First Dual-Baseline Search for Active to Sterile Neutrino Oscillations from NOvA

V Hewes, for the NOvA Experiment

Fermilab JETP seminar

January 20th 2022

Overview

Phenomenology of neutrino oscillations

The NOvA experiment

Analysis techniques

Event selections

Systematic uncertainties

Results

Neutrino oscillations

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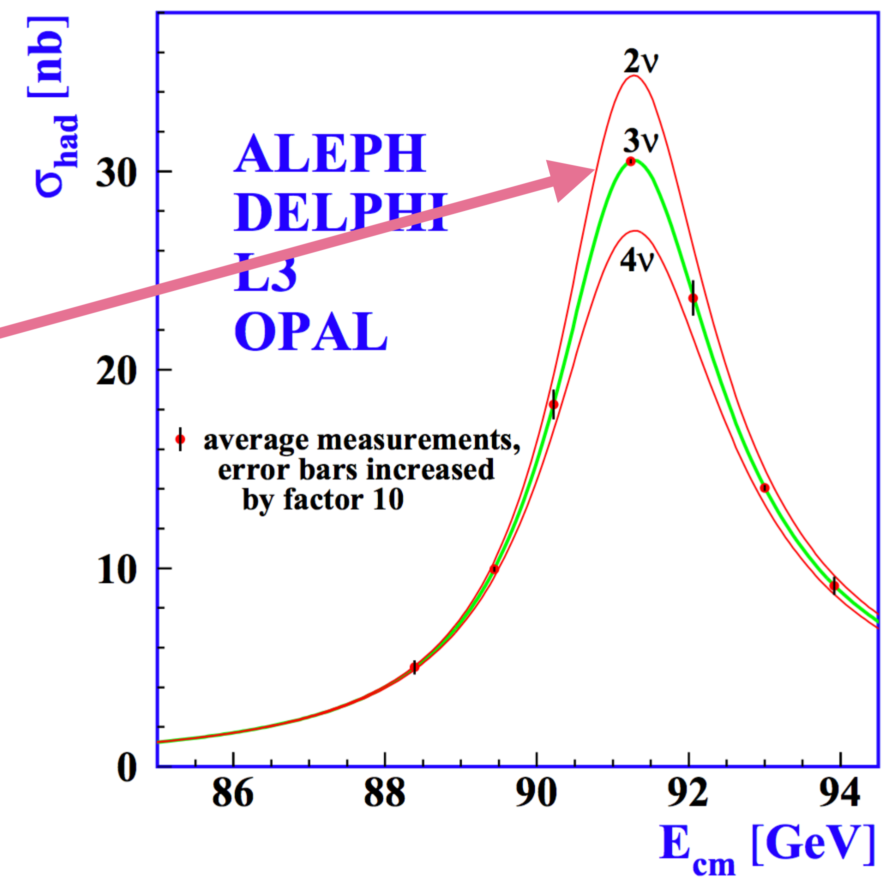

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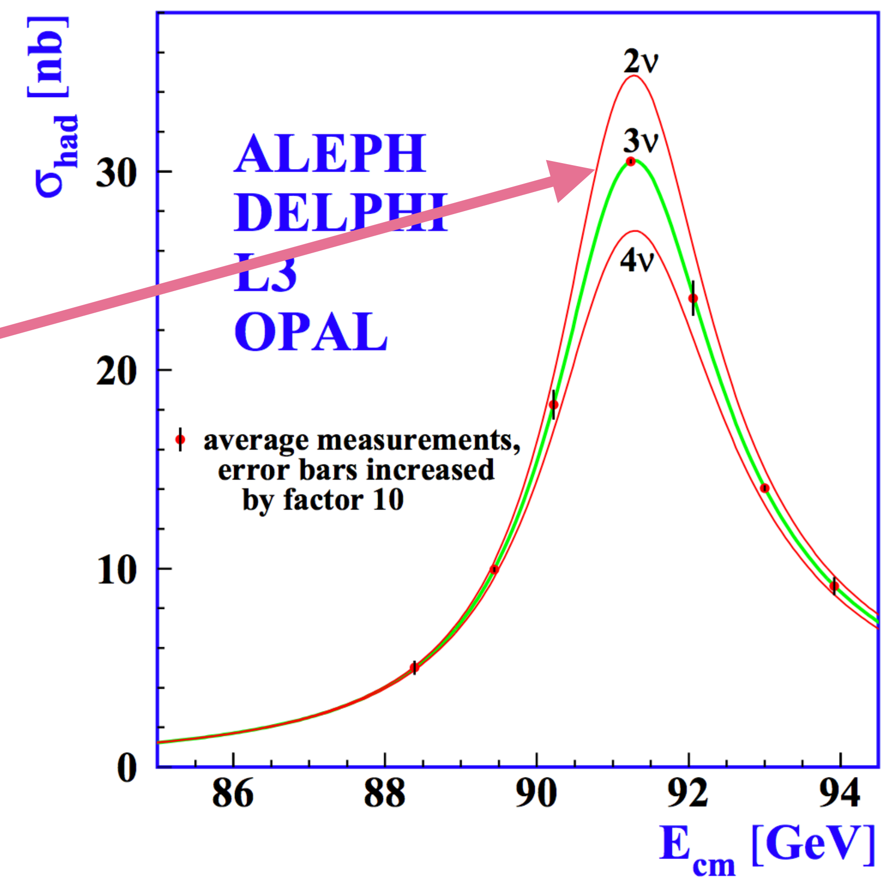

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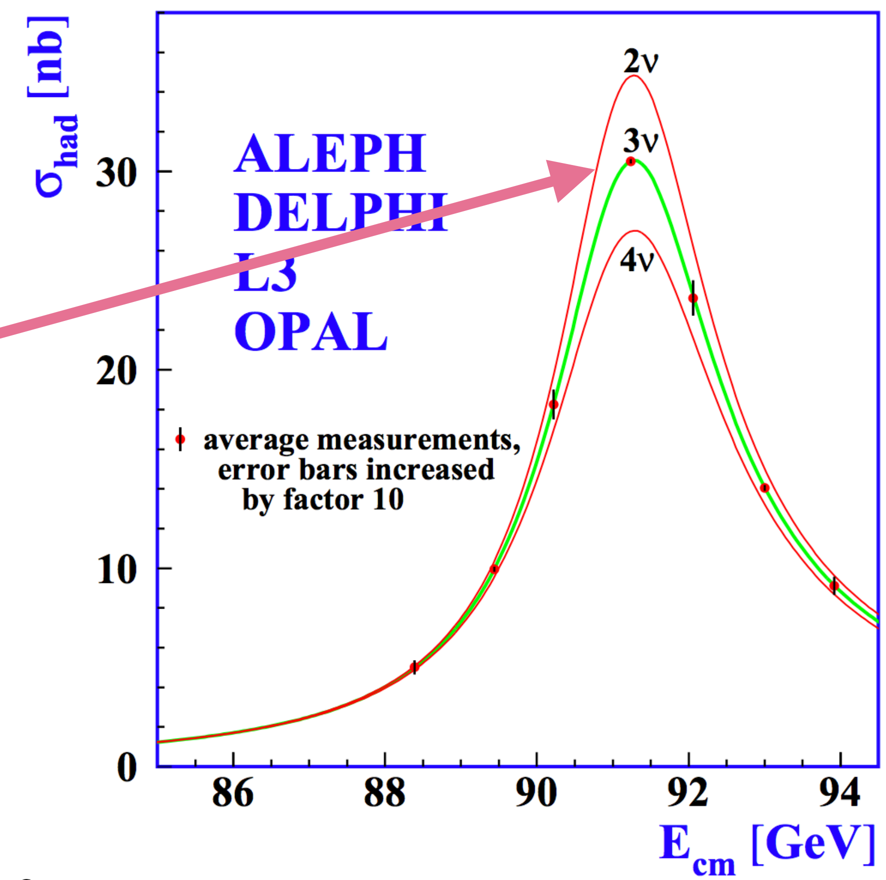
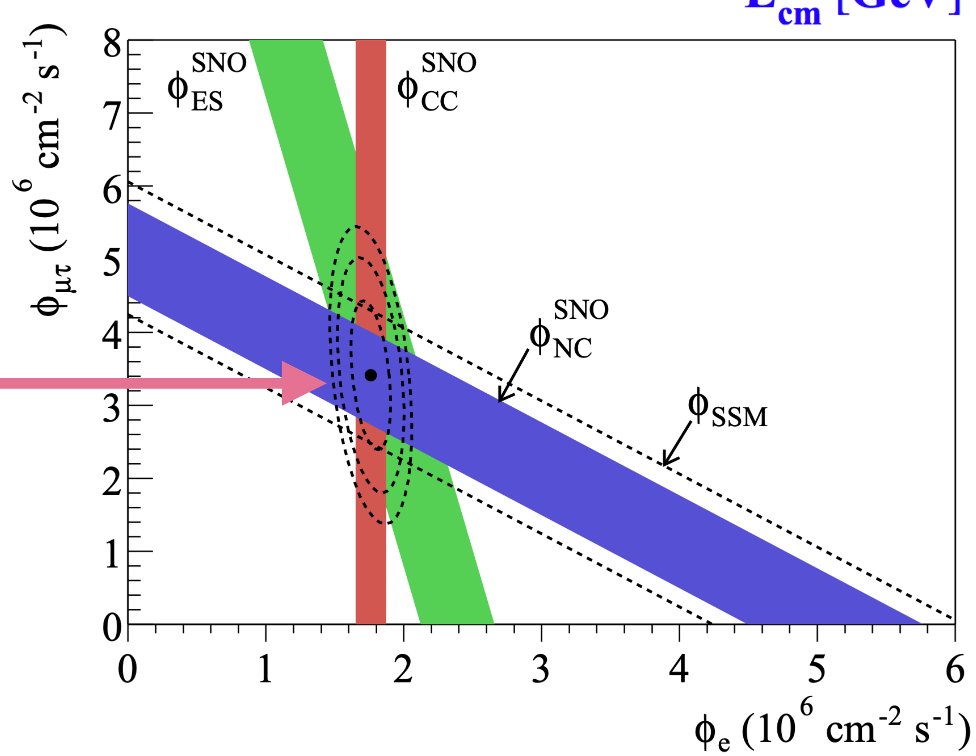
  - Sudbury Neutrino Observatory resolved this problem with **neutrino flavour mixing** (arXiv:0204008).





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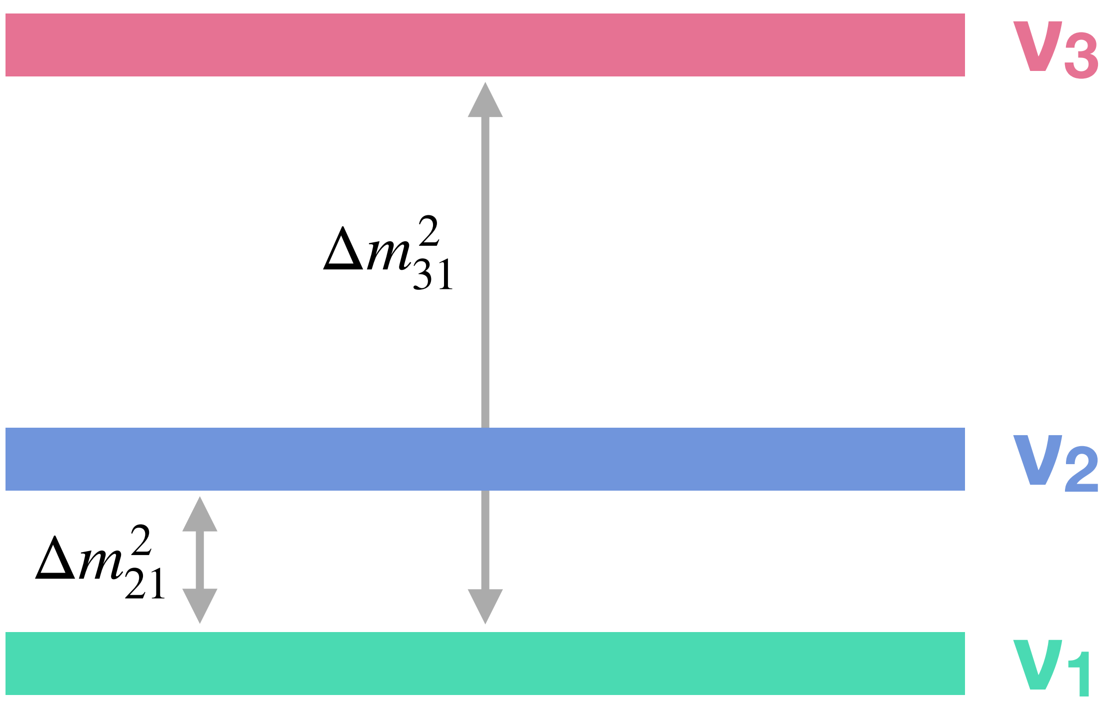

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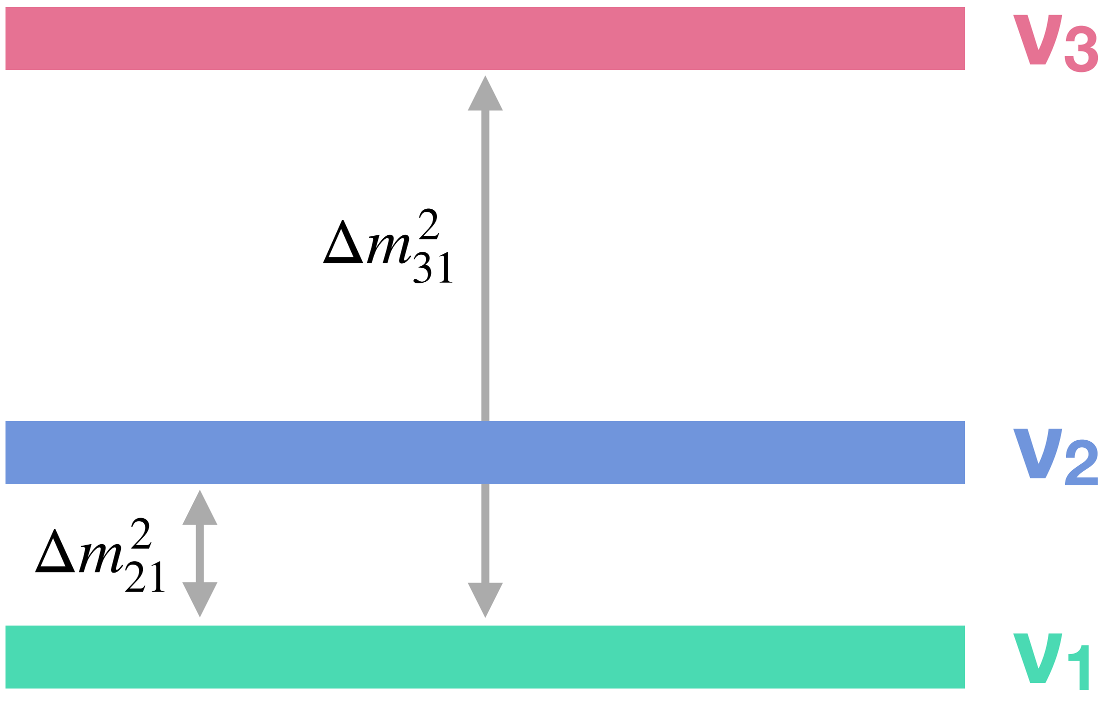

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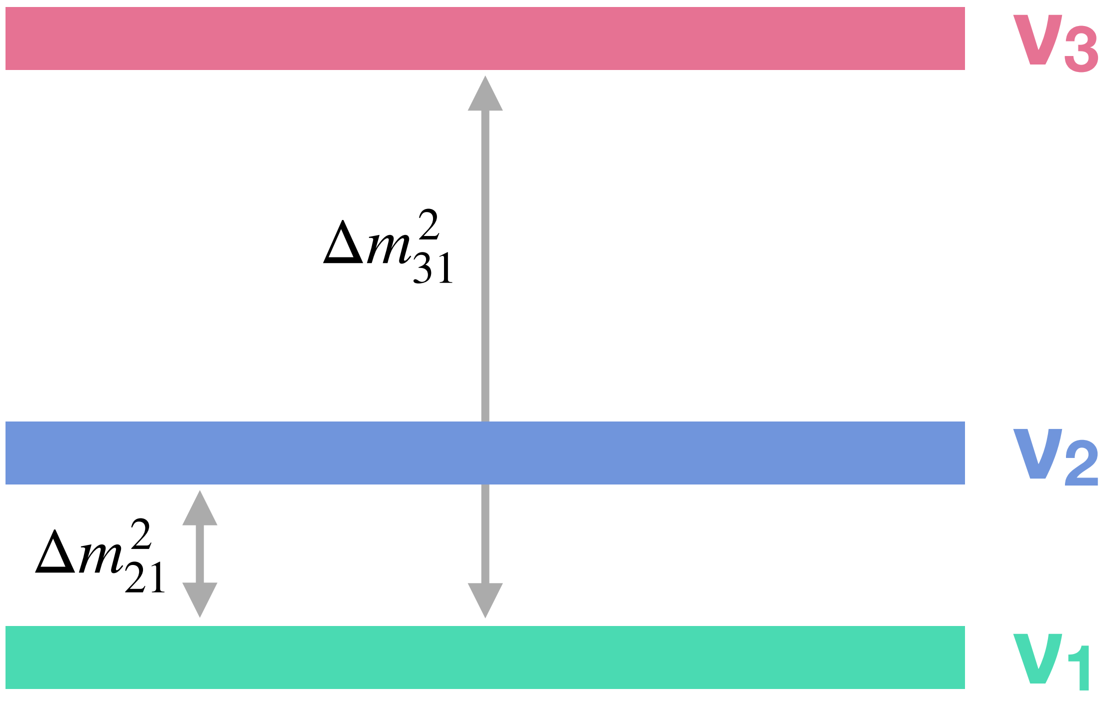

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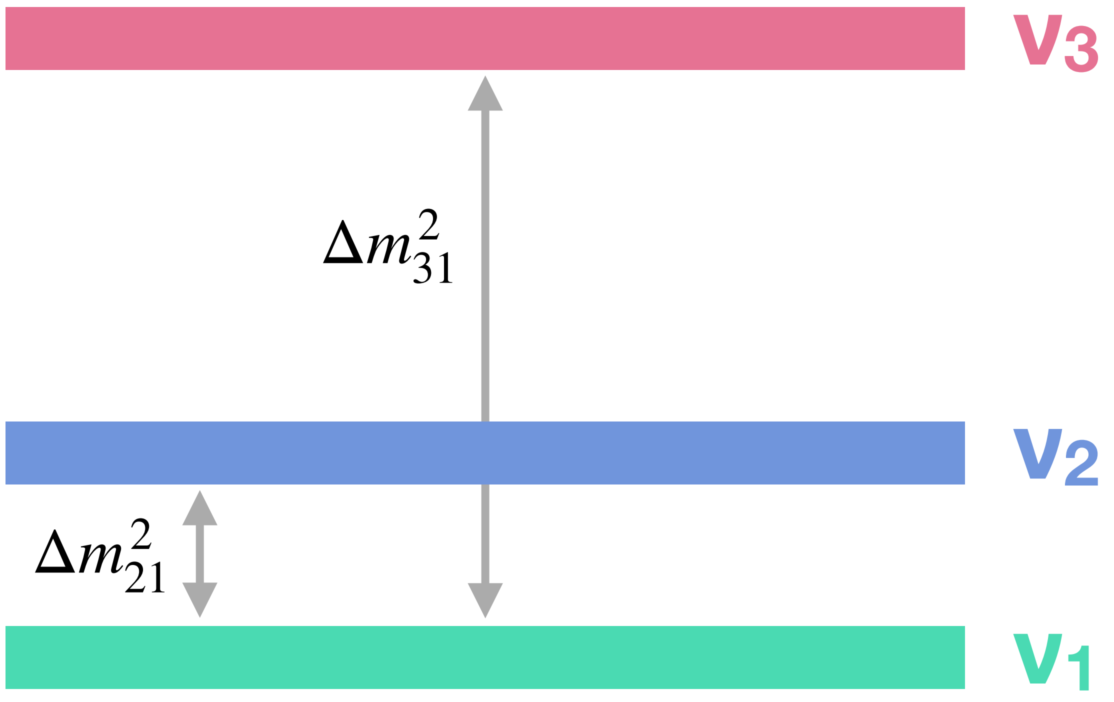

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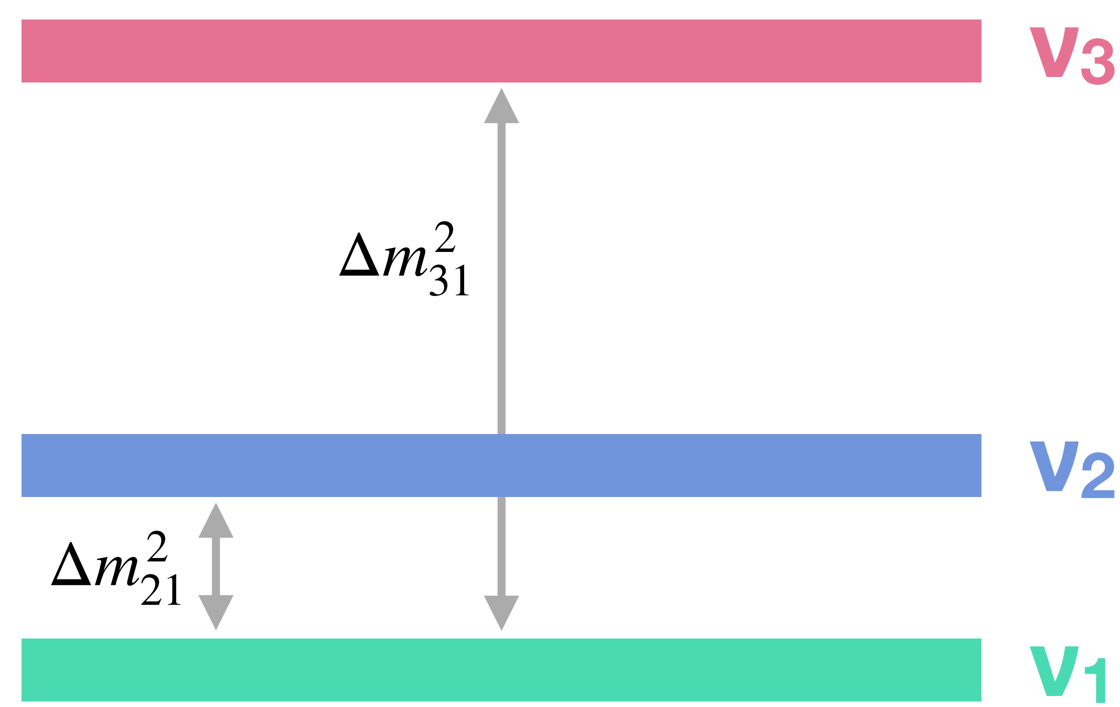

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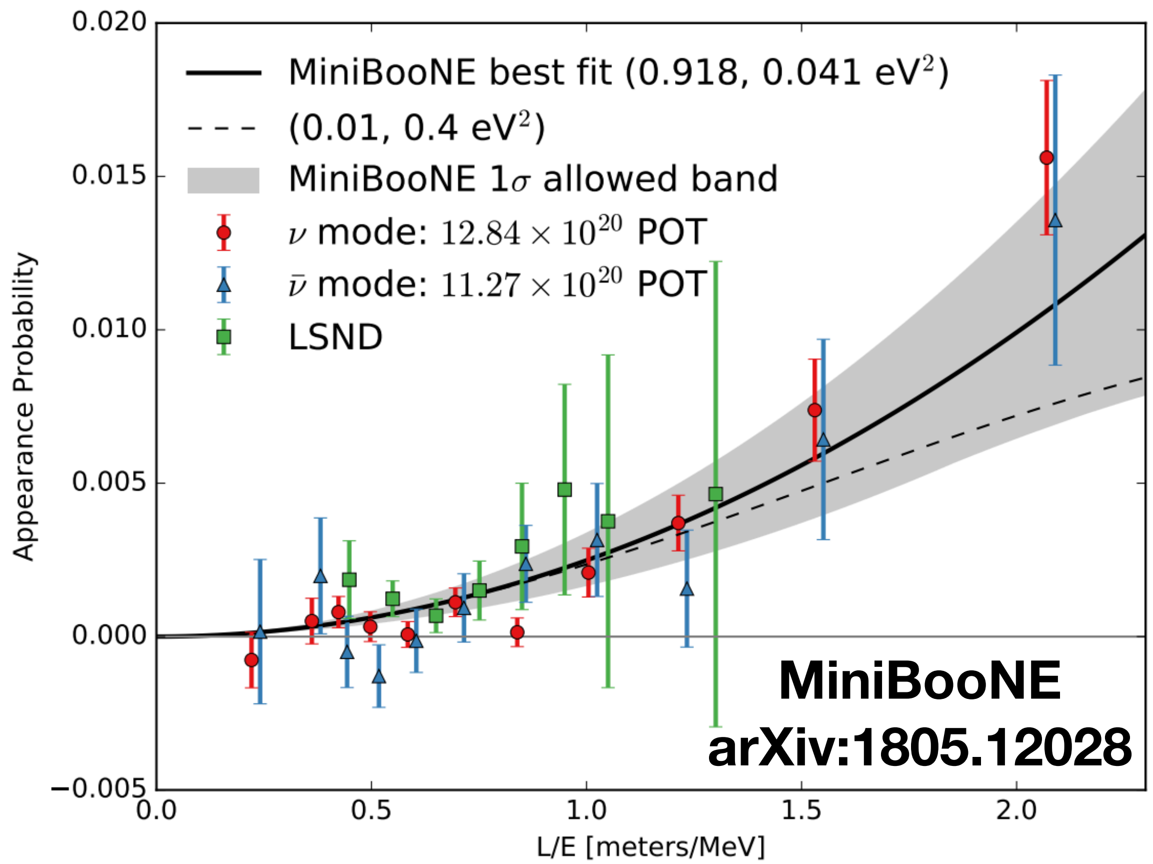
Oscillation probability depends on the **energy** and **path length** of the neutrino.

$$P_{\alpha\beta} = \left| \delta_{\alpha\beta} - \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right) \right|$$

Experimental low-energy excesses



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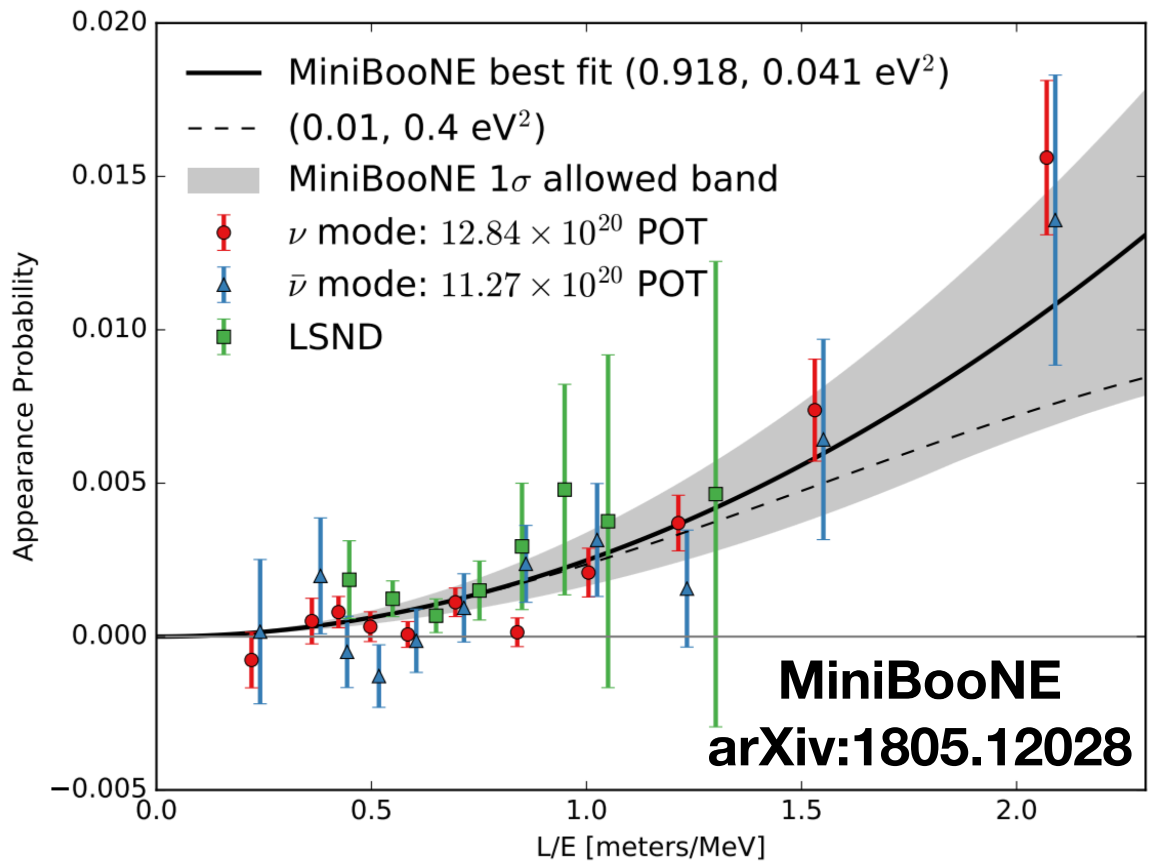
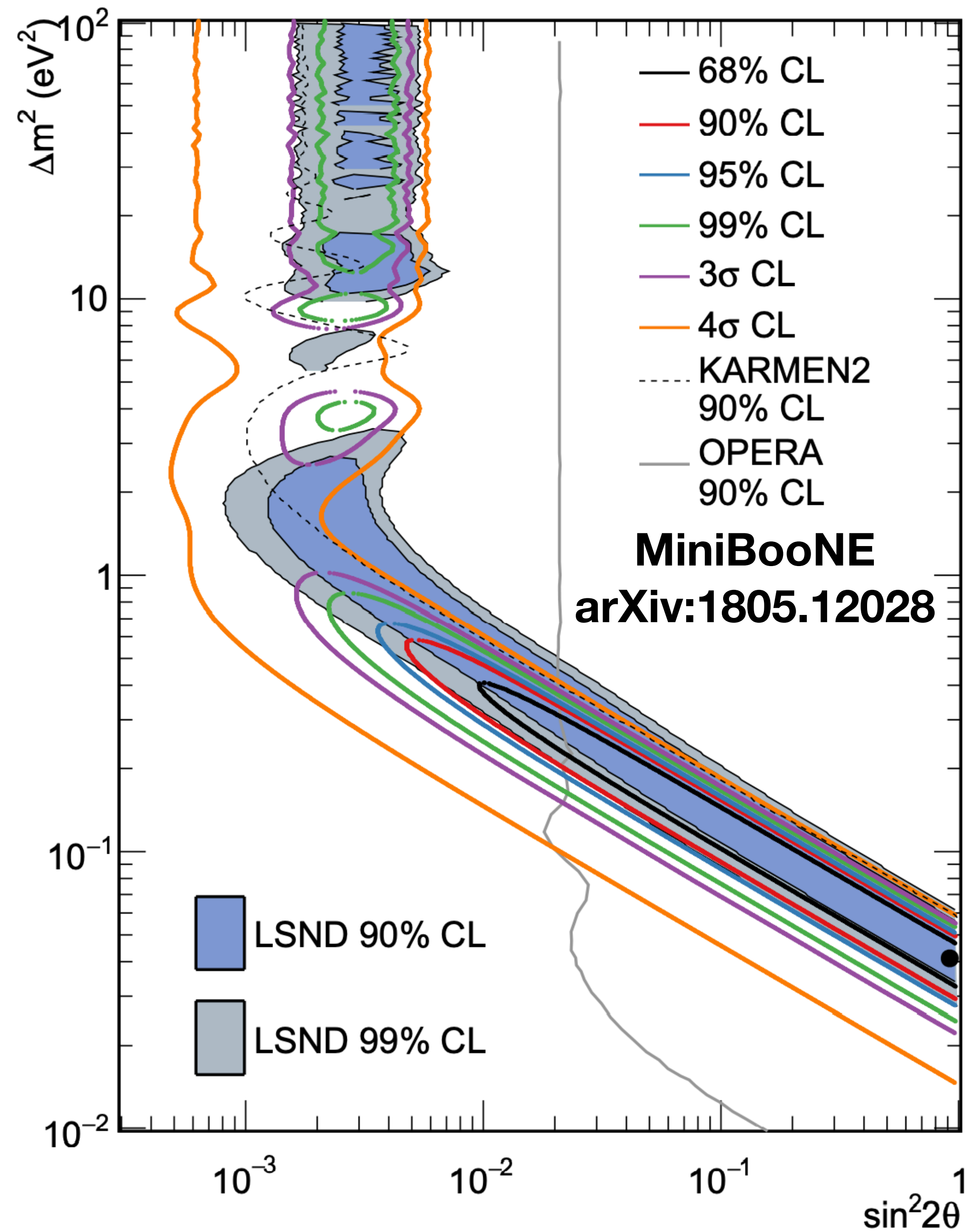


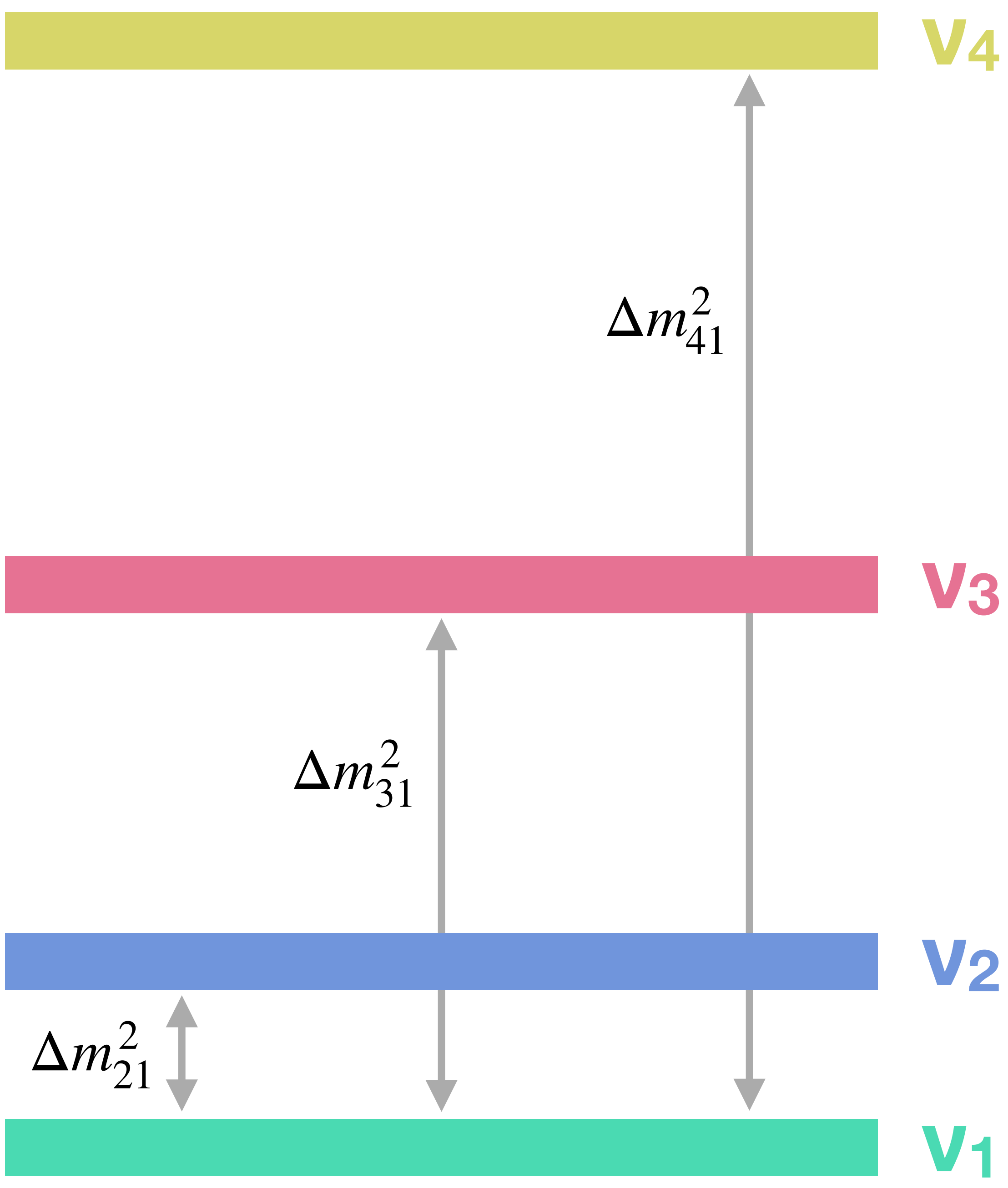


- The LSND and MiniBooNE experiments observed an **excess in neutrino and antineutrino events** at the m/MeV range of L/E.

- Their proposed explanation was a **fourth sterile neutrino state**, which modifies the mixing of the neutrino mass states to allow anomalous ν_e appearance.

3+1 Flavour Neutrino Oscillations

- Expand the 3-Flavour model by introducing an additional mass state $\boldsymbol{\nu_4}$ and flavour state $\boldsymbol{\nu_s}$.



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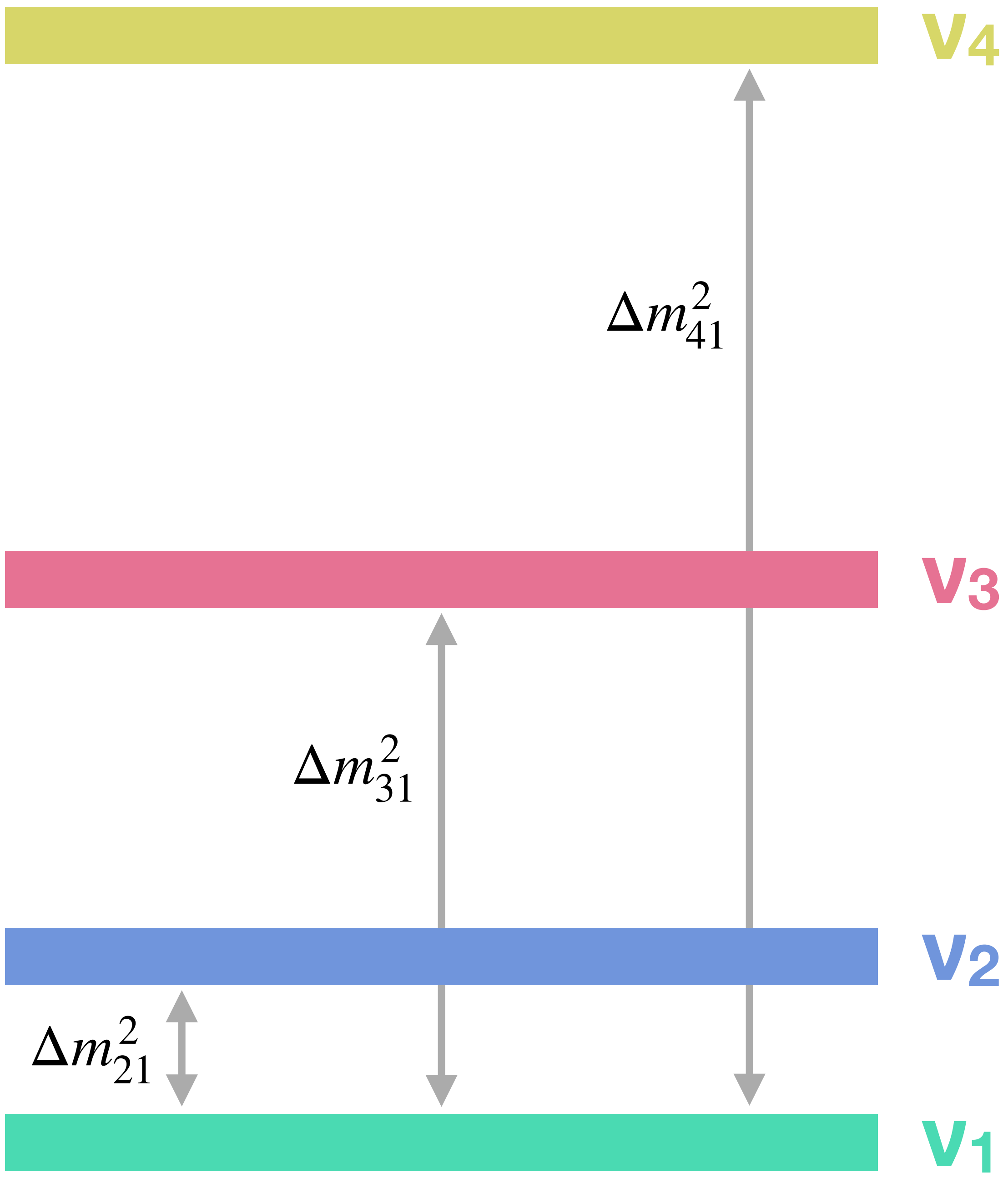

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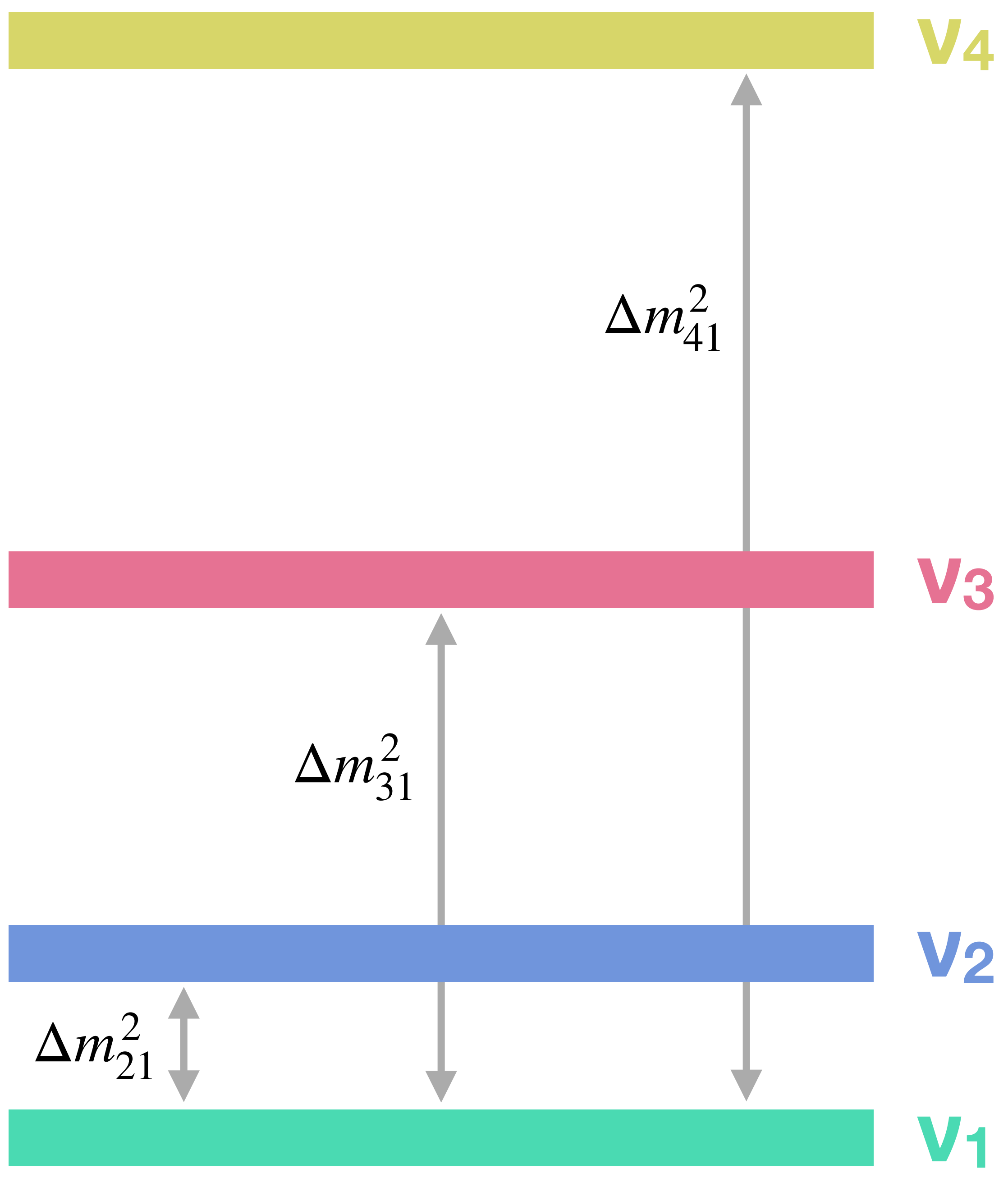

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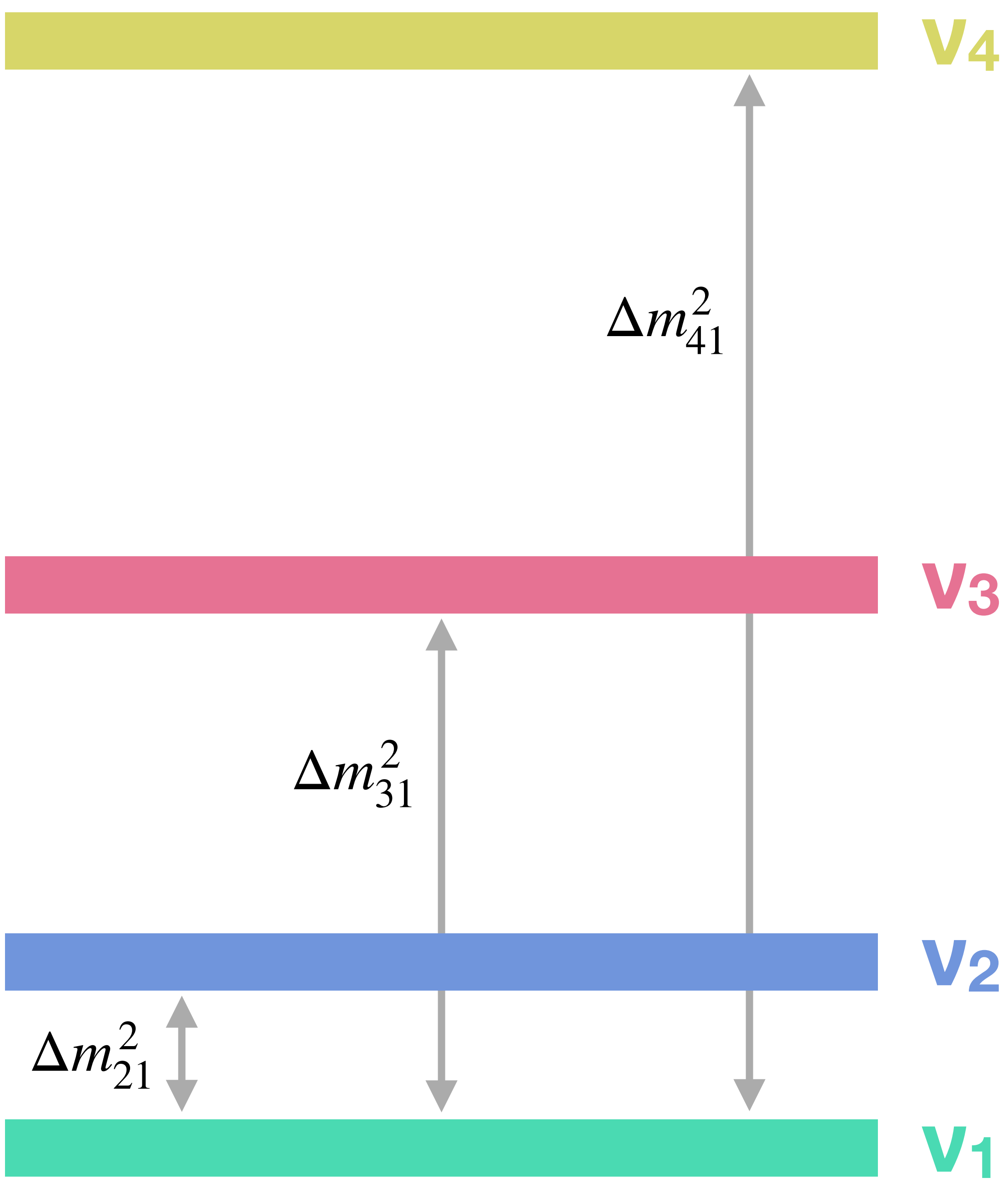

Experimental landscape

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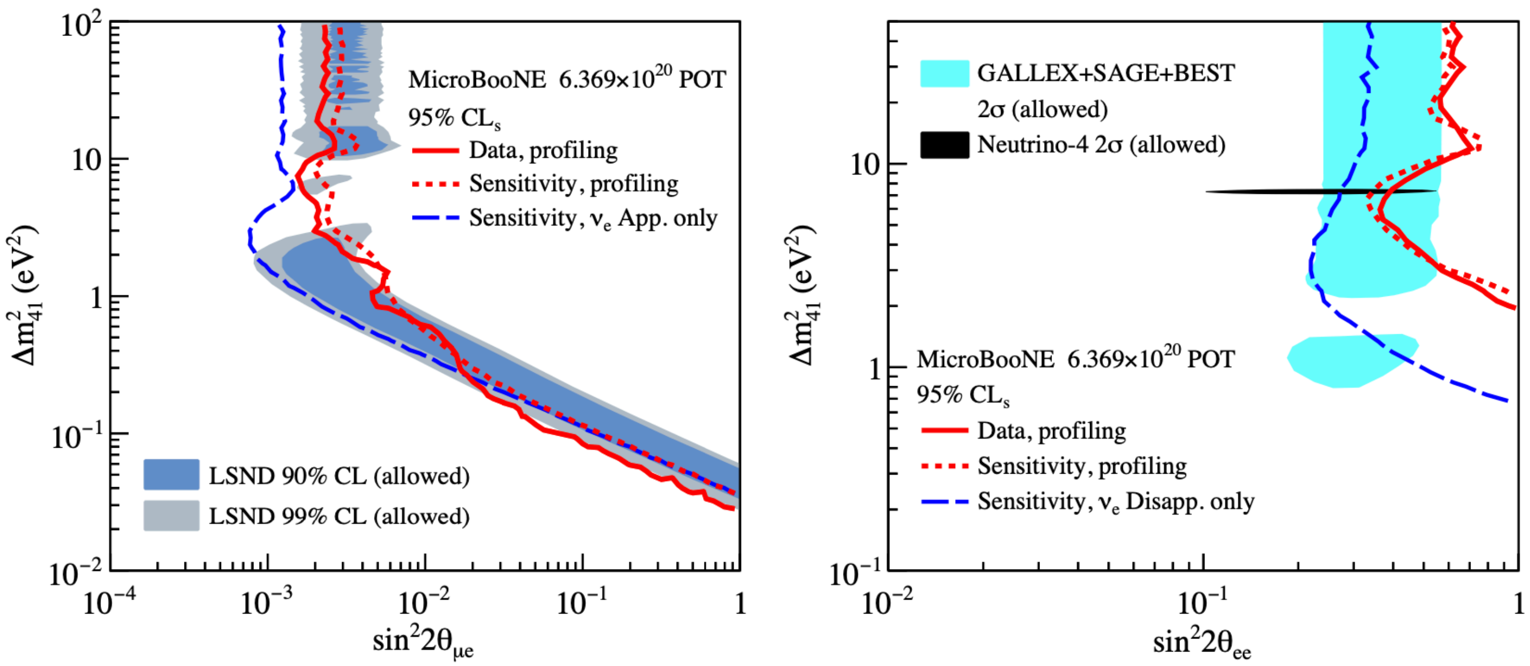
arXiv:2106.04673



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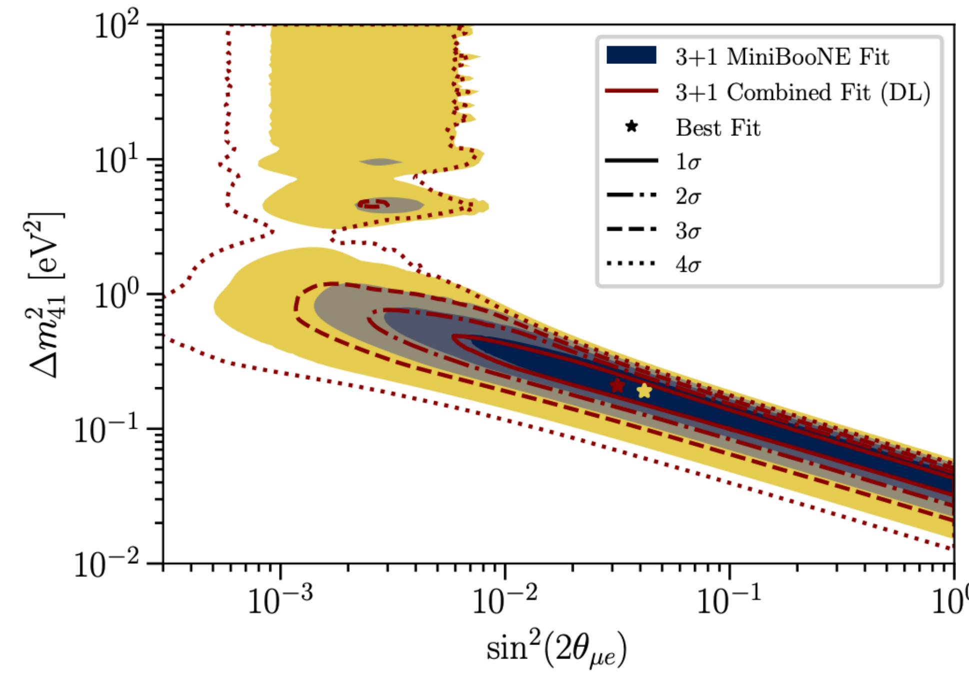
- MicroBooNE+MiniBooNE joint fit still prefers a 3+1 best fit, and excludes 3F at >3σ.



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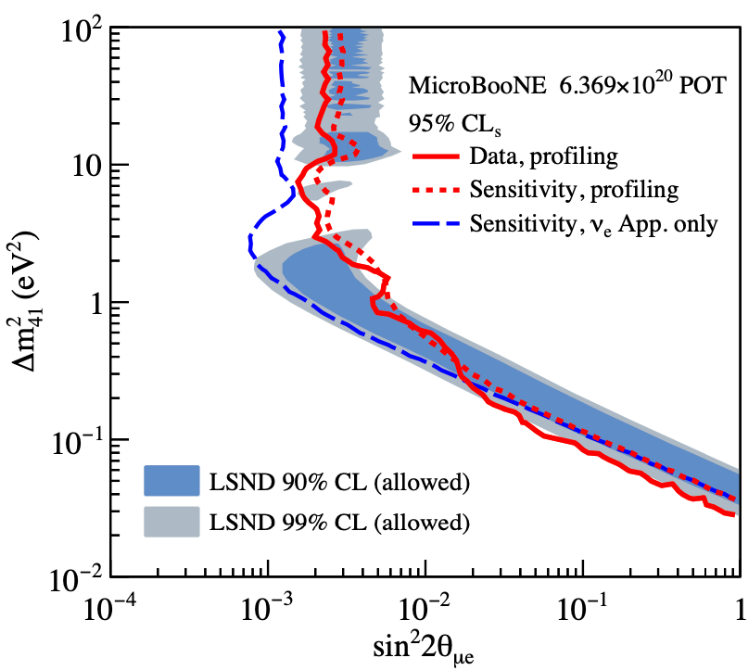
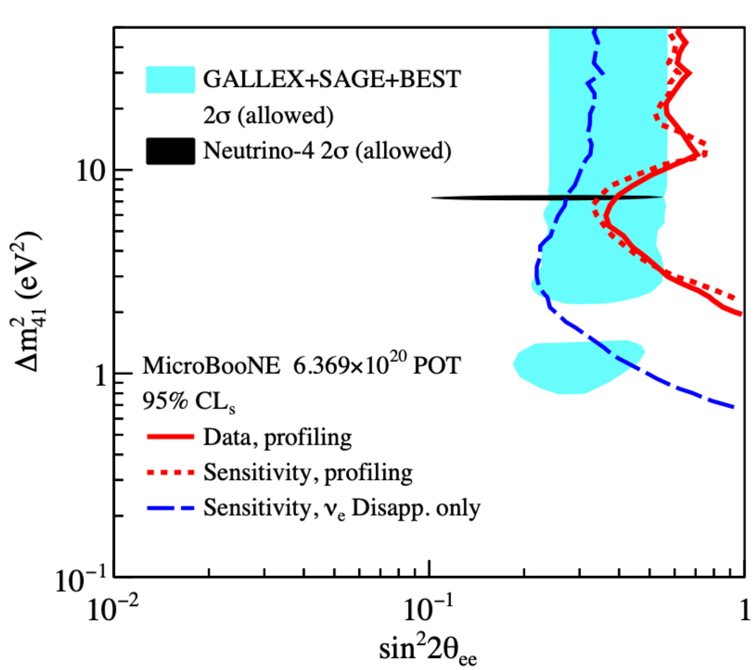
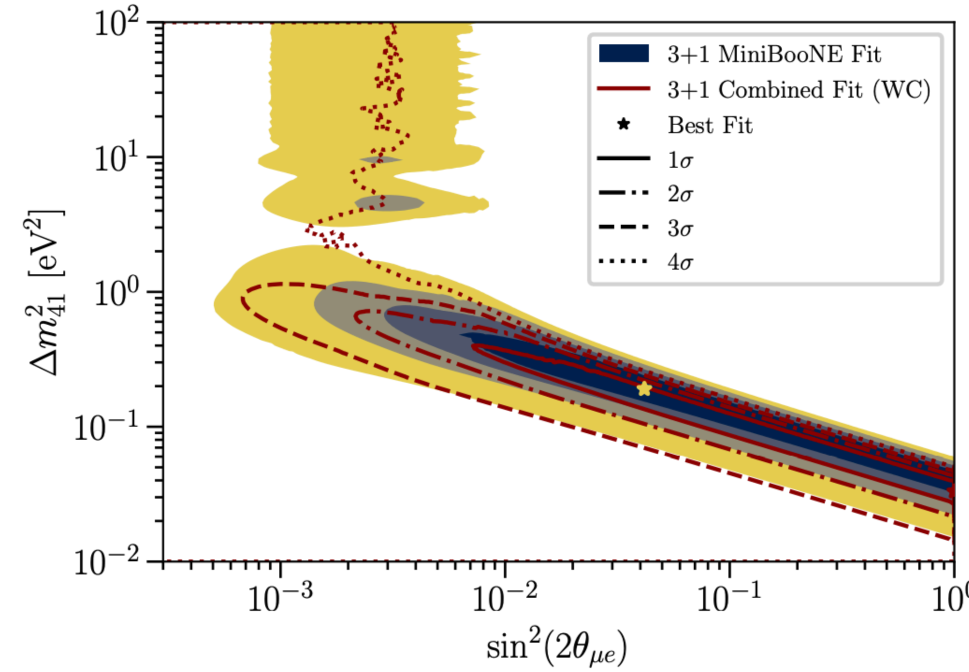




arXiv:2201.01724



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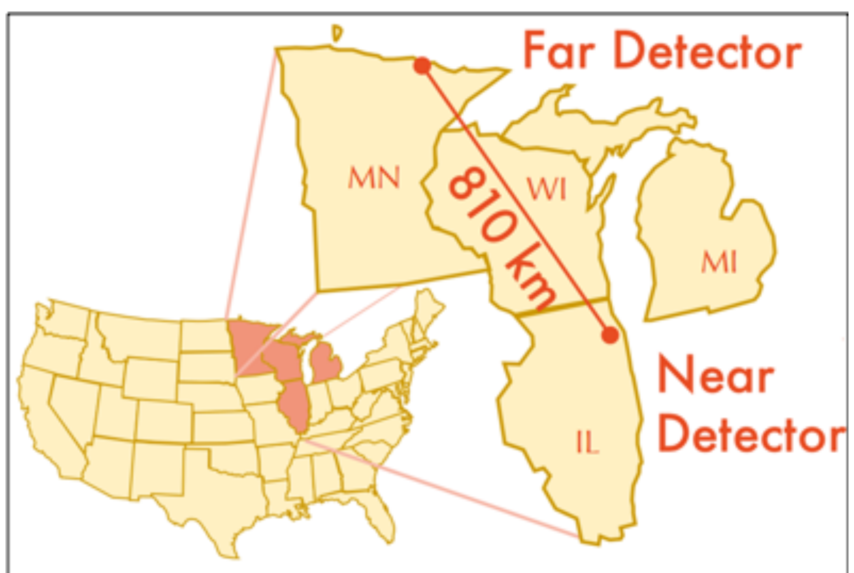
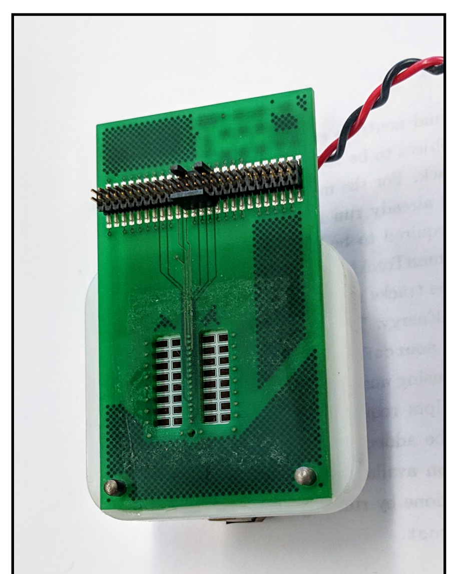
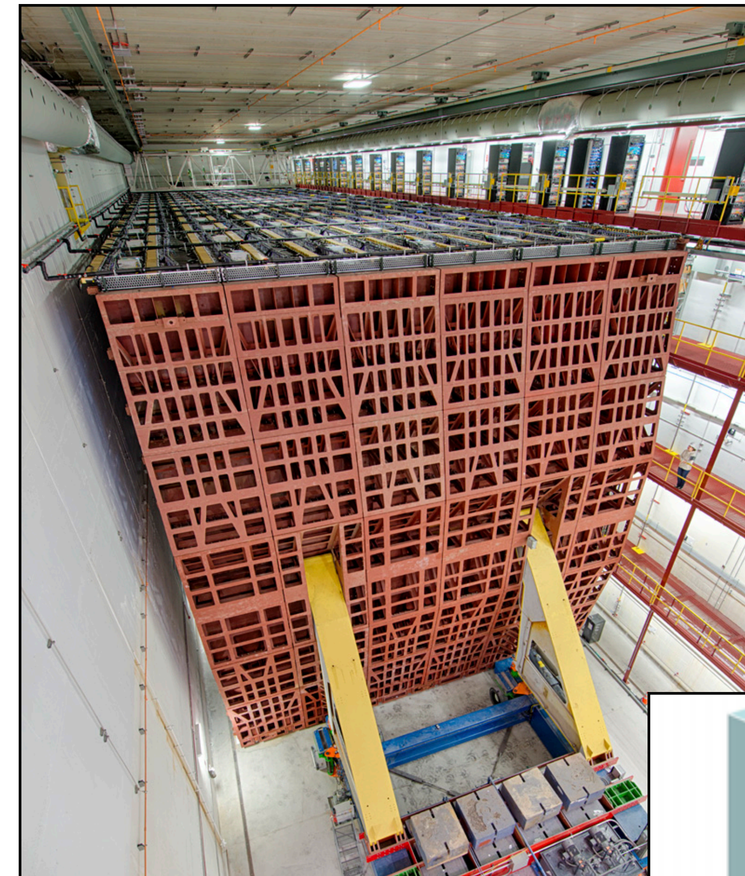
The NOvA Experiment

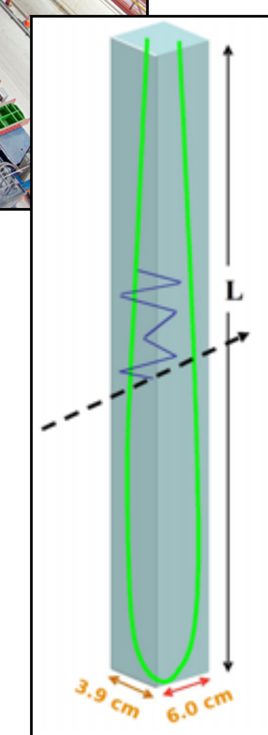
- **NOvA** is a long-baseline accelerator experiment based at Fermilab.
- Measures neutrinos from Fermilab's **NuMI beam**.
- Functionally equivalent near and far detectors.
  - Liquid scintillator **sampling tracking calorimeter**.
  - Both detectors are **14 mrad off-axis**.
  - **ND:** 1km baseline, FNAL, 300 tons.
  - **FD:** 810km baseline, on-surface at Ash River, 14 kt.



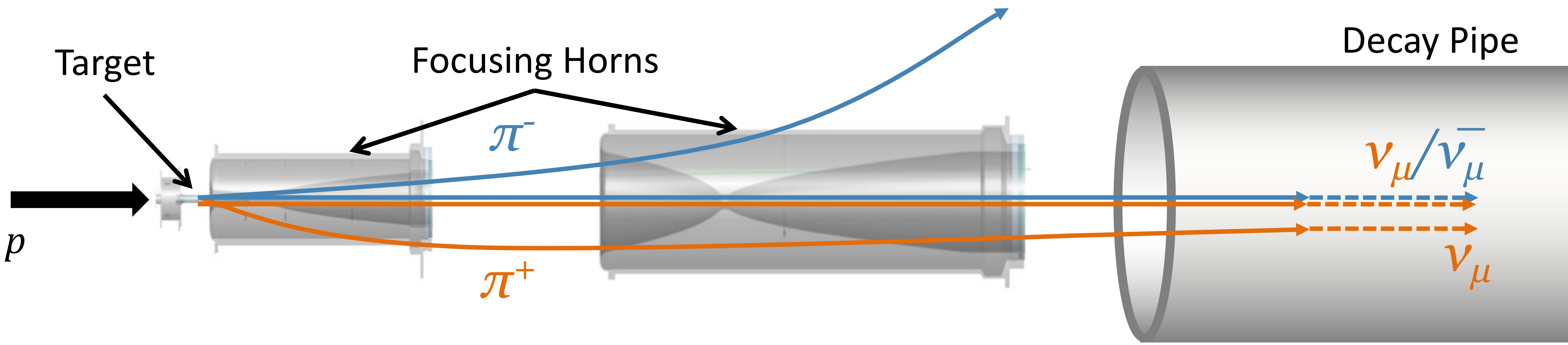




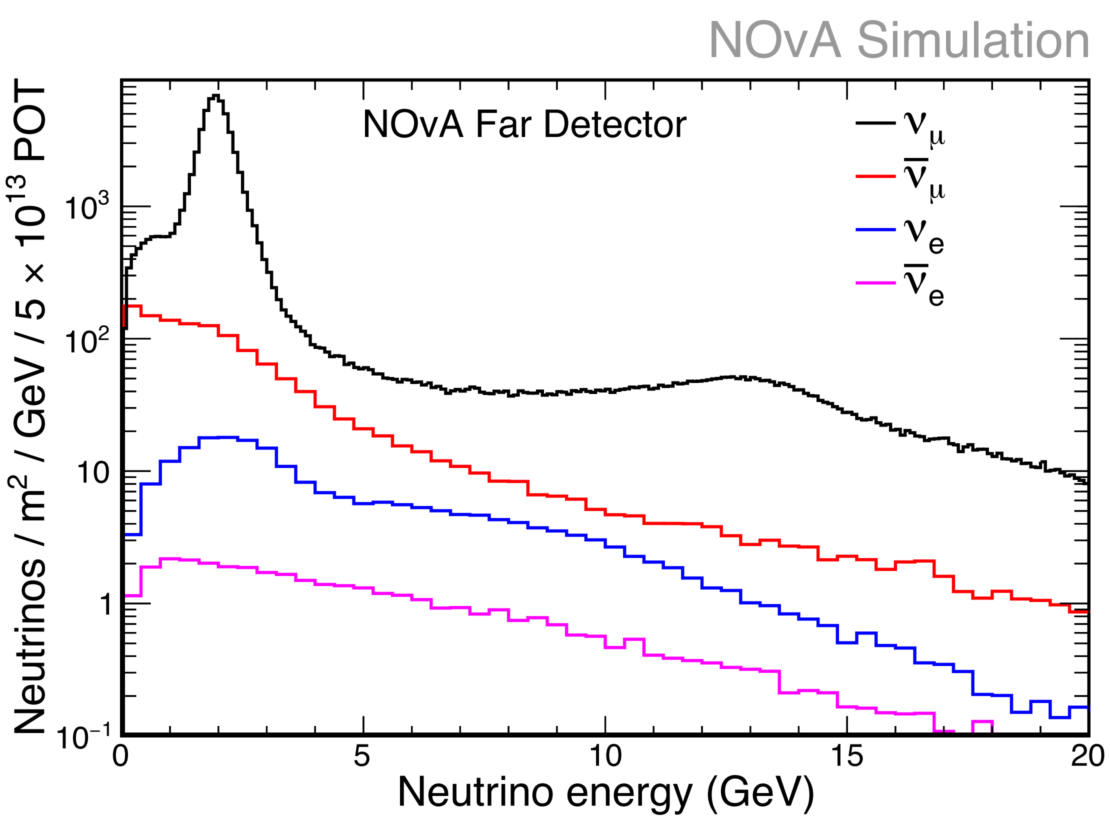
- Charged particles produce light when propagating through scintillator.
- Picked up by wavelength-shifting fibers (right) and amplified by avalanche photodiodes (left).



NuMI Beam



- Protons accelerated at Fermilab's Main Injector.
- These protons are incident on a target, and interact to produce **pions** and **kaons**.
- π & κ focused using magnetic horns.
- Focused π & κ decay in flight to neutrinos.



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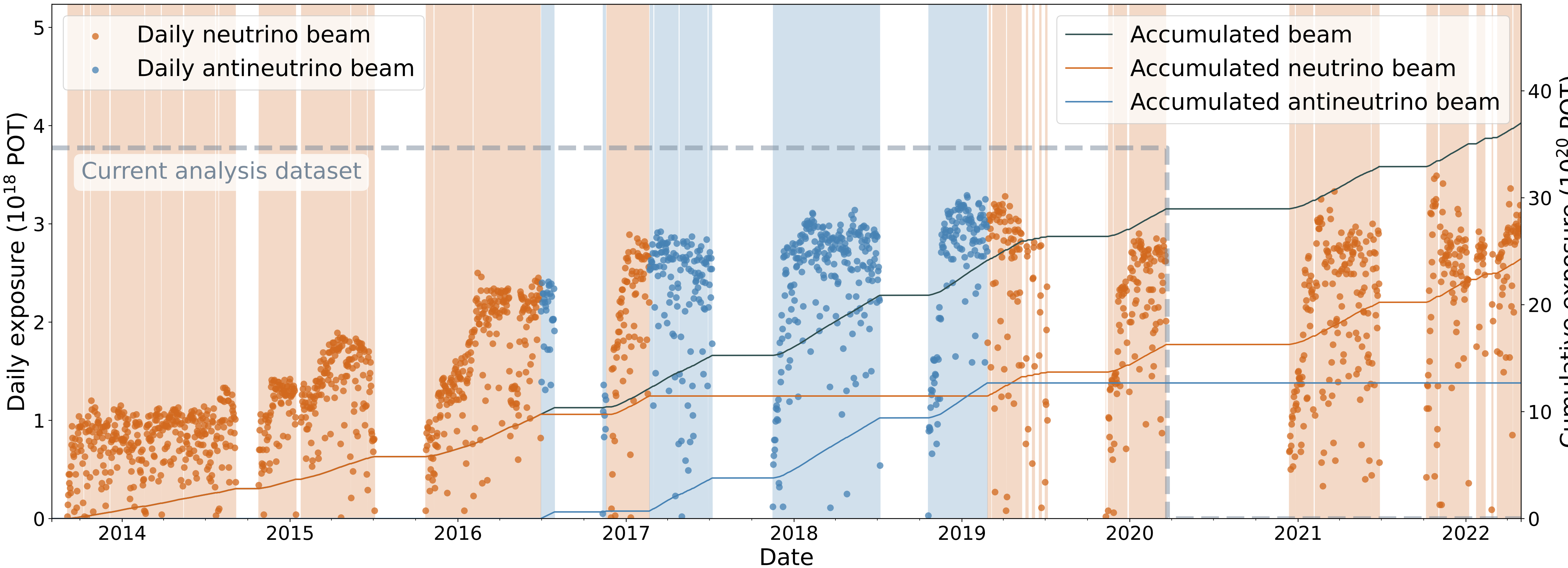
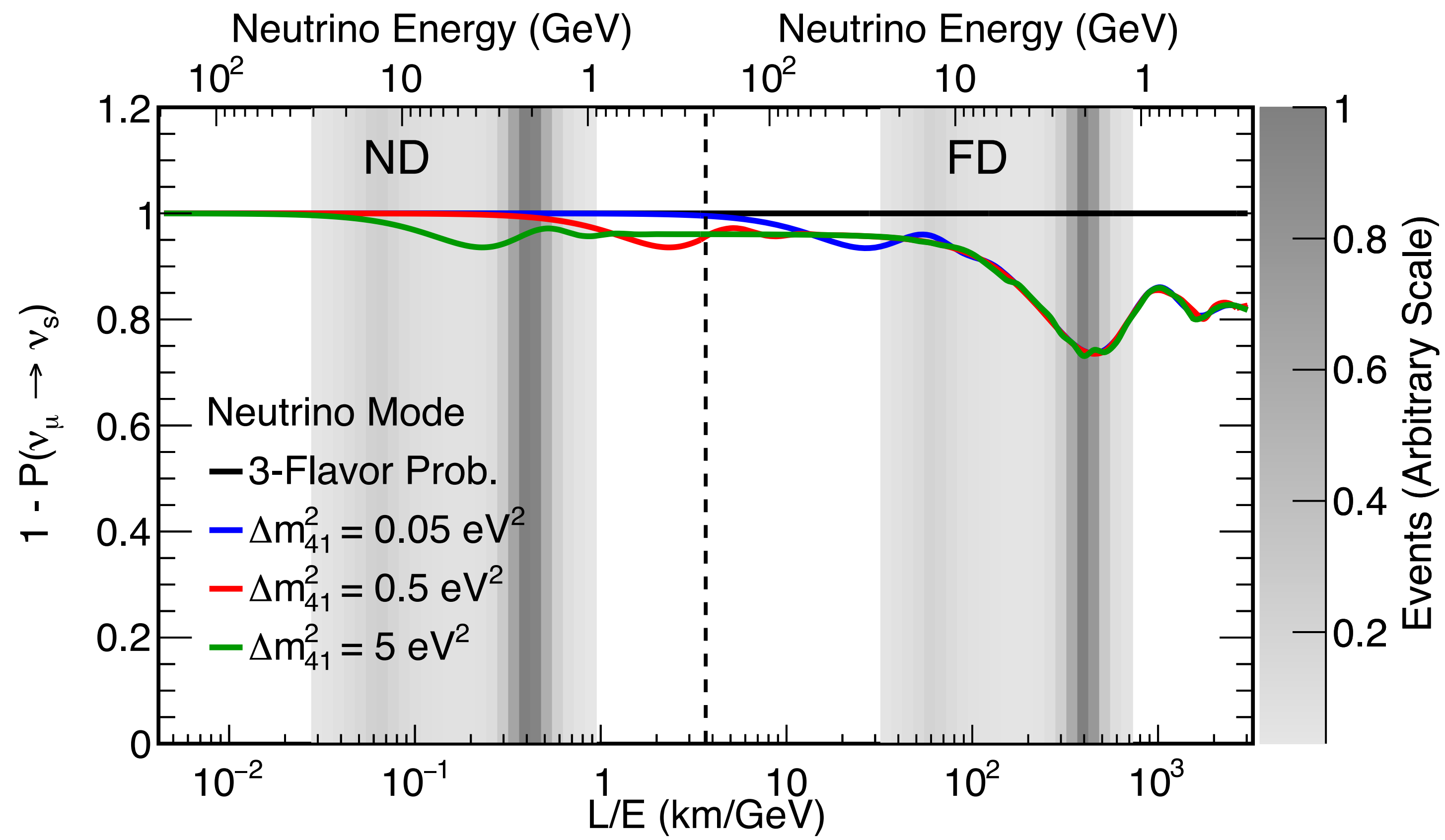


- NOvA uses the **Neutrinos at the Main Injector (NuMI)** beamline.
- This analysis utilises the **neutrino dataset** only.
  - **11.0** × **10^{20}** Protons on Target in the near detector.
  - **13.6** × **10^{20}** Protons on Target equivalent in the far detector.

3+1 oscillations at NOvA: Neutral Currents

- Probe 3+1 sterile oscillations in NOvA through **neutral current disappearance**.



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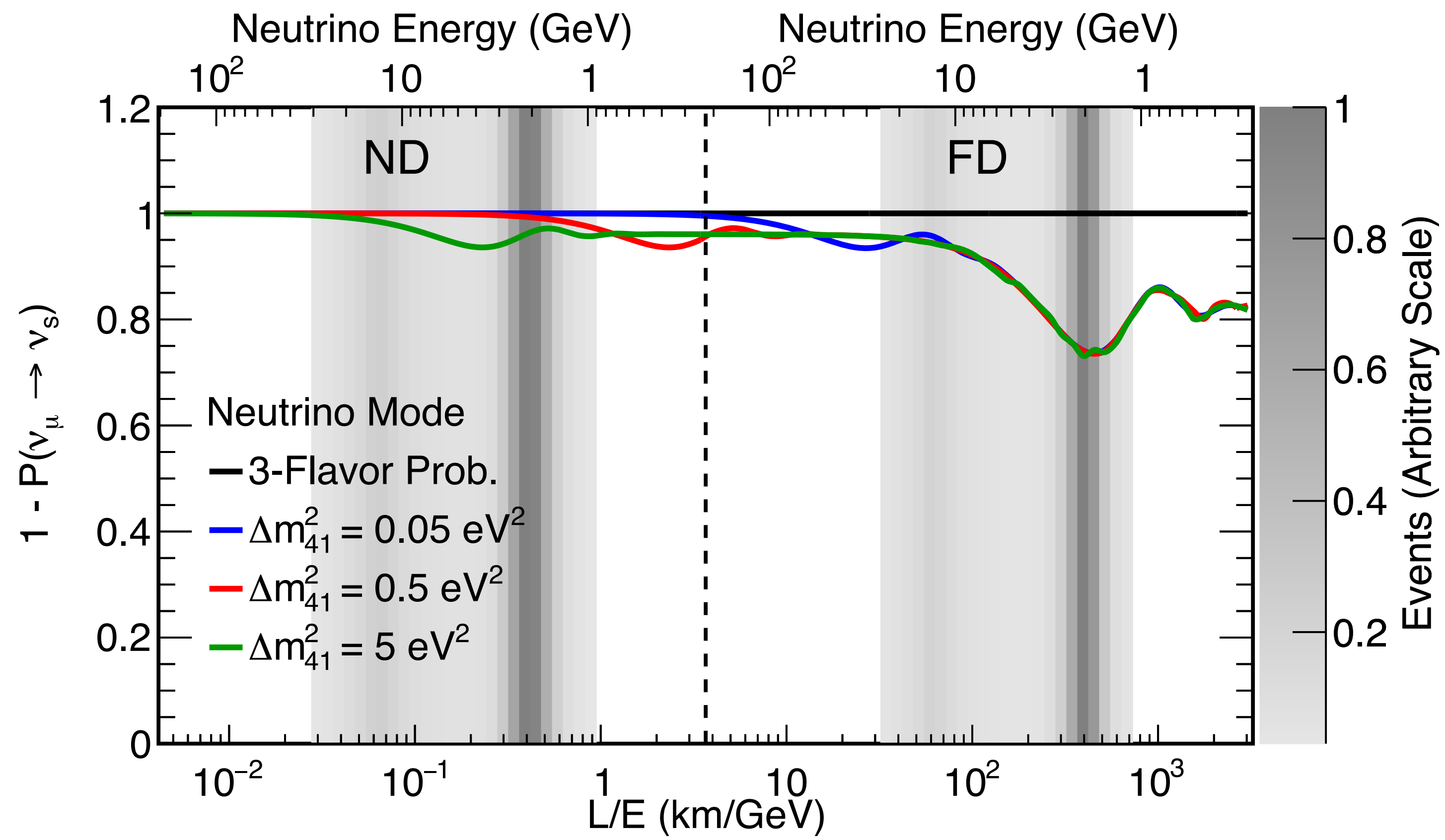

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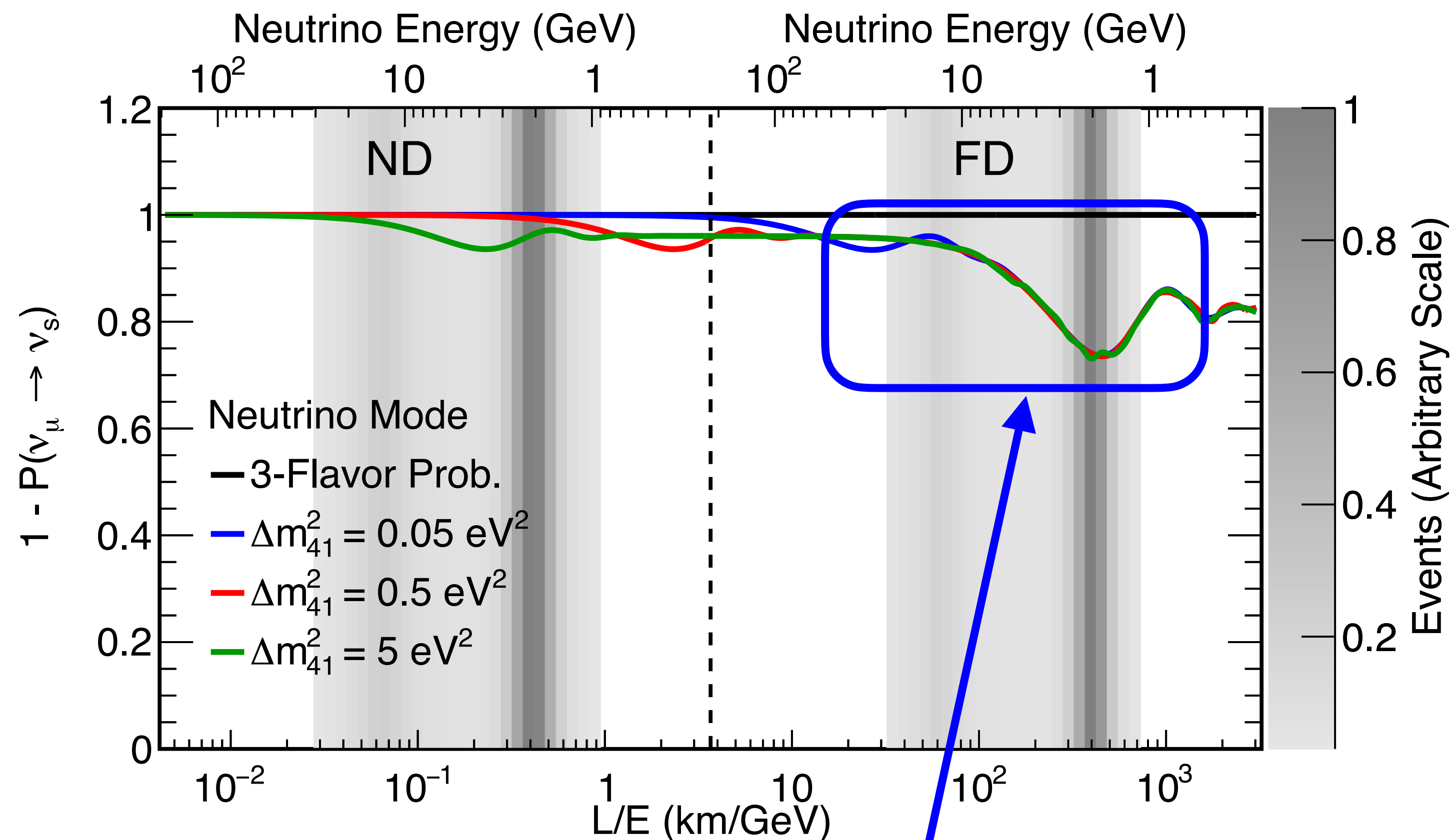

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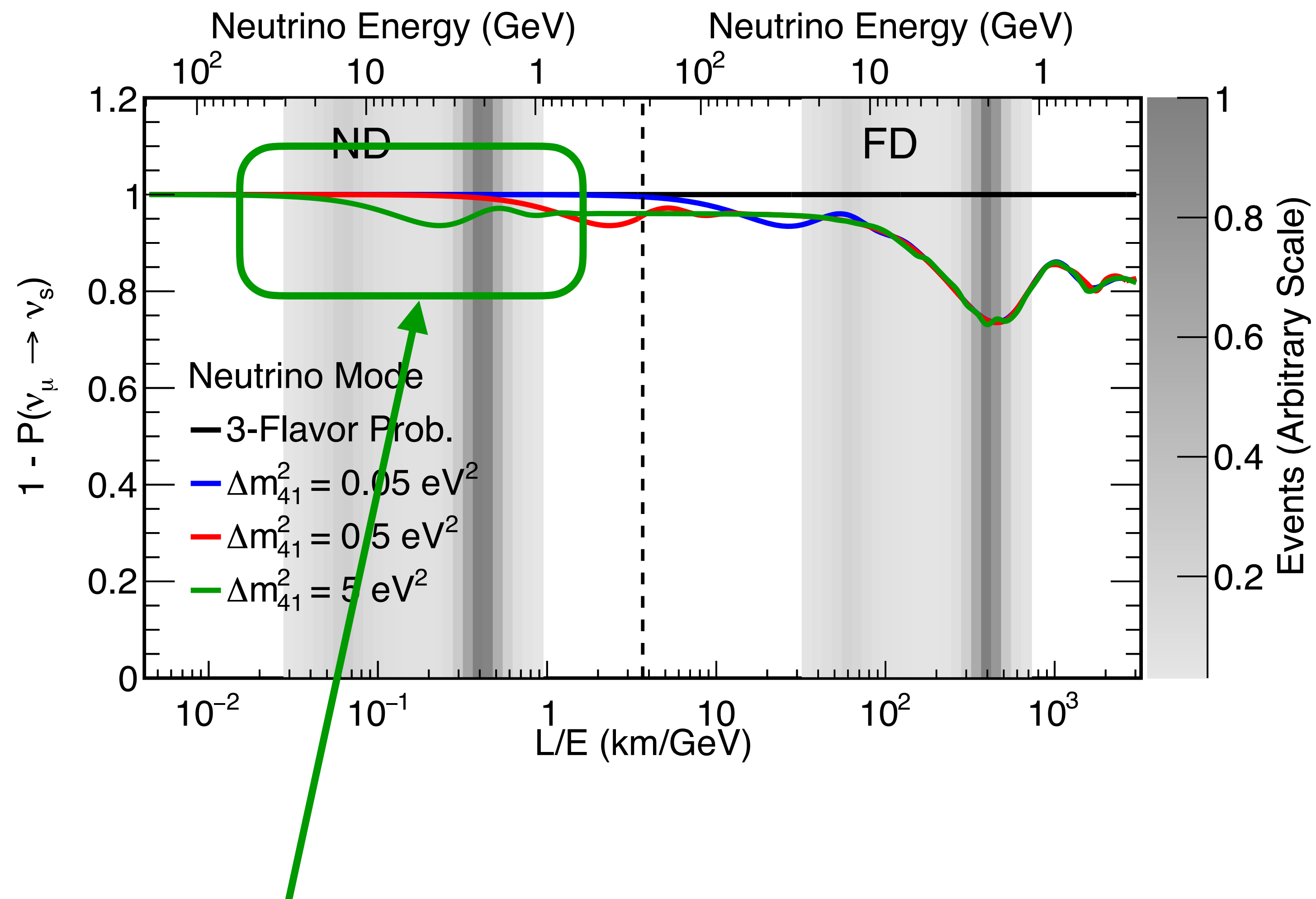

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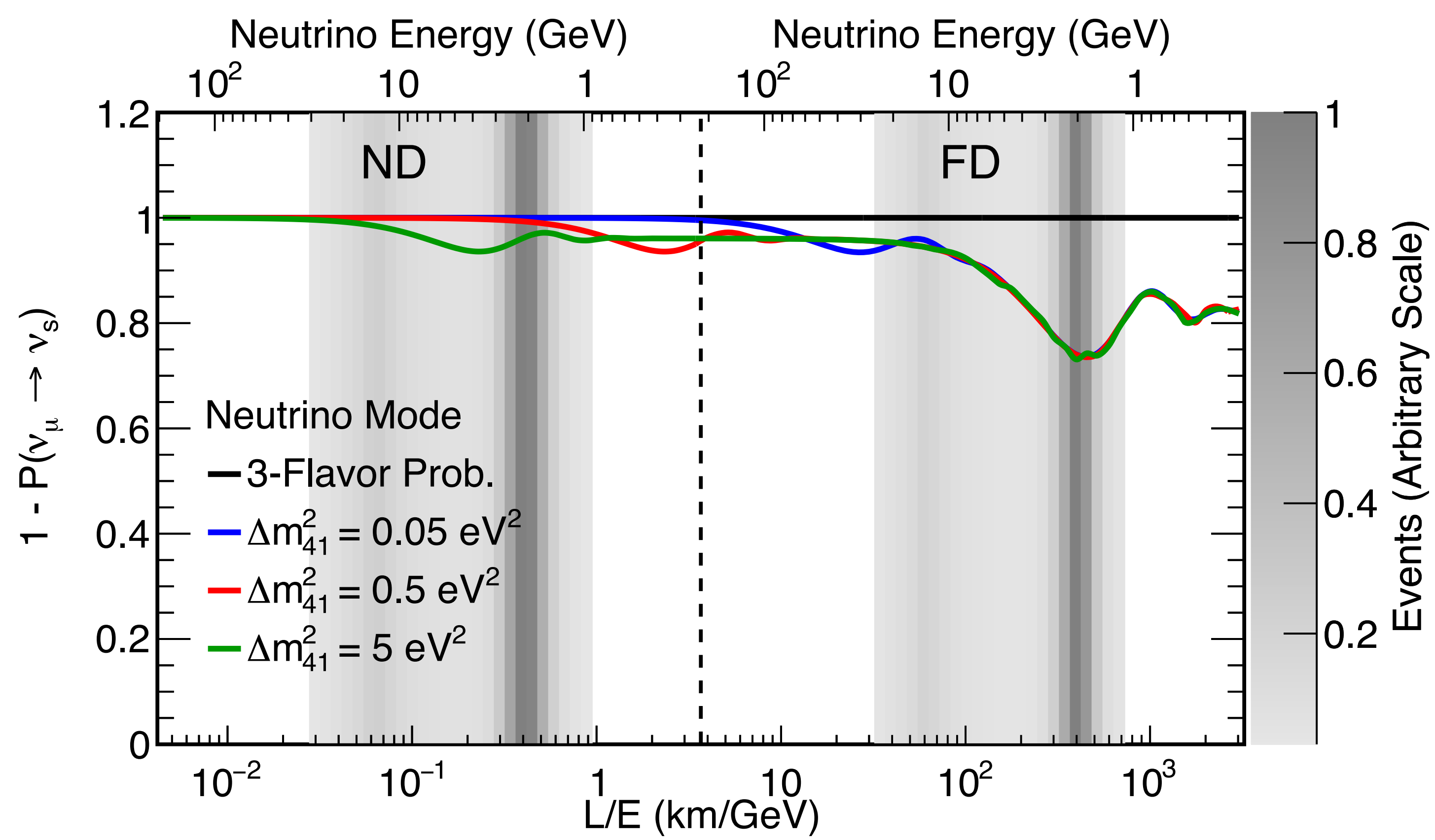

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$$\Delta_{ij} \equiv \frac{\Delta m^2_{ij}L}{4E}$$

Terms in yellow only appear in far detector, due to interplay with 3f oscillations.

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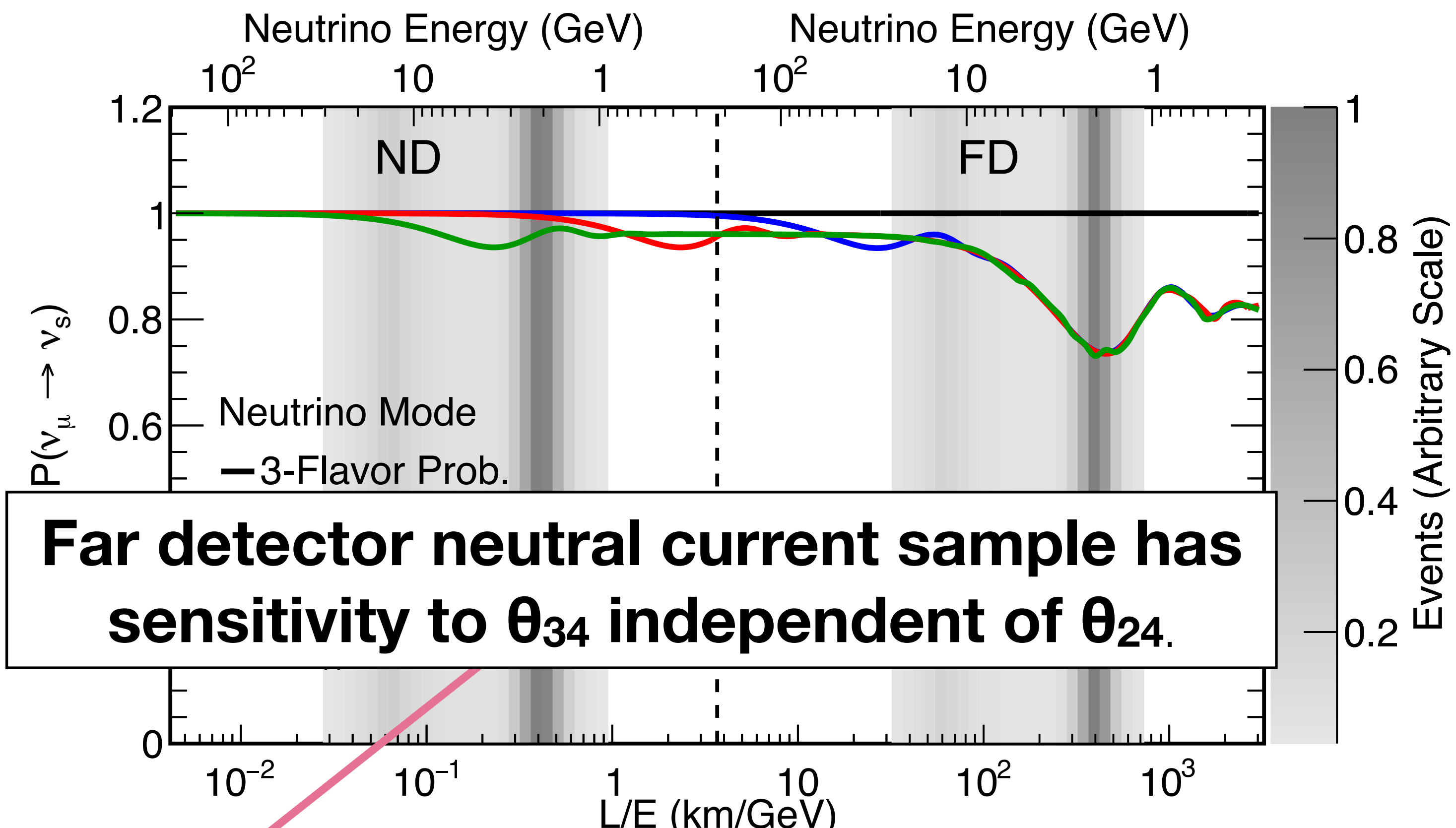

Far detector neutral current sample has sensitivity to θ_{34} independent of θ_{24}.

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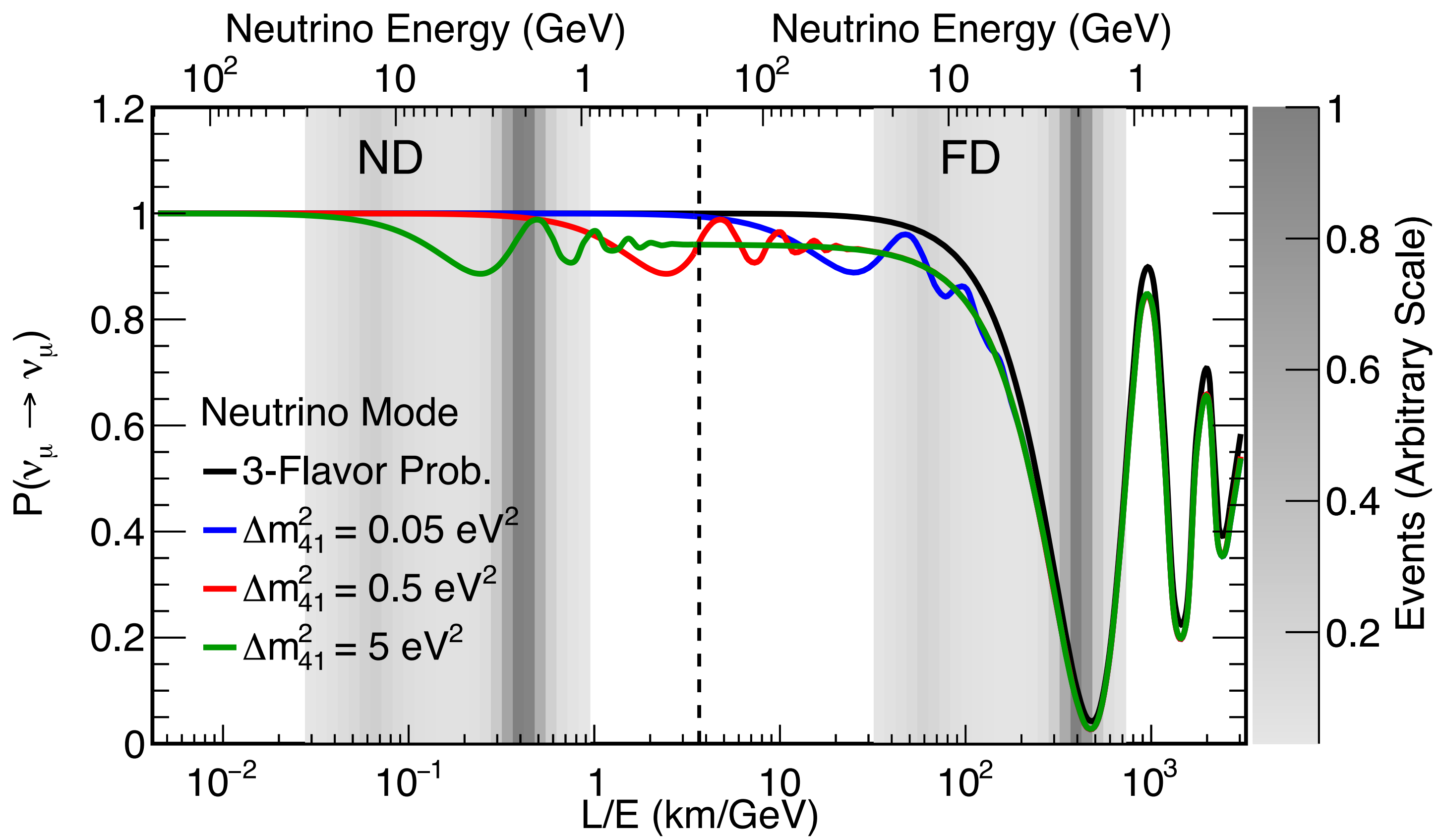

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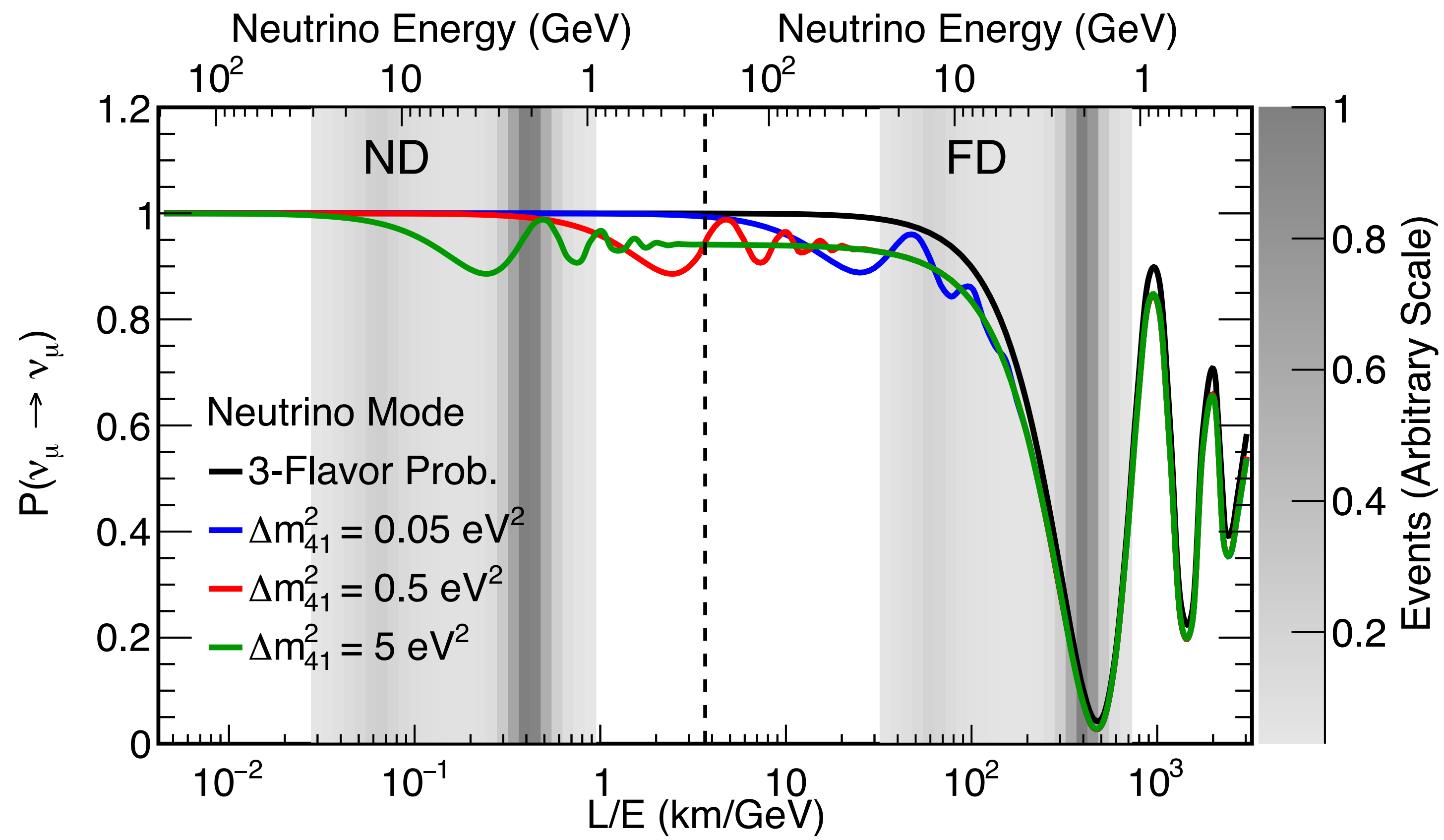

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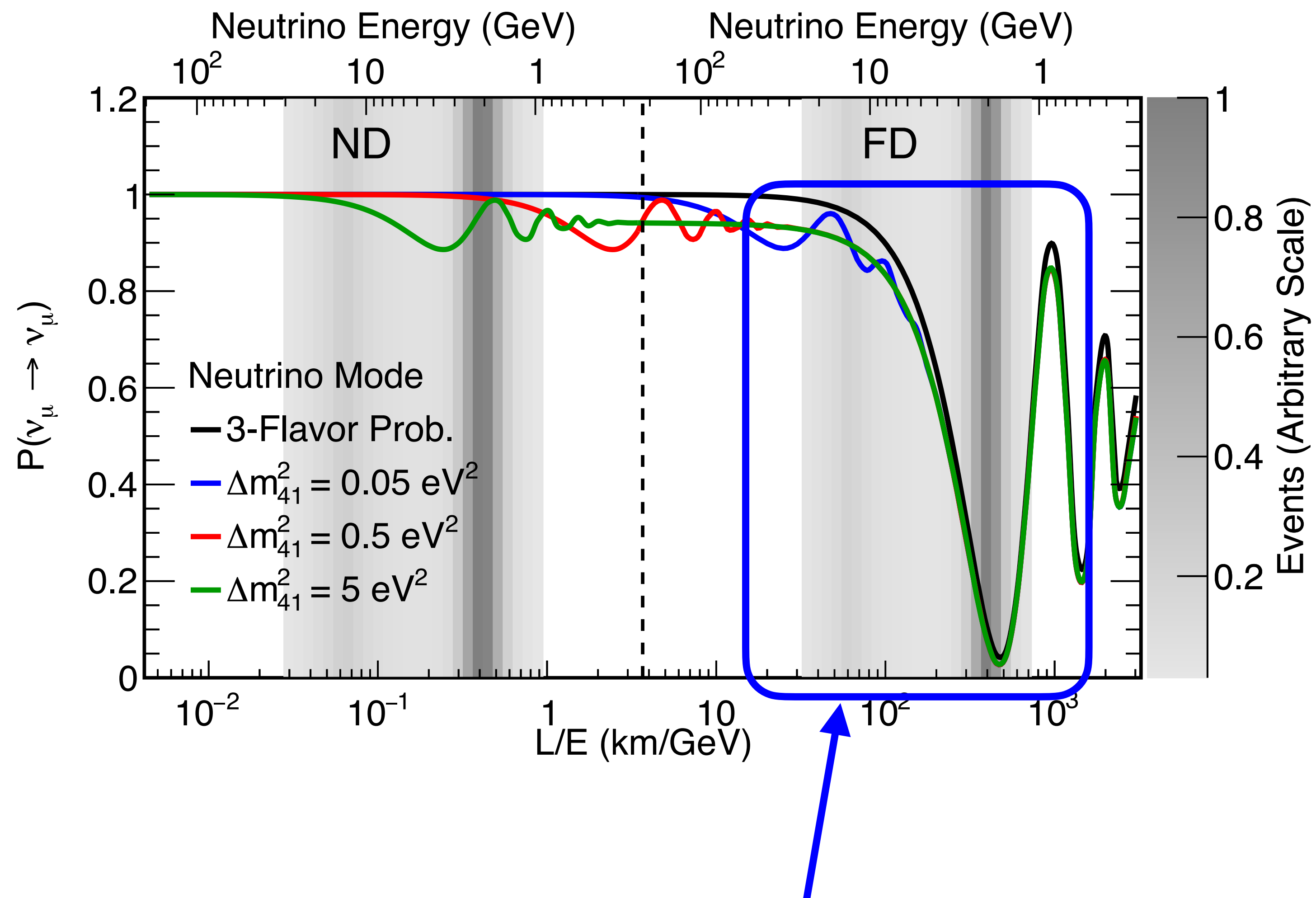

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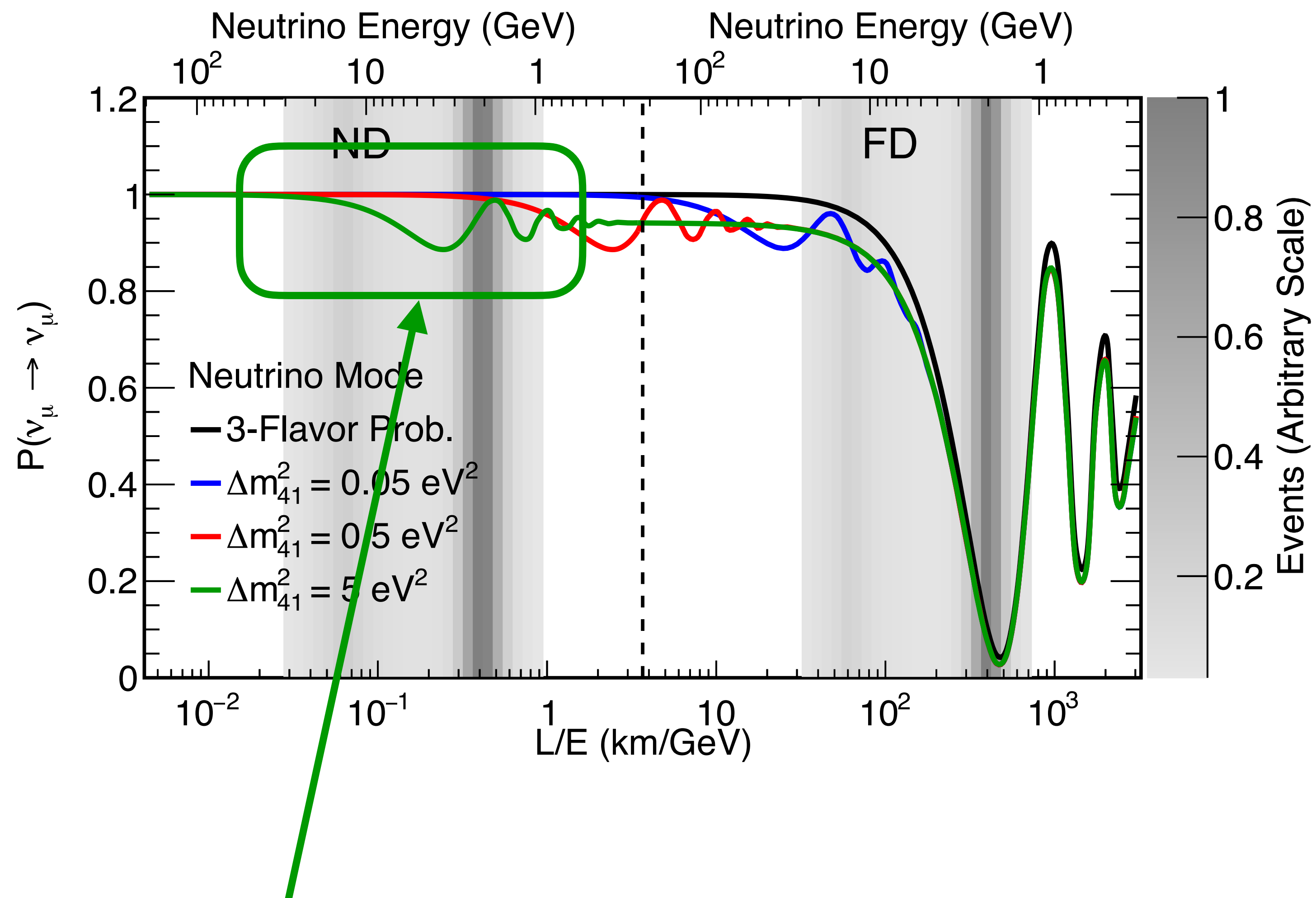

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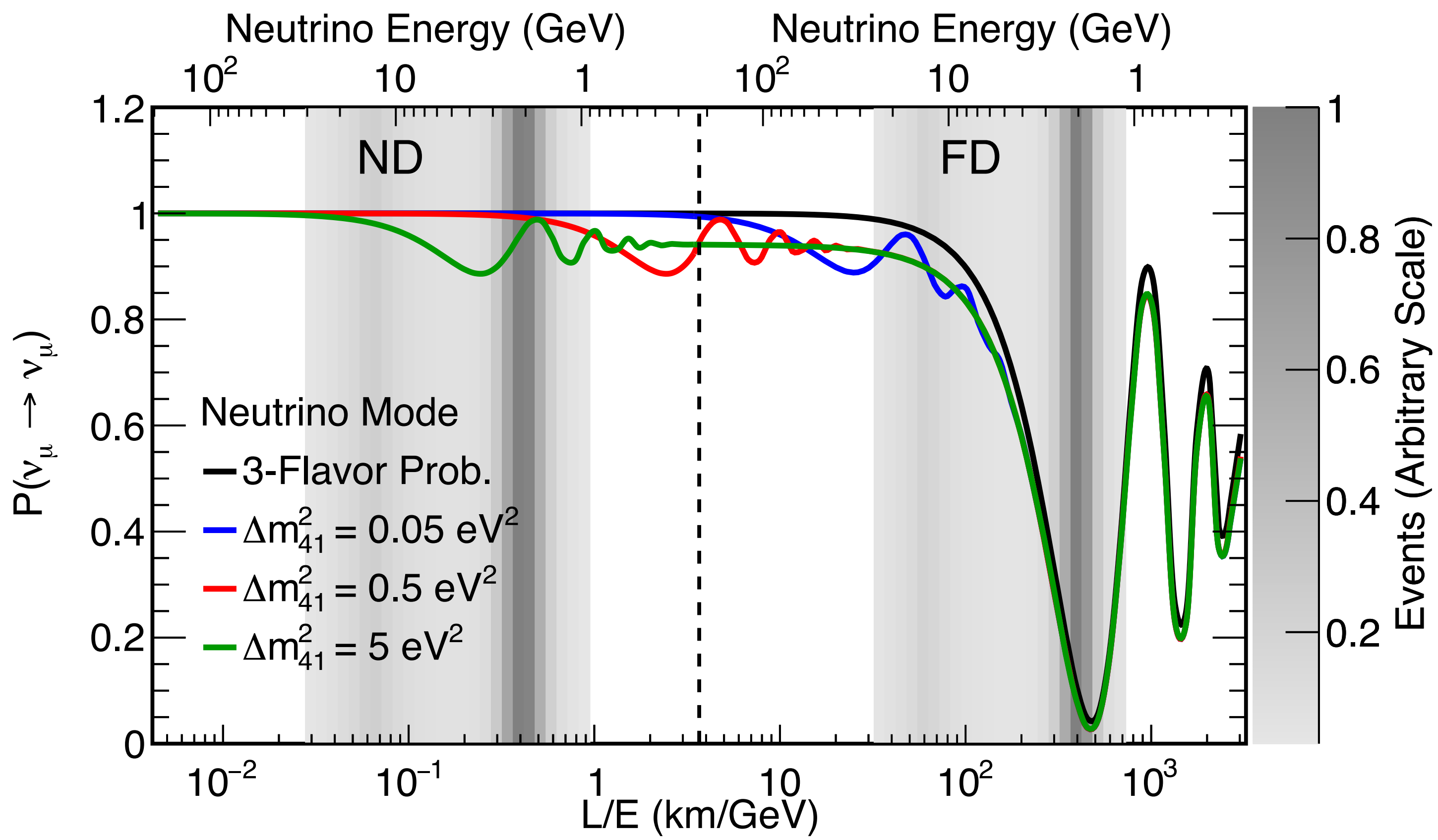

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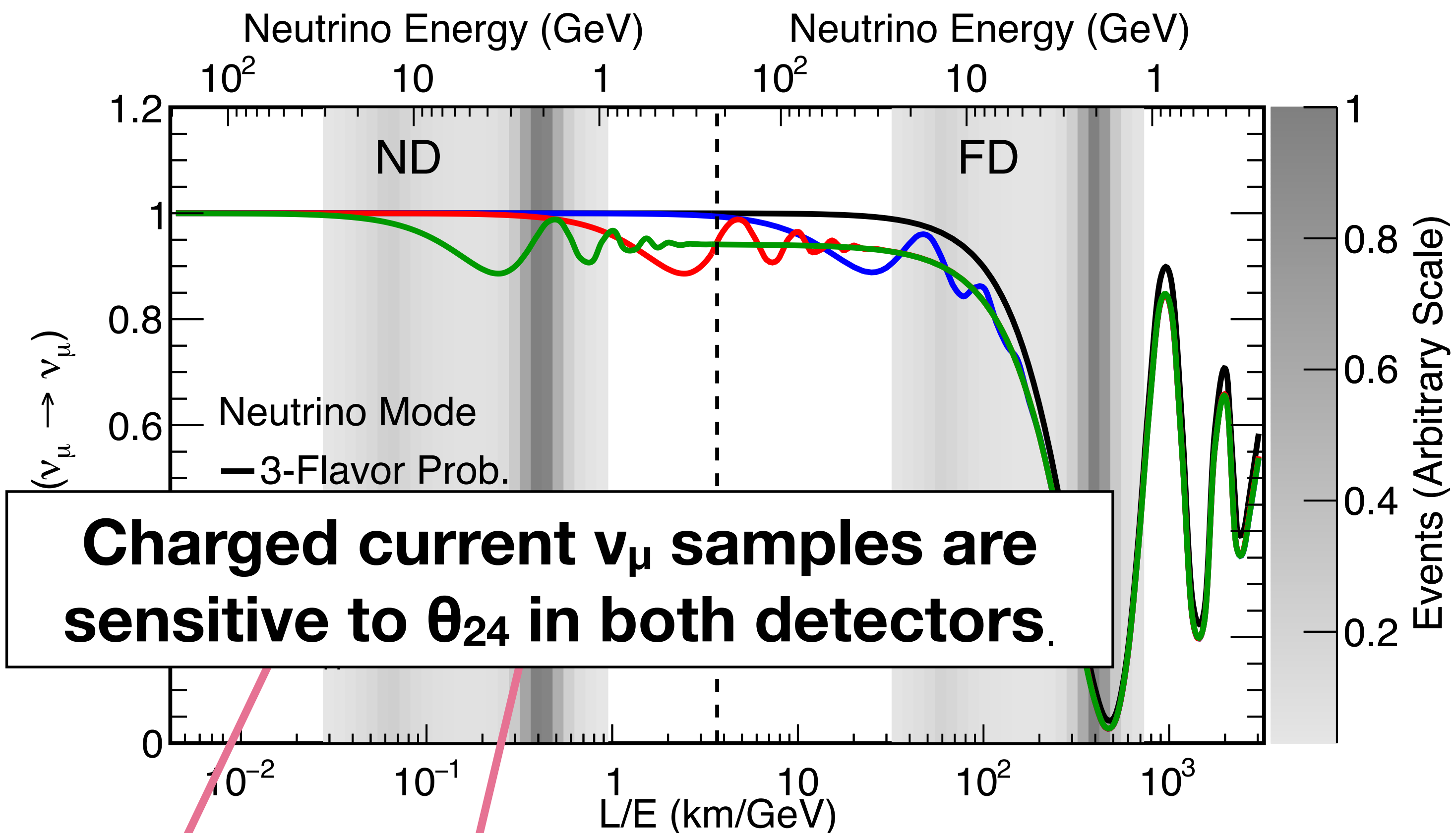

Charged current ν_μ samples are sensitive to θ_{24} in both detectors.

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2 2\theta_{24} \sin^2 \Delta_{41}$$
$$+2 \sin^2 2\theta_{23} \sin^2 \theta_{24} \sin^2 \Delta_{31}$$
$$-\sin^2 2\theta_{23} \sin^2 \Delta_{31}$$

$$\Delta_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E}$$

Terms in yellow only appear in far detector, due to interplay with 3f oscillations.

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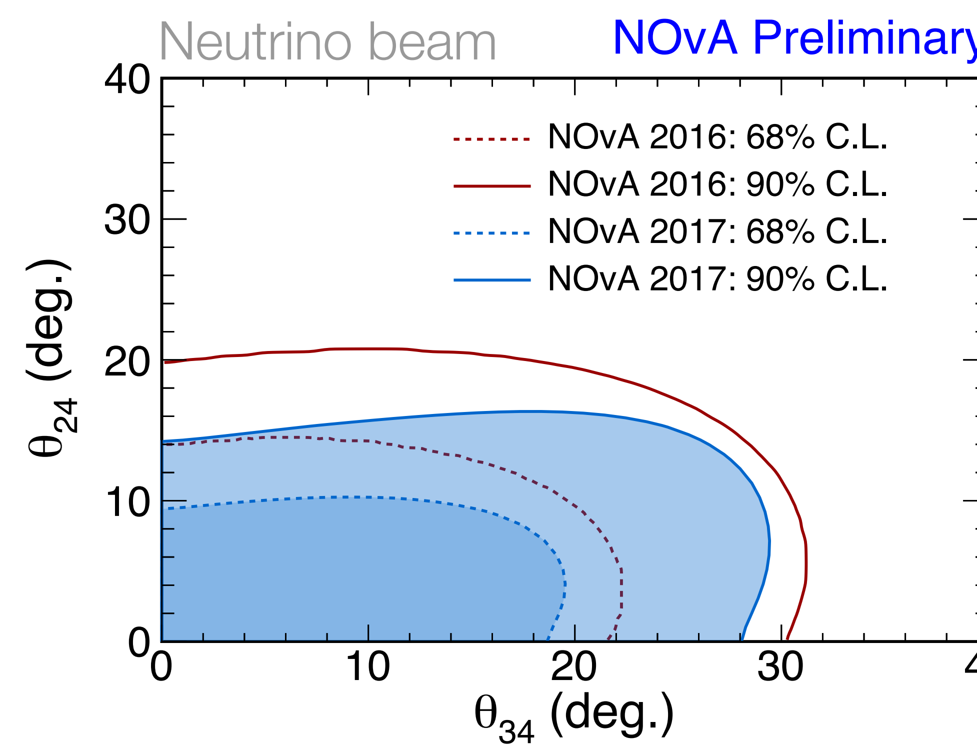
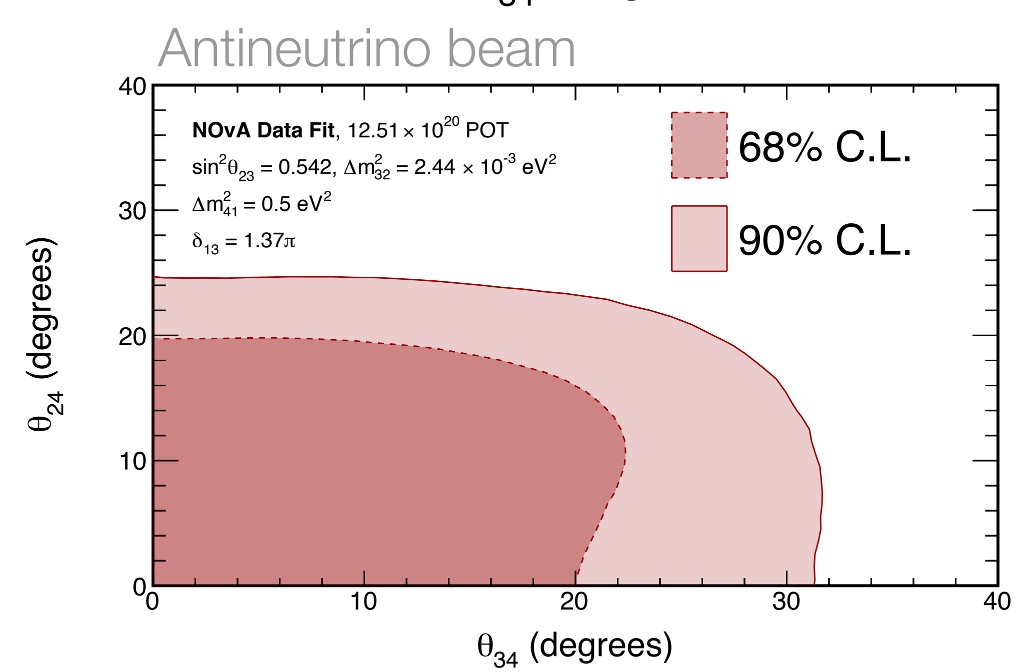
Previous NOvA 3+1 results

Phys.Rev.D **96 (2017) 7, 072006**

- Previous NOvA 3+1 searches used a **near-to-far ratio** approach for cancelling systematic uncertainties.





Phys. Rev. Lett. **127, 201801**

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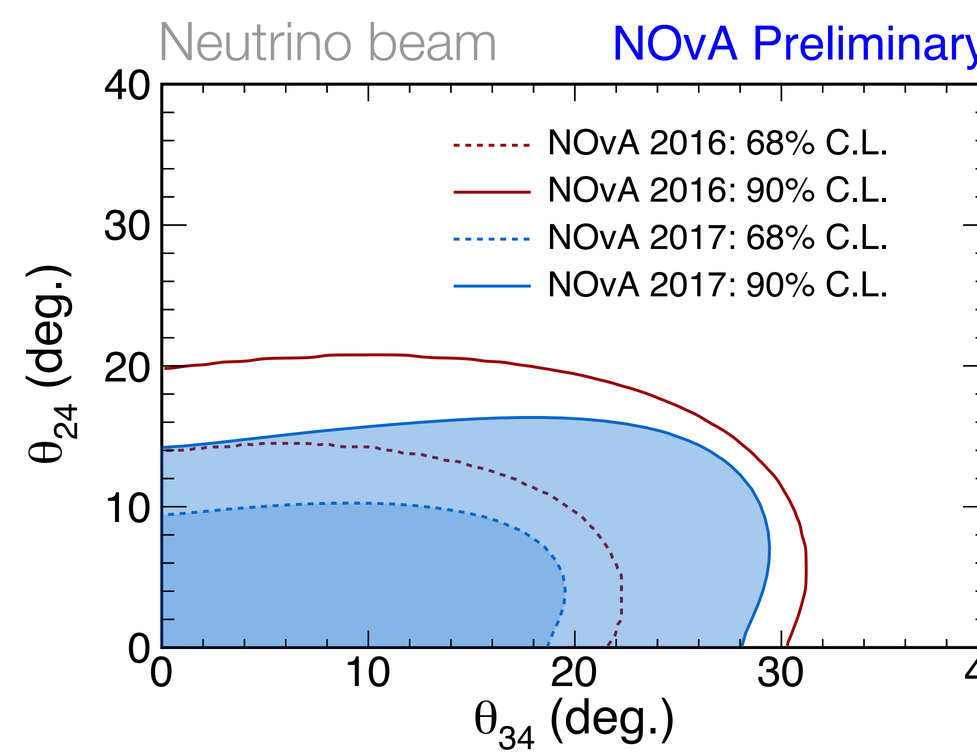

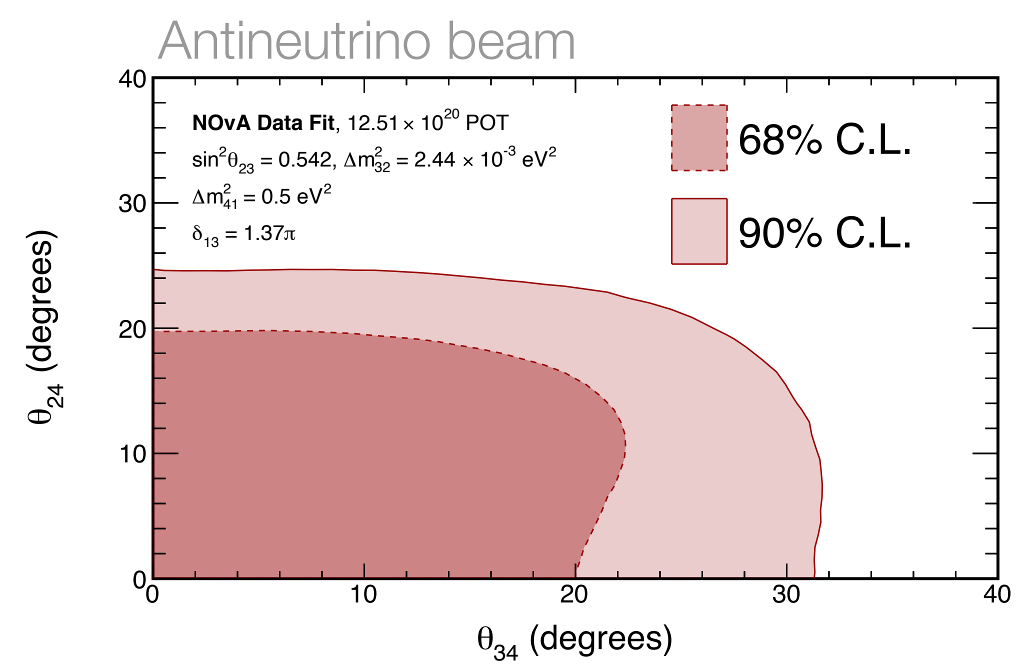

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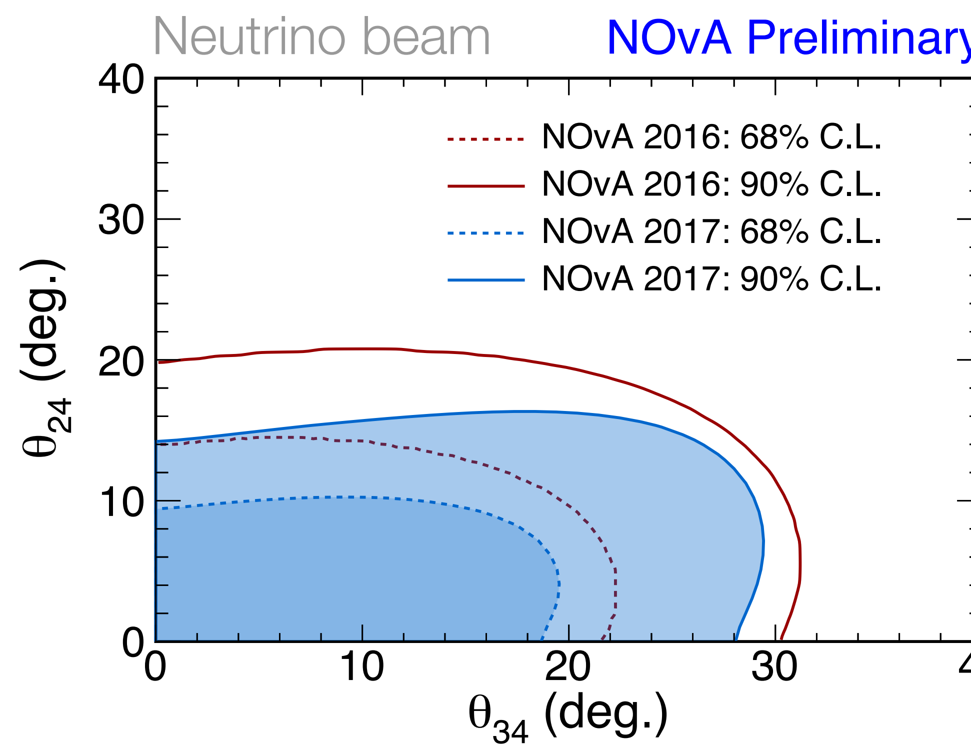

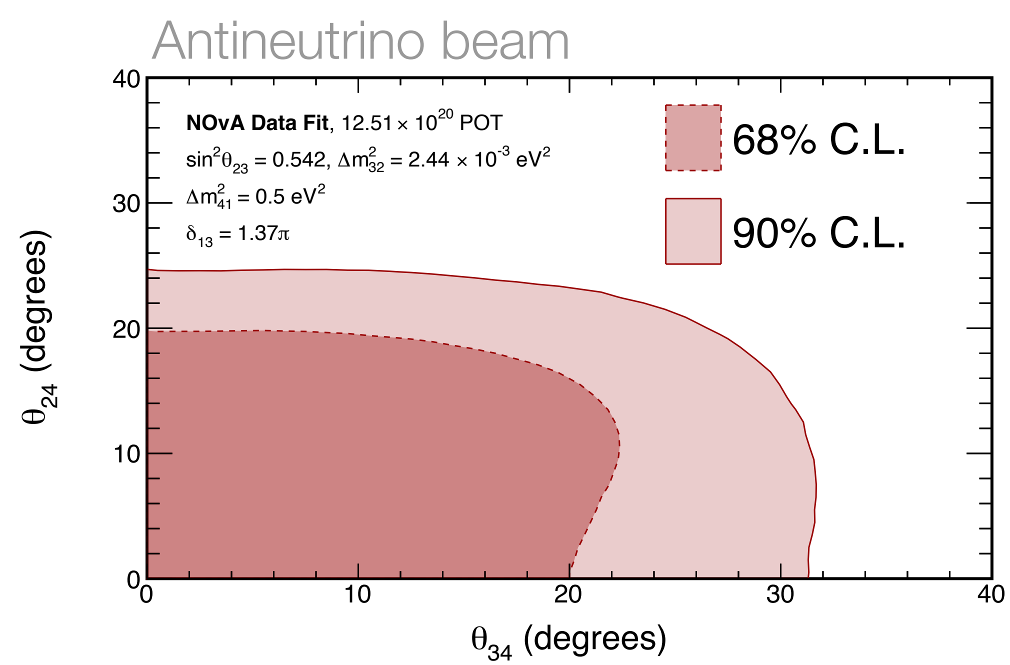

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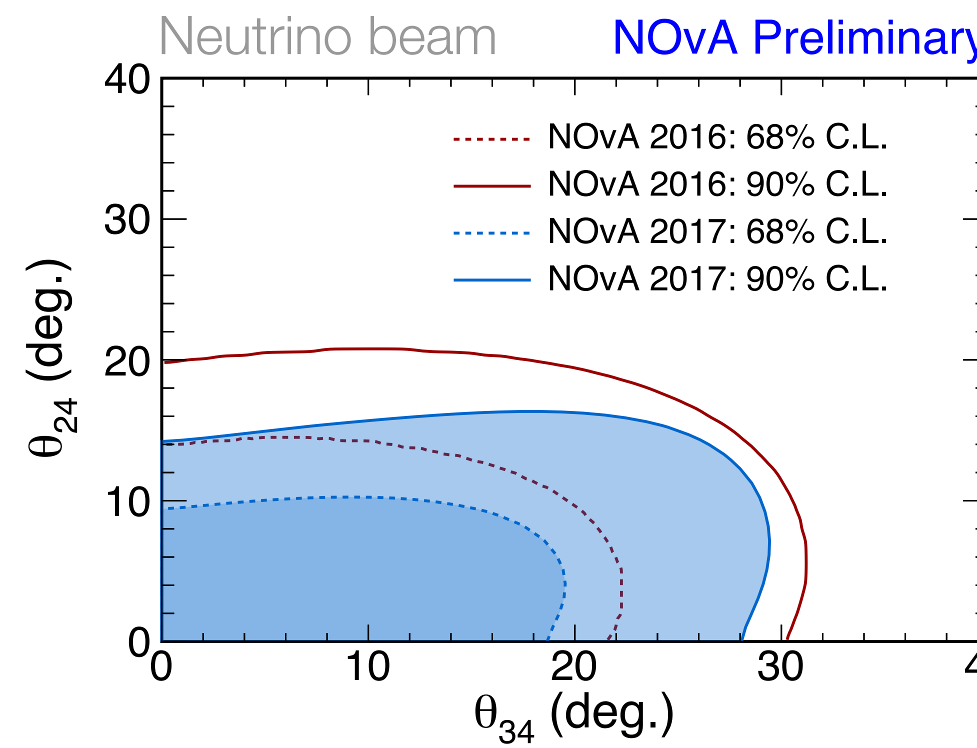

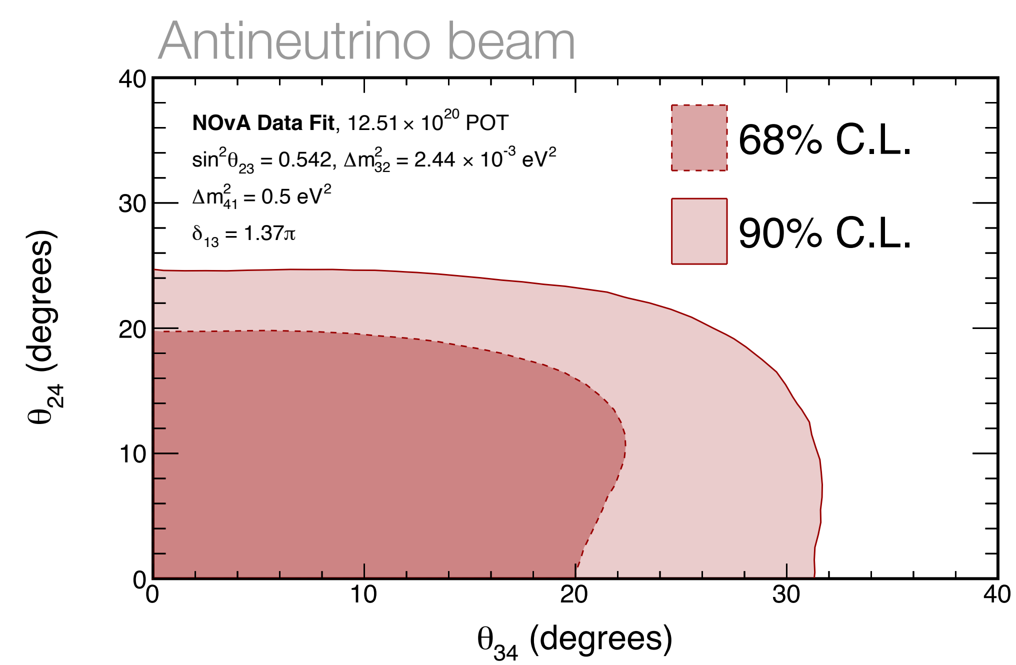

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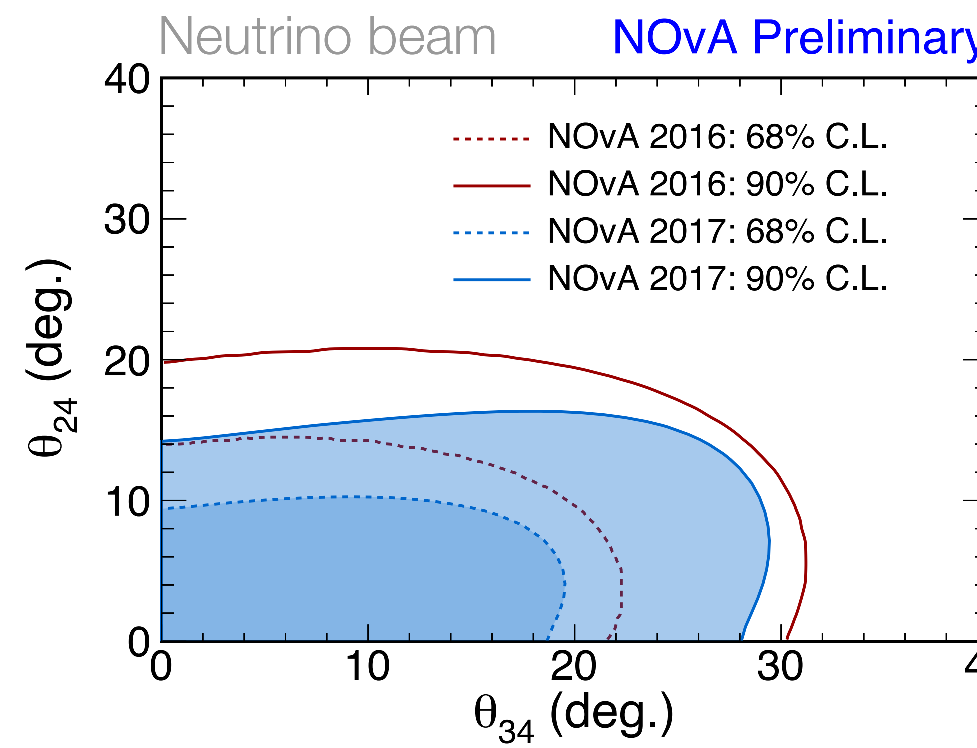

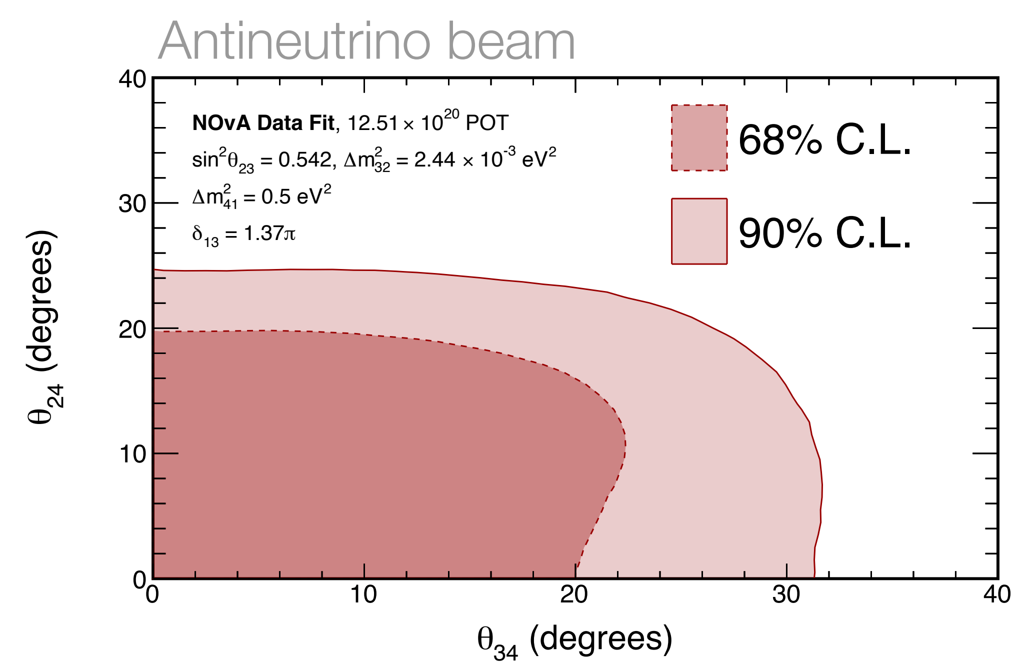

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- This approach uses the near detector to **constrain systematic uncertainties**.
- Analyses are limited to the $0.05 < \Delta m_{41}^2 < 0.5$ eV^2 region of phase space.
  - **No sterile oscillations** in the near detector.
  - **Rapid oscillations averaging to a normalisation shift** in the far detector.

Dual-baseline approach

Far detector

Neutral current

Normalisation shift at $\Delta m_{41}^2 > 0.05$ eV^2.

Sensitive to θ_{24} and θ_{34}.

Independent sensitivity to θ_{34}.

The **far detector neutral current selection** is the only sample considered by previous NOvA sterile analyses.

Dual-baseline approach

Far detector

Neutral current

Normalisation shift
at $\Delta m_{41}^2 > 0.05$ eV^2.

Sensitive to θ_{24} and θ_{34}.

Independent sensitivity to θ_{34}.

Moving to a **two-detector fit** approach allows for **cancellation of systematic uncertainties** while being **sensitive to oscillations in either detector**.

Dual-baseline approach

	Near detector	**Far detector**
Neutral current	Near detector oscillations manifest at $\Delta m_{41}^2 > 0.5$ eV^2. Sensitive to θ_{24} and θ_{34}.	Normalisation shift at $\Delta m_{41}^2 > 0.05$ eV^2. Sensitive to θ_{24} and θ_{34}. Independent sensitivity to θ_{34}.

Fitting in the near detector allows us to **probe two different regions of L/E simultaneously**.

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Dual-baseline approach

	Near detector	**Far detector**
Neutral current	Near de… manifest … Sensitiv…	Normalisation shift … V^2. … θ$_{34}$. Independent sensitivity to θ$_{34}$.
Charged current ν_μ	Near detector oscillations manifest at $\Delta m_{41}^2 > 0.5$ eV^2. Sensitive to θ_{24}.	Normalisation shift at $\Delta m_{41}^2 > 0.05$ eV^2. Sensitive to θ_{24}.

Adding in the **charged current ν_μ selections** gives us **independent constraints on θ_{24}**, as well as **further breaking systematic degeneracies**.

Dual-baseline approach

	Near detector	**Far detector**
Neutral current	Near detector oscillations manifest at $\Delta m_{41}^2 > 0.5$ eV^2. Sensitive to θ_{24} and θ_{34}.	Normalisation shift at $\Delta m_{41}^2 > 0.05$ eV^2. Sensitive to θ_{24} and θ_{34}. Independent sensitivity to θ_{34}.
Charged current ν_μ	Near detector oscillations manifest at $\Delta m_{41}^2 > 0.5$ eV^2. Sensitive to θ_{24}.	Normalisation shift at $\Delta m_{41}^2 > 0.05$ eV^2. Sensitive to θ_{24}.

Analysis approaches

CMF (Covariance Matrix Fit)

- Event-by-event fit framework for calculating exact oscillation probabilities.
- Use standard Gaussian multivariate χ^2 with Combined Neyman-Pearson statistical uncertainties.

$$\chi^2_{CNP} = \sum_i \frac{(N_i^{CV} - N_i^{data})^2}{3/\left(\frac{1}{N_i^{data}} + \frac{2}{N_i^{CV}}\right)}$$

$$\chi^2 = \sum_{i,j} \left[N_i^{data} - N_i^{model}(\Theta)\right] \times C_{ij}^{-1} \times \left[N_j^{data} - N_j^{model}(\Theta)\right]$$

arXiv:1903.07185

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arXiv:1903.07185

PISCES (Parameter Inference with Systematic Covariance and Exact Statistics)

- Use covariance matrix to efficiently solve for systematic pulls.
- Exact statistical treatment of statistical uncertainties with Poisson likelihood.

$$\chi^2 = 2\sum_i^N \left[\left(\sum_\alpha^M \mu_{\alpha i} s_{\alpha i}\right) - x_i + x_i \log\left(\frac{x_i}{\sum_\alpha^M \mu_{\alpha i} s_{\alpha i}}\right)\right] + \sum_{ij}^N \sum_{\alpha\beta}^M (s_{\alpha i} - 1) F_{\alpha i \beta j} (s_{\beta j} - 1)$$

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Event selection

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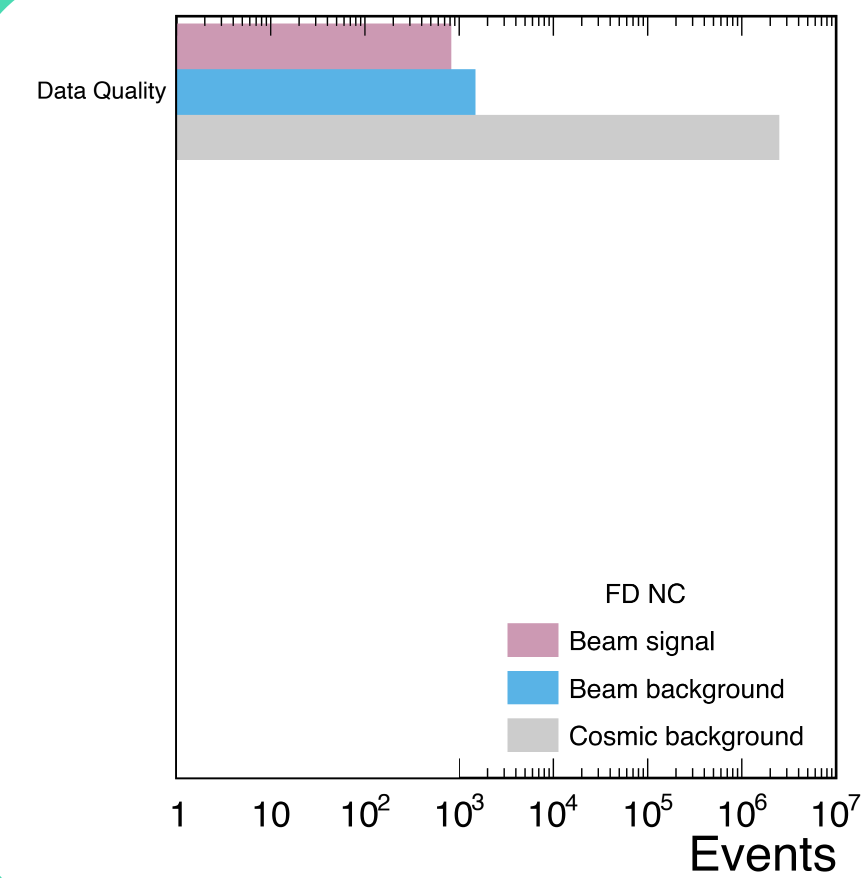
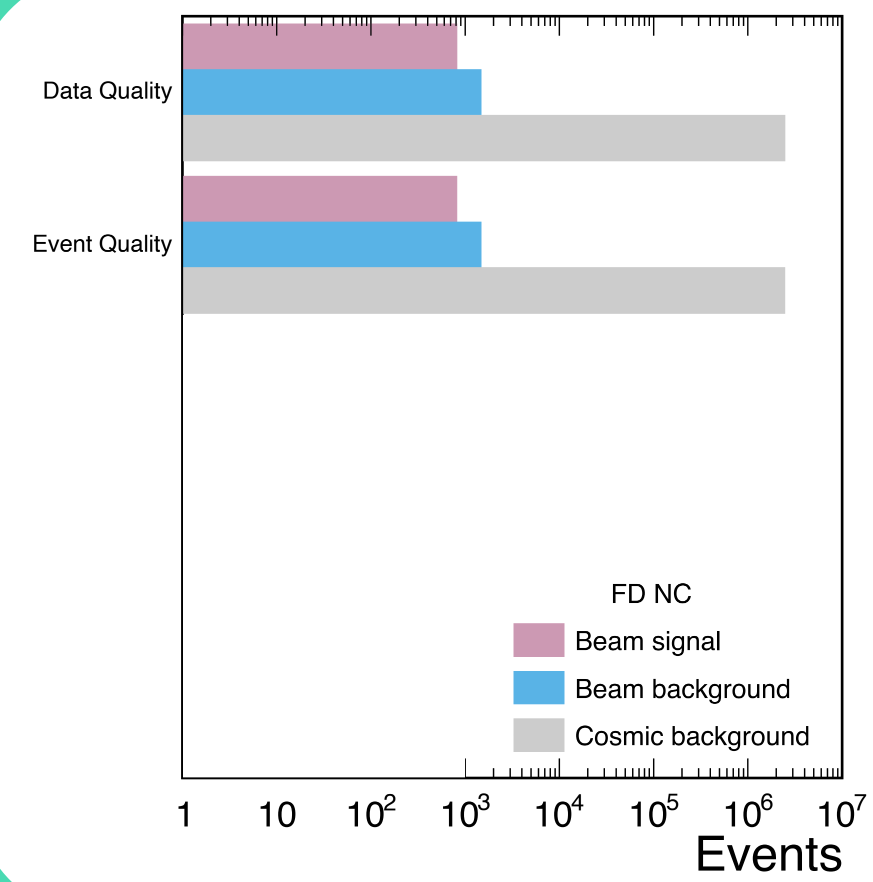


Far detector NC selection

Event selection

- Charged Current ν_μ and Neutral Current events are selected using the following criteria:

  - **Event quality**



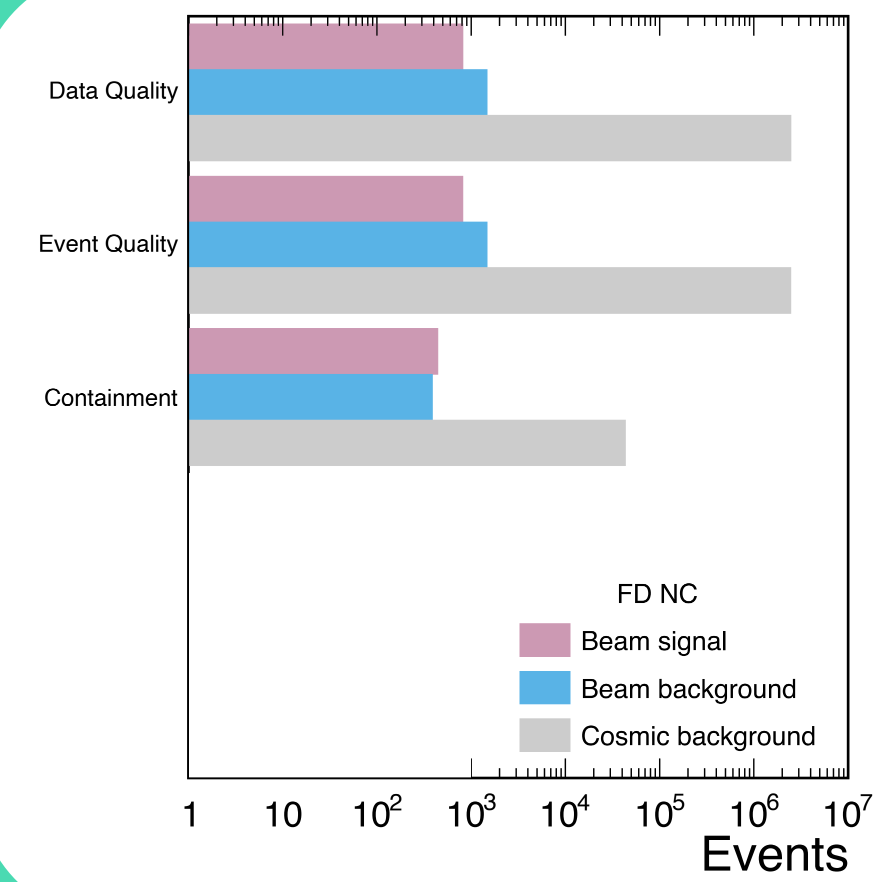
- **Event quality**
  - Require reconstructed vertex and prong(s).
  - Minimum threshold for extent of event.

Event selection

- Charged Current ν_μ and Neutral Current events are selected using the following criteria:

  - **Event quality**

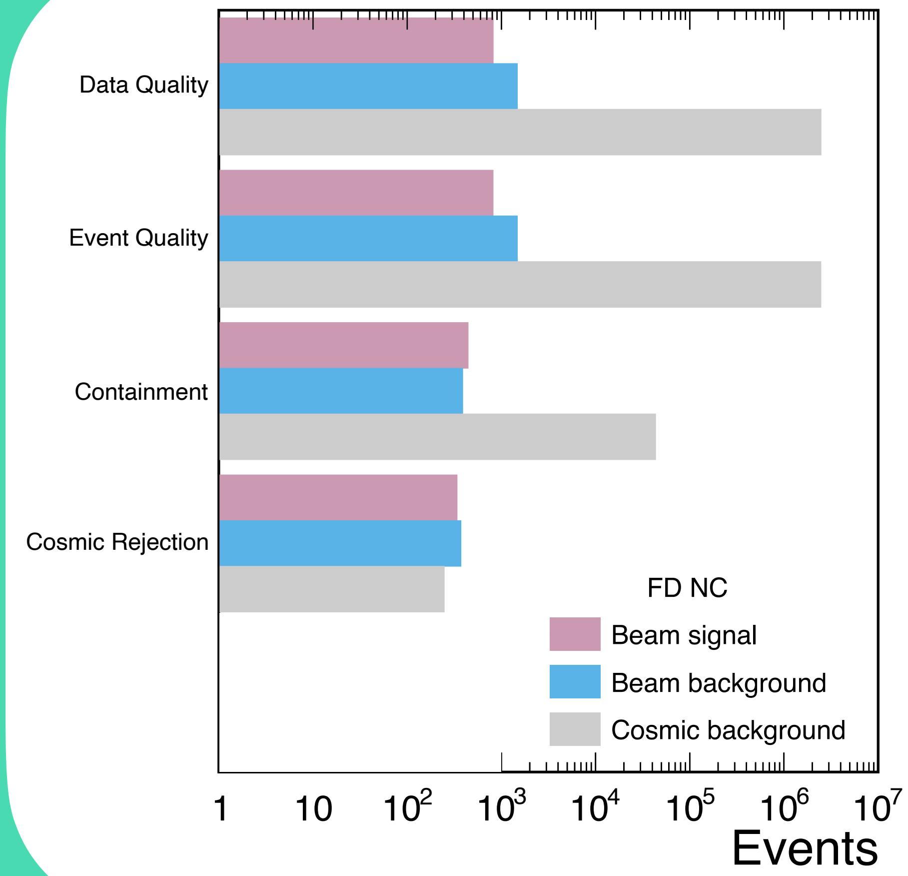
  - **Containment**



- **Containment**
  - Reconstructed vertex must be inside fiducial volume.
  - Large distance between prong extrema and detector boundary.

Event selection

- Charged Current ν_μ and Neutral Current events are selected using the following criteria:
  - **Event quality**
  - **Containment**
  - **Cosmic background rejection**

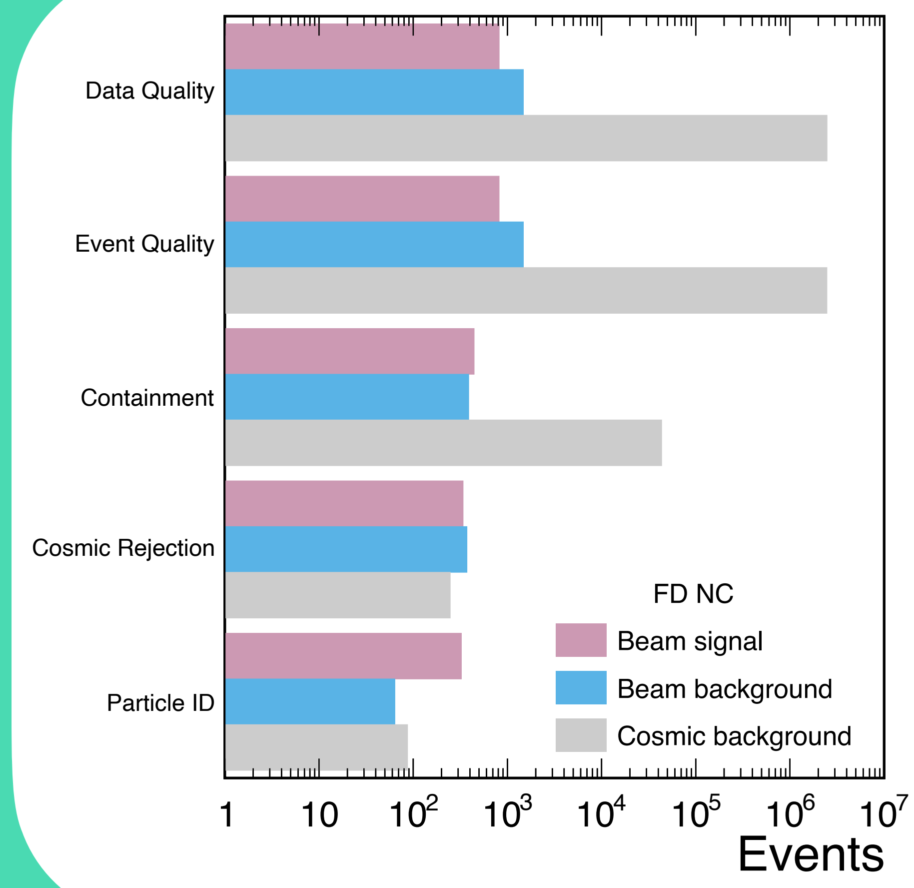


- **Cosmic background rejection**
  - Boosted Decision Tree (BDT) trained on reconstructed quantities to reject cosmic background events.

Event selection

- Charged Current ν_μ and Neutral Current events are selected using the following criteria:

  - **Event quality**
  - **Containment**
  - **Cosmic background rejection**
  - **Neutrino flavour identification**



- **Neutrino flavour identification**
  - Convolutional Neural Network (CNN) for identifying the flavour of the neutrino interaction candidate.

Event selection

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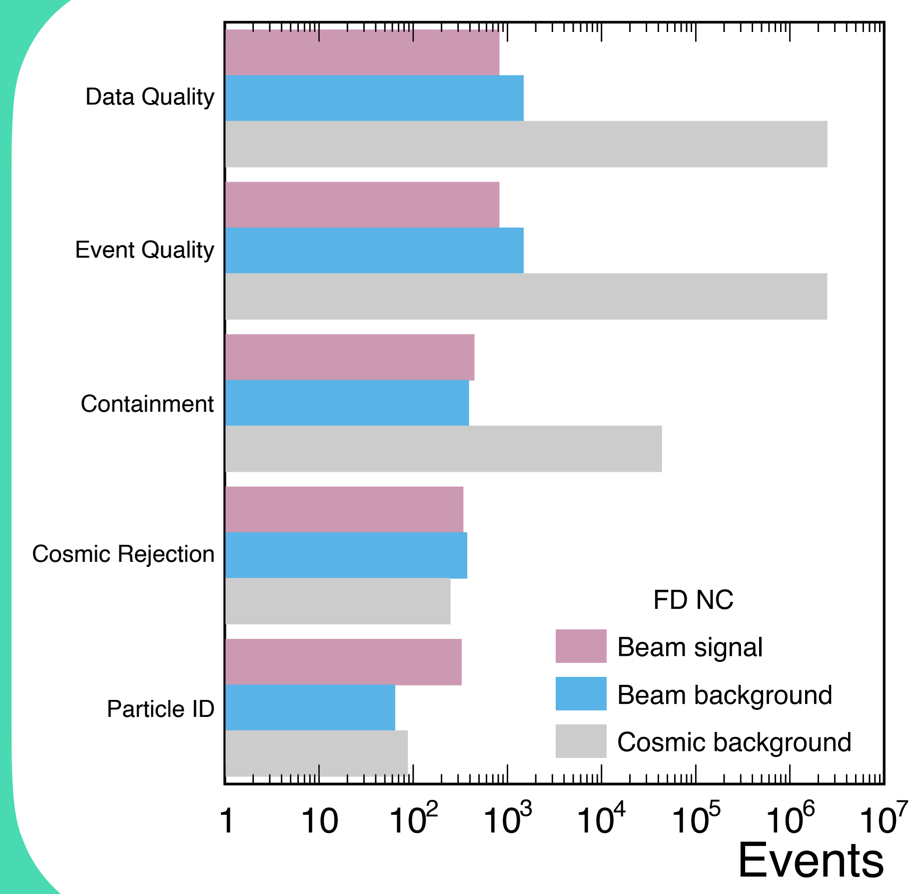

Far detector NC selection

Event selection

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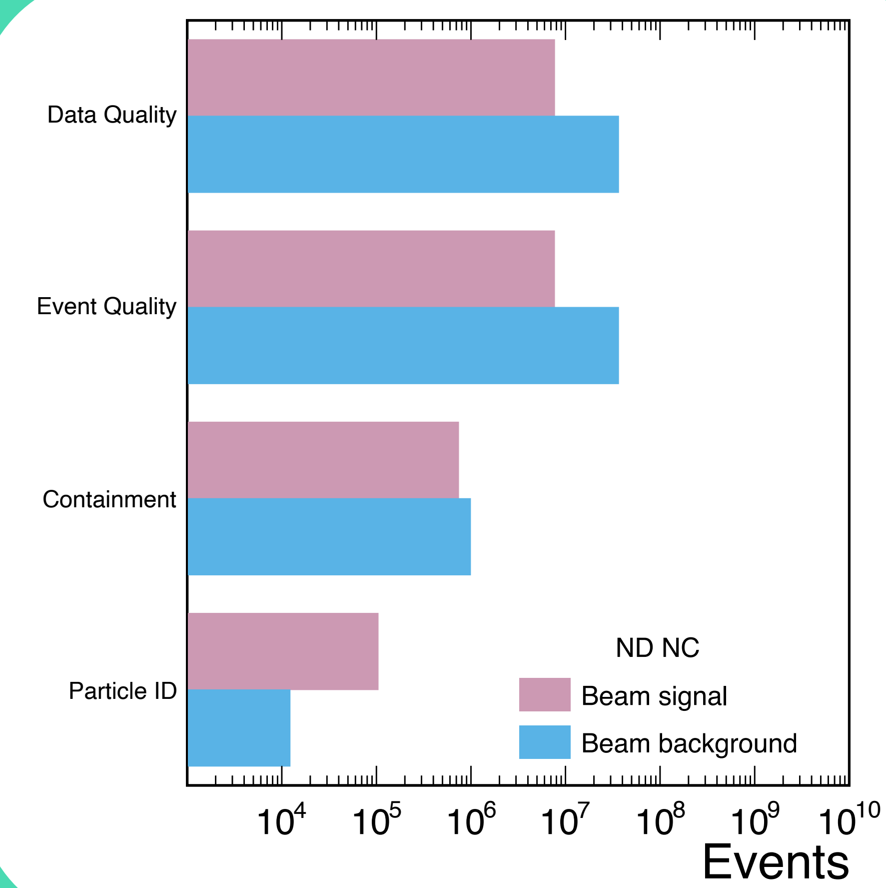

Near detector NC selection

Event selection

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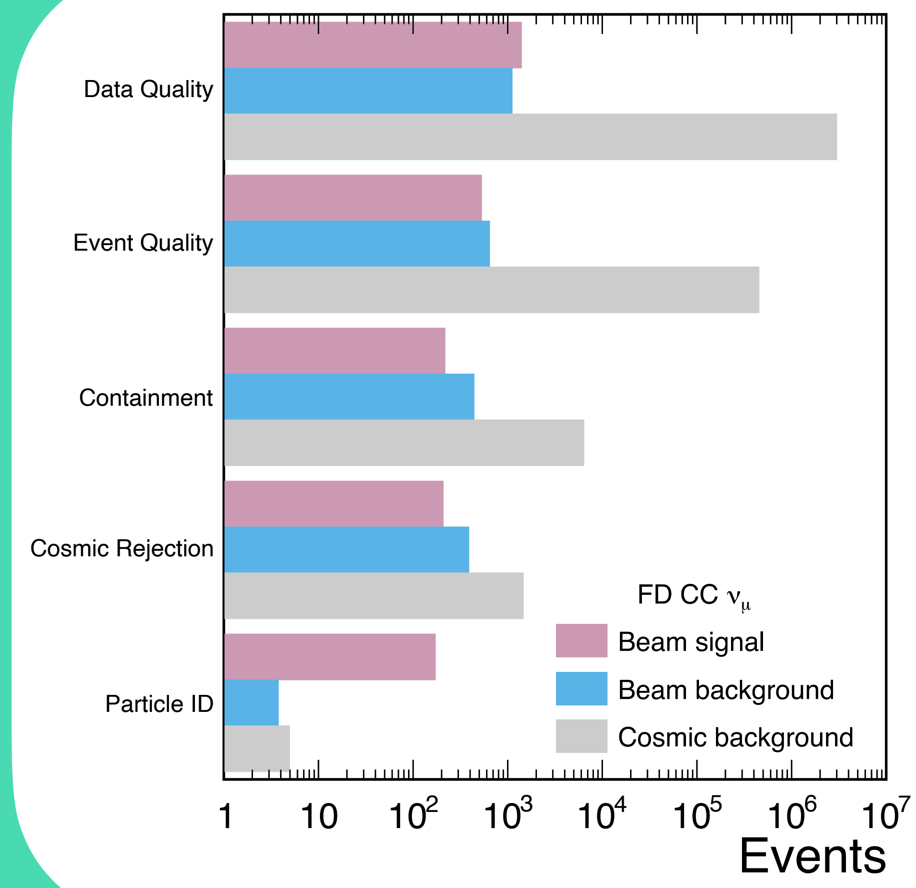

Far detector CC ν_μ selection

Event selection

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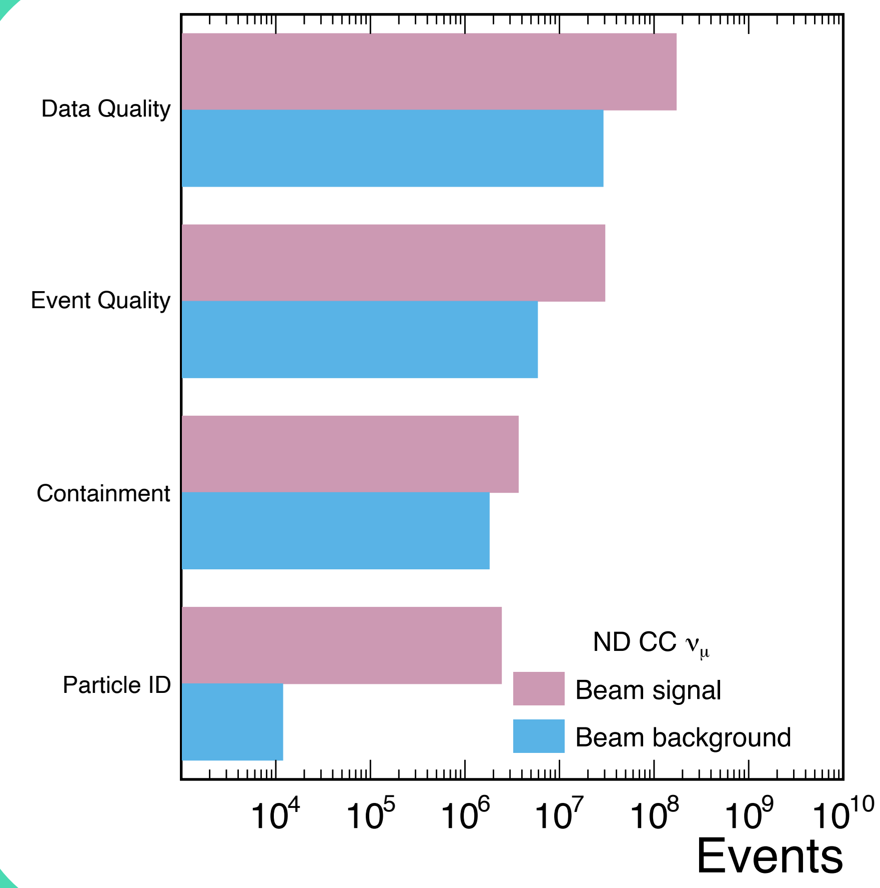

Near detector CC ν_μ selection

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- Comprehensive suite of systematic uncertainties considered:

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  - **Beam flux** (hadron production & beam transport)

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  - **Cross-sections**
  - **Detector response**

Systematic uncertainties

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  - **Cross-sections**
  - **Detector response**
  - **Normalisation**

Systematic uncertainties

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  - **Normalisation**
  - ...and more!

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- Some uncertainties require special treatment in this new analysis approach.

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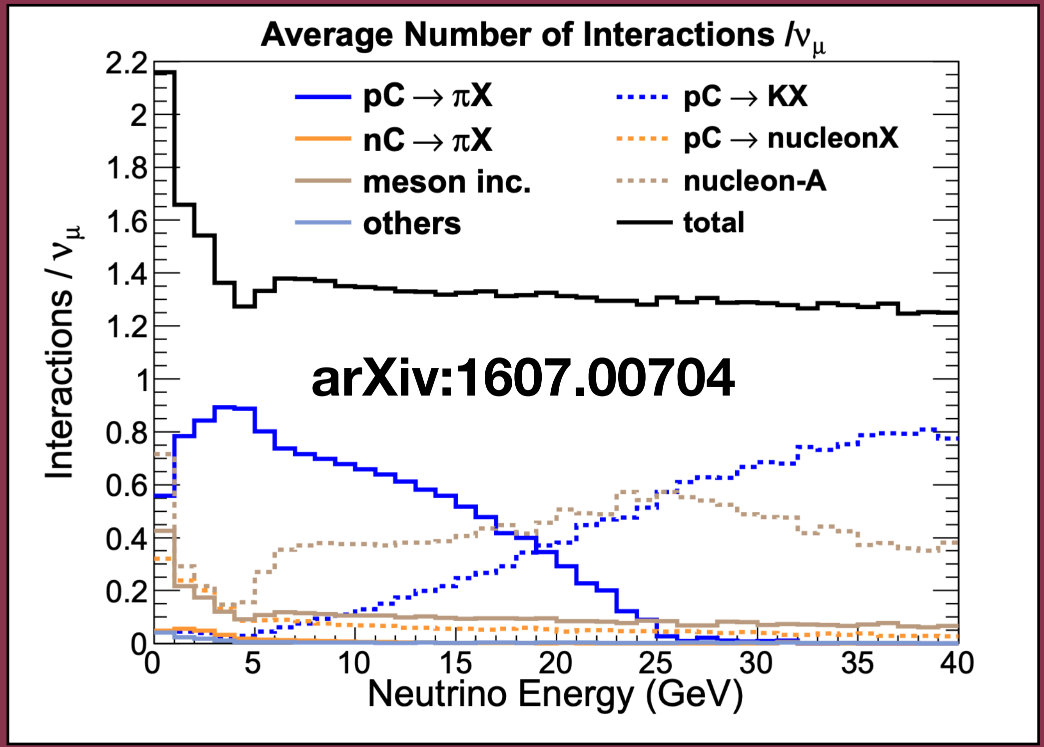
Kaon Ancestors

- Neutral current samples select neutrinos with true energies > 20 GeV.
- Significant population of kaon ancestors.
- Constrain with horn-off data to **5%**.



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  - **Detector response**
  - **Normalisation**
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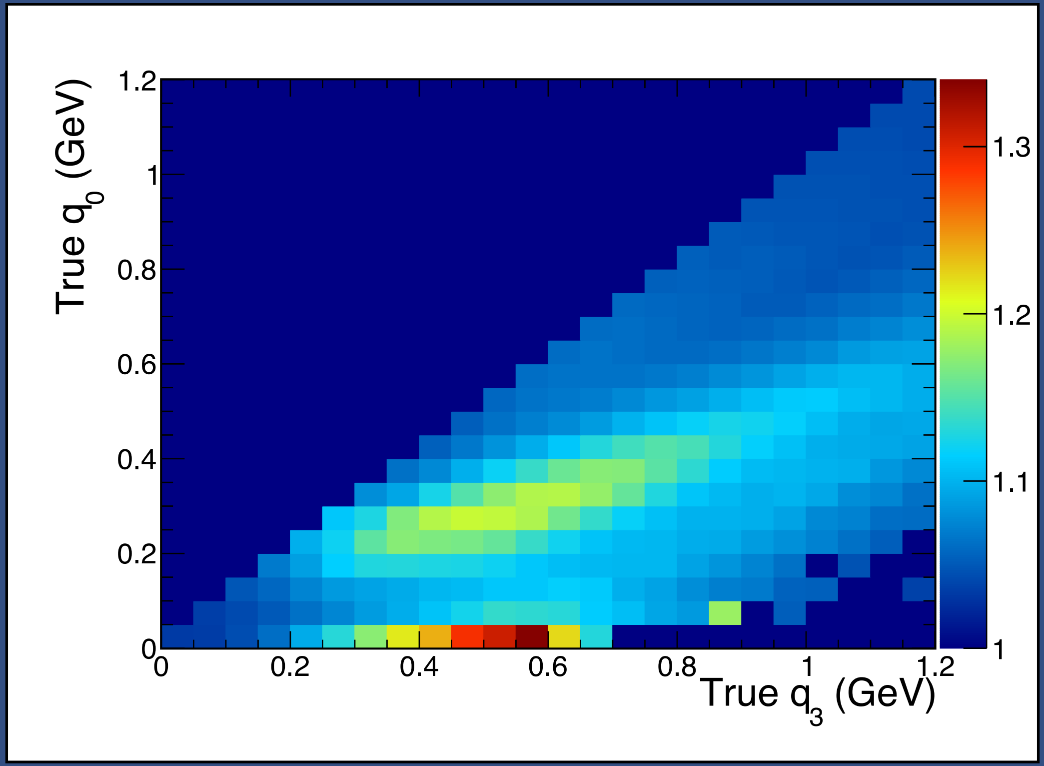
2p2h events

- Cannot use standard NOvA cross-section reweight due to potential signal in ND.
- Instead of correcting central value, introduce new MEC model spread uncertainties.



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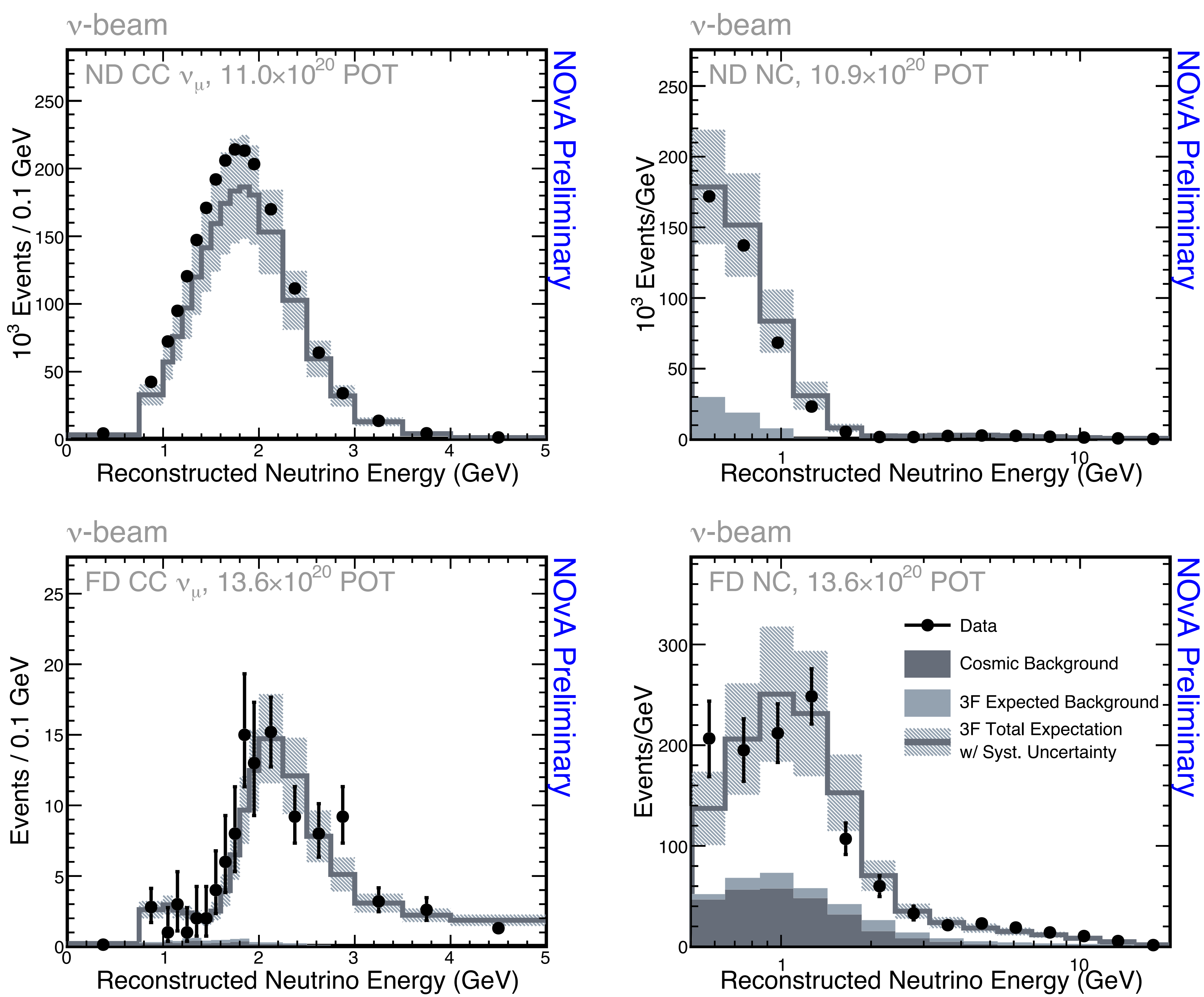
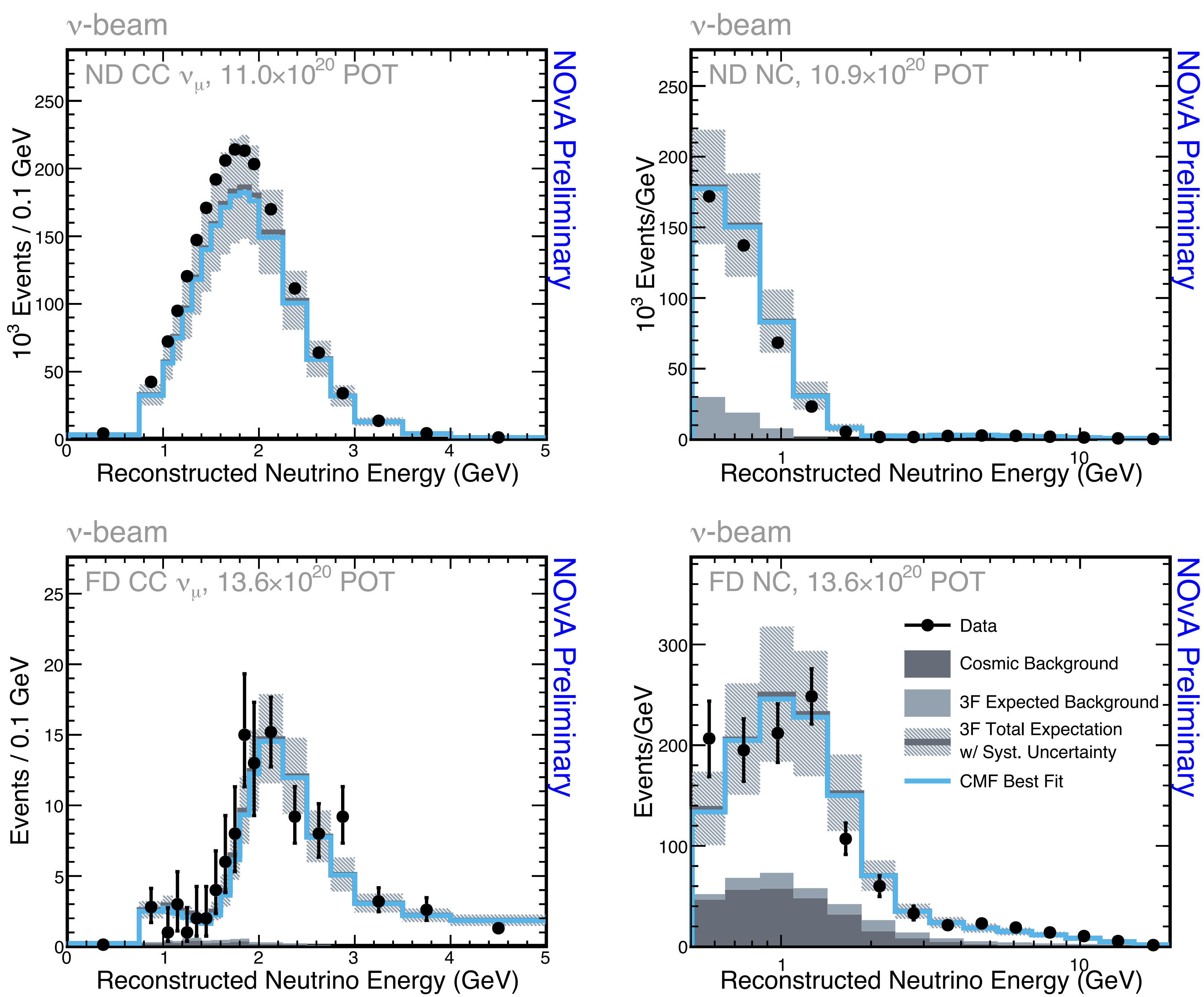


Consistent with
no sterile oscillations
at 90% confidence level.

Results



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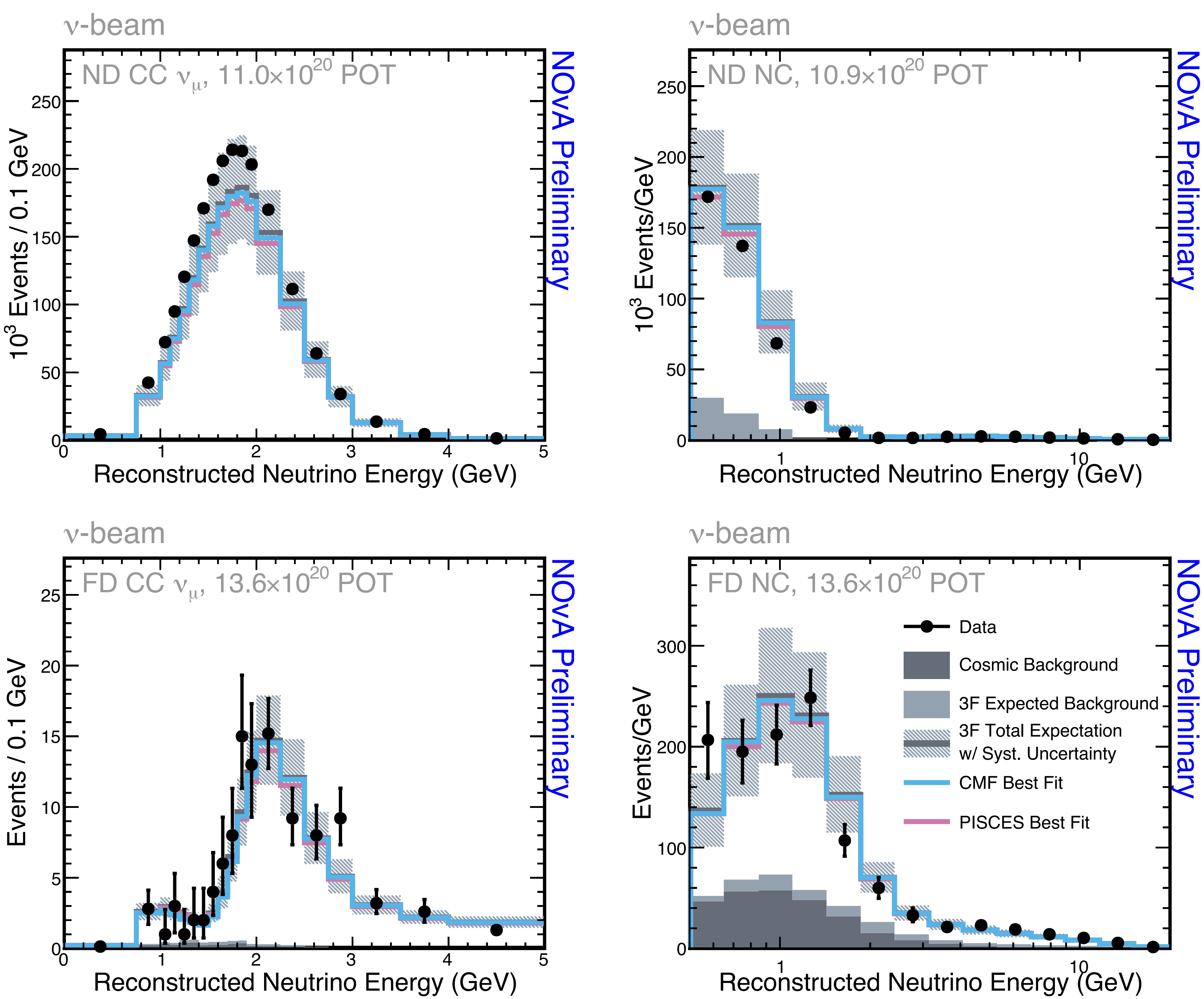

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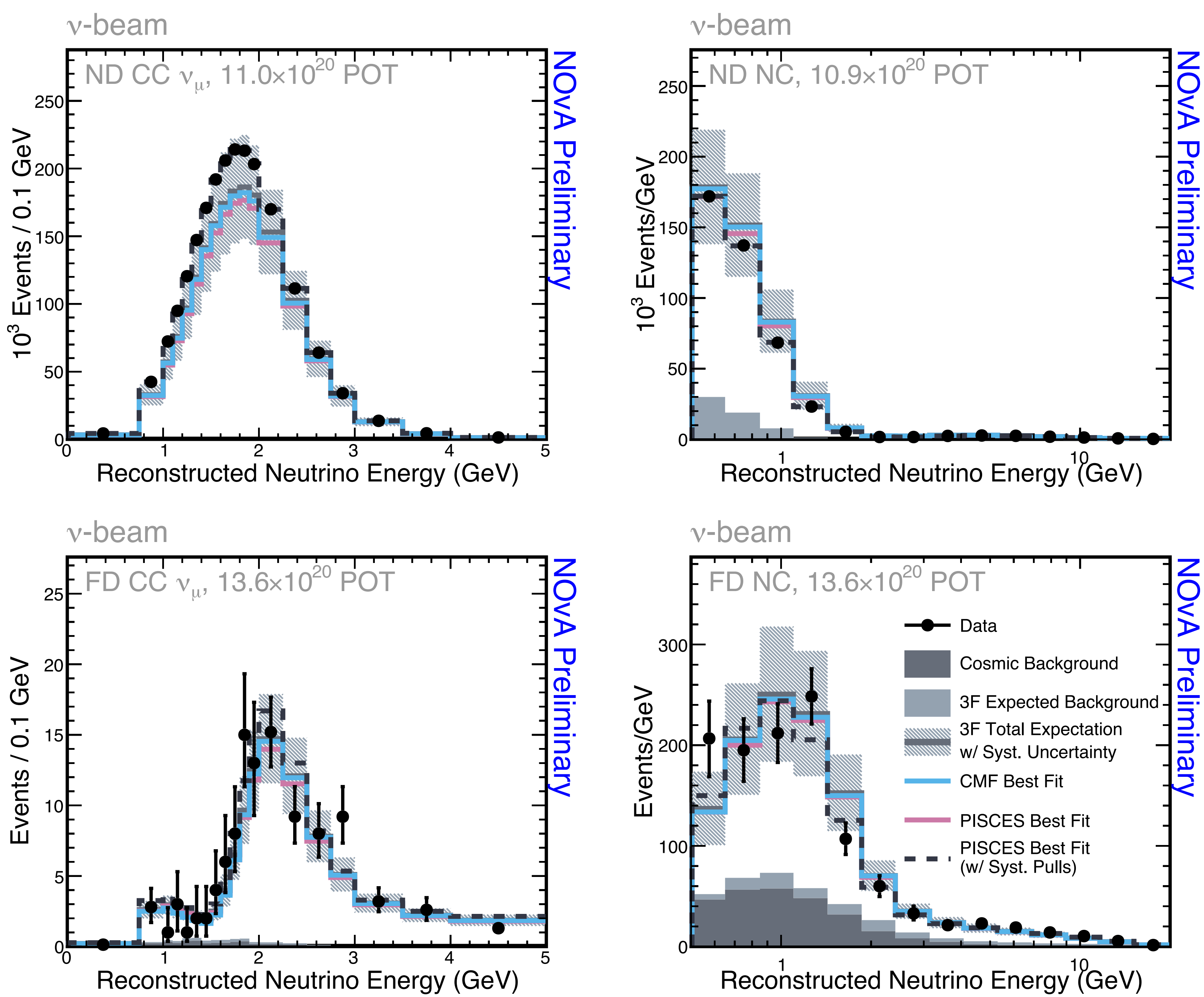

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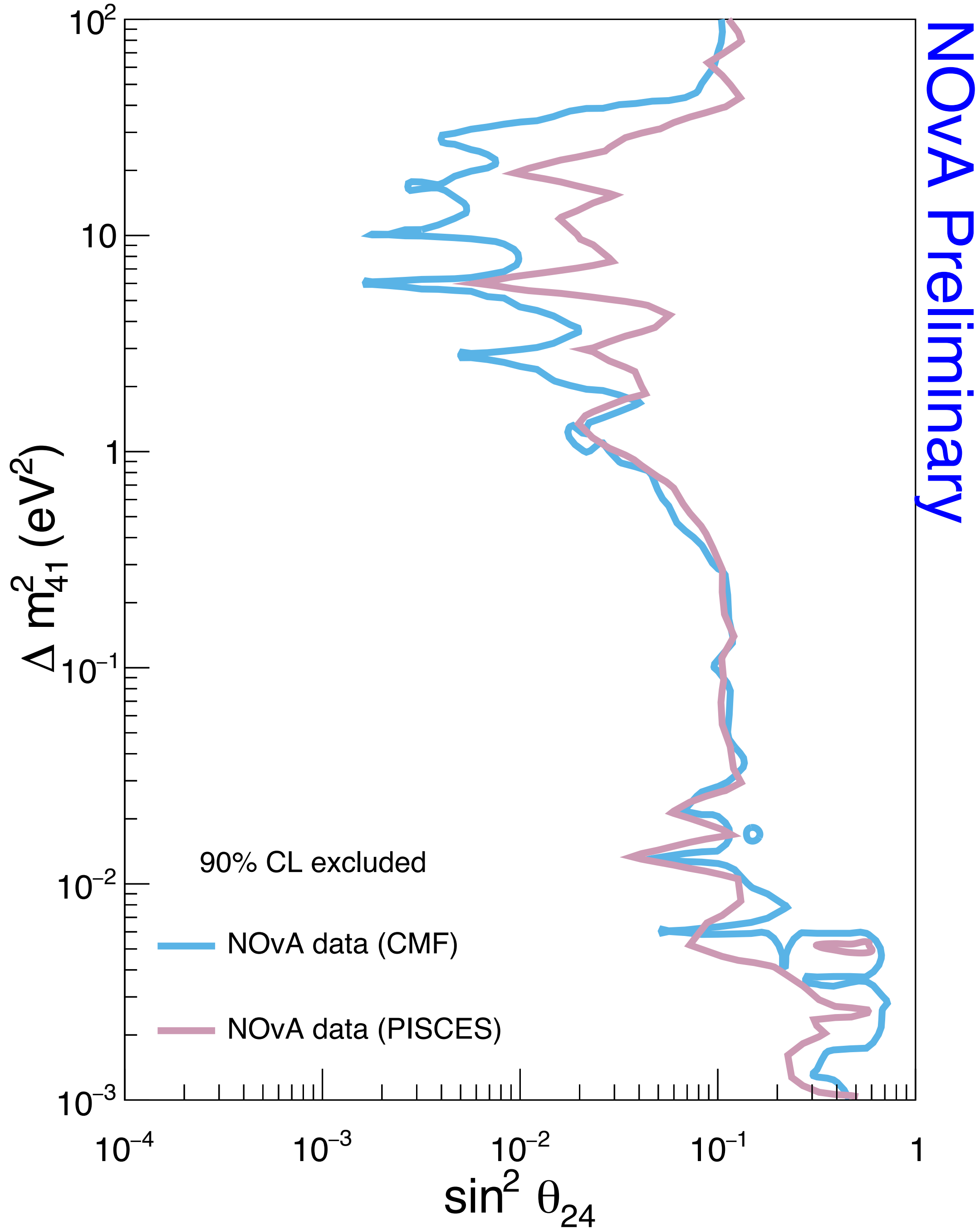
$\sin^2\theta_{24}$ vs Δm^2_{41} limits

Neutrino Beam



- Profile $\boldsymbol{\theta_{23}}$, $\boldsymbol{\Delta m^2_{32}}$, $\boldsymbol{\theta_{34}}$ and $\boldsymbol{\delta_{24}}$.
  - Other 3f PMNS parameters held fixed at recent NuFit values.
  - $\boldsymbol{\theta_{14}}$ fixed at zero due to constraints from reactor data.
  - Loose Gaussian constraint applied to $\boldsymbol{\Delta m^2_{32}}$.
- 90% CL critical values corrected using Profiled Feldman Cousins approach (arXiv:2207.14353).

$\sin^2\theta_{24}$ vs Δm^2_{41} limits

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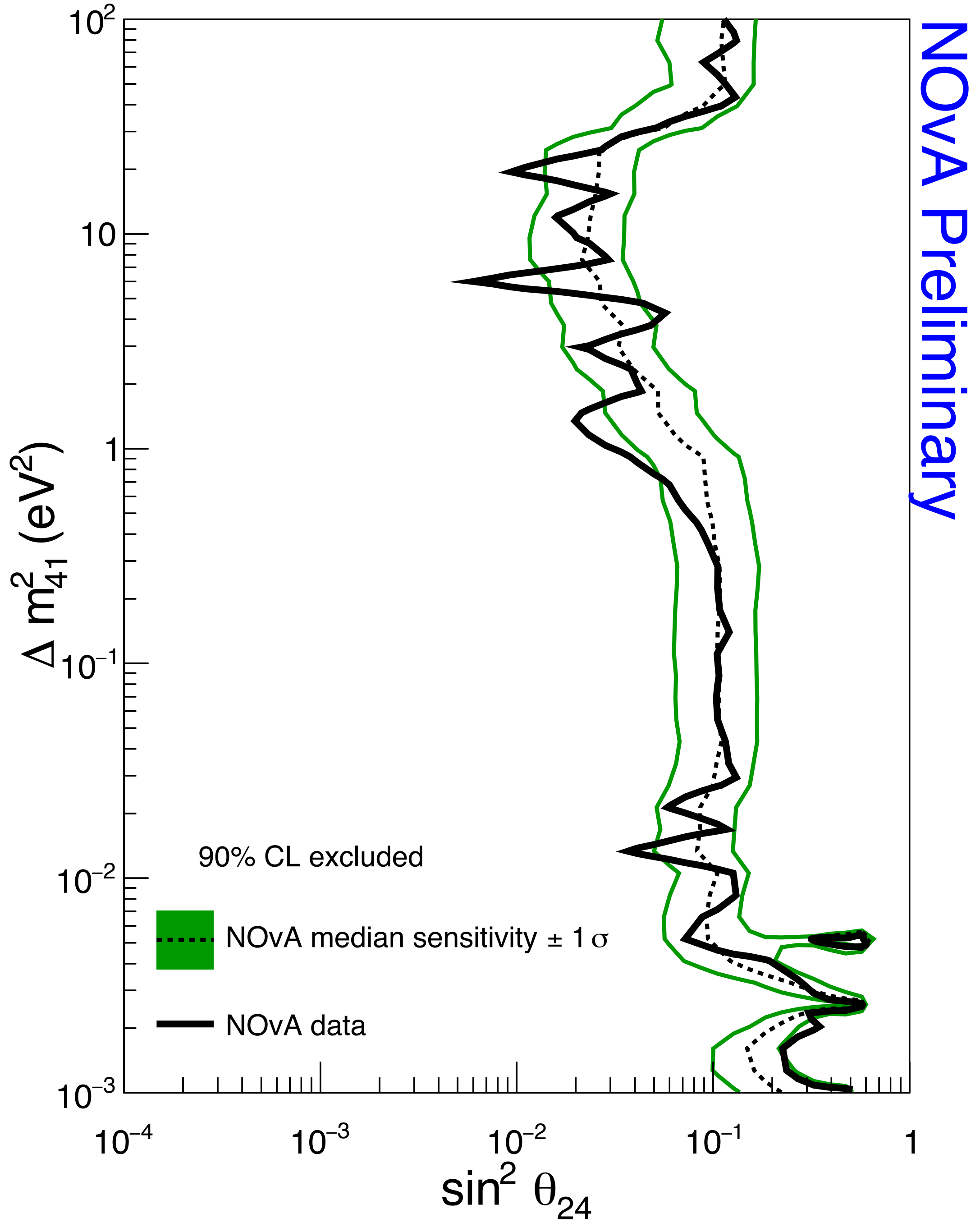

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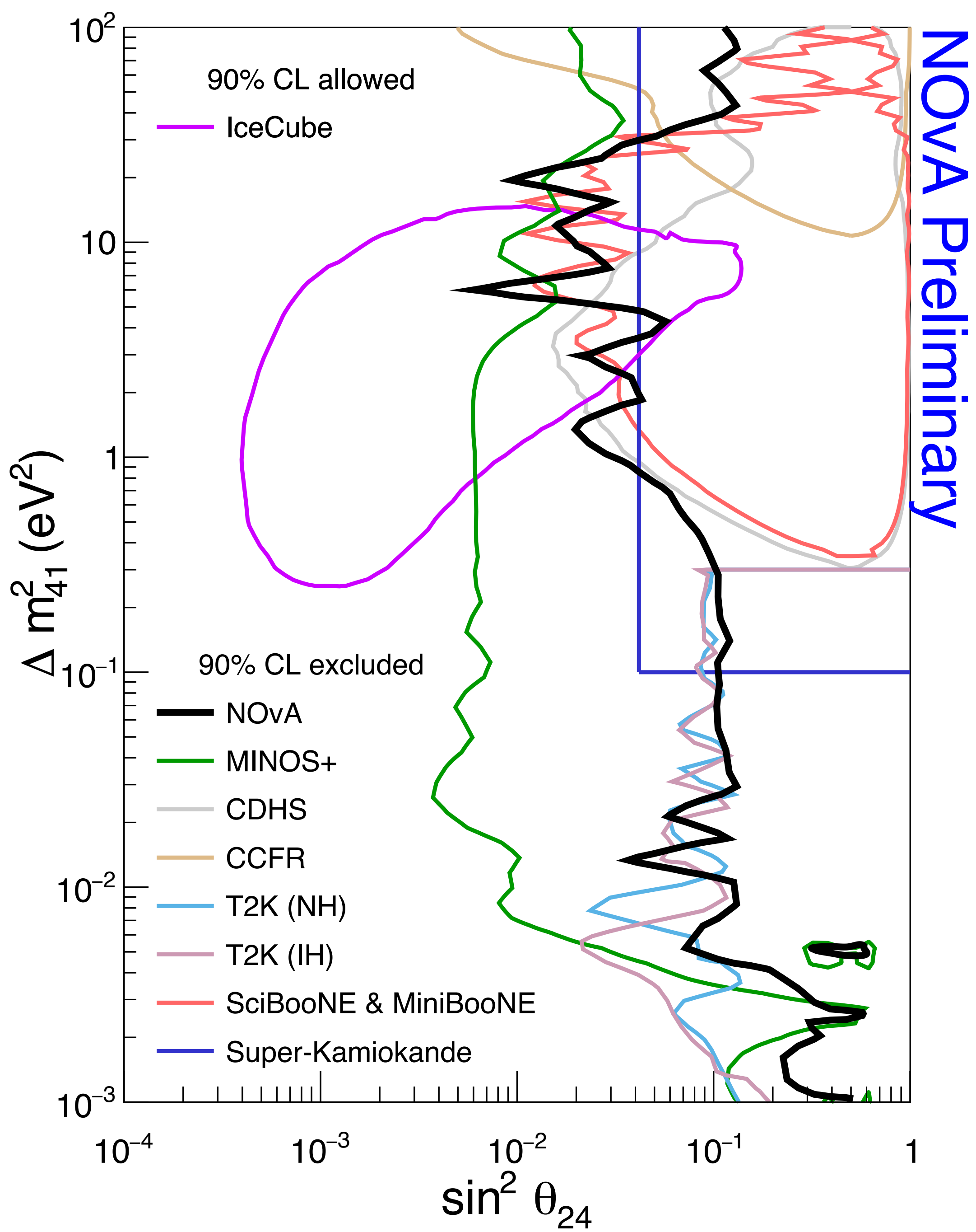
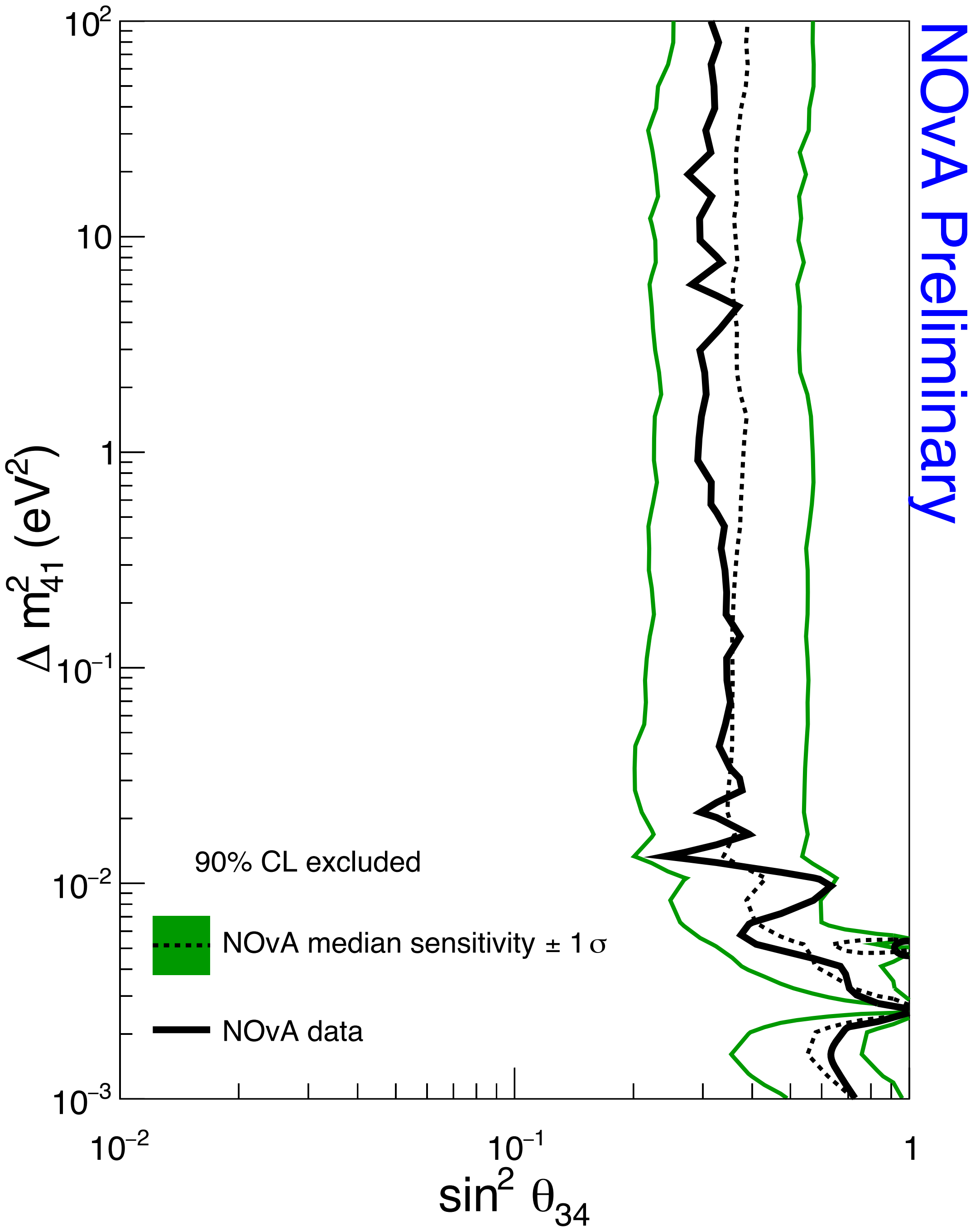


- Profile **θ_{23}**, **Δm^2_{32}**, **θ_{34}** and **δ_{24}**.
  - Other 3f PMNS parameters held fixed at recent NuFit values.
  - **θ_{14}** fixed at zero due to constraints from reactor data.
  - Loose Gaussian constraint applied to **Δm^2_{32}**.
- 90% CL critical values corrected using Profiled Feldman Cousins approach (arXiv:2207.14353).
- **Competitive limits on θ_{24} in high Δm^2_{41} regime**.

$\sin^2\theta_{34}$ vs Δm^2_{41} limits

Neutrino Beam



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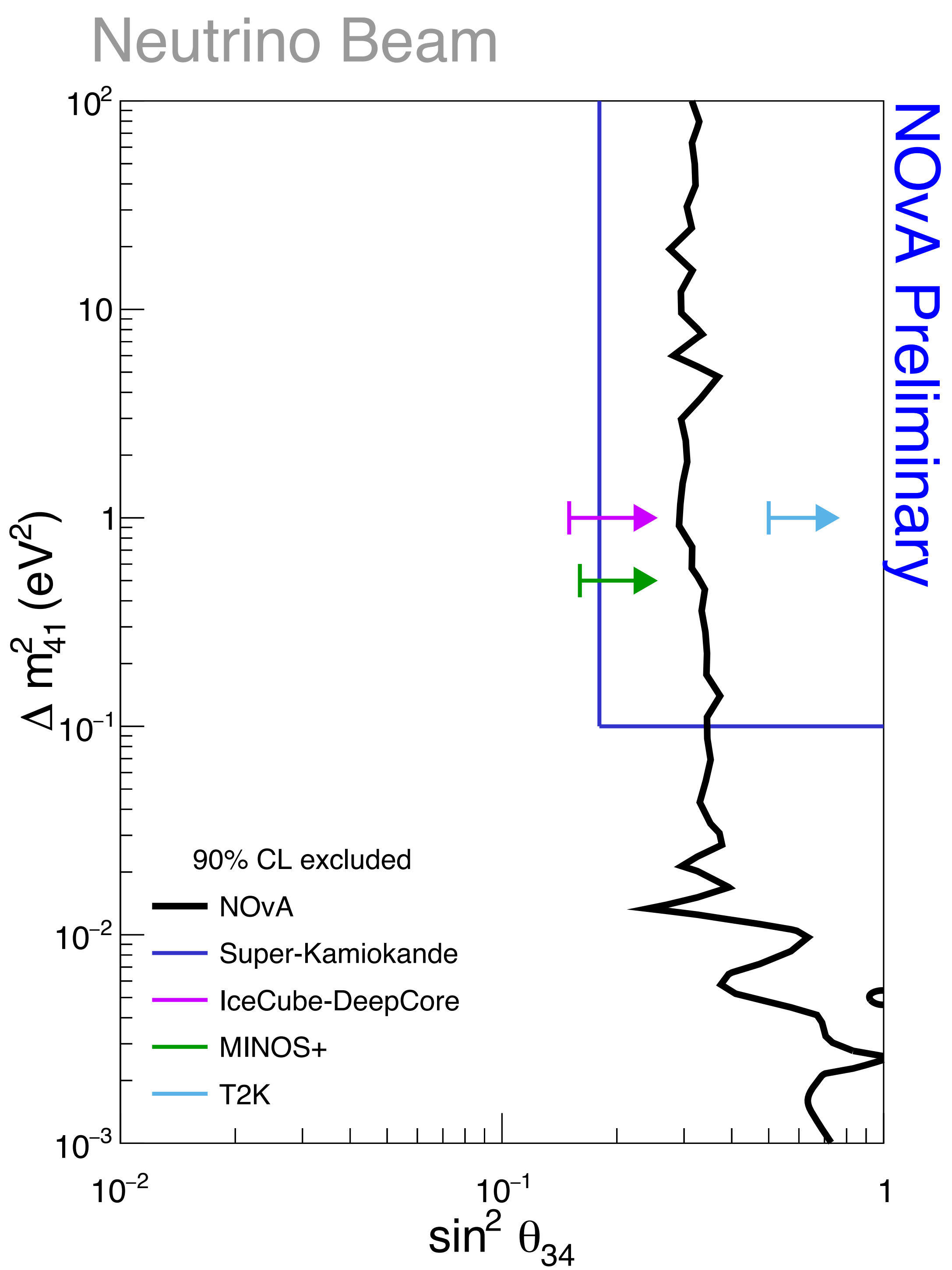
$\sin^2\theta_{34}$ vs Δm^2_{41} limits



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- **World-leading limits in θ_{34} as a function of Δm^2_{41}.**

$\sin^2 2\theta_{\mu\tau}$

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- Short-baseline effective parameterisation:

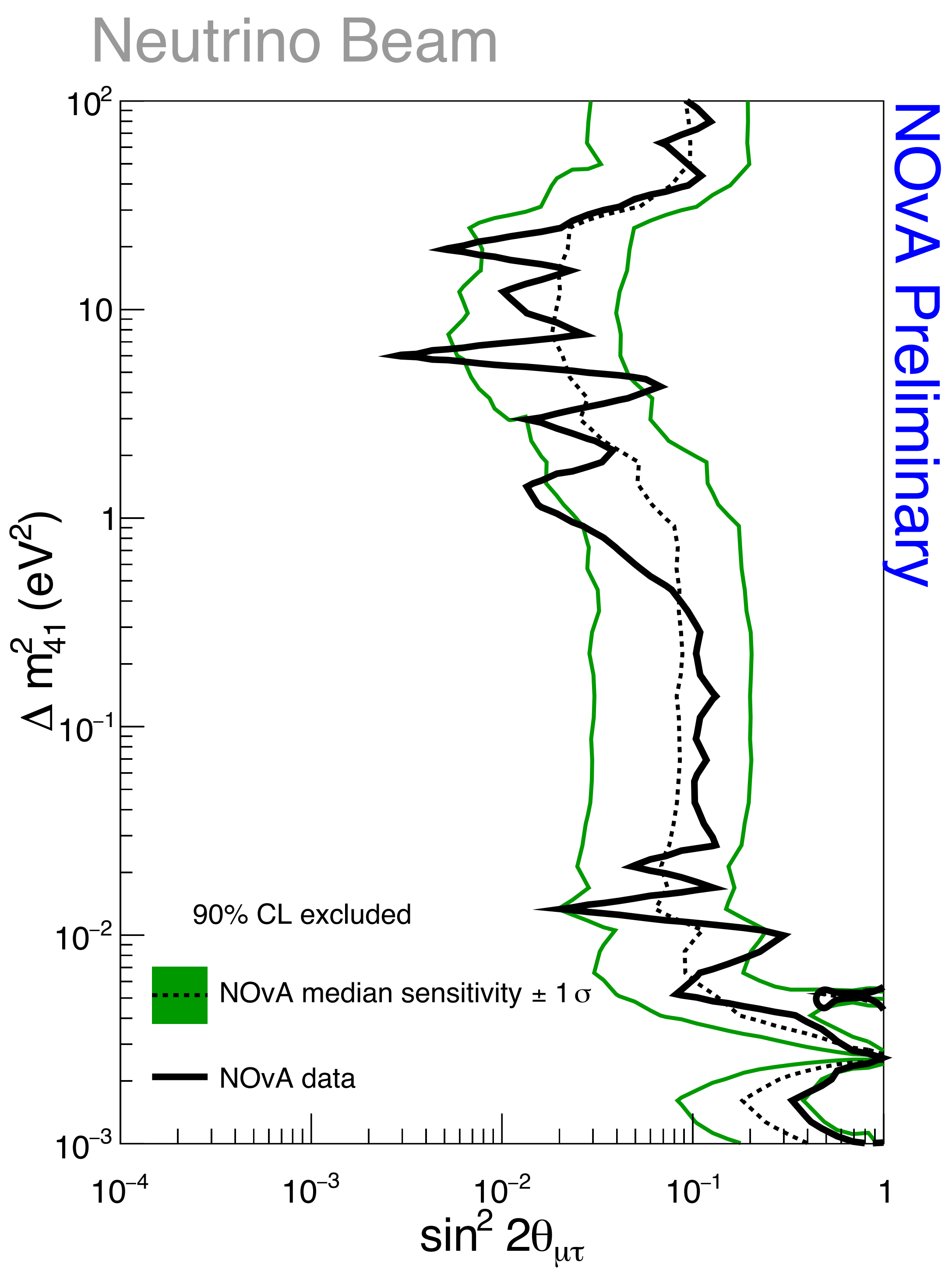
$$P_{\alpha\beta}^{(SBL)} \approx \left| \delta_{\alpha\beta} - \sin^2 2\theta_{\alpha\beta} \sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right) \right|$$

$$\sin^2 2\theta_{\alpha\beta} = 4|U_{\alpha 4}|^2 |\delta_{\alpha\beta} - |U_{\beta 4}|^2|$$

$$\sin^2 2\theta_{\mu\tau} = 4|U_{\mu 4}|^2 |U_{\tau 4}|^2 = \sin^2 2\theta_{24} \sin^2 \theta_{34}$$

- When constructing $\sin^2 2\theta_{\mu\tau}$ surfaces, profile over an effective parameter $\theta_{\mu\tau}^{prof}$ that controls the relative contribution of θ_{24} and θ_{34} to the product.

$\sin^2 2\theta_{\mu\tau}$ vs Δm^2_{41} limits



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$\sin^2 2\theta_{\mu\tau}$ vs Δm^2_{41} limits

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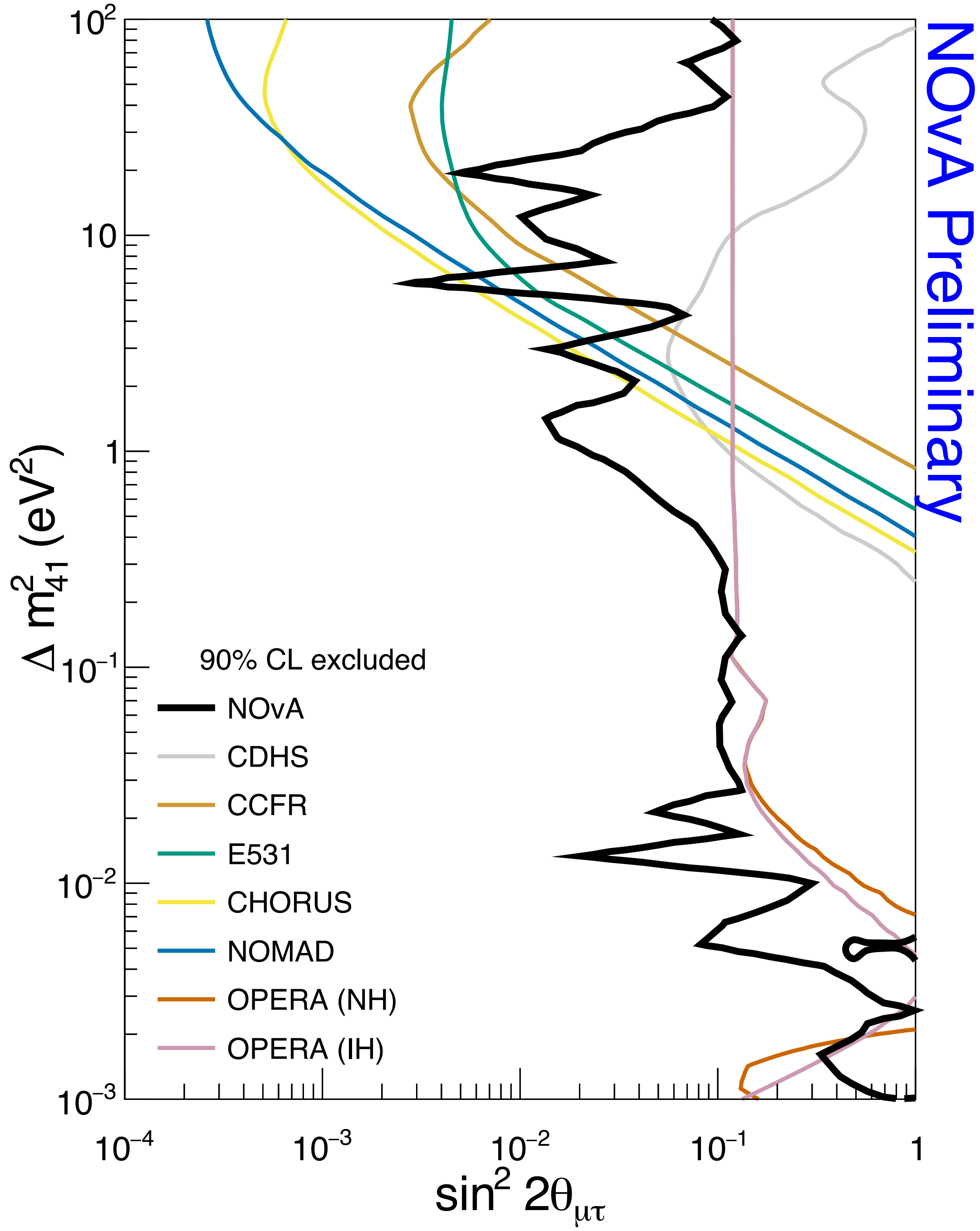

- Profile $\boldsymbol{\theta_{23}}$, $\boldsymbol{\Delta m_{32}^2}$, $\boldsymbol{\theta_{\mu\tau}^{prof}}$ and $\boldsymbol{\delta_{24}}$.
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  - $\boldsymbol{\theta_{14}}$ fixed at zero due to constraints from reactor data.
  - Loose Gaussian constraint applied to $\boldsymbol{\Delta m_{32}^2}$.
- 90% CL critical values corrected using Profiled Feldman Cousins approach (arXiv:2207.14353).
- **World-leading limits on $\boldsymbol{\theta_{\mu\tau}}$ in low $\boldsymbol{\Delta m_{41}^2}$ regime**.

Future plans

- Much scope for expanding two-detector fit mechanism in future:

Future plans

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  - **Constraining oscillations:**

Future plans

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Future plans

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  - **Constraining oscillations:**
    - Introduce antineutrino dataset.
    - Expand to include ν_e selection.

Future plans

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    - Incorporate control samples used for extrapolation analysis into fit directly.

Summary

- Searched for evidence of neutrinos oscillating from an active to sterile state in both NOvA detectors.

- No evidence of sterile neutrino oscillations found at 90% confidence level.

- First exclusion contour in **$\sin^2\theta_{34}$ vs Δm_{41}^2** space.

- **World-leading sensitivity in $\sin^2 2\theta_{\mu\tau}$ at low Δm_{41}^2.**

- Strong potential for future searches with improved sensitivity.


Thank you!

Backups

Neutrino Oscillations

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After propagation, the neutrino now exists in a different superposition of mass states, and can be measured in a different flavour.

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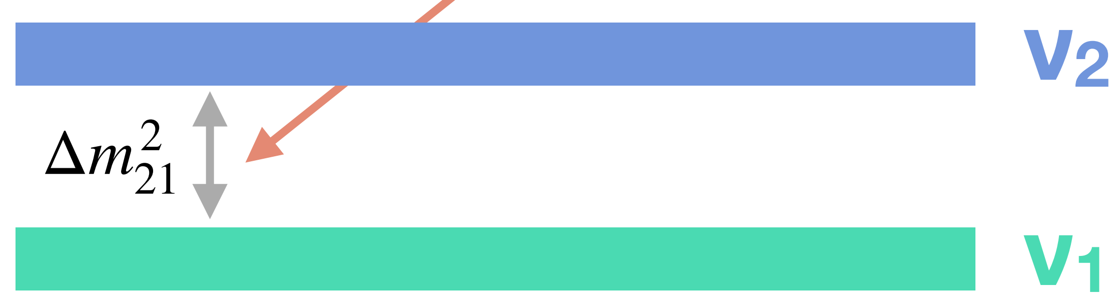
It is also described by two parameters, a **mixing angle** and a **mass splitting**.

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



PISCES

- Statistical uncertainty is provided by a comparison of the data to the systematically shifted prediction via a Poisson likelihood:

$$\chi^2_{\text{stat}} = 2\sum_i^N \left[\left(\sum_\alpha^M \mu_{\alpha i}s_{\alpha i}\right) - x_i + x_i \log\left(\frac{x_i}{\sum_\alpha^M \mu_{\alpha i}s_{\alpha i}}\right)\right]$$

- An additional penalty term is applied to penalise the systematic uncertainties for pulling away from nominal:

$$\chi^2_{\text{syst}} = \sum_{ij}^N \sum_{\alpha\beta}^M (s_{\alpha i} - 1)F_{\alpha i\beta j}(s_{\beta j} - 1)$$

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Exact Statistics

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Parameter Inference

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α = beam component
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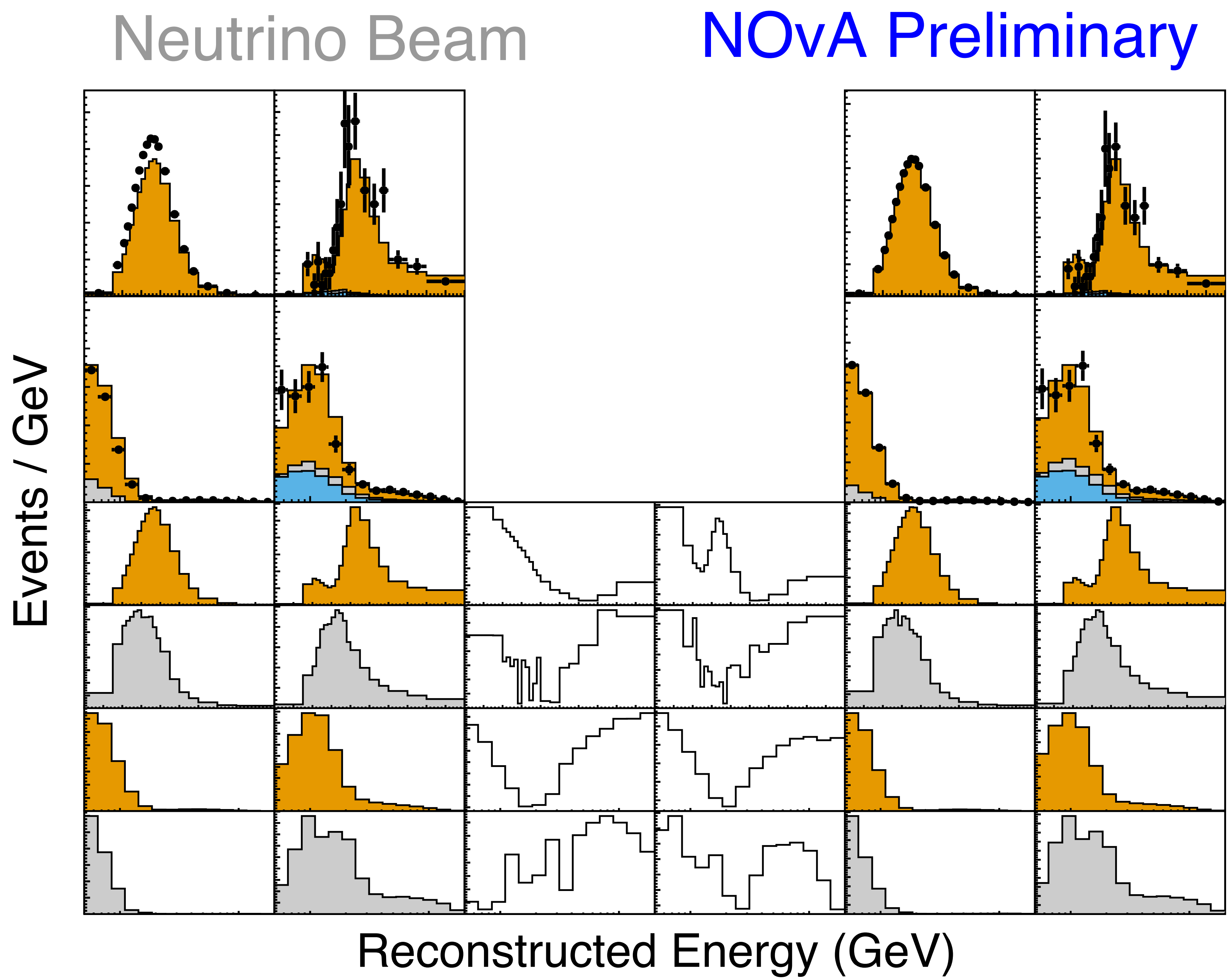
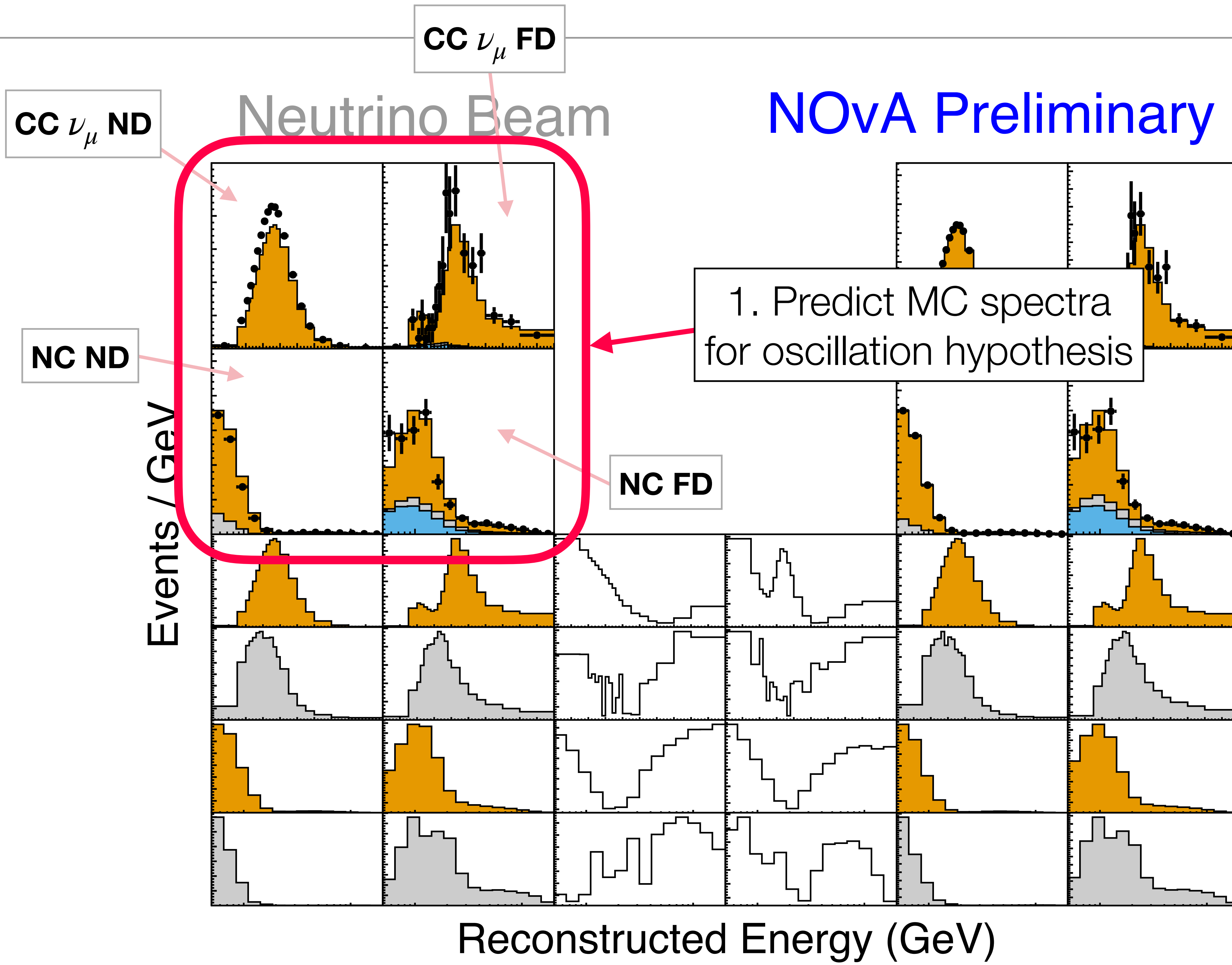
PISCES demonstration



PISCES demonstration



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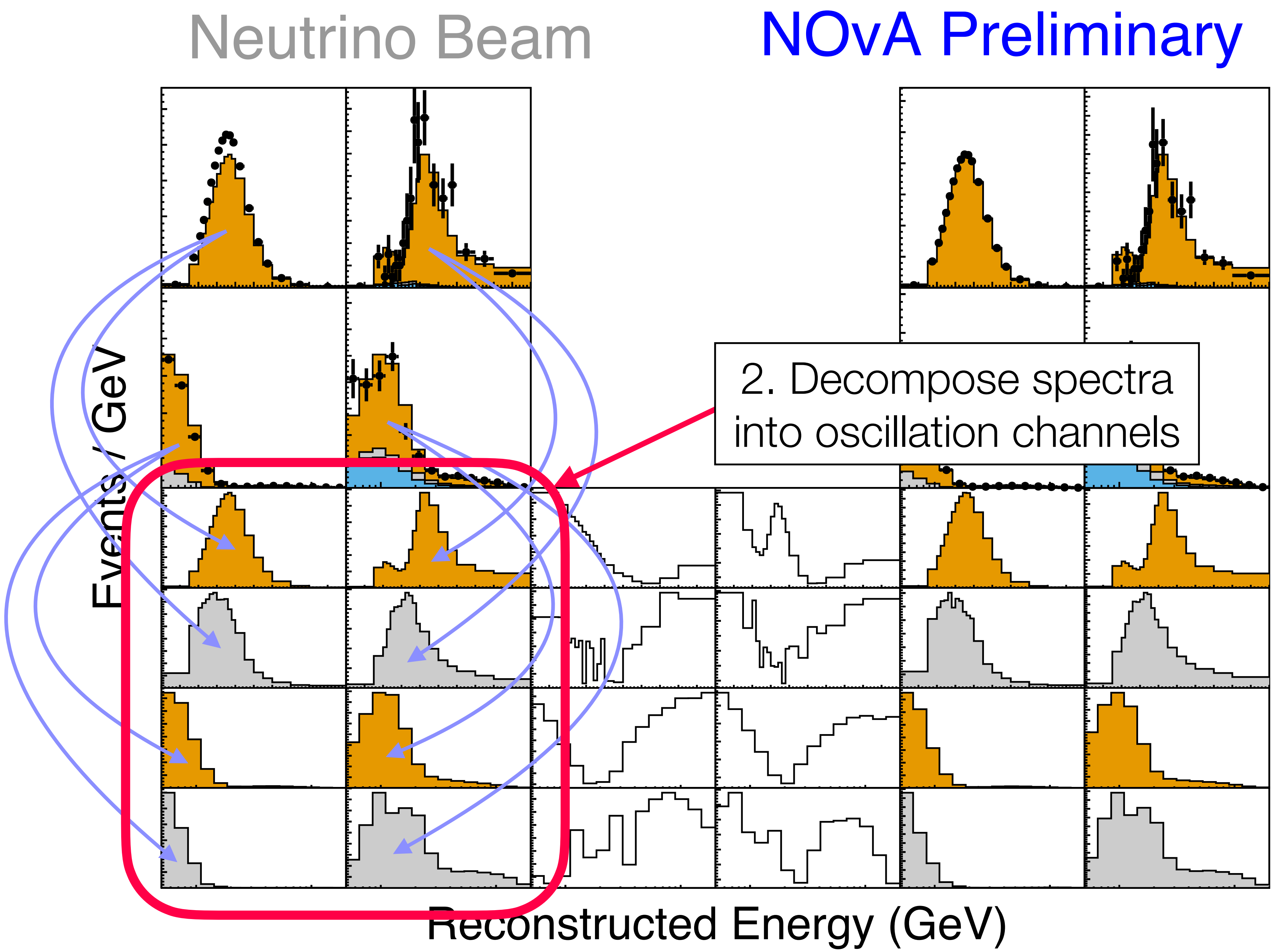

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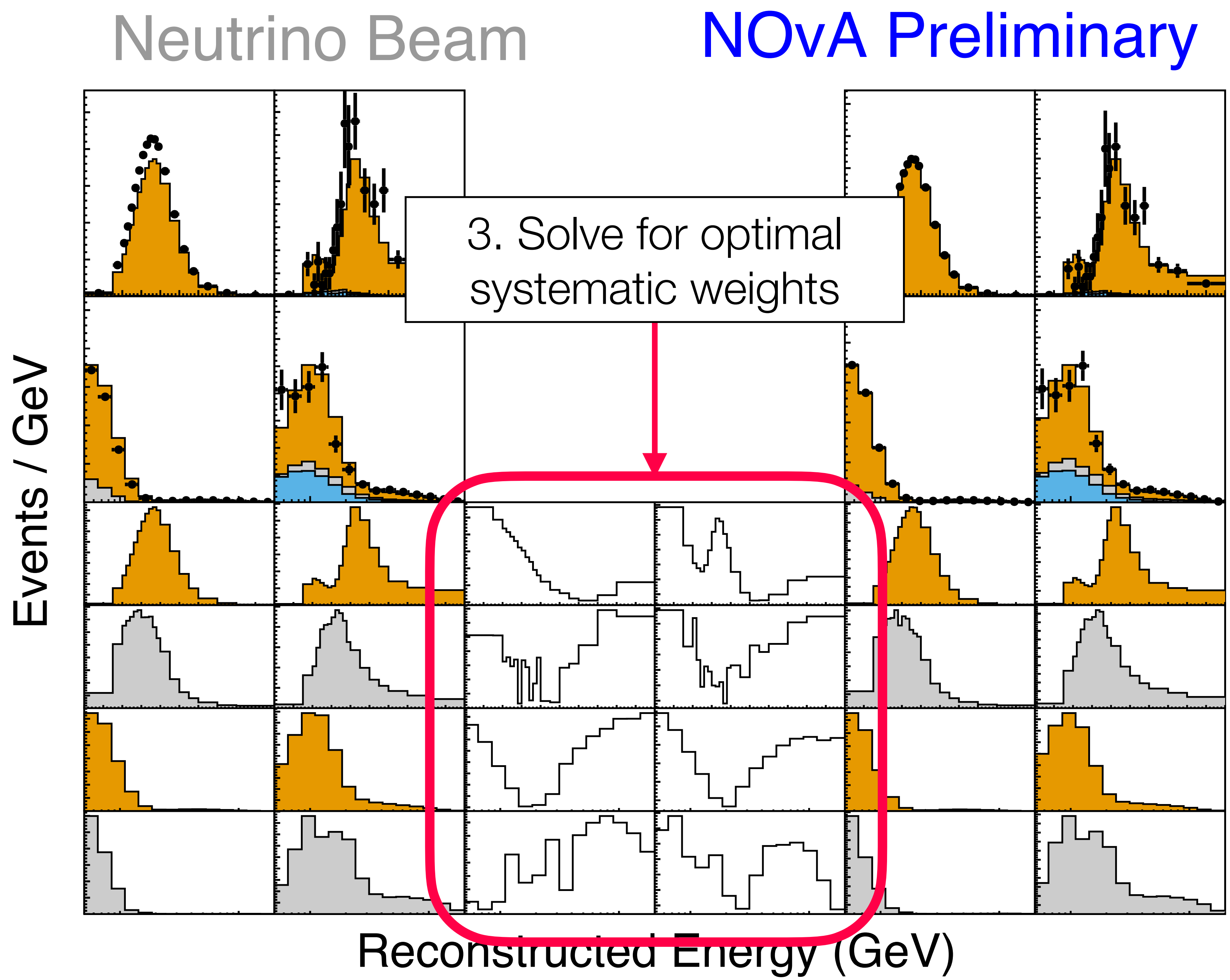

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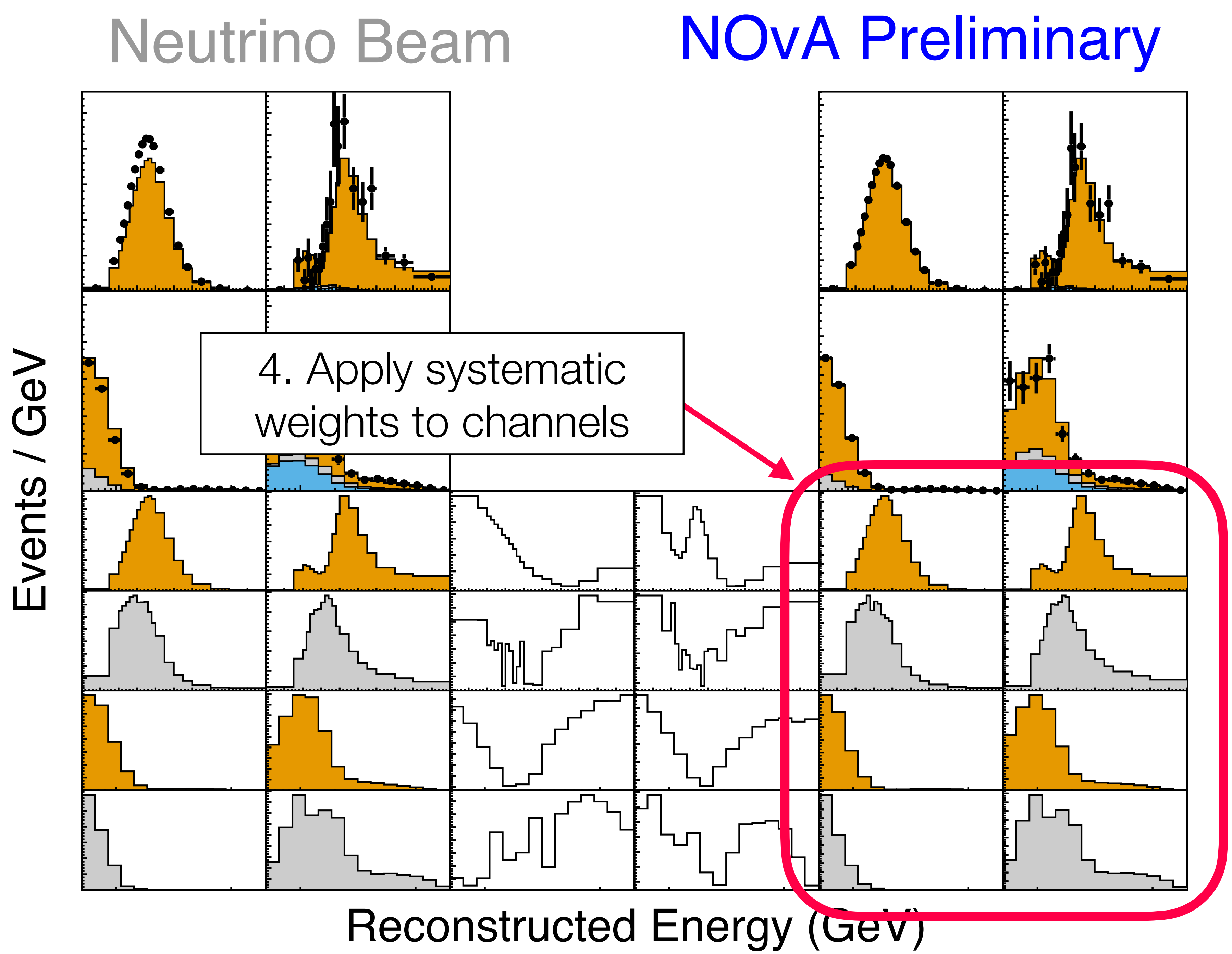

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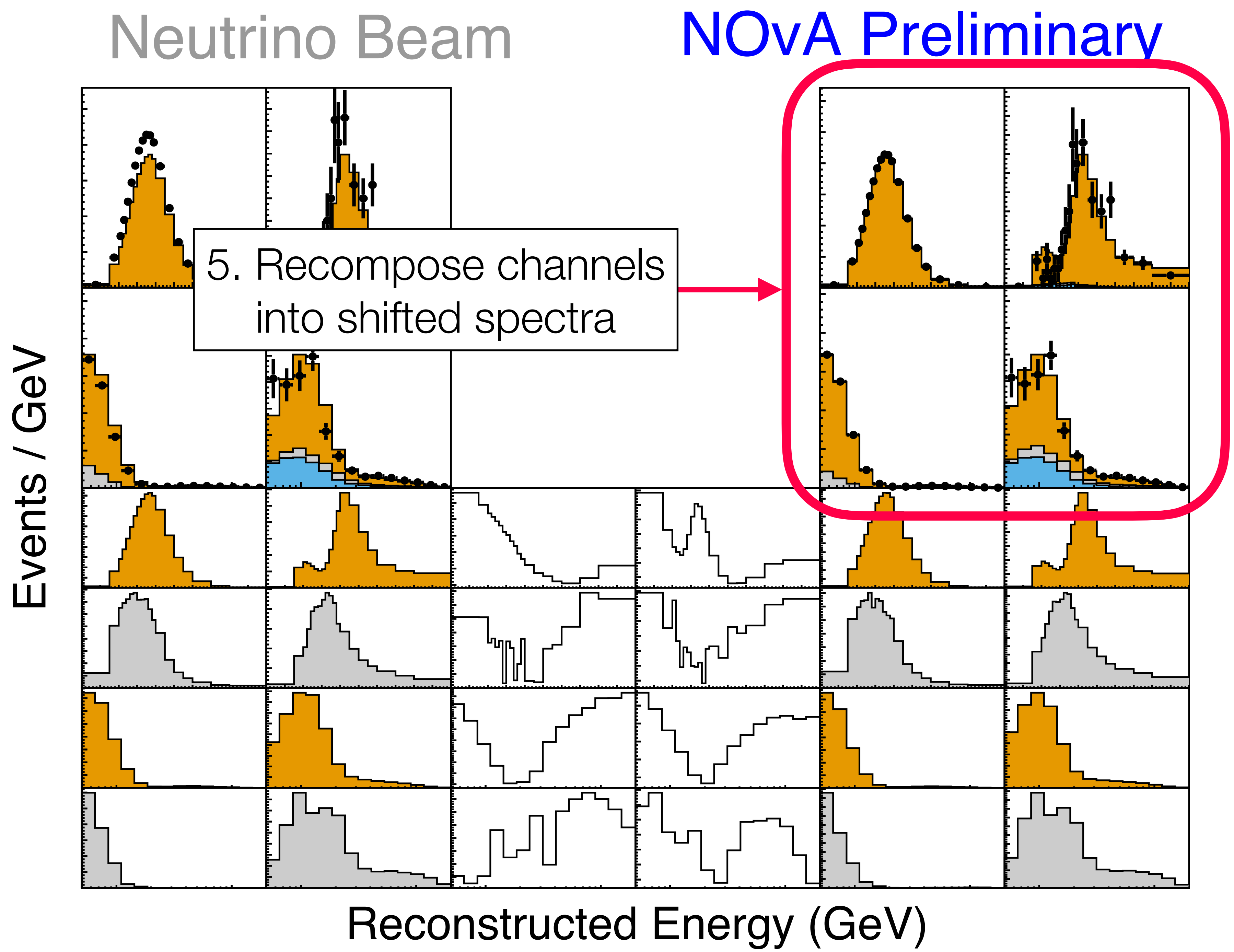
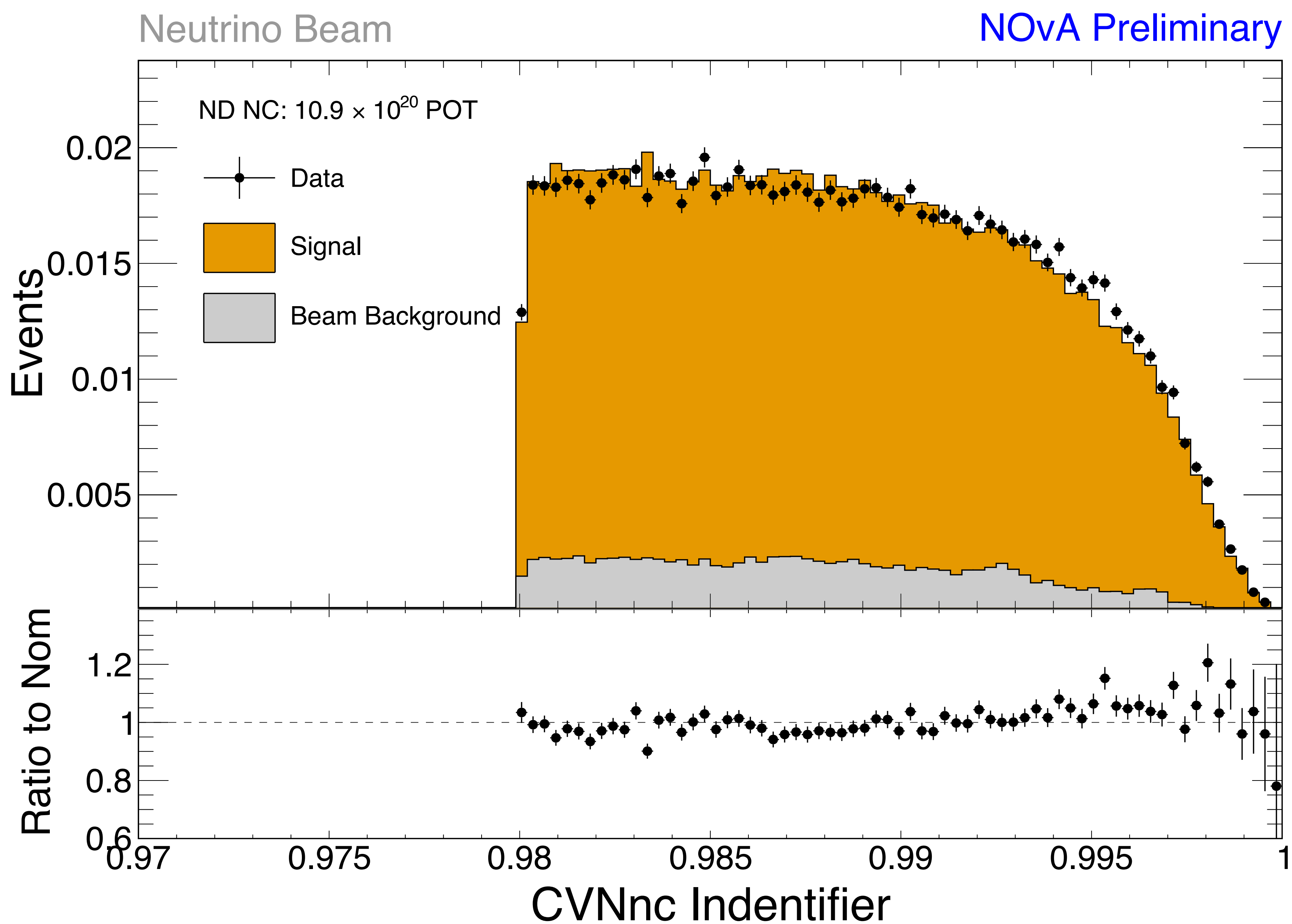


Neutral current near detector PID



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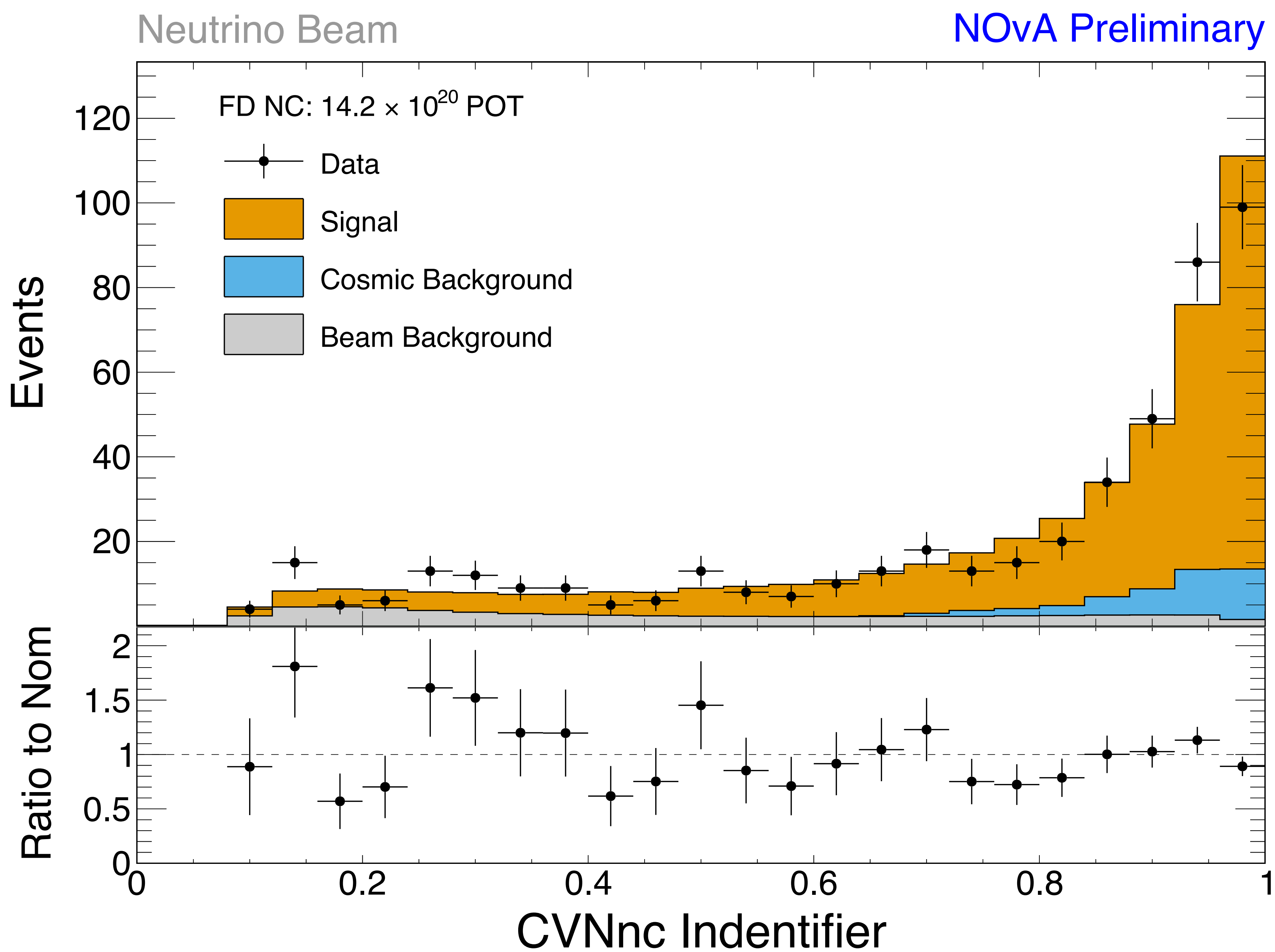
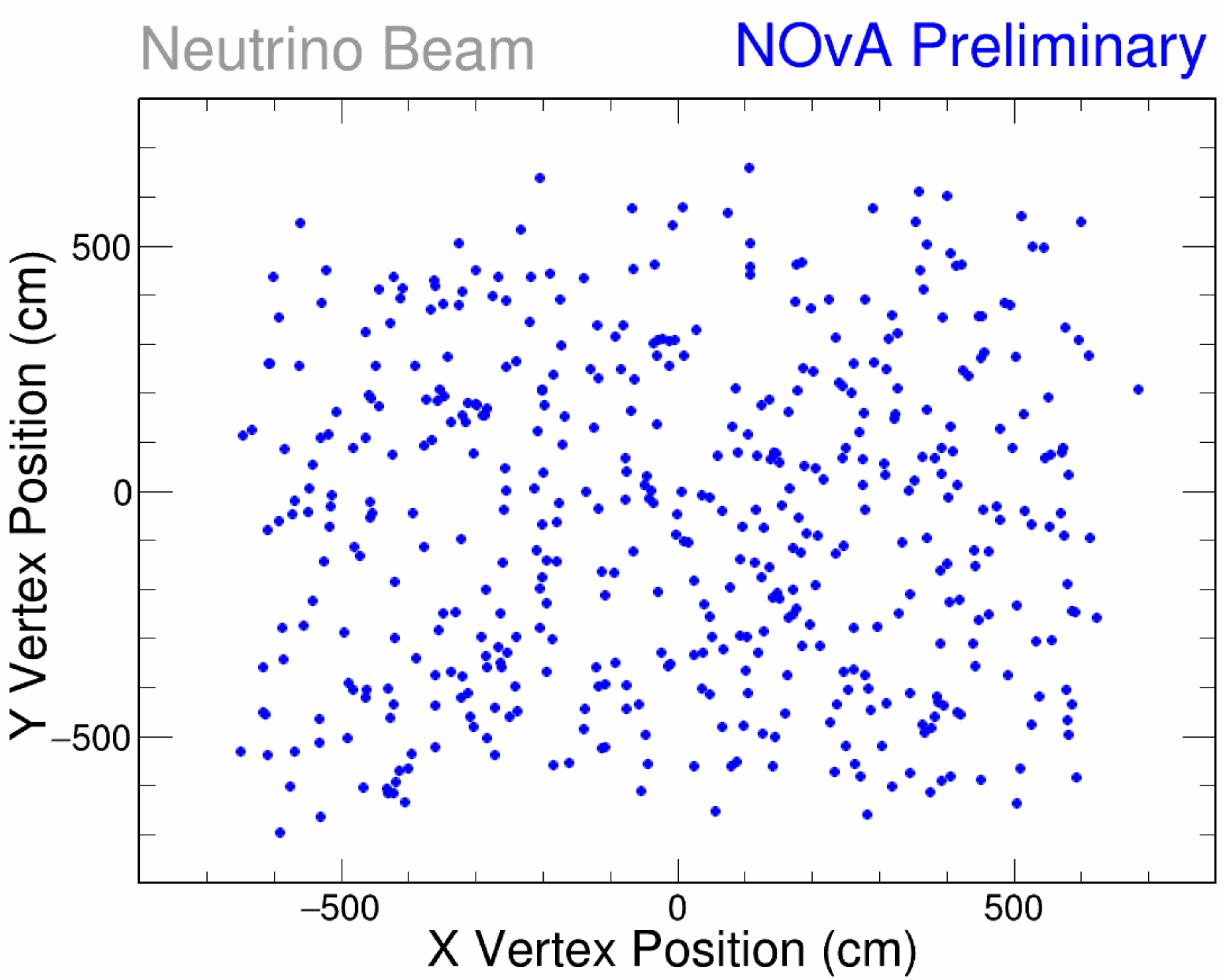


Neutral current far detector vertex position



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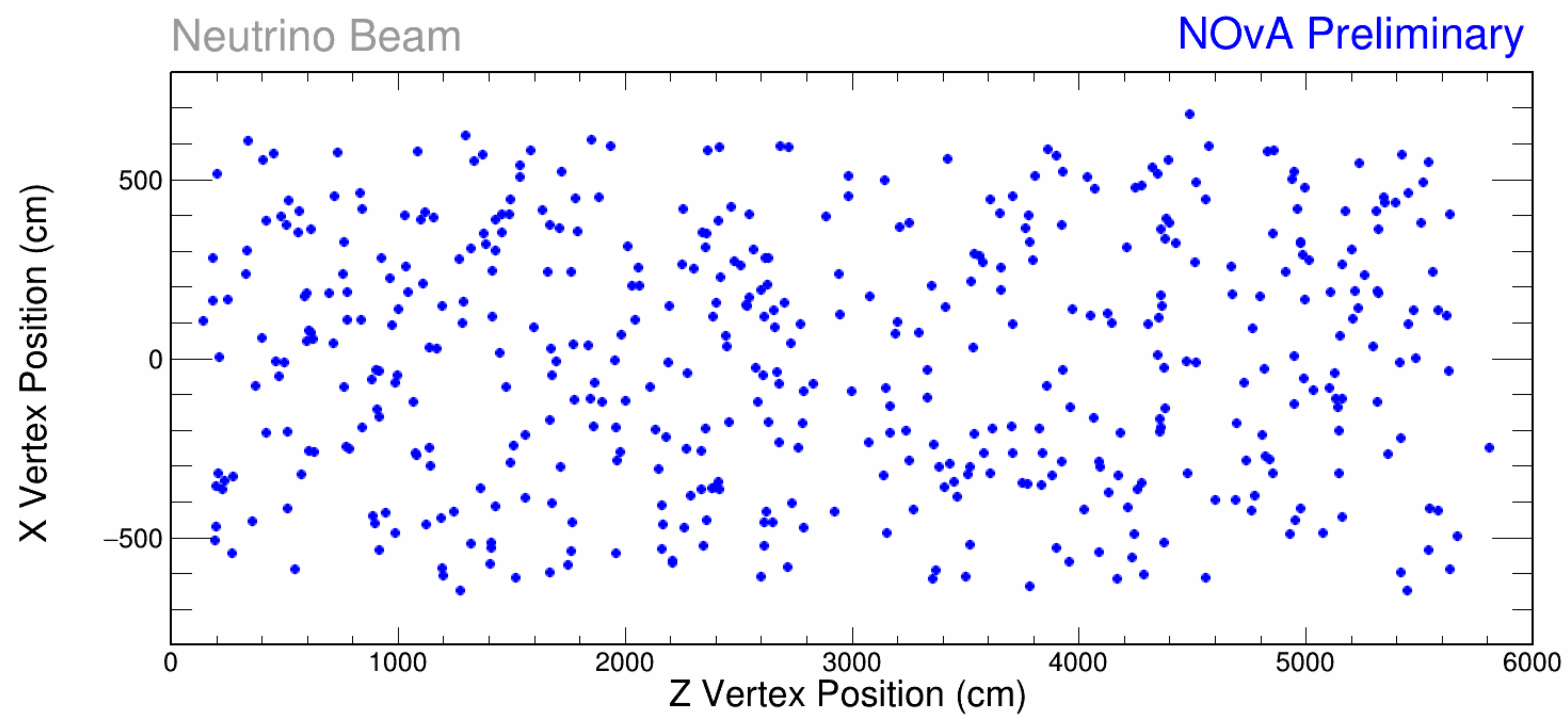

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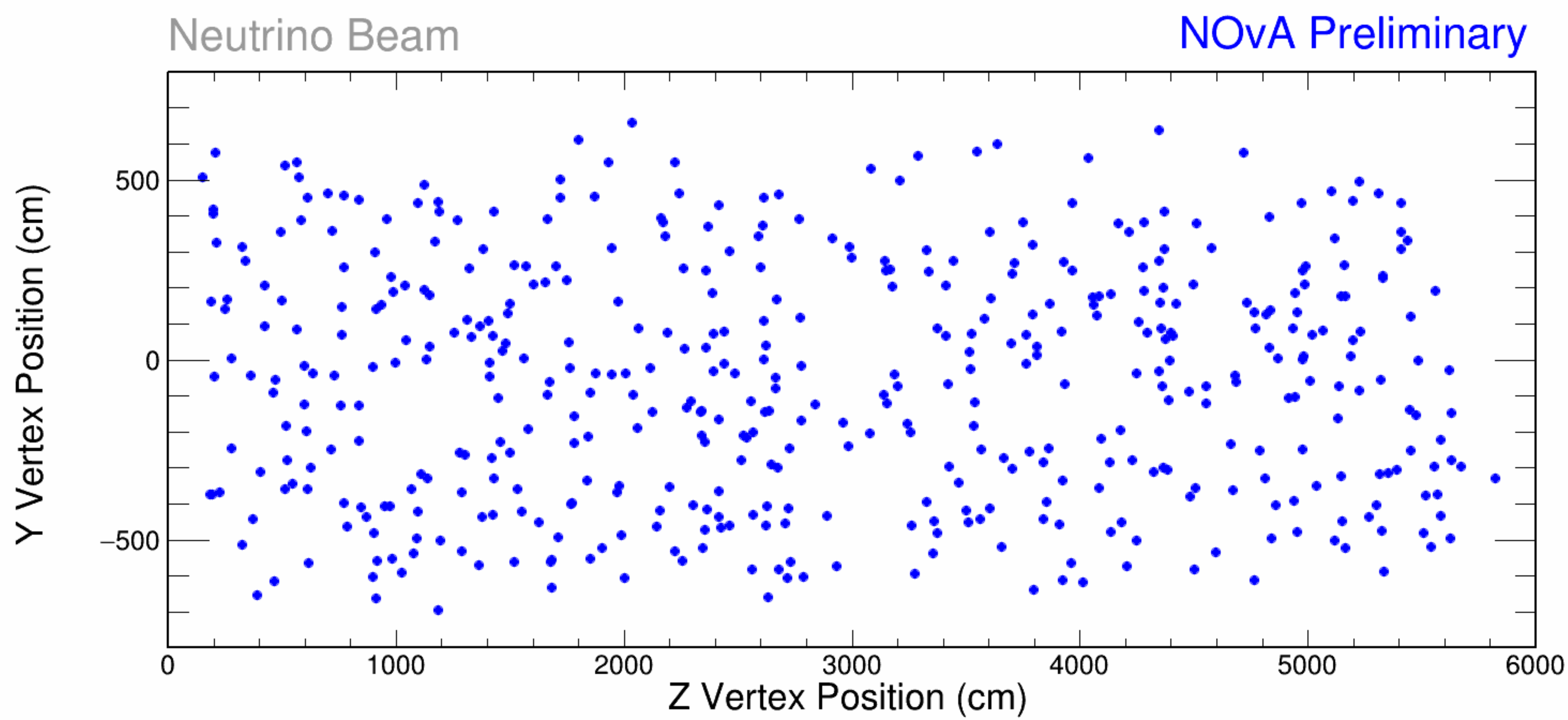

Neutral current near detector selection

	Efficiency	Purity
Data quality	100%	17.40%
Event quality	99.82%	17.38%
Containment	9.65%	42.79%
Neutrino Flavour ID	1.36%	89.51%

Neutral current far detector selection

	Efficiency	Purity
Data quality	100%	0.03%
Event quality	99.82%	0.033%
Containment	54.18%	1.00%
Cosmic Rejection	41.36%	35.34%
Neutrino Flavour ID	39.65%	68.25%

Charged current ν_μ near detector selection

	Efficiency	Purity
Data quality	100%	85.58%
Event quality	17.60%	83.77%
Containment	2.14%	66.78%
Neutrino Flavour ID	1.42%	99.52%

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Charged current ν_μ far detector selection

	Efficiency	Purity
Data quality	100%	0.05%
Event quality	37.79%	0.12%
Containment	15.53%	3.09%
Cosmic Rejection	14.88%	10.12%
Neutrino Flavour ID	12.29%	95.18%

Event counts

ND ν_μ CC	
Data	2826066
Prediction	2448720 ± 451259
Signal	2436864
Background	11855

FD ν_μ CC	
Data	209
Prediction	180.55 ± 34.79
Signal	171.88
Background	3.72
Cosmic	4.95

ND NC	
Data	103109
Prediction	115776 ± 25381
Signal	103635
Background	12142

FD NC	
Data	469
Prediction	475.59 ± 30.36
Signal	324.51
Background	63.9
Cosmic	87.13