

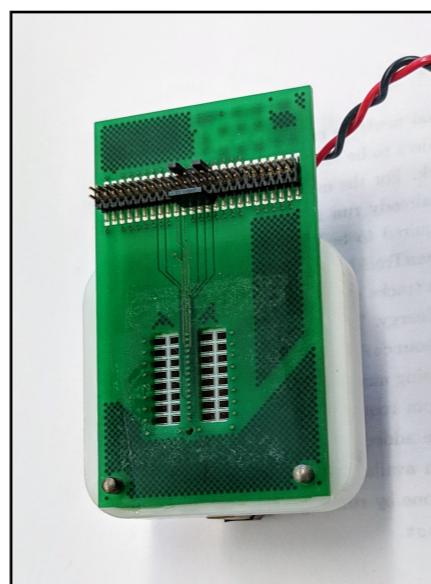
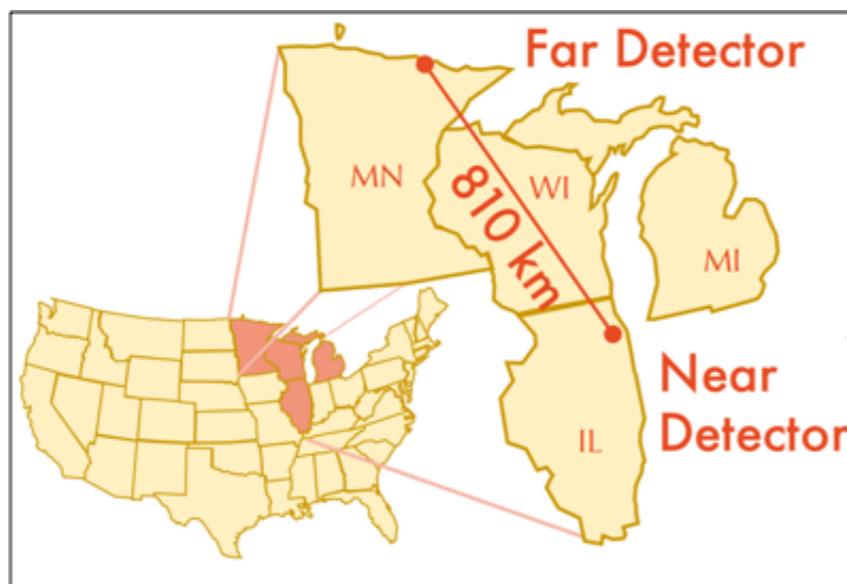


Beyond Standard Model Neutrino Oscillations at NOvA

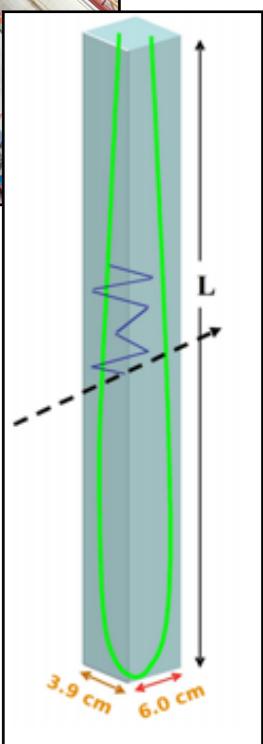
V Hewes, for the NOvA collaboration
23rd International Workshop on Neutrinos from Accelerators
2nd August 2022

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.
 - Plastic and liquid scintillator **sampling tracking calorimeter**.
 - **ND:** 1km baseline, FNAL, 300 tons.
 - **FD:** 810km baseline, Ash River, 14 kt, 14 mrad off-axis.



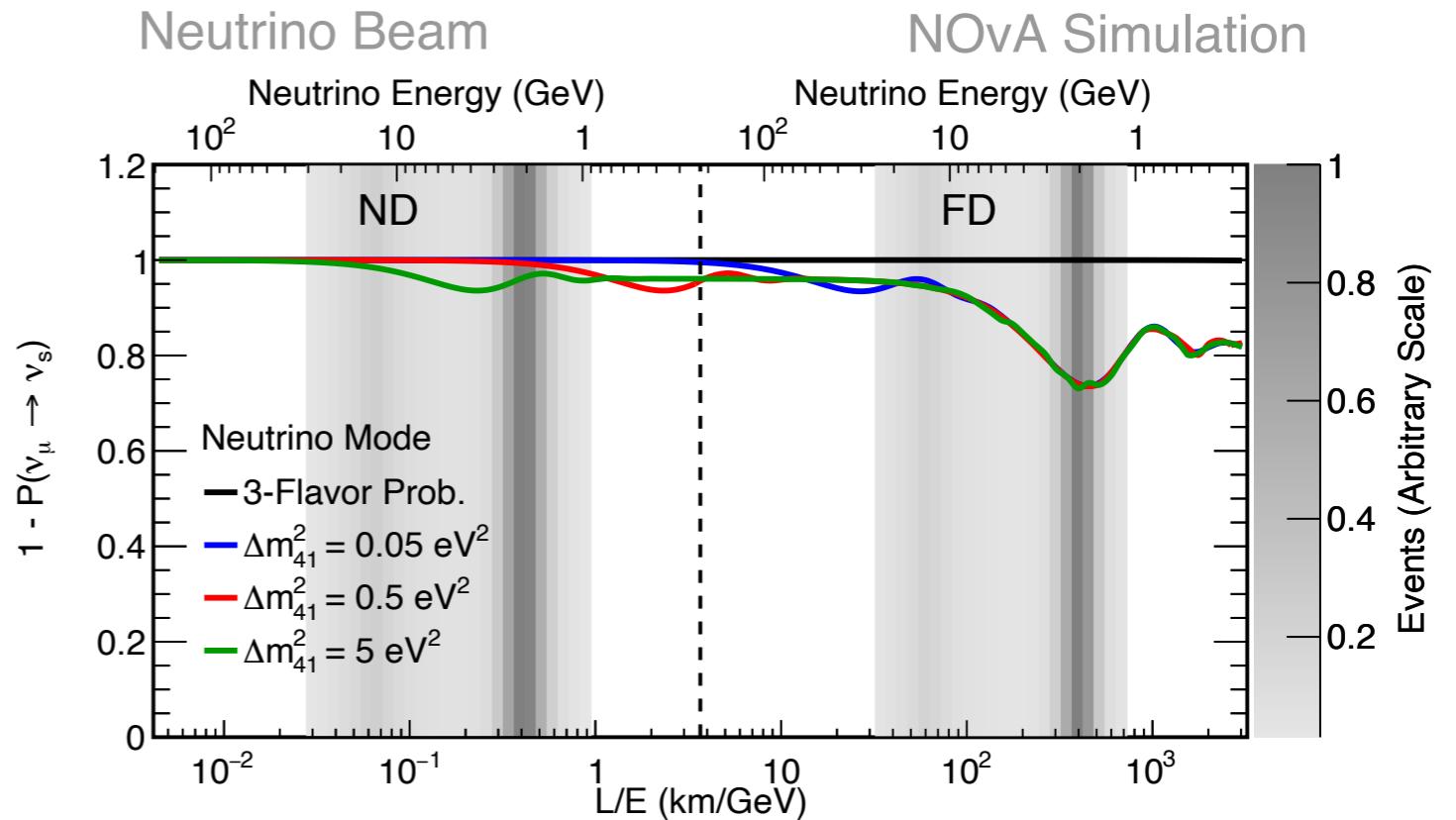
- Charged particles produce light when propagating through scintillator.
- Picked up by wavelength-shifting fibers (right) and amplified by avalanche photodiodes (left).



3+1 sterile neutrino oscillations

3+1 oscillations at NOvA: Neutral Currents

- Probe 3+1 sterile oscillations in NOvA through **neutral current disappearance**.
- NC interactions are flavour-independent.
 - Clean measurement of **active \rightarrow sterile** disappearance.
- At larger $\Delta m_{41}^2 > 0.1 \text{ eV}^2$, rapid oscillations in far detector average out to overall normalisation shift downwards.



$$1 - P(\nu_\mu \rightarrow \nu_s) \approx 1 - \cos^4 \theta_{14} \cos^2 \theta_{34} \sin^2 2\theta_{24} \sin^2 \Delta_{41}$$

$$- \sin^2 \theta_{34} \sin^2 2\theta_{23} \sin^2 \Delta_{31}$$

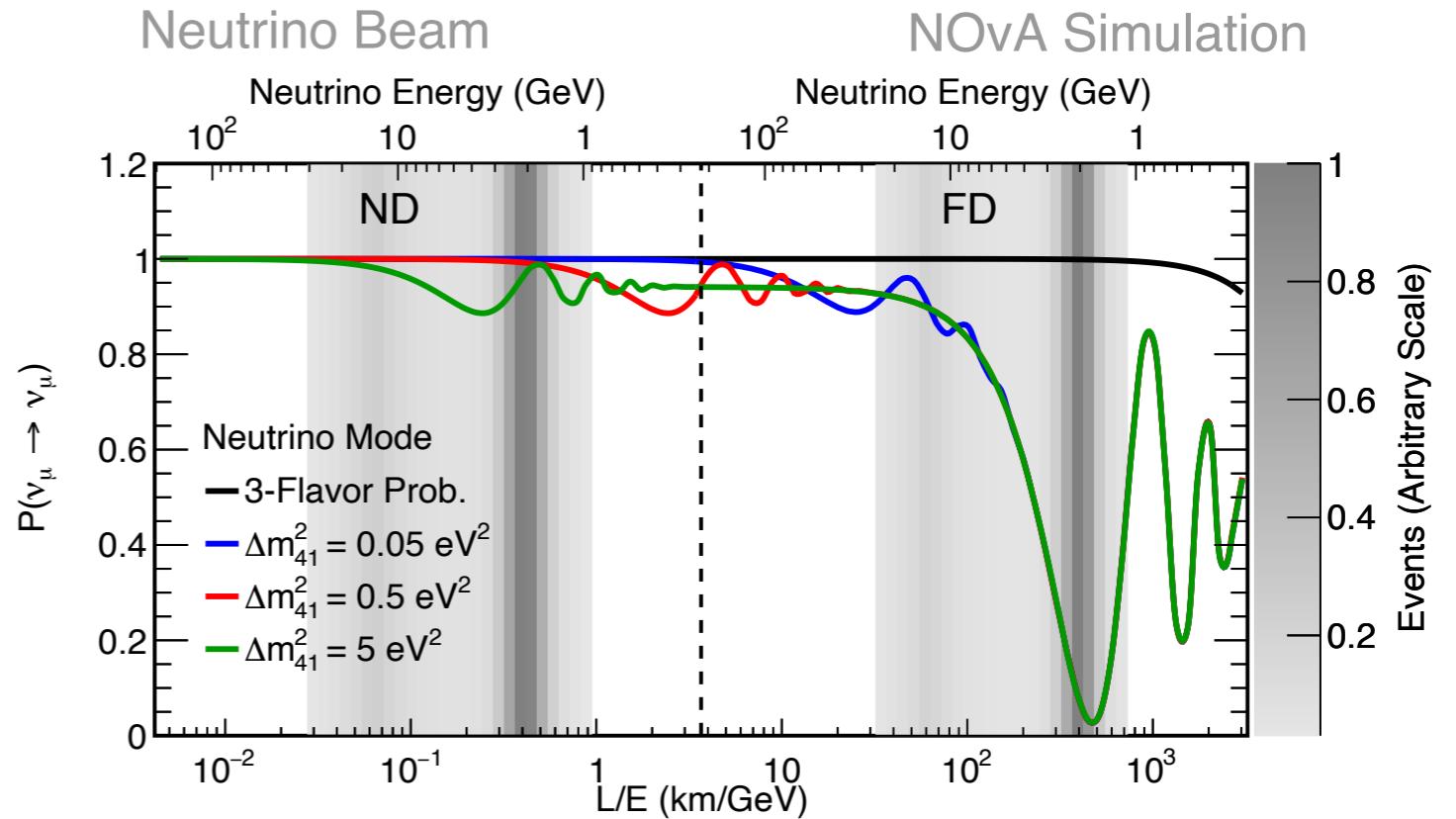
$$+ \frac{1}{2} \sin \delta_{24} \sin \theta_{24} \sin 2\theta_{23} \sin \Delta_{31}$$

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

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

3+1 oscillations at NOvA: ν_μ Charged Currents

- Probe 3+1 sterile oscillations in NOvA through **charged current** ν_μ **disappearance**.
- Sterile neutrinos manifest as additional ν_μ disappearance, above any expected from standard 3-flavour oscillations.
- At larger $\Delta m_{41}^2 > 0.1 \text{ eV}^2$, rapid oscillations in far detector average out to overall normalisation shift downwards.



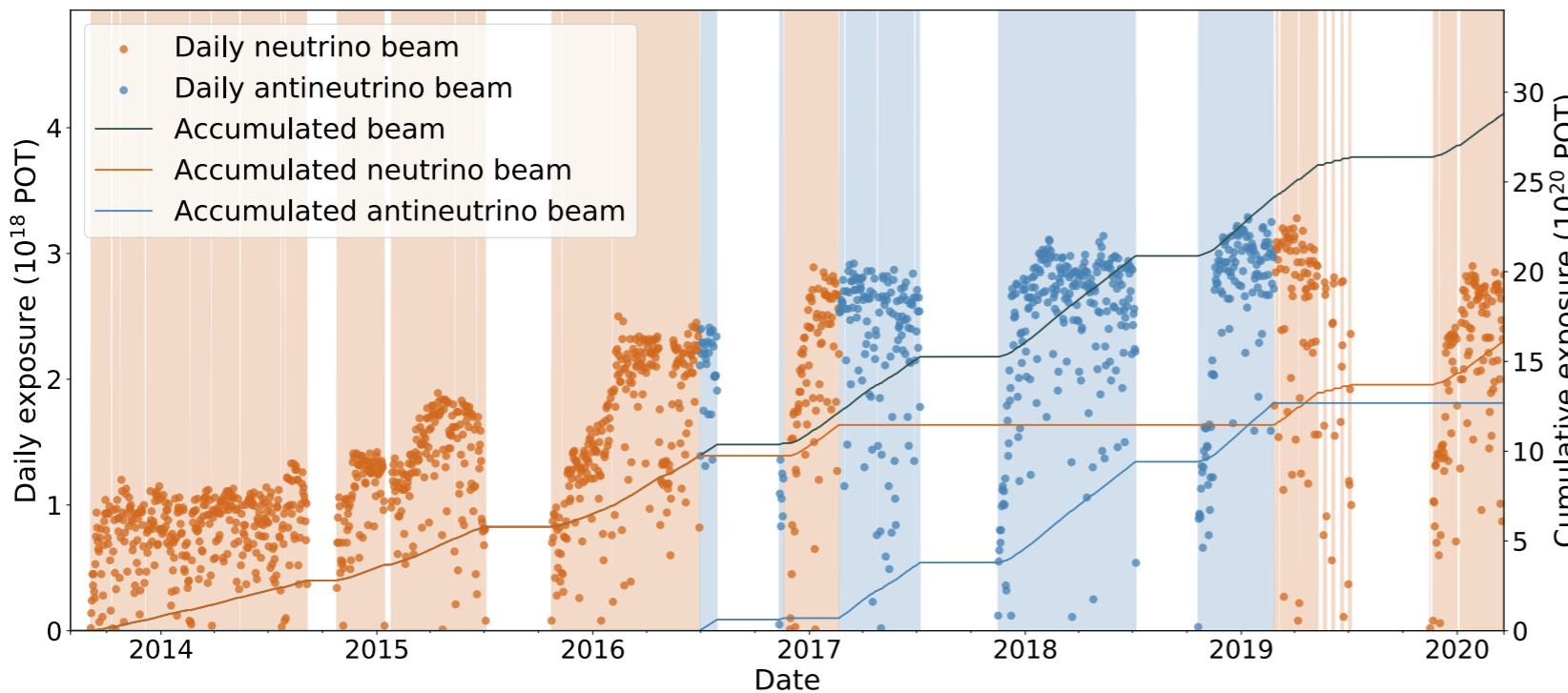
$$\begin{aligned}
 P(\nu_\mu \rightarrow \nu_\mu) \approx & 1 - \sin^2 2\theta_{24} \sin^2 \Delta_{41} \\
 & + 2 \sin^2 2\theta_{23} \sin^2 \theta_{24} \sin^2 \Delta_{31} \\
 & - \sin^2 2\theta_{23} \sin^2 \Delta_{31}
 \end{aligned}$$

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

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

3+1 sterile neutrino oscillation analysis

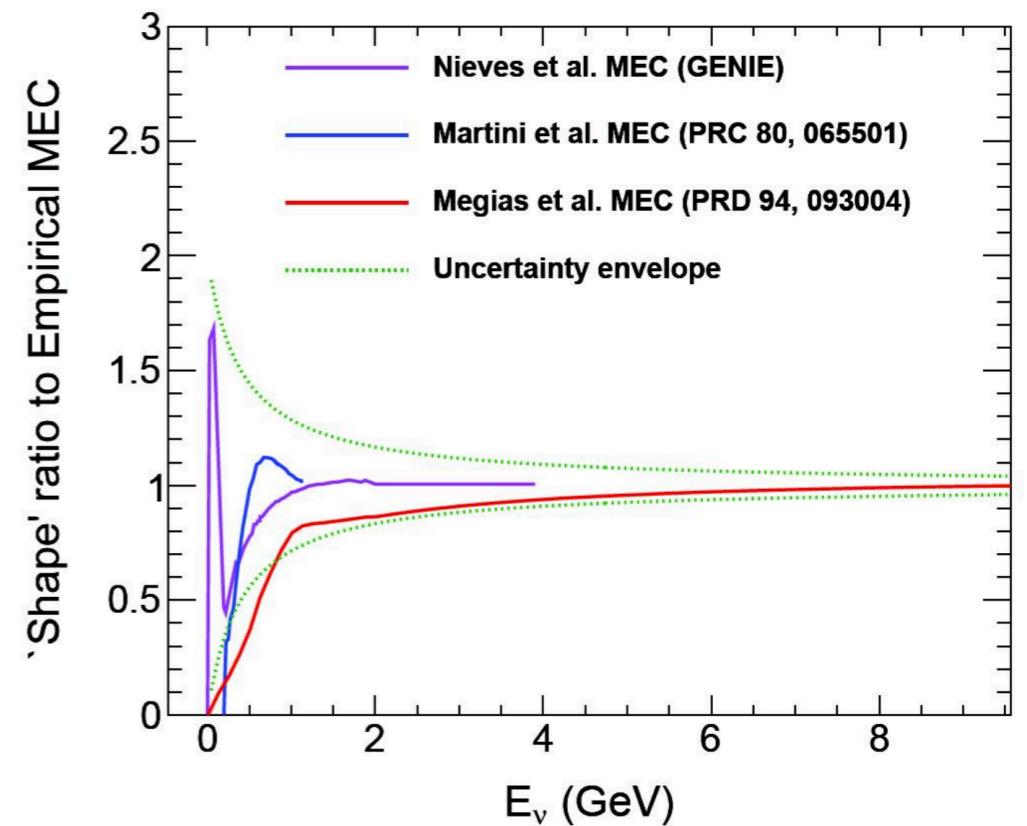
- NOvA's new 3+1 sterile neutrino search utilises a **two-detector fit** approach with **neutral current (NC)** and **charged current (CC) ν_μ** samples.
 - The ability to fit to oscillation signals in the near detector significantly expands reach in Δm_{41}^2 space probed.
 - Analysis performed with two independent approaches, **PISCES** and **CMF**.
 - Both methods utilise different novel Gaussian multivariate test statistics and find consistent results, acting as a crosscheck on each other.



- Utilise neutrino-mode subset of 2020 3-flavour analysis dataset ([arxiv:2108.08219](https://arxiv.org/abs/2108.08219))
 - 11.0×10^{20} POT in the near detector.
 - 13.6×10^{20} POT equivalent in the far detector.

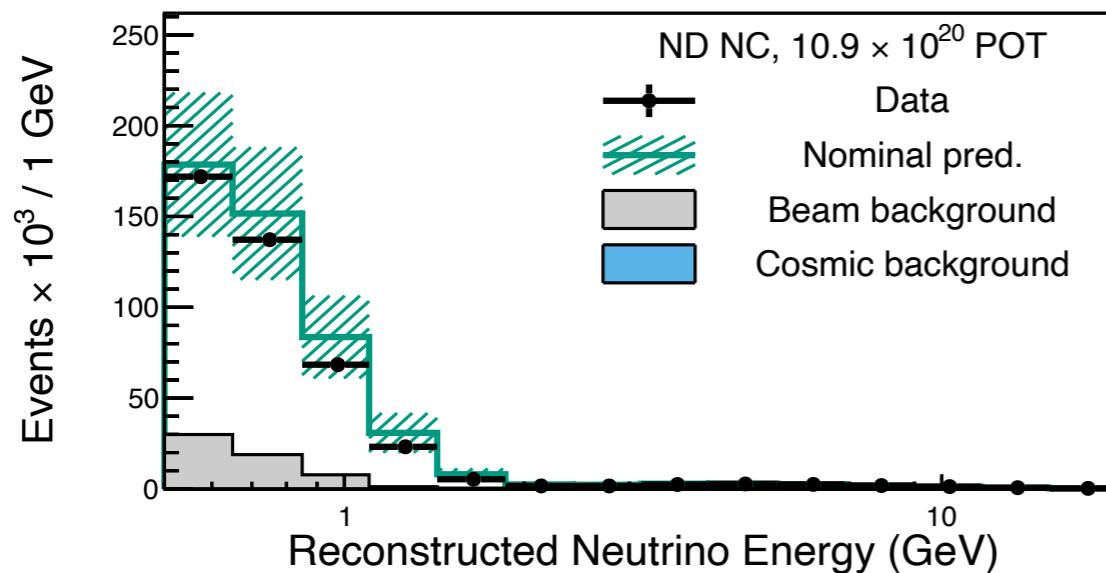
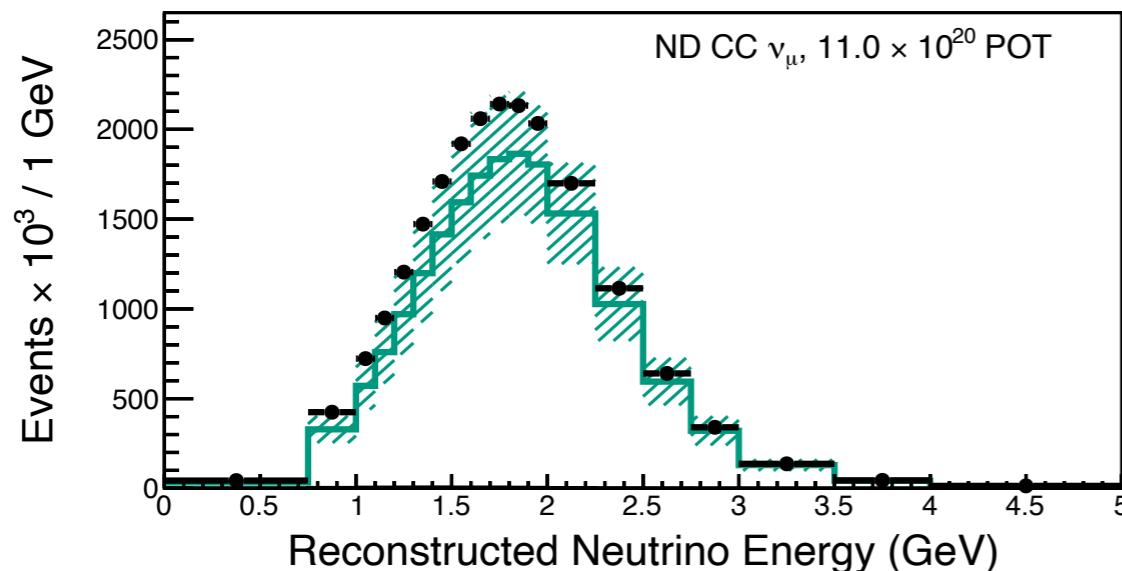
Systematic uncertainties

- This analysis utilises new normalisation and model spread uncertainties for Meson Exchange Current (MEC) events.
 - NOvA's standard data-driven cross-section tune cannot be used for this analysis, as it relies on near detector data.
- New 5% normalisation uncertainty on neutrinos with kaon ancestors, based on horn-off neutrino data.
- Full suite of systematic uncertainties:
 - GENIE cross-section reweights.
 - Beam transport & PPFX flux.
 - Detector response.
 - Overall normalisation.
 - ...plus more minor uncertainties.

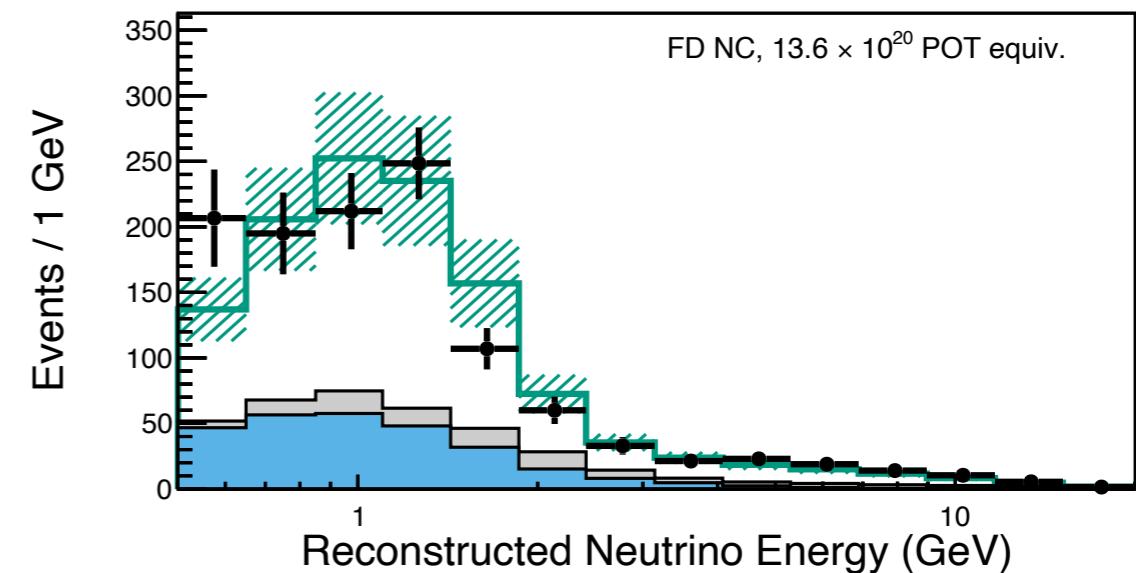
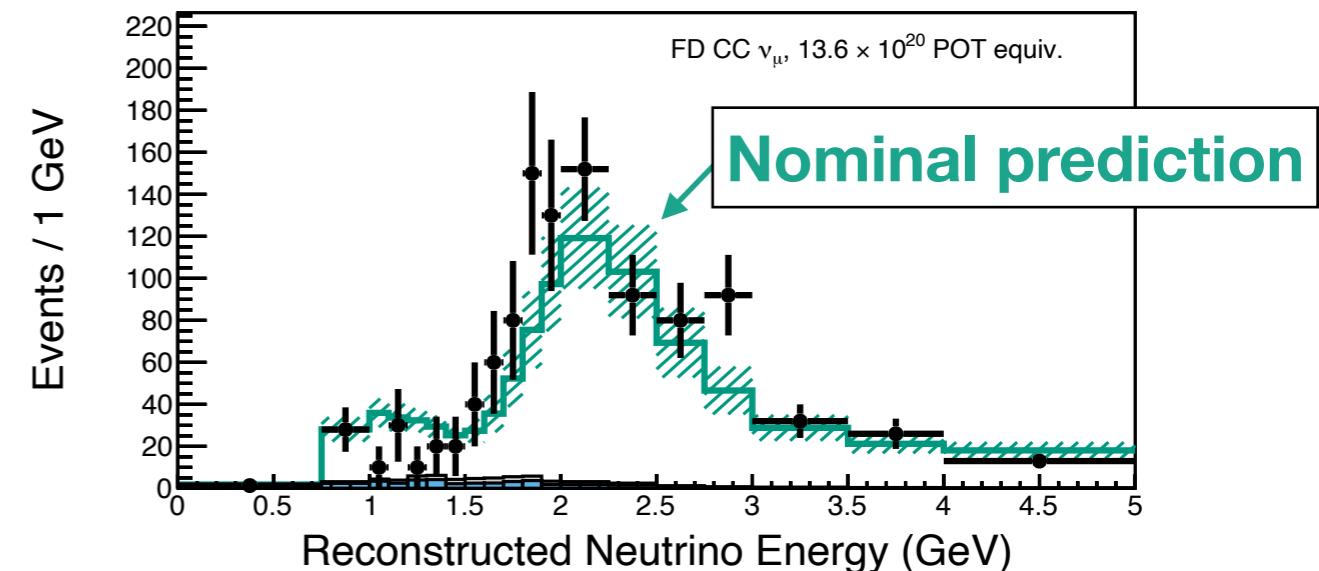


Sterile neutrino search results

Neutrino Beam

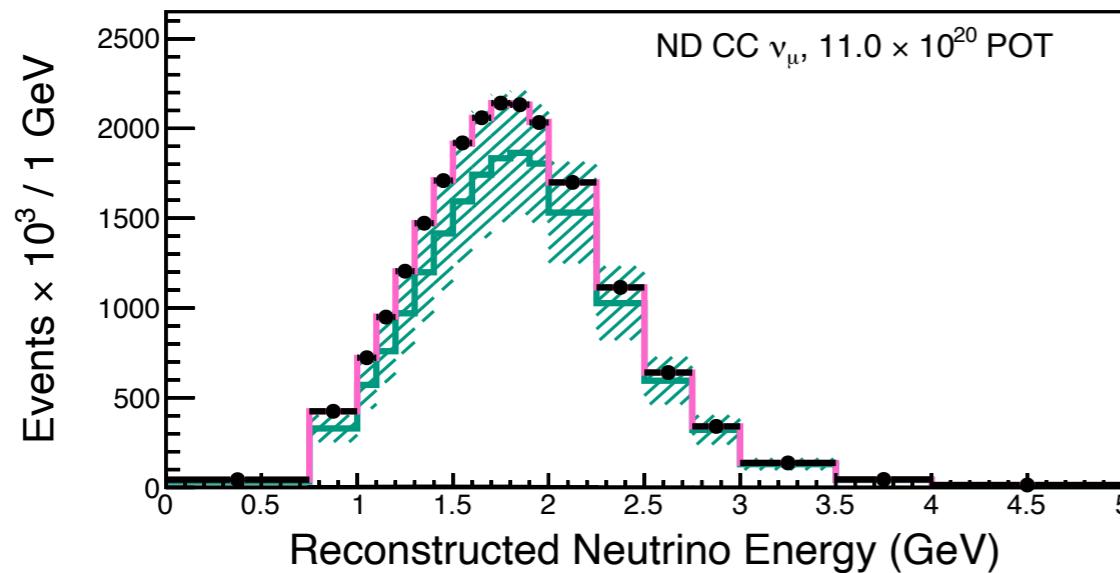


NOvA Preliminary

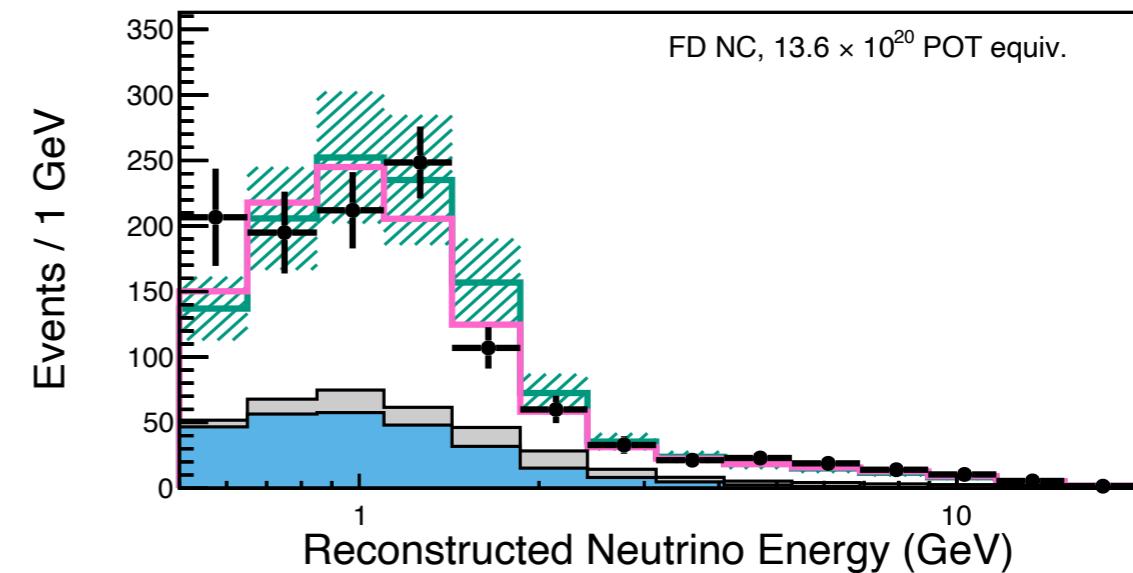
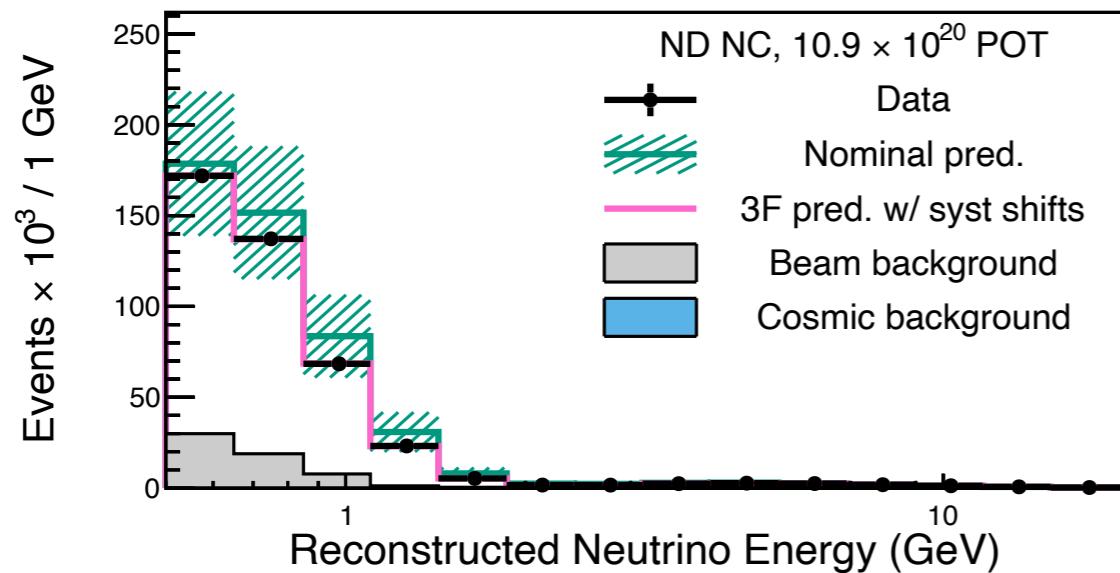
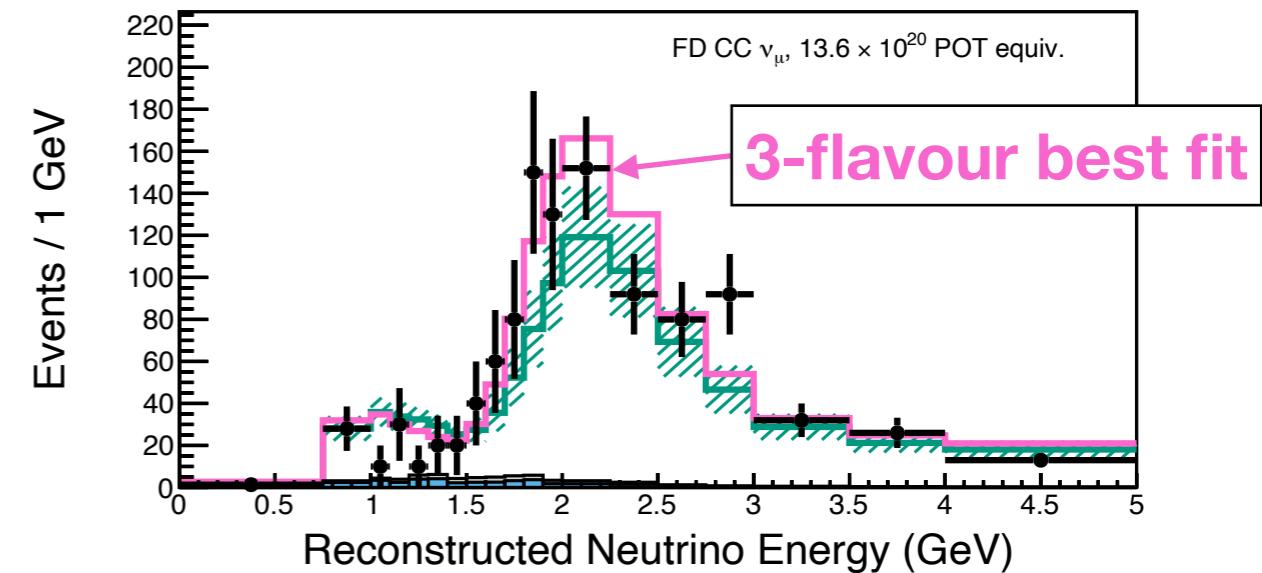


Sterile neutrino search results

Neutrino Beam

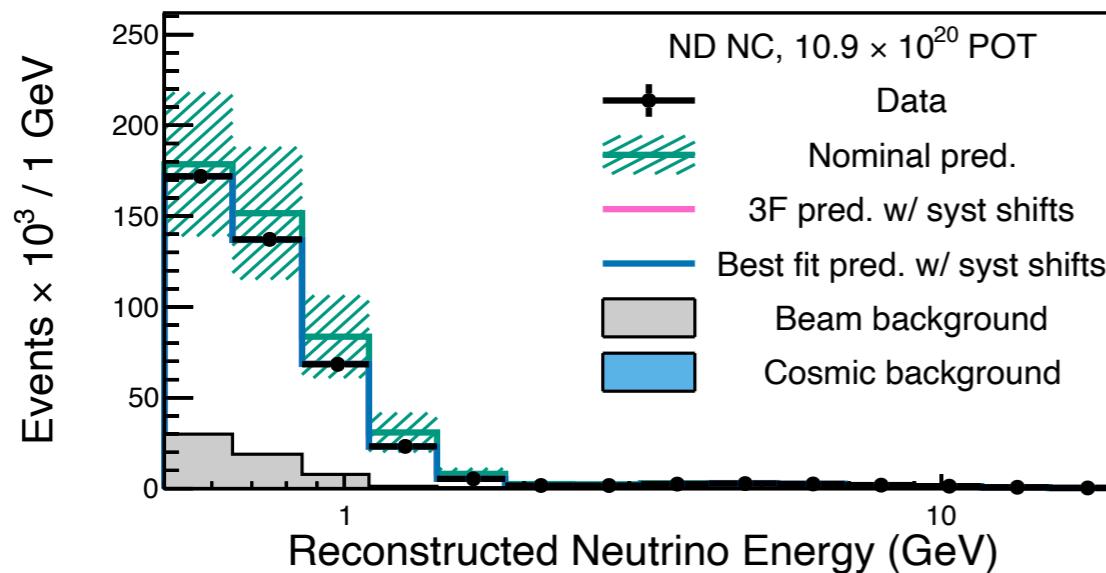
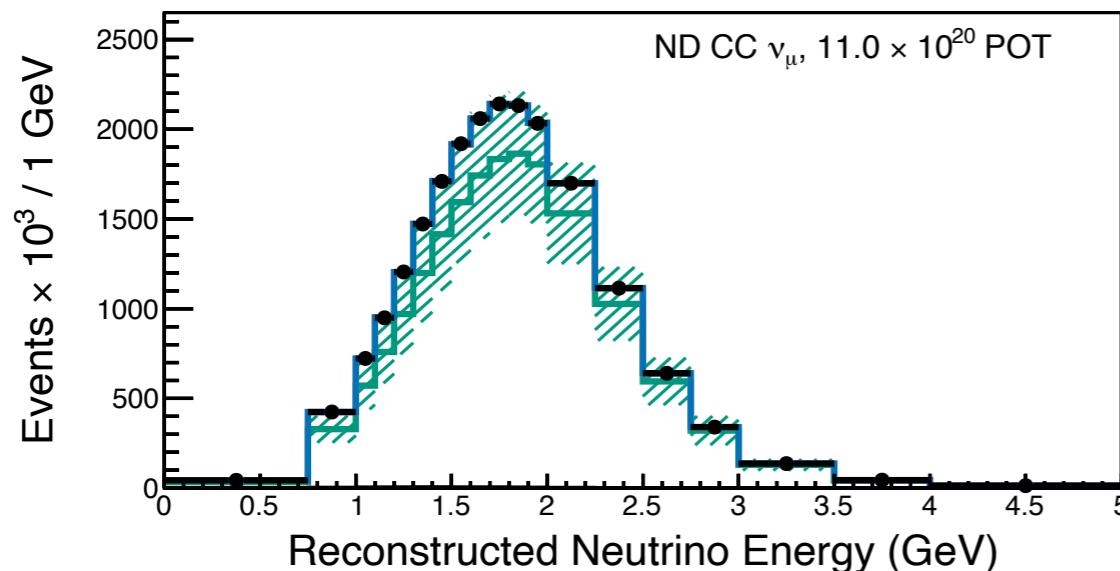


NOvA Preliminary

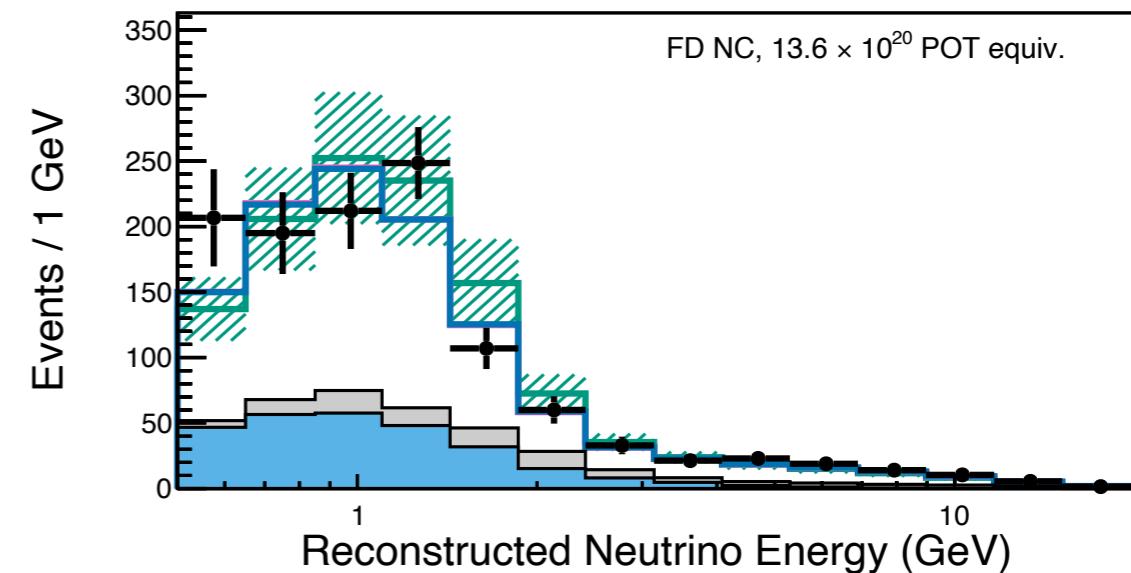
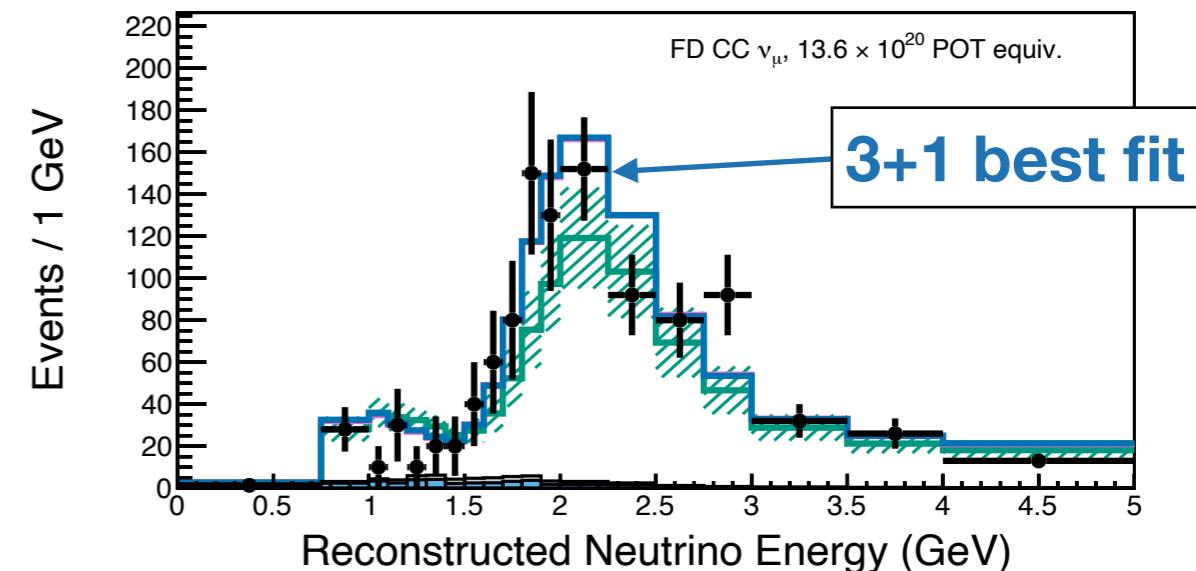


Sterile neutrino search results

Neutrino Beam

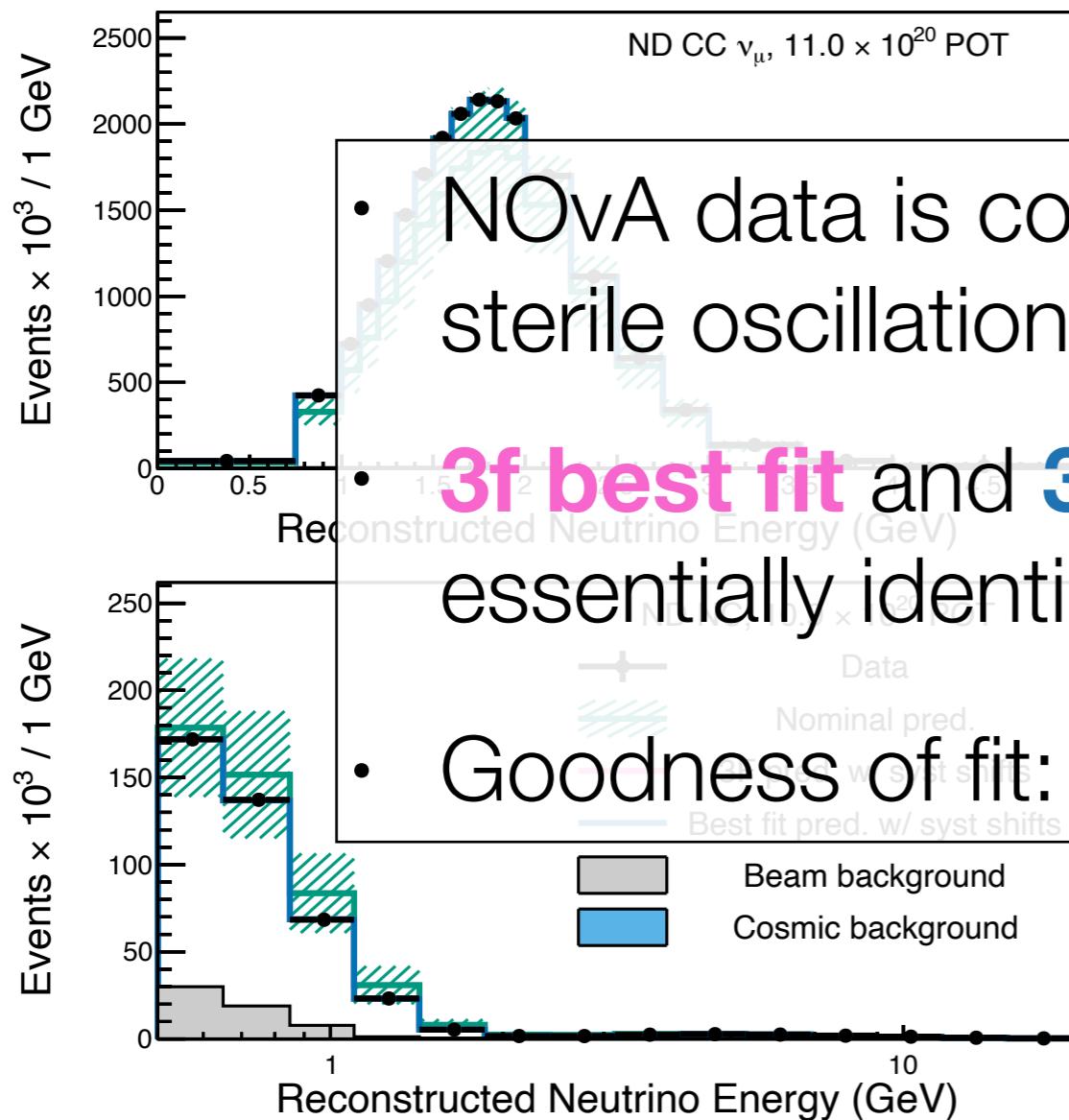


NOvA Preliminary

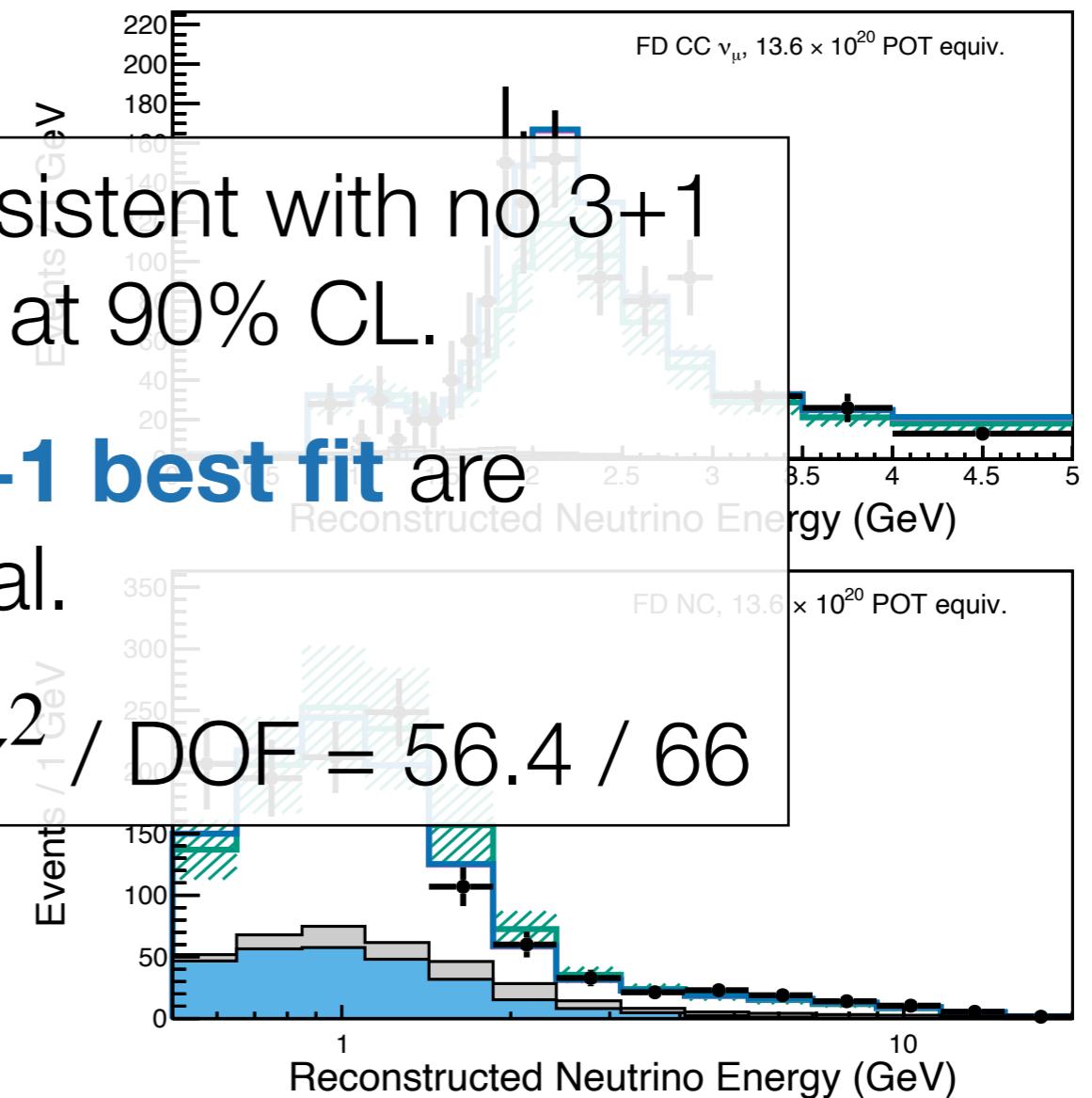


Sterile neutrino search results

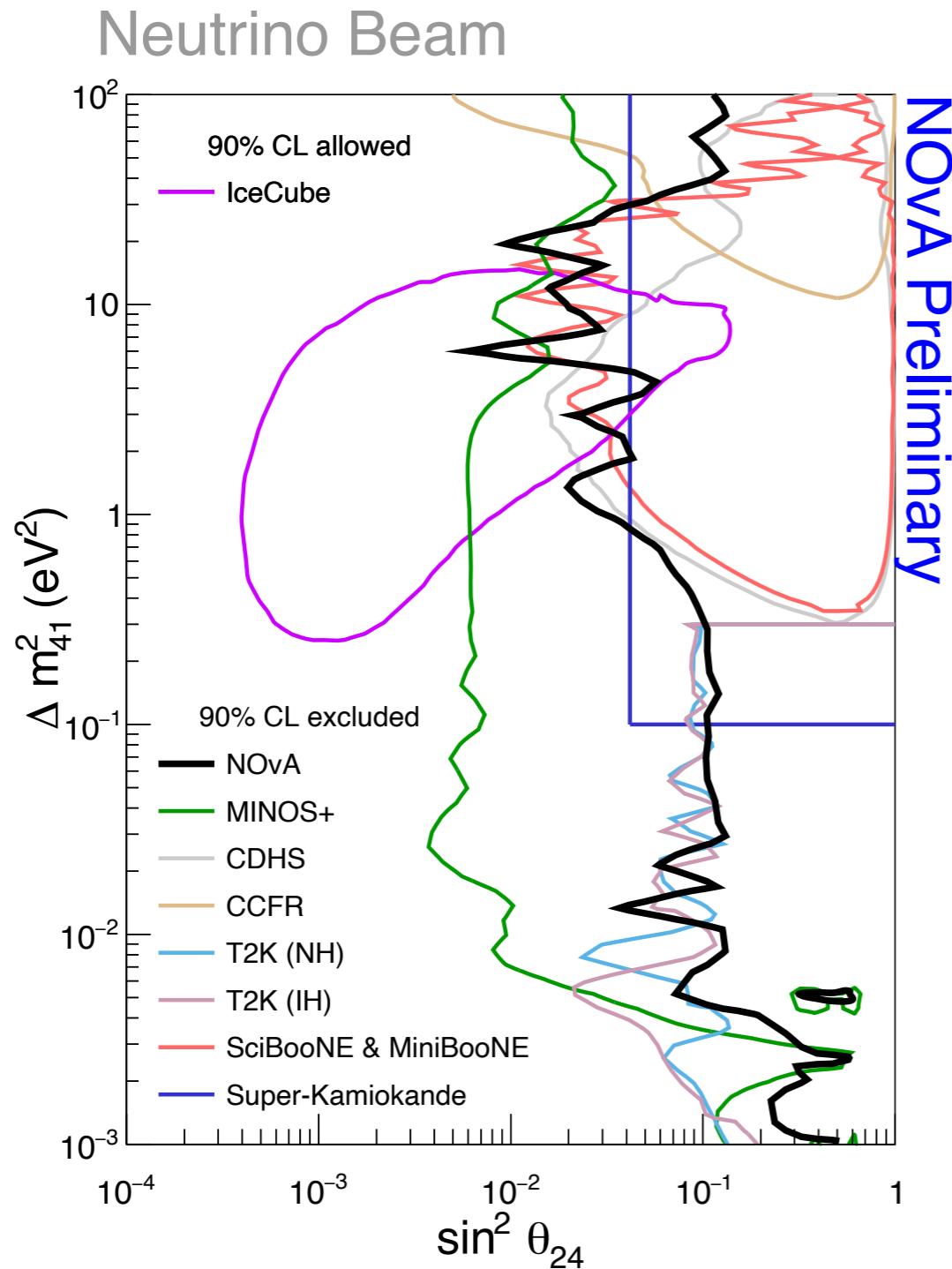
Neutrino Beam



NOvA Preliminary



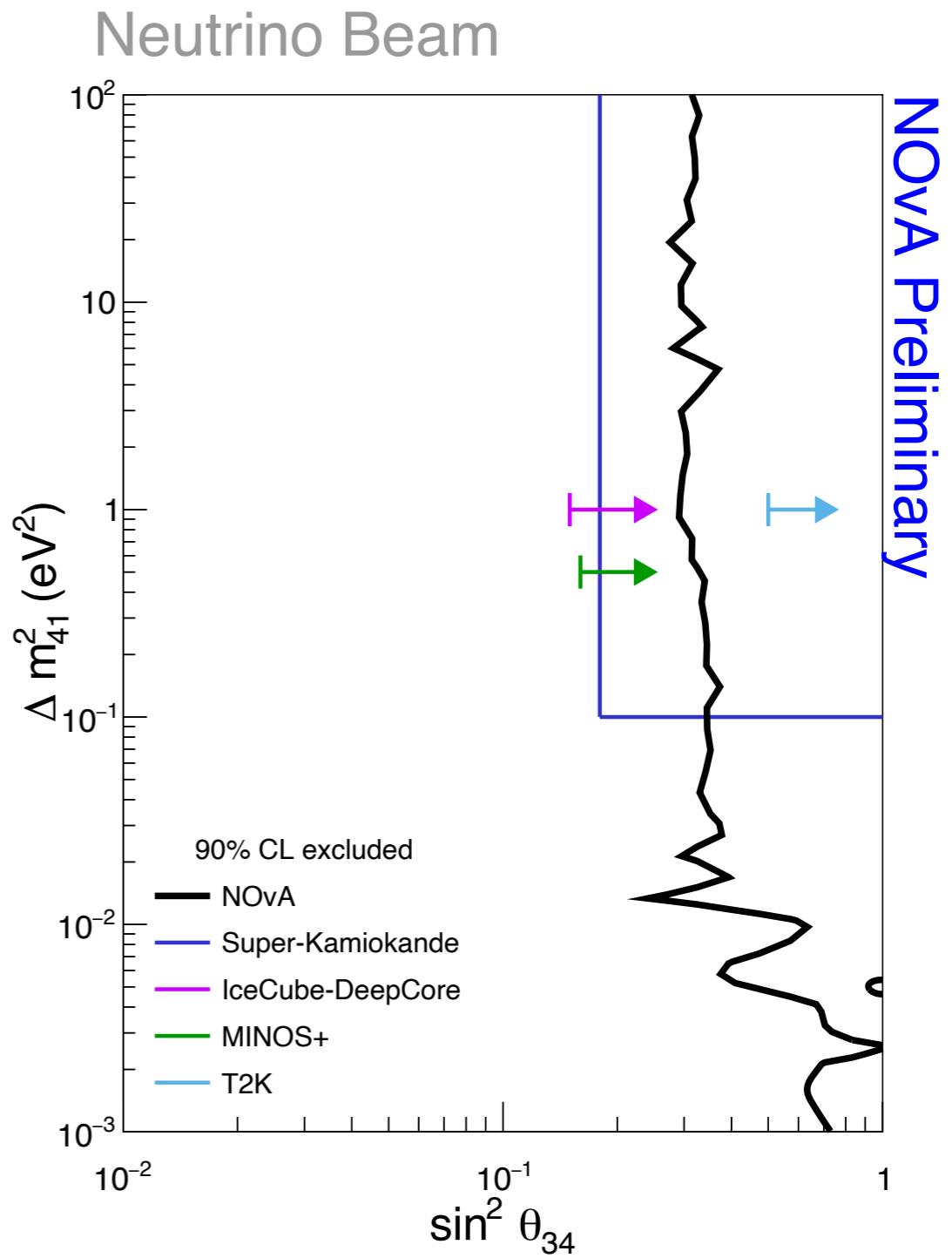
$\sin^2 \theta_{24}$ vs Δm_{41}^2 limits



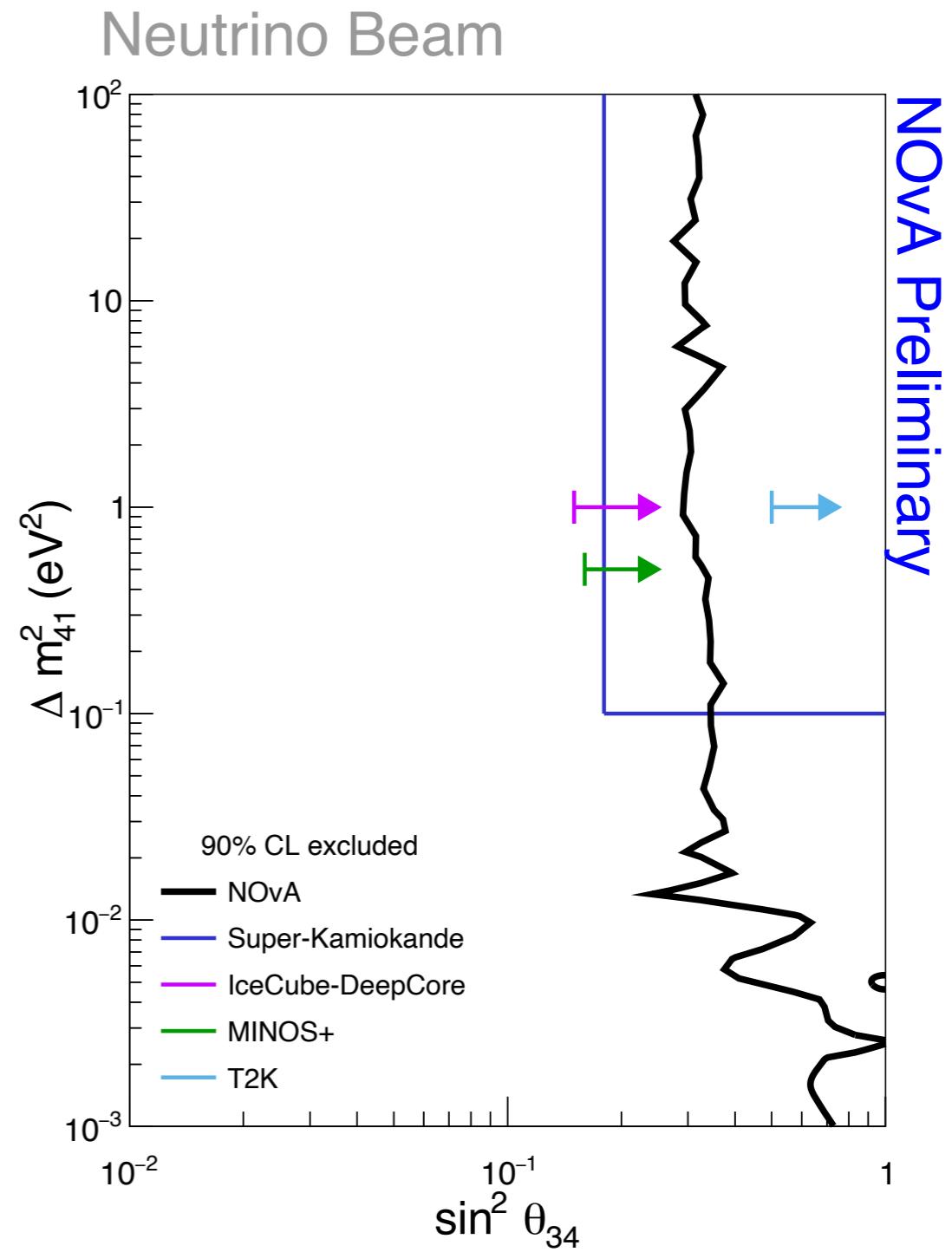
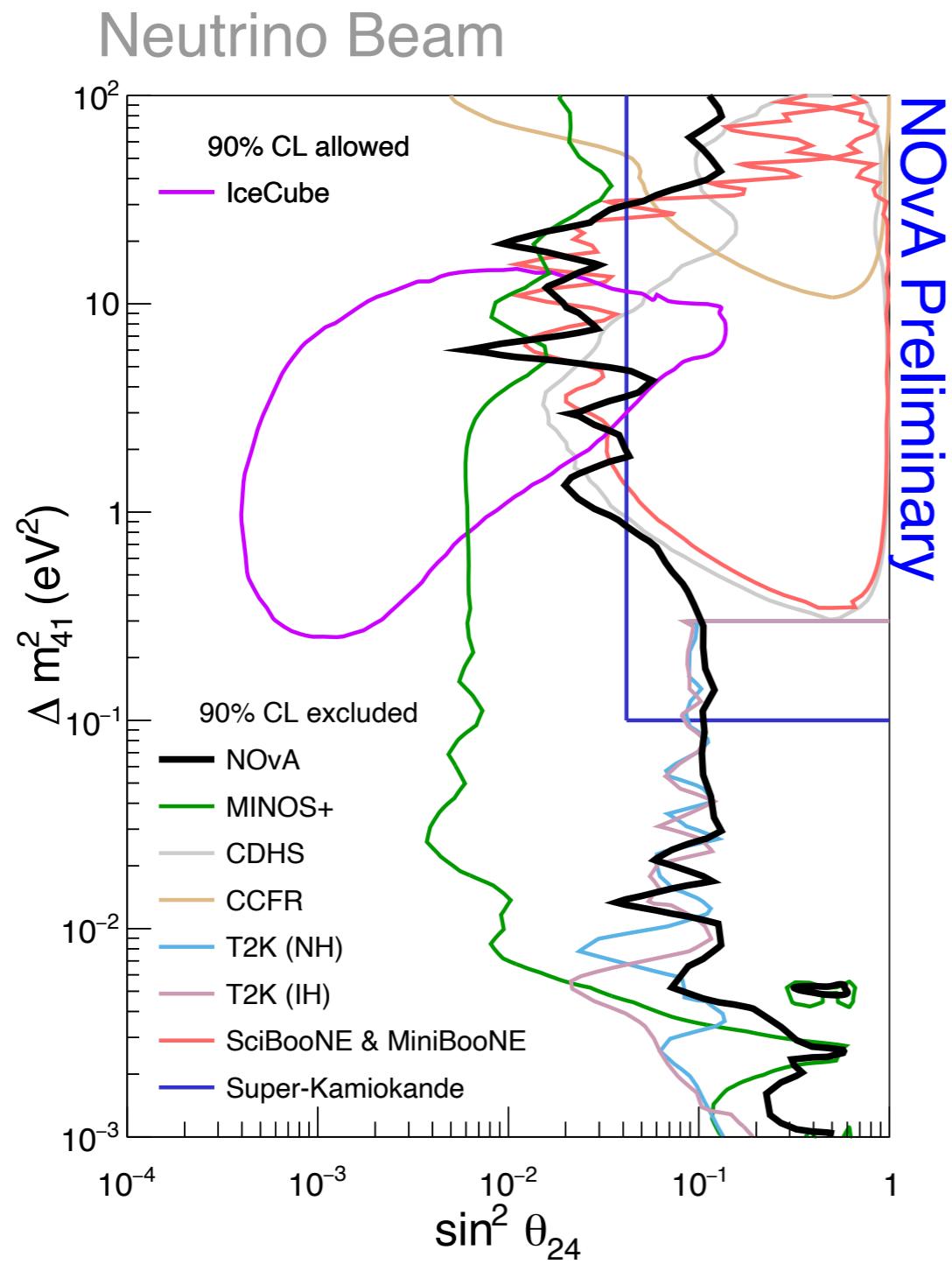
- Competitive limits on θ_{24} in high Δm_{41}^2 regime.
- Profile θ_{23} , Δm_{32}^2 , θ_{34} and δ_{24} .
 - Other 3f PMNS parameters held fixed at recent NuFit values.
 - θ_{14} fixed at zero due to constraints from reactor data.
 - Loose Gaussian constraint applied to Δm_{32}^2 .
- 90% CL critical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

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

- World-leading limits in θ_{34} as a function of Δm_{41}^2 .
- Profile θ_{23} , Δm_{32}^2 , θ_{24} 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_{32}^2 .
- 90% CL critical values corrected using Profiled Feldman Cousins approach.



90% CL contours



Non-standard interactions

Non-standard interactions

- **Non-standard interactions (NSI)** modify standard 3-flavour neutrino oscillations by introducing anomalous interactions between neutrinos and matter, in addition to the standard MSW effect.

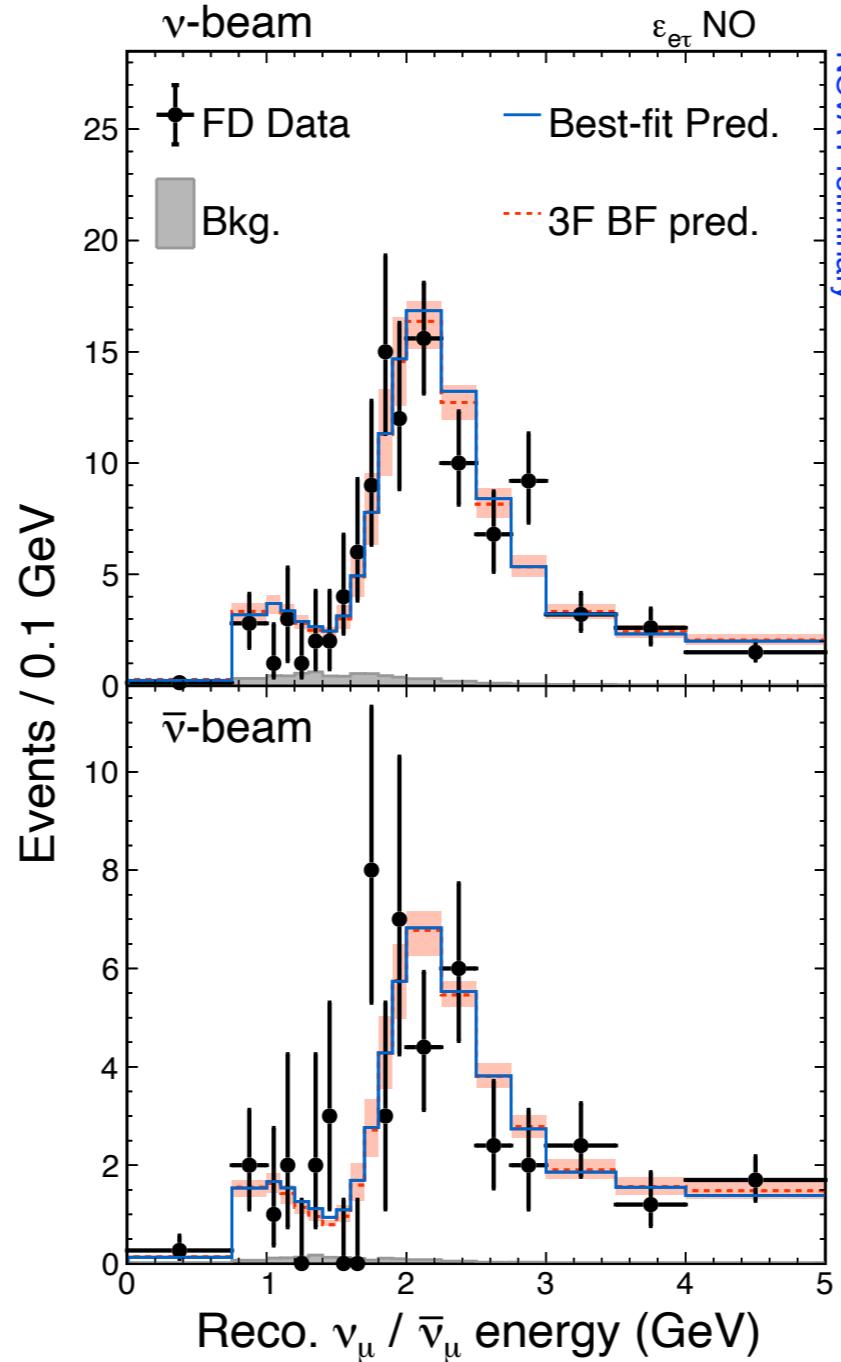
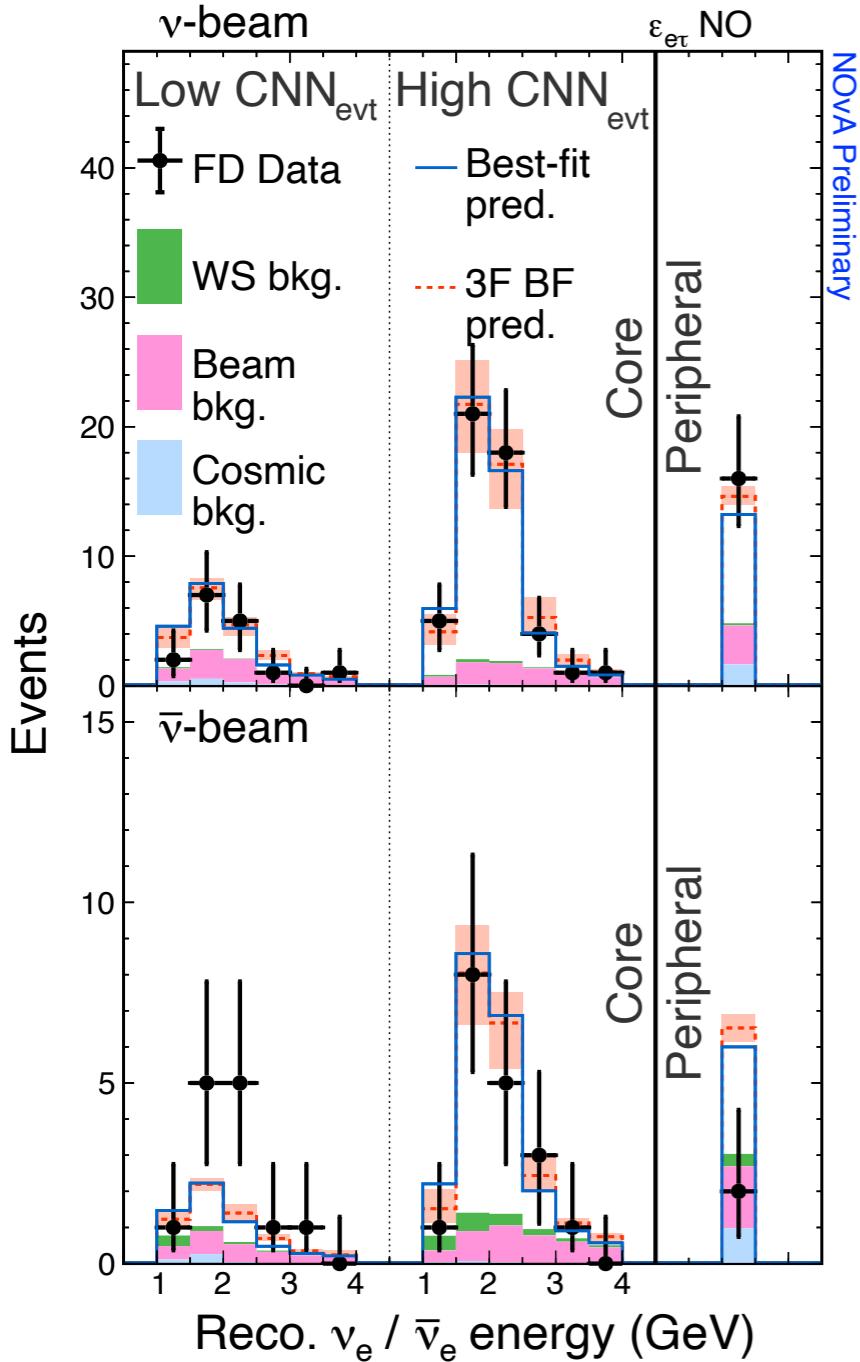
$$\mathcal{H} = U \mathcal{H} U^\dagger + \mathcal{H}_{\text{matter}} + \mathcal{H}_{\text{NSI}}$$

$$\mathcal{H} = \frac{1}{2E} \left[U_{\text{PMNS}} \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{pmatrix} U_{\text{PMNS}}^\dagger + a \begin{pmatrix} 1 + \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon^{\tau\tau} \end{pmatrix} \right]$$

$$\epsilon_{\alpha\beta} \equiv |\epsilon_{\alpha\beta}| e^{i\delta_{\alpha\beta}} \quad a \equiv 2\sqrt{2}G_F N_e E \quad (\text{Wolfenstein matter potential})$$

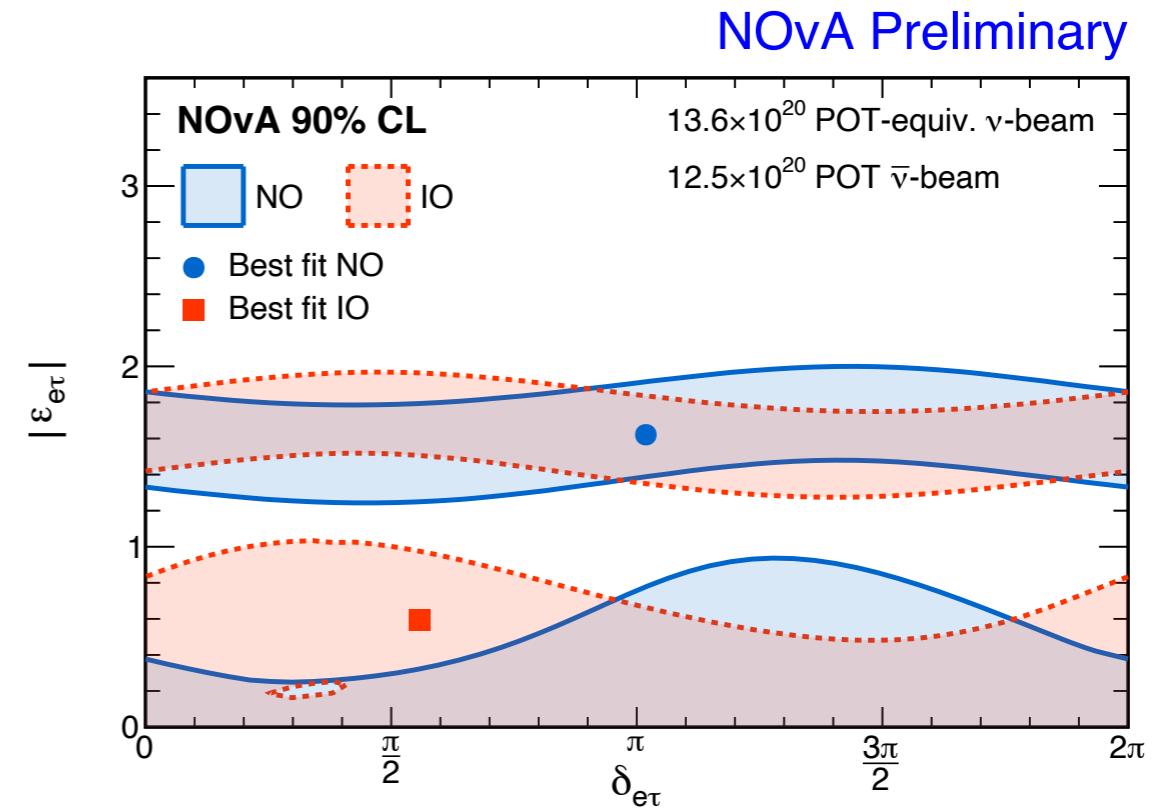
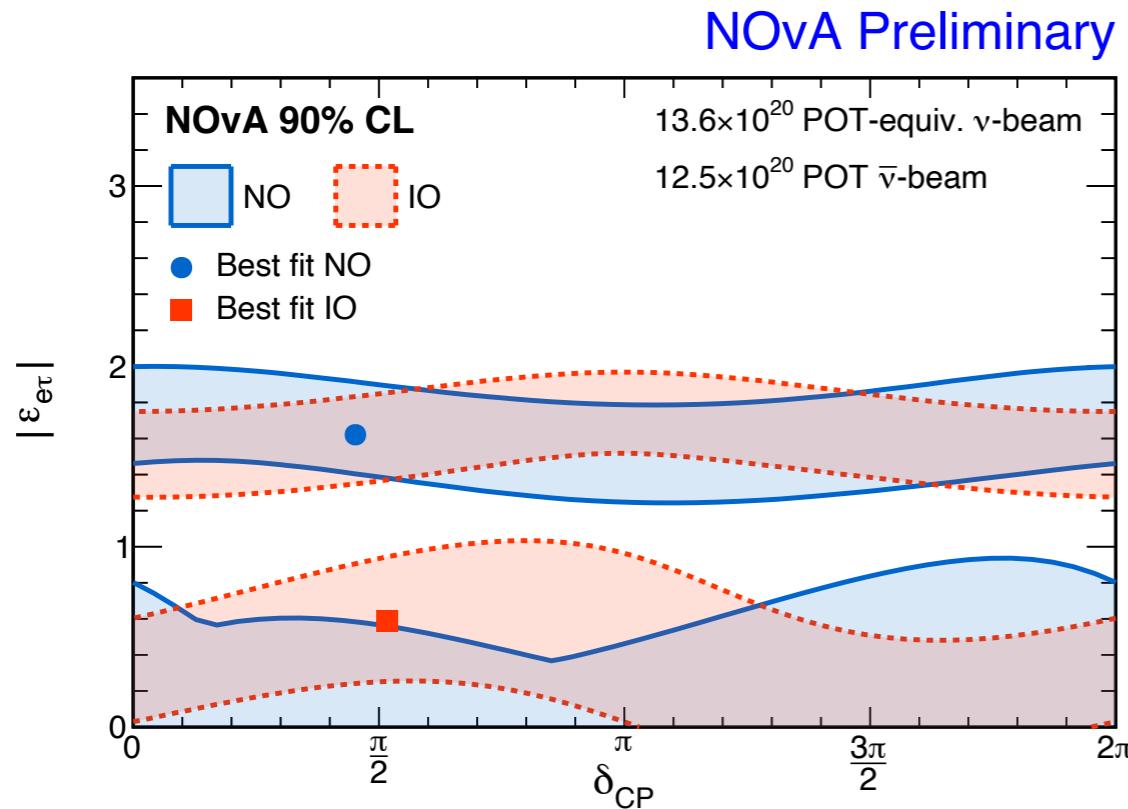
- NOvA's first probe of NSI uses 2020 oscillation dataset to investigate complex off-diagonal ϵ terms.

NSI $\epsilon_{e\tau}$ analysis spectra



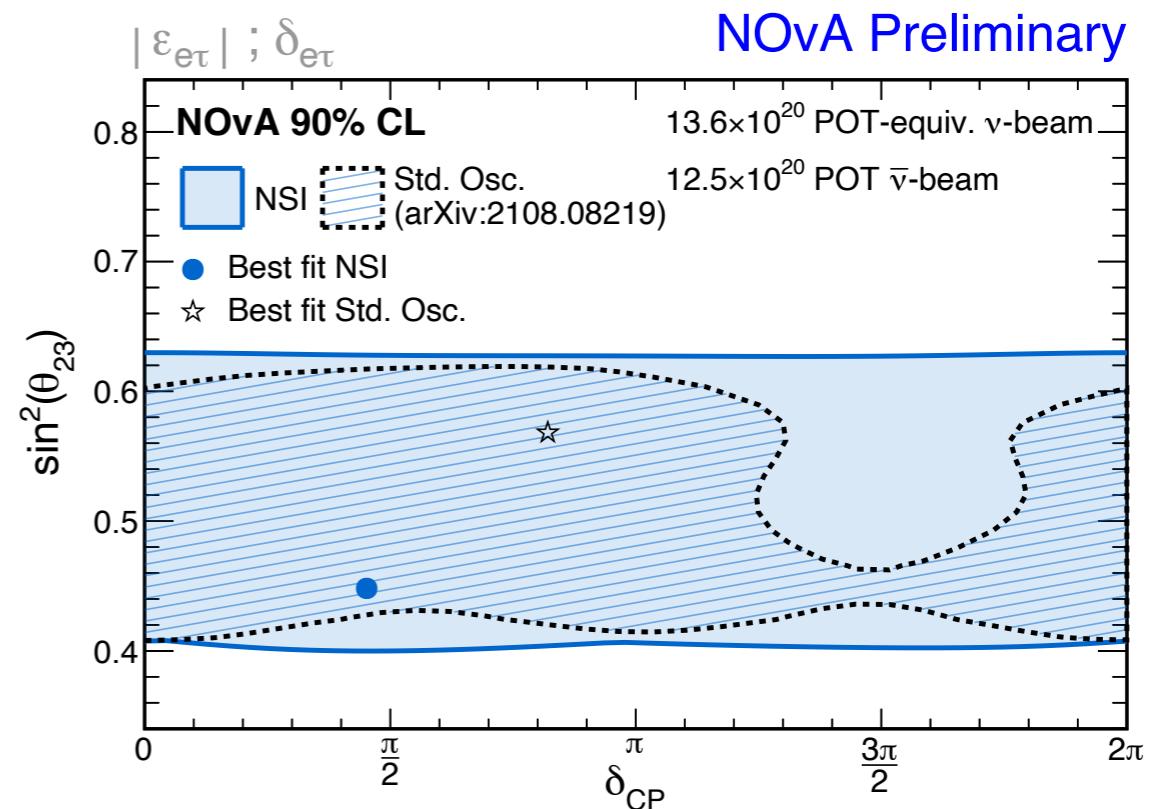
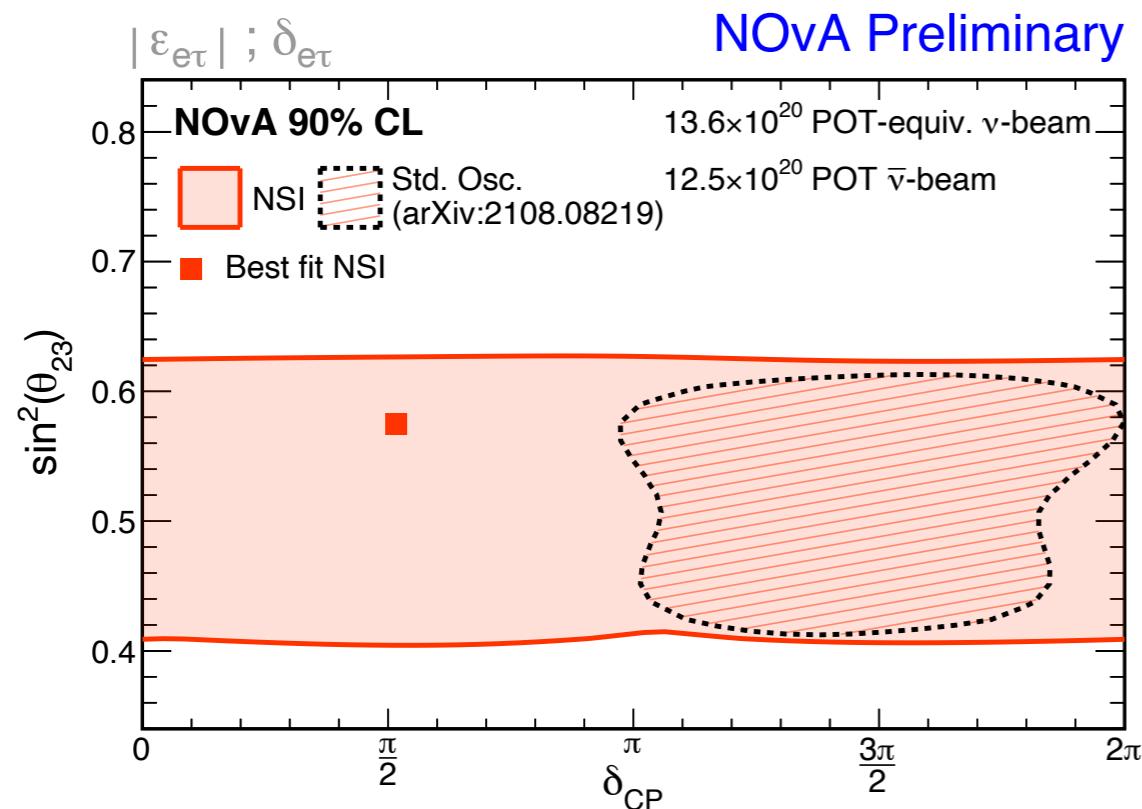
- Fit to CC ν_e and ν_μ selections in both neutrino and antineutrino beam modes.
- Consider only $\epsilon_{e\tau}$ NSI parameter.
- NSI best fit similar to standard 3f oscillation best fit from 2020.
 - $\Delta\chi^2 \approx 0.65$
- Consistent with standard oscillations.

NSI $\epsilon_{e\tau}$ 90% CL limits



- Perform oscillation fits in terms of $|\epsilon_{e\tau}|$ against phases δ_{CP} and $\delta_{e\tau}$.
- Upper band in both fits is a result of degeneracy between the two phases, which becomes dominant at large $|\epsilon_{e\tau}|$.

NSI $\epsilon_{e\tau}$ 90% CL limits



- Introducing NSI via $\epsilon_{e\tau}$ into standard 3f oscillation fit profoundly affects sensitivity to CP violation.
- Much sensitivity to δ_{CP} in 3f interpretation is lost when introducing NSI, due to degeneracy with $\delta_{e\tau}$ phase.

Summary

- NOvA's new 3+1 sterile neutrino search finds no evidence of sterile oscillations at 90% CL.
 - Utilises two-detector approach to fit over broad range of sterile parameter space.
 - New systematic uncertainties introduced to ensure robust treatment of cross-sections in near detector.
- Search for non-standard oscillations finds data is consistent with standard oscillations at 90% CL.
 - Additional degrees of freedom introduced in NSI model can lead to loss of sensitivity to standard CP-violating phase.
- **3+1 sterile and NSI searches both consistent with standard 3-flavour oscillations at 90% CL.**

Backup

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:

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

- The final test statistic is the combination of the **Poisson likelihood statistical term** and the **Gaussian multivariate systematic term**:

$$\chi^2 = \chi^2_{\text{syst}} + \chi^2_{\text{stat}}$$

i = analysis bin
 α = beam component
 μ = nominal prediction

s = systematic shift
 x = data
 F = covariance matrix

PISCES

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

Exact Statistics

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

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

Systematic Covariance

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

- The final test statistic is the combination of the **Poisson likelihood statistical term** and the **Gaussian multivariate systematic term**:

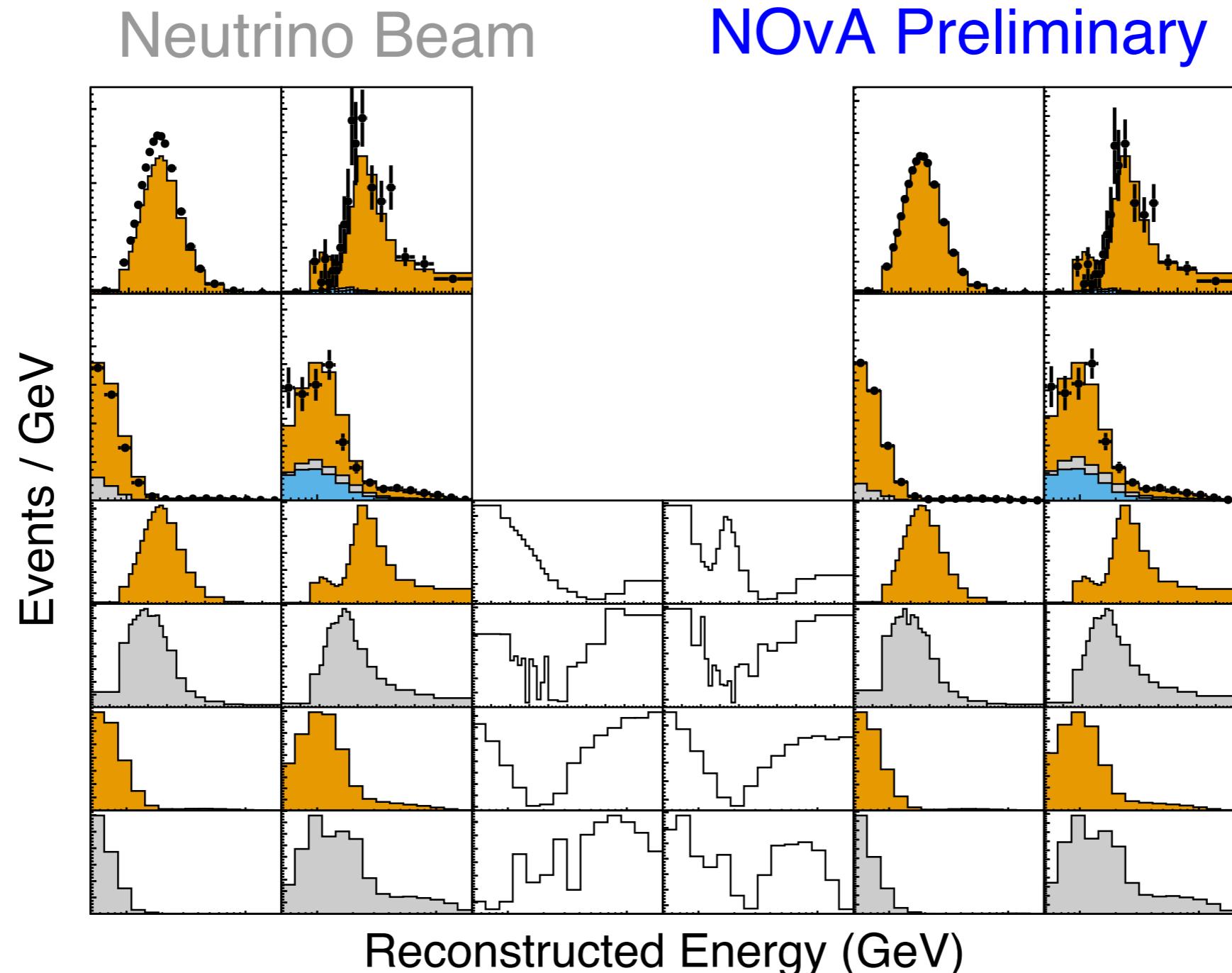
$$\chi^2 = \chi^2_{\text{syst}} + \chi^2_{\text{stat}}$$

Parameter Inference

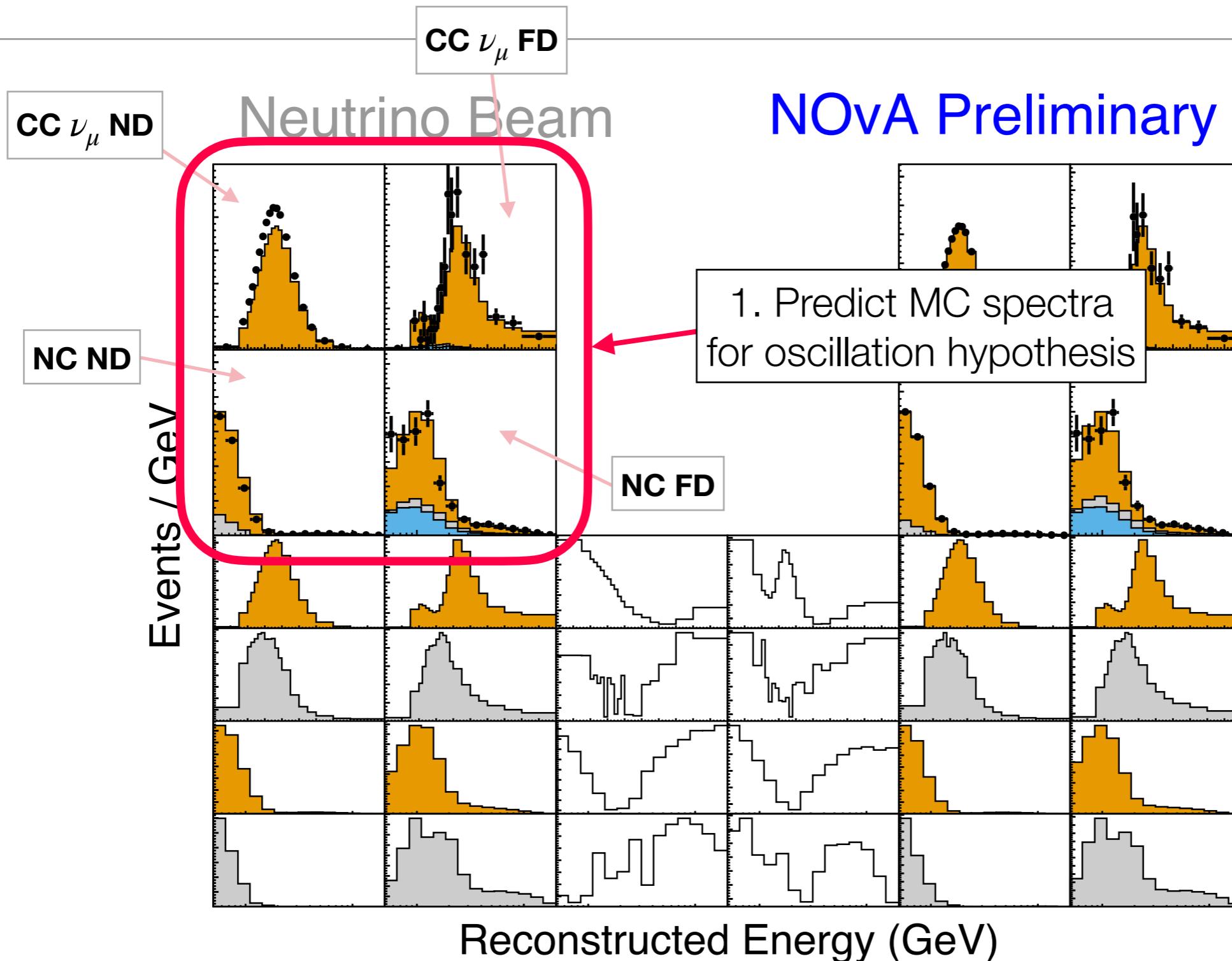
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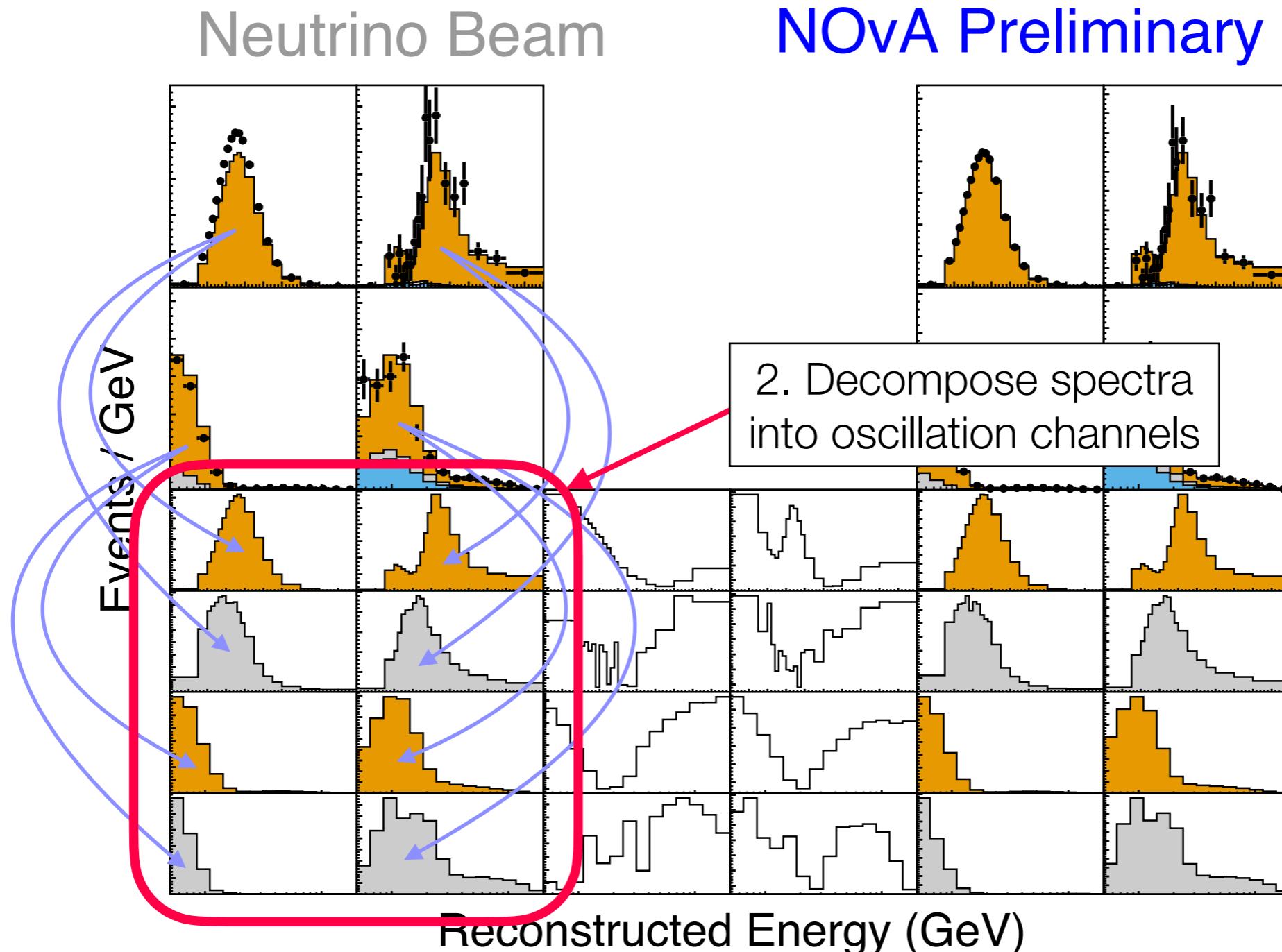
PISCES demonstration



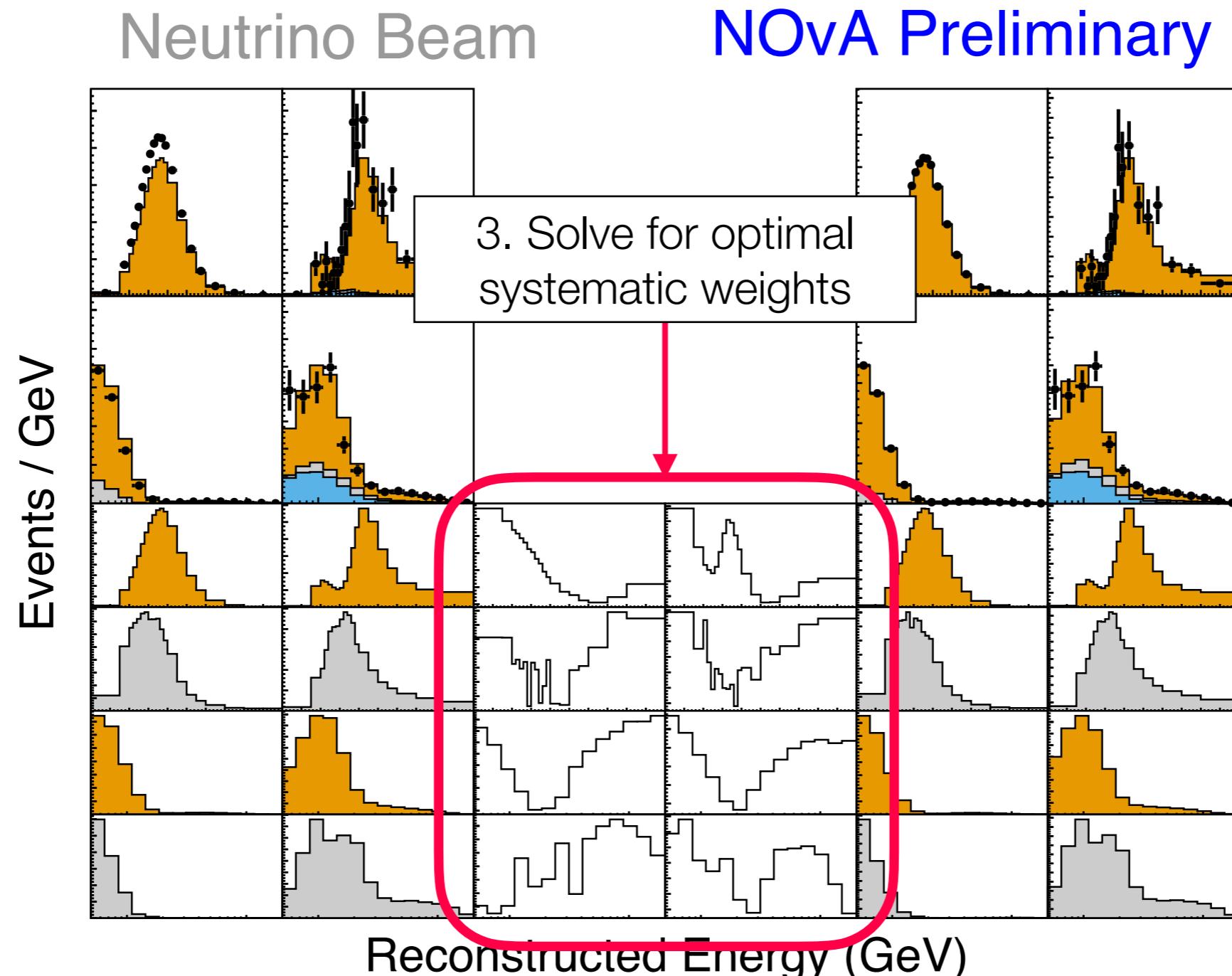
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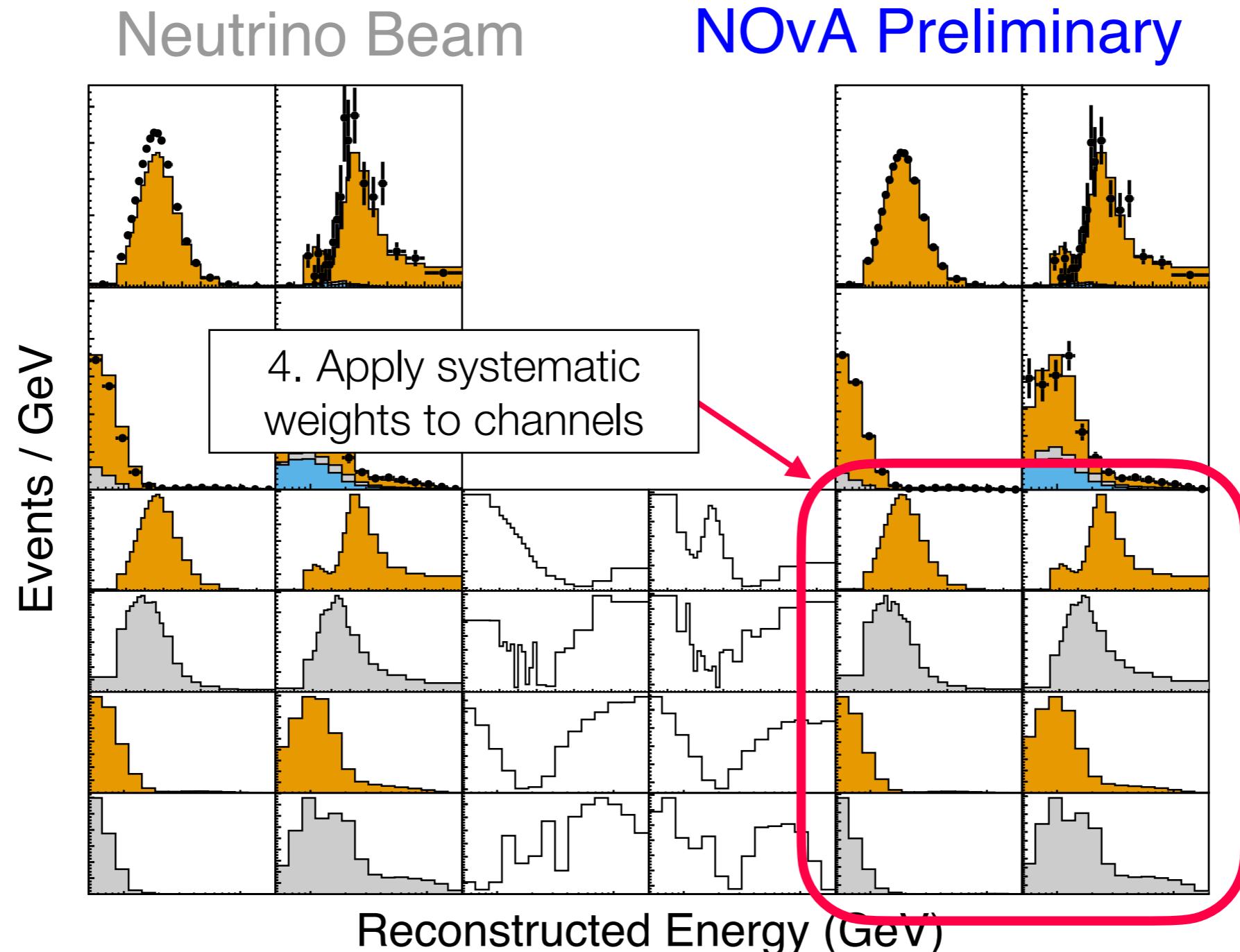
PISCES demonstration



PISCES demonstration



PISCES demonstration



PISCES demonstration

