



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

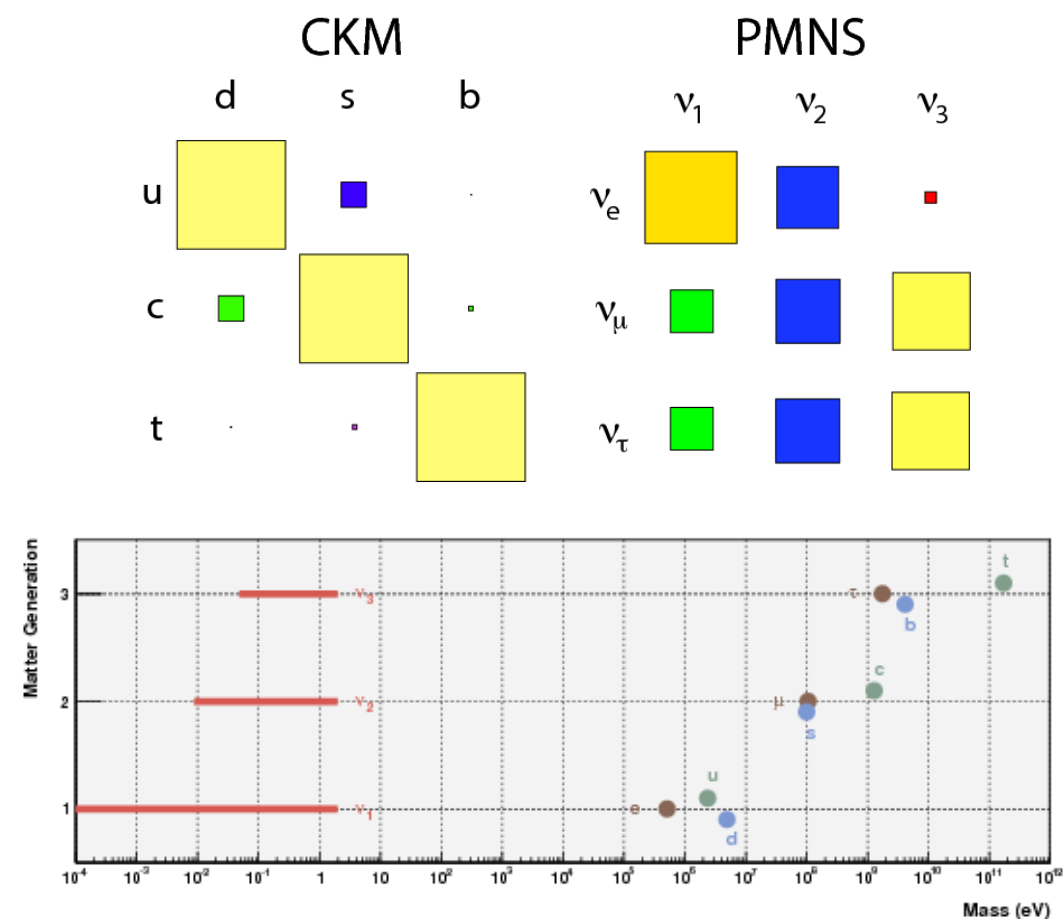
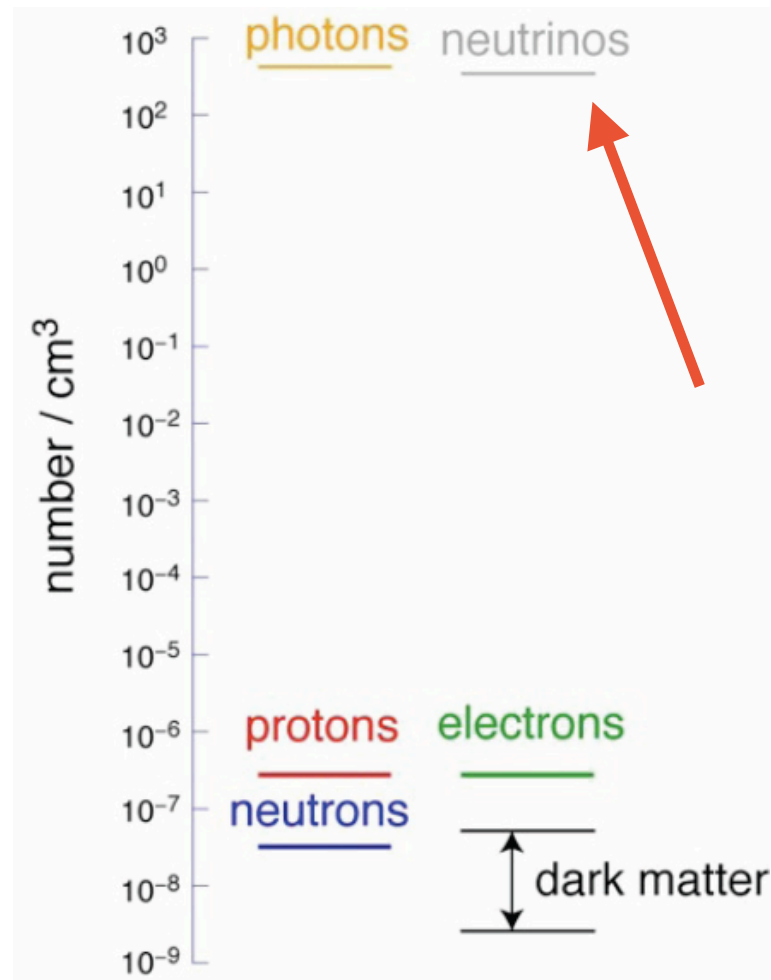
Alexander Booth

University of Warwick Seminar Series

November 14th, 2024

Neutrinos 101

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!



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





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- Each flavour is a superposition of different masses.

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

A diagram showing the relationship between neutrino mass eigenstates (ν_1 , ν_2) and flavor eigenstates (ν_e , ν_μ). The flavor eigenstates are represented by blue arrows along the horizontal and vertical axes. The mass eigenstates are represented by red arrows. The angle between the ν_e axis and the ν_2 axis is labeled θ .





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



- Each flavour is a superposition of different masses.

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





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

ν_e ν_μ ν_τ ν_1 ν_2 ν_3

PMNS matrix

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

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}





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

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

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

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

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3 angles, 1
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θ_{23}

$\theta_{13} \quad \delta$

θ_{12}



3-flavour Neutrino Oscillations



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

$$\Delta m_{32}^2 \approx 2 \times 10^{-3} \text{eV}^2$$

$$\Delta m_{31}^2 \sim \Delta m_{32}^2$$

$$\Delta m_{21}^2 \approx +8 \times 10^{-5} \text{eV}^2$$

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

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

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

“Atmospheric”
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θ_{23}

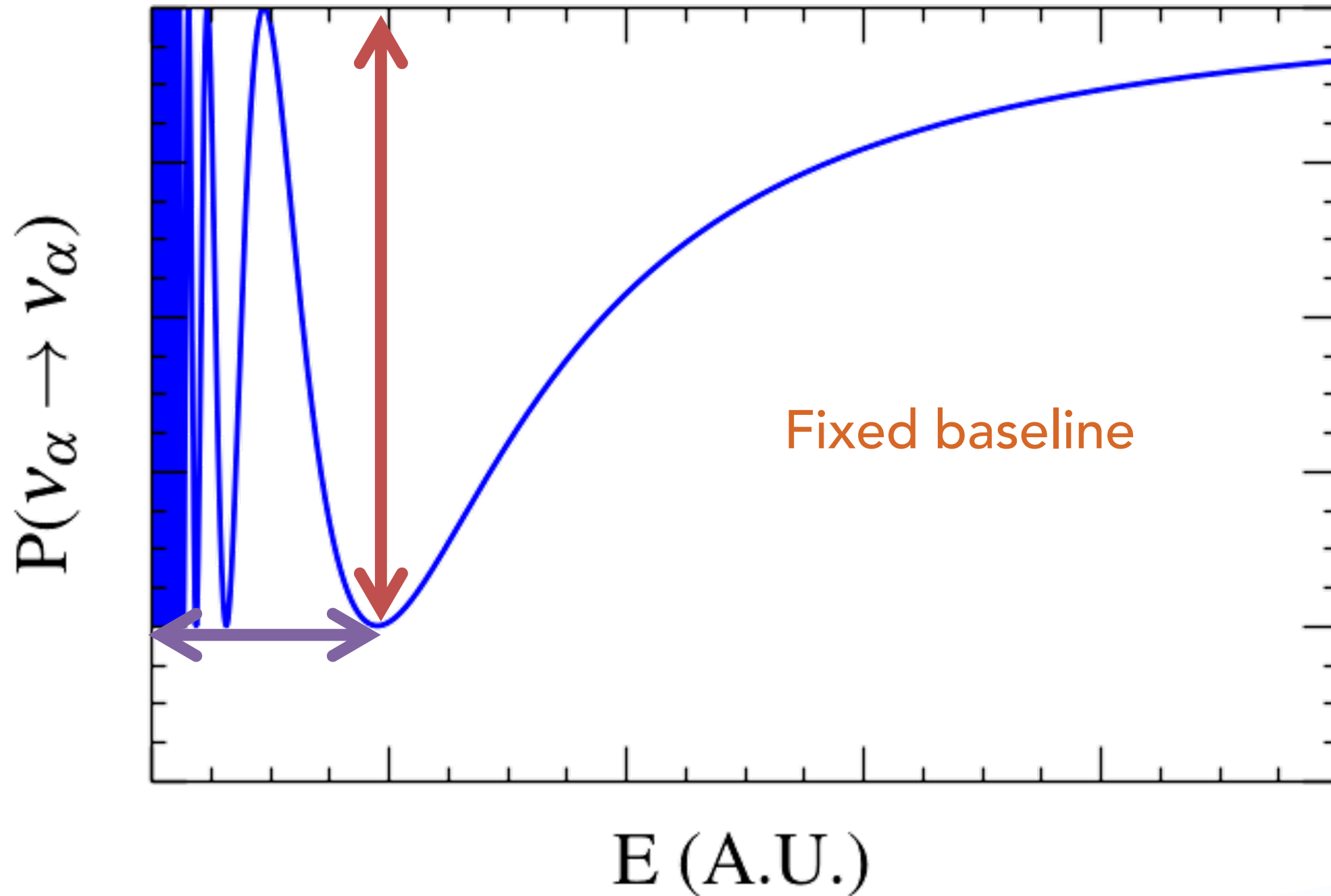
θ_{13} δ

θ_{12}

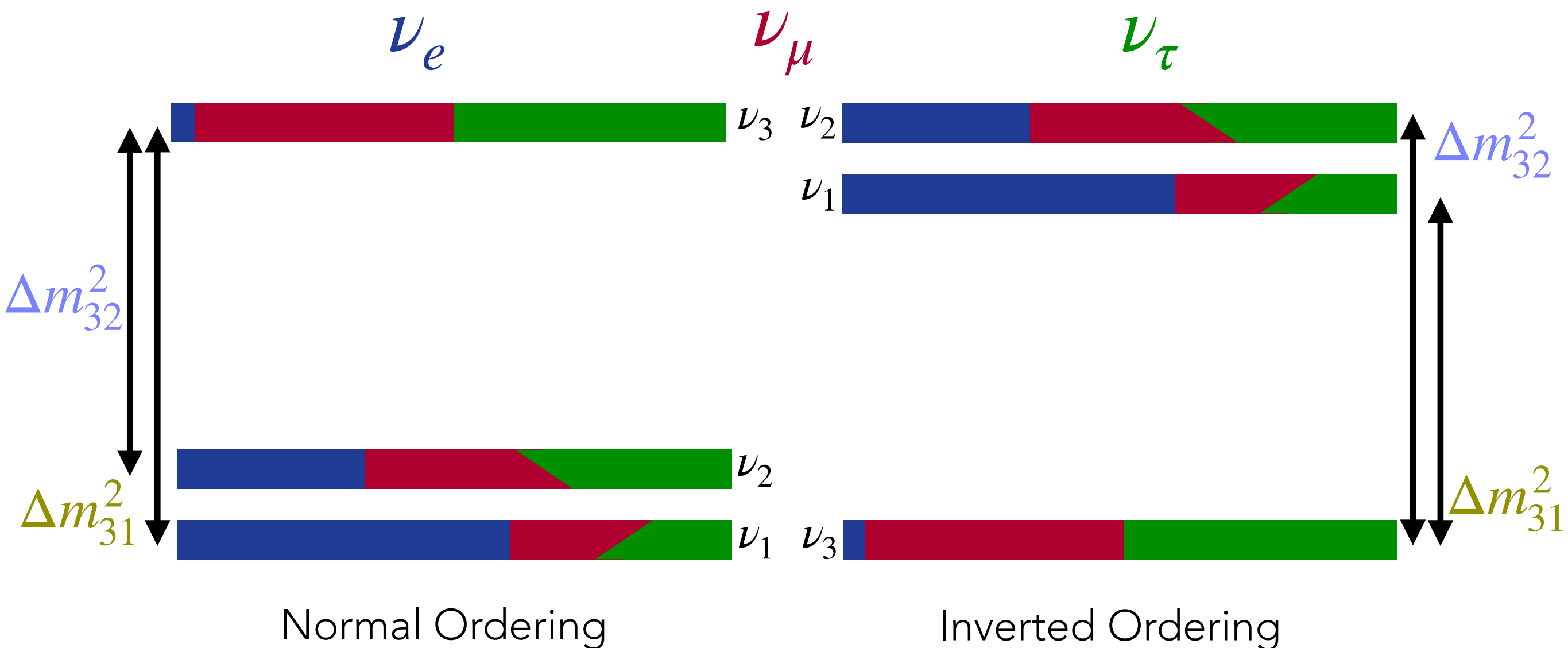
For given splitting, there is an L/E defining maximum (minimum) transition probability.



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

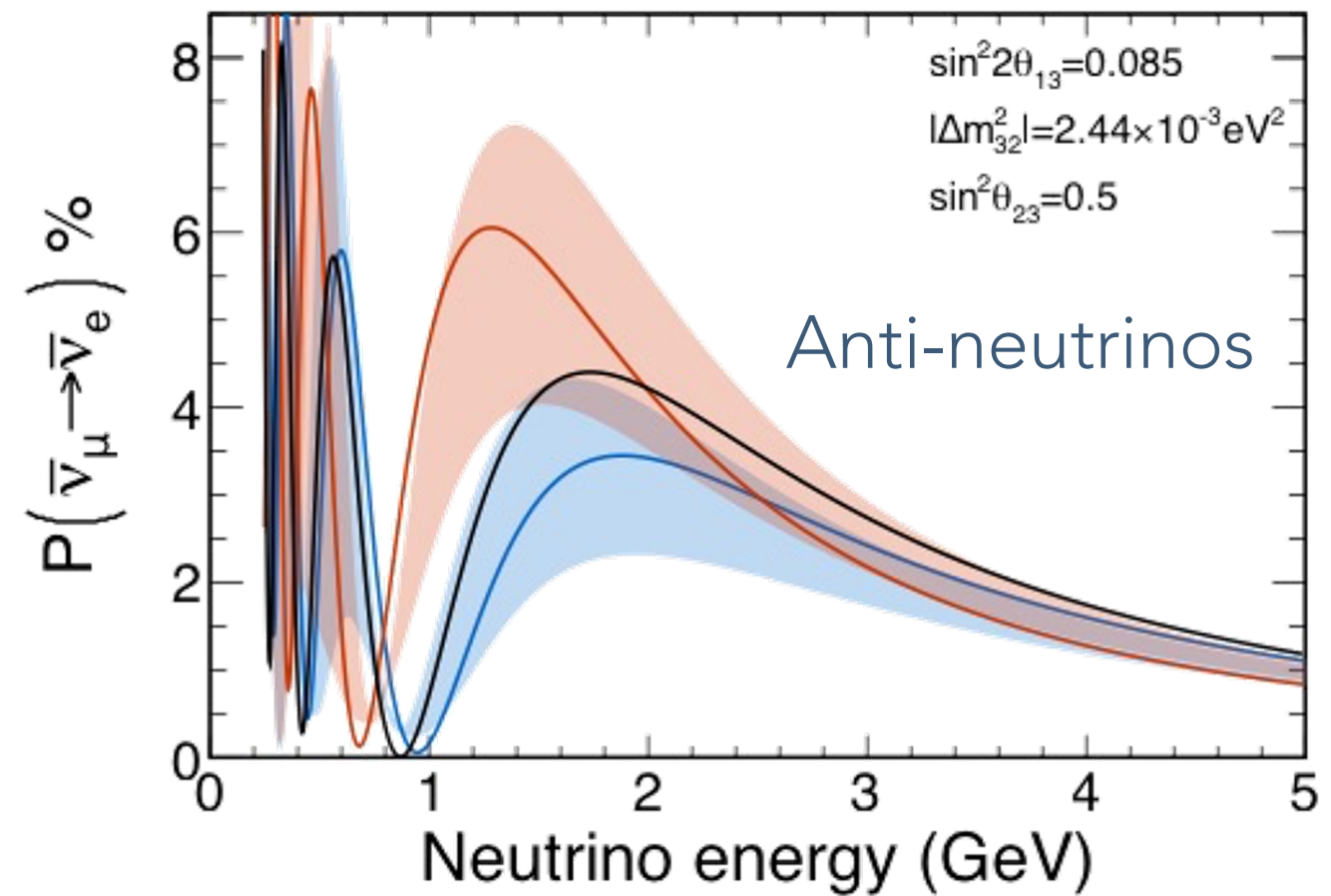
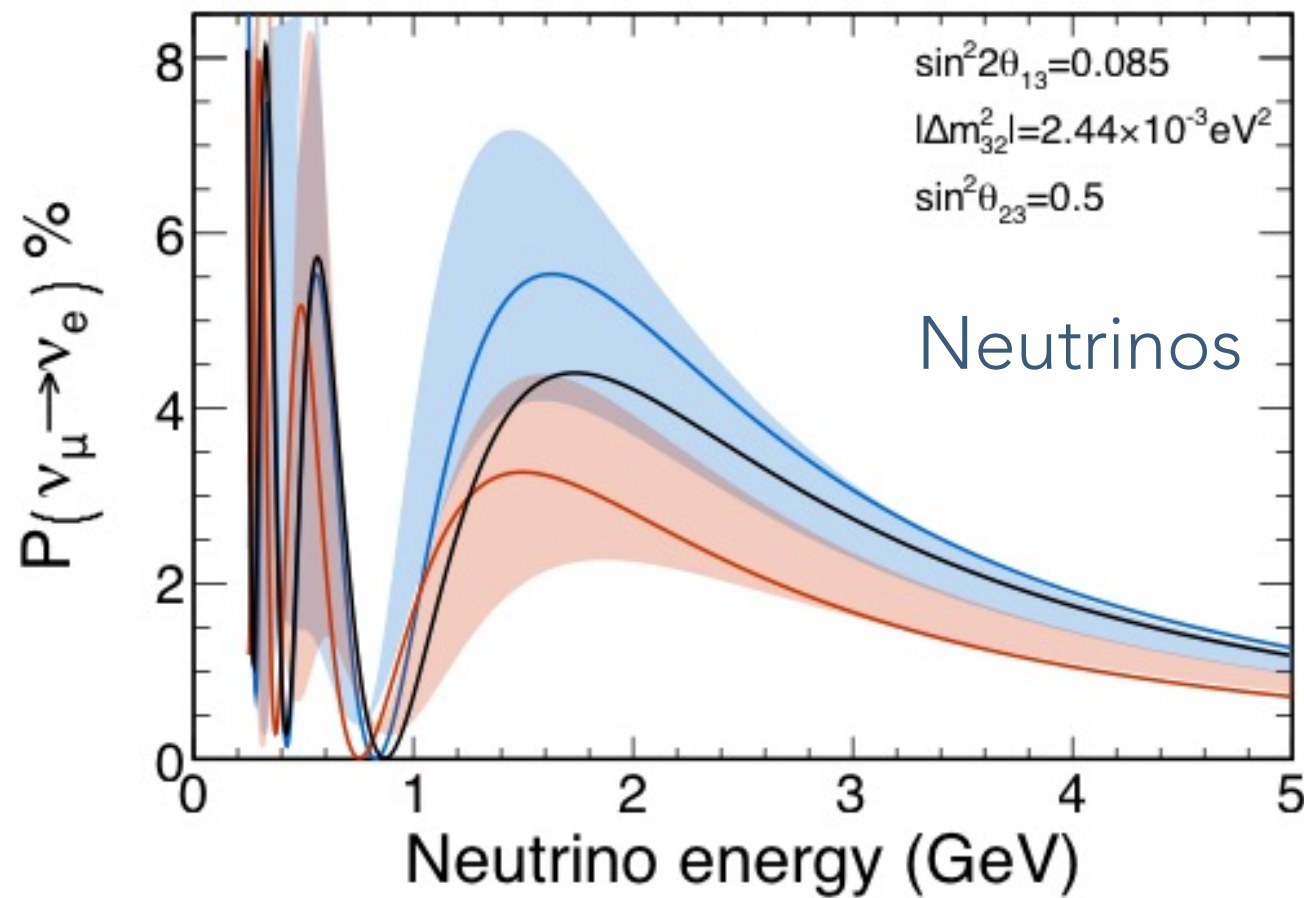


Mass Ordering & MSW Effect



- 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!**





Normal Ordering

Vacuum

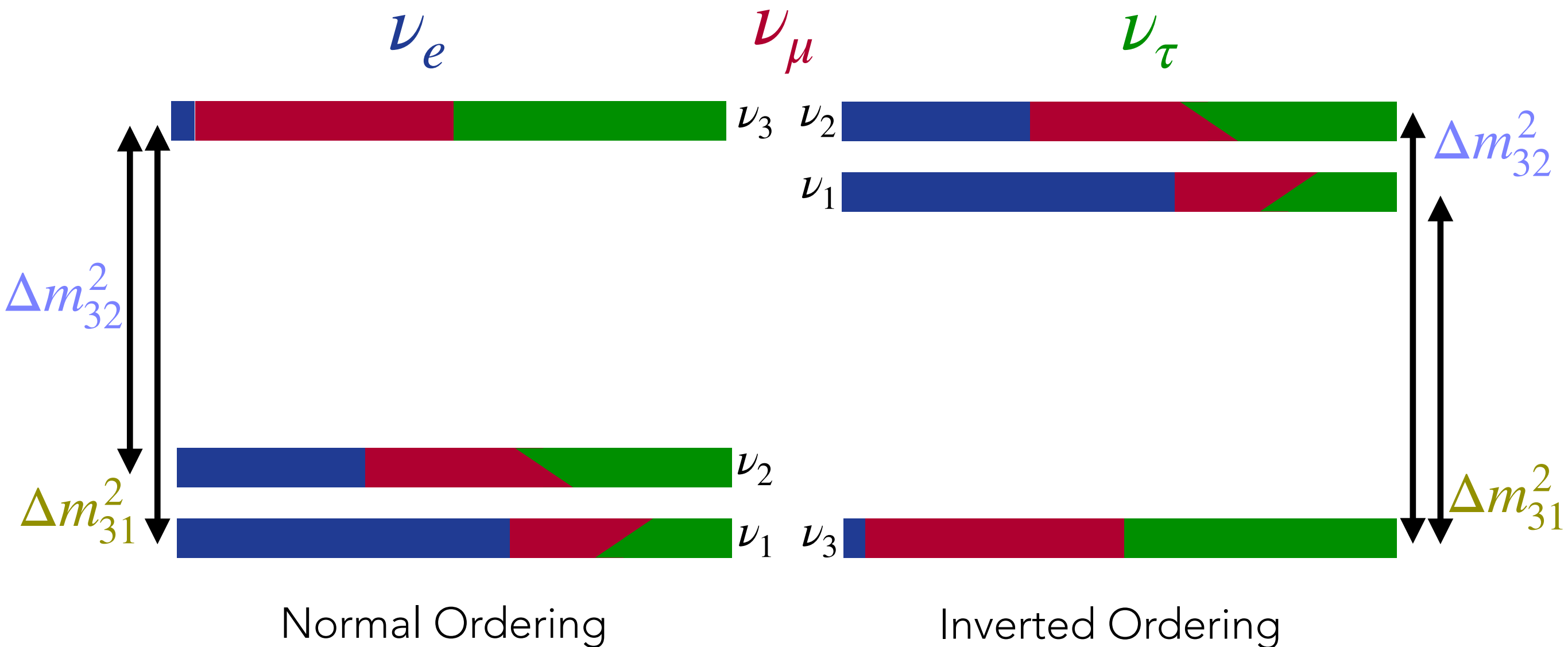
Inverted Ordering

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

Open Questions: Appearance



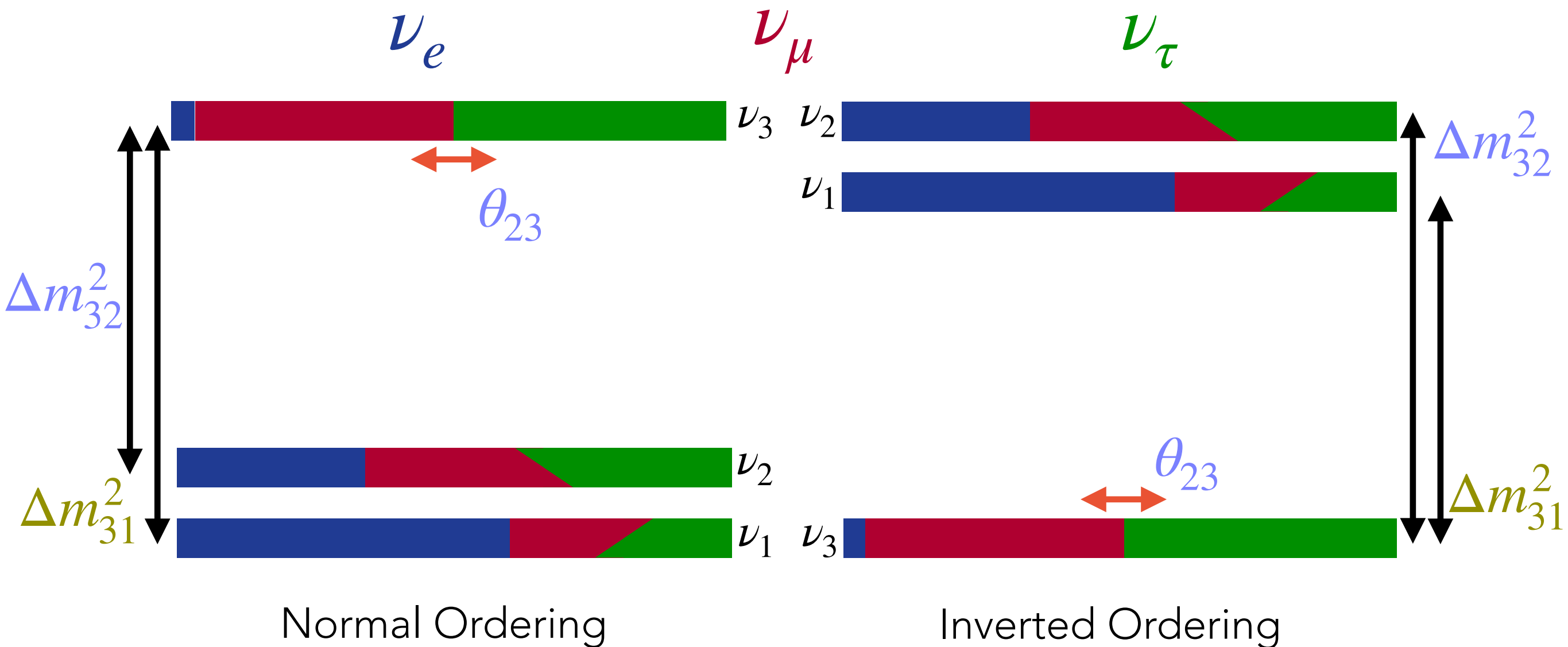
- $\nu_\mu \rightarrow \nu_e$ depends on:
 - Mass ordering and matter effects.
 - Octant of θ_{23} .
 - CP phase: δ_{CP} .



Open Questions: Appearance



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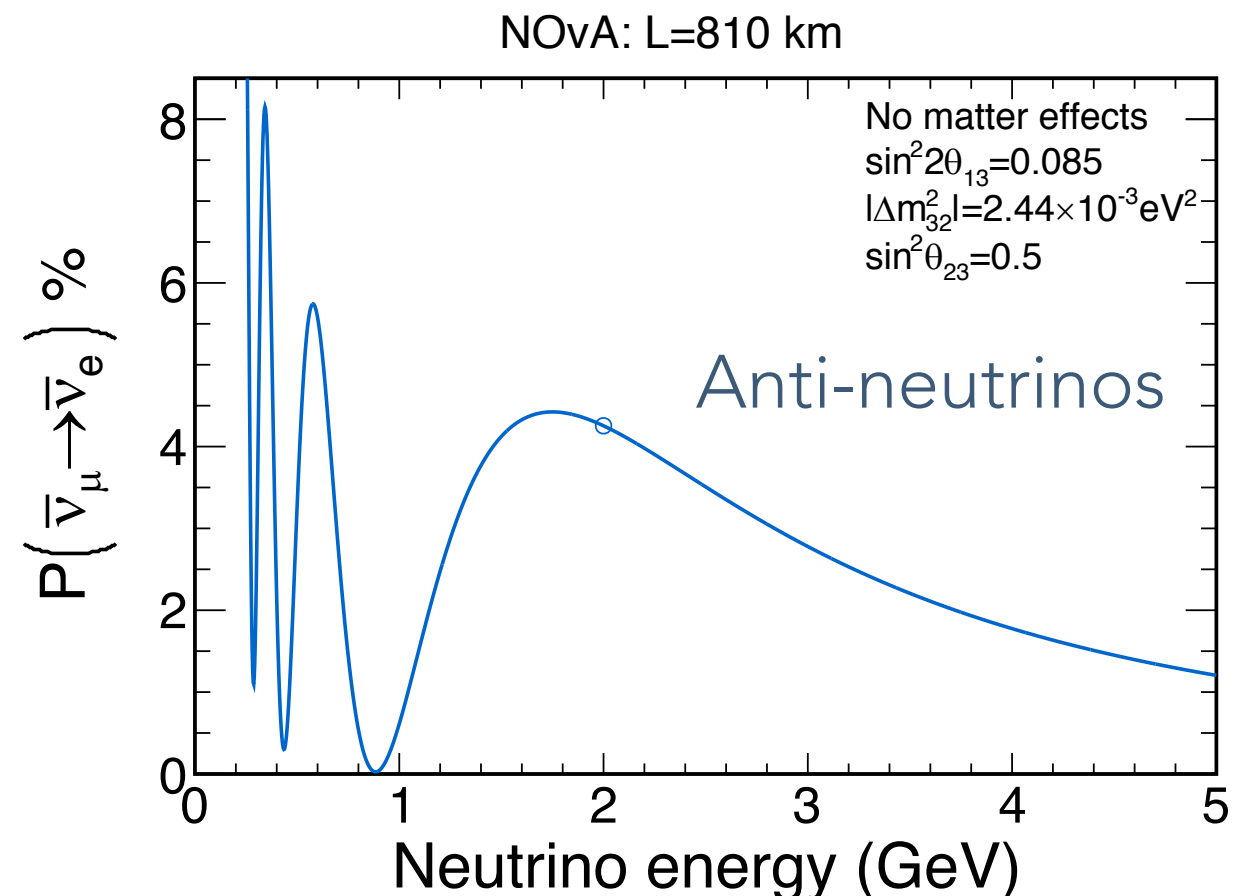
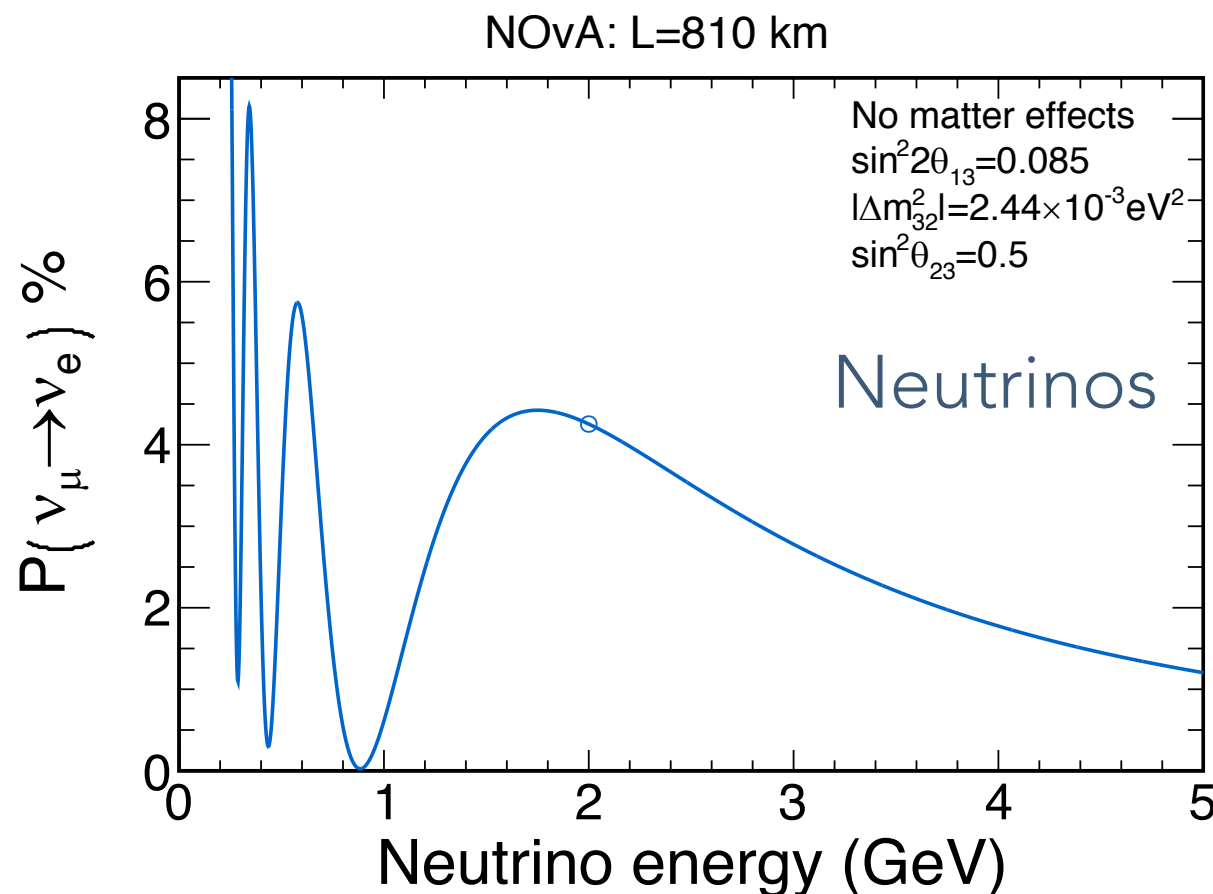




- $\nu_\mu \rightarrow \nu_e$ depends on:

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

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

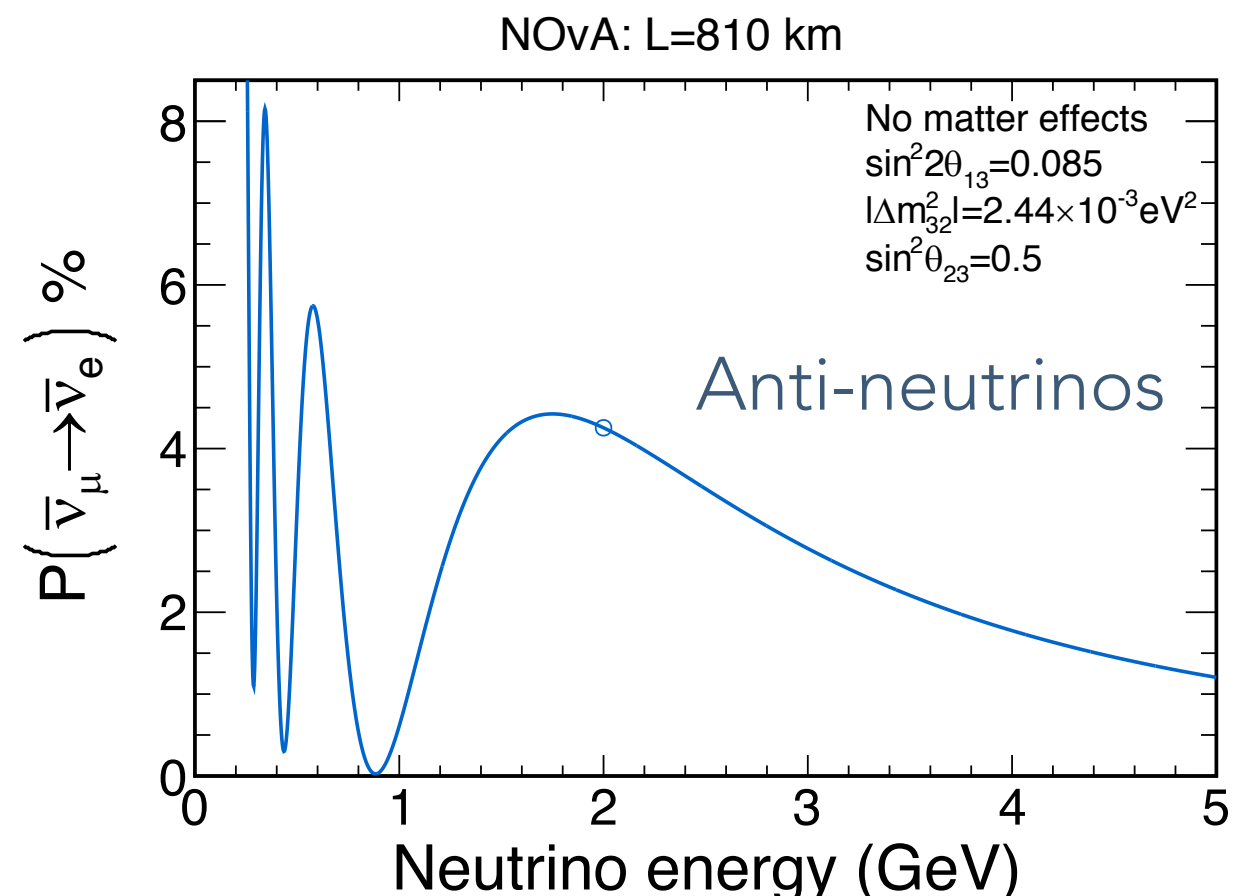
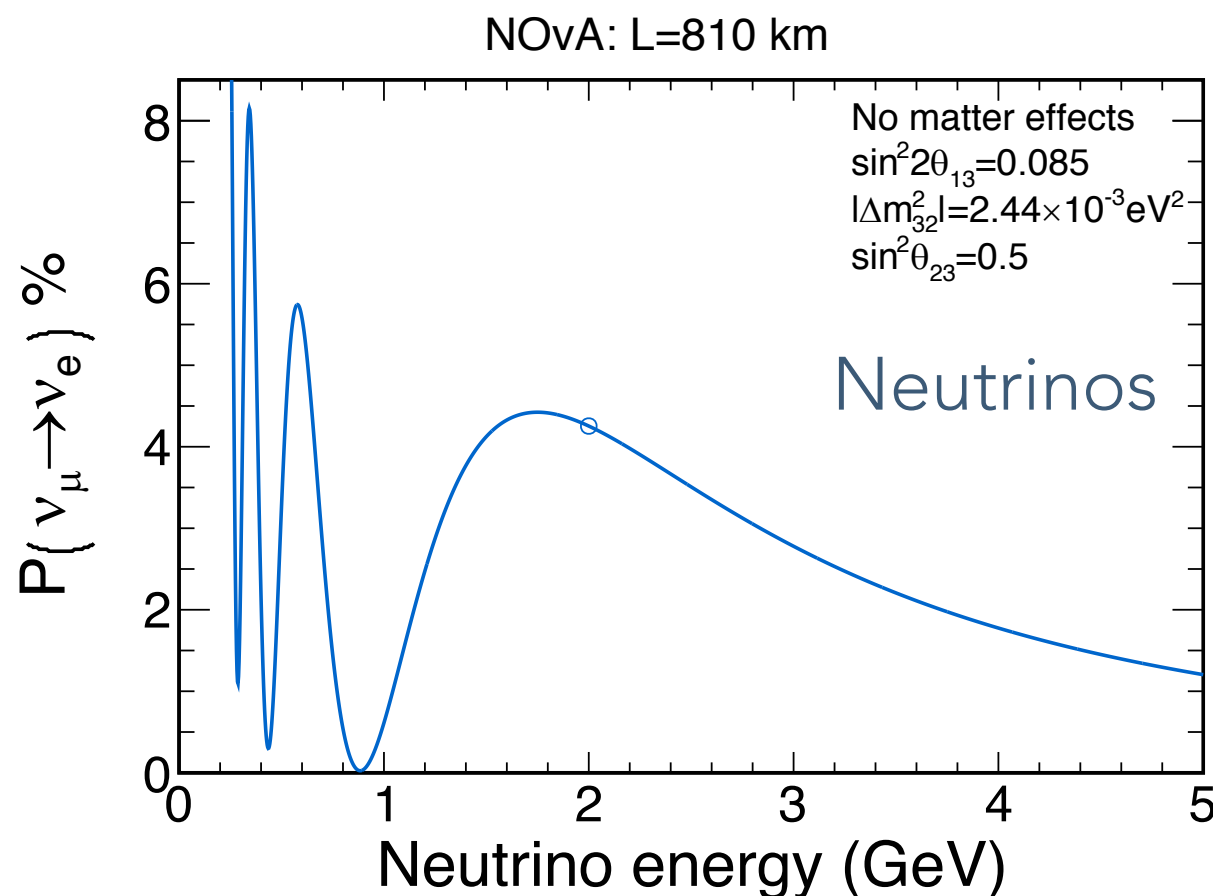




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CP conserved



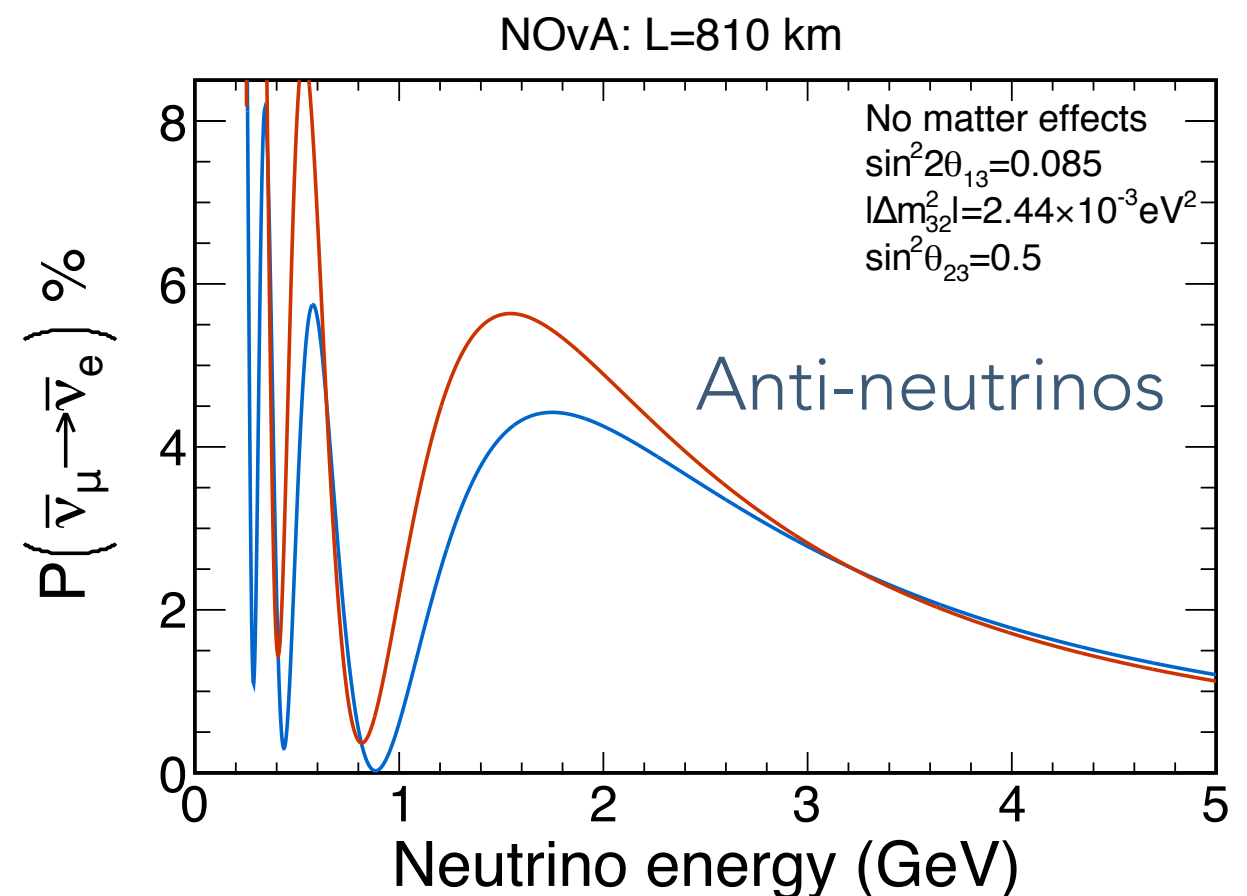
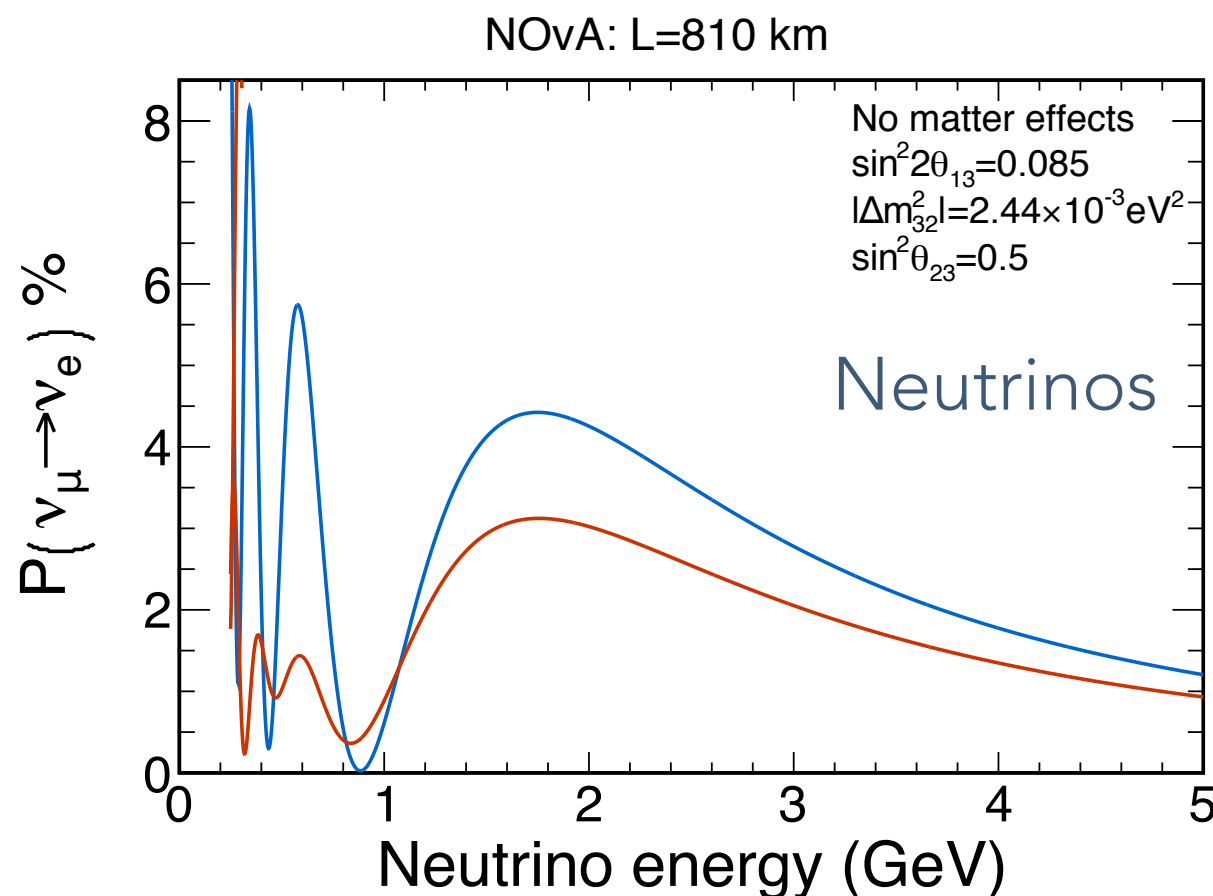


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- CP phase: δ_{CP} .

CP conserved

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



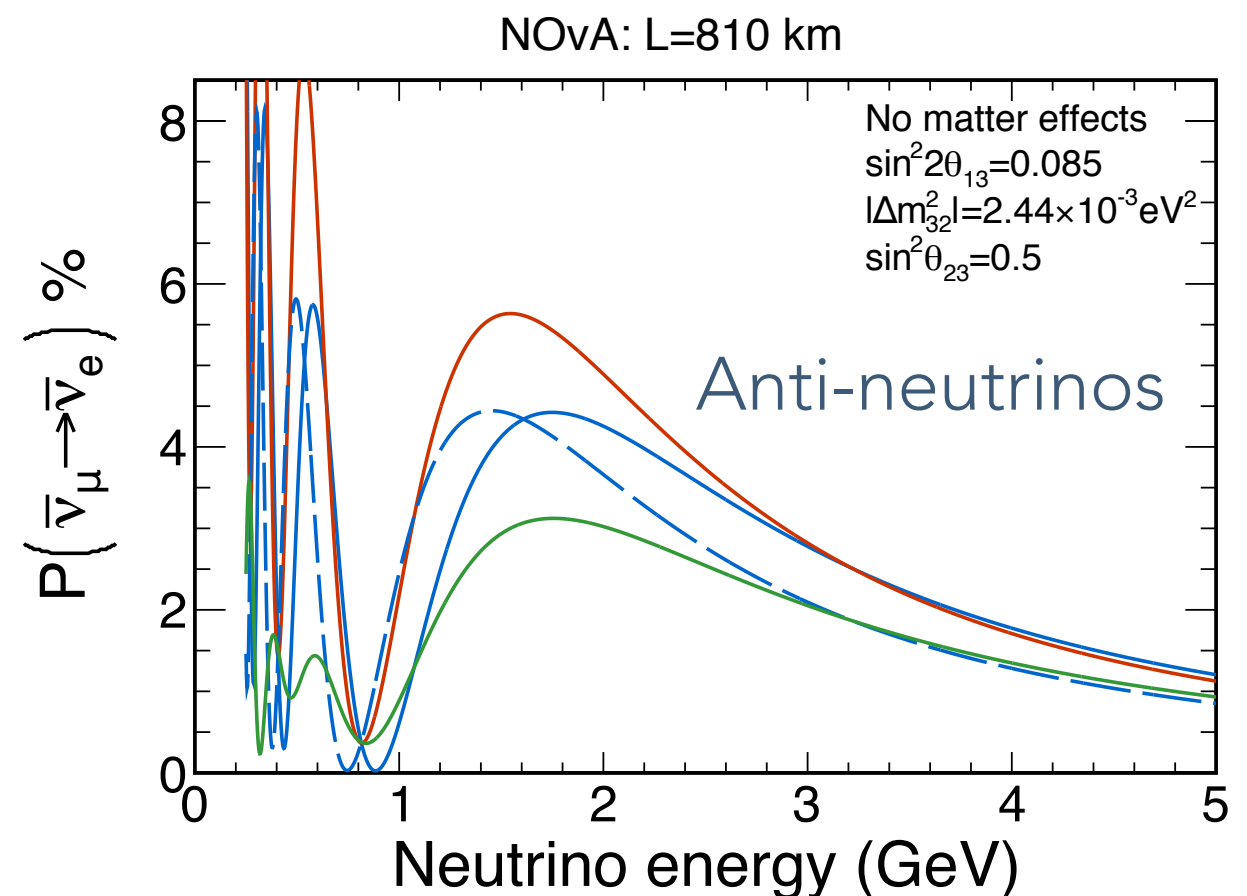
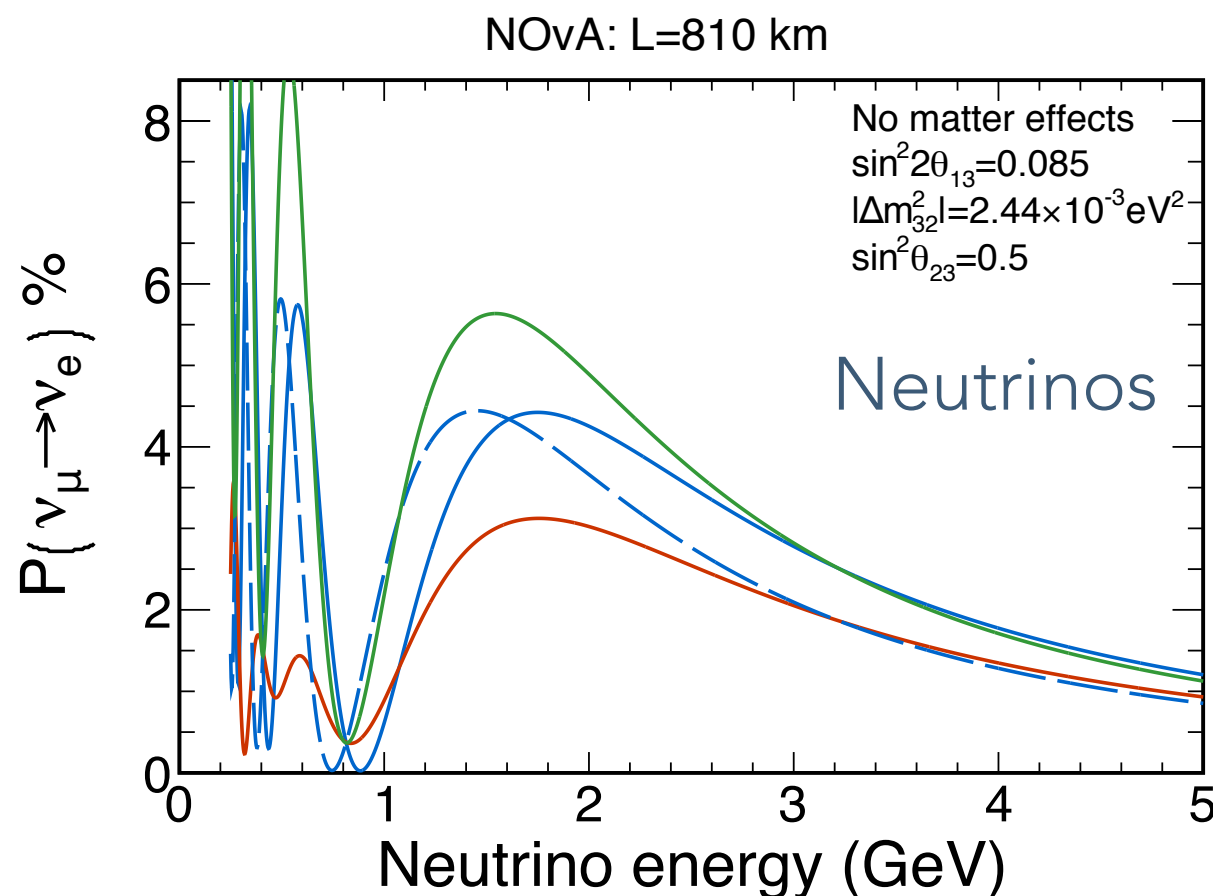


- $\nu_\mu \rightarrow \nu_e$ depends on:

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CP conserved

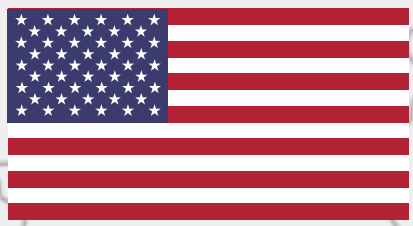
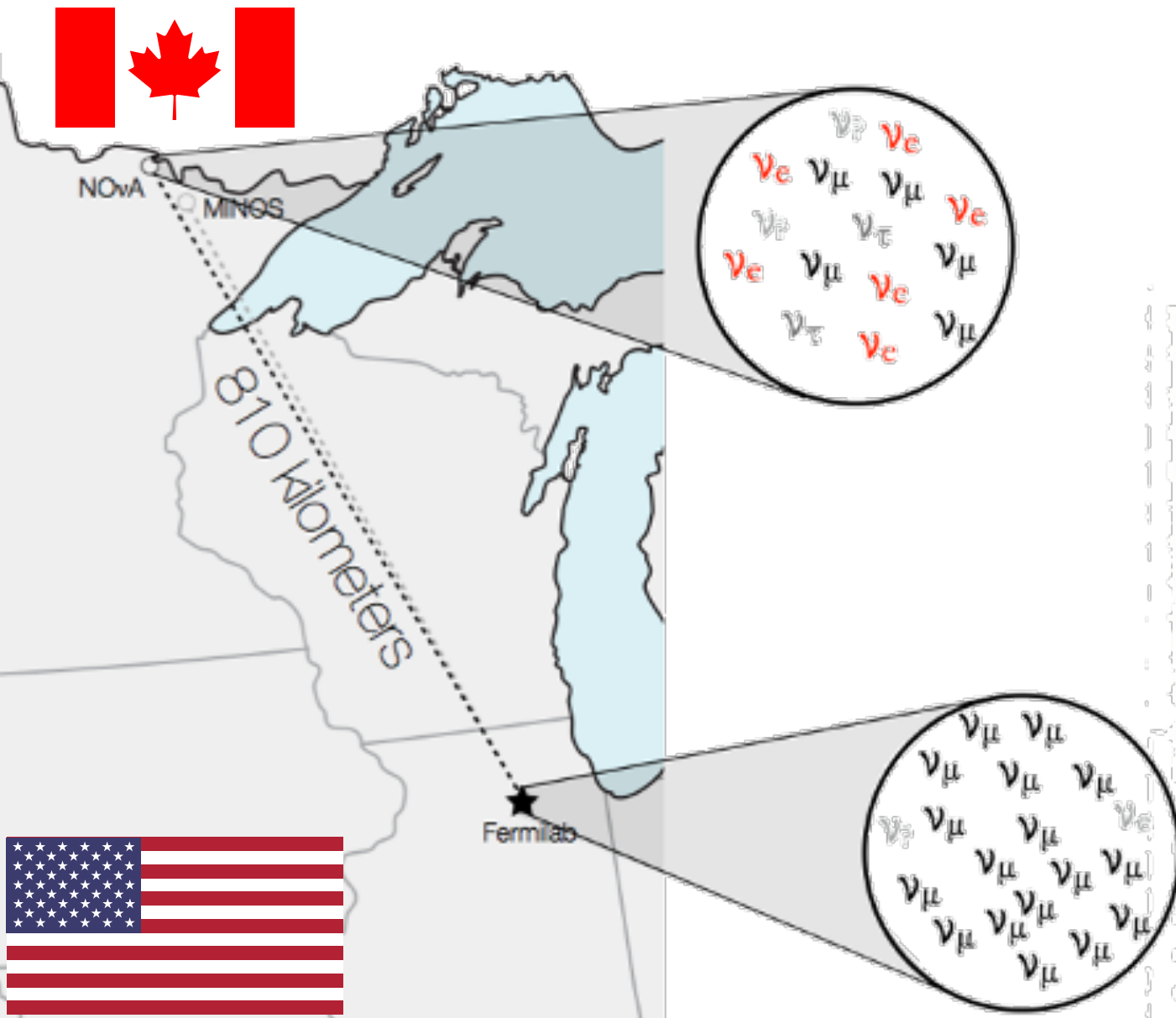
$$\delta_{CP} = \pi/2 \quad \delta_{CP} = 3\pi/2$$



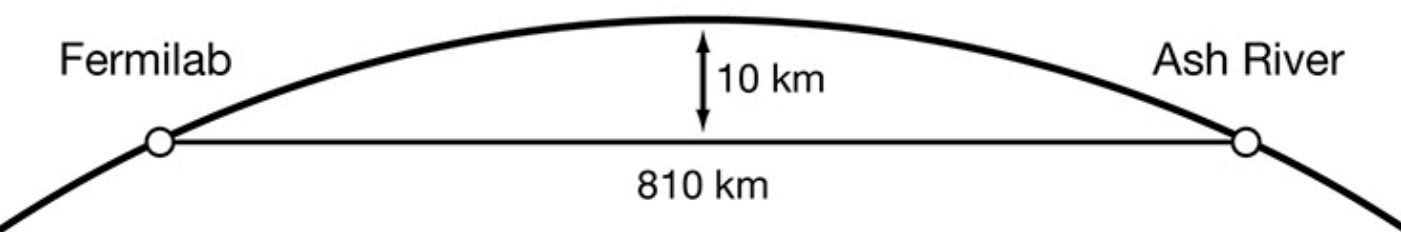
- Neutrinos are well worth studying!
- There are 7 parameters governing 3-flavour oscillation.
- NOvA is interested in 3.
- Make measurements by measuring muon neutrino disappearance probabilities ($P(\nu_\mu \rightarrow \nu_\mu)$) and electron neutrino appearance probabilities ($P(\nu_\mu \rightarrow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

NOvA Experimental Setup

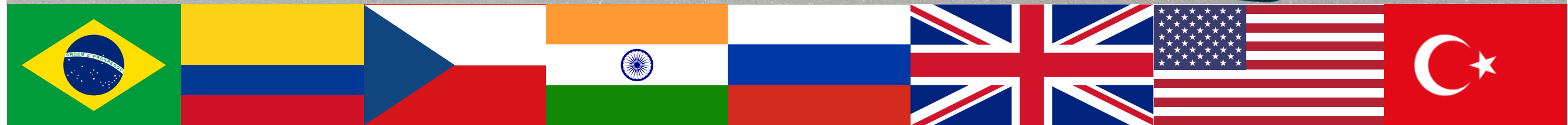
NOvA Overview



- 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:
 - $\nu_\mu \rightarrow \nu_\mu, \nu_\mu \rightarrow \nu_e$
 - $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu, \bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- Other goals include:
 - Search for sterile neutrinos.
 - Neutrino cross sections.
 - Supernova neutrinos.
 - Cosmic ray physics.



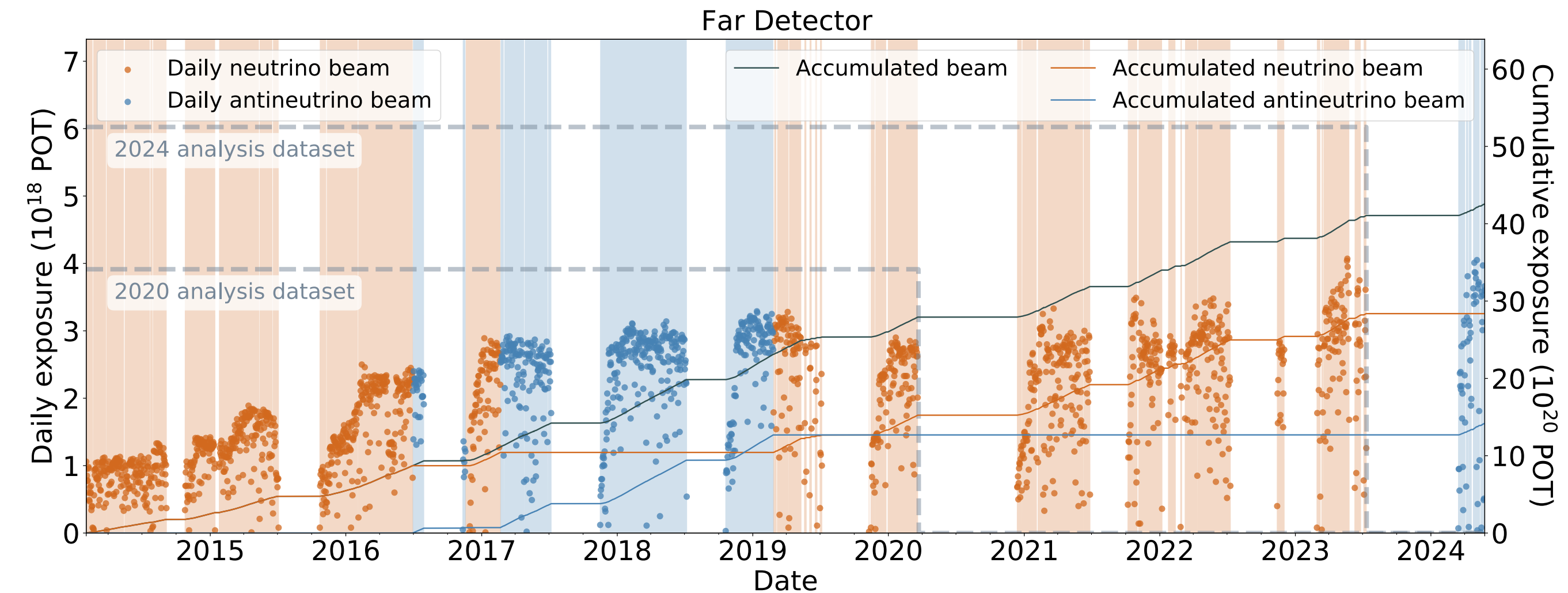
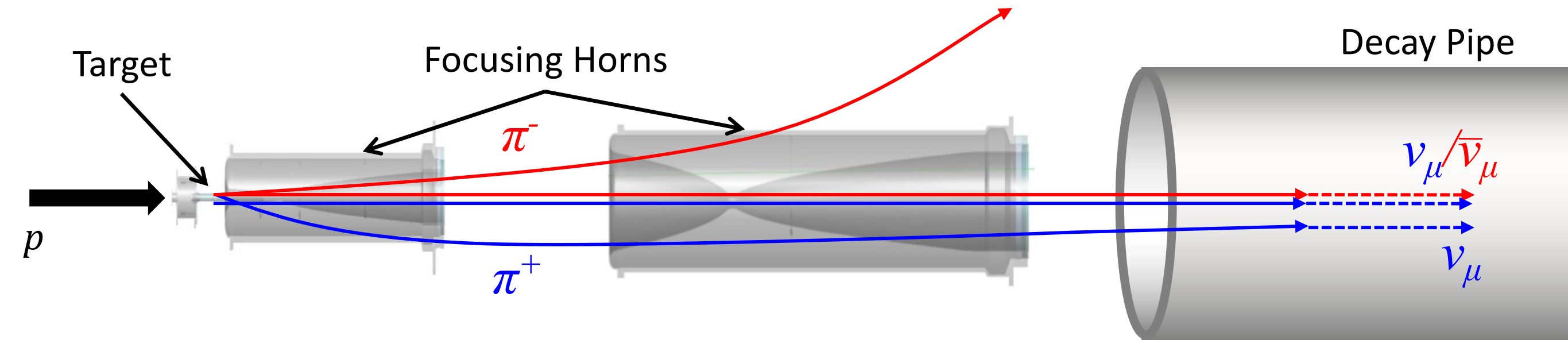
The NOvA Collaboration

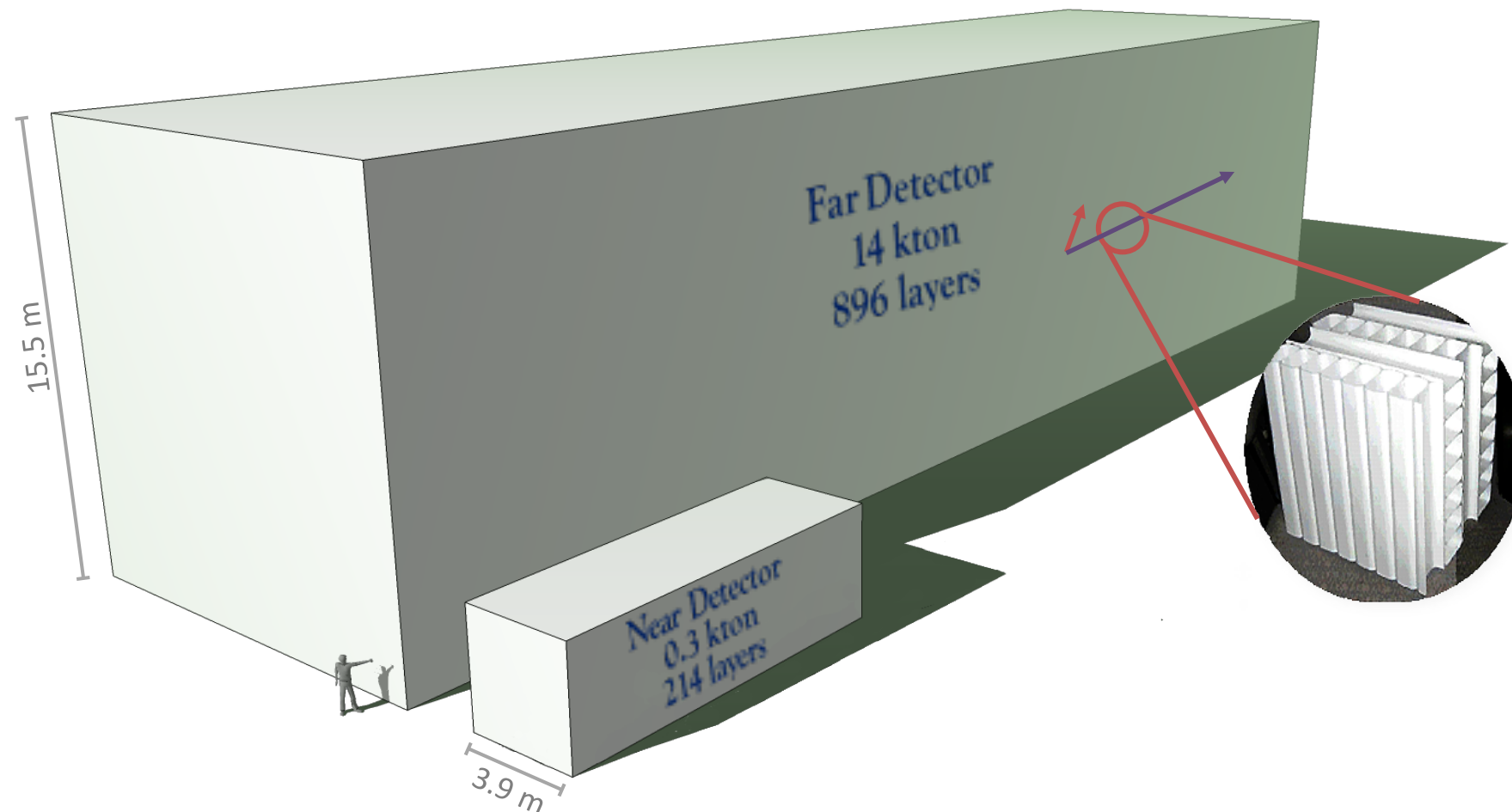


> 260 people, ~ 50 institutions, 8 countries

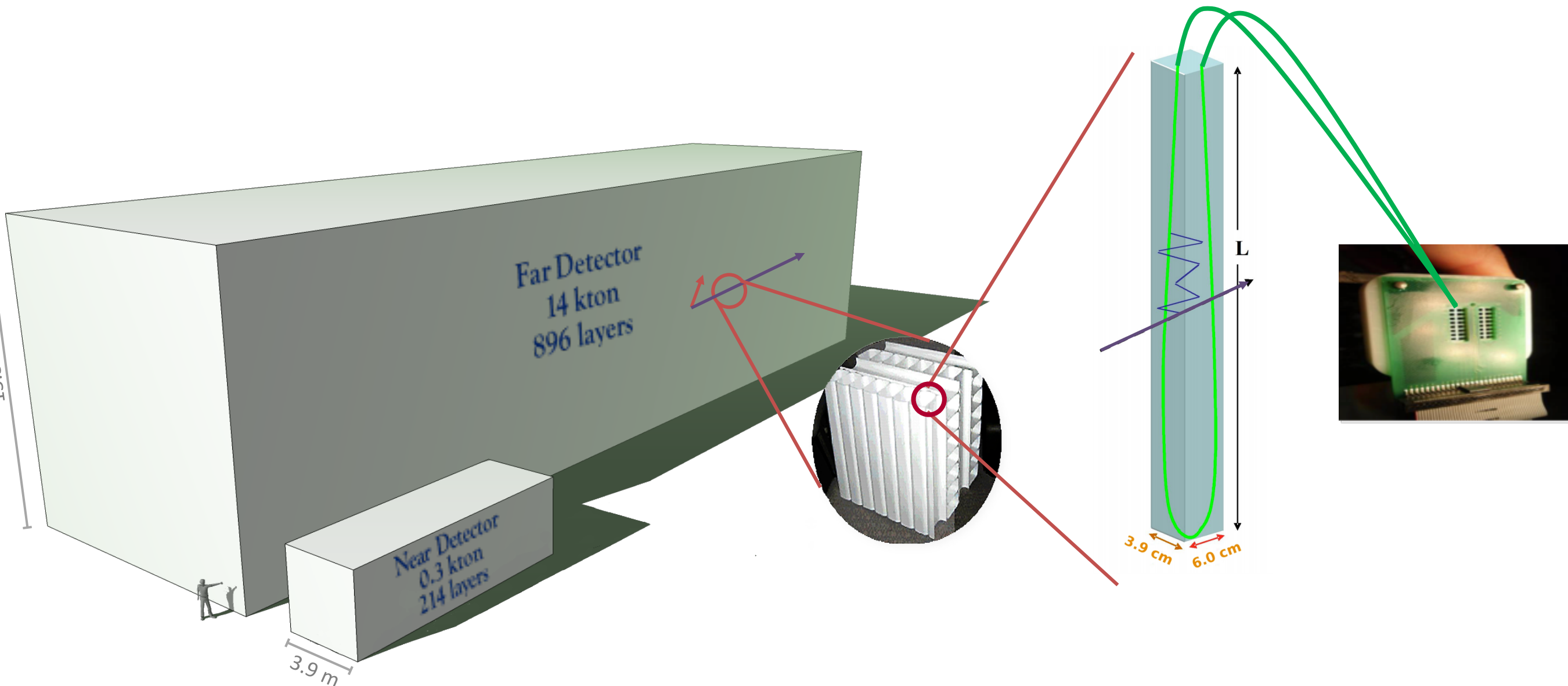


How We Make Neutrinos: NuMI Beam





- 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.



- 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



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





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





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!





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**.

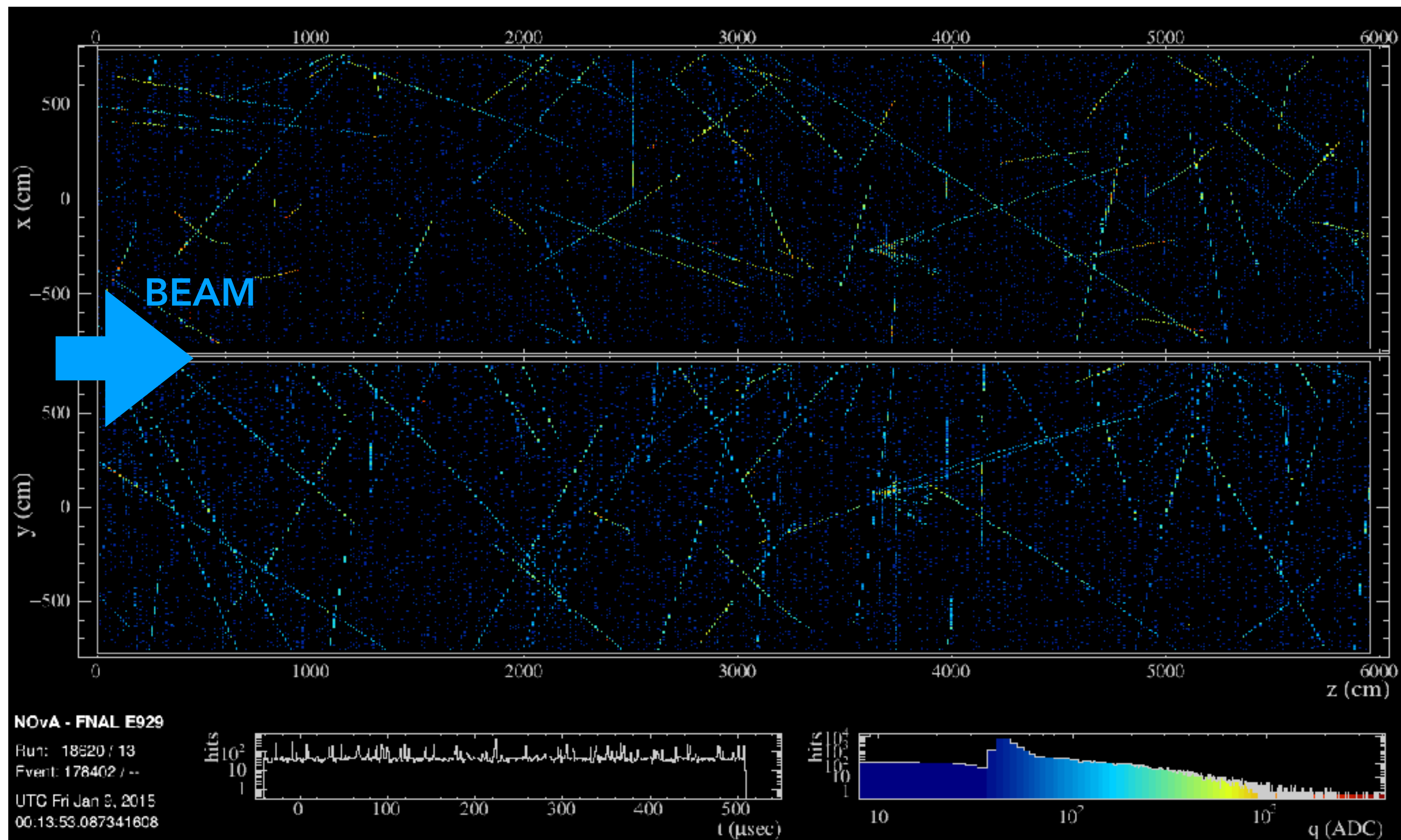
Extrapolation

Models

Improved!



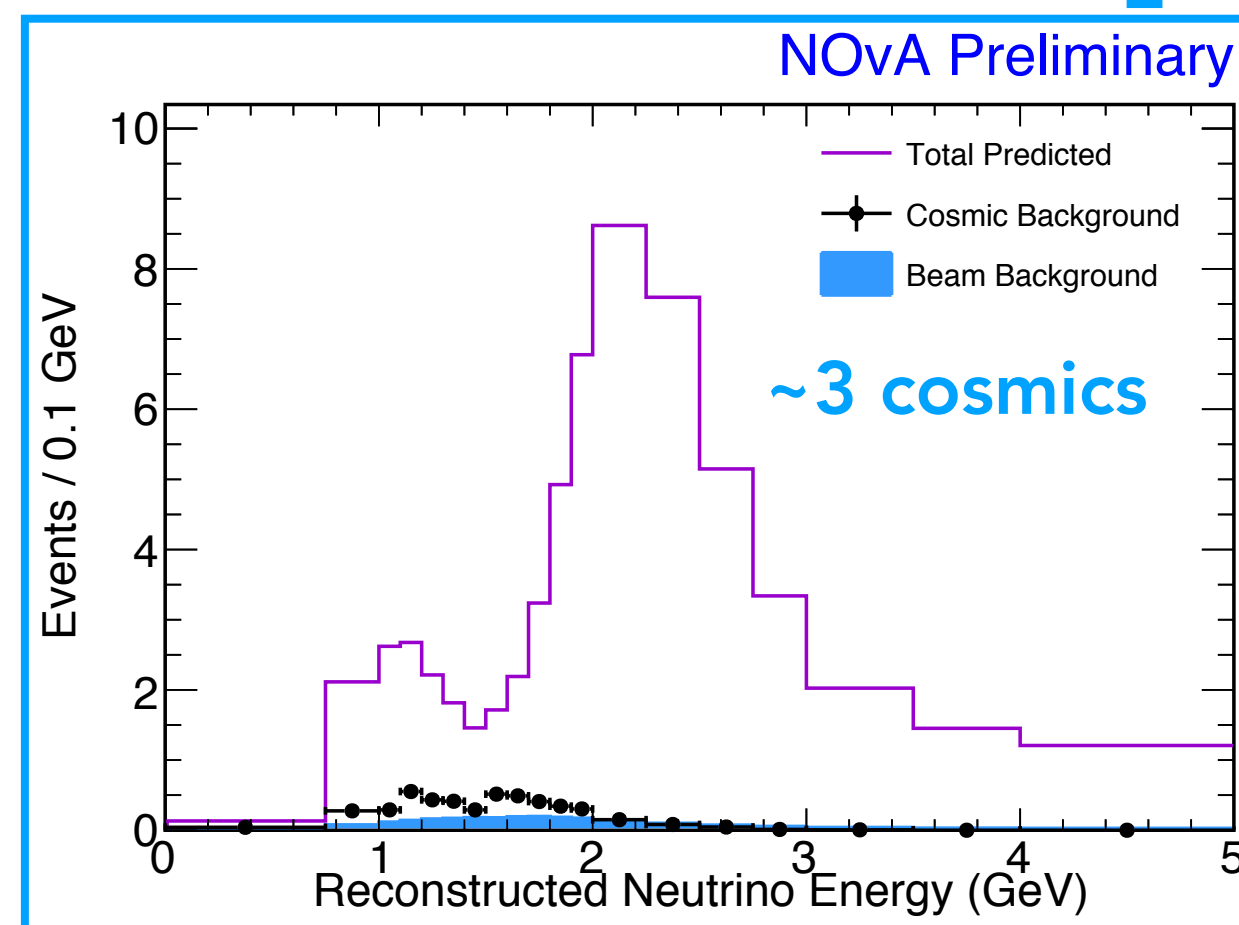
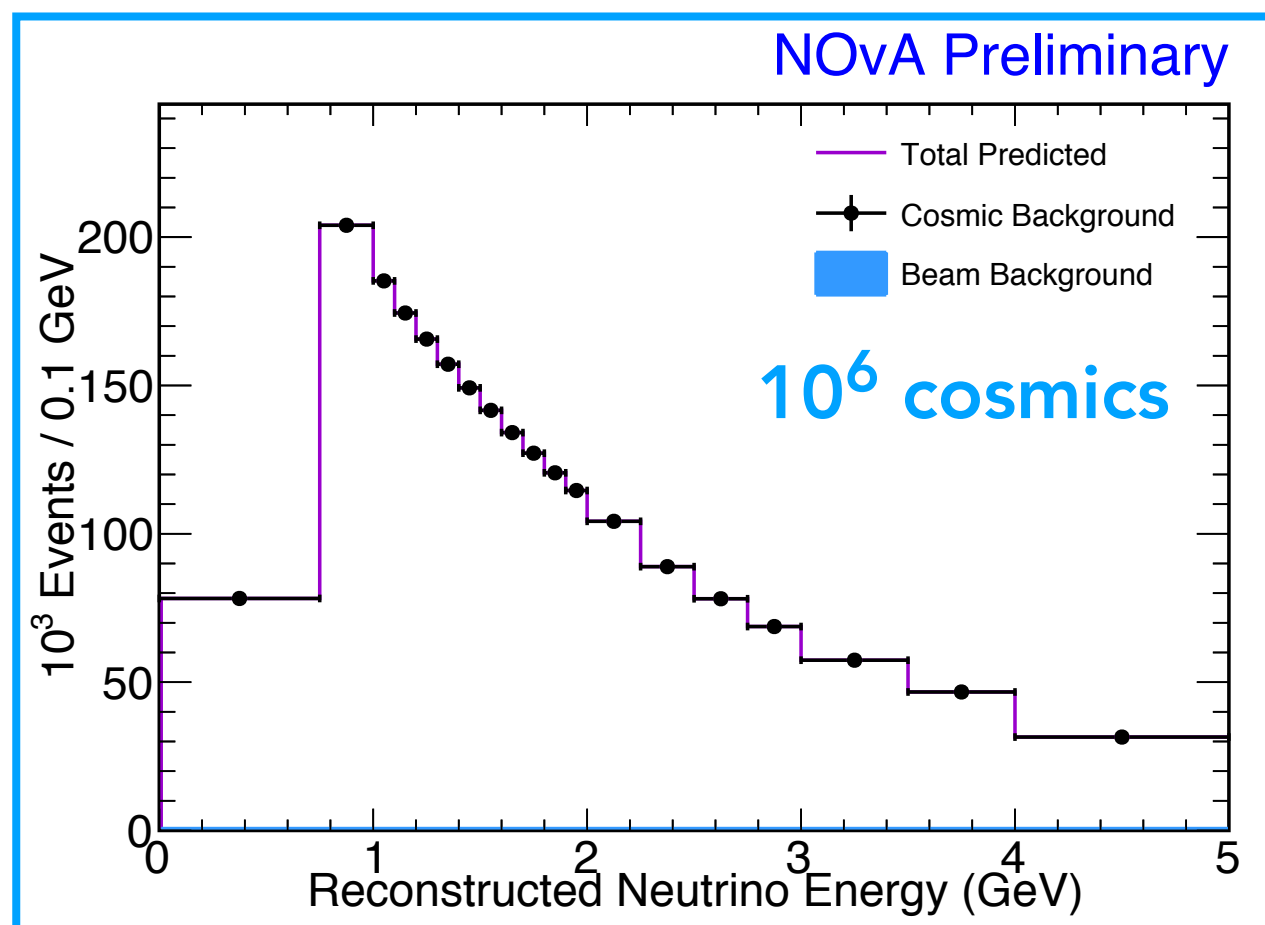
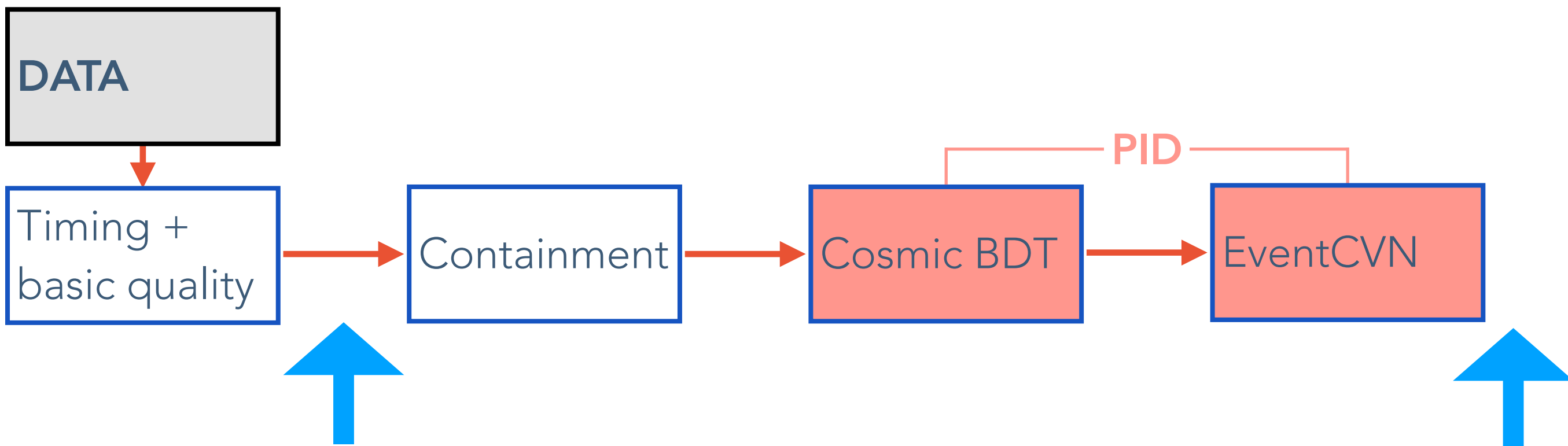
Selection: Cosmic Rejection



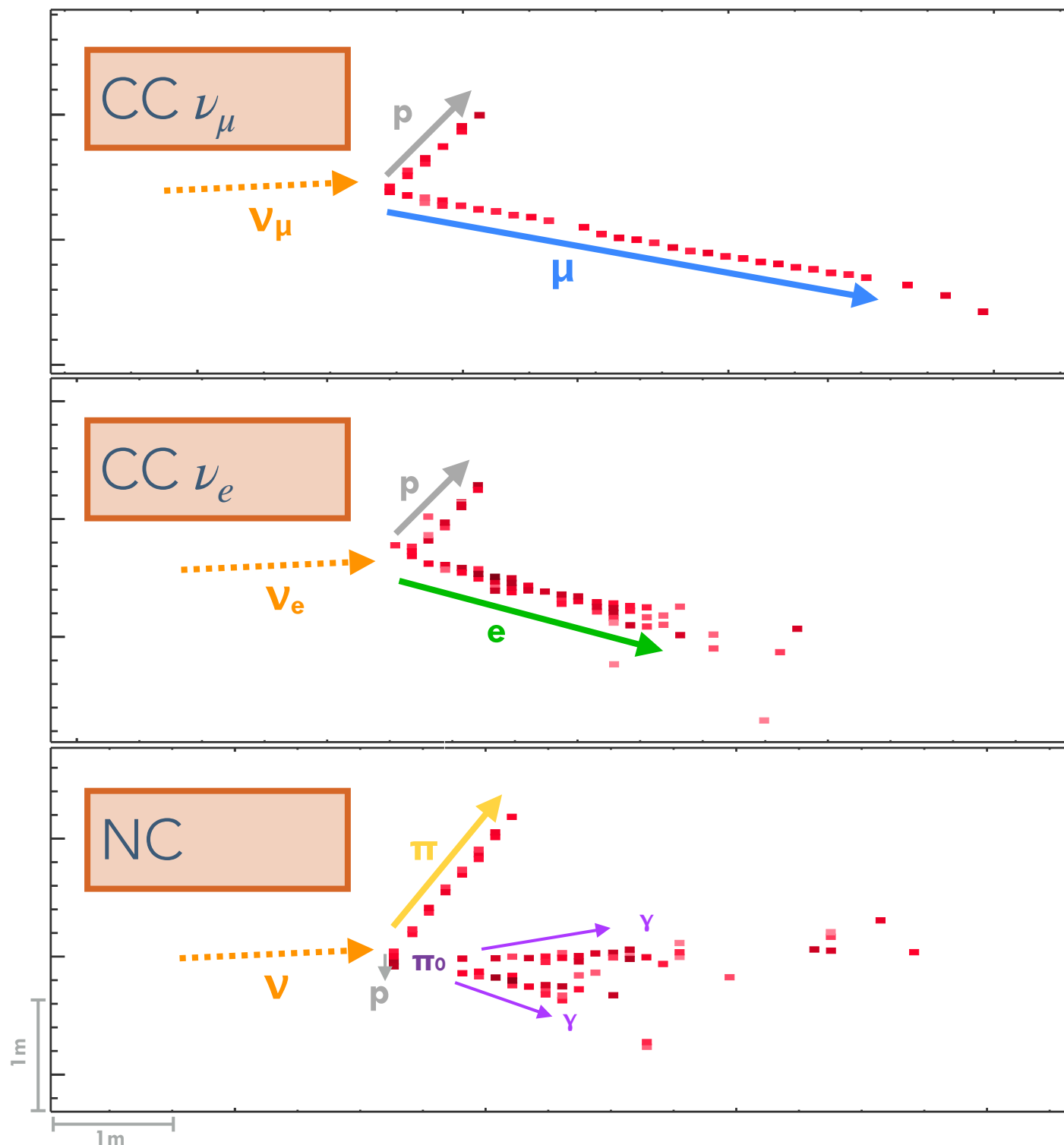
Cosmic rejection critical for FD: 11 billion cosmic rays/day



Selection: ν_μ



Selecting & Identifying Neutrinos



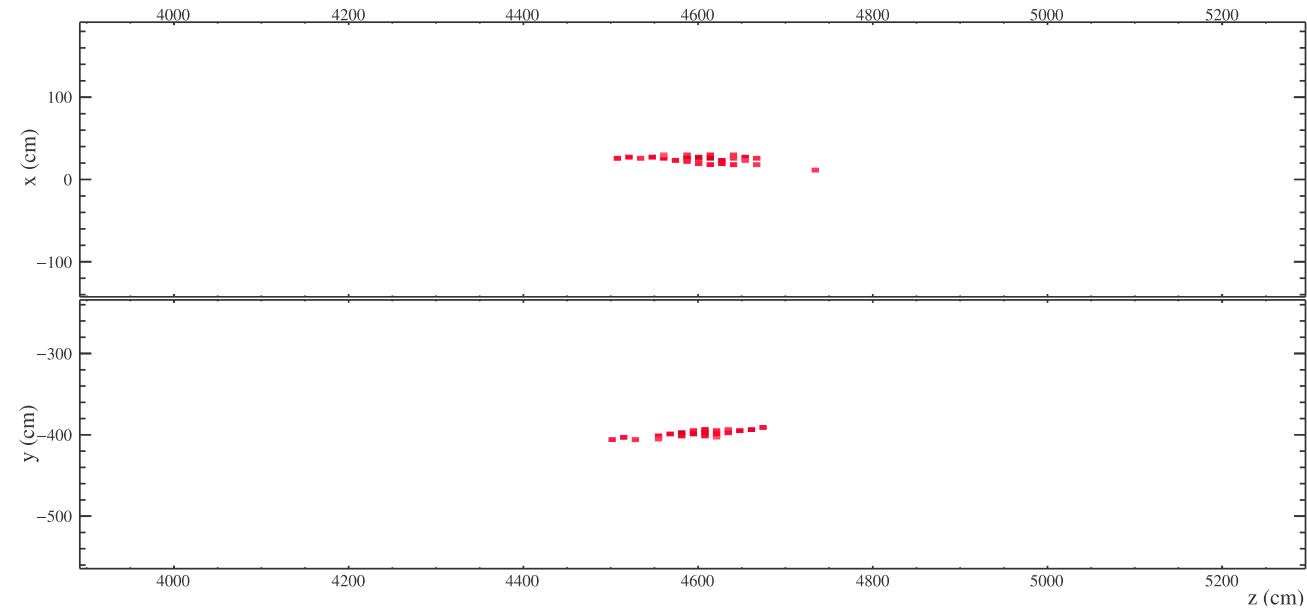
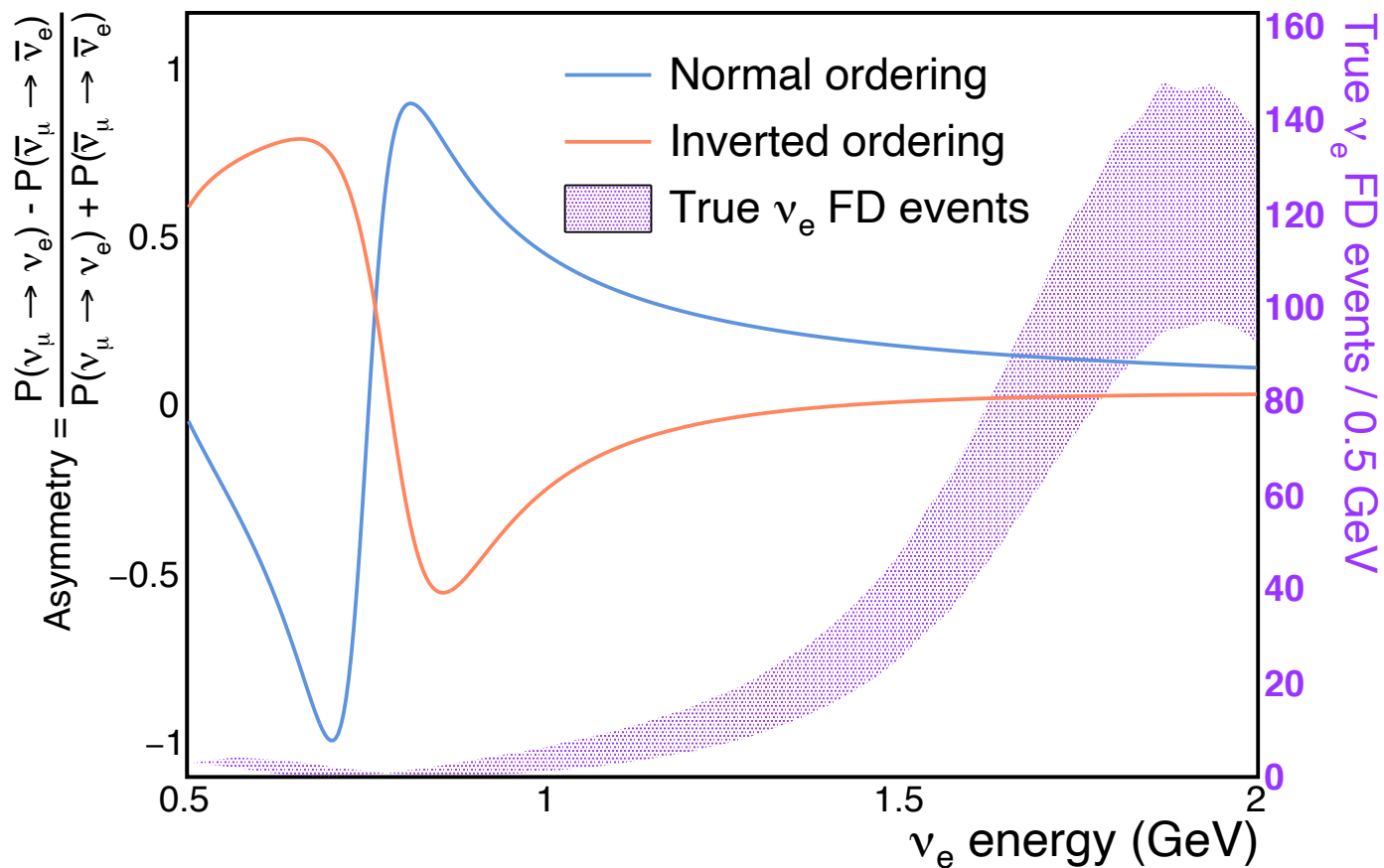
- Use **convolutional neural network** technique from deep learning.
 - NOvA was first HEP experiment to use CNN for PID.
- Successive layers of "feature maps":
 - Create many variants of original image which enhance different features.
 - Variations which are best for enhancing most important features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



Expanding ν_e Candidate Selection



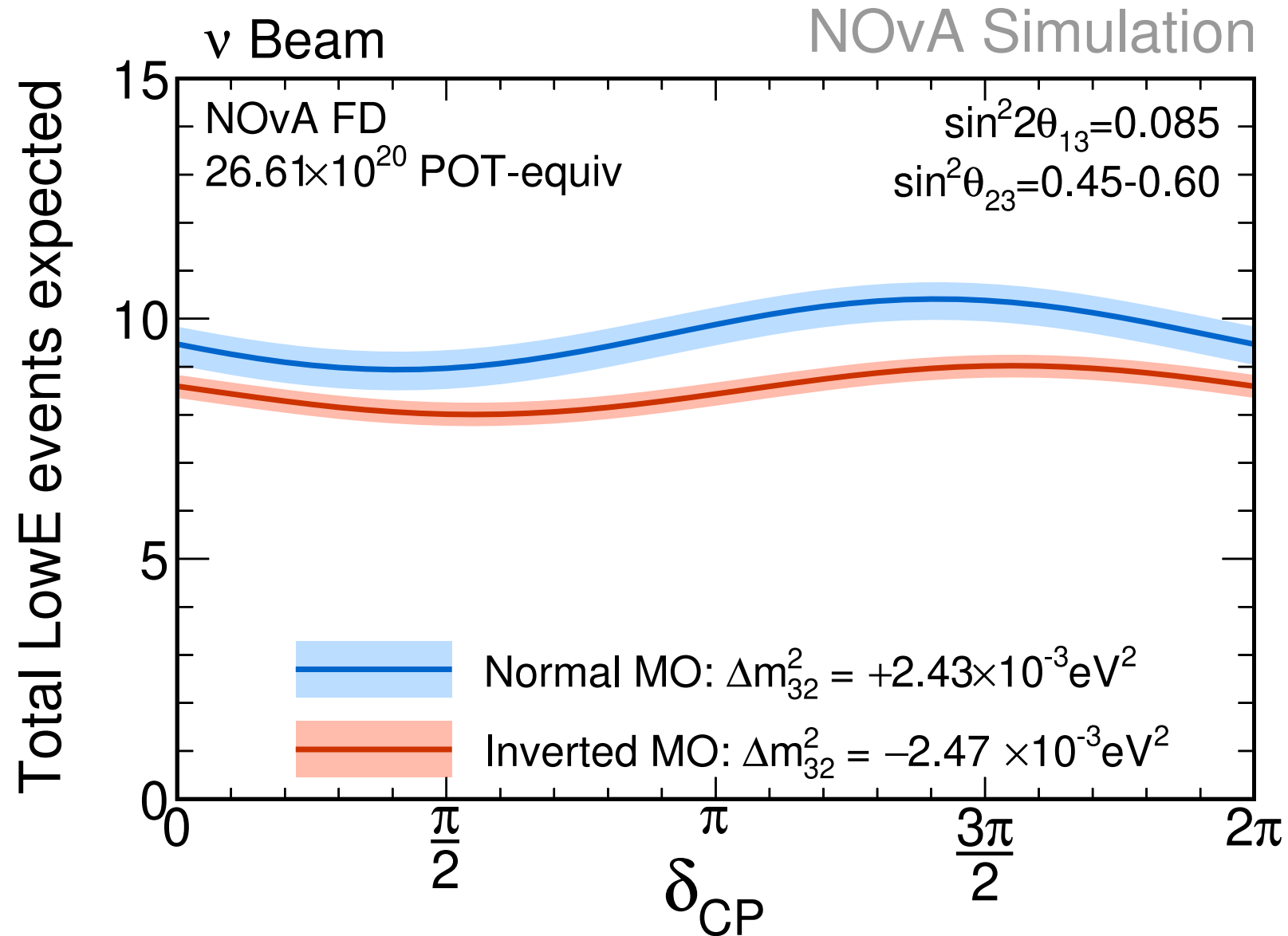
NOvA Simulation



- 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.



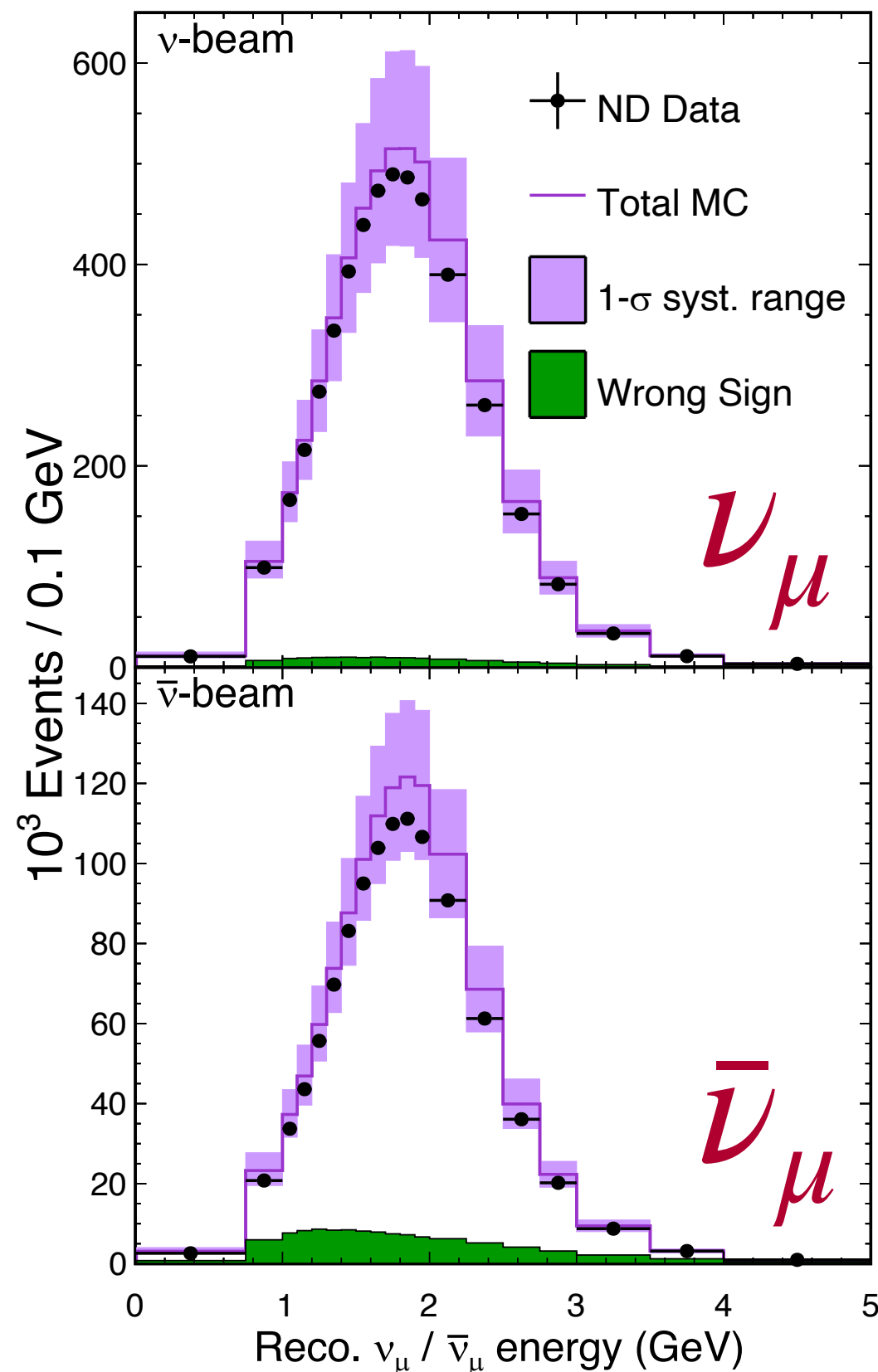
Expanding ν_e Candidate Selection



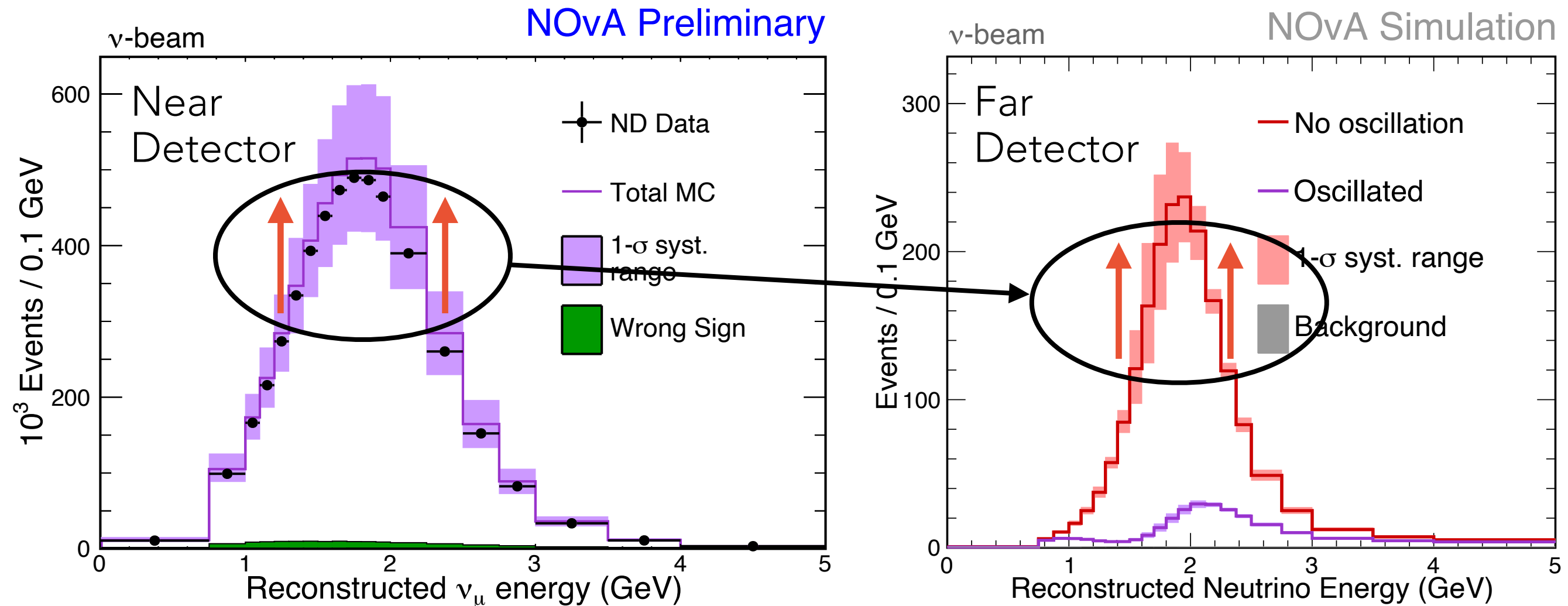
- Good separation in some regions.
- Only have sufficient statistics in the neutrino beam mode sample. Analogous sample in antineutrino beam mode is currently too small.
- Provides increase in sensitivity to the mass ordering of $\sim$ few %.



NOvA Preliminary

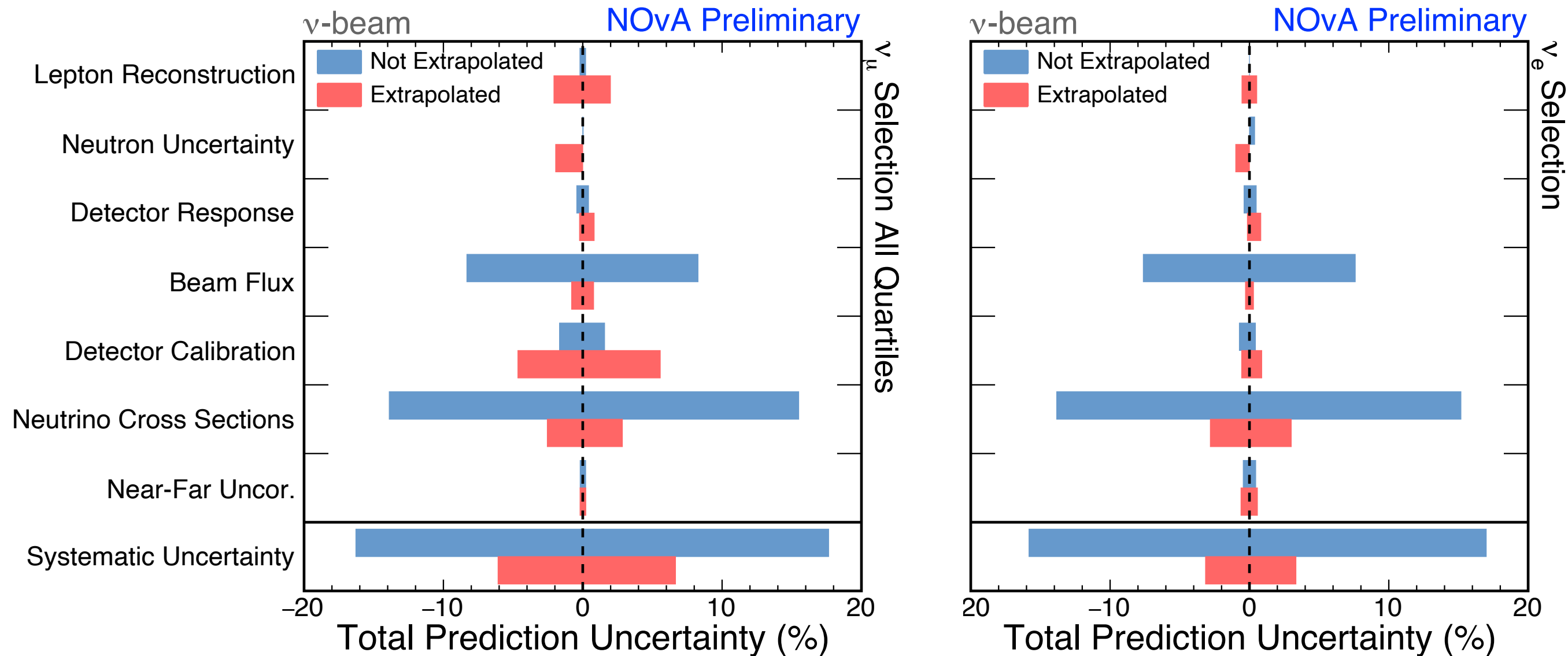


- Band around MC shows the large impact of flux and cross-section uncertainties when using a single detector.
- Use samples as a data constraint on what we predict at the Far Detector.
- These samples are used to predict both the ν_μ and the ν_e signal spectra at the Far Detector.
- Appearing ν_e 's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



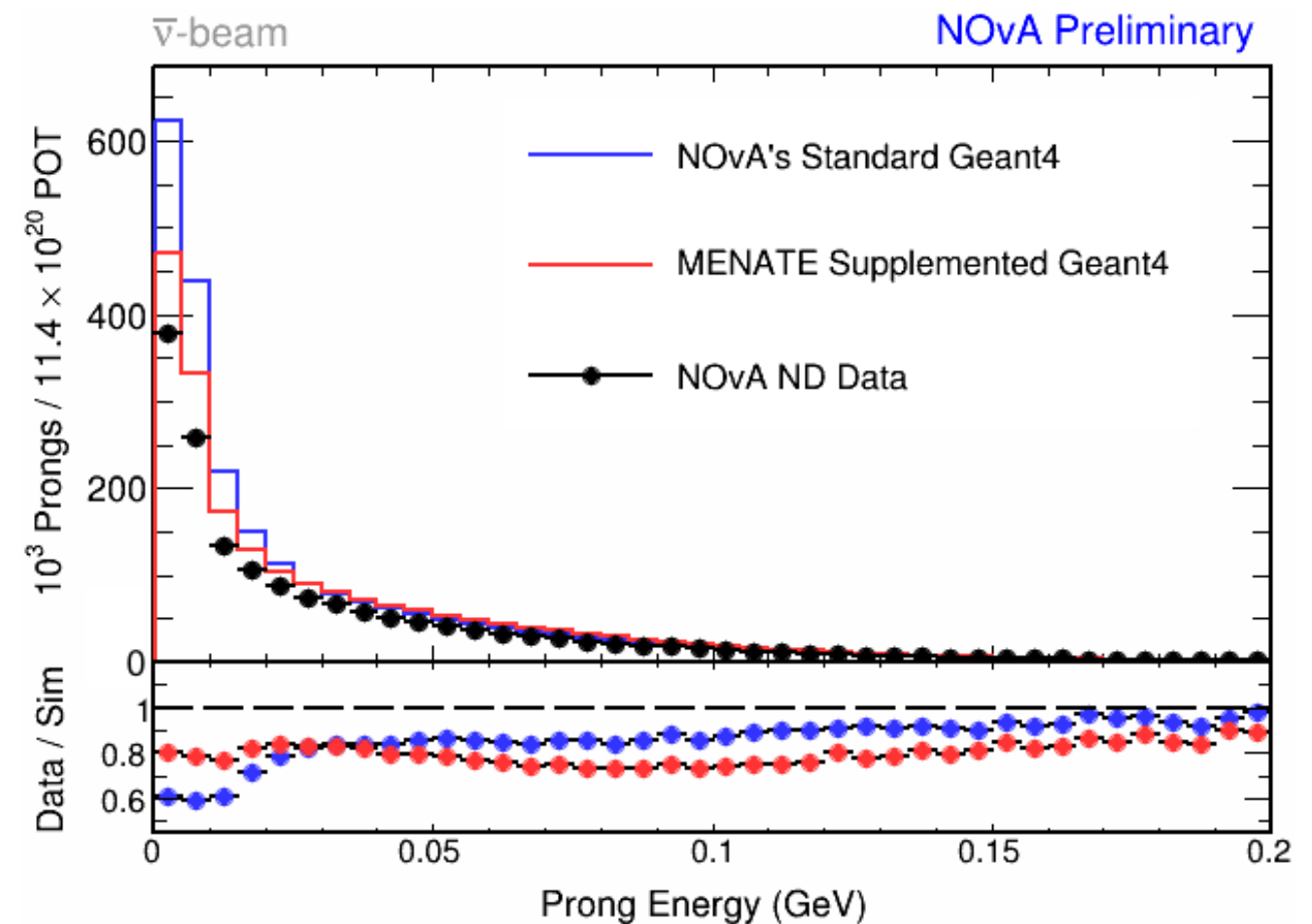
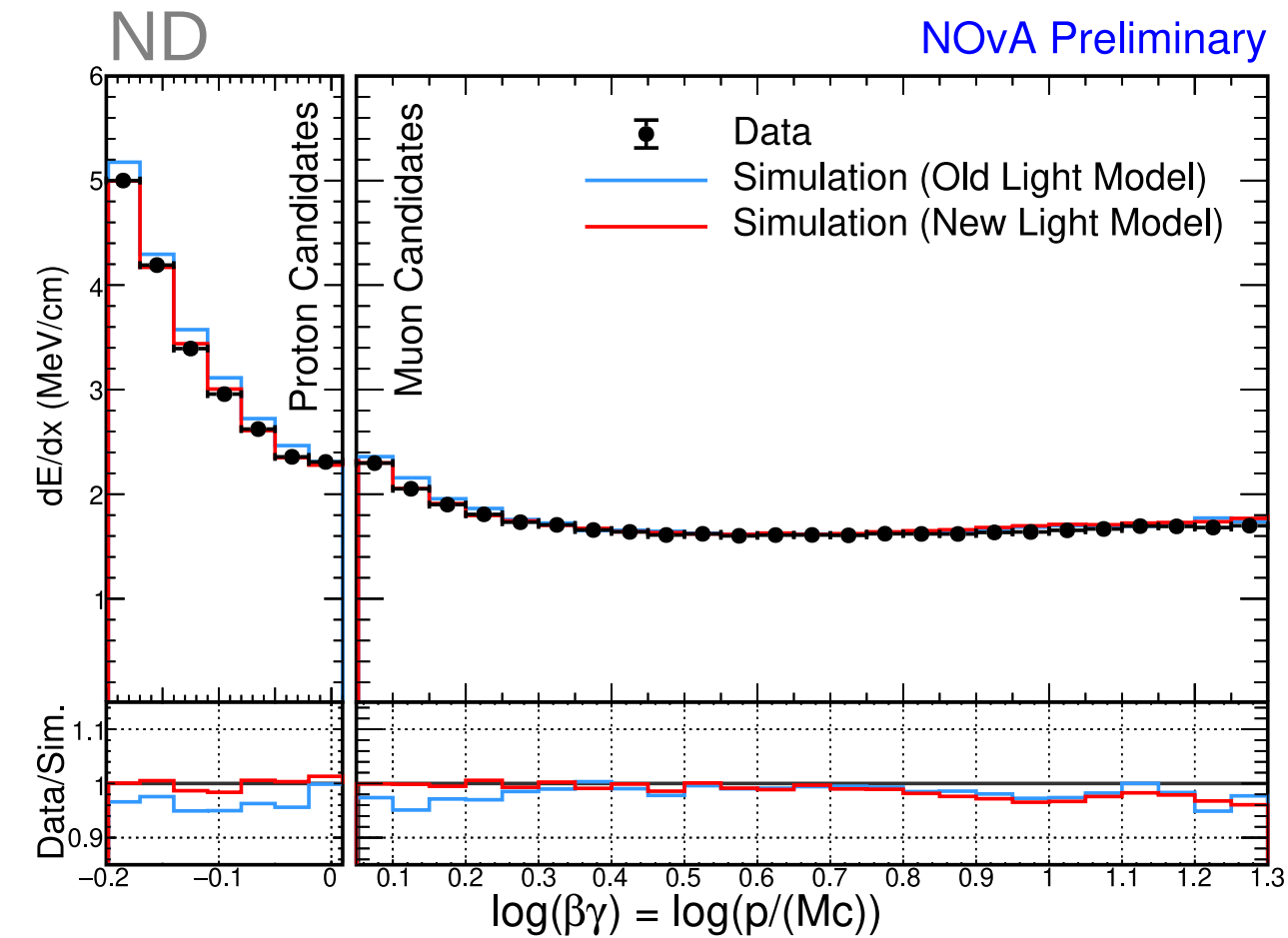
- Observe data-MC differences at the ND, use them to modify the FD MC.
- Significantly reduces the impact of uncertainties correlated between detectors.
 - Especially effective at rate effects like the flux (7% to 0.3%).

Impact of Systematic Uncertainty

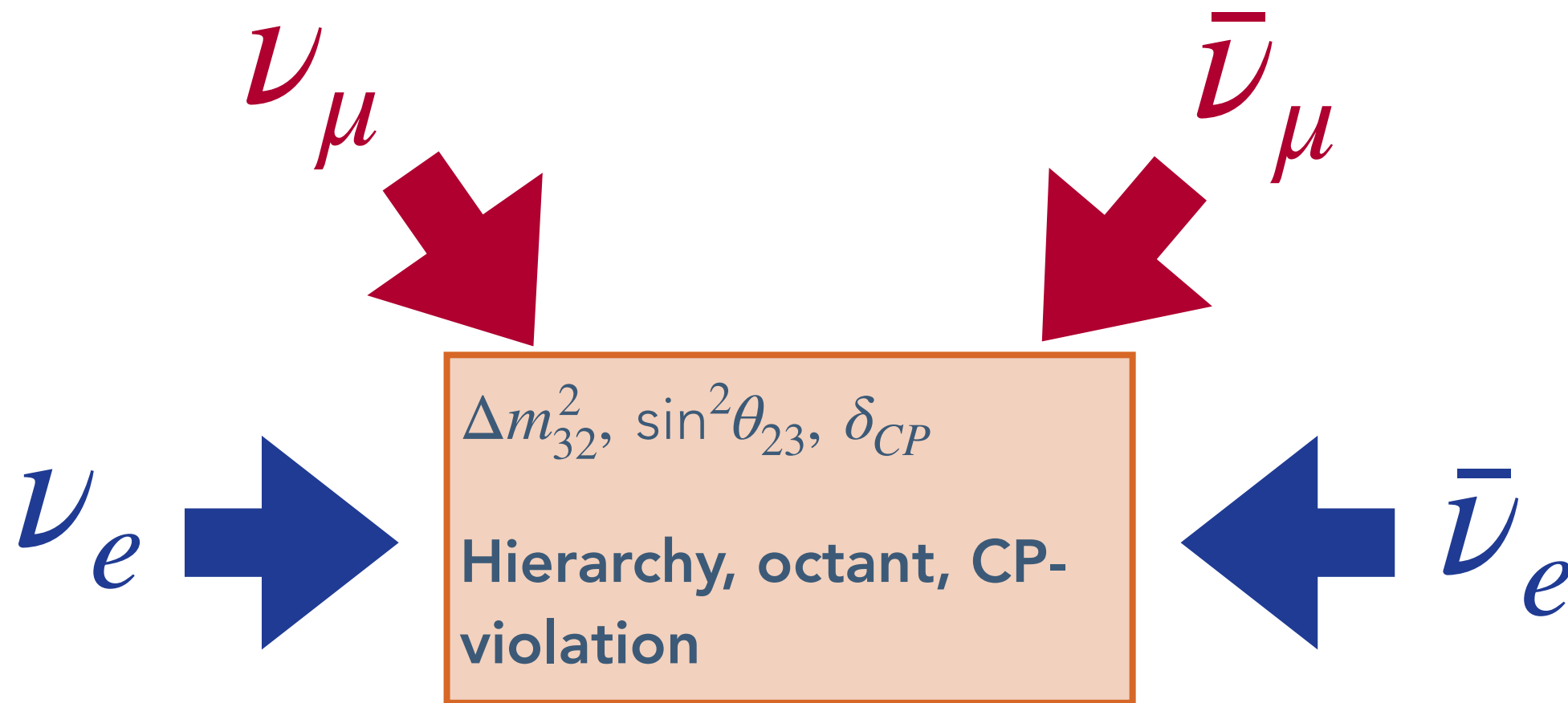


- Overall systematic reduction is 10 to 15 percentage points.
- Systematics related to neutron propagation and detector response are now subdominant.



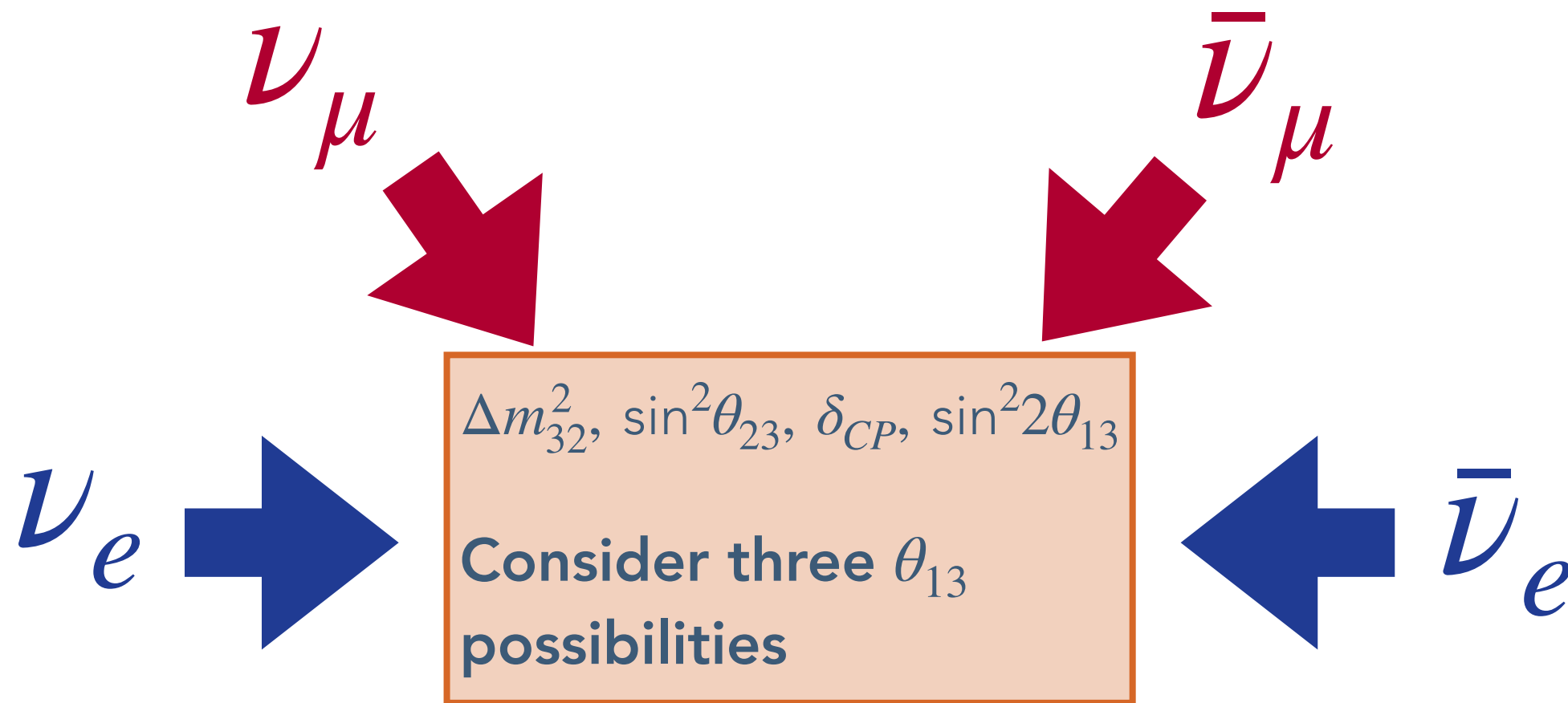


- Improved model of light production in the mineral oil (scintillation and Cherenkov) in both detectors.
- Dedicated bench measurements and studies of stopping proton and muon candidates in data.
- Difference between MENATE and default GEANT4.10.4 used to motivate a systematic uncertainty.
- In future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



- 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.

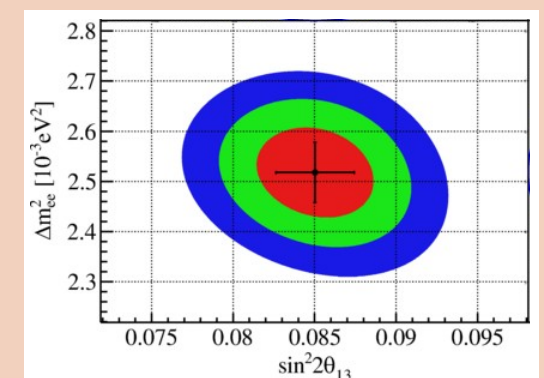




θ_{13} unconstrained
(NOvA only)

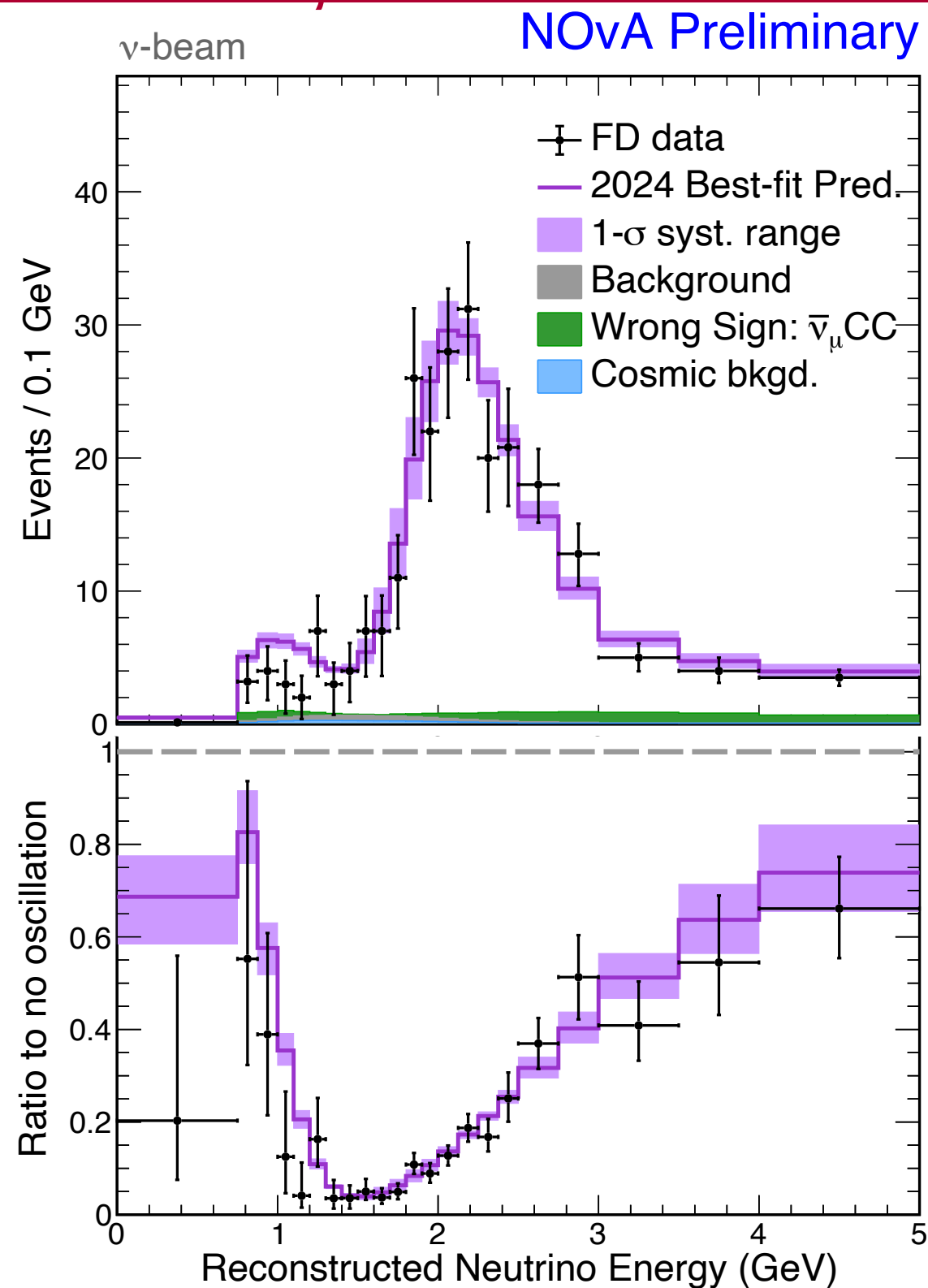
Daya Bay 1D θ_{13}
constraint
($\sin^2 2\theta_{13} = 0.0851 \pm 0.0024$)

Daya Bay 2D
($\Delta m_{32}^2, \theta_{13}$) constraint
(PRL 130, 161802)

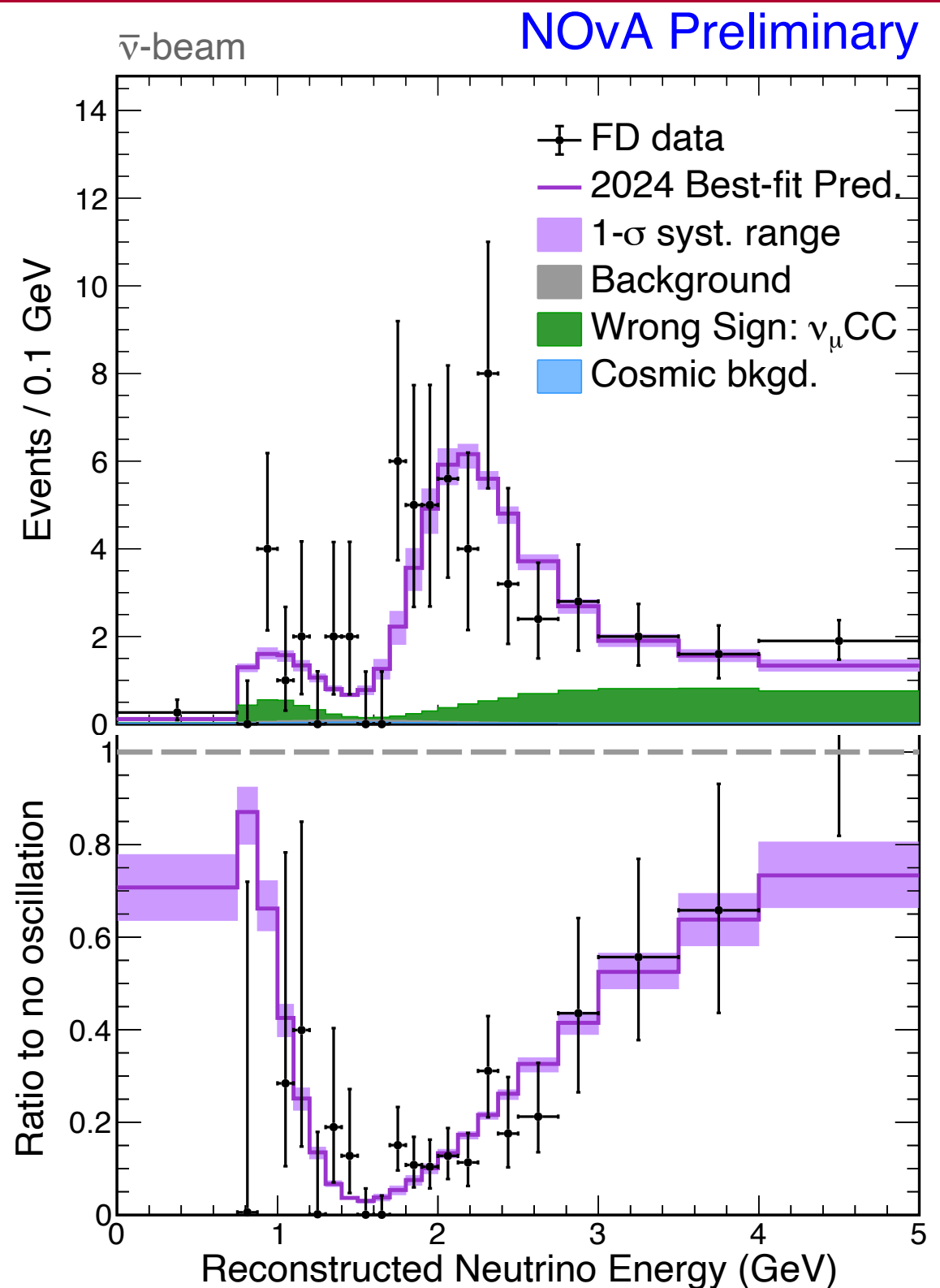


Results

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



384 events, 11.3 background



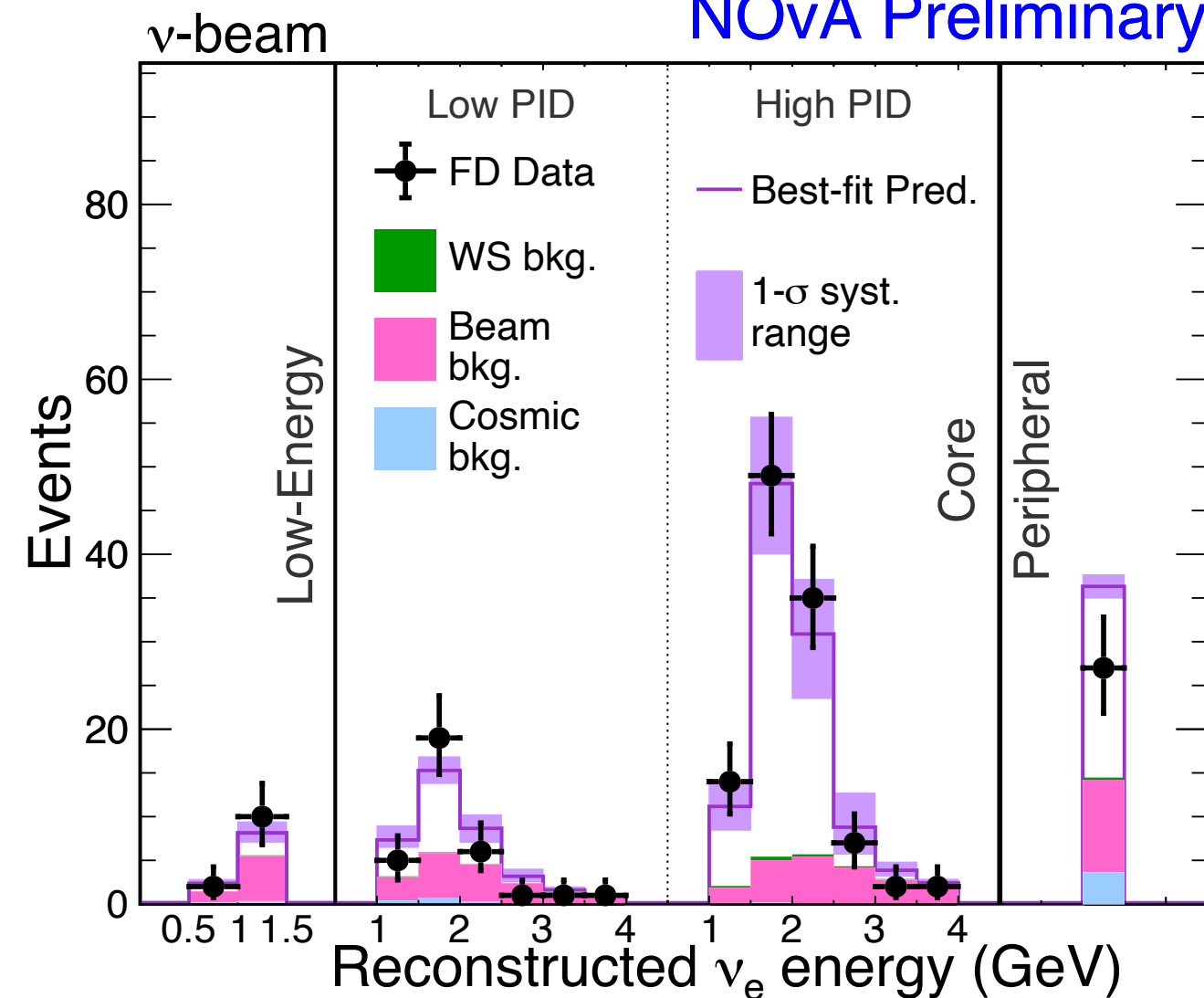
106 events, 1.7 background



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

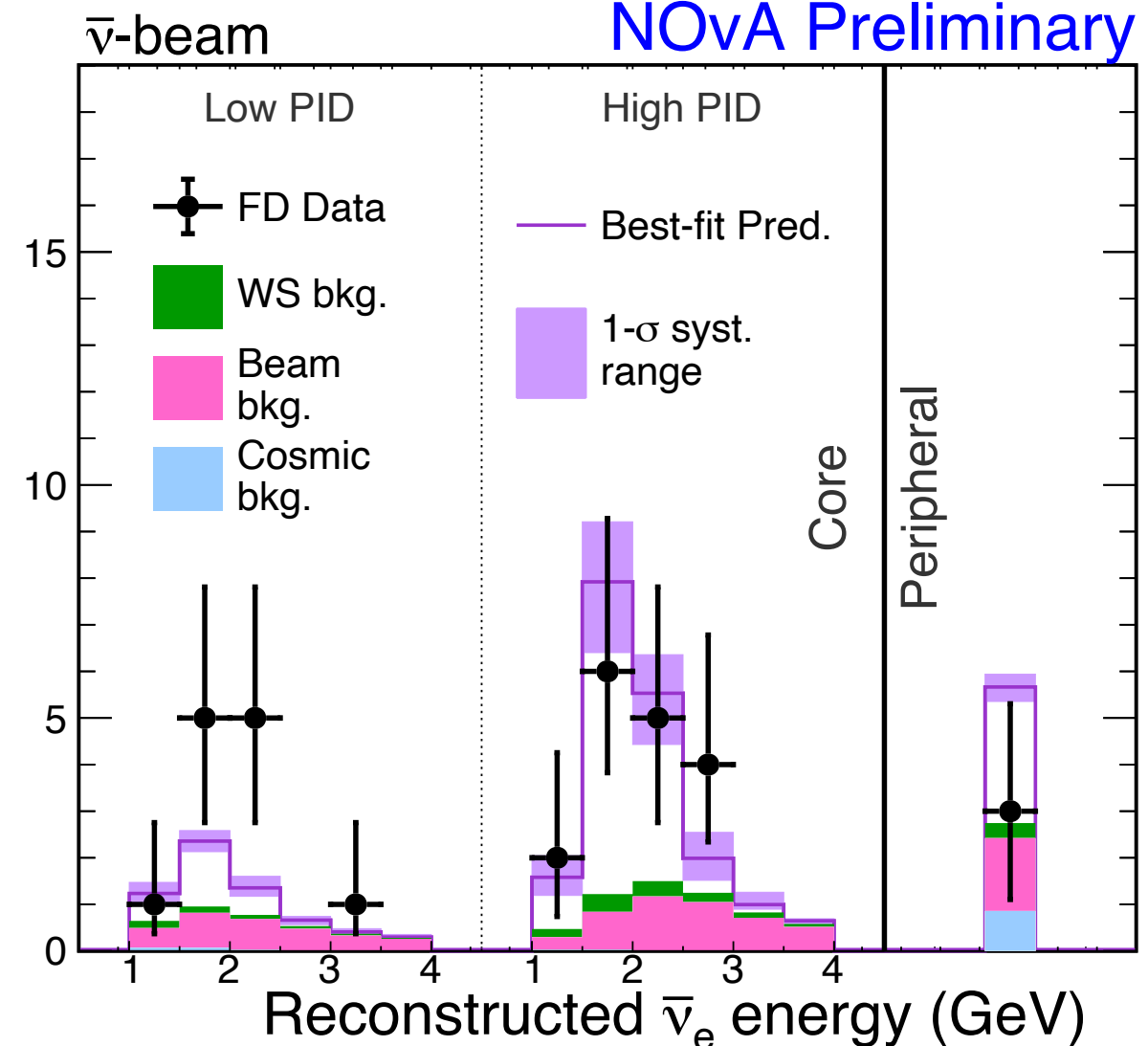


NOvA Preliminary



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

NOvA Preliminary

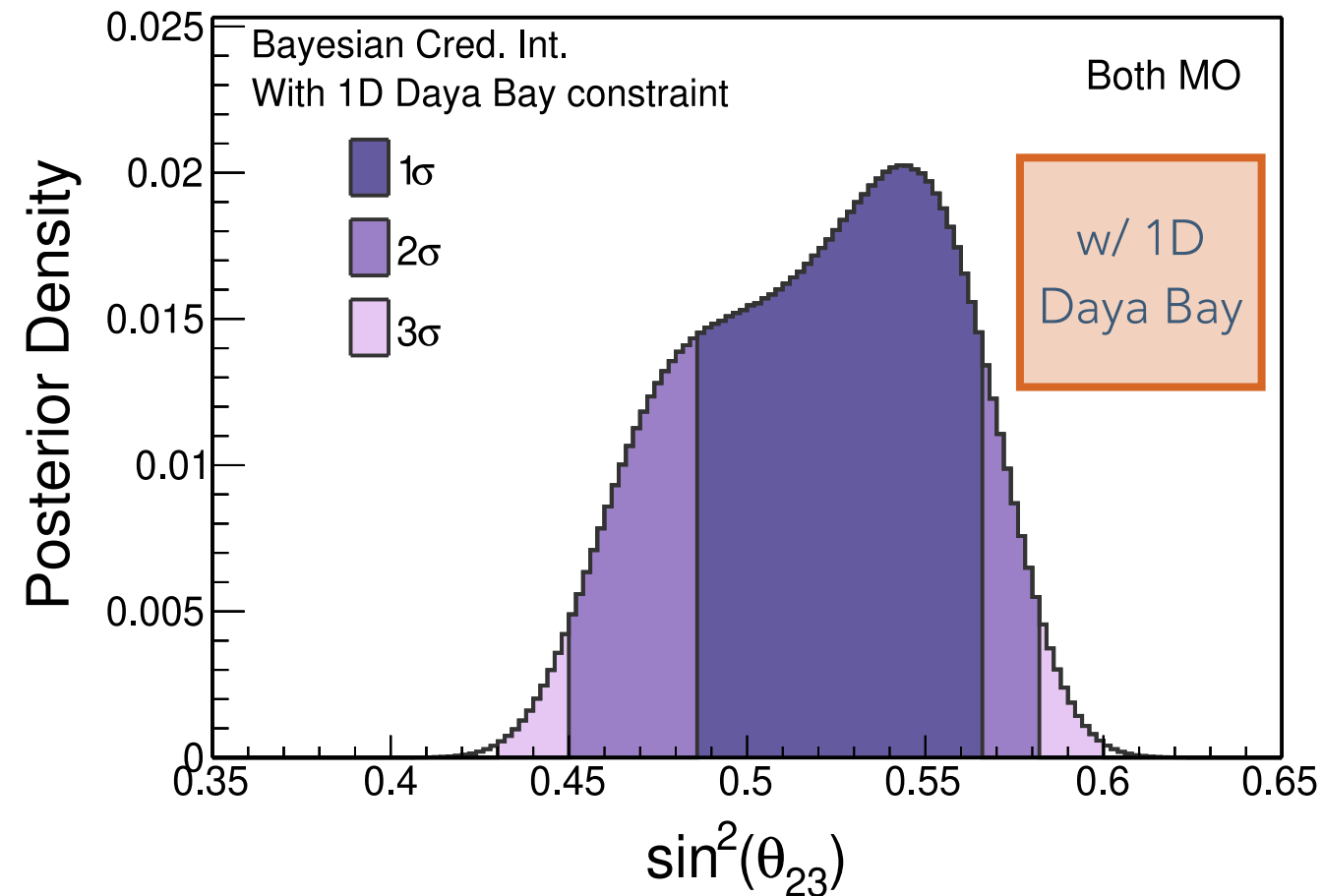
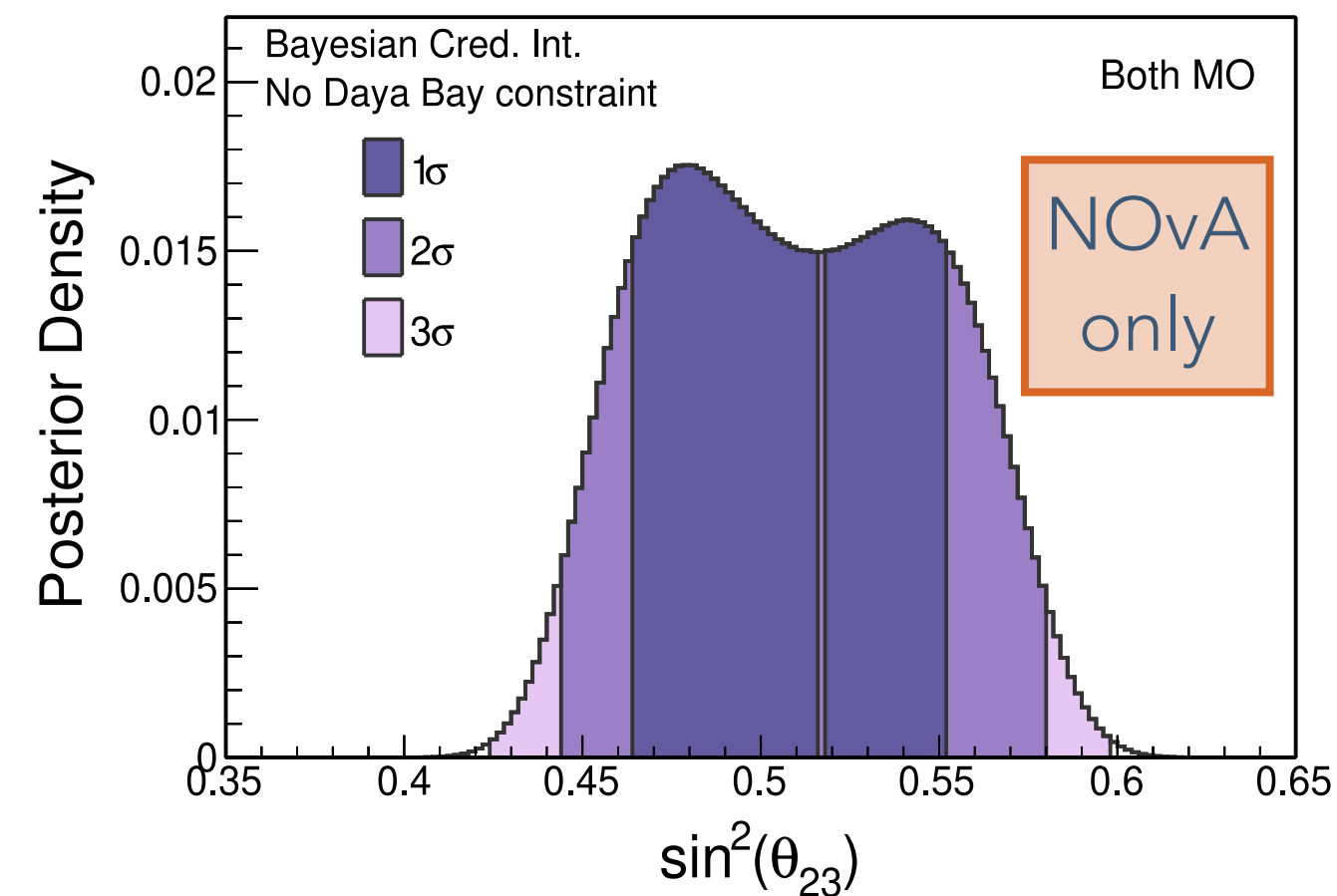


Total Observed	32	Range
Total Prediction	30.4	28-38
Wrong-sign	2.1	1.0-3.2
Beam Bkgd.	9.0	
Cosmic Bkgd.	1.1	
Total Bkgd.	12.2	11-13



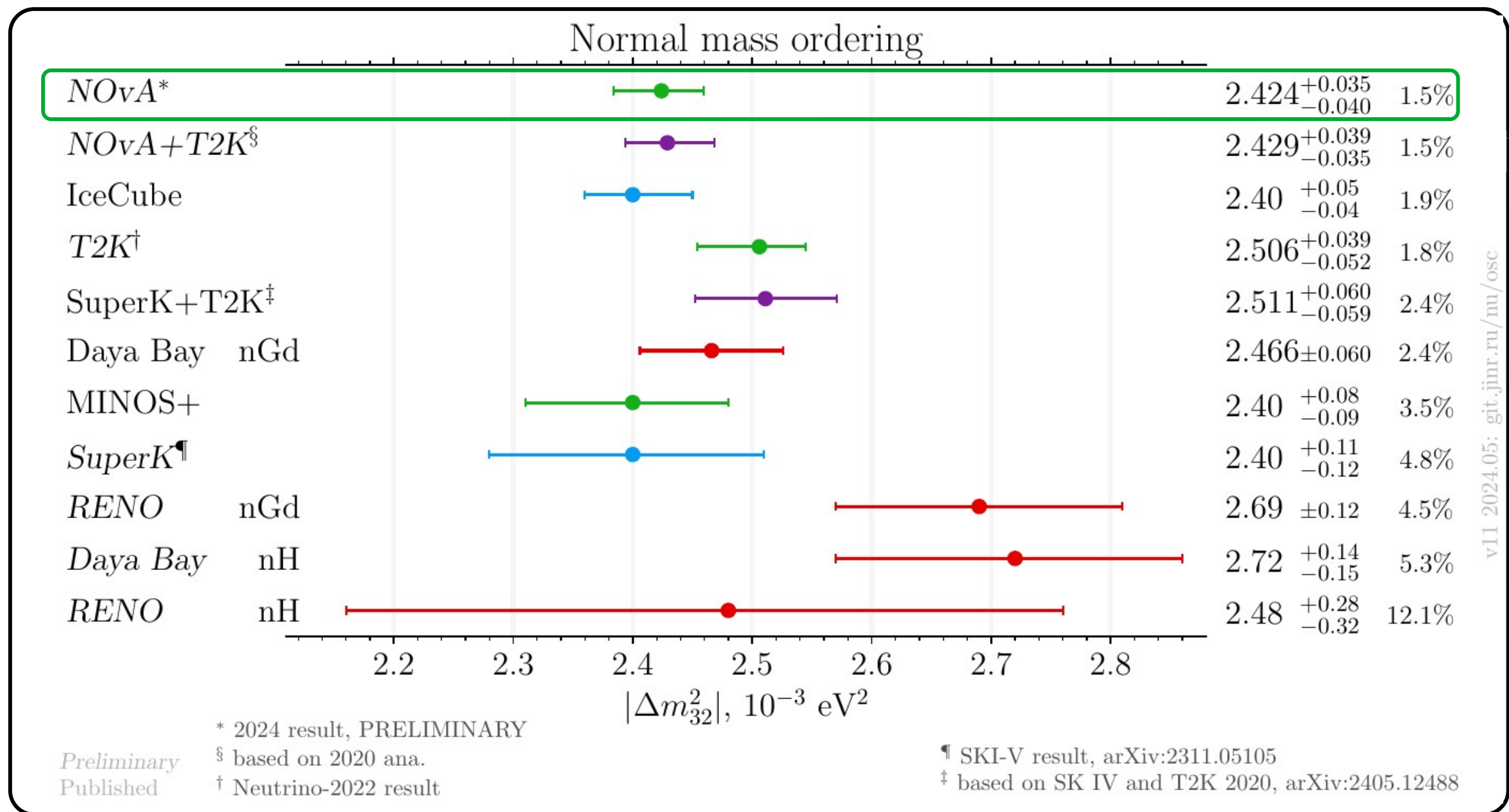
NOvA Preliminary

NOvA Preliminary



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

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

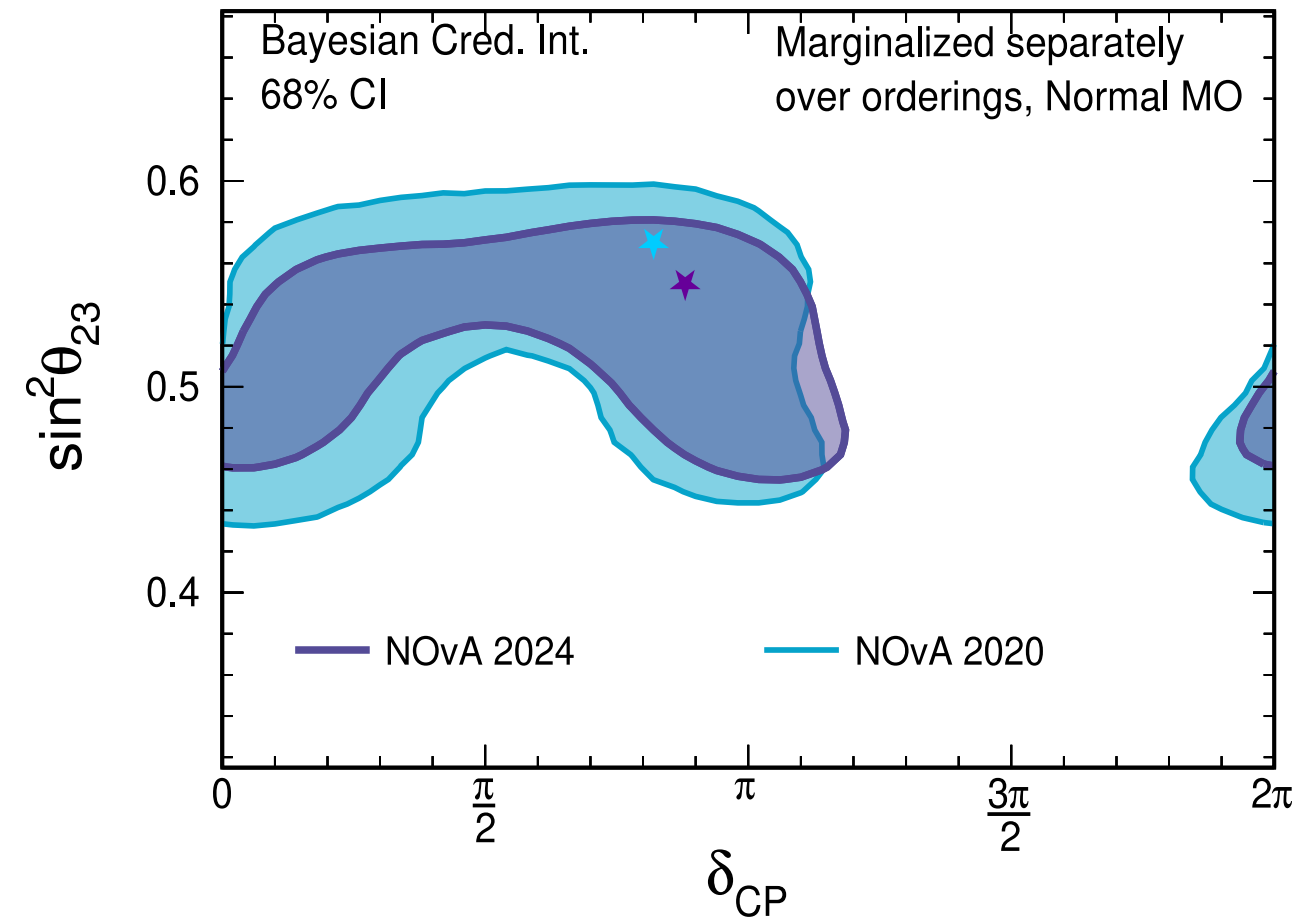


Most precise single experiment measurement of Δm_{32}^2 .

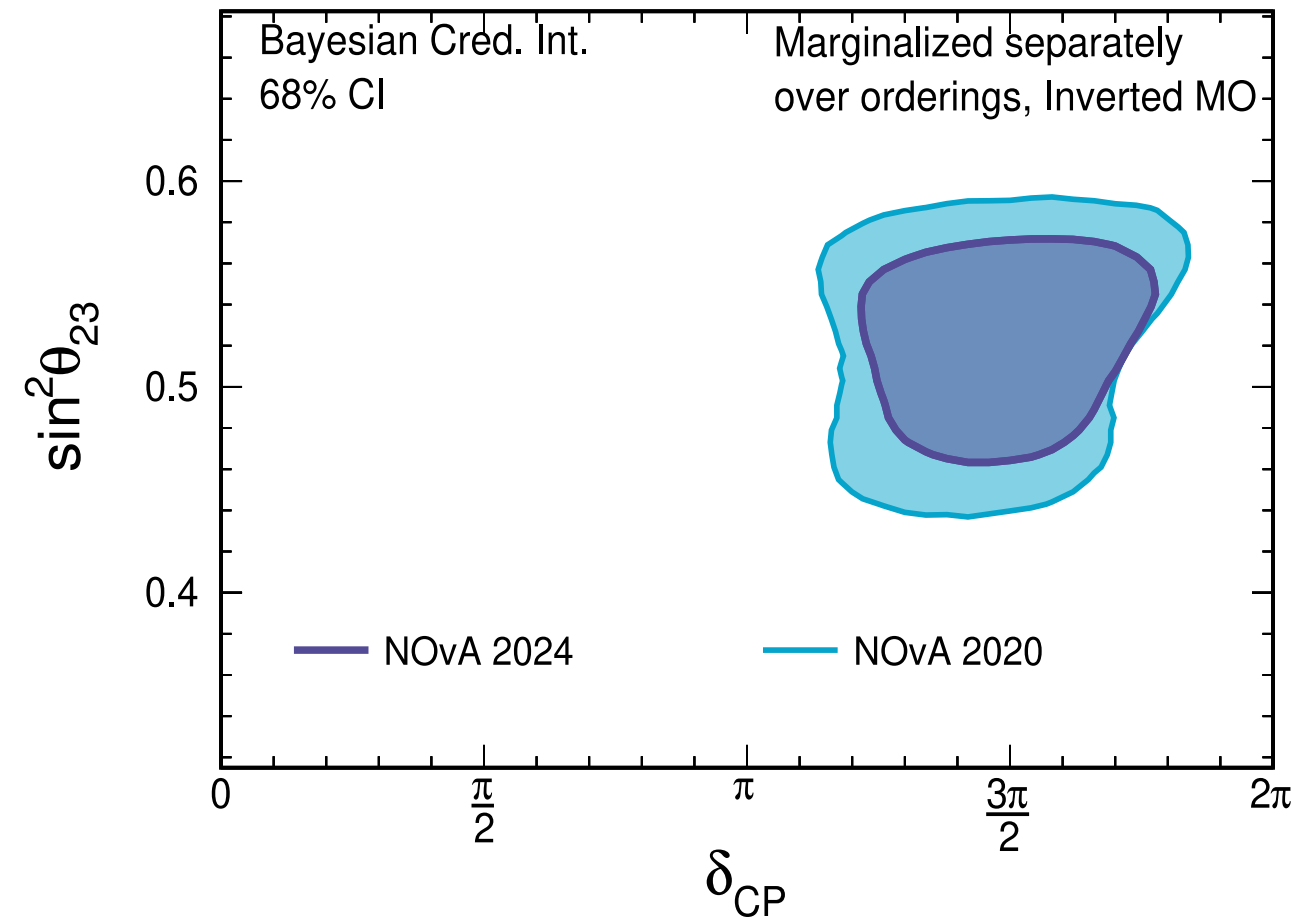
Mass Ordering with θ_{23} & δ_{CP}



NOvA Preliminary



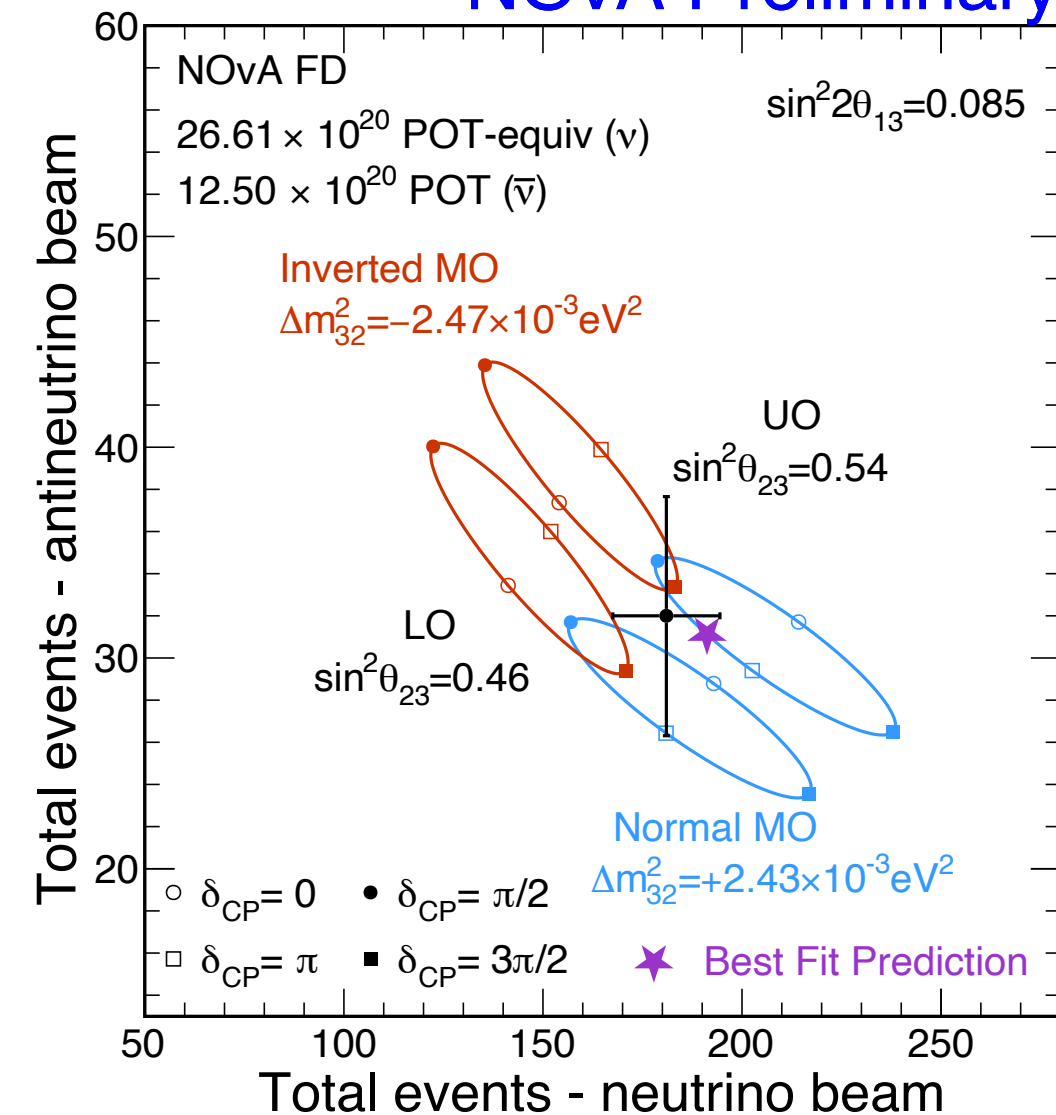
NOvA Preliminary



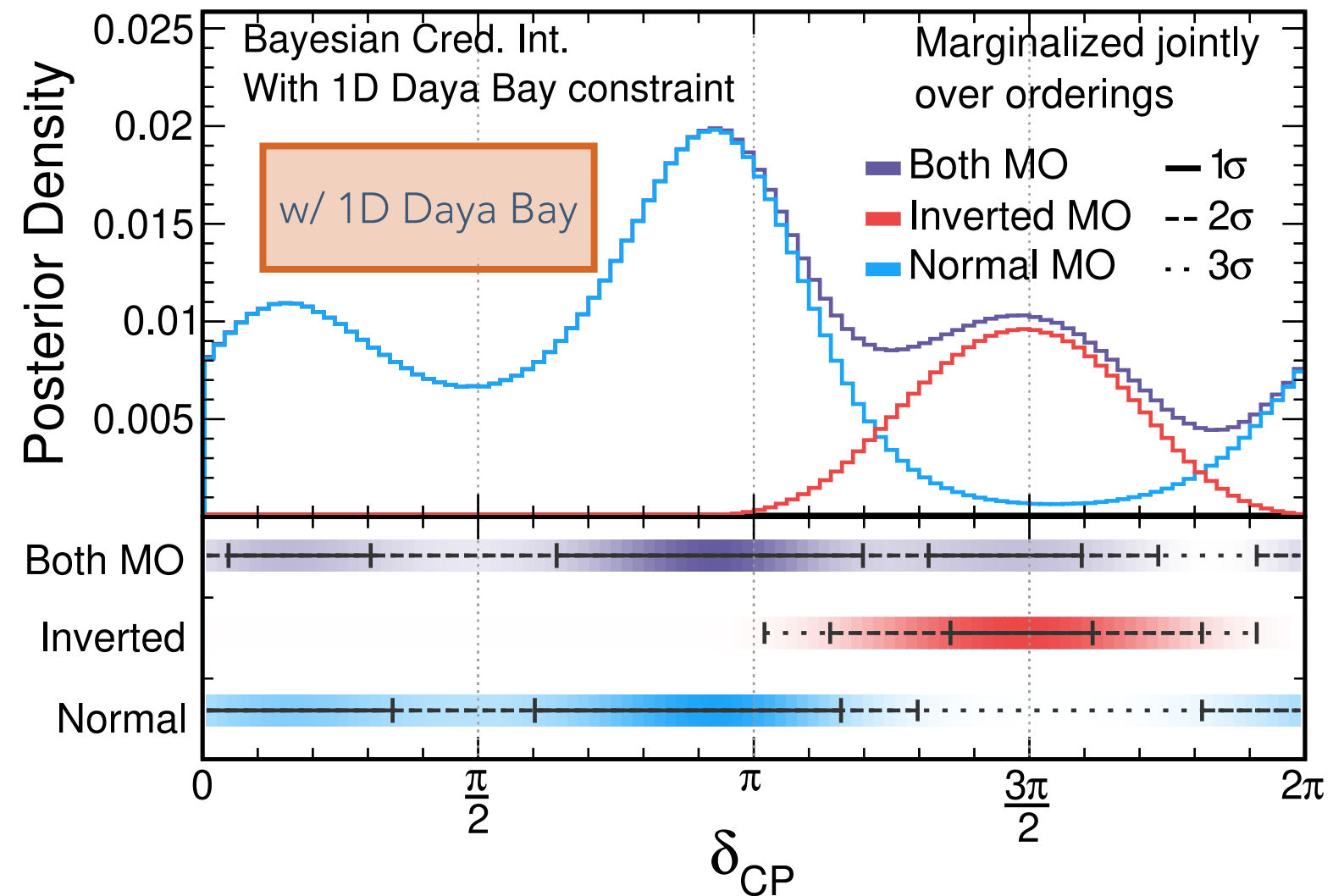
- Consistency with previous result (*different reactor constraints used).
- Tighter contours almost everywhere.



NOvA Preliminary



NOvA Preliminary

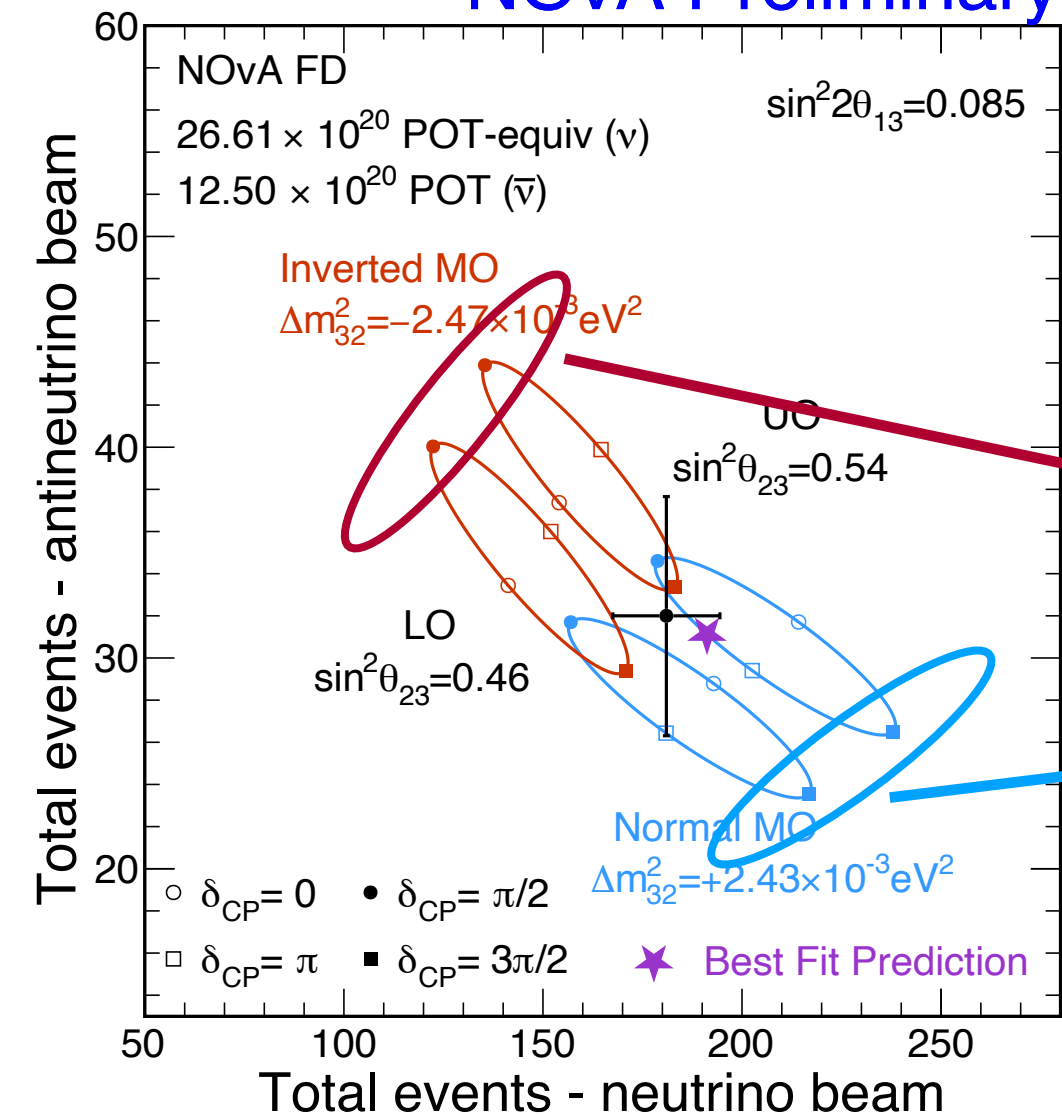


- No strong asymmetry in the rates of appearance of ν_e and $\bar{\nu}_e$.

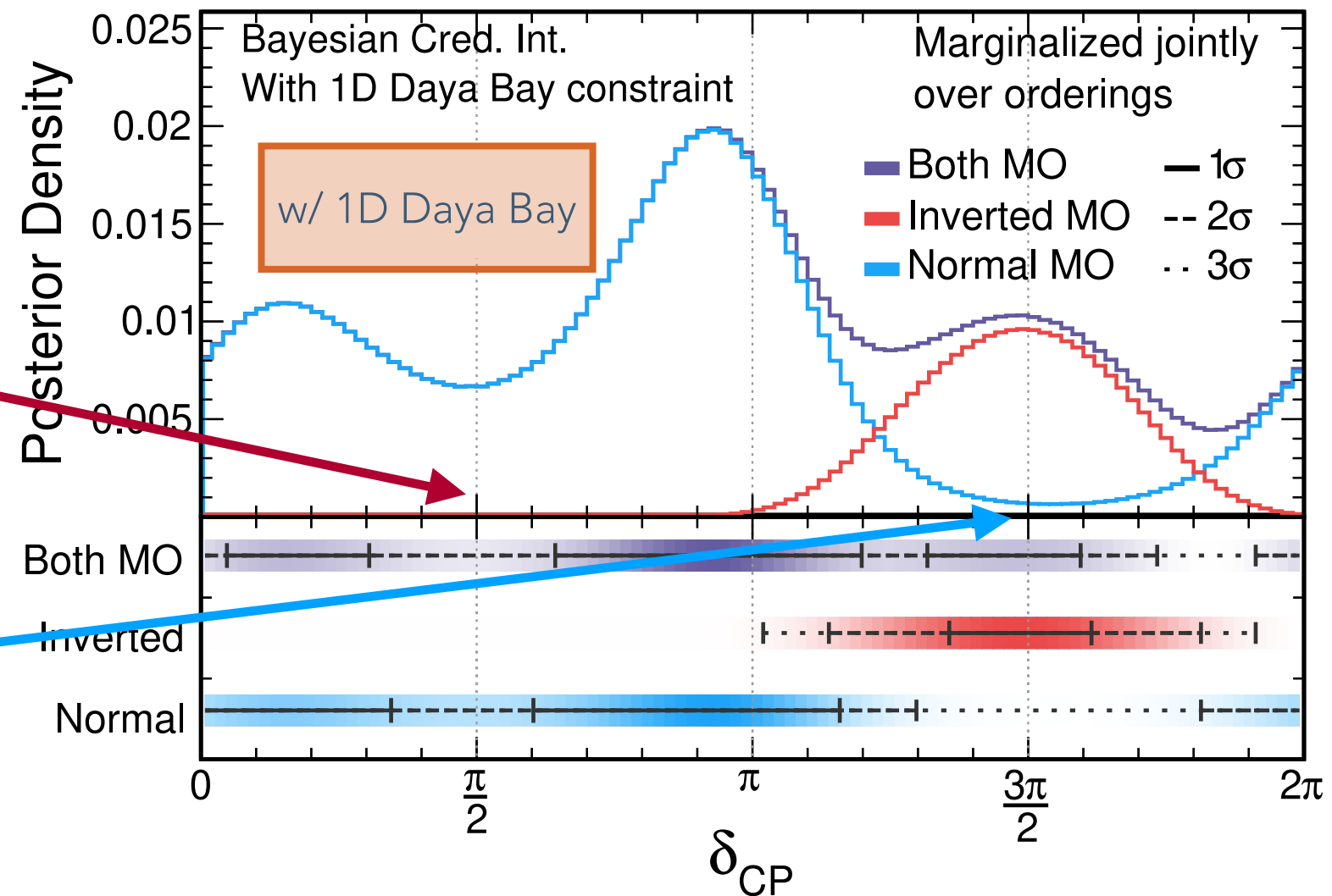


Mass Ordering with δ_{CP}

NOvA Preliminary



NOvA Preliminary



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

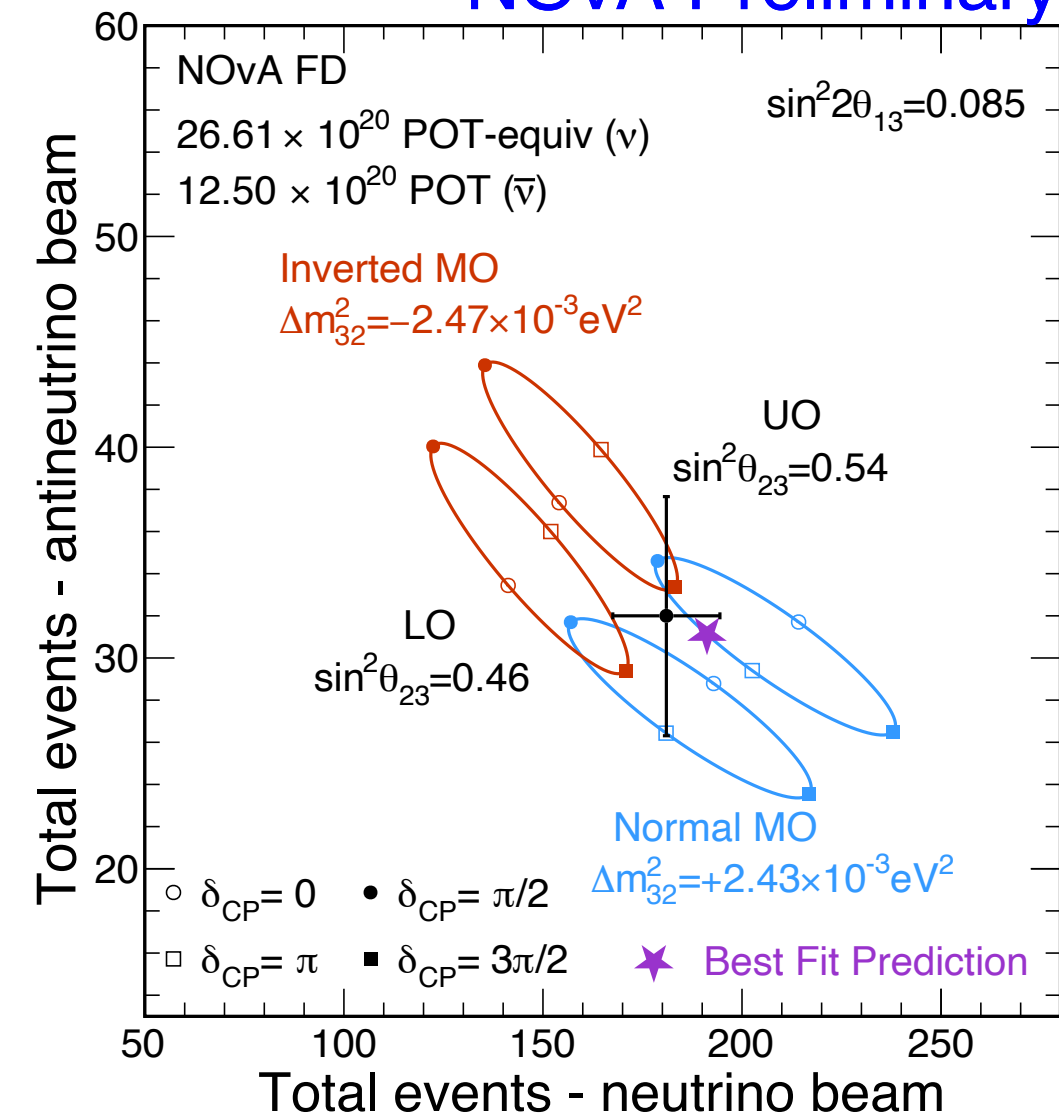
Exclude IO $\delta_{CP} = \frac{\pi}{2}$ at $> 3\sigma$

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

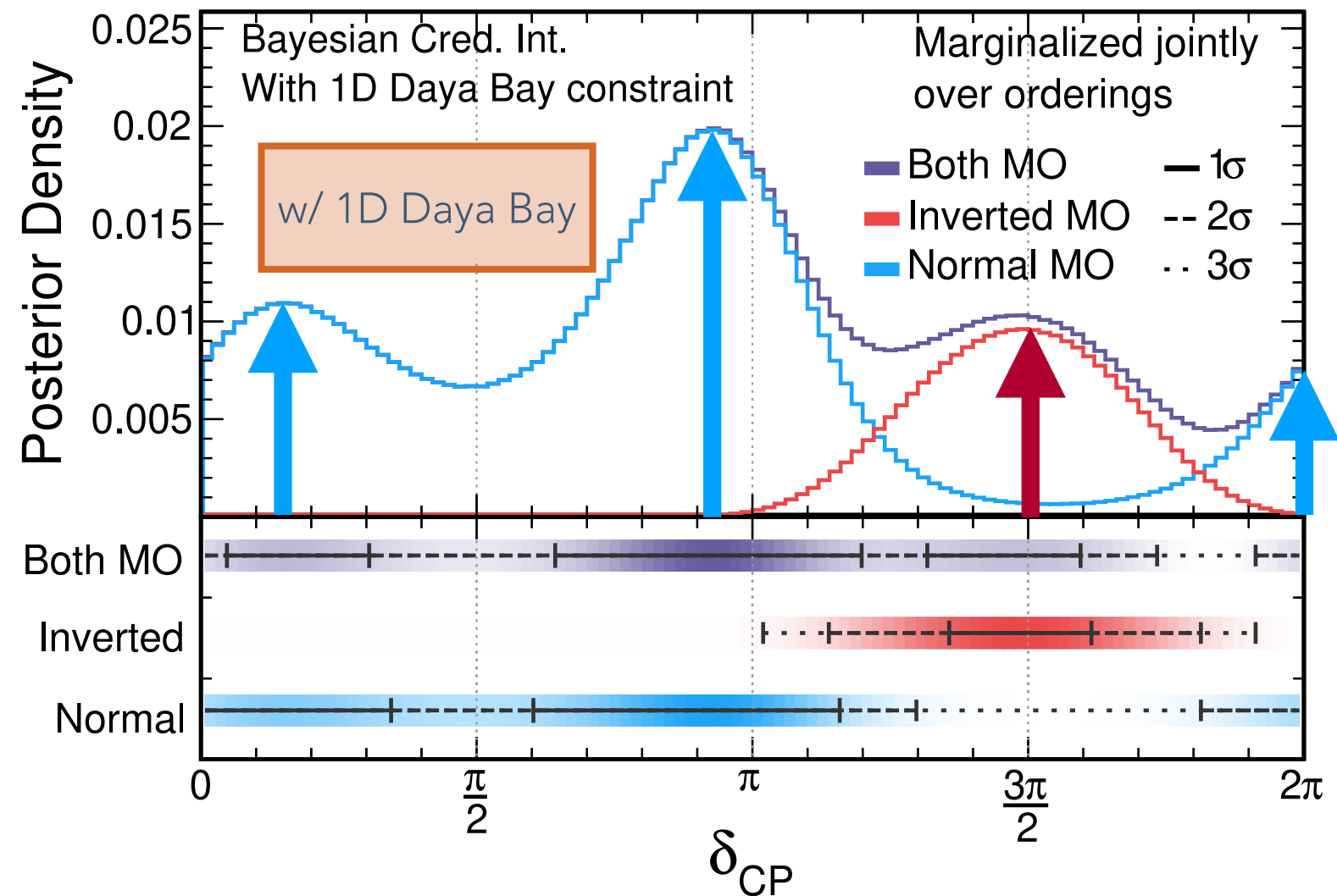




NOvA Preliminary



NOvA Preliminary



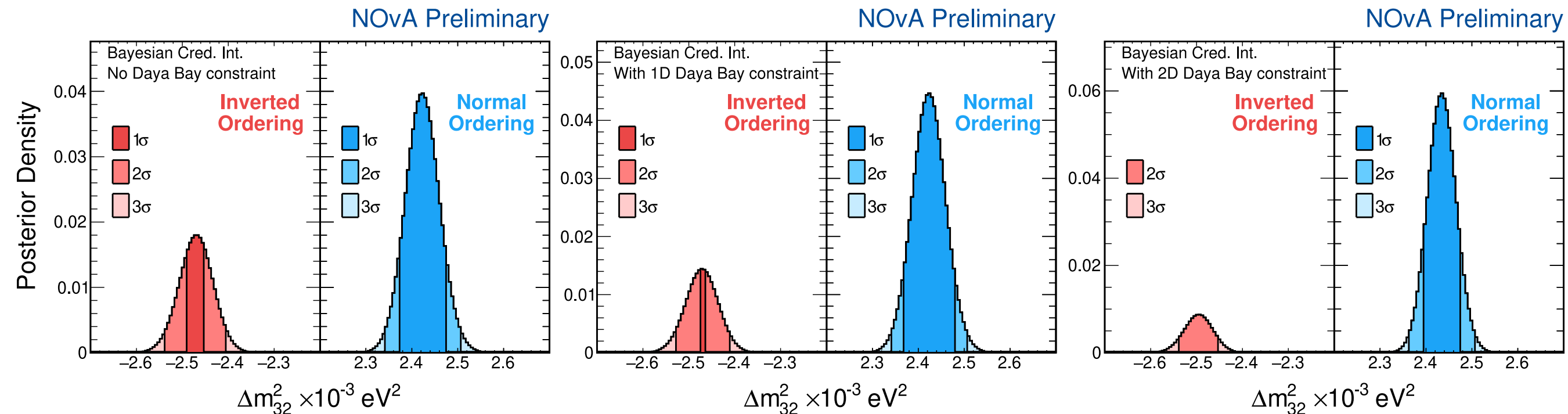
- No strong asymmetry in the rates of appearance of ν_e and $\bar{\nu}_e$.
- Disfavour ordering- δ_{CP} combinations which would produce asymmetry.

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 (1.4 σ^*)

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

BF: 6.9, 87% odds (1.6 σ^*)

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

*Frequentist significance.





- 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_{32}^2 (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_{32}^2 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.





Back-up

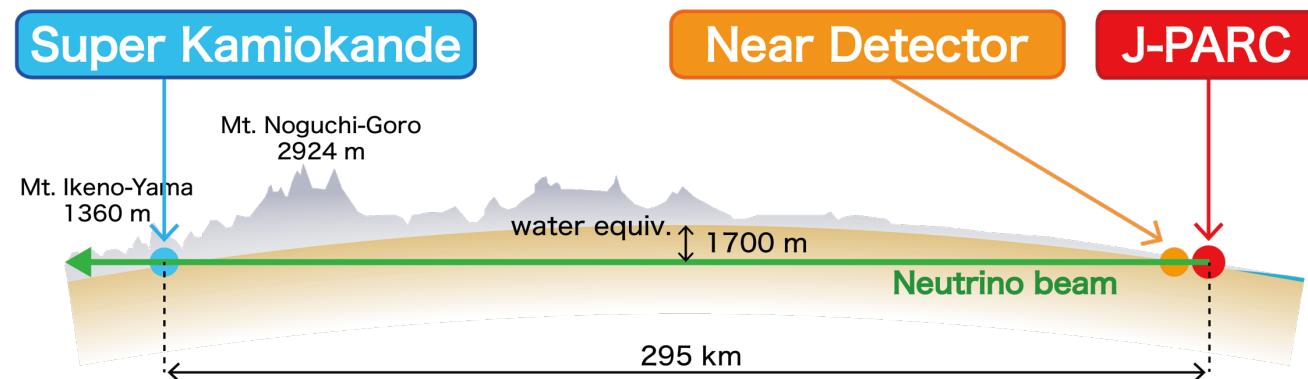
T2K-NOvA Joint Fit

Combining Long-baseline Experiments

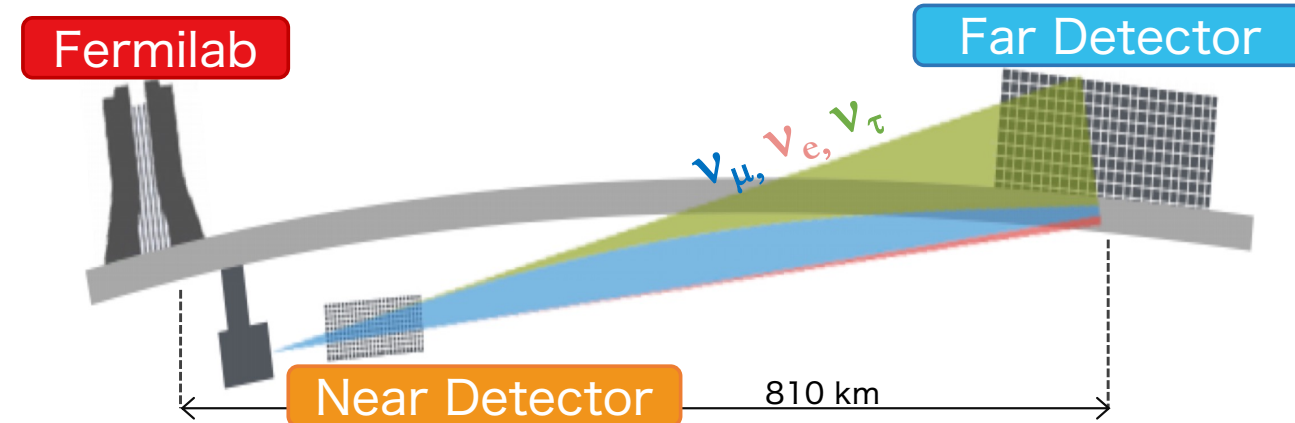
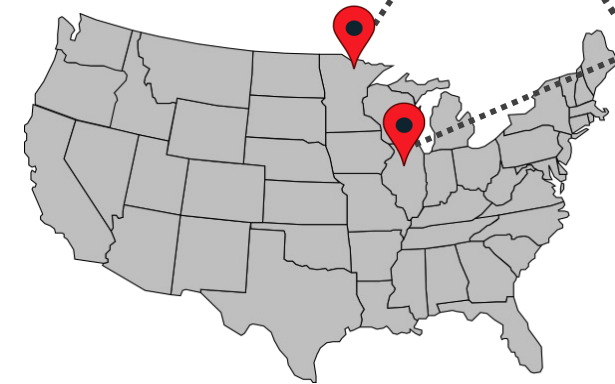


T2K

Japan



USA



Combining Long-baseline Experiments

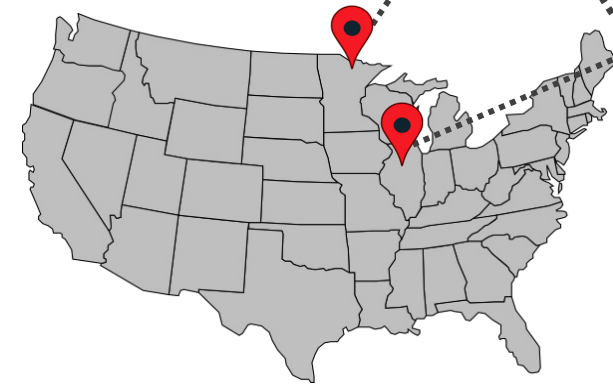


T2K

Japan



USA



Ash River, MN

MN

WI

Fermilab

IL

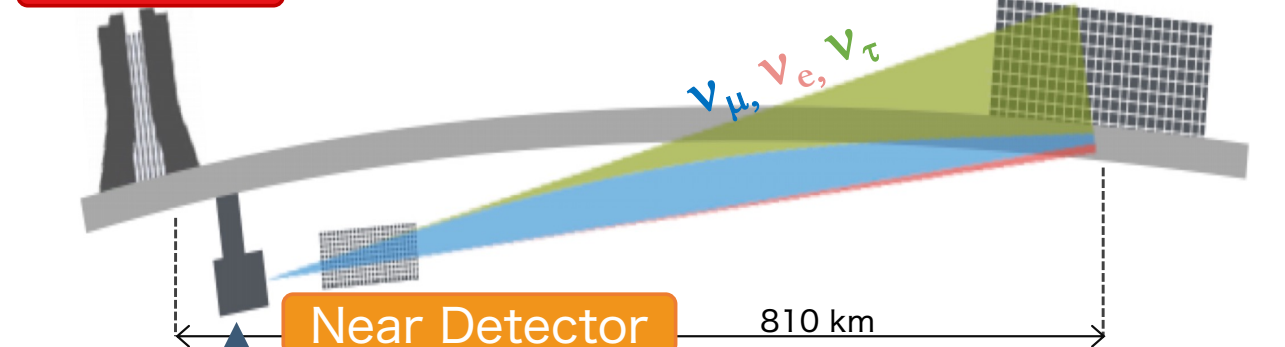
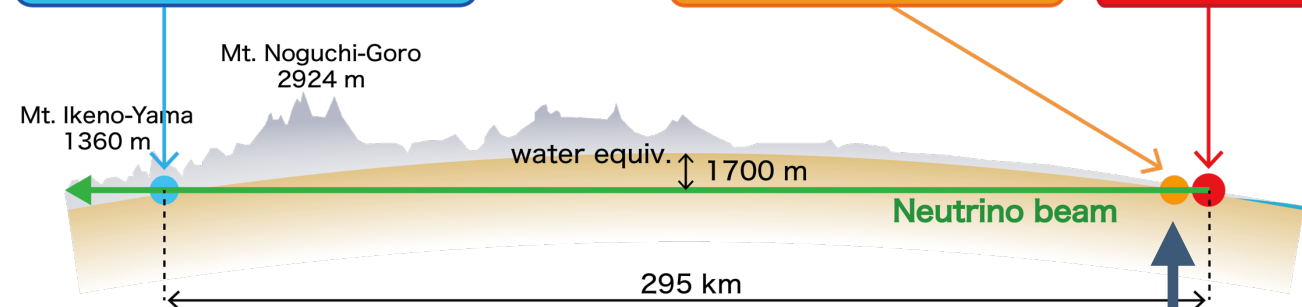
Super Kamiokande

Near Detector

J-PARC

Fermilab

Far Detector



Beam energies

0.6 GeV

2 GeV

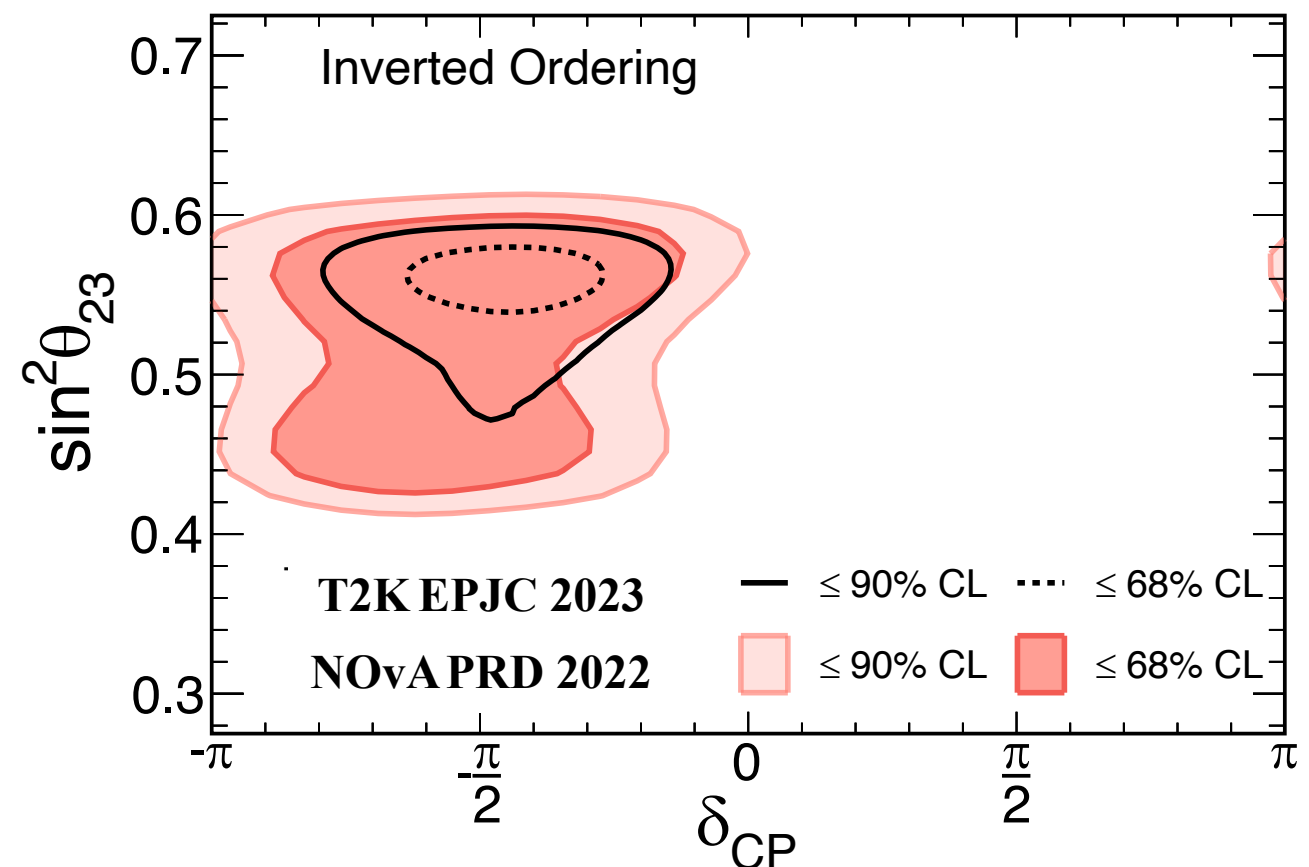
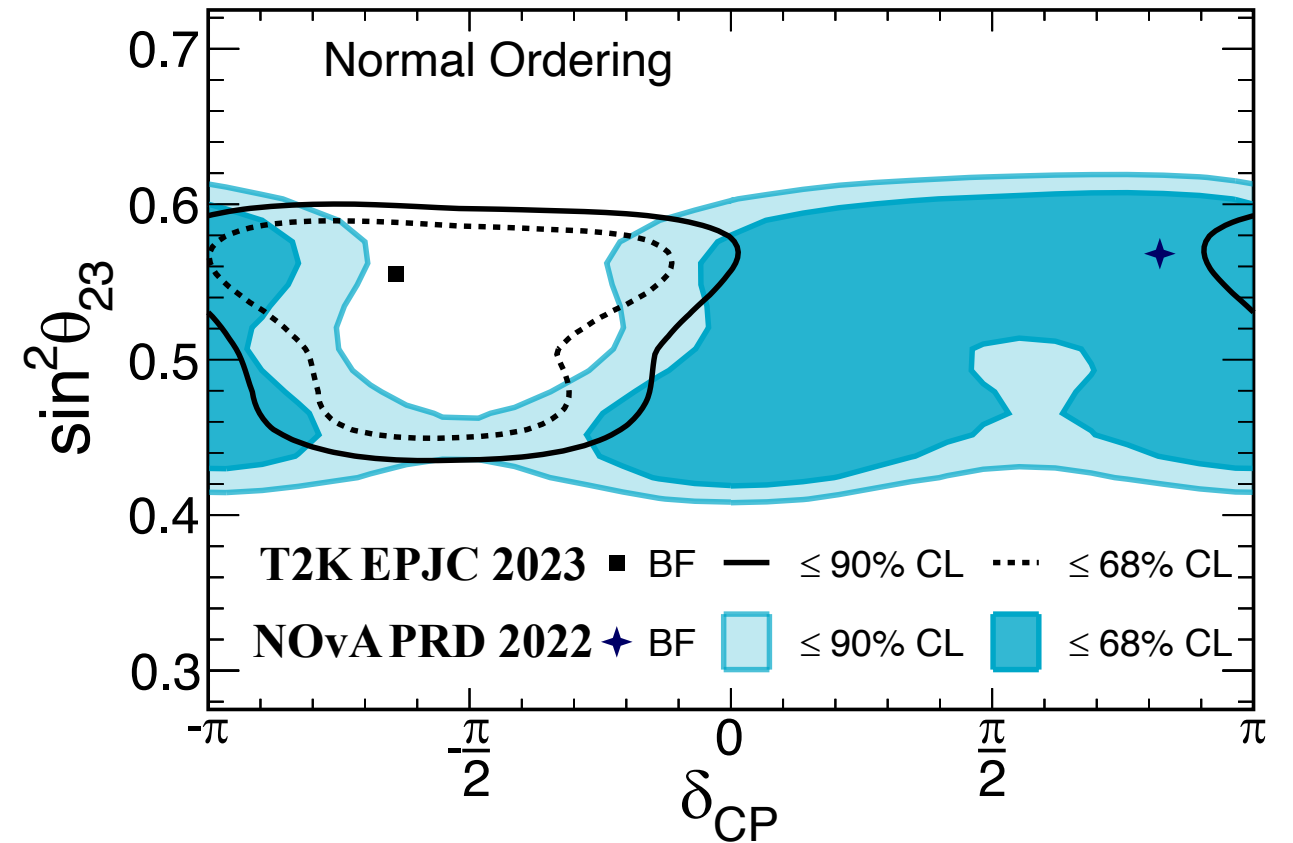
Baselines



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.

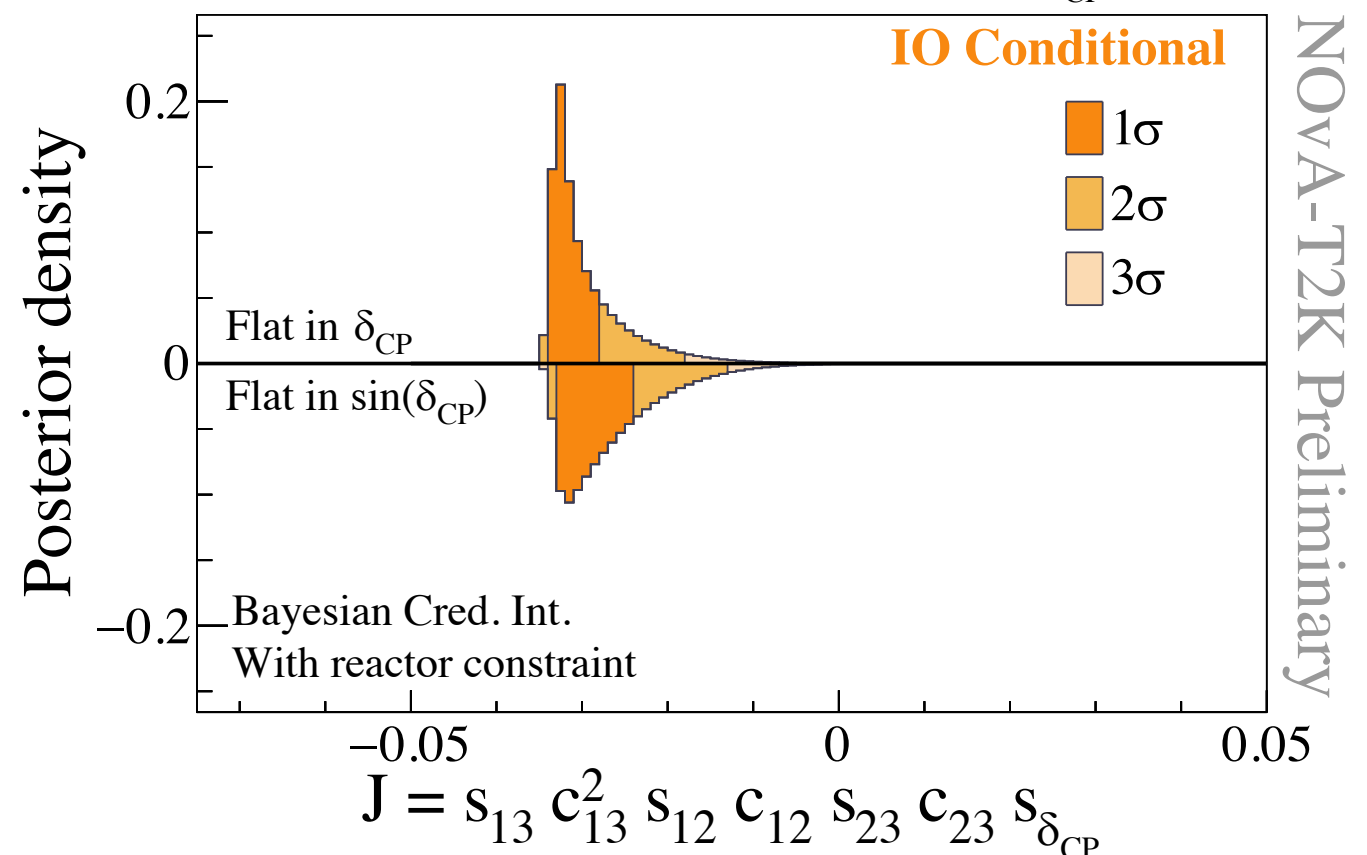
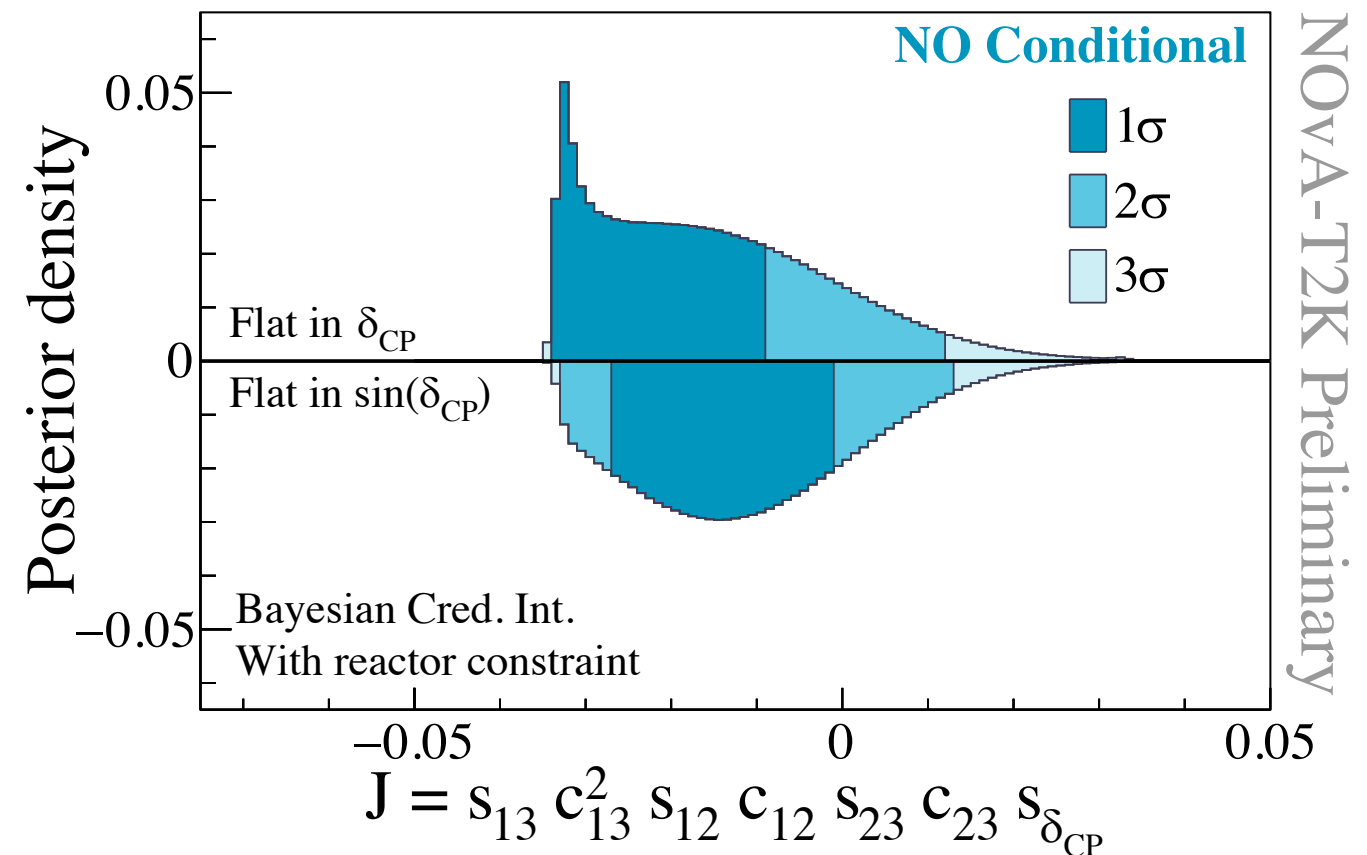


- Jarlskog-invariant is **parameterisation-independent*** way to measure CP violation.

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

$J = 0$: CP conserved, $J \neq 0$: 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 .

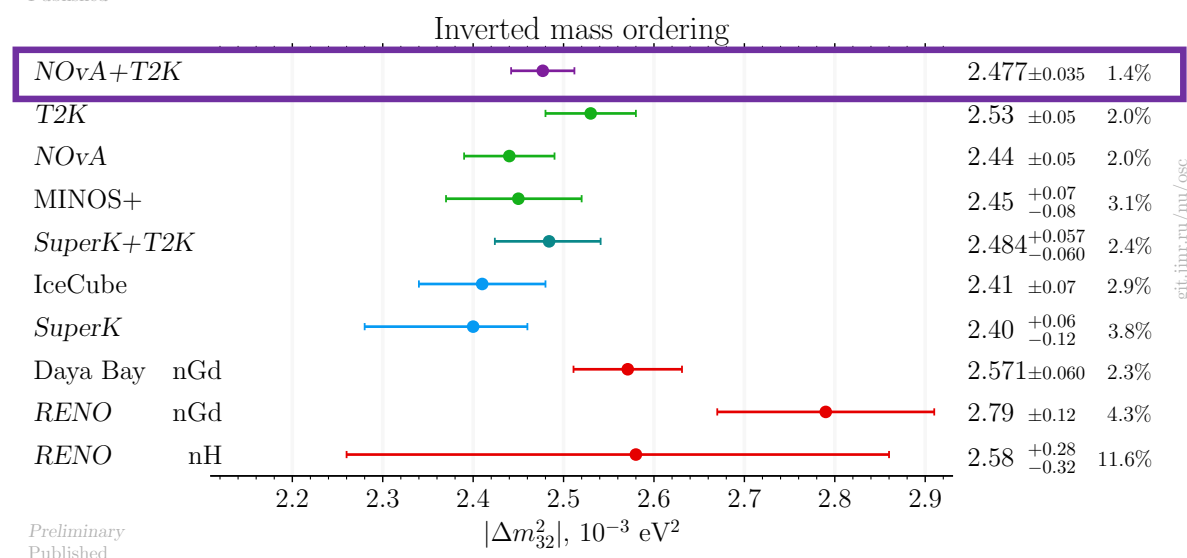
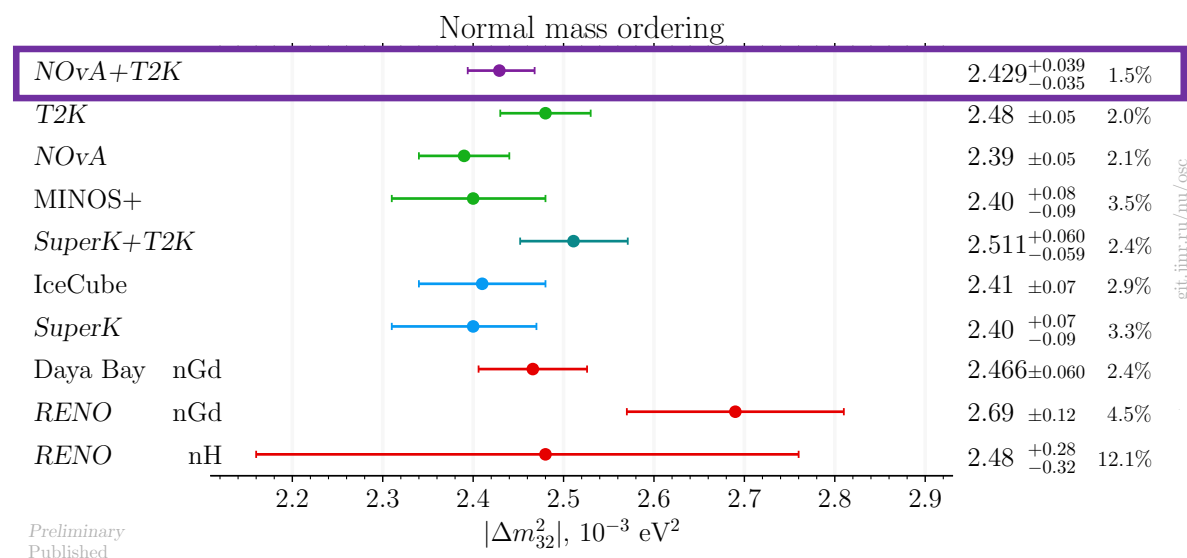


*Phys. Rev. D 100, 053004 (2019)

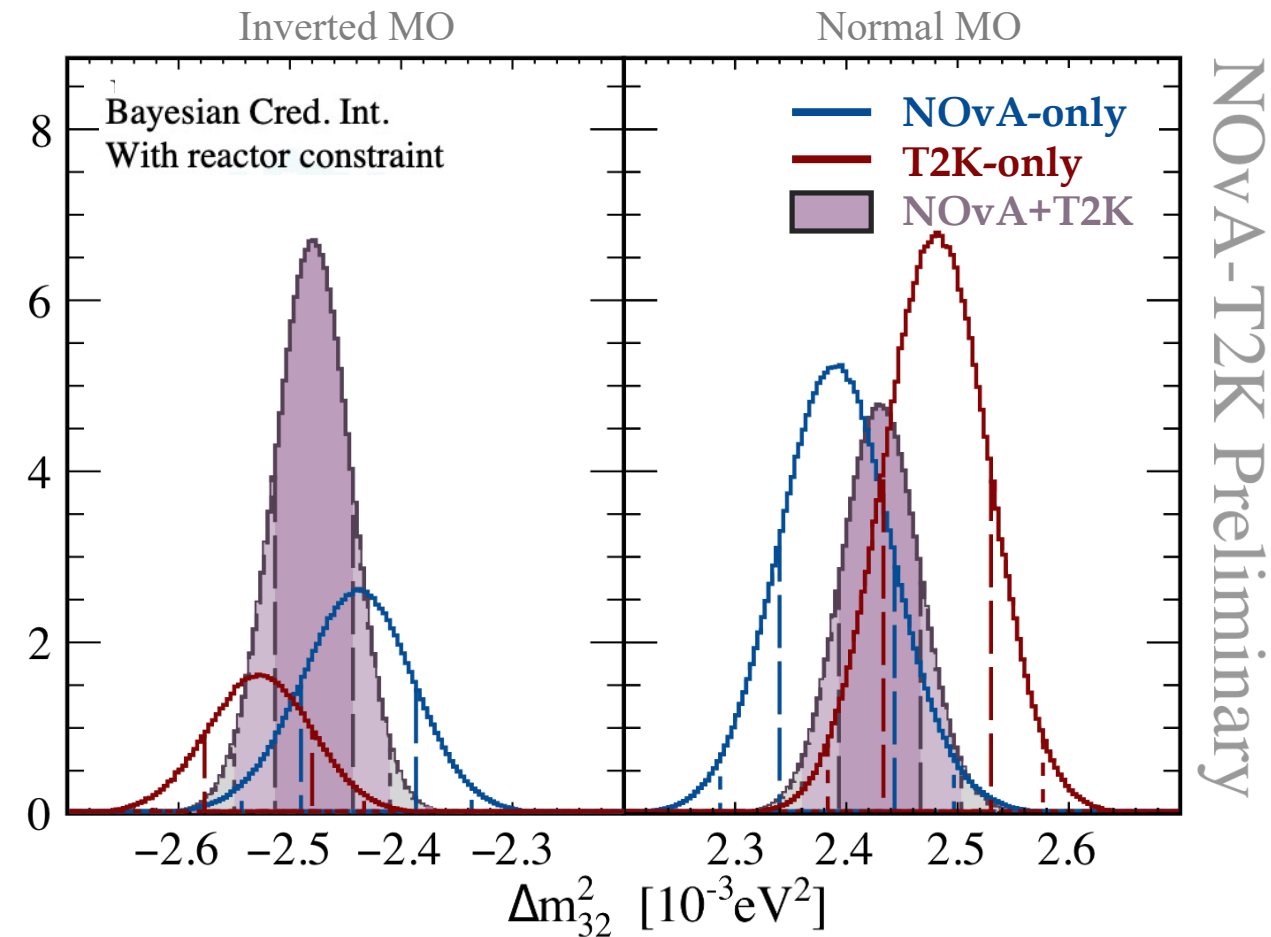
Δm_{32}^2 & Mass Ordering



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



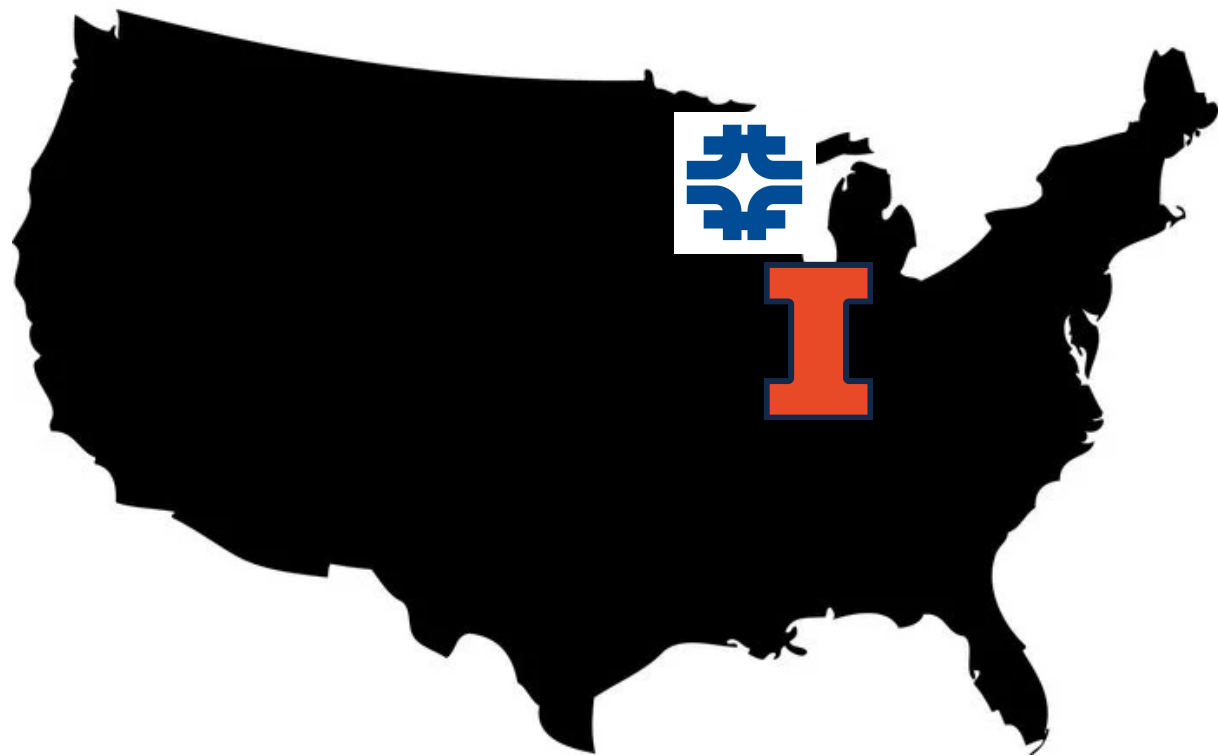
Posterior density



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



A Bit About Me...



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

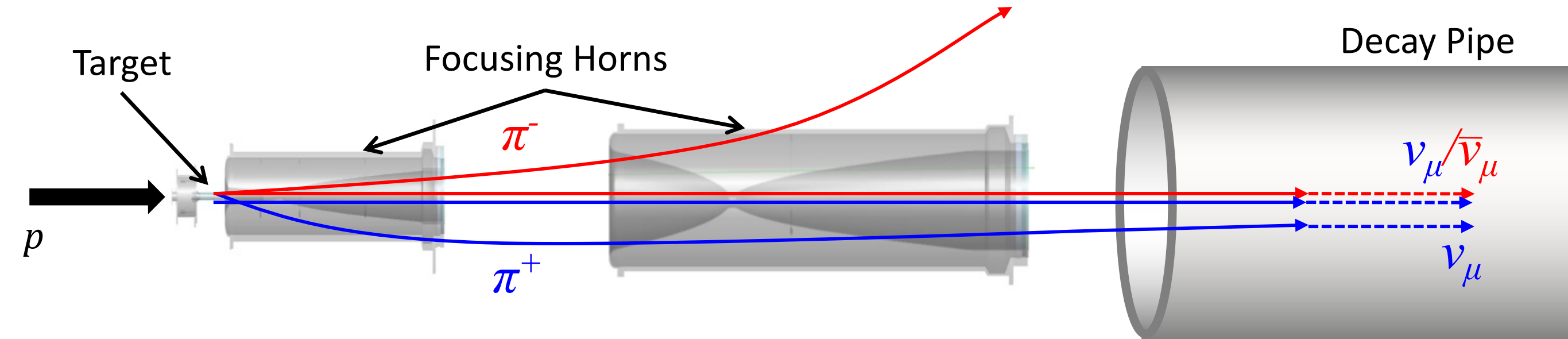


The NOvA Collaboration

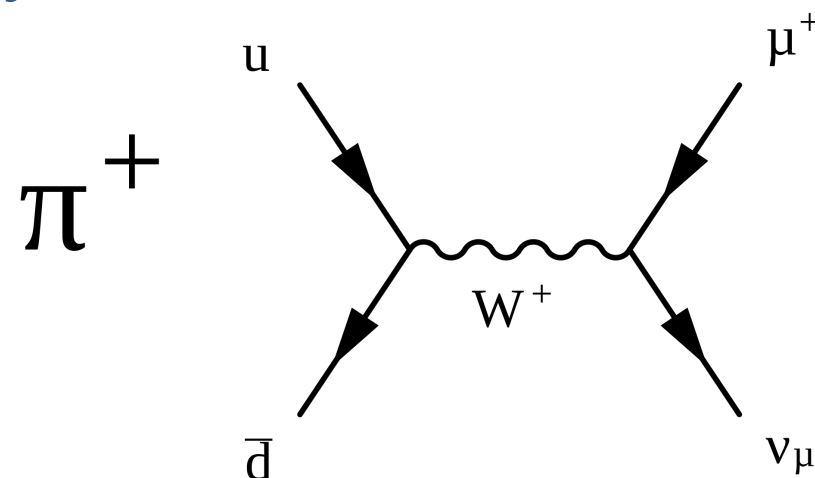


QMUL is one of the collaboration's newest institutions.

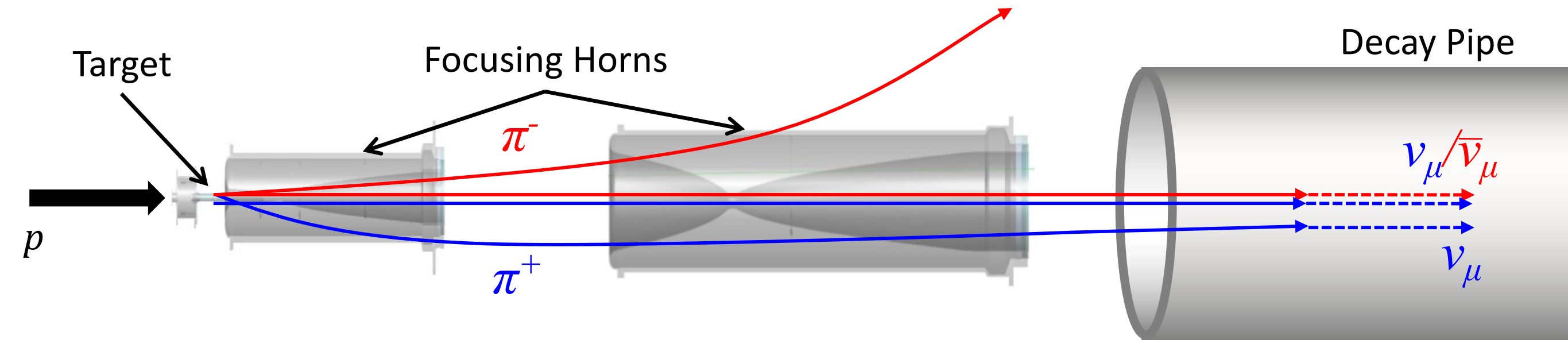




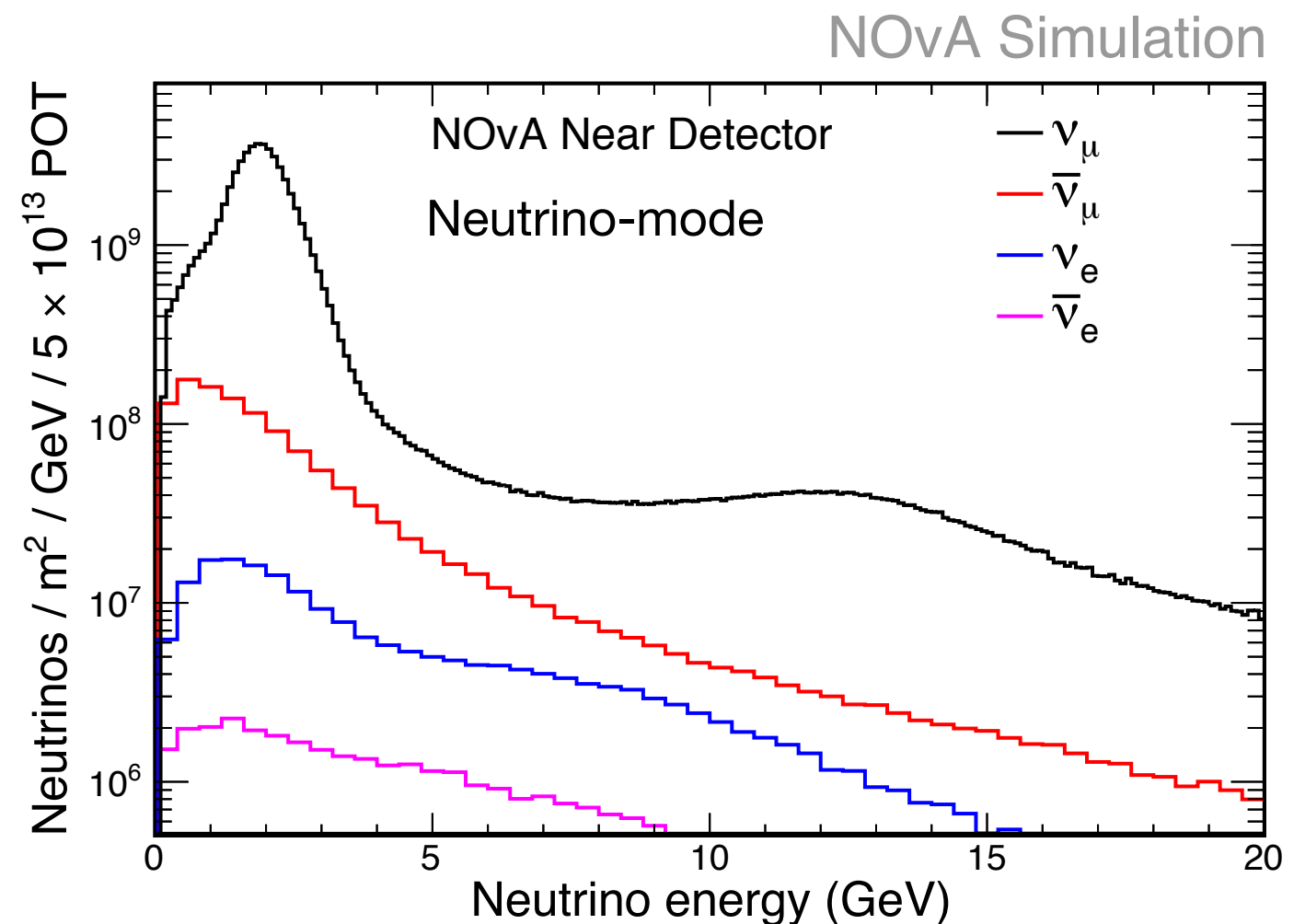
- 120 GeV protons from main injector onto graphite target.
- Spill every ~ 1.5 s, lasts 10 μ s.
- Hadron spray directed by focussing horns (± 200 kA, FHC/RHC).
- Pions decay (mostly) to muon/muon neutrino pairs.



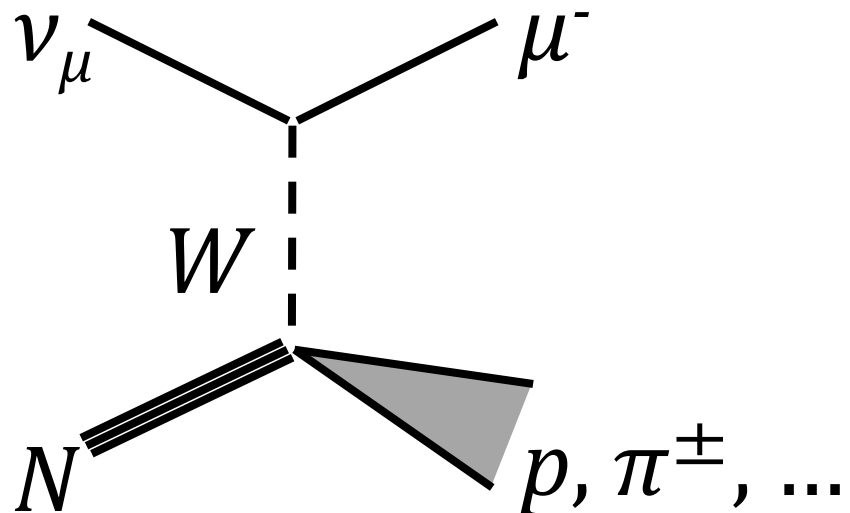
How We Make Neutrinos: NuMI Beam



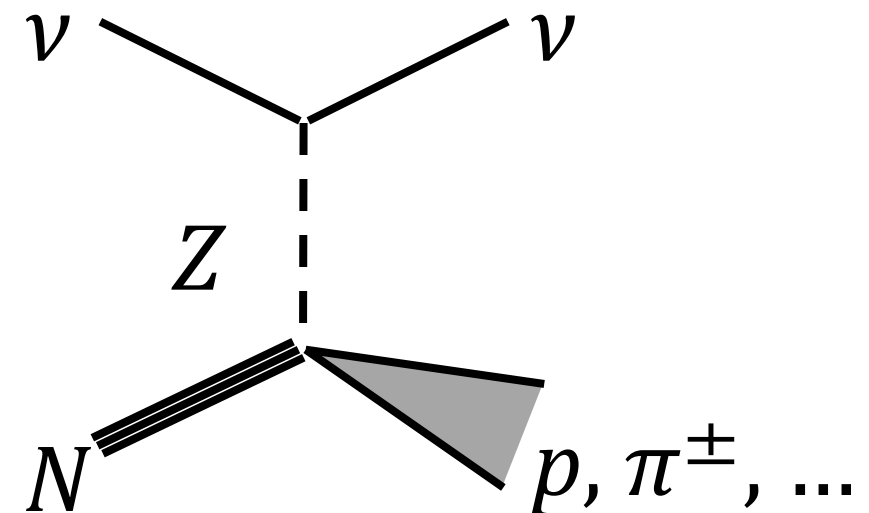
- 14 mrad off axis, peak at 2 GeV.
- 96% pure ν_μ , 3% $\bar{\nu}_\mu$.
- $\sim 1\%$ $\nu_e + \bar{\nu}_e$



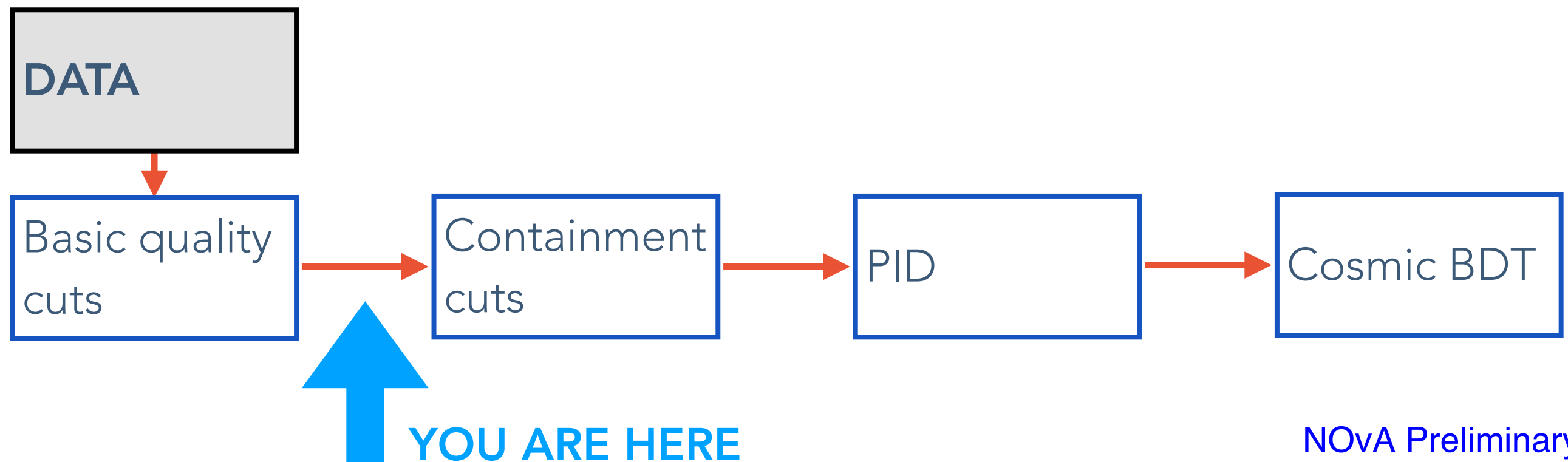
Charged Current



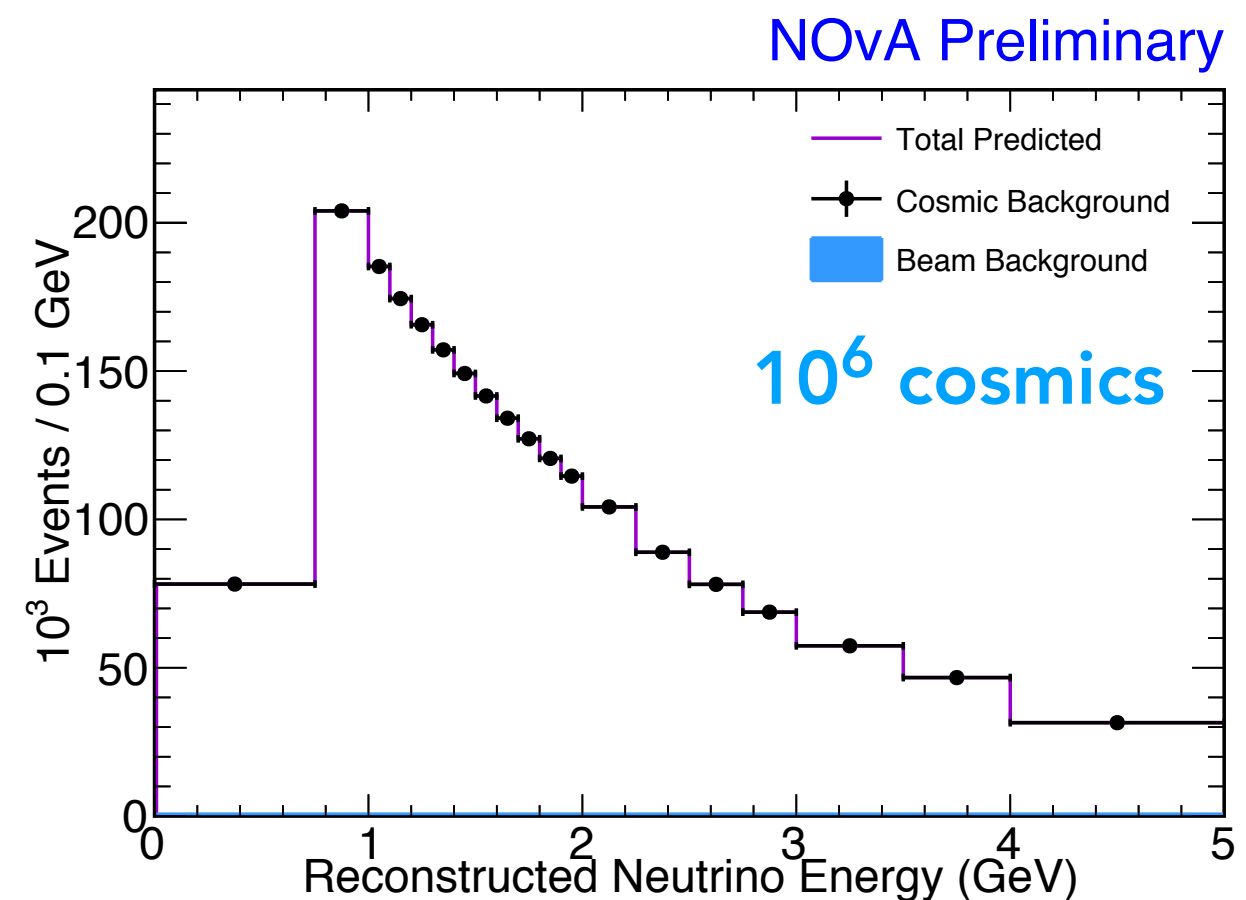
Neutral Current

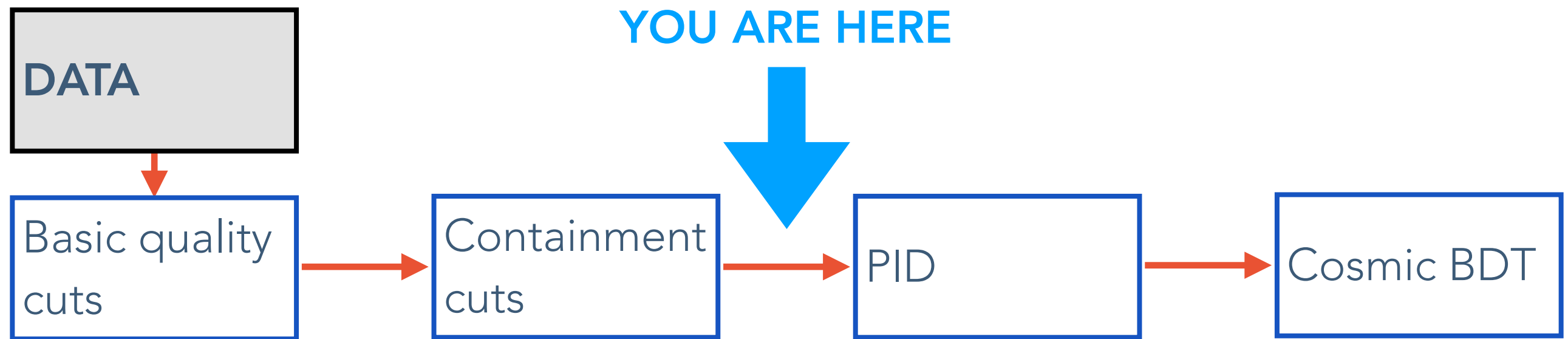


- Observe charged particles after a neutrino interacts with a nucleus.
- Lepton:
 - ν_μ CC $\rightarrow \mu^-$, ν_e CC $\rightarrow e^-$.
 - NC, no visible lepton.
- Hadronic shower:
 - May contain protons, one or more $\pi^\pm$, etc.
 - May have EM components from $\pi^0 \rightarrow \gamma\gamma$

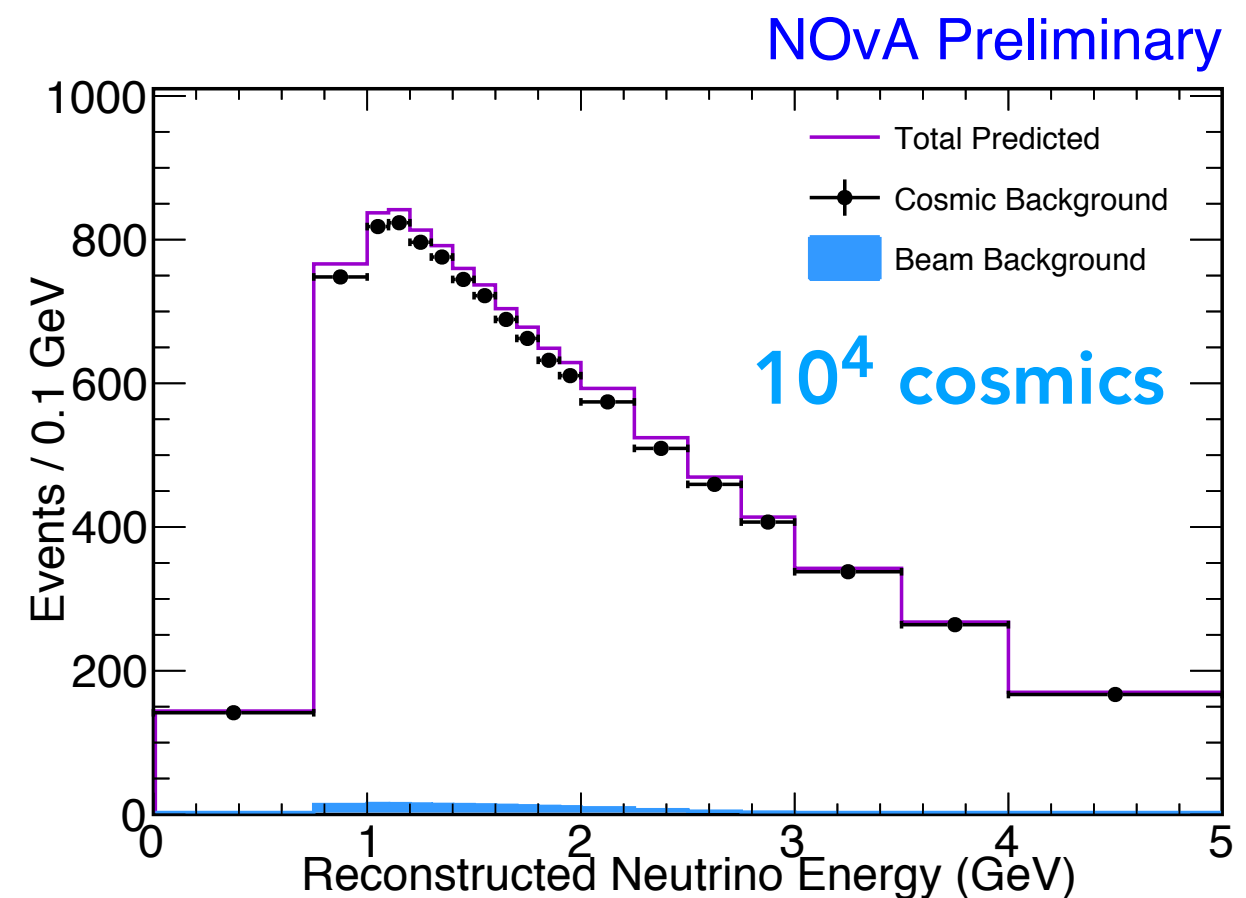


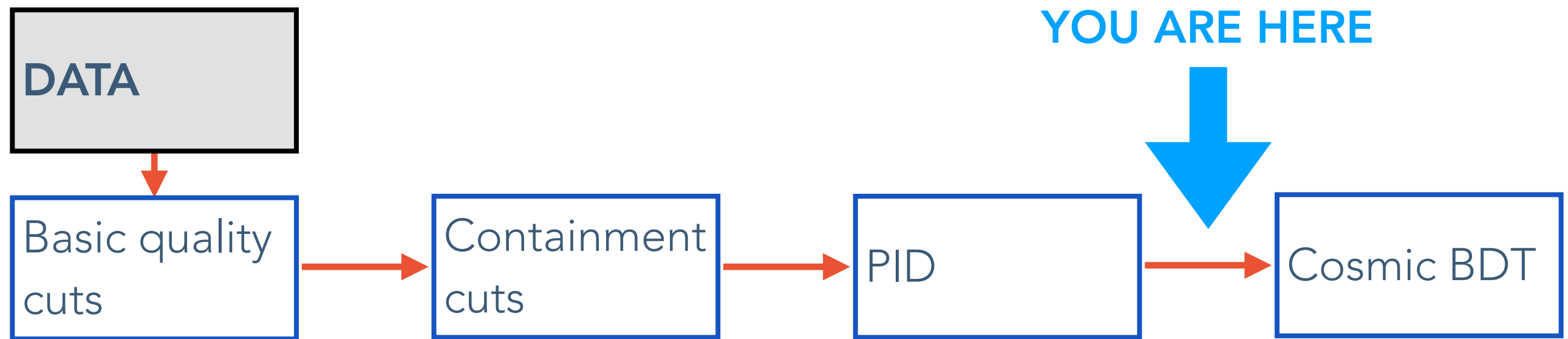
- Even with pulsed beam and excellent timing resolution, still a significant amount of cosmic background.
- Basic quality:
 - Number of hits, track angle, reasonable energy reconstructed.



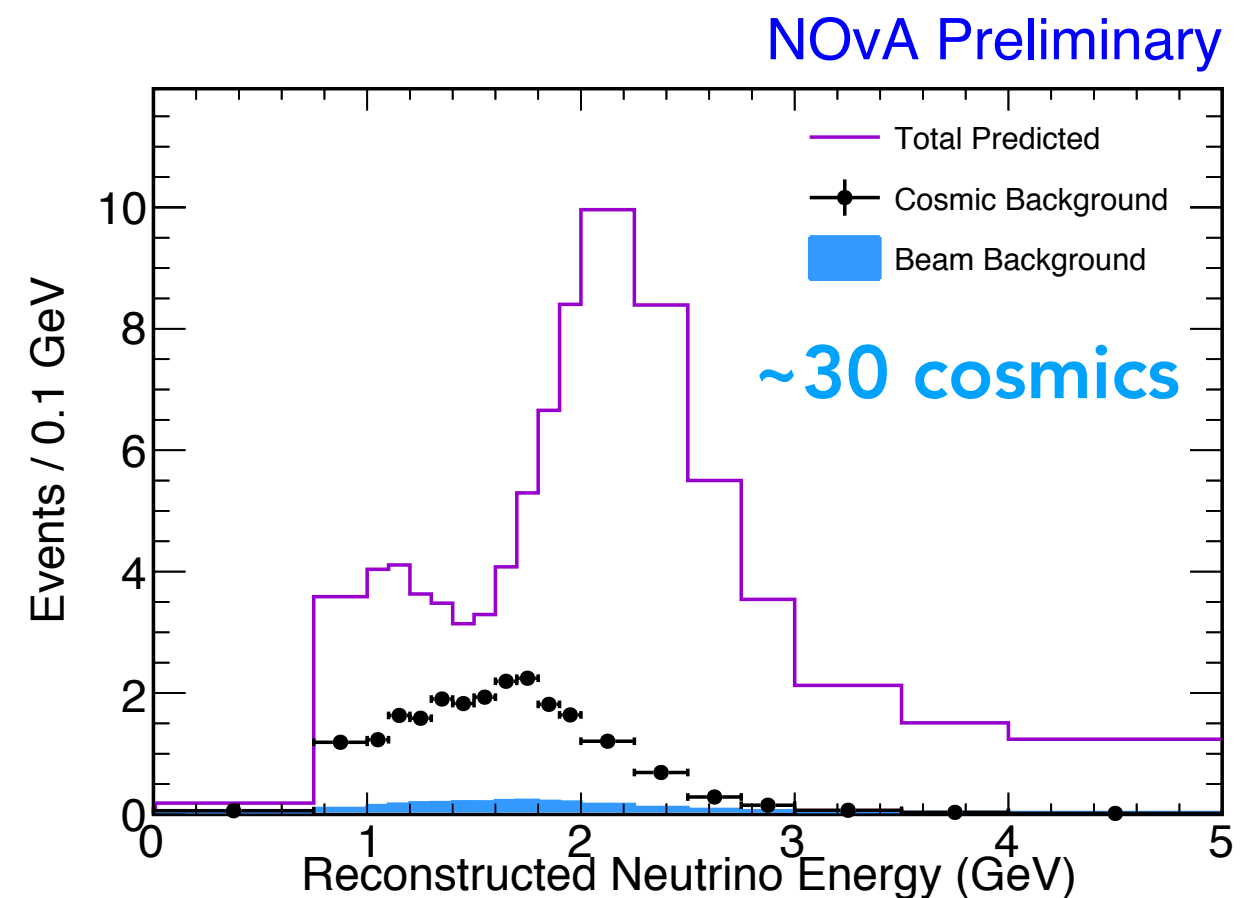


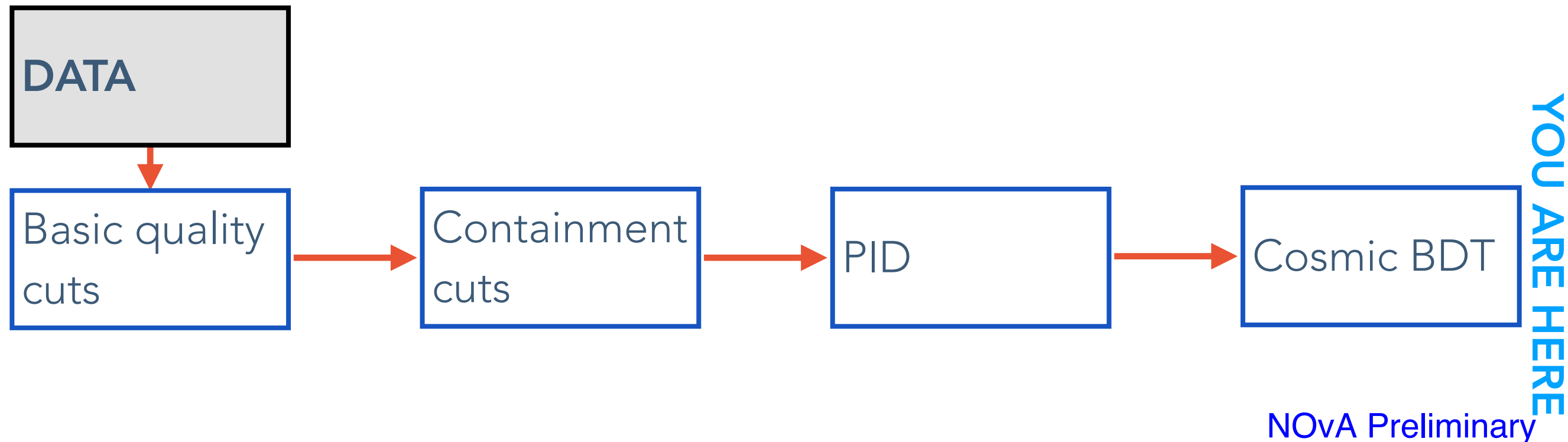
- Even with pulsed beam and excellent timing resolution, still a significant amount of cosmic background.
- Containment cuts:
 - Vertices in the fiducial volume.
 - Event contained within the detector.



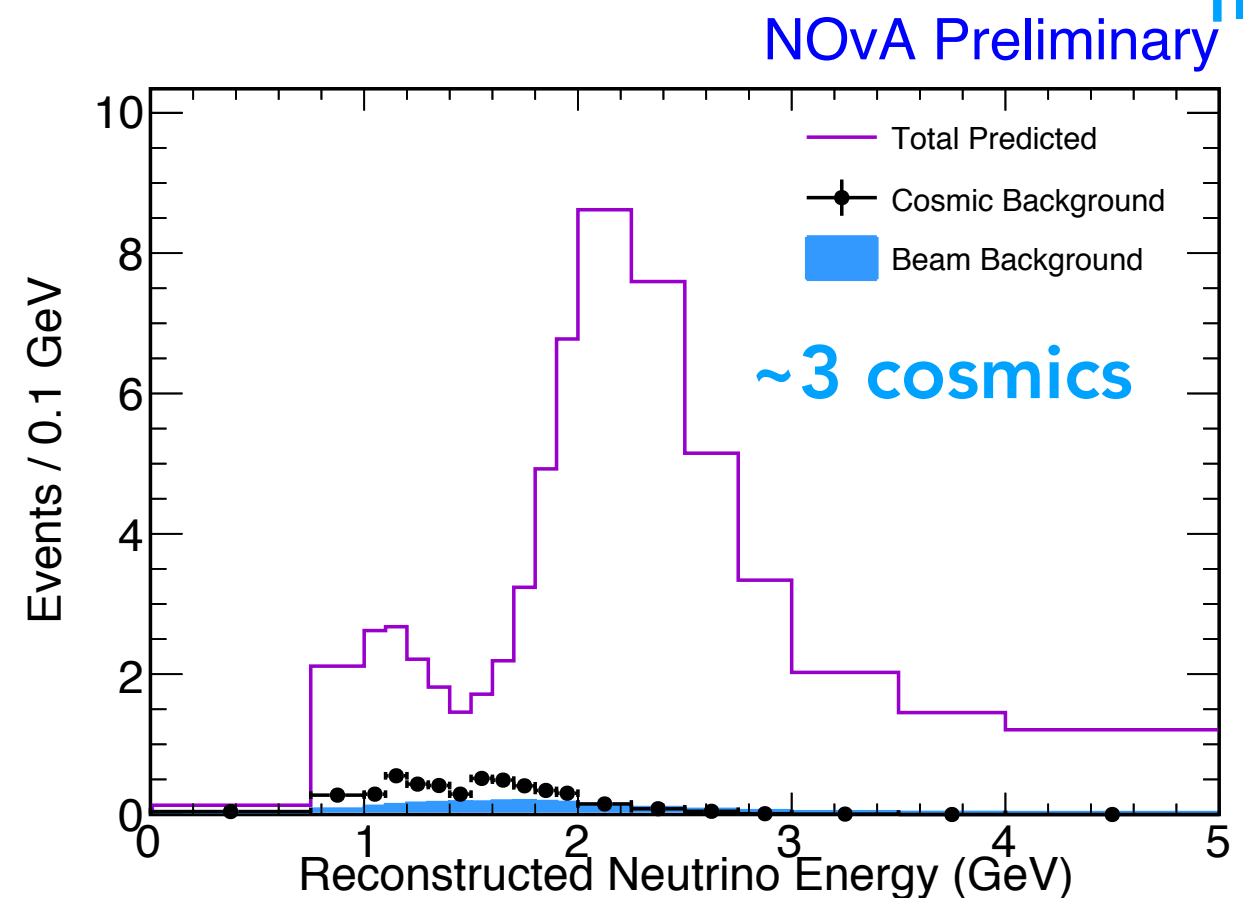


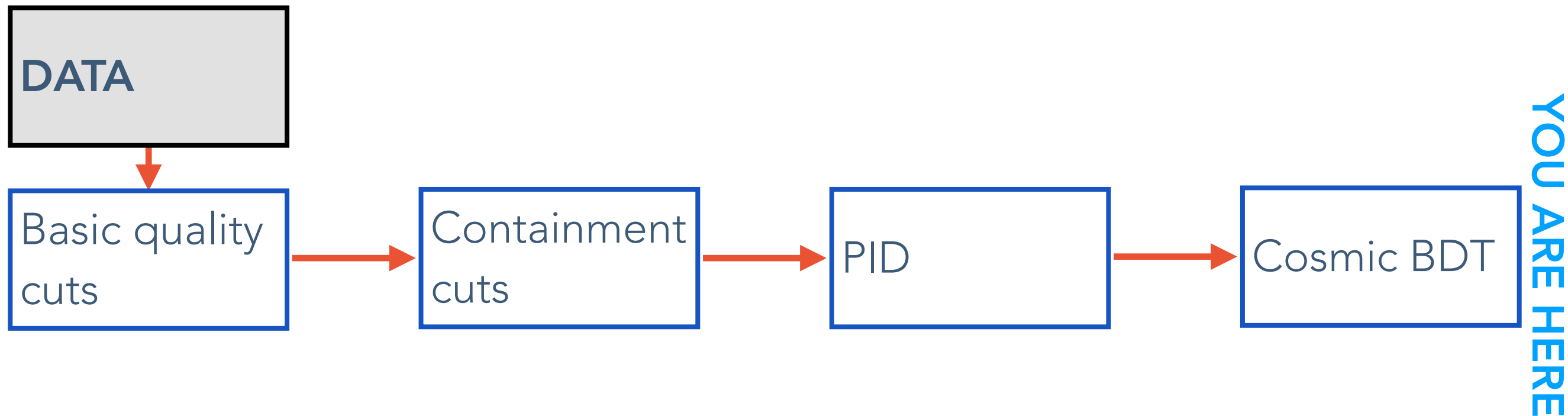
- Even with pulsed beam and excellent timing resolution, still a significant amount of cosmic background.
- PID:
 - Deep learning approach.



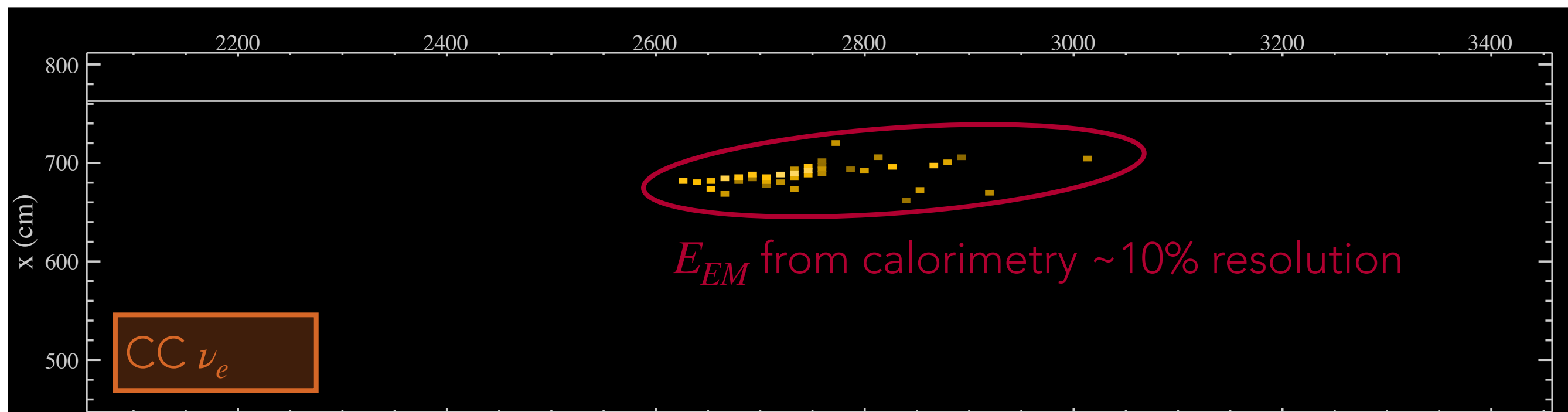
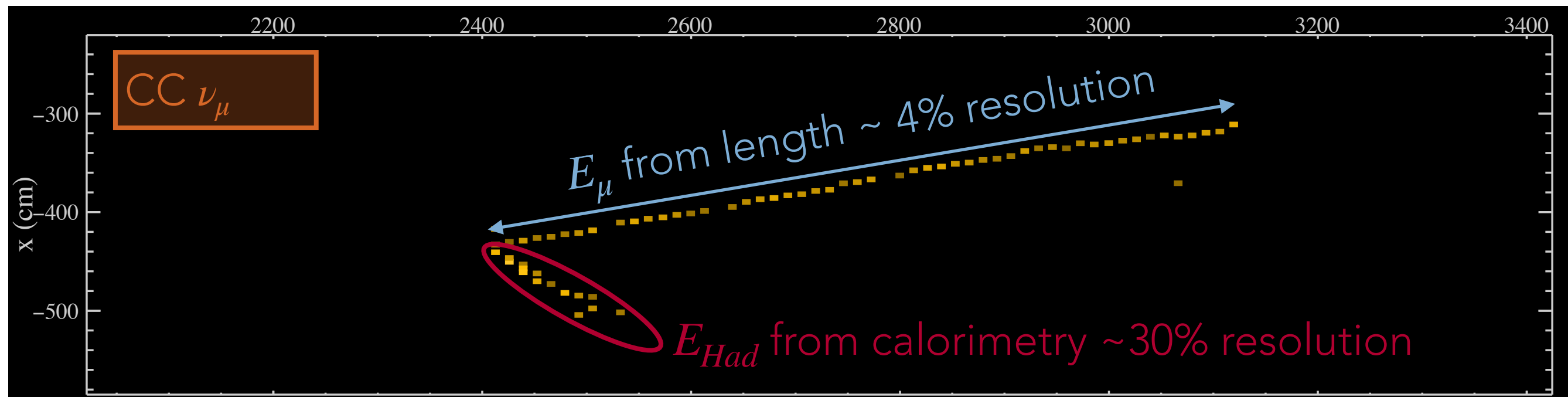


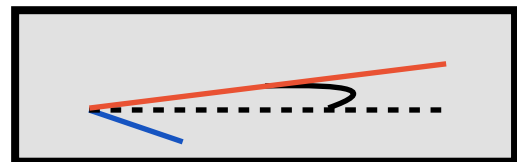
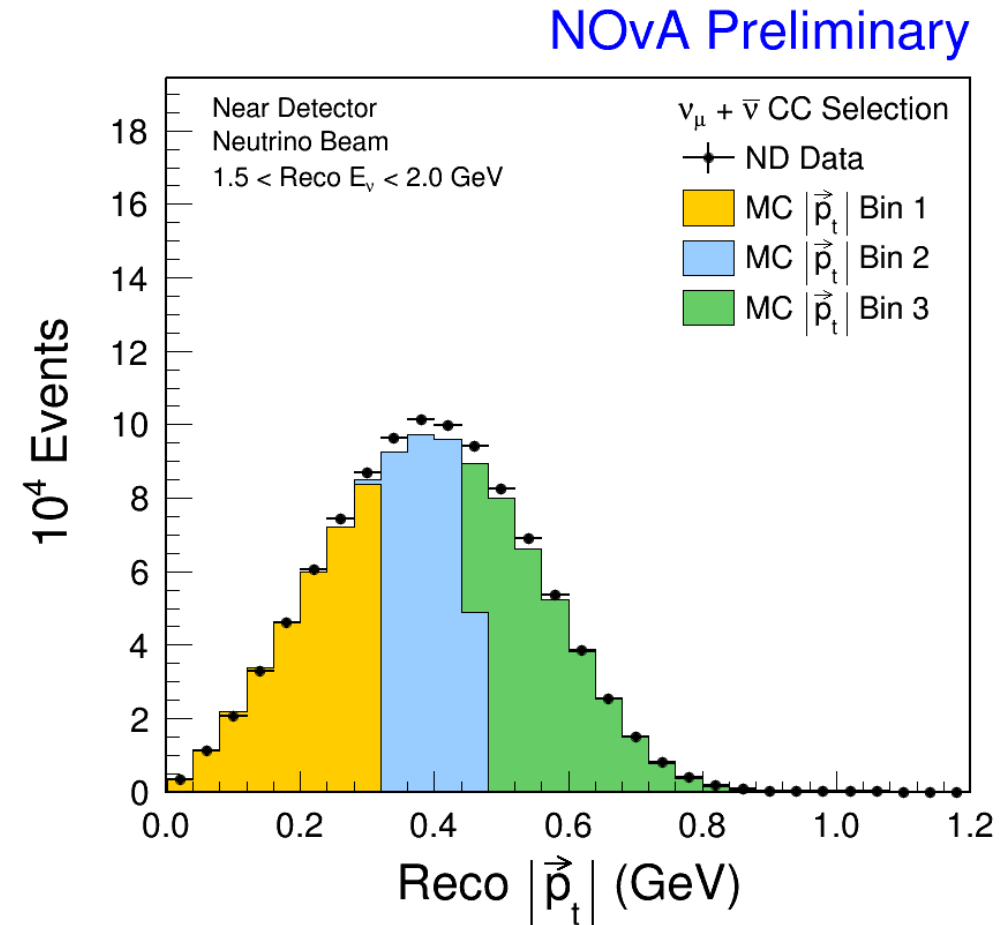
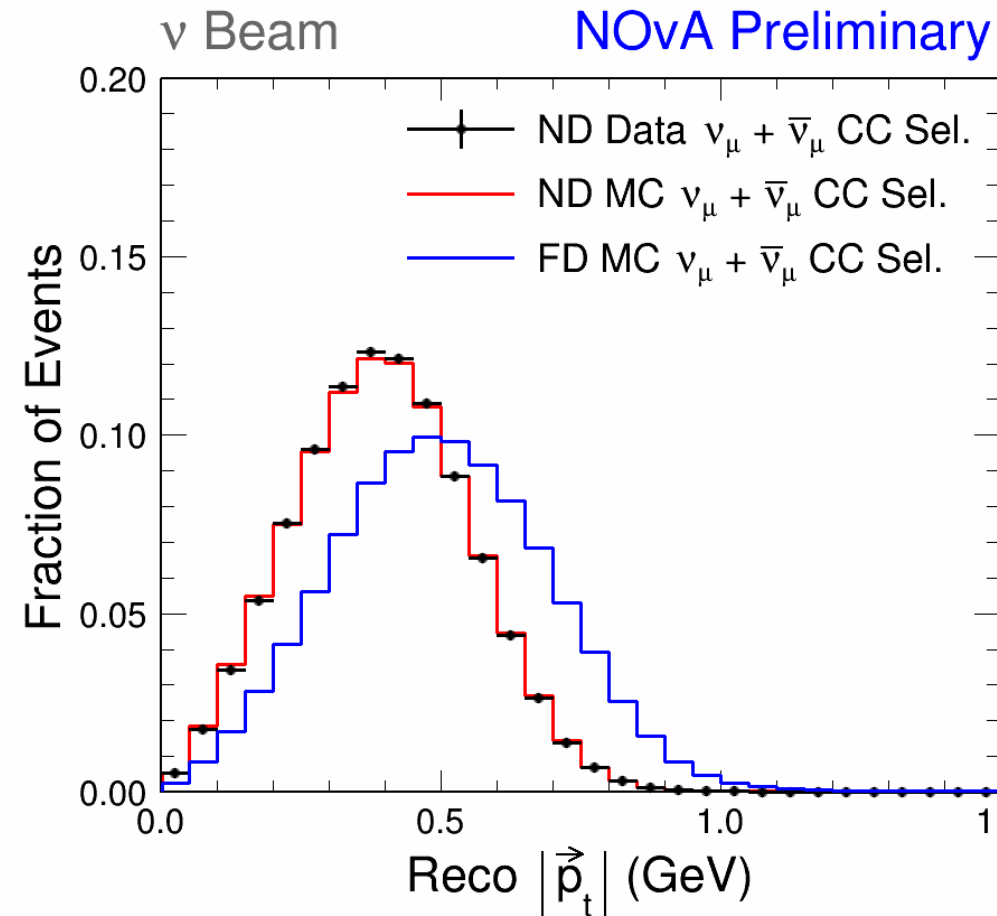
- Even with pulsed beam and excellent timing resolution, still a significant amount of cosmic background.
- Cosmic BDT:
 - Tuned to reject cosmic ray events.



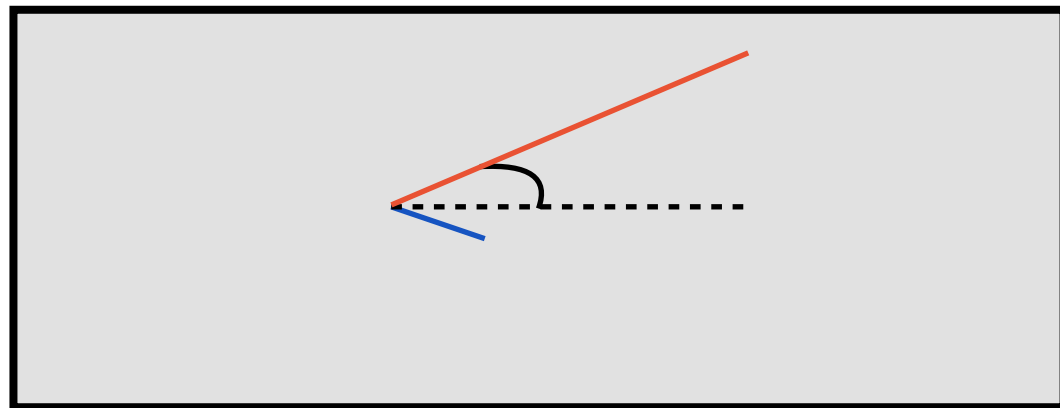


- Electron neutrino sample has second 'peripheral' sample containing high-confidence electron neutrino events close to detector walls.





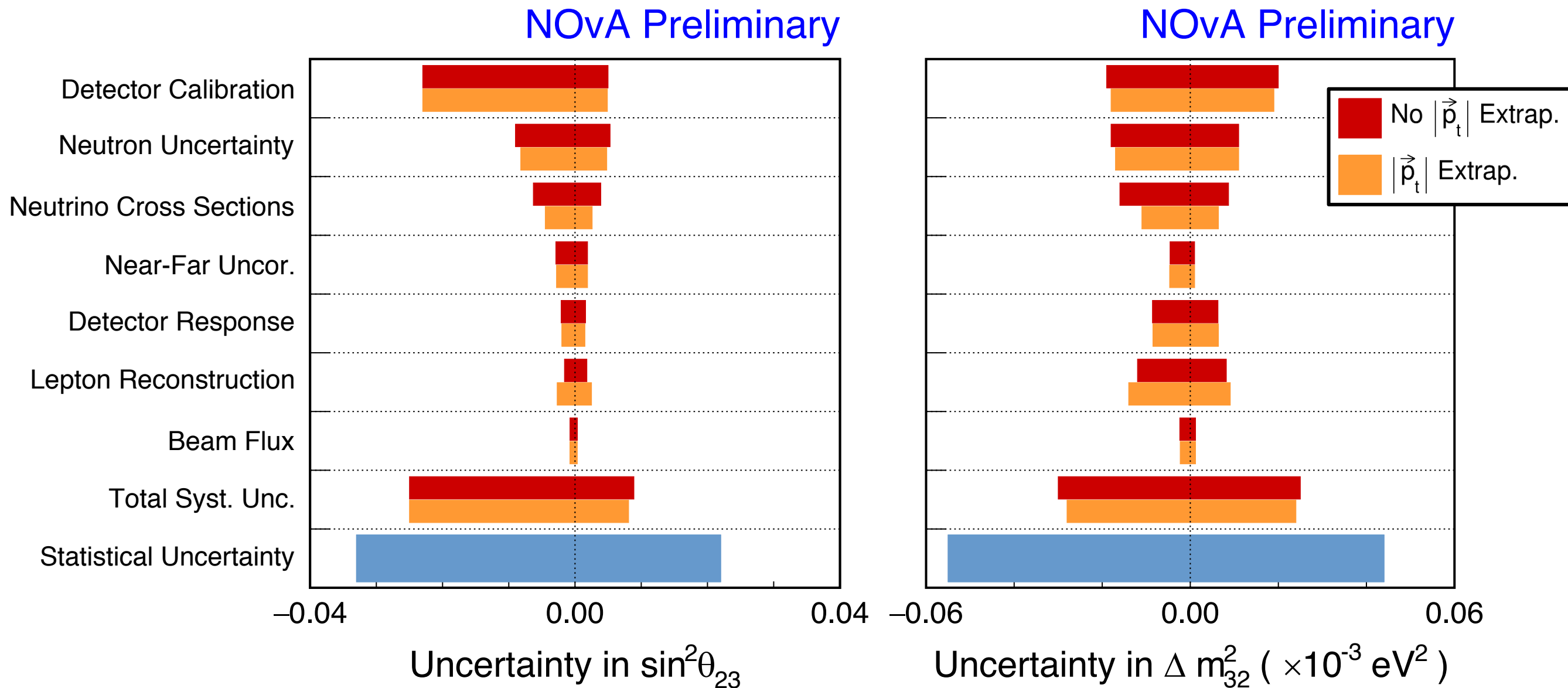
ND



FD

- 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

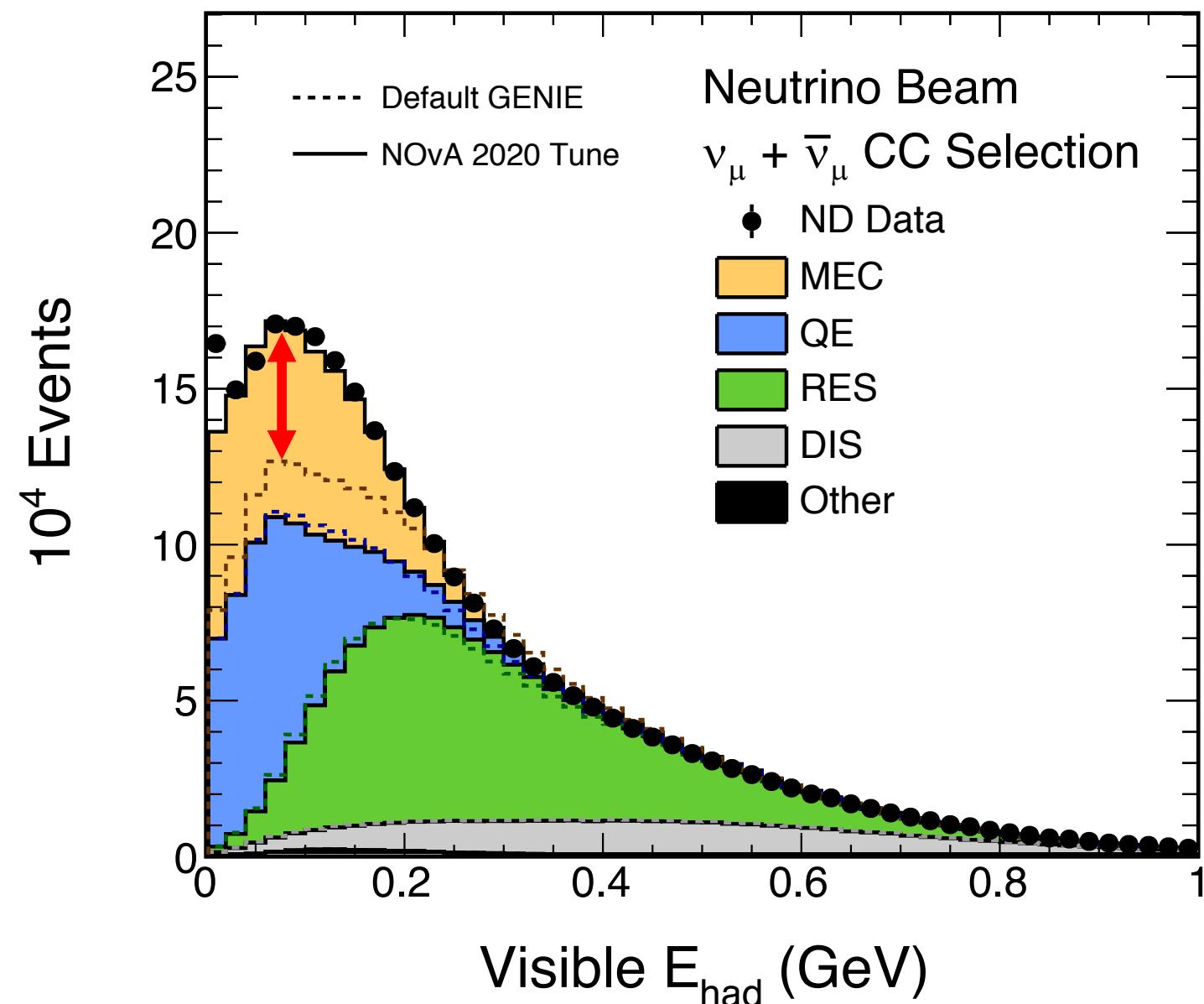


- Overall systematic reduction is 5-10%.
- 30% reduction in cross-section uncertainties.
 - Reduces the size of systematics most likely to contain “unknown unknowns.”
 - Slight increase in systematics on lepton reconstruction.

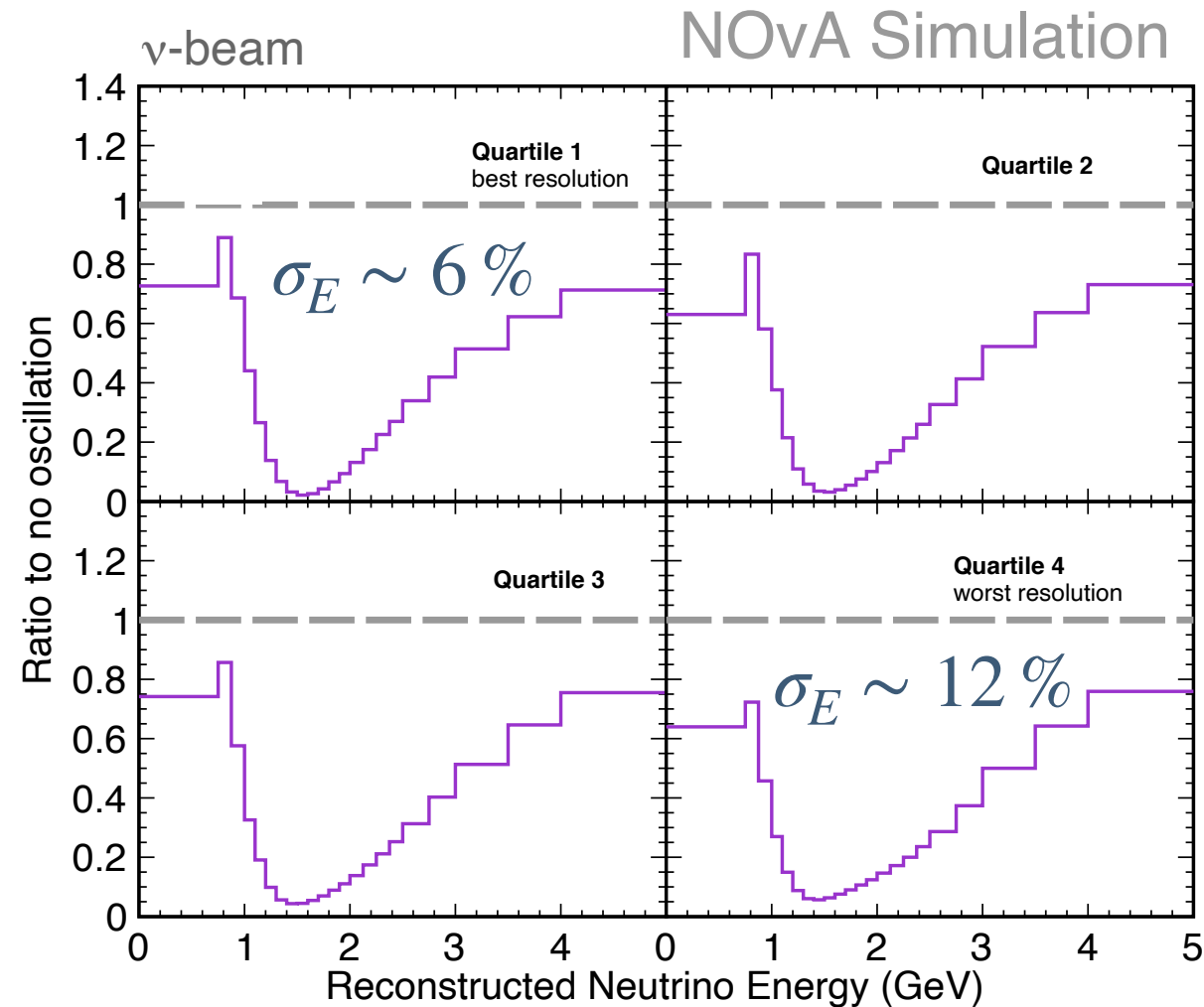


NOvA Preliminary

- Understanding of neutrino interactions is constantly evolving.
- Upgrade to GENIE 3.0.6, gives freedom to choose 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.

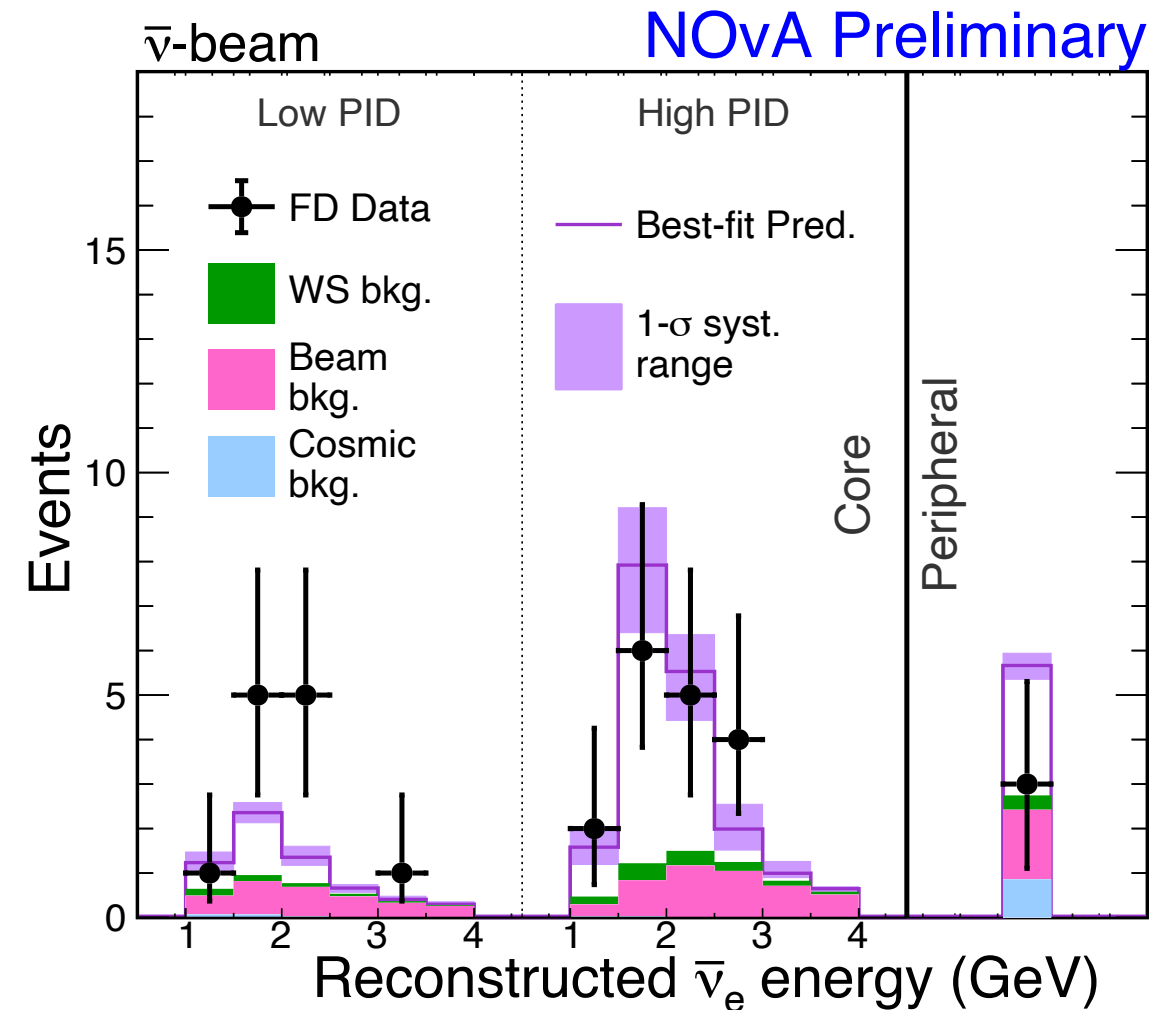


Improving Sensitivity to Oscillations



ν_μ

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

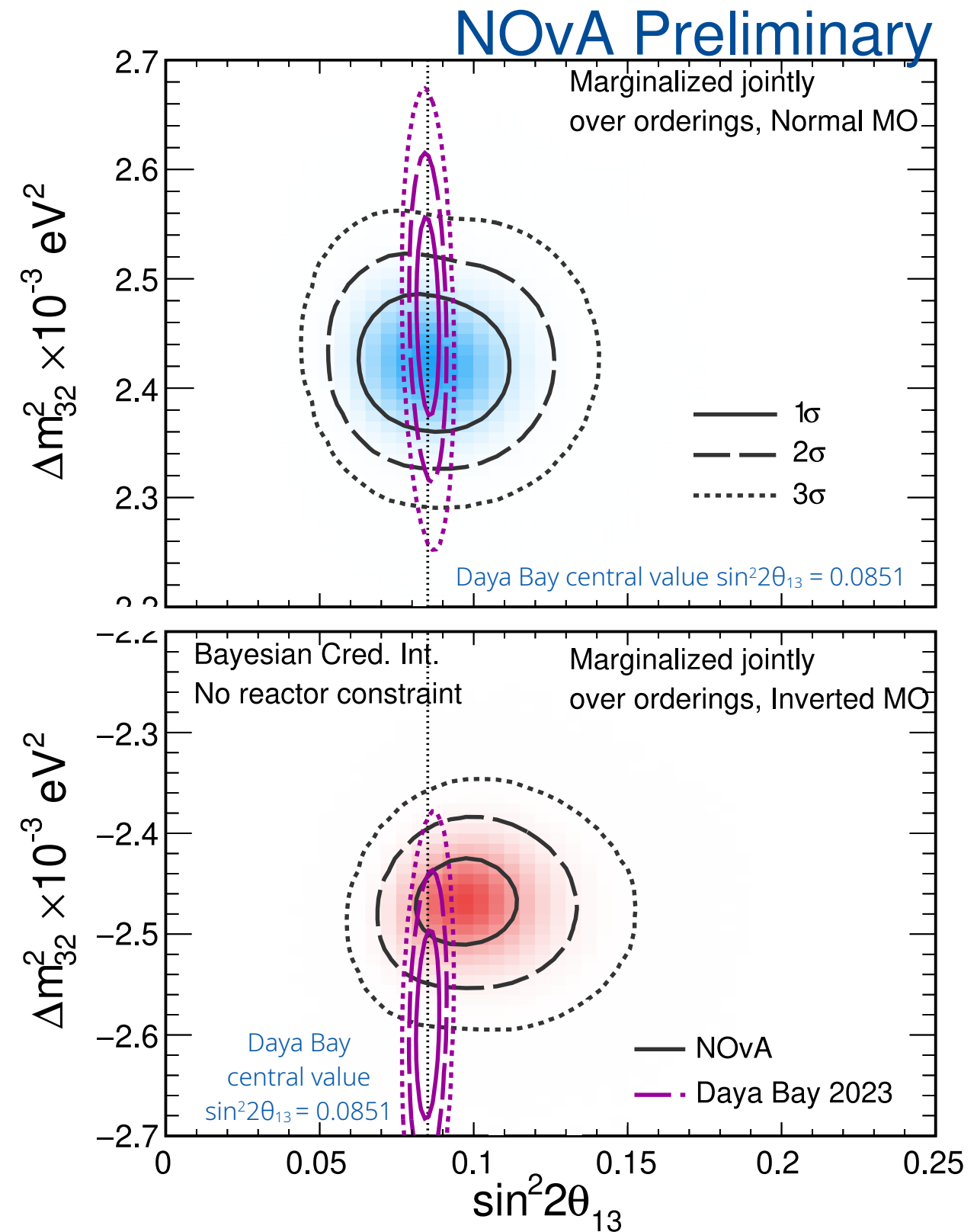
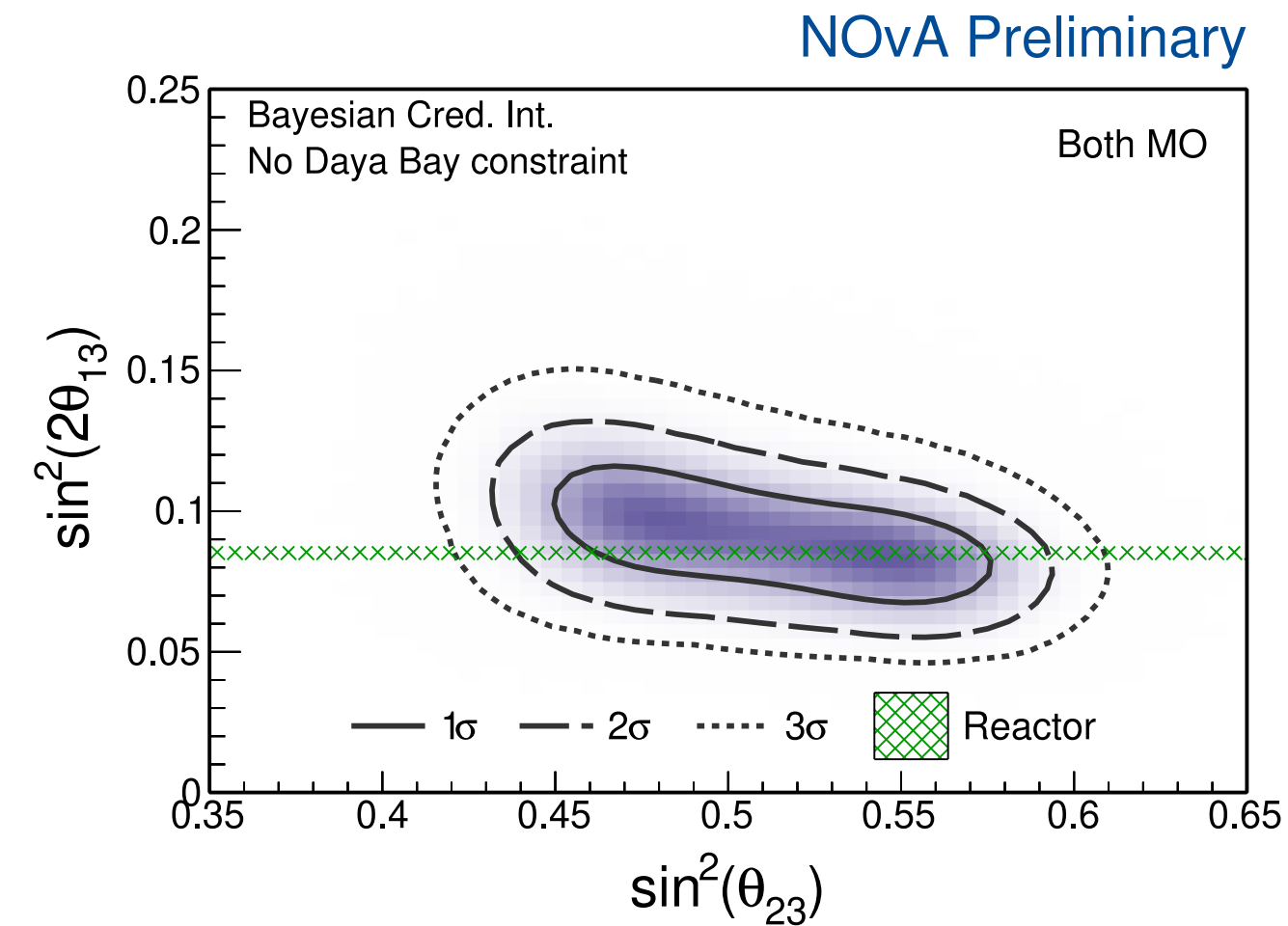


ν_e

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



Daya Bay / NOvA Correlations



J. Wolcott



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

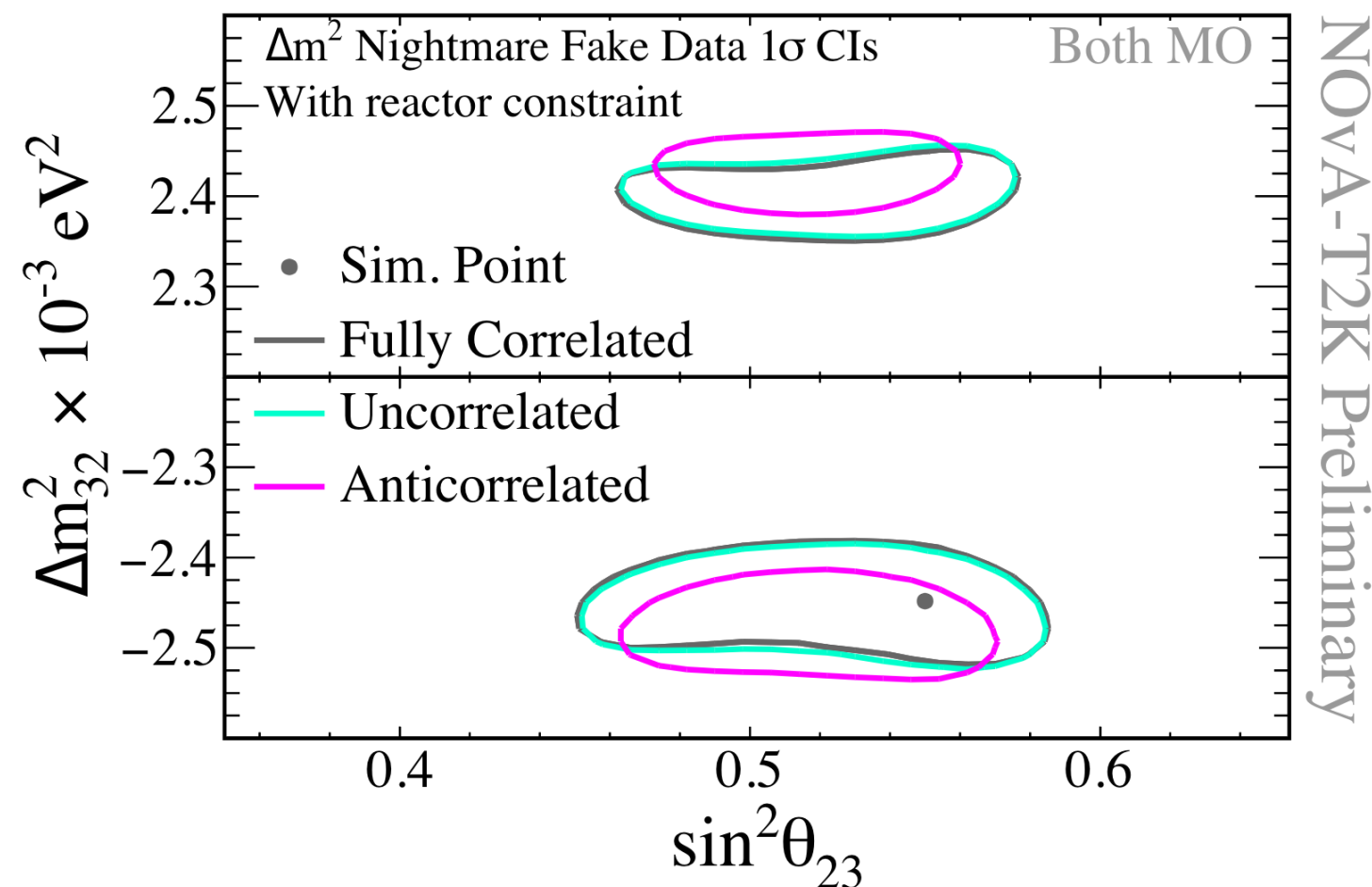
❑ No significant correlations between the experiments

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

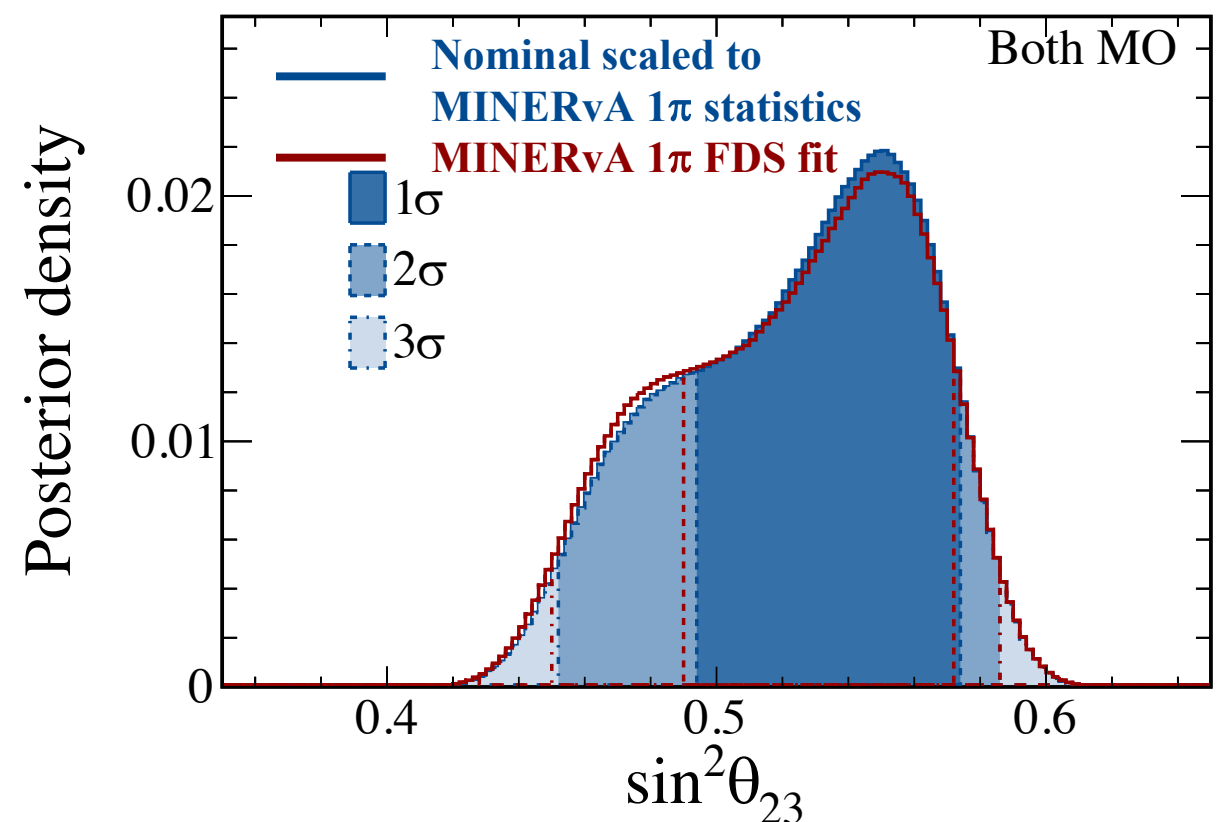
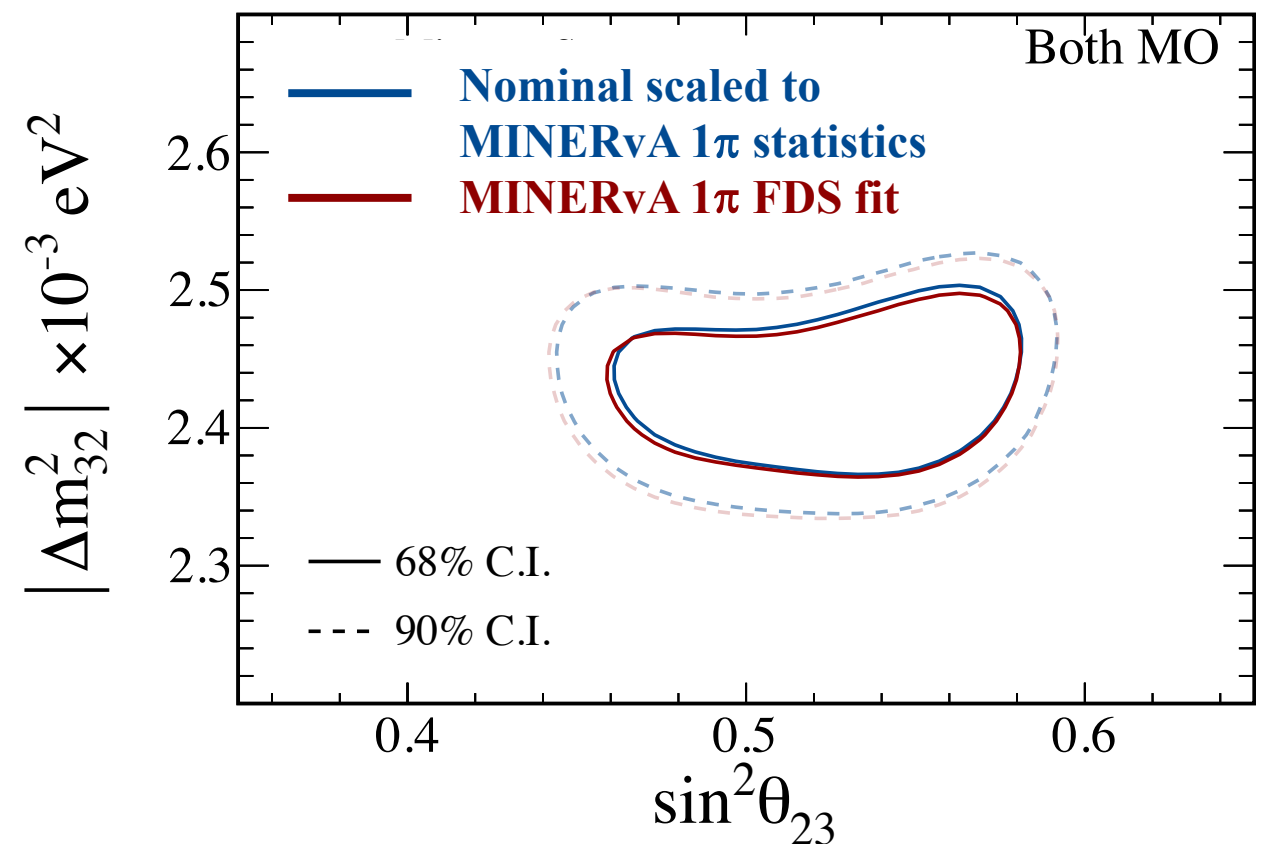
- ❑ Impact of correlations is negligible on the results at the current statistical significance.
- ❑ Merits continued investigations for higher data exposures.

Z. Vallari



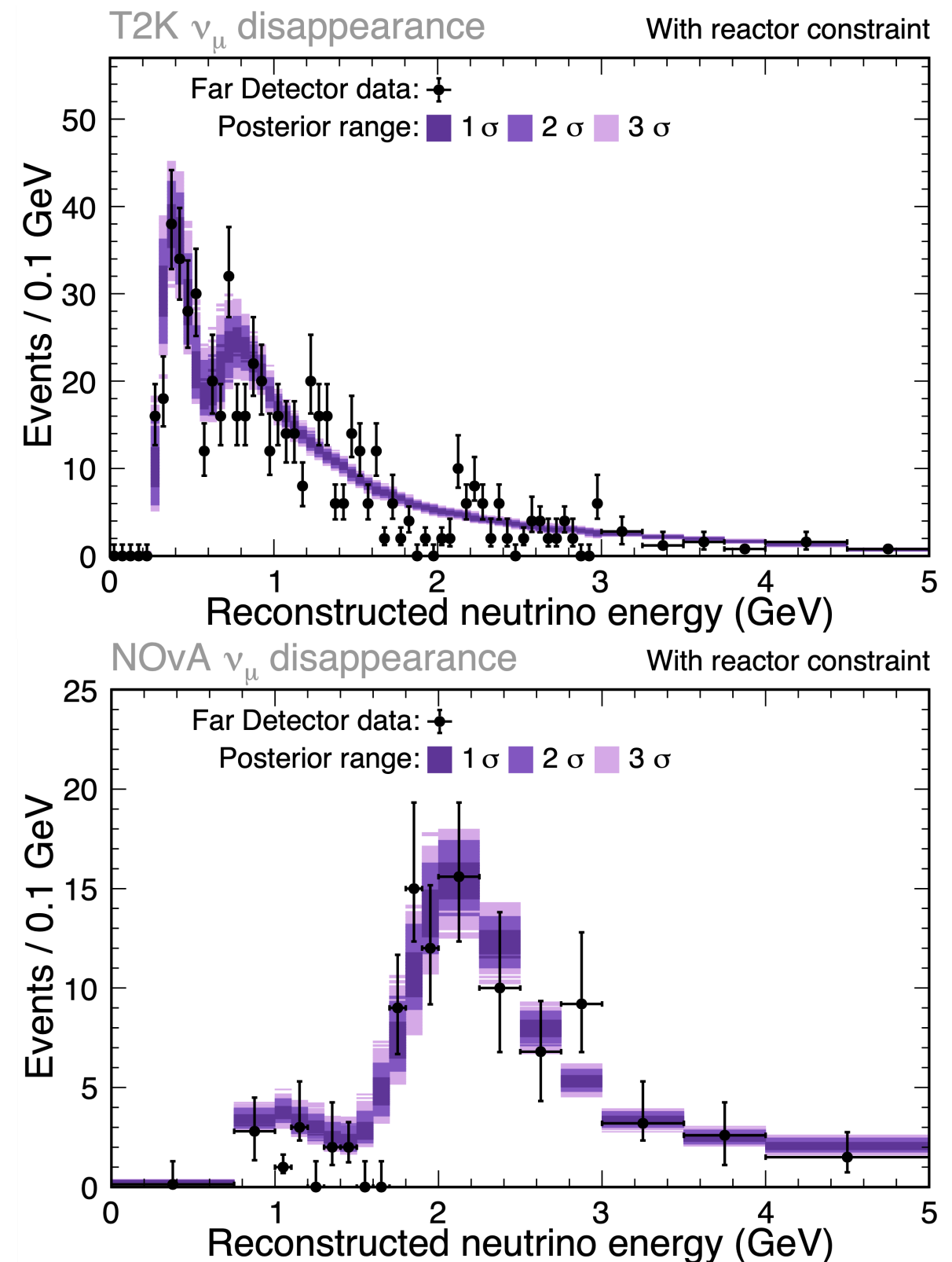
- **Strategy:** evaluate a range of artificial scenarios to assess the impact of possible correlations:
 - ▶ E.g, fabricate parameters for each experiment which should have significant bias on Δm^2_{32} and $\sin^2 \theta_{23}$ (size of uncertainty comparable to the statistical uncertainty).
 - ▶ Study 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 $\rightarrow$ leaving systematics like these uncorrelated wouldn't have a significant impact in the analysis.

- 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.**

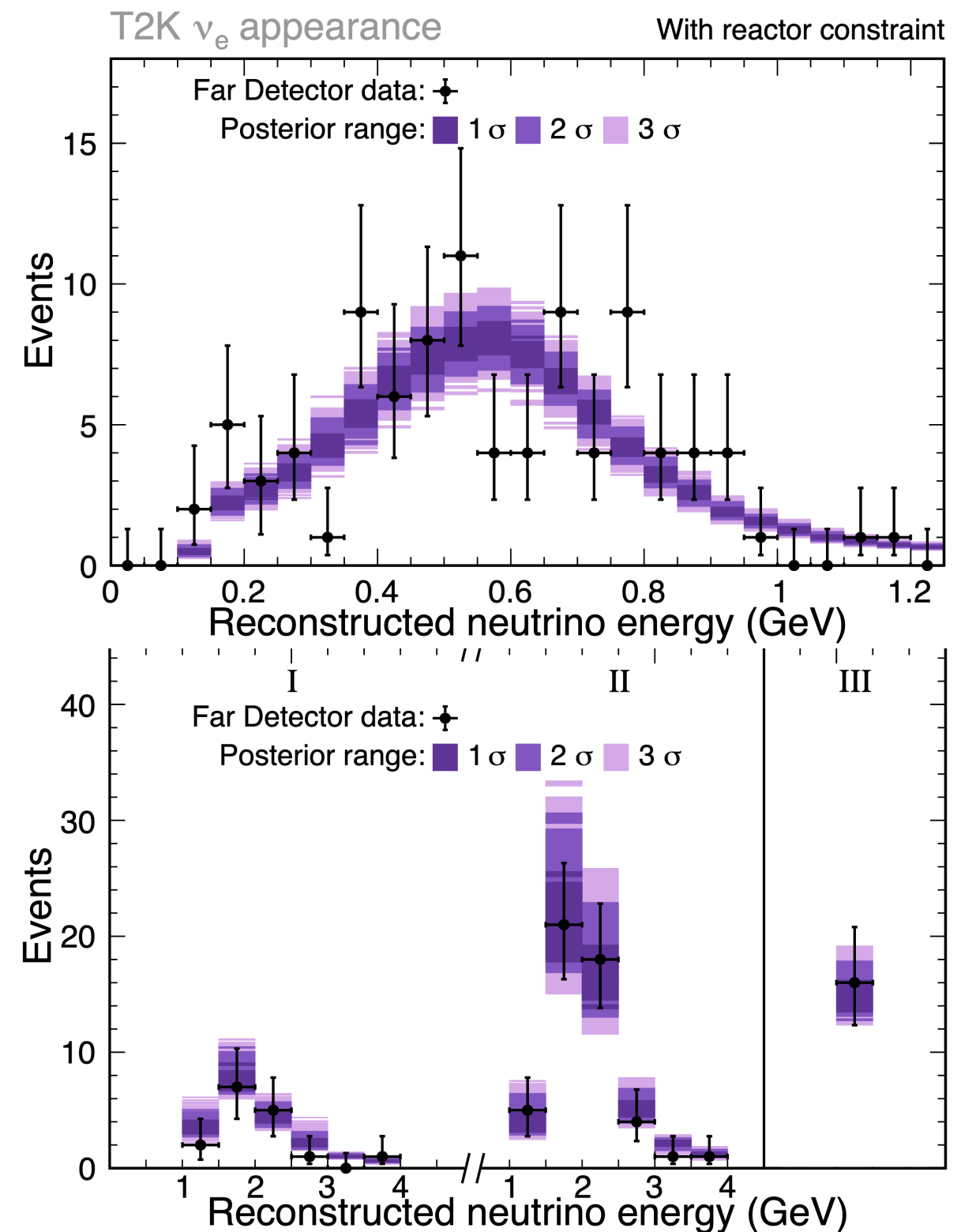


*Phys. Rev. D 100, 072005 (2019)

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



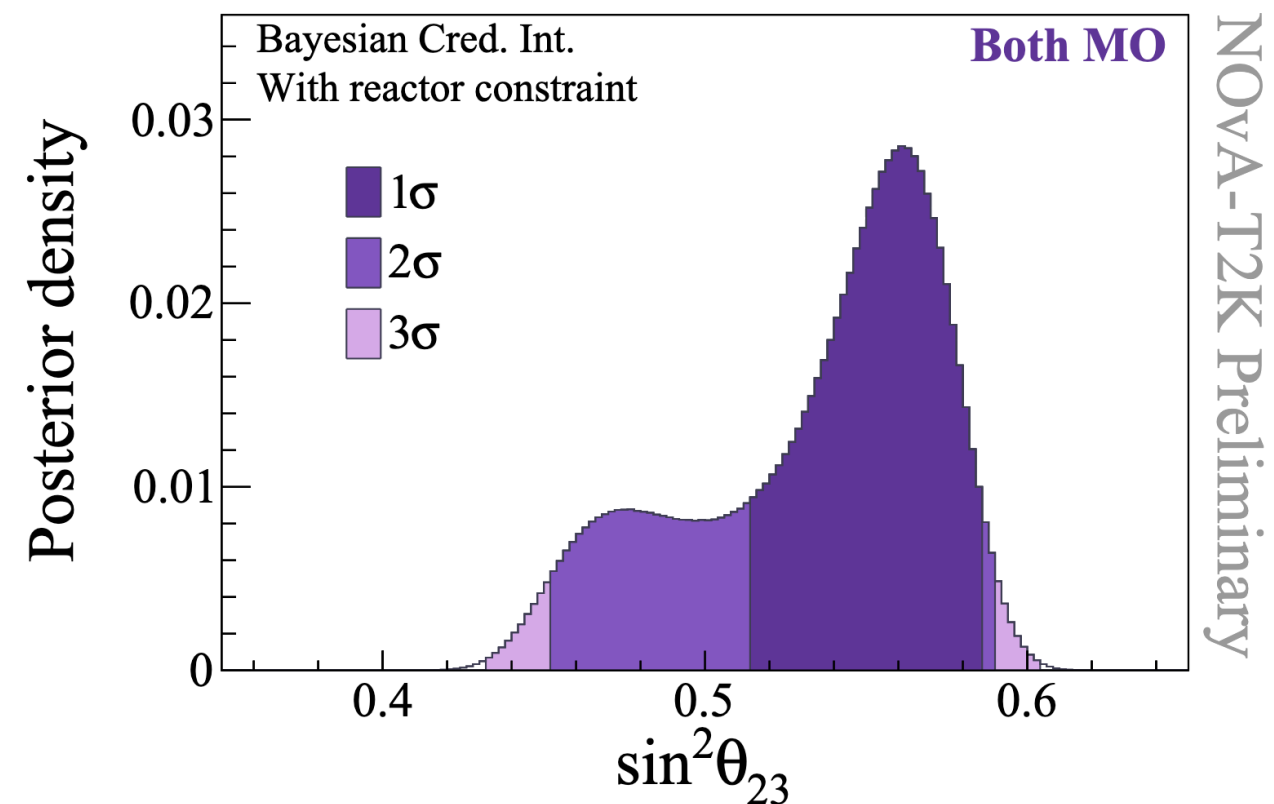
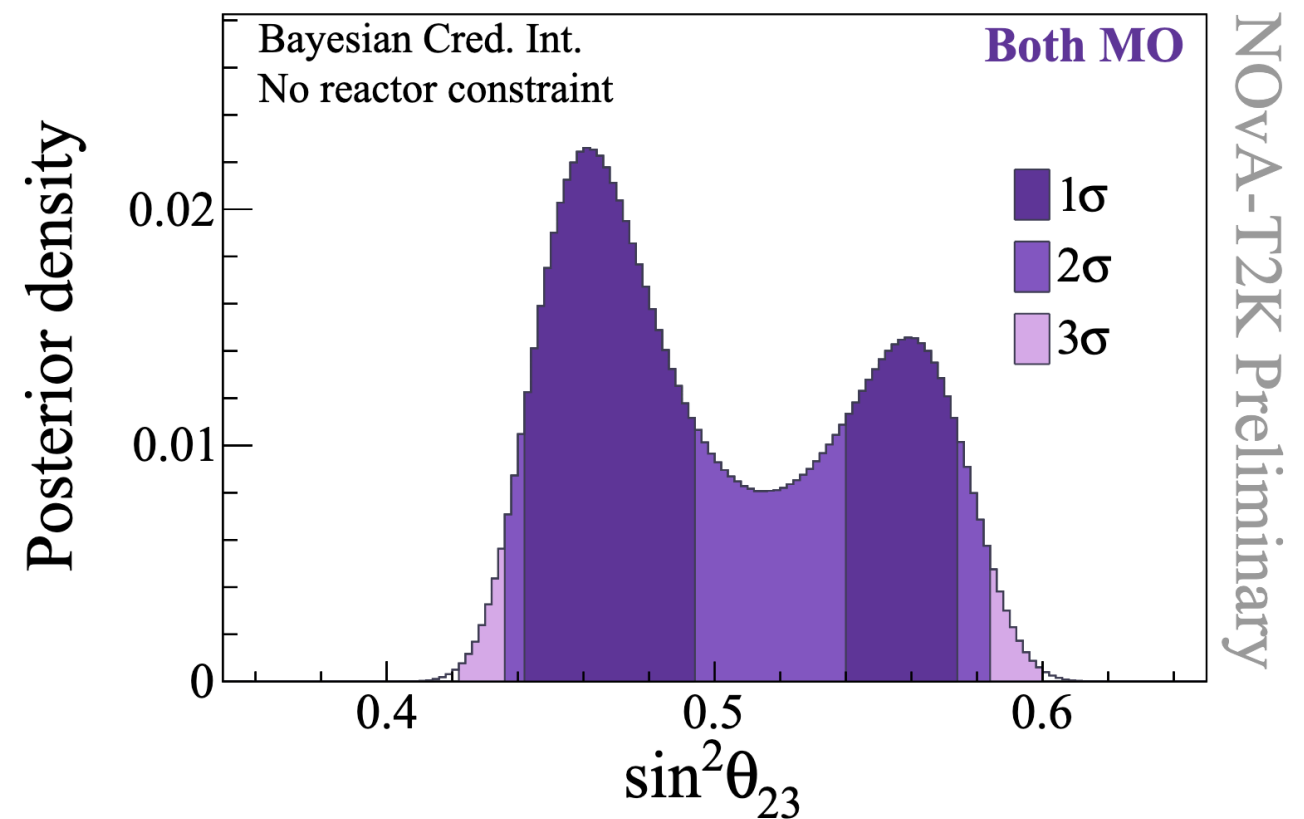
Channel	NOvA	T2K	Combined
ν_e	0.90	0.19 (ν_e) 0.79 ($\nu_e 1\pi$)	0.62
$\bar{\nu}_e$	0.21	0.67	0.40
ν_μ	0.68	0.48	0.62
$\bar{\nu}_\mu$	0.38	0.87	0.72
Total	0.64	0.72	0.75

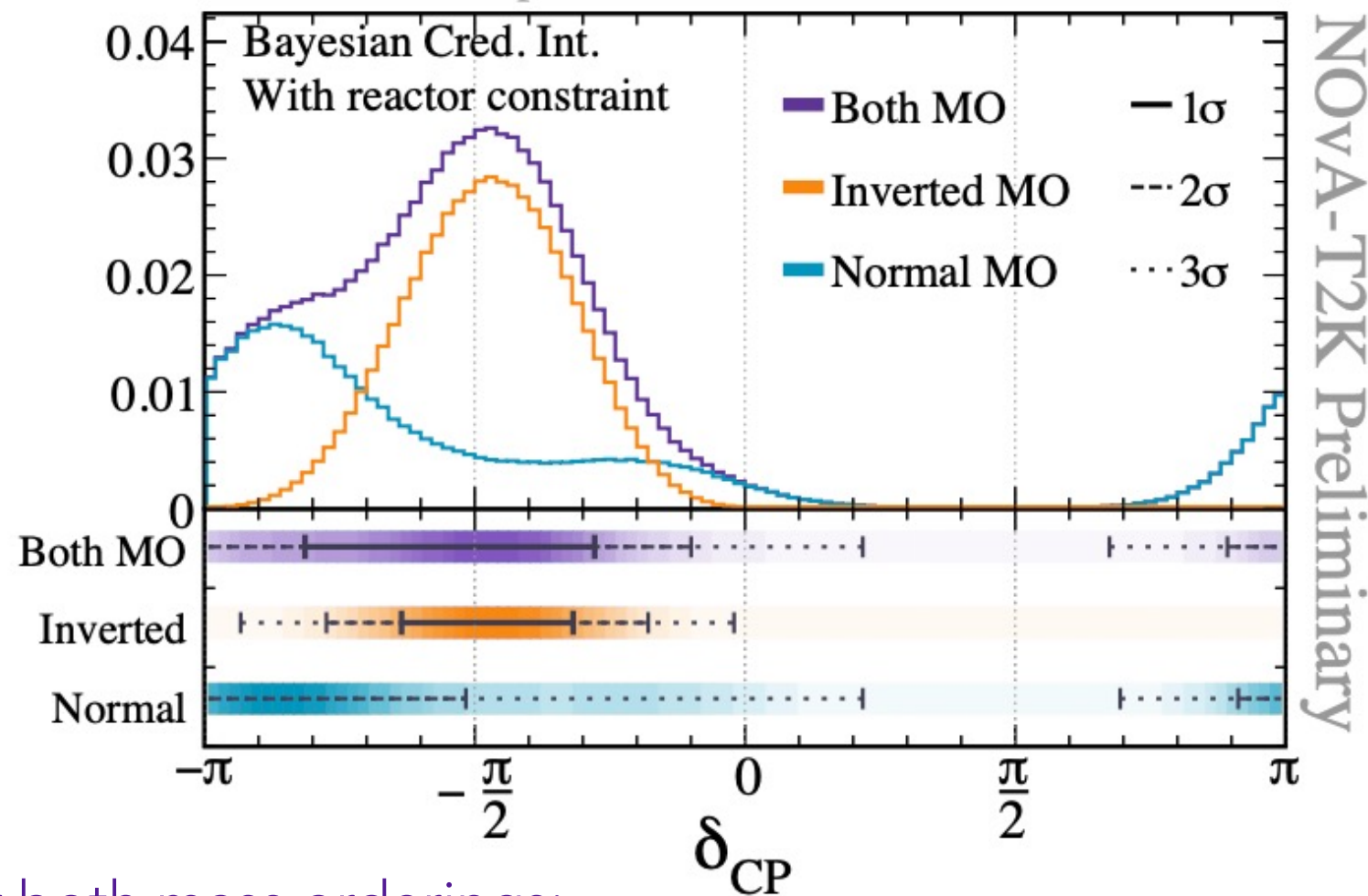


Mixing Angles: θ_{23}



	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.