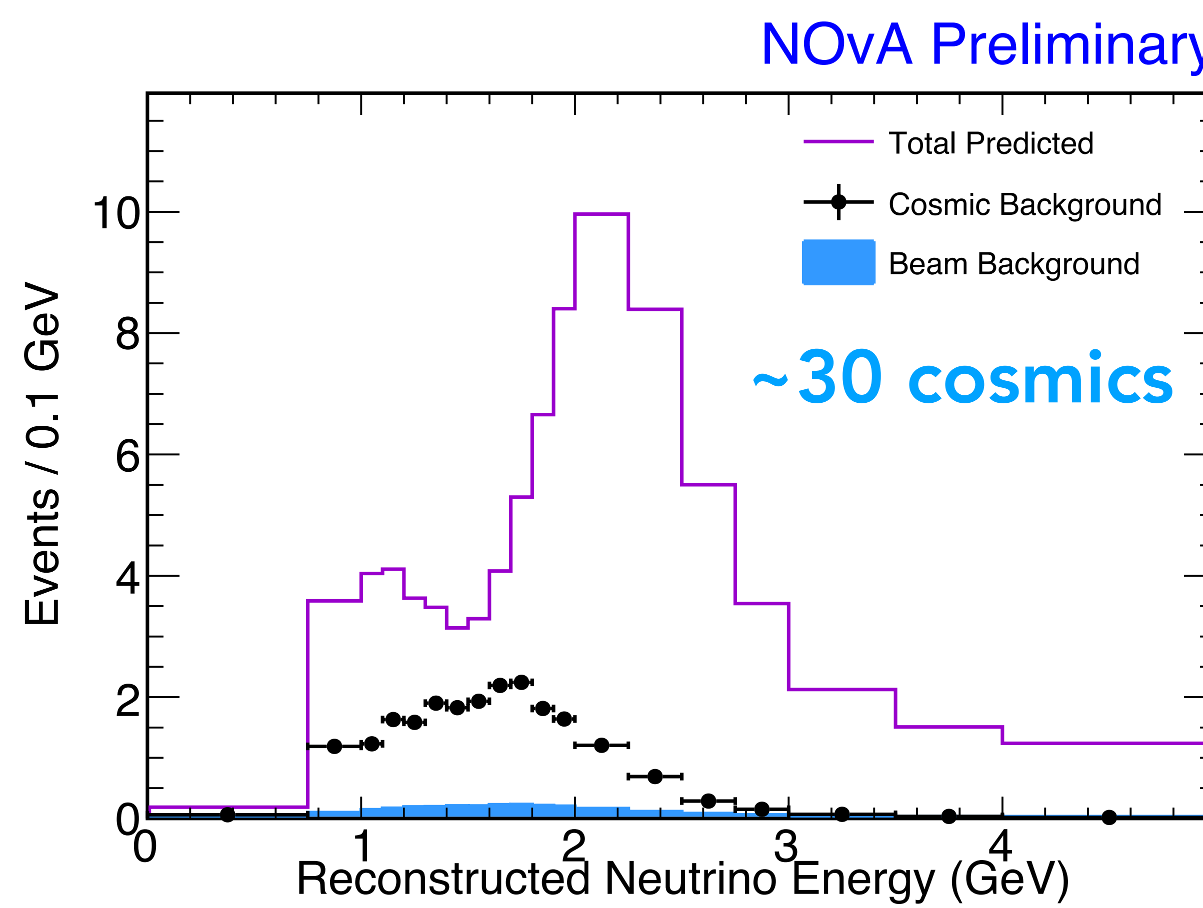
- Even with pulsed beam and excellent timing resolution, still a significant amount of cosmic background.
- Containment cuts:
  - Vertices in the fiducial volume.
  - Event contained within the detector.



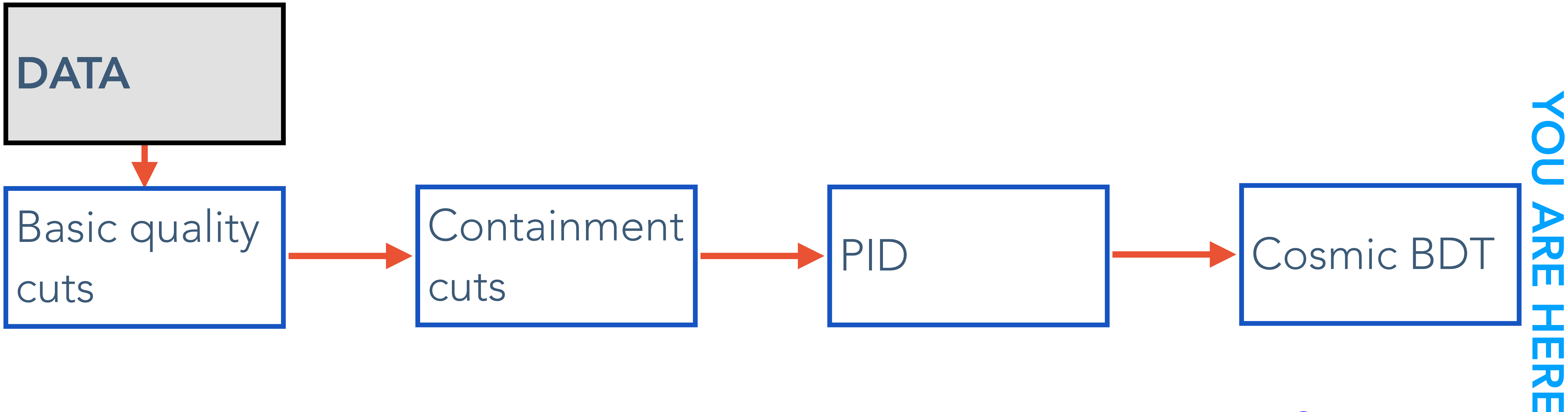
Selection: ν_μ



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

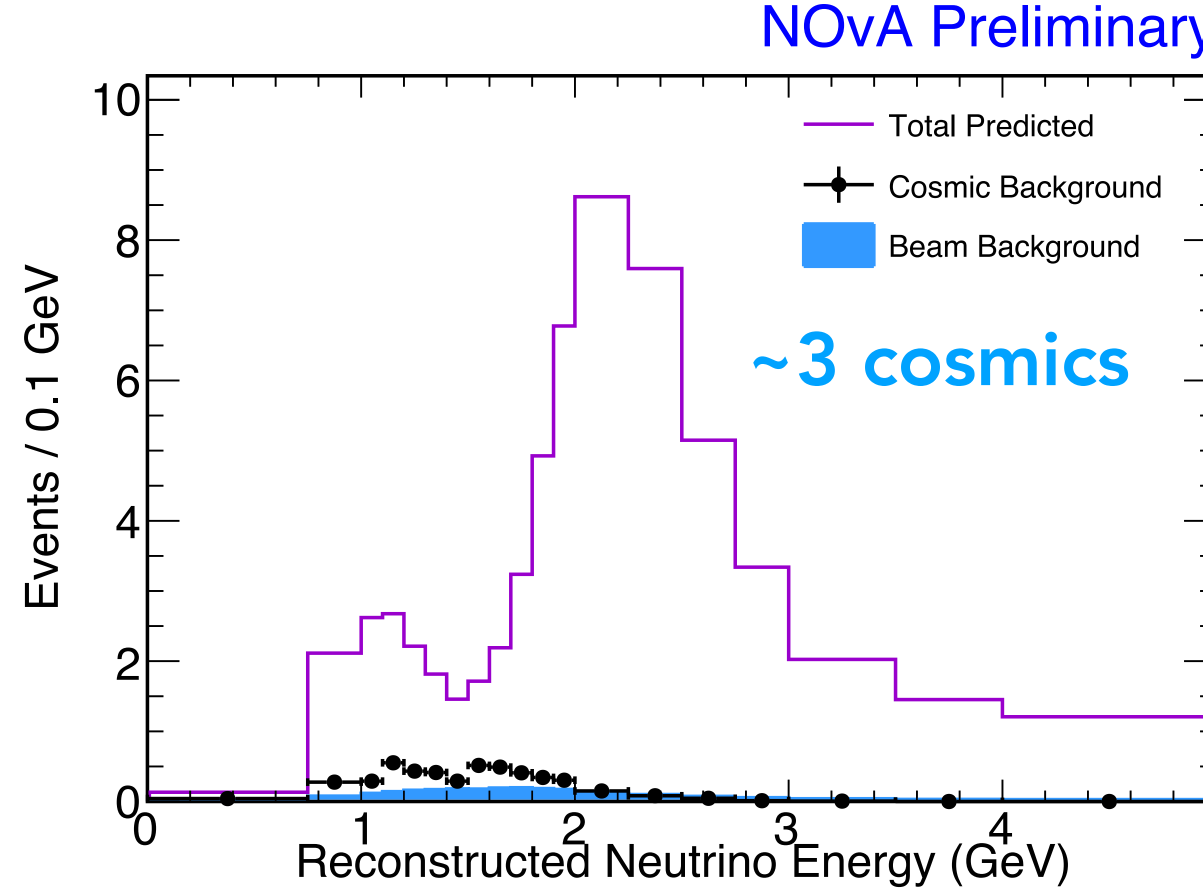


Selection: ν_μ

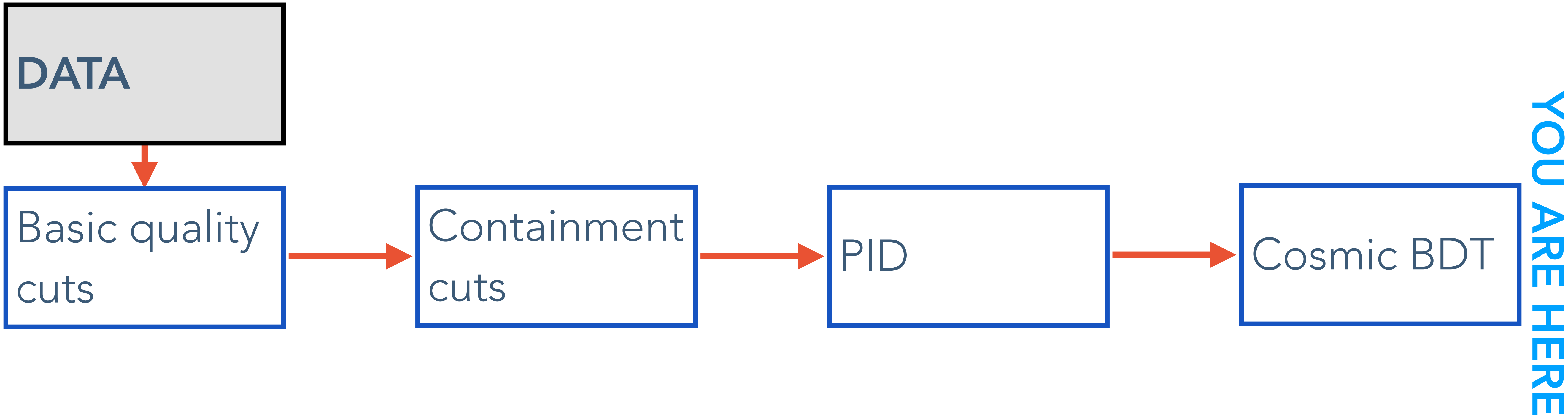


- Even with pulsed beam and excellent timing resolution, still a significant amount of cosmic background.

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

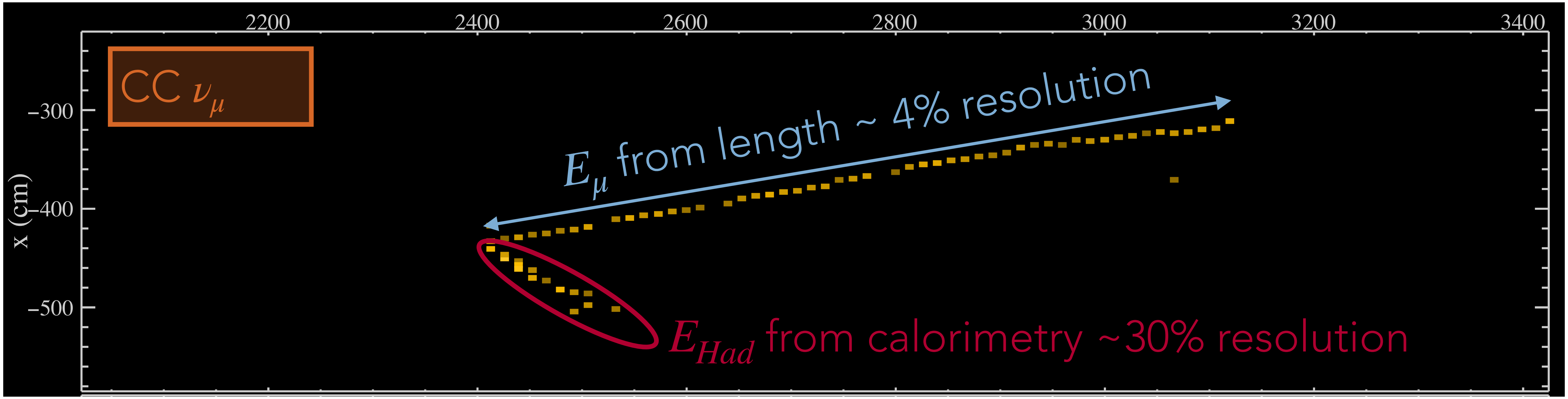


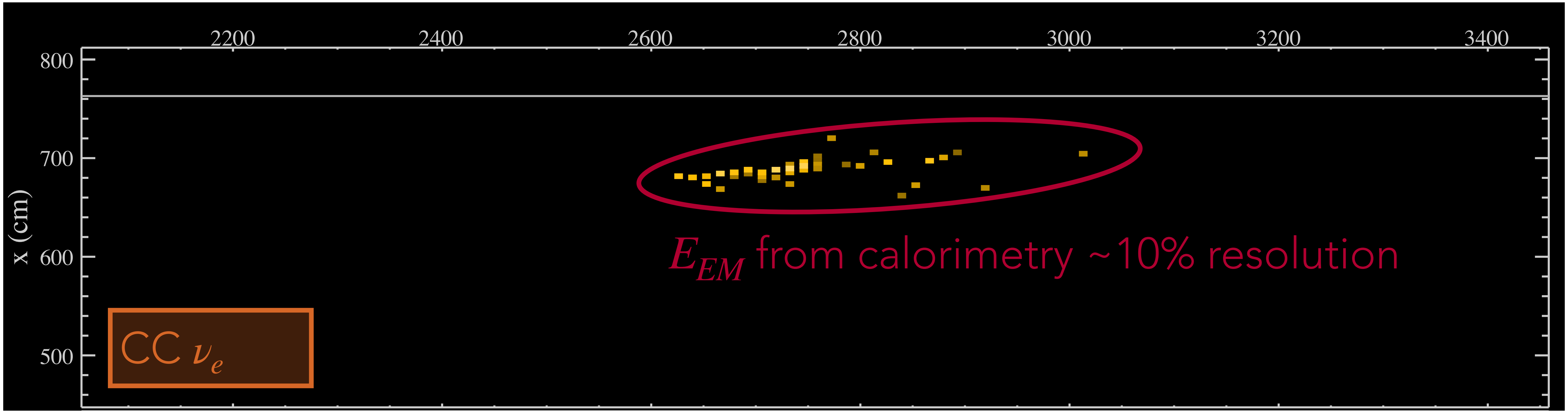
Selection



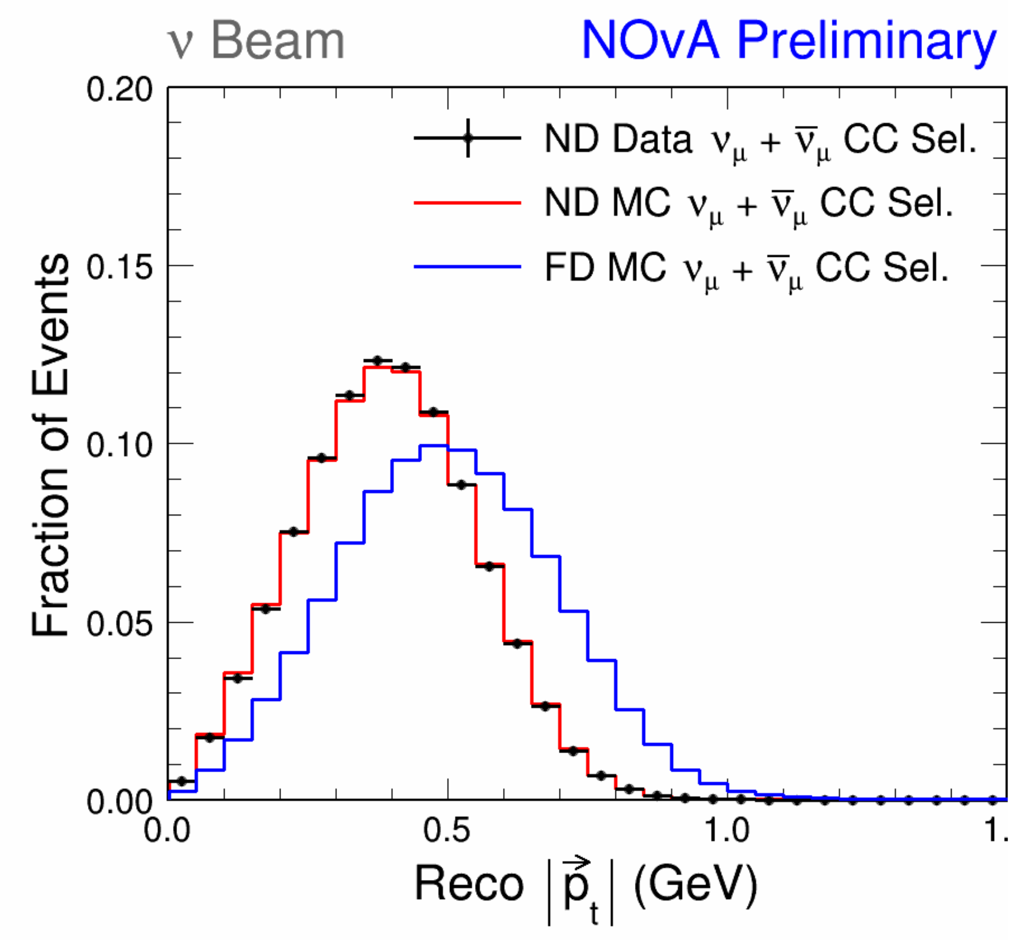
- Electron neutrino sample has second 'peripheral' sample containing high-confidence electron neutrino events close to detector walls.

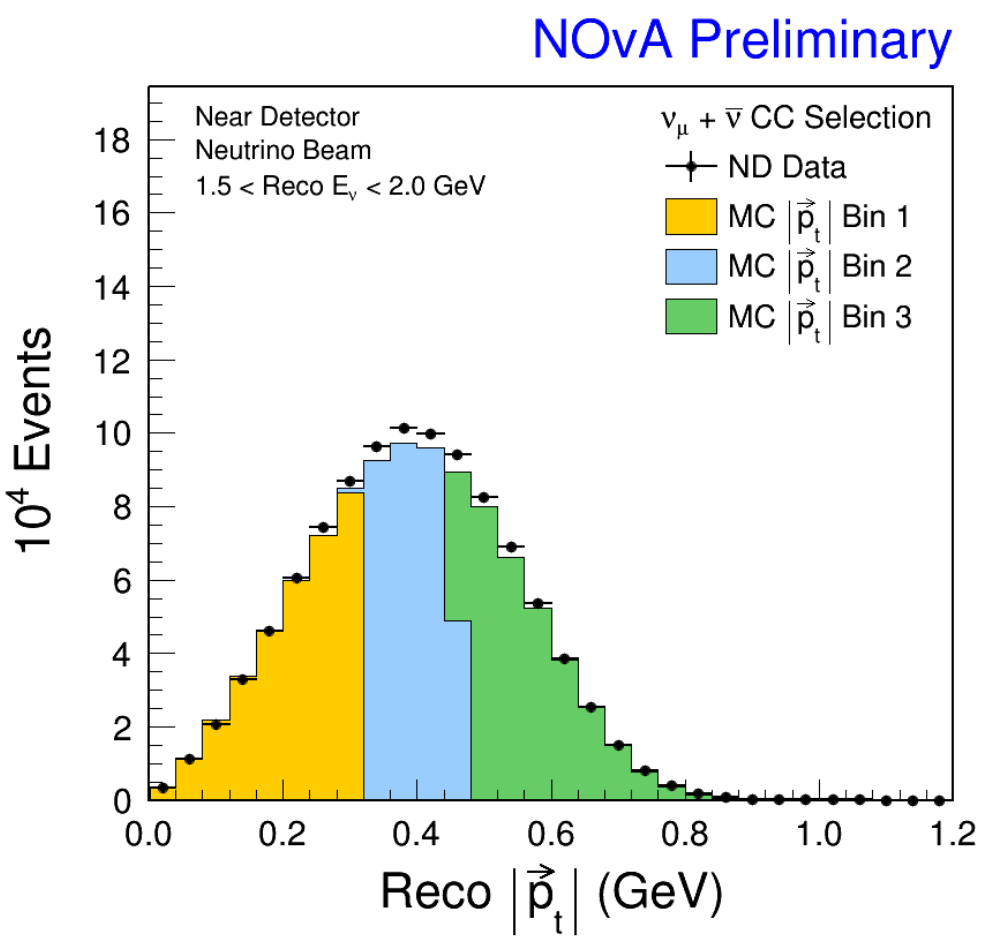
Energy Reconstruction

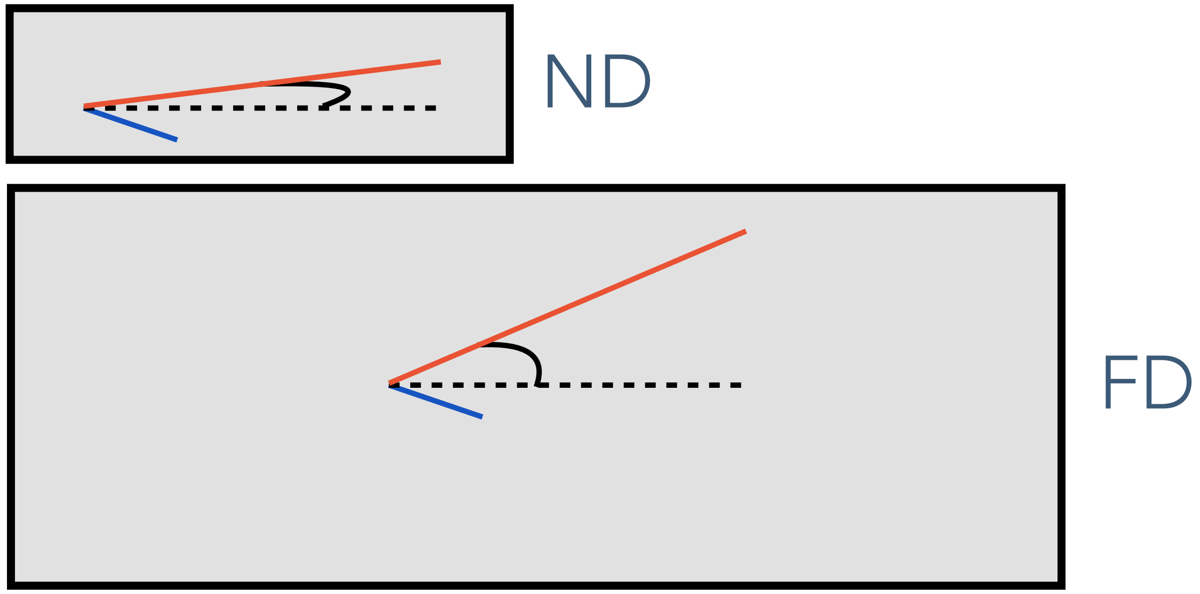




Extrapolating Kinematics

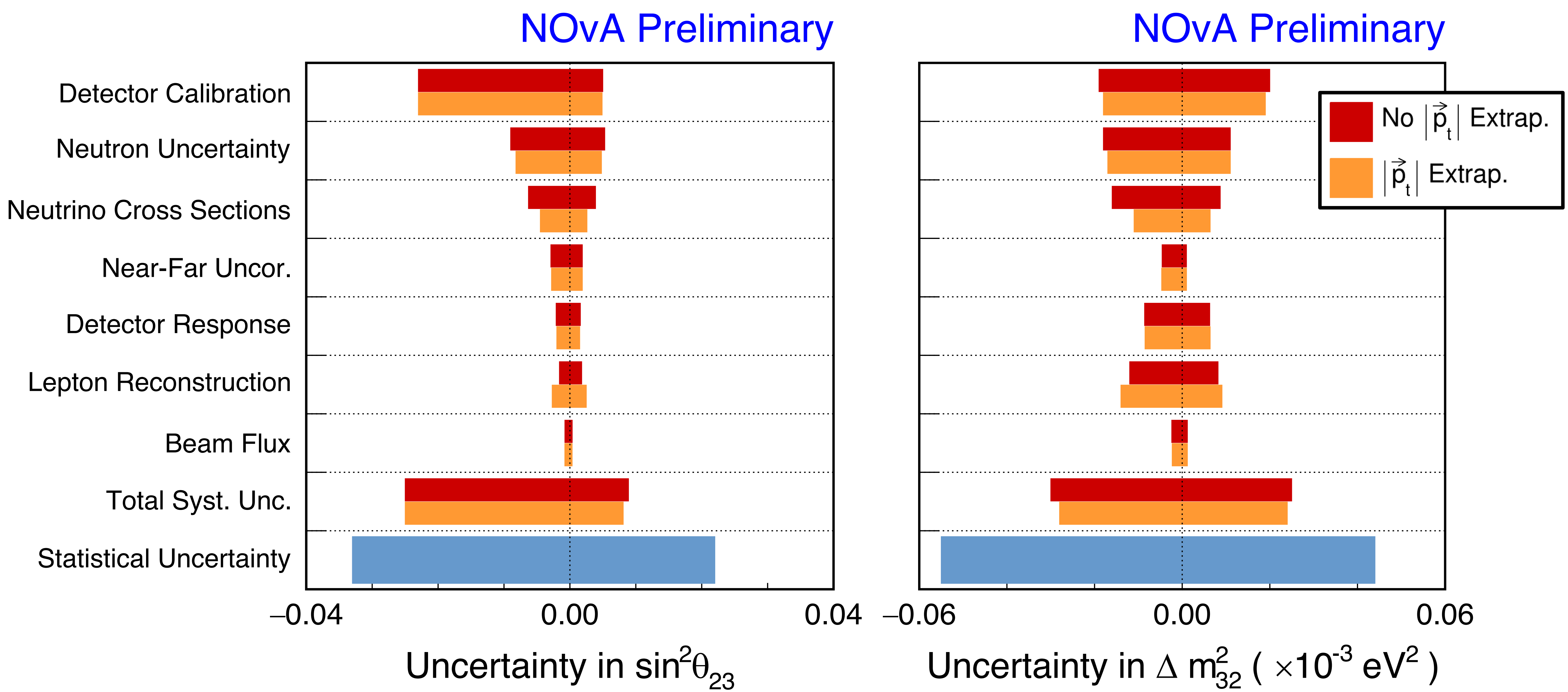






- Mitigate by extrapolating in bins of lepton transverse momentum, p_t.
- Split the ND sample into 3 bins of p_t, extrapolate each separately to the FD.
  - Effectively "rebalances" the kinematics to better match between the detectors.
  - Re-sum the p_t bins before fitting.

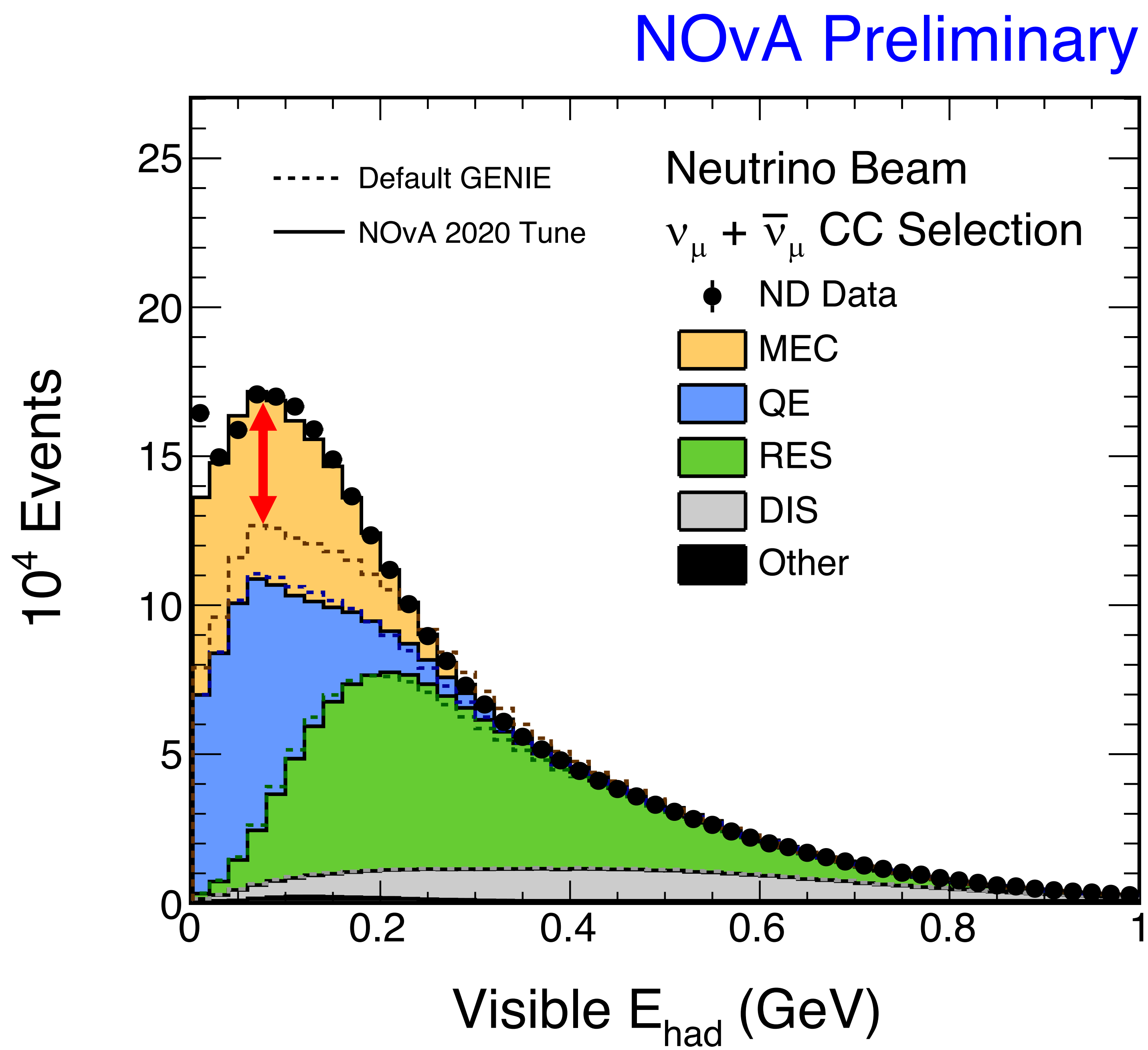
Systematic Uncertainties with p_t Extrapolation



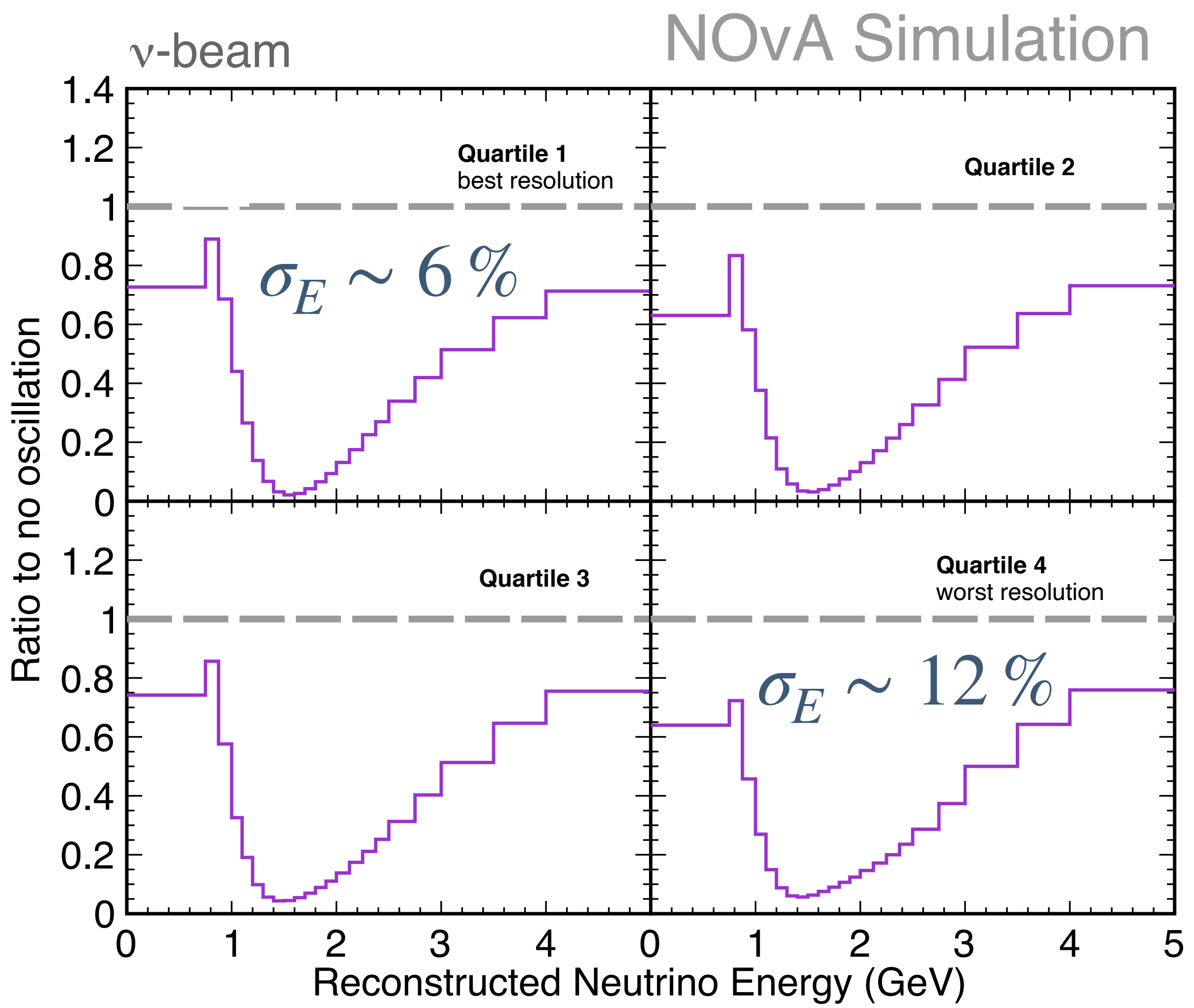
- Overall systematic reduction is 5-10%.
- 30% reduction in cross-section uncertainties.
  - Reduces the size of systematics most likely to contain "unknown unknowns."
  - Slight increase in systematics on lepton reconstruction.

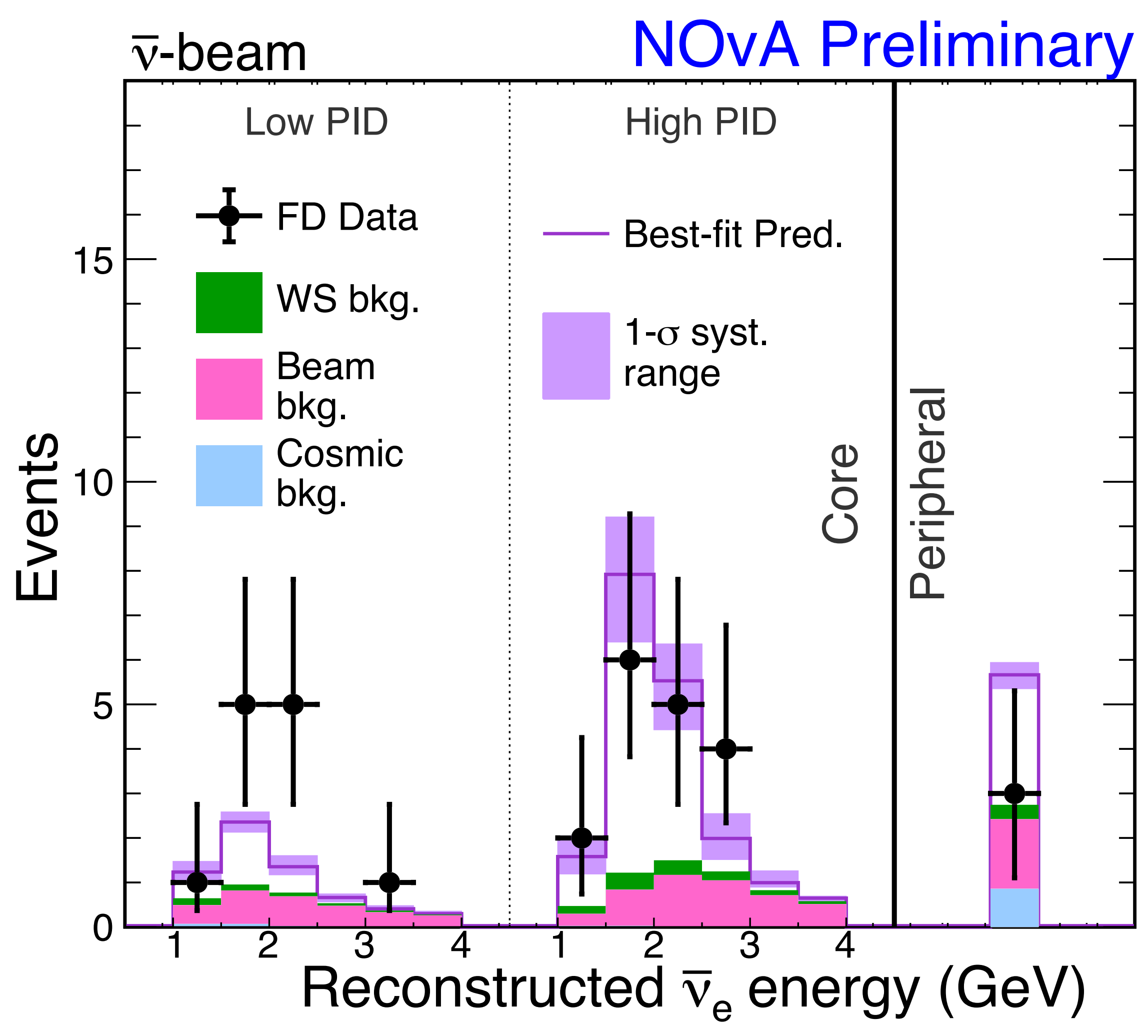
Neutrino Interaction Model

- 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.



Improving Sensitivity to Oscillations





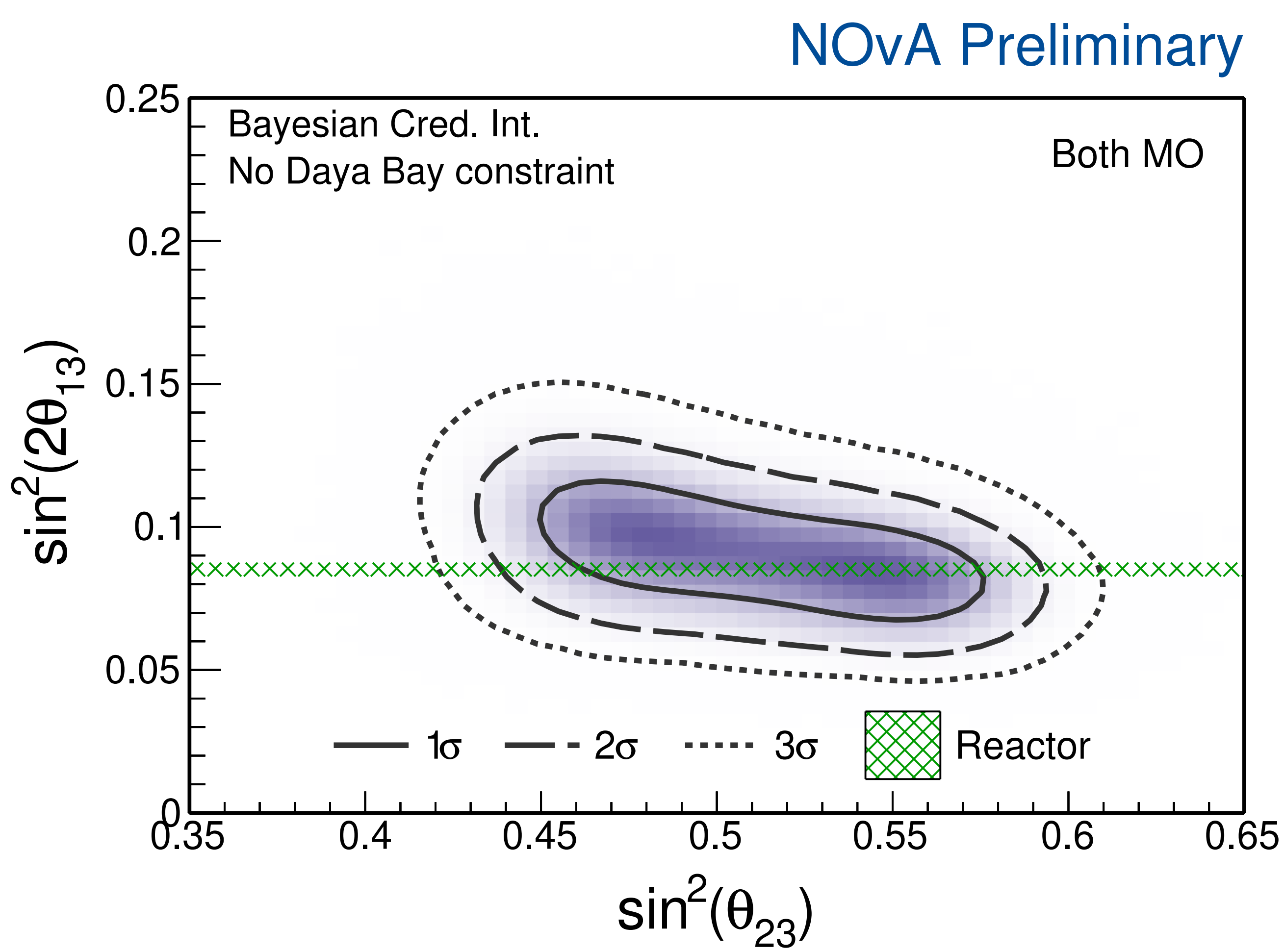
ν_μ

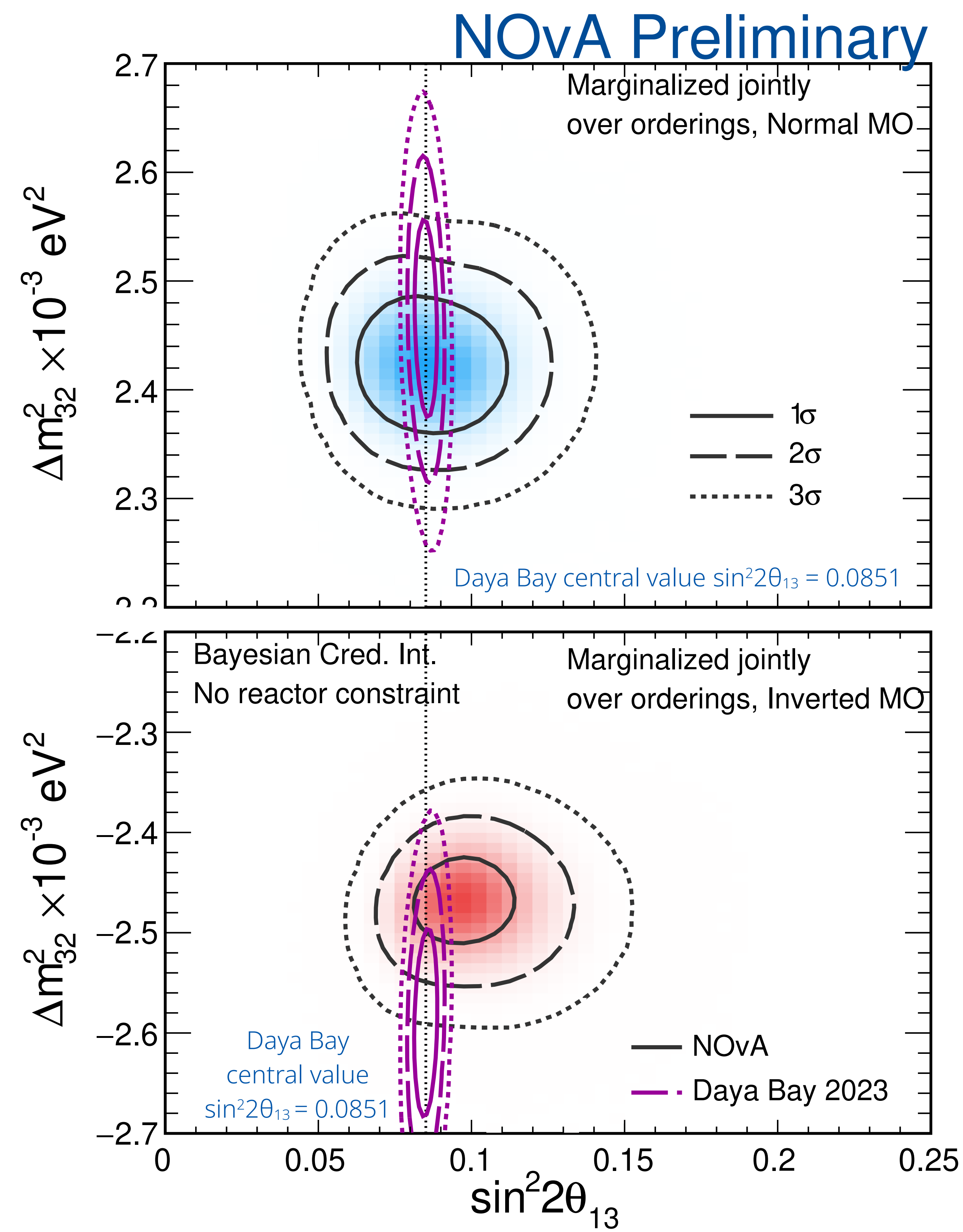
- Sensitivity depends primarily on the shape of the energy spectrum.
- Bin by energy resolution: bins of hadronic energy fraction.

ν_e

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

Daya Bay / NOvA Correlations





J. Wolcott

Models & Systematics

Challenge: Decide what common physics parameters the two experiments have, should they be correlated and by how much.

Flux Model

- Different energies
- Different tuning to external data
  - thin target vs thick target data
- Enters the analysis differently

❑ No significant correlations between the experiments

Detector Model

- Different detector design and targets
- Different selections
  - inclusive vs exclusive outgoing pions
- Different energy reconstruction
  - calorimetric vs lepton kinematics

❑ No significant correlations between the experiments

Cross Section Model

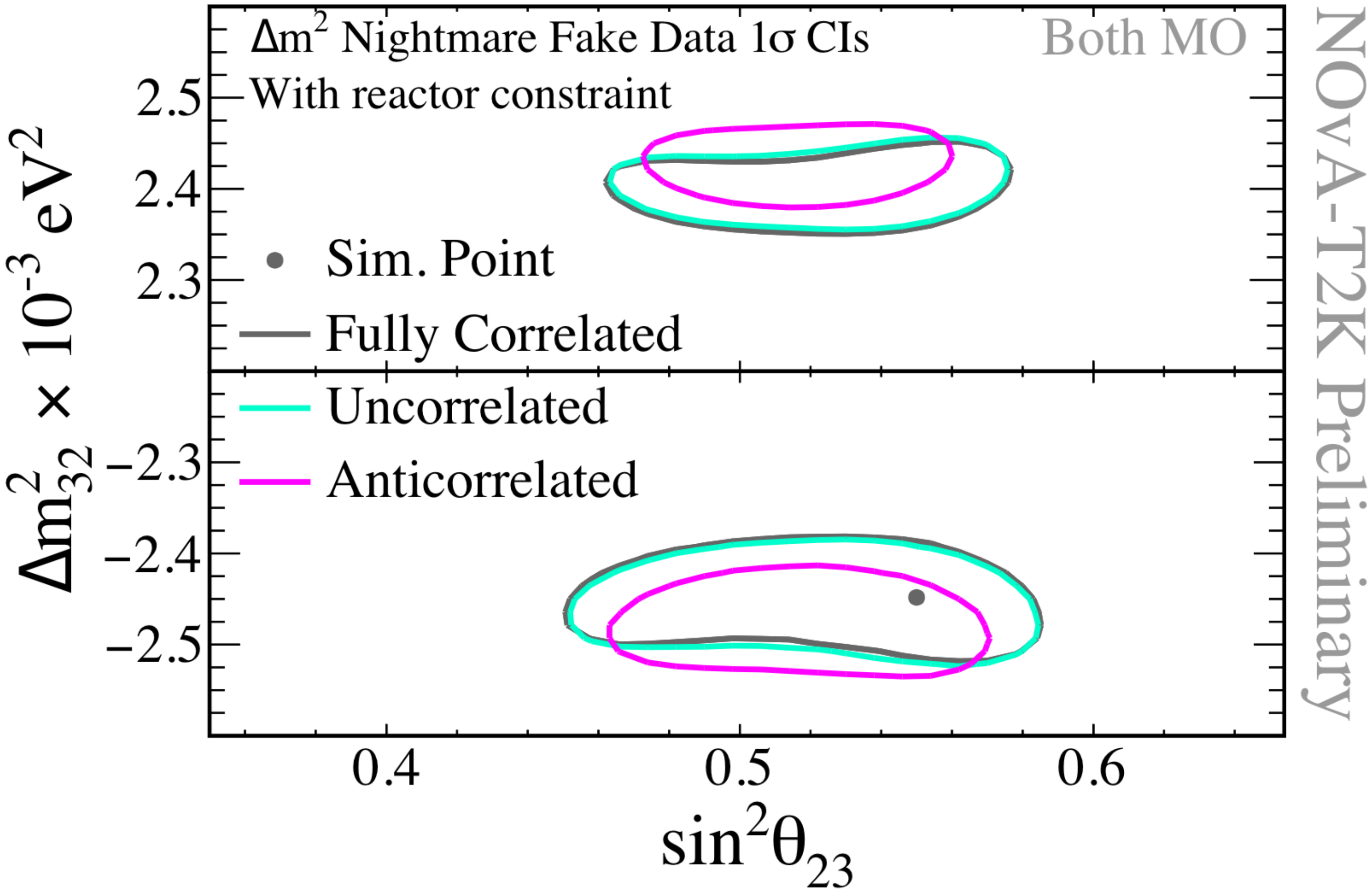
- As the underlying physics is fundamentally the same, we expect correlations
- Different neutrino interaction models
  - optimized for different energy ranges
- Systematics are designed for individual models and analysis strategies

❑ Impact of correlations is negligible on the results at the current statistical significance.

❑ Merits continued investigations for higher data exposures.

Z. Vallari

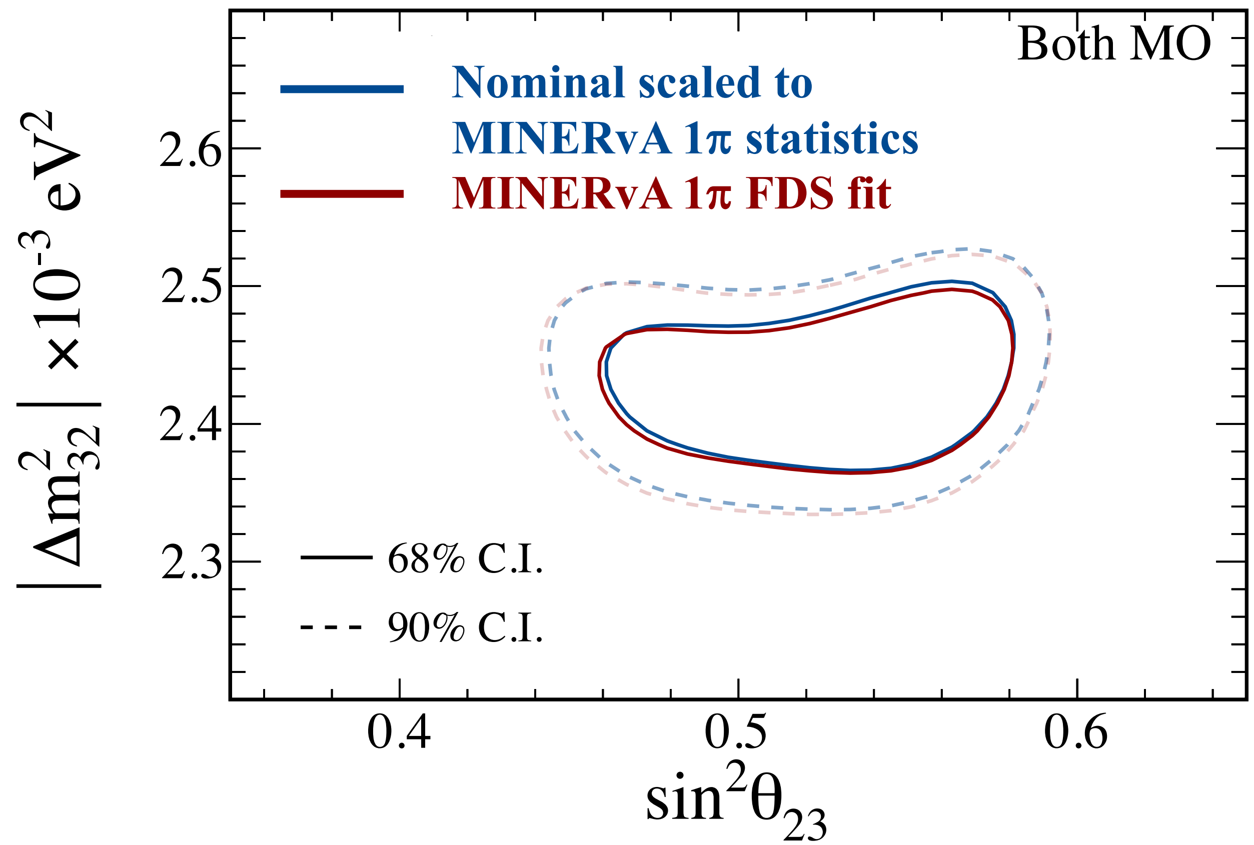
Studying Correlations

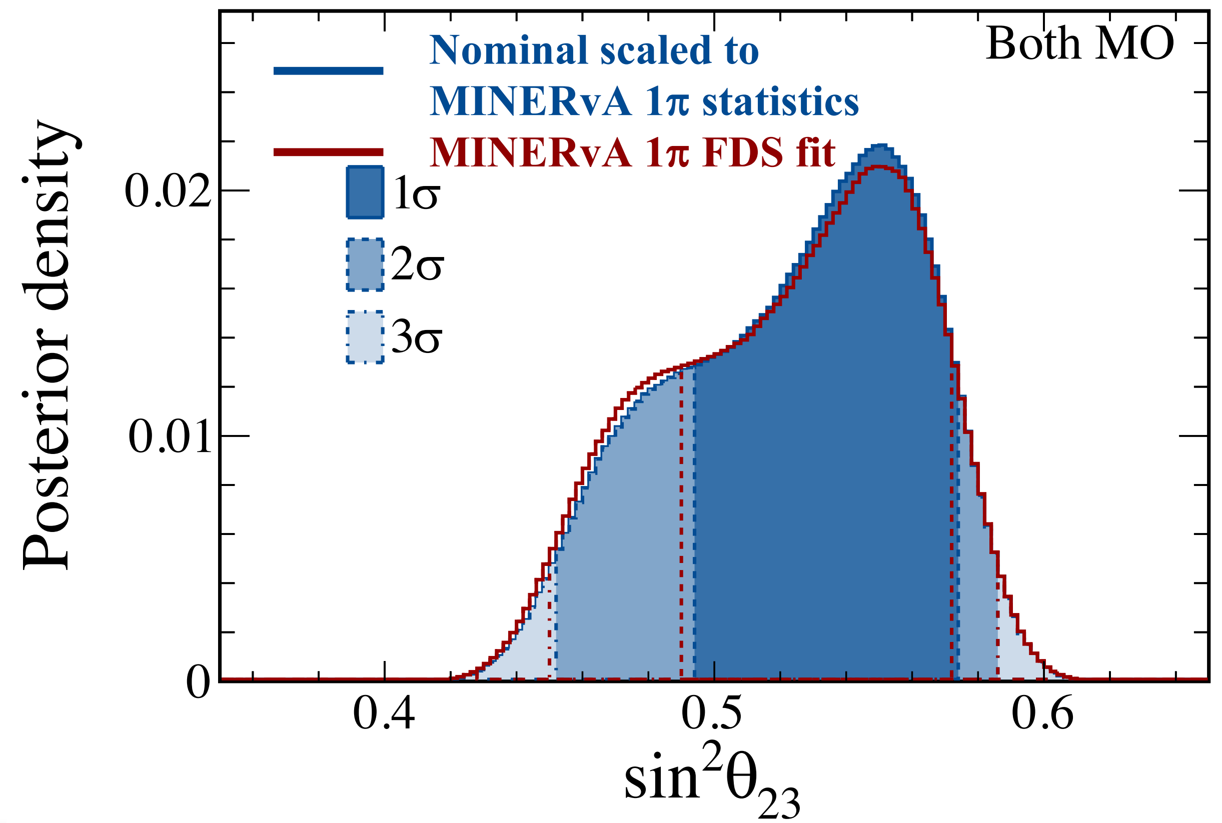


- **Strategy:** evaluate a range of artificial scenarios to asses the impact of possible correlations:
  - E.g, fabricate parameters for each experiment which should have significant bias on Δm^2_{32} and $\sin^2\theta_{23}$ (size of uncertainty comparable to the statistical uncertainty).
  - Study the impact of fully correlating, uncorrelating and fully anti-correlating these parameters.
  - Uncorrelated and correctly correlated (full correlation) credible intervals agree very well while incorrectly correlating systematics shows a bias -> leaving systematics like these uncorrelated wouldn't have a significant impact in the analysis.

Studying Alternate Models

- Ensure analysis is robust to **alternate neutrino interaction models**.
  - Generate **mock data** by changing part of simulation to use an alternative model.
  - Fit these mock datasets and check impact on oscillation results.
- Pre-decided thresholds for bias:
  - **Change in width** of 1D intervals should be no larger than **10%**.
  - **Change in central value** should be no larger than **50% of systemic uncertainty.**
- Investigated a range of alternative models at different oscillation points.
  - Example: suppression in single pion channel seen in MINERvA results*.
  - **No alternative model test failed the pre-set threshold for bias.**

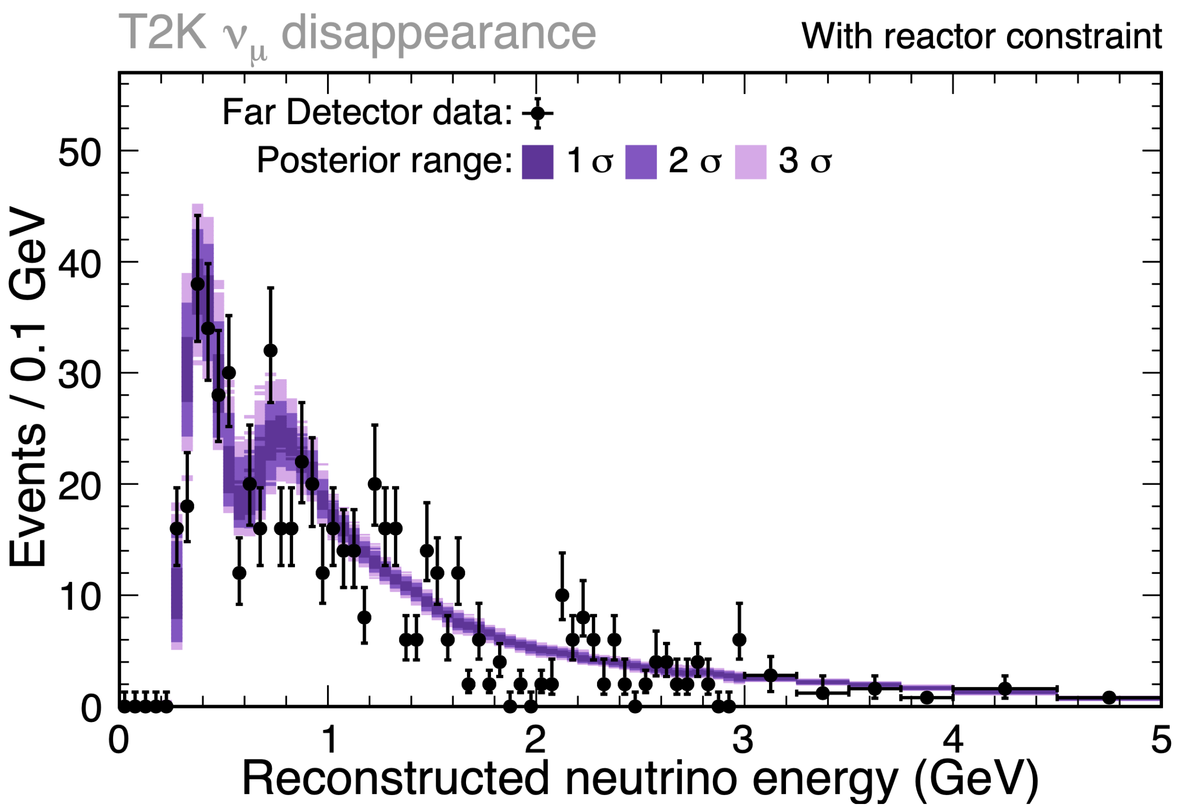


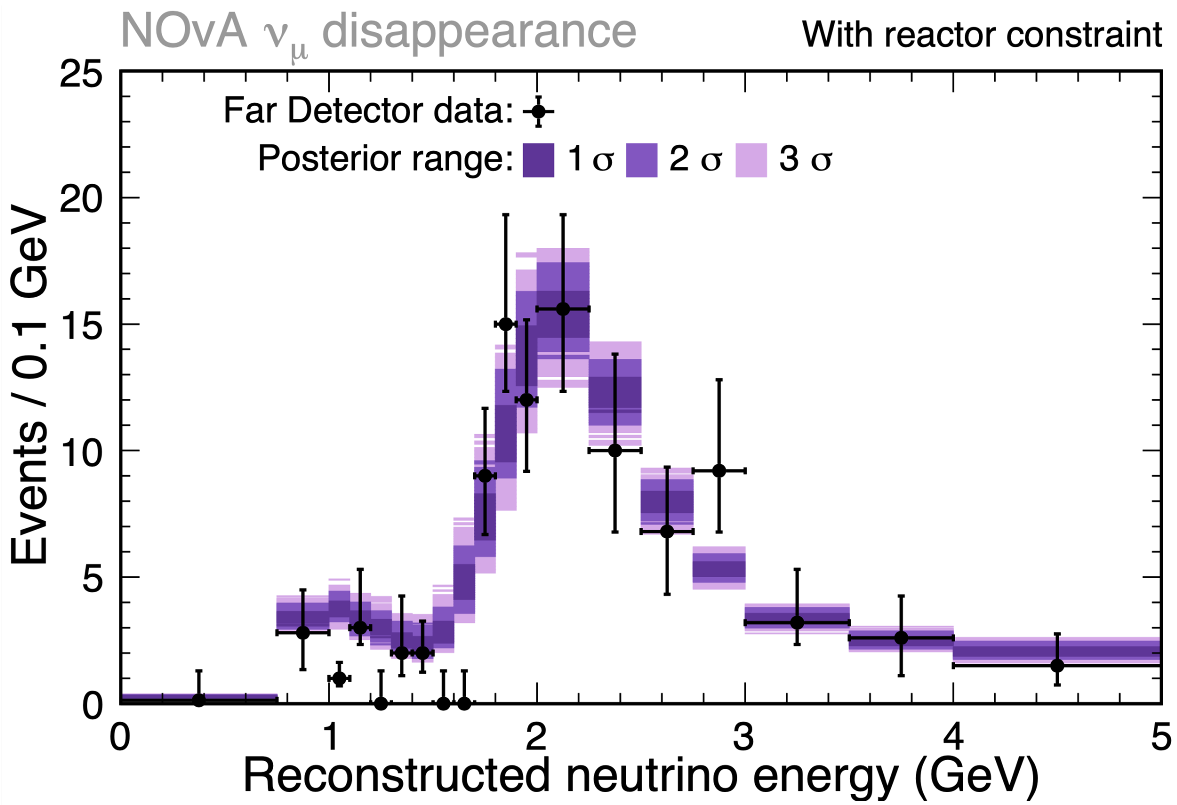


*Phys. Rev. D 100, 072005 (2019)

FD Data Samples

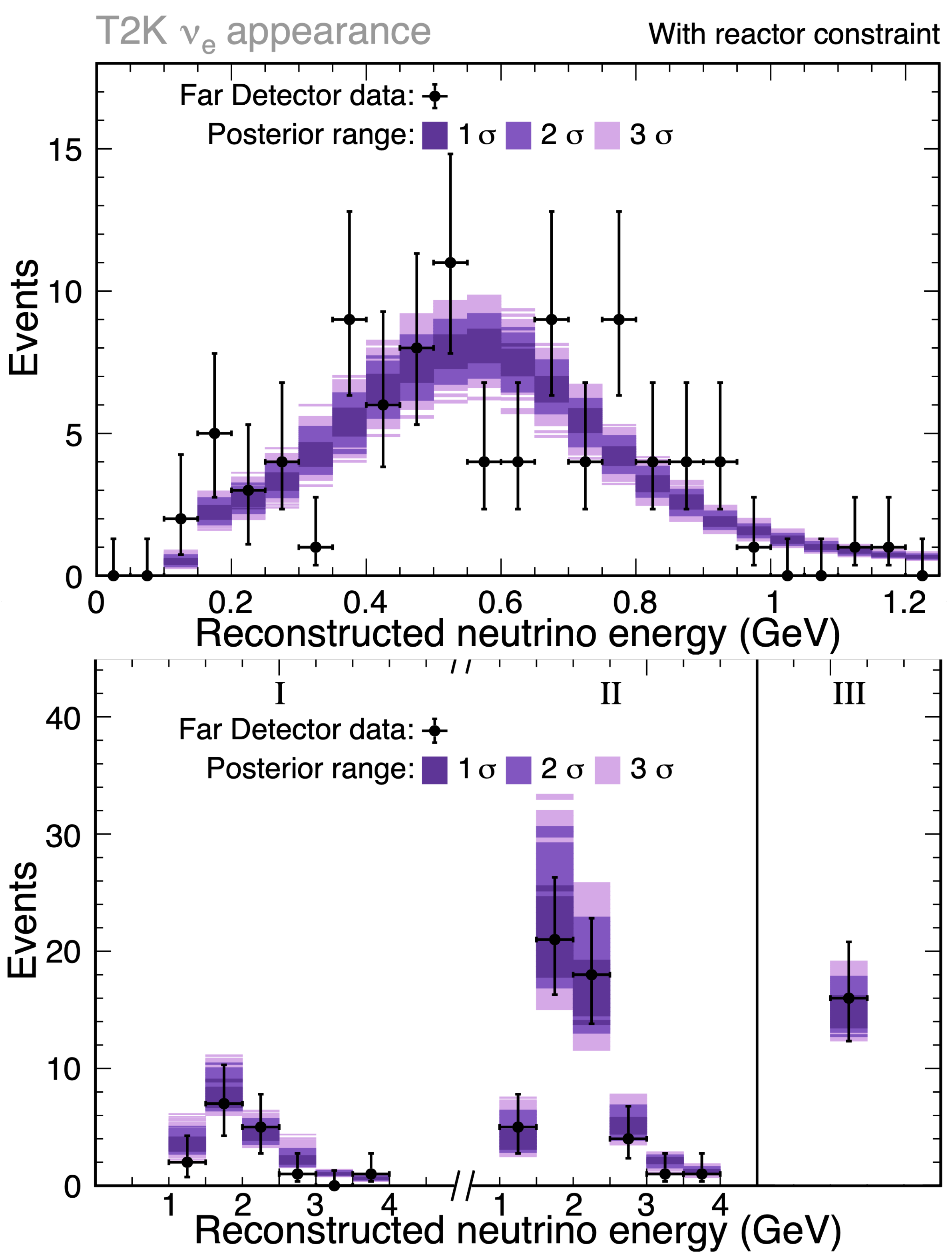
Channel	NOvA	T2K	Combined
ν_e	82	94 (ν_e) 14 ($\nu_e 1\pi$)	190
$\bar{\nu}_e$	33	16	49
ν_μ	211	318	529
$\bar{\nu}_\mu$	105	137	242
Total	431	579	1010





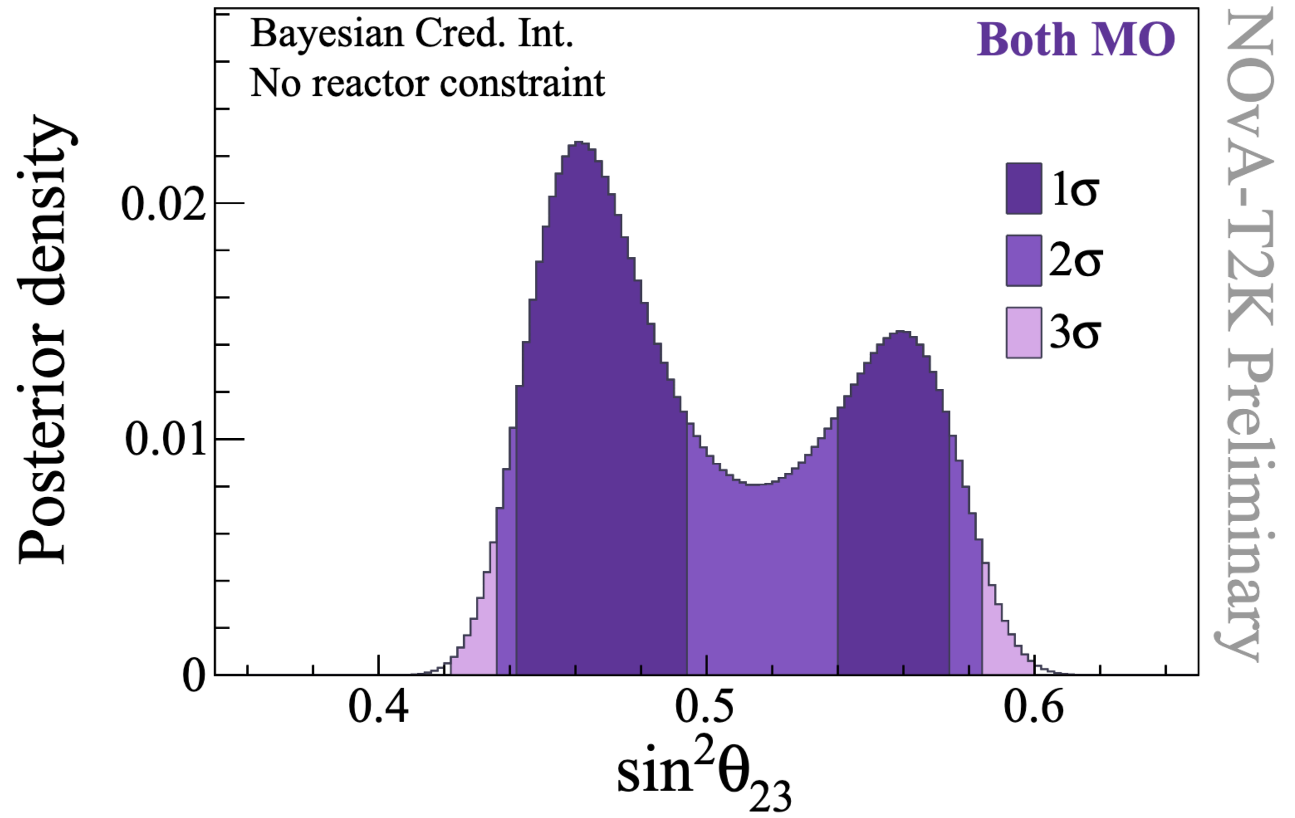
FD Data Samples

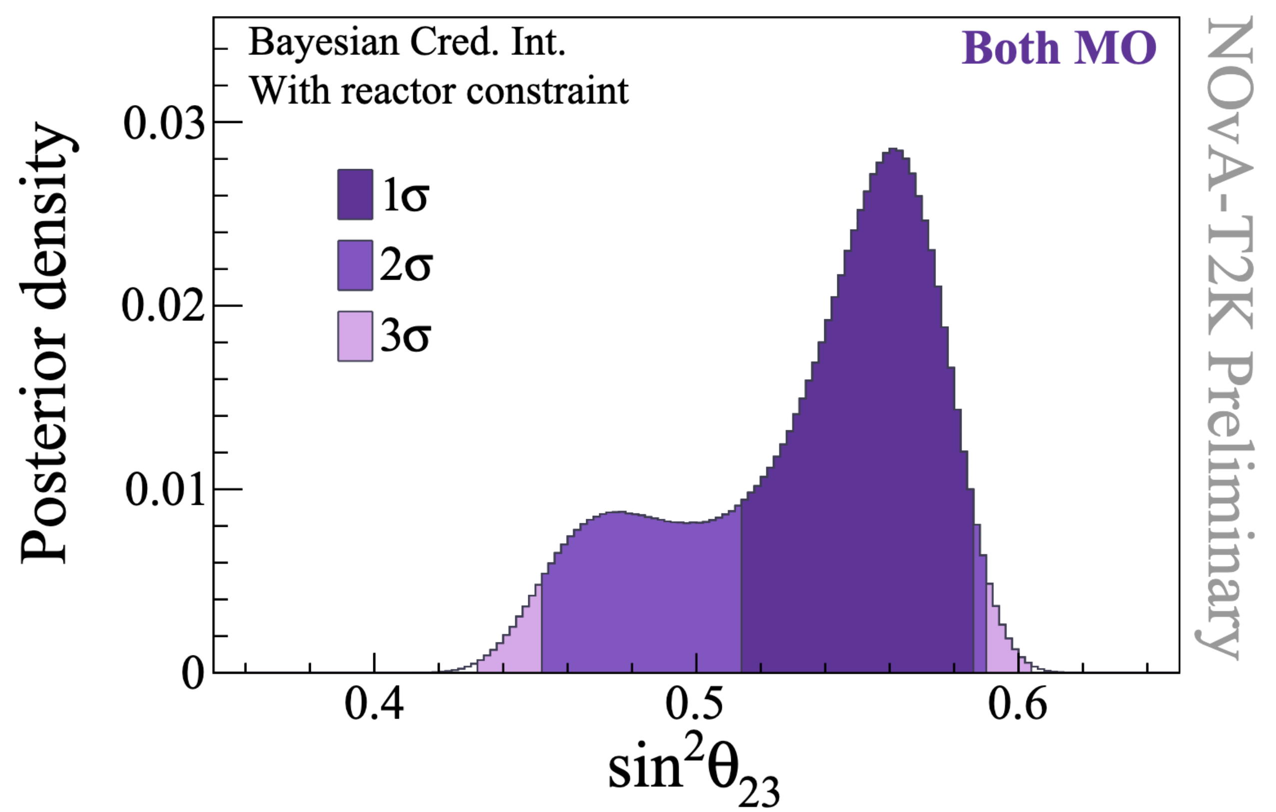
Channel	NOvA	T2K	Combined
ν_e	0.90	0.19 (ν_e) 0.79 ($\nu_e 1\pi$)	0.62
$\bar{\nu}_e$	0.21	0.67	0.40
ν_μ	0.68	0.48	0.62
$\bar{\nu}_\mu$	0.38	0.87	0.72
Total	0.64	0.72	0.75

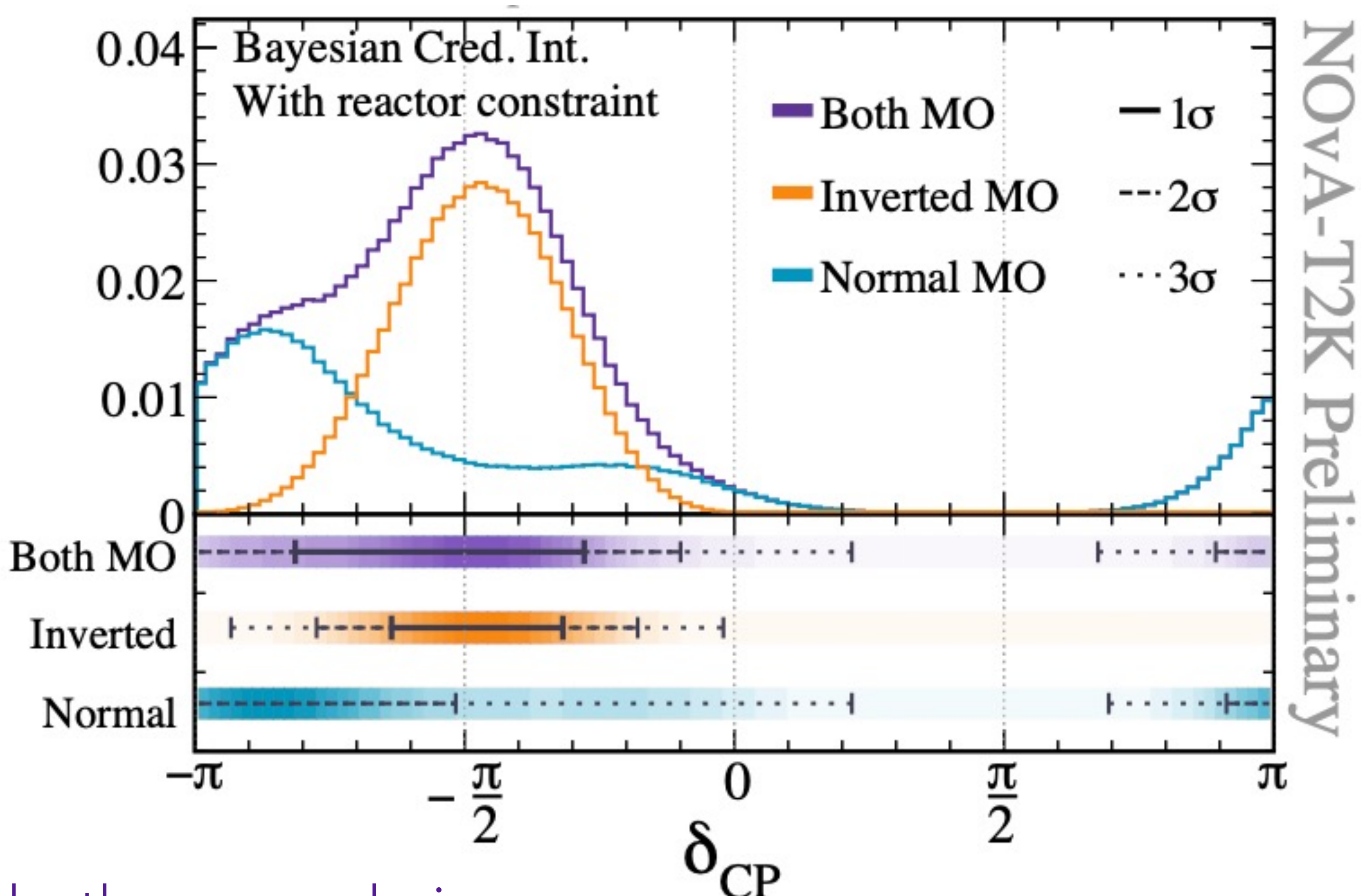


Mixing Angles: θ_{23}

	NOvA - T2K w/o reactor	NOvA – T2K – w/ reactor
Bayes factor	1.17 (~54% C.I) (Lower Octant/Upper Octant)	3.58 (~78% CI) (Upper Octant/Lower Octant)







- For both mass orderings:
  - $\delta_{CP} = \frac{\pi}{2}$ lies outside of the 3σ credible interval.

- In the Normal Ordering:
  - Broad range of permissible δ_{CP} values.

- In the Inverted Ordering:
  - CP conserving values $\delta_{CP} = 0$ and $\delta_{CP} = \pi$ lie outside the 3σ credible interval.