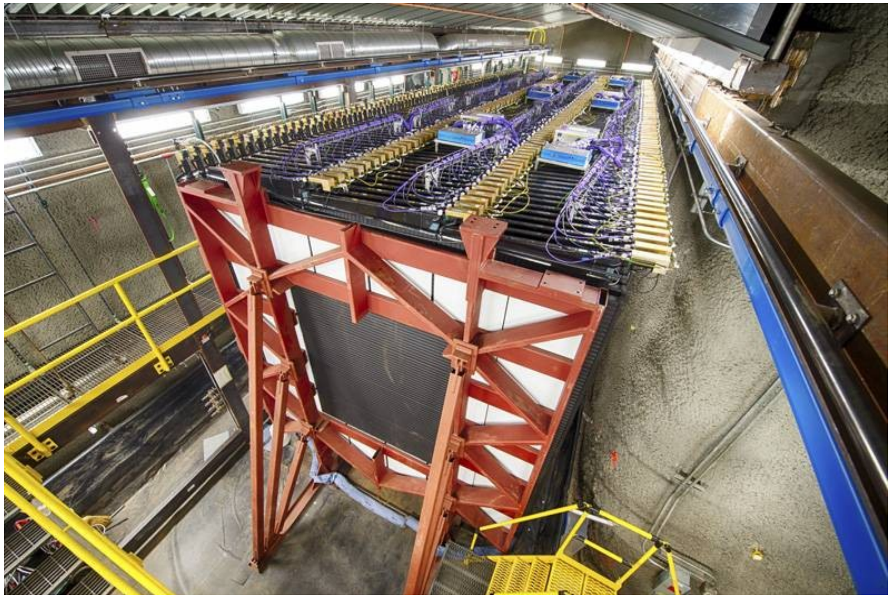
NOvA Results on Long-Baseline Oscillations



Adam Aurisano
University of Cincinnati
on behalf of the NOvA Collaboration

NOW 2022
5 September 2022

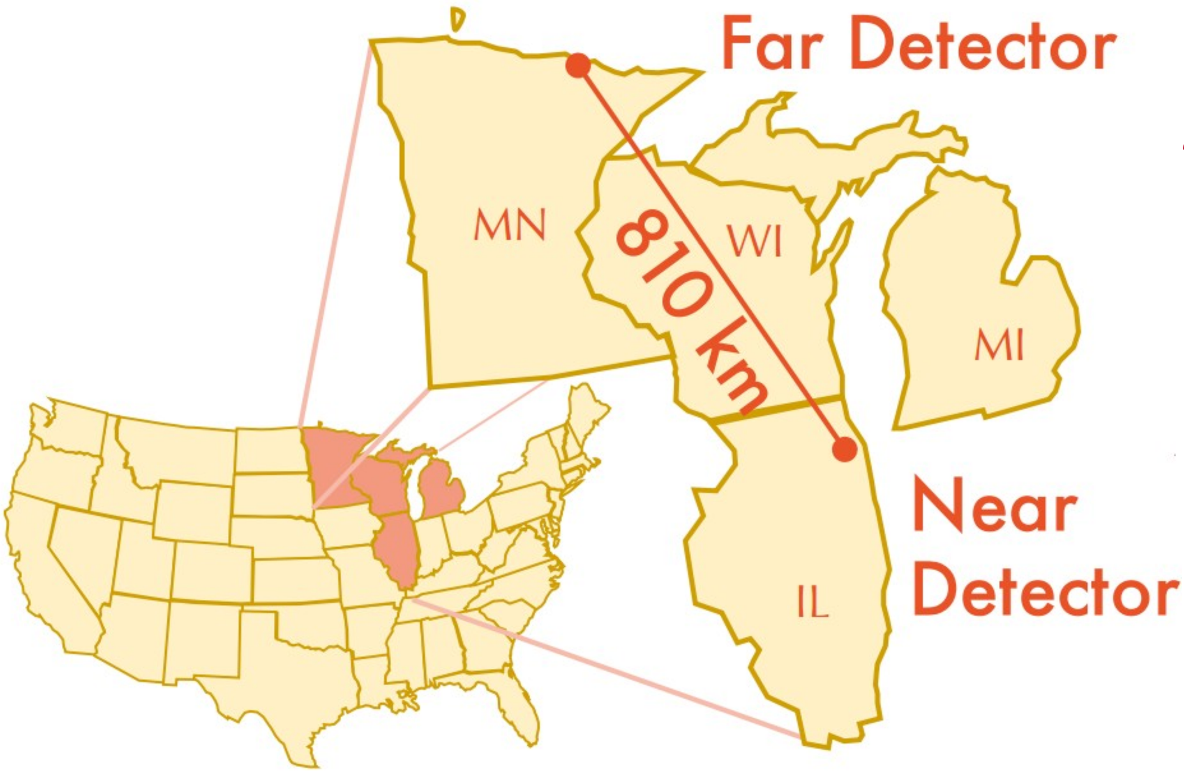
U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

- NOvA Overview
- New search for sterile neutrinos
  - ν_μ-CC and NC disappearance
  - Two-detector joint fit
- New search for non-standard interactions
  - ν_μ-CC disappearance and ν_e-CC appearance
- Three-flavor oscillation results
  - ν_μ-CC disappearance and ν_e-CC appearance
  - Bayesian re-analysis
- Conclusions

NuMI Off-Axis ν_e Appearance Experiment

NOvA is a long-baseline neutrino oscillation experiment located 14 mrad off-axis from the NuMI beam designed to measure:



ν_e appearance

- Mass ordering
- CP violation
- θ_{23} octant

ν_μ disappearance

- Improved precision on $|\Delta m^2_{32}|$ and θ_{23}

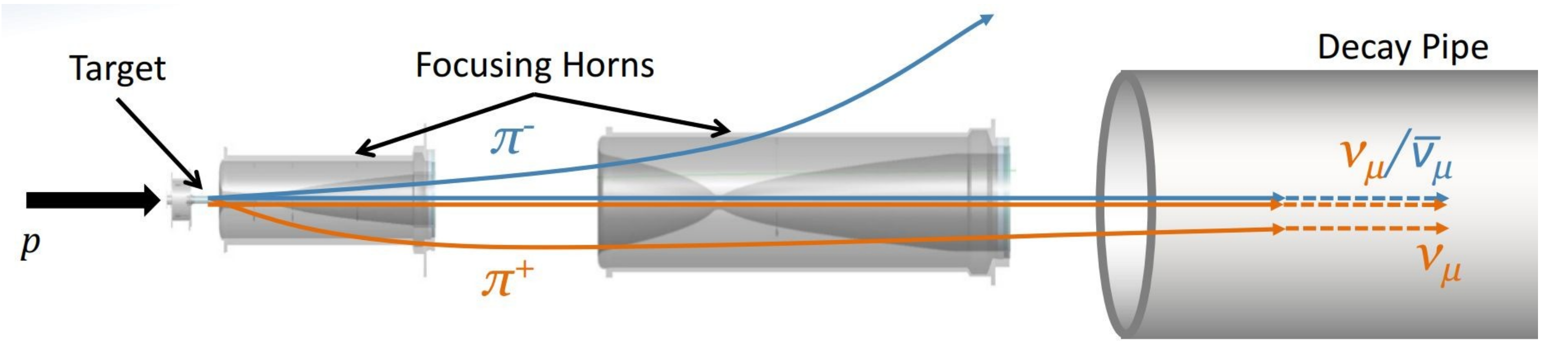
NC disappearance

- Search for sterile neutrinos
- Constrain θ_{34} and θ_{24}

Others

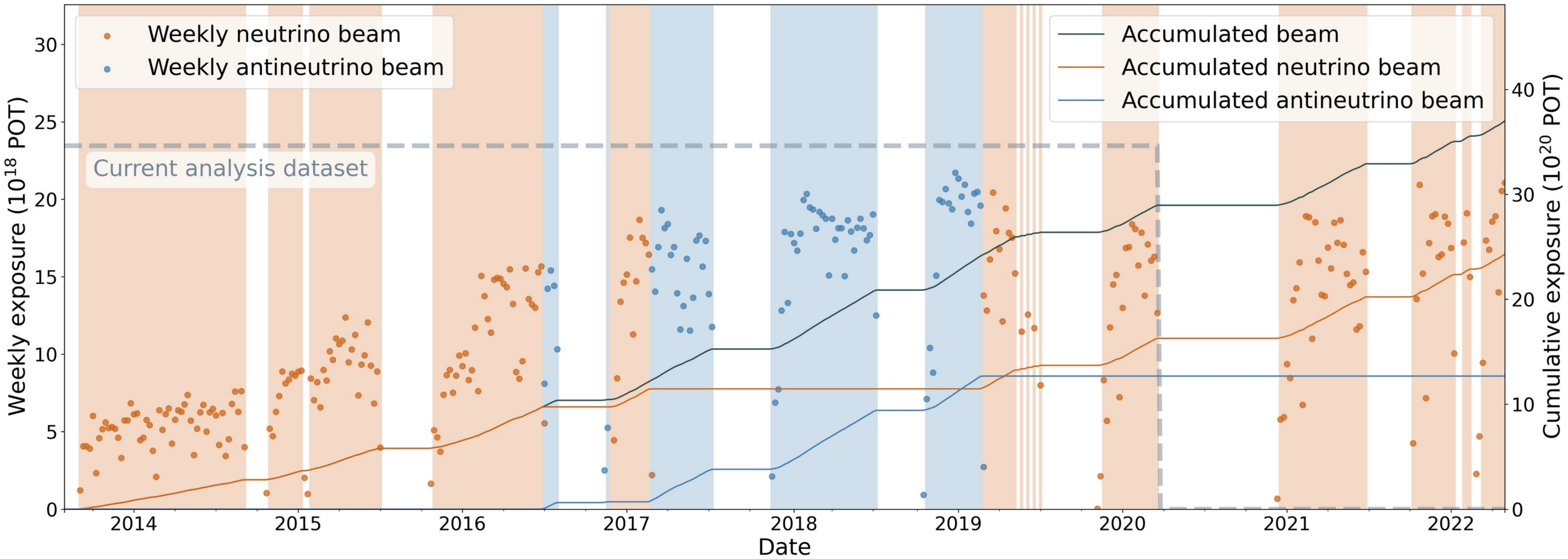
- Short-baseline oscillations
- Cross sections
- NSI
- Supernovae
- Exotics

NuMI Neutrino Beam

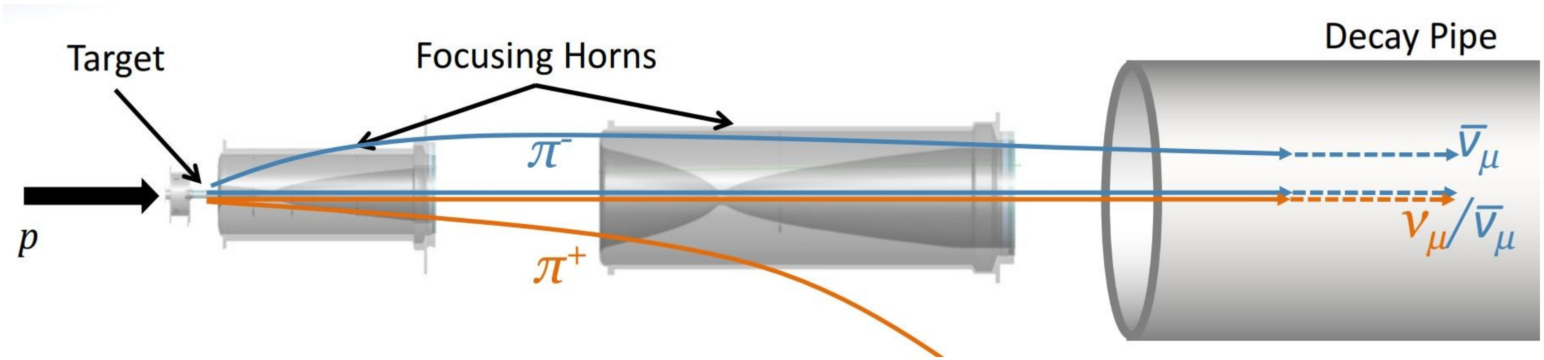


Recorded 13.6 x 10^{20} POT equivalent in neutrino mode at the FD

- Used in sterile, NSI, and three-flavor analyses

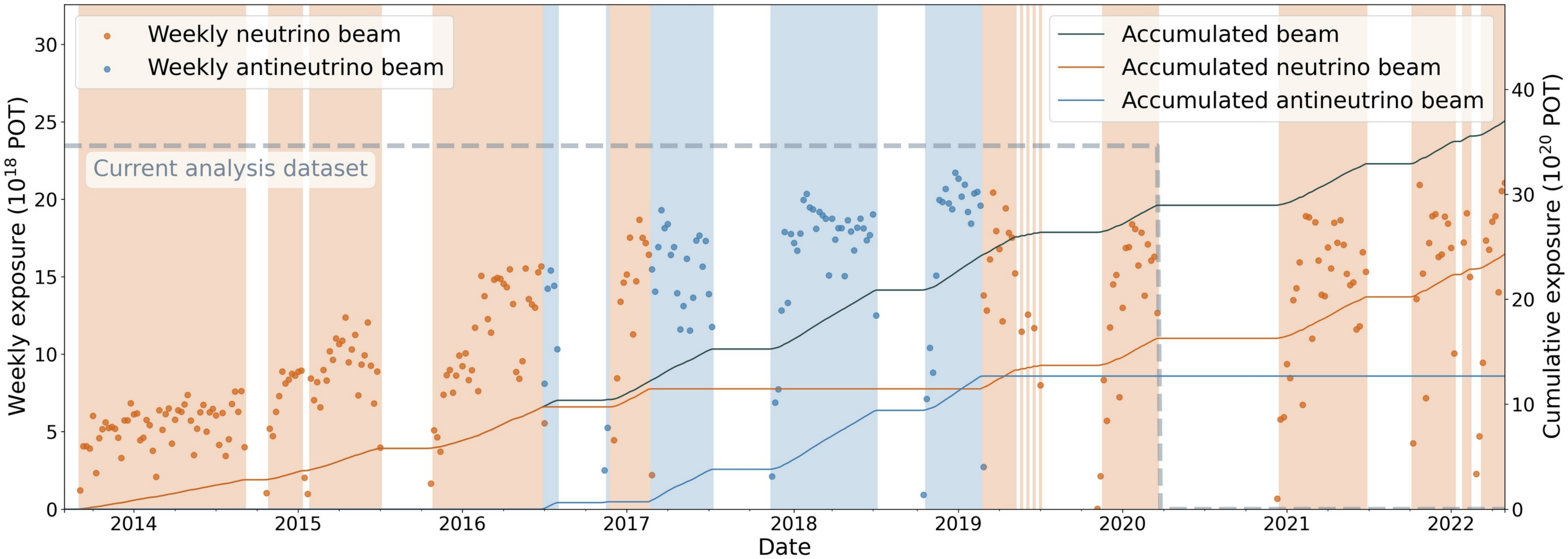


NuMI Antineutrino Beam



Recorded 12.5 x 10^{20} POT-equivalent in antineutrino mode at the FD

- Used in NSI and three-flavor analyses

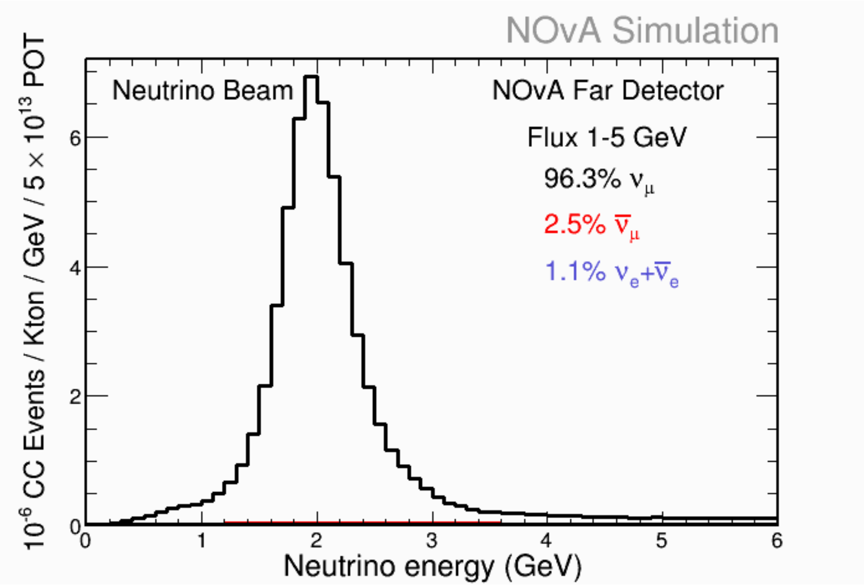


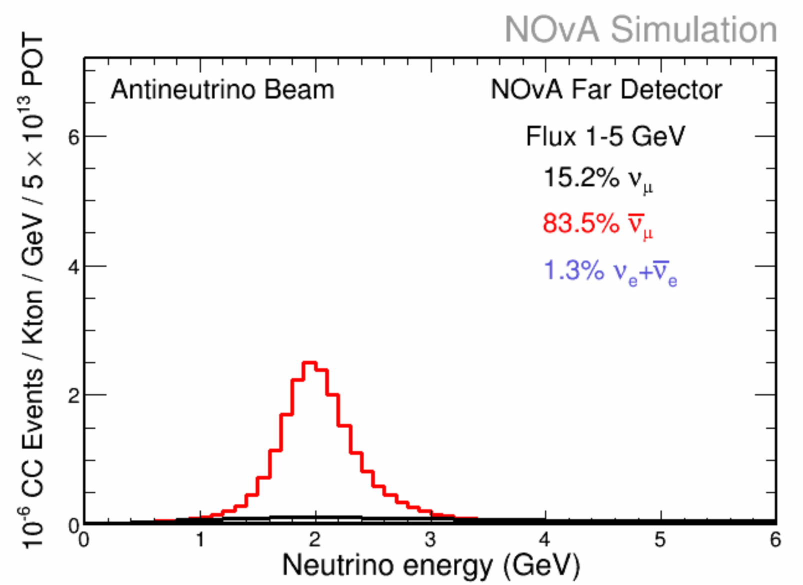
Off-axis Flux

- Flux narrowly peaked at ~2 GeV
- High ν_μ ($\bar{\nu}_\mu$) purity
- New beamline components installed
  - New power record: 893 kW

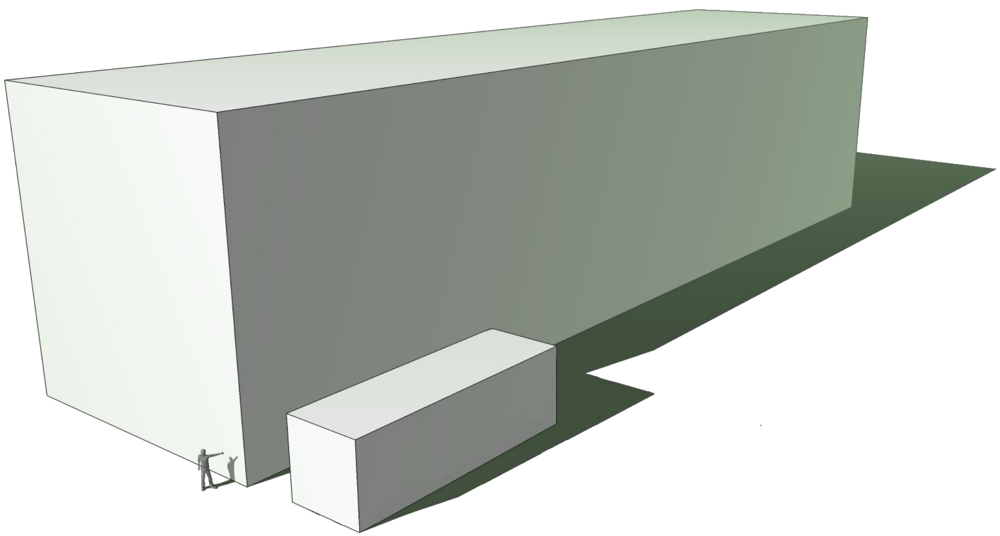
MW-capable target (installed 2019)

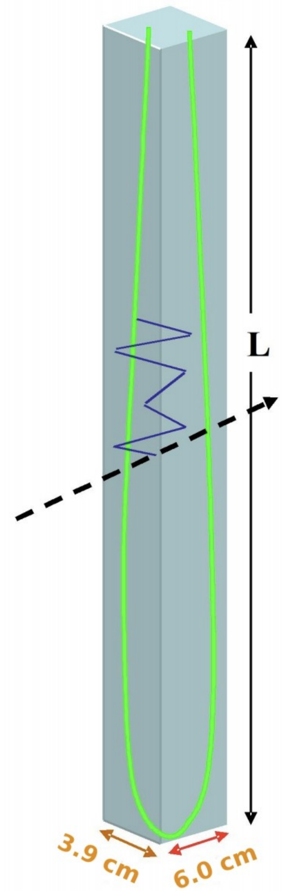
MW-capable horn (installed 2020)



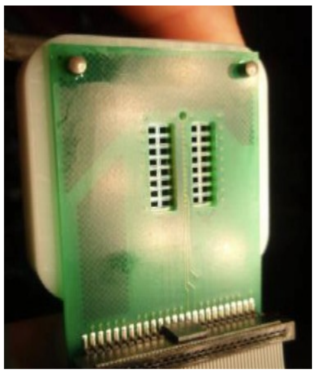


NOvA Detector Design





Low Z tracking calorimeter composed of alternating horizontal and vertical planes of liquid scintillator filled cells.



Wavelength shifting fibers carry light out of the cells to APDs.

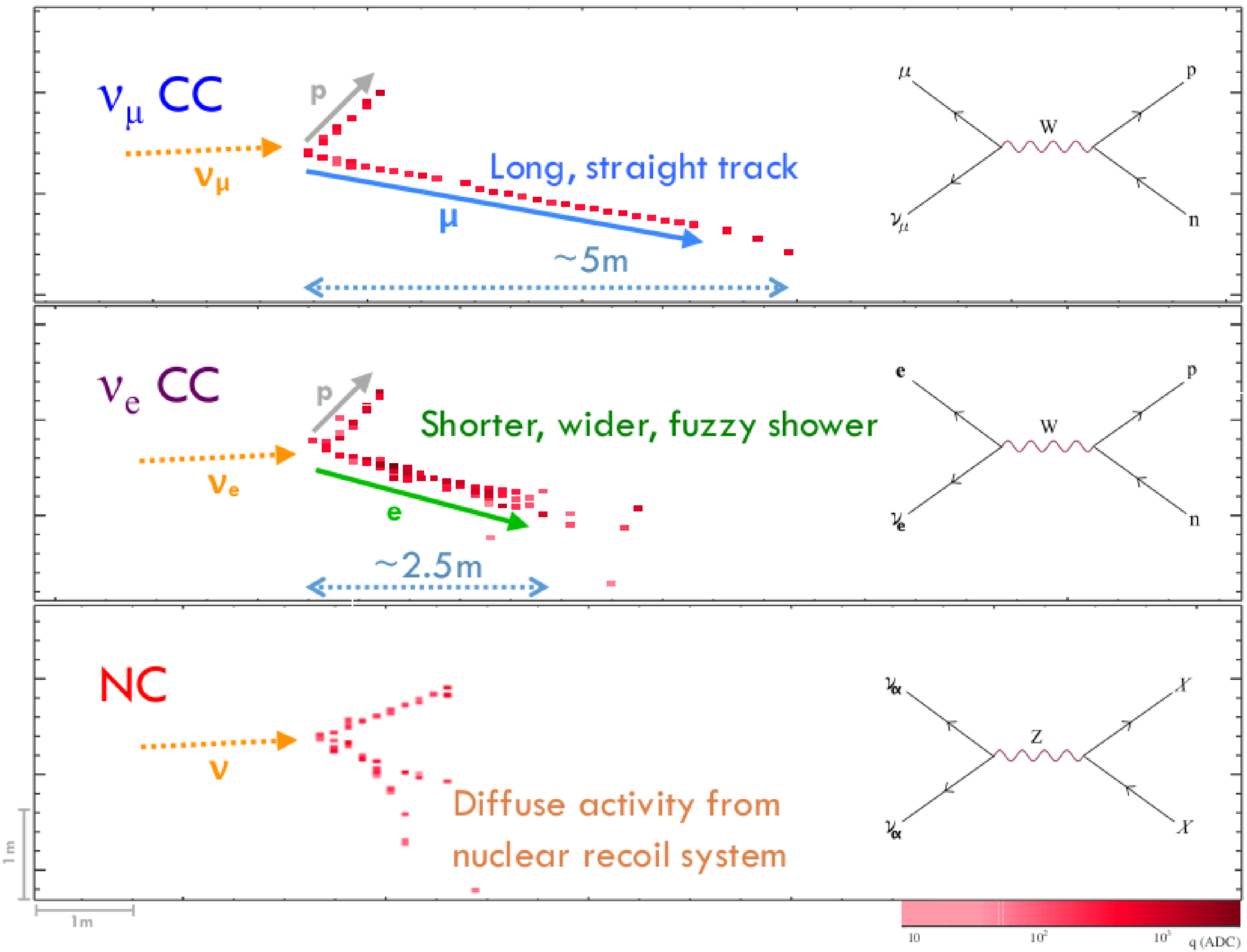
Far detector (FD)

- 14 kton
- 15m x 15m x 60m
- 65% active mass
- ~344,000 channels

Near detector (ND)

- 0.3 kton
- 3.8m x 3.8m x 12.8m (main detector)
- Functionally equivalent to FD for systematic uncertainty reduction
- ~20,000 channels

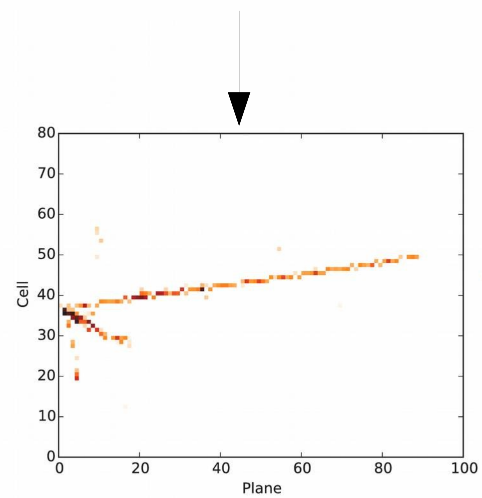
Event Topologies



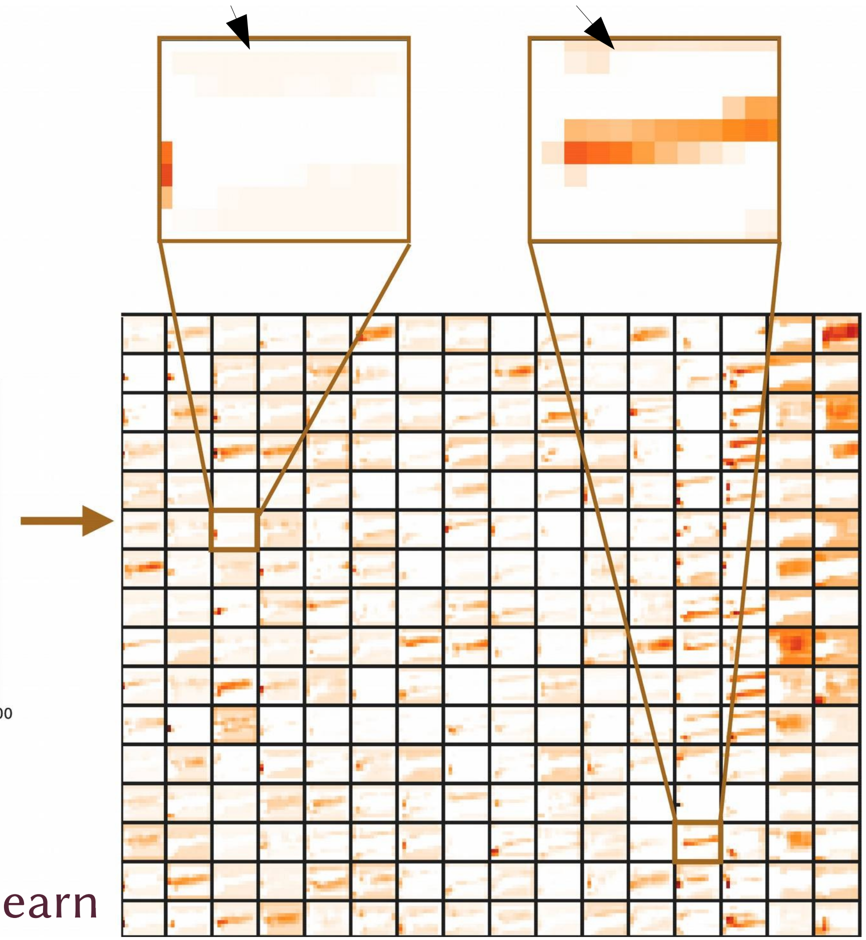
Neutrino Interaction Classifier

- Convolutional Visual Network (CVN) is a selection algorithm based on Deep-Learning techniques
- Uses all information in minimally reconstructed events
- Is a multi-purpose classifier
  - Capable of selecting ν_e, ν_μ, ν_τ, NC, and cosmics

Use reconstructed energy in each cell as input



Individual learned filters are sensitive to physics: e.g. hadronic activity or muon tracks



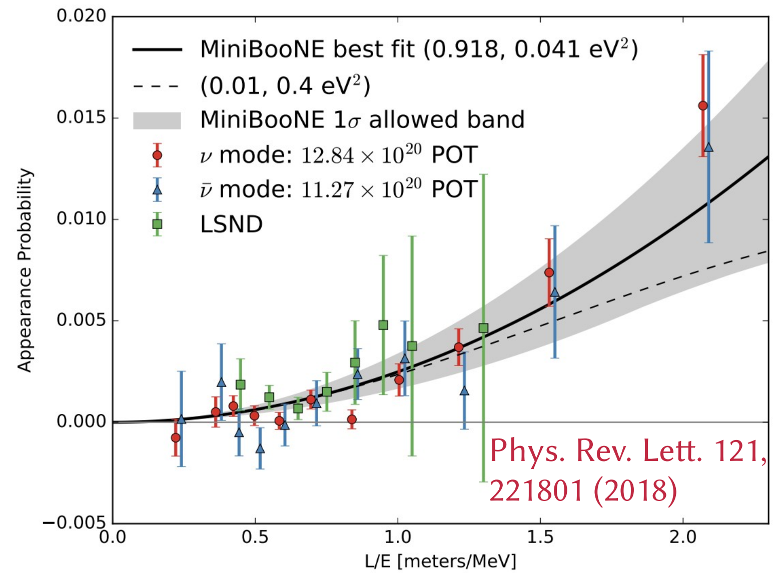
Convolutional layers learn filters to optimally extract features from the data

JINST 11 (2016) P09001

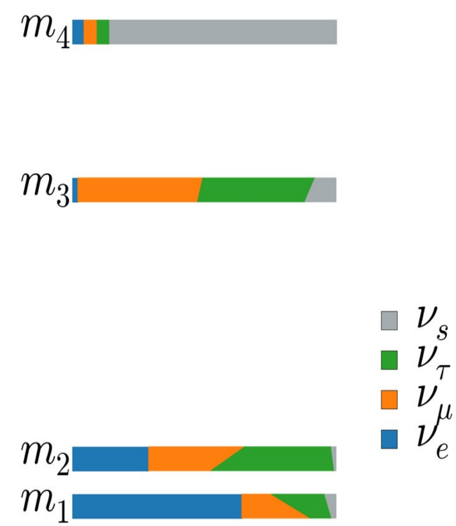
Sterile Neutrinos

Sterile Neutrinos

- Short-baseline experiments (LSND, MiniBooNE) observed anomalous excesses of ν_e ($\bar{\nu}_e$) in ν_μ ($\bar{\nu}_\mu$) beams
- BEST observed anomalous deficit in ν_e from a ^{51}Cr neutrino source over short baselines
- Anomalies could all be explained by oscillations driven by a mass splitting $\Delta m^2 \sim 1$ eV^2
  - Not consistent with three known active flavors
- Simplest model adds one new mass state and one new, sterile flavor state
  - 3+1 model contains 6 new parameters

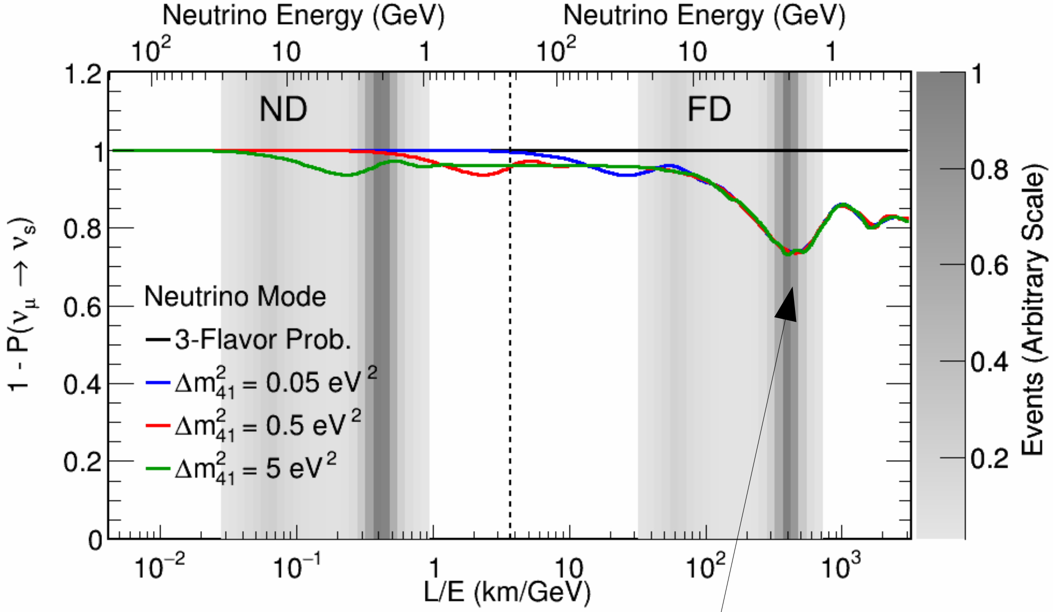


Phys. Rev. Lett. 121, 221801 (2018)



3+1 NC Disappearance

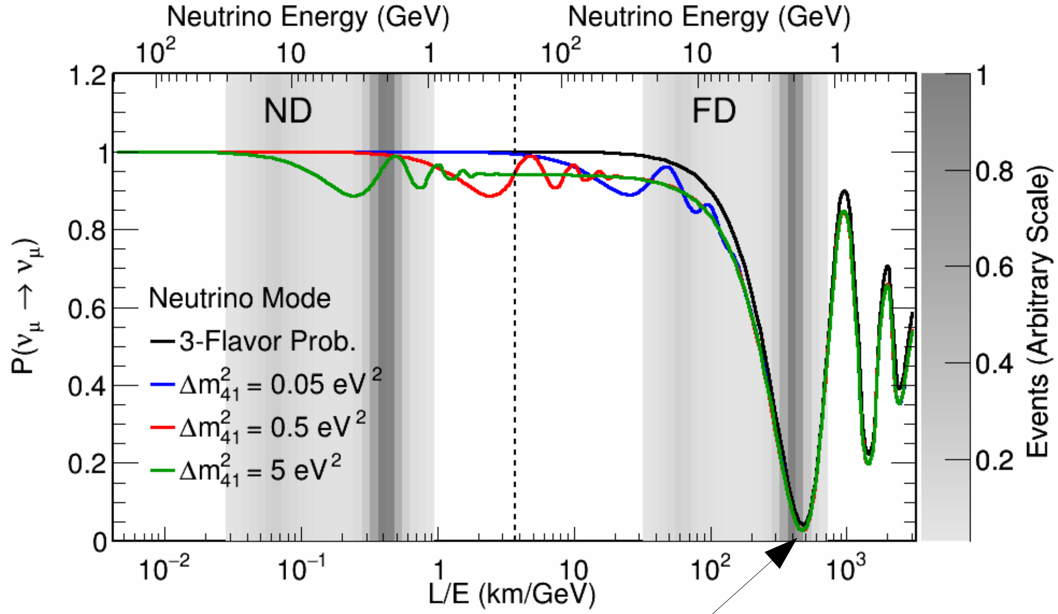
- Due to lepton universality, NC interaction rate is invariant under three flavor oscillations
  - NC disappearance is clear signal of active → sterile disappearance
- Δm_{41}^2 independent terms lead to oscillations at beam peak in FD
- For large Δm_{41}^2, NC disappearance can occur in ND



$$1 - P(\nu_\mu \rightarrow \nu_s) \approx 1 - \cos^4\theta_{14}\cos^2\theta_{34}\sin^2 2\theta_{24}\sin^2\Delta_{41}$$
$$+ \sin^2\theta_{34}\sin^2 2\theta_{23}\sin^2\Delta_{31}$$
$$- \frac{1}{2}\sin\delta_{24}\sin\theta_{24}\sin 2\theta_{34}\sin 2\theta_{23}\sin 2\Delta_{31}$$

3+1 ν_μ CC Disappearance

- Sterile neutrinos manifest as additional ν_μ disappearance above that expected from three flavor oscillations
- Interplay between θ_{23} and θ_{24} affect depth of atmospheric maximum
- Modulations are possible at high energy in FD
- For large Δm_{41}^2, ν_μ disappearance can occur in ND

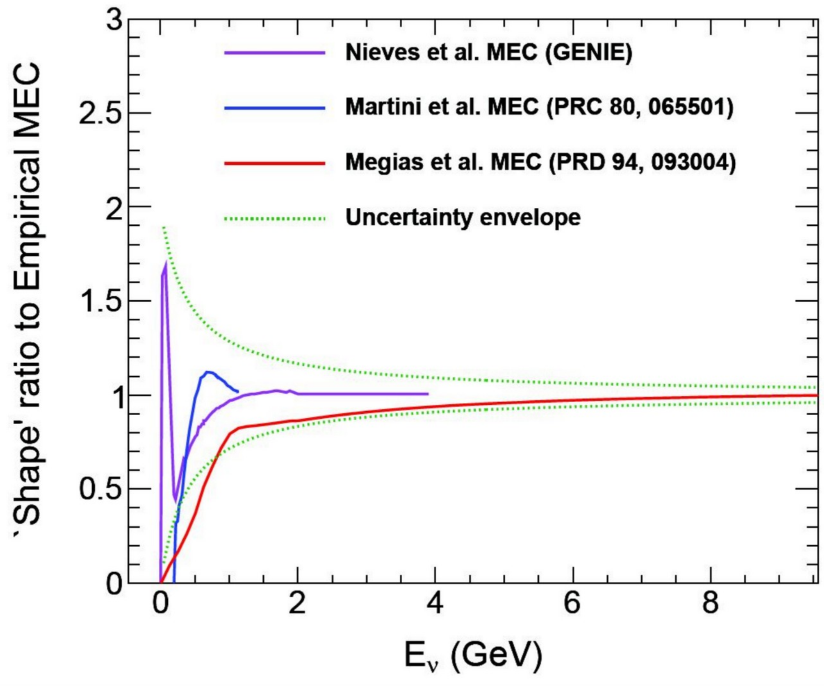


$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \cos 2\theta_{24} \sin^2 \Delta_{31} - \sin^2 2\theta_{24} \sin^2 \Delta_{41}$$

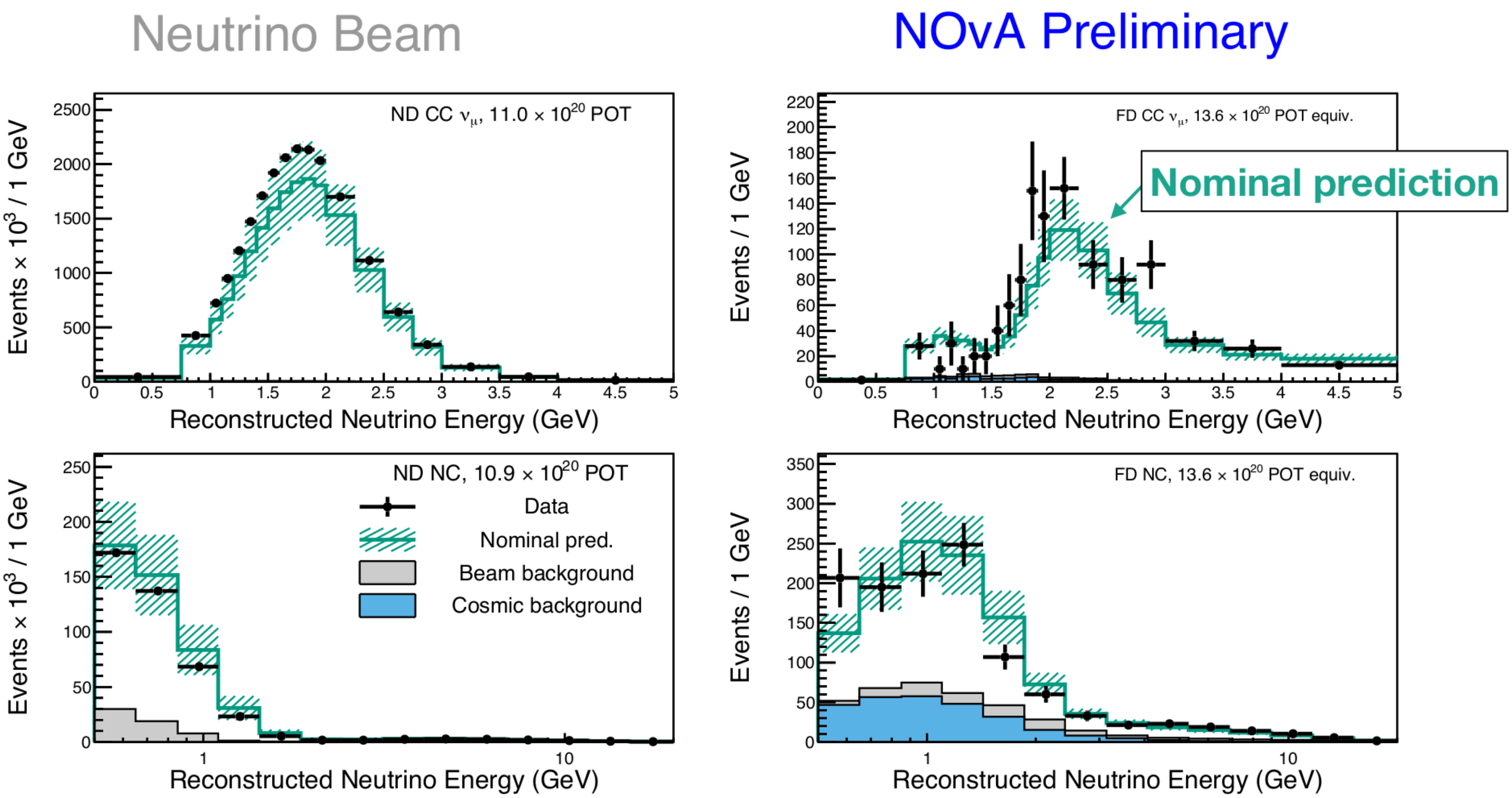
3+1 Oscillation Analysis

- New 3+1 sterile neutrino search uses a two-detector fit approach with NC and ν_μ CC samples
  - Ability to fit oscillation signals in ND significantly expands reach in Δm_{41}^2
  - Analysis performed with two independent approaches, PISCES and CMF
    - Both methods use different novel Gaussian multivariate test statistics and find consistent results, acting as a crosscheck on each other
  - Covariance matrix approaches capture ND-FD correlations in systematic uncertainties

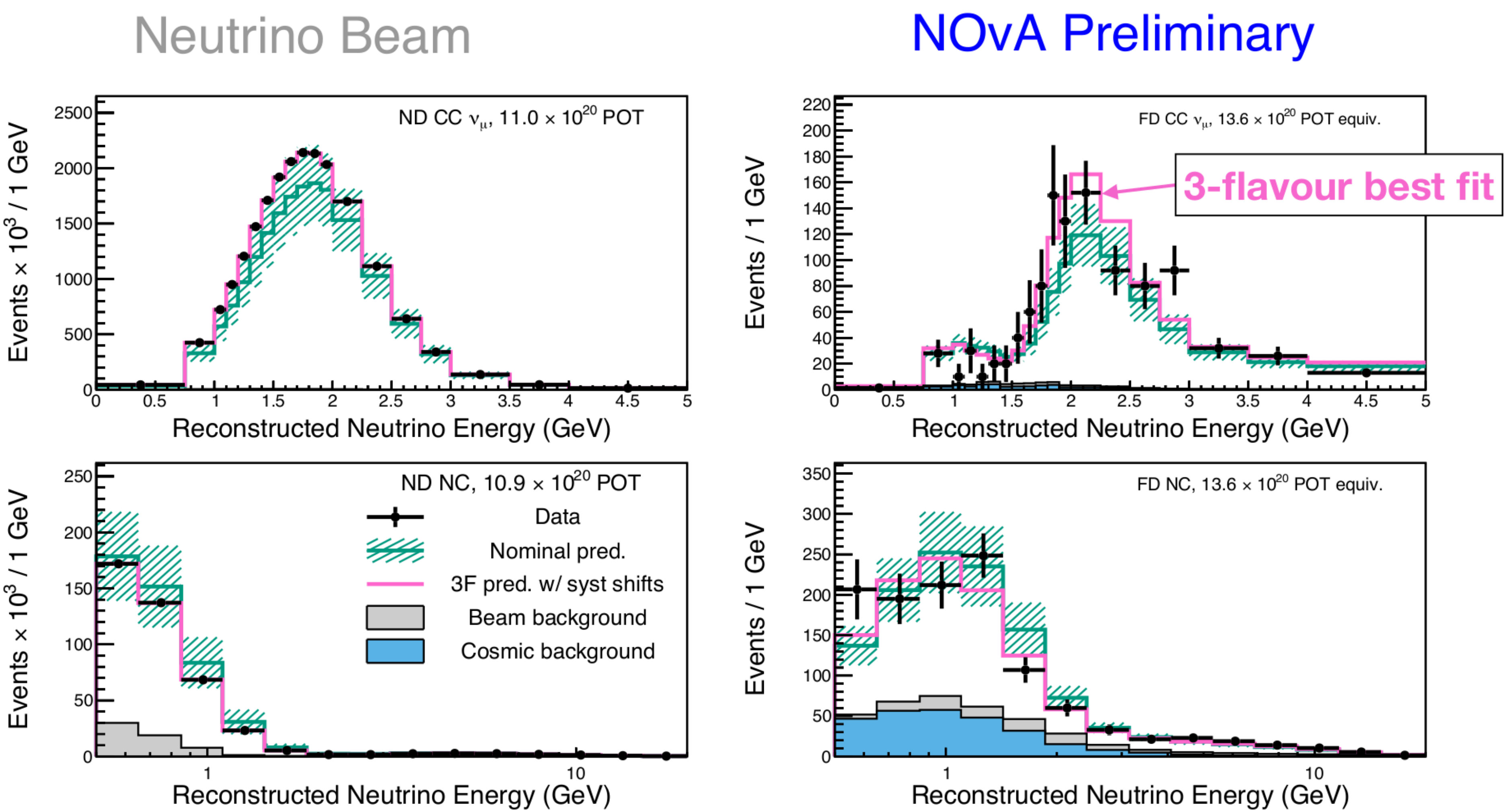
- Analysis uses new normalization and model spread uncertainties for 2p2h events
  - NOvA's standard data-driven cross-section tune uses ND data, so cannot be used
- New 5% normalization uncertainty on neutrinos with kaon ancestors, based on horn-off neutrino data



Sterile Neutrino Search Results

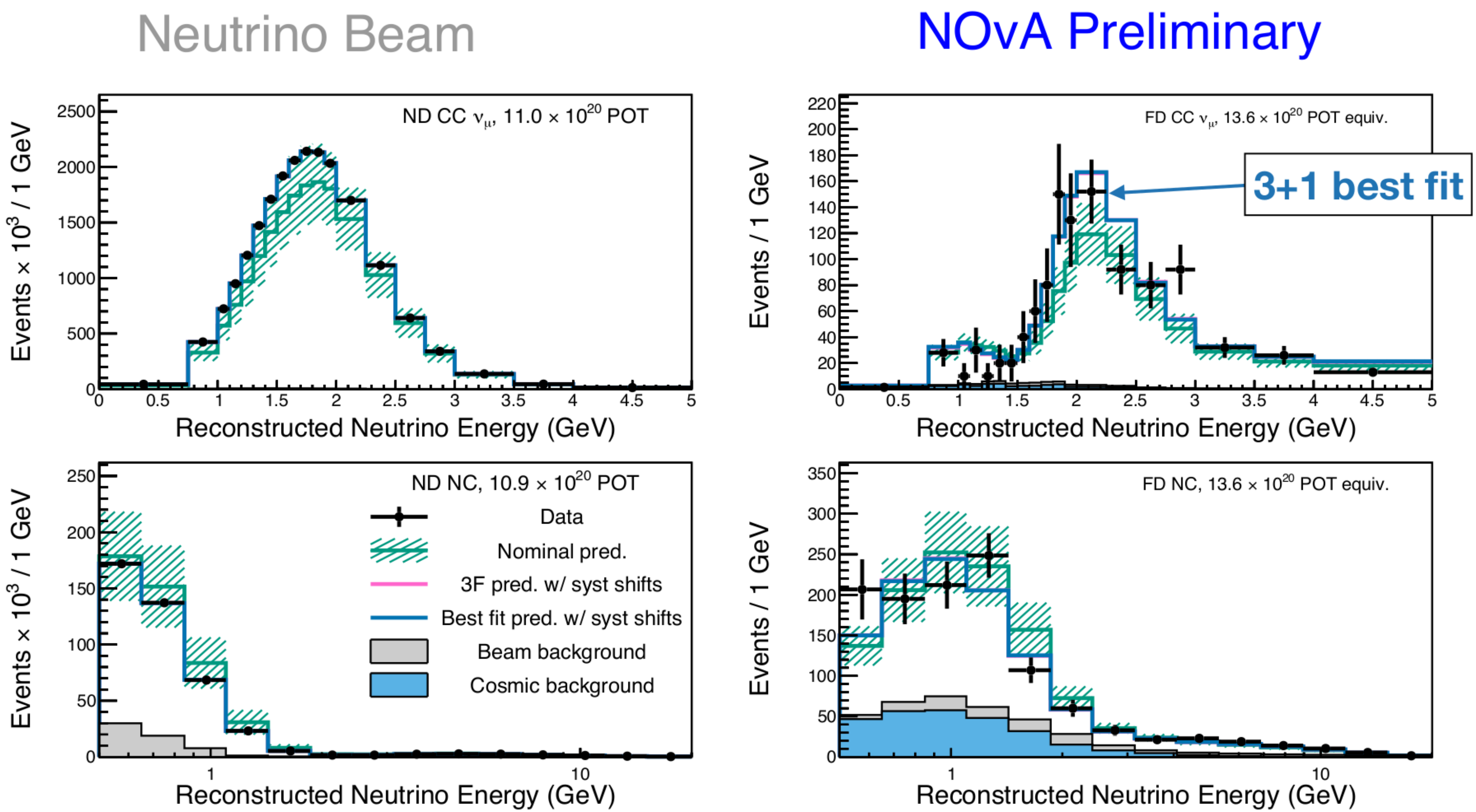


Sterile Neutrino Search Results



Pink line includes both 3-flavor oscillations and effect of correlated systematics

Sterile Neutrino Search Results

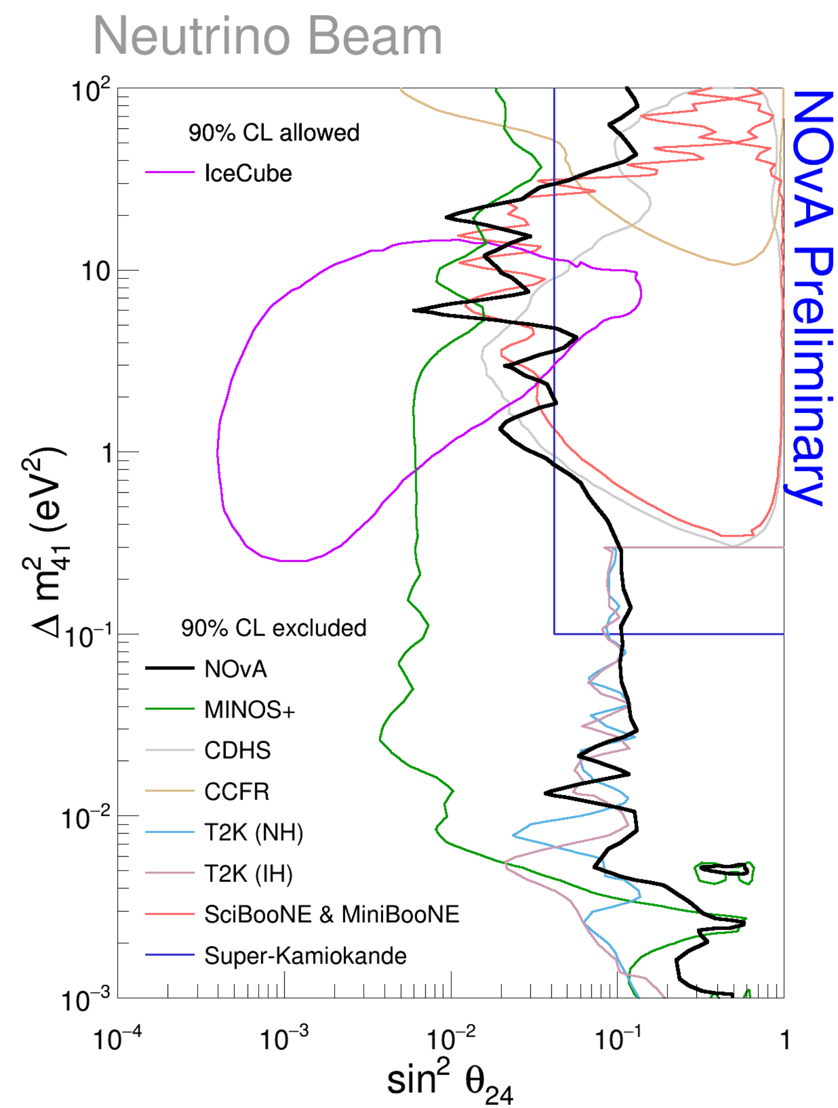


3 and 3+1 flavor best fits ~ identical

Goodness of fit: χ^2/DOF = 56.4/66

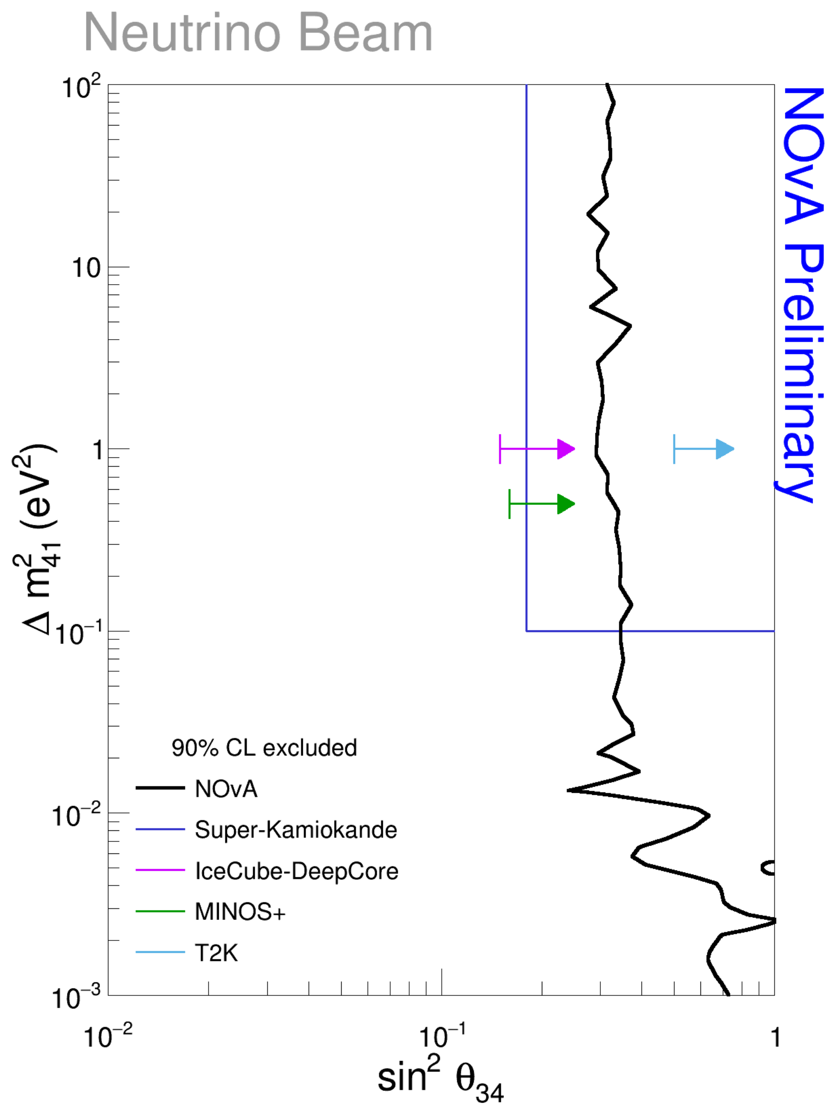
Δm_{41}^2 vs. $\sin^2\theta_{24}$ Limits

- Competitive limits on θ_{24} in high Δm_{41}^2 regime
- Profile θ_{23}, Δm_{32}^2, θ_{34}, and δ_{24}
  - Other three flavor 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



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

- World-leading limits on θ_{34} for small Δm_{41}^2
- Profile θ_{23}, Δm_{32}^2, θ_{24}, and δ_{24}
  - Other three flavor 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



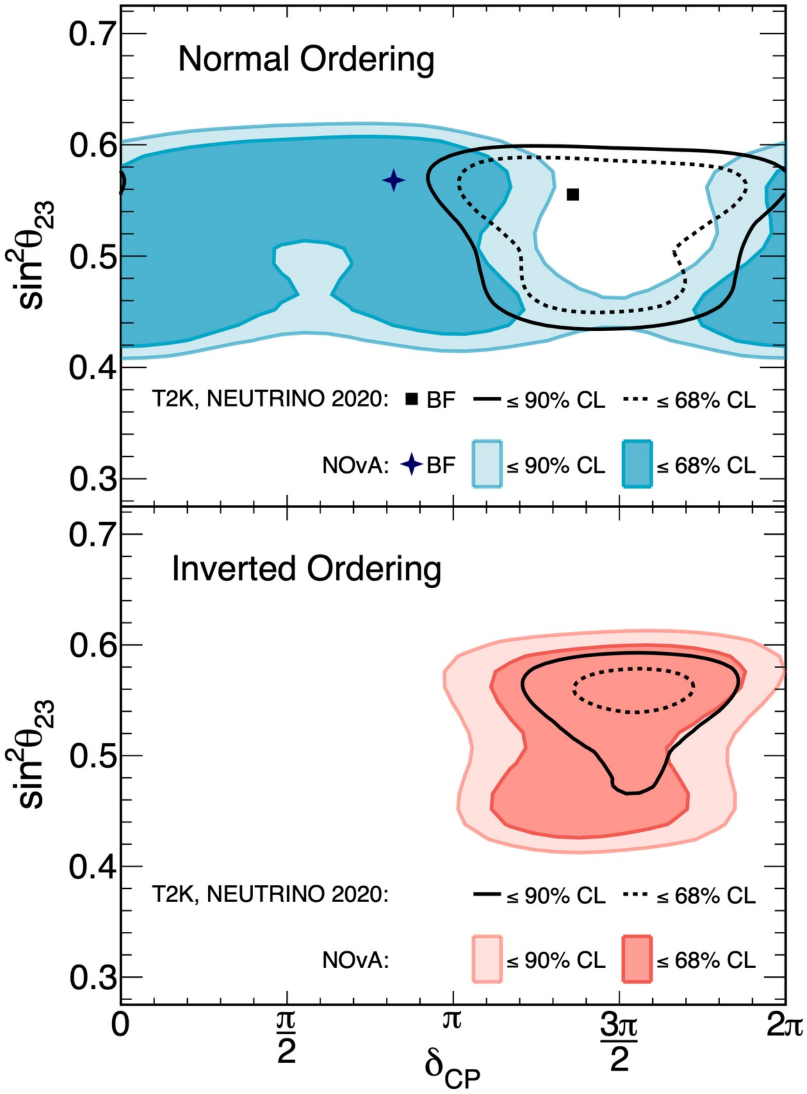
Sterile Neutrino Takeaways

- No evidence for sterile neutrinos in NOvA data
- New constraints on 3+1 model
  - Competitive θ_{24} limits at high Δm_{41}^2
  - World leading θ_{34} limits at low Δm_{41}^2

Non-Standard Interactions

NOvA and T2K

- NOvA and T2K data preferences broadly compatible
  - Most probable regions (in NO) distinct, but significant 1σ contour overlap
  - IO surfaces very similar
- Official NOvA + T2K joint analysis is expected later in 2022
  - Will help quantify level tension (or not)
- If tension were to increase in future, what could it mean?



Non-Standard Interactions

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

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

$$a = 2\sqrt{2}G_F N_e E$$

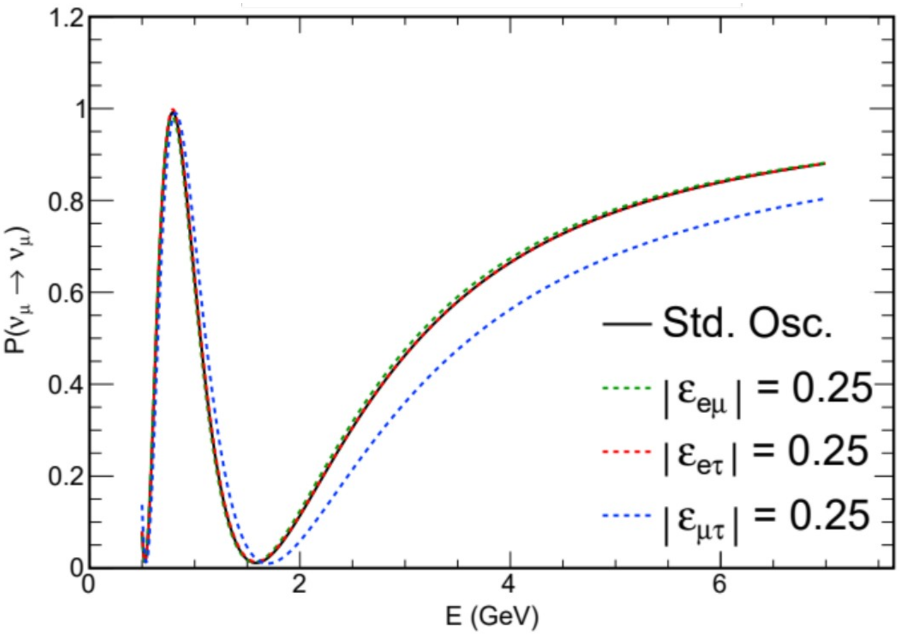
$$\epsilon_{\alpha\beta} = |\epsilon_{\alpha\beta}|e^{i\delta_{\alpha\beta}}$$

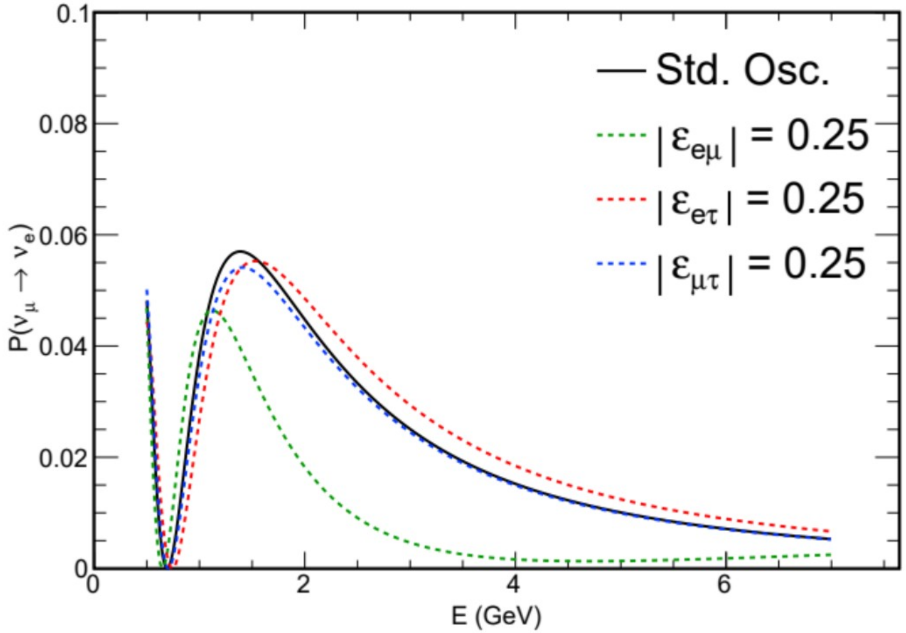
Wolfenstein matter potential

Introduces 9 new parameters:
On-diagonal: NSI-induced mass squared splittings (real valued)
neglected in this analysis
Off-diagonal: NSI-induced mixing angles (complex)
fit these individually

Search for NSI

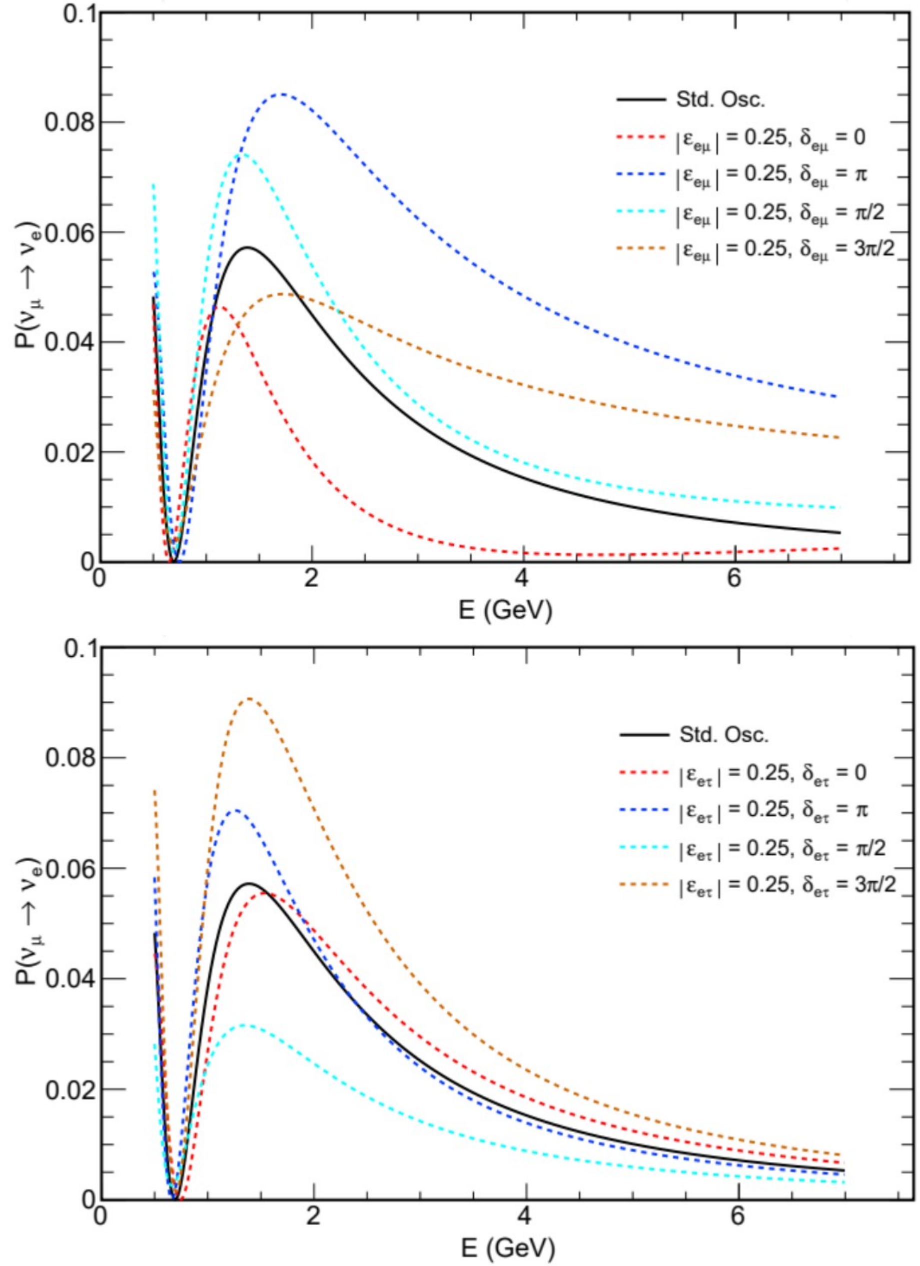
- NOvA's 810 km baseline is associated with strong matter effects
- Off-diagonal anomalous matter effects can produce substantial changes in NOvA predictions
- Use ν_μ, $\bar{\nu}_\mu$ disappearance and ν_e, $\bar{\nu}_e$ appearance spectra



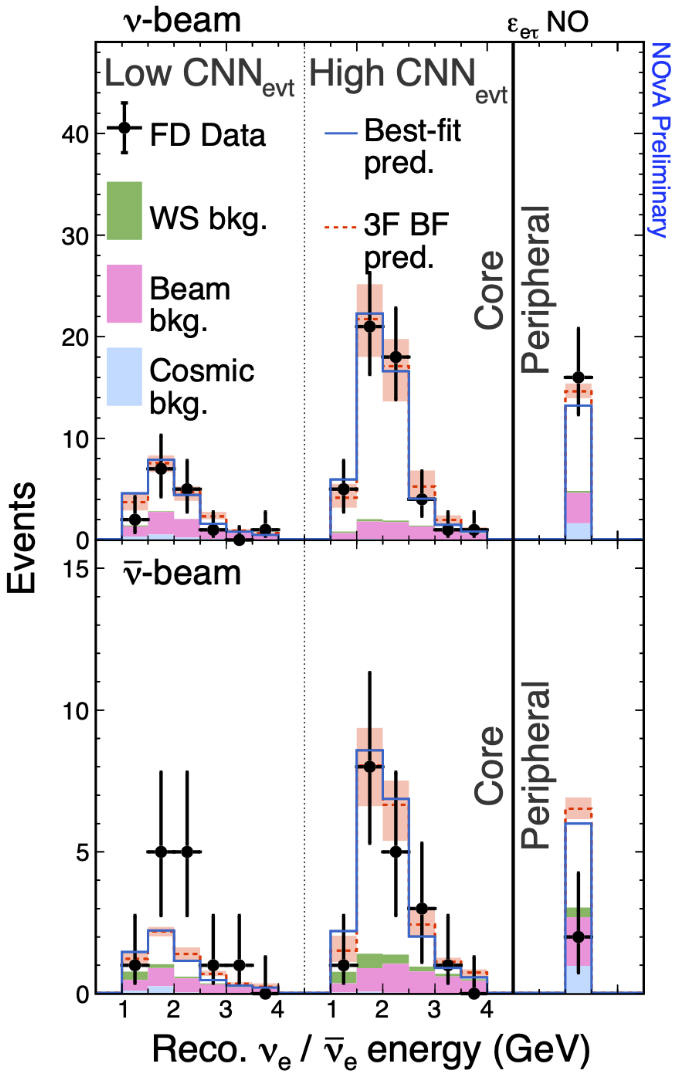


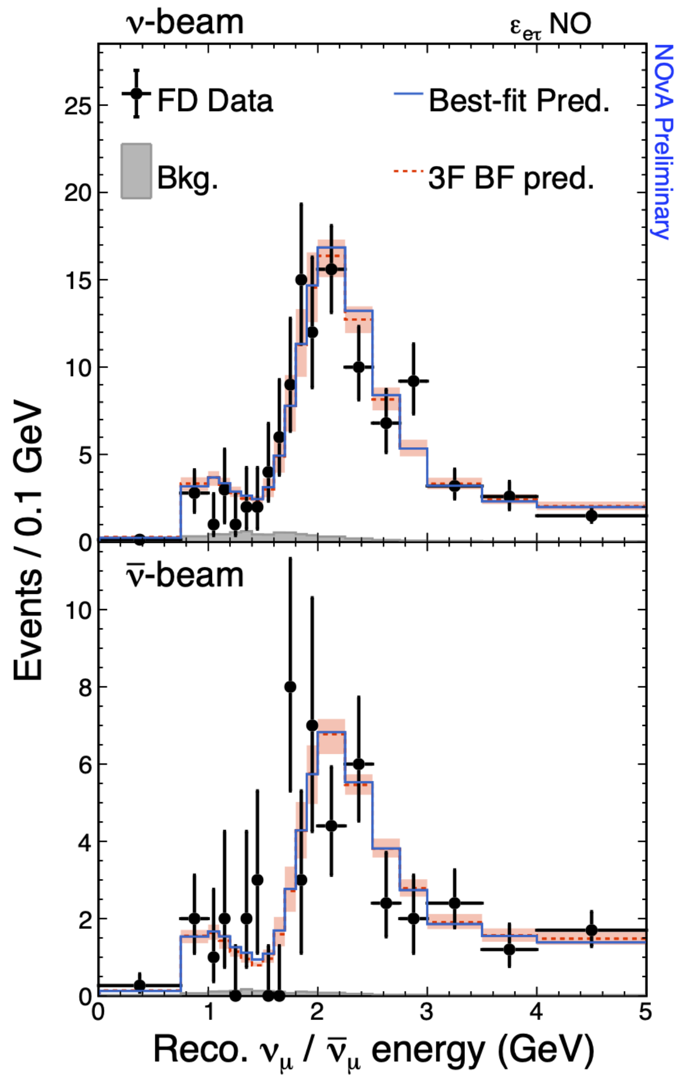
Search for NSI

- NOvA's 810 km baseline is associated with strong matter effects
- Off-diagonal anomalous matter effects can produce substantial changes in NOvA predictions
- Use ν_μ, $\bar{\nu}_\mu$ disappearance and ν_e, $\bar{\nu}_e$ appearance spectra



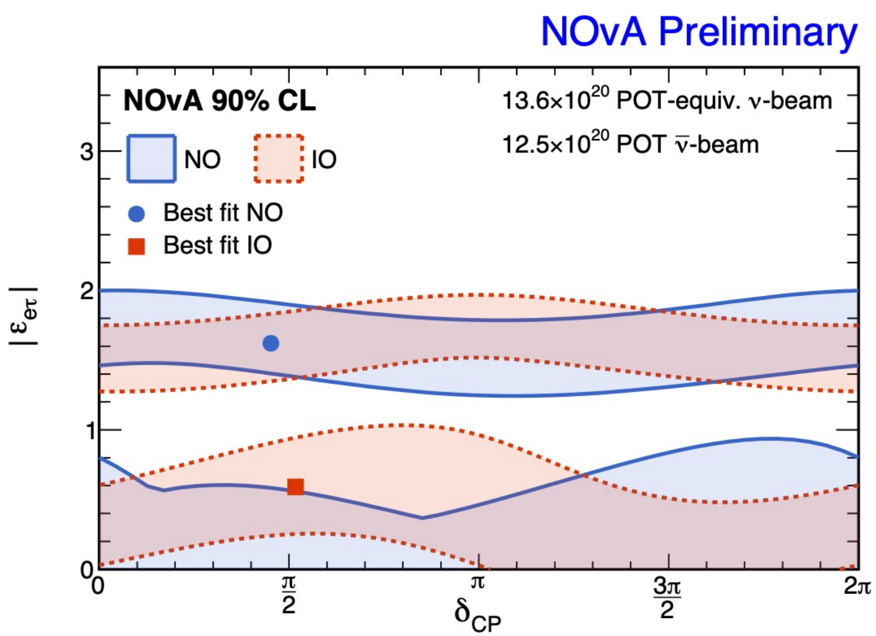
NSI $\varepsilon_{e\tau}$ Analysis Spectra

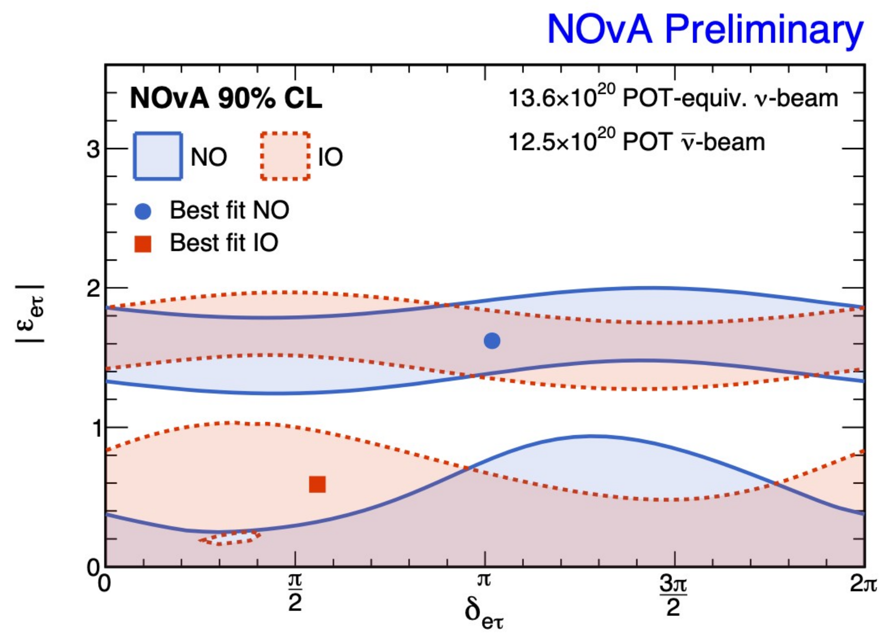




- Fit to CC ν_e and ν_μ selections in both neutrino and antineutrino beam modes
- Allow three-flavor parameters and one off-diagonal parameter (and phase) to vary
- $\varepsilon_{e\tau}$ case yields a best fits very similar to a three-flavor only fit
  - $\Delta\chi^2 \sim 0.65$
- Consistent with standard oscillations
  - $\varepsilon_{e\mu}$ and $\varepsilon_{\mu\tau}$ yield similar results

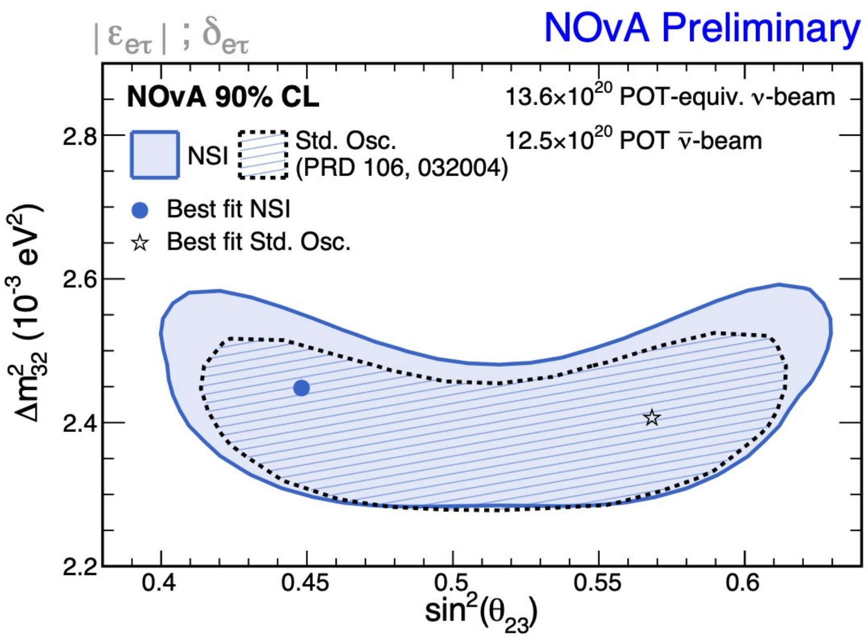
NSI $\varepsilon_{e\tau}$ 90% CL Limits

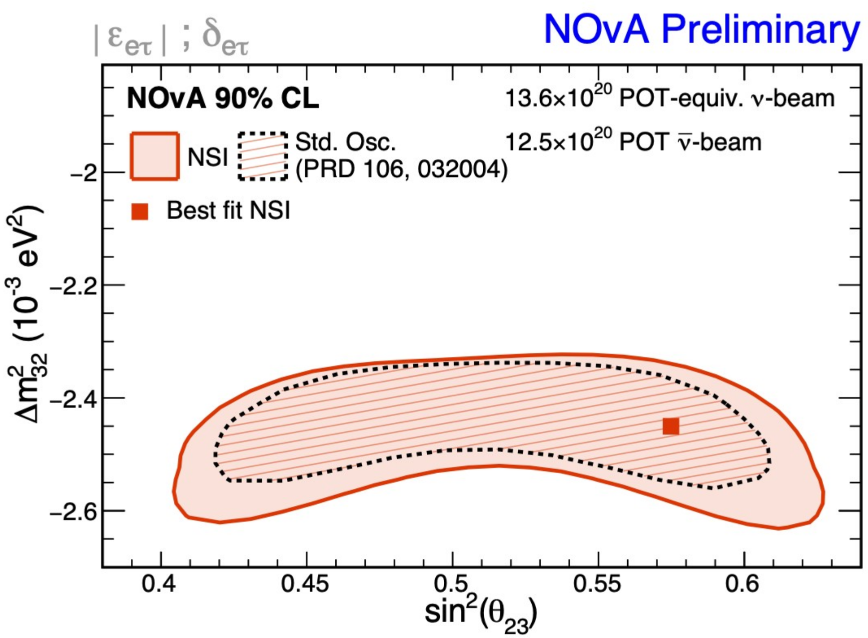




- Perform oscillation fits in terms of $|\varepsilon_{e\tau}|$ against phases δ_{CP} and $\delta_{e\tau}$
- Upper band in both fits is a result of degeneracy between the two phases, which becomes dominant at large $|\varepsilon_{e\tau}|$

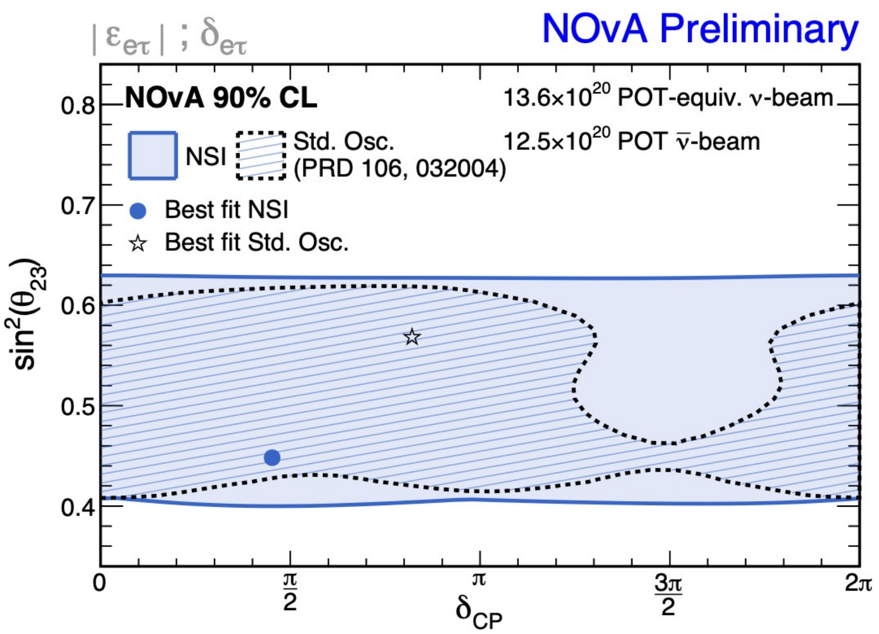
NSI $\varepsilon_{e\tau}$ 90% CL Limits

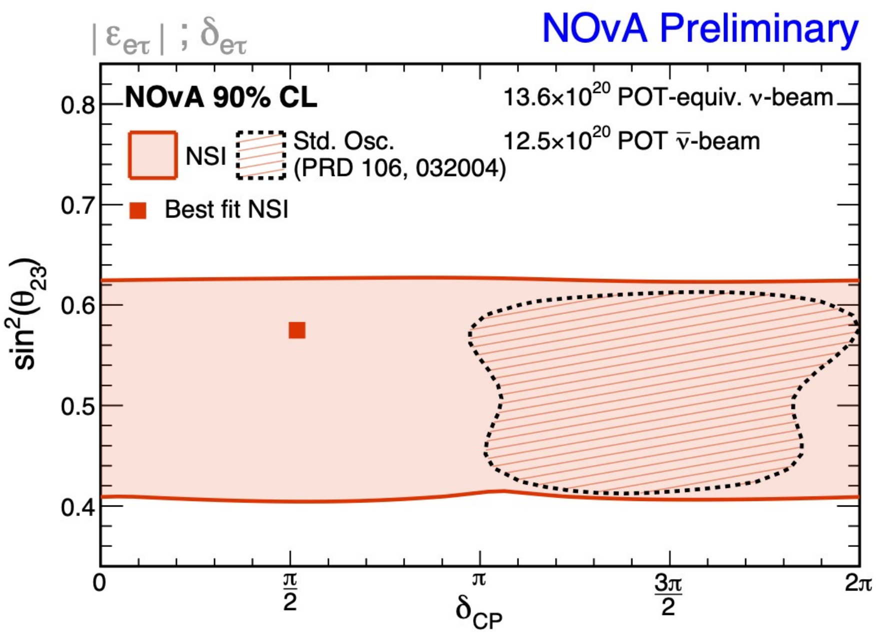




- Introducing NSI via $\varepsilon_{e\tau}$ into three flavor oscillations has minimal effect on constraint on Δm_{32}^2 and $\sin^2(\theta_{23})$
- Allowing $\varepsilon_{\mu\tau}$ to be free induces larger effects in this space

NSI $\varepsilon_{e\tau}$ 90% CL Limits





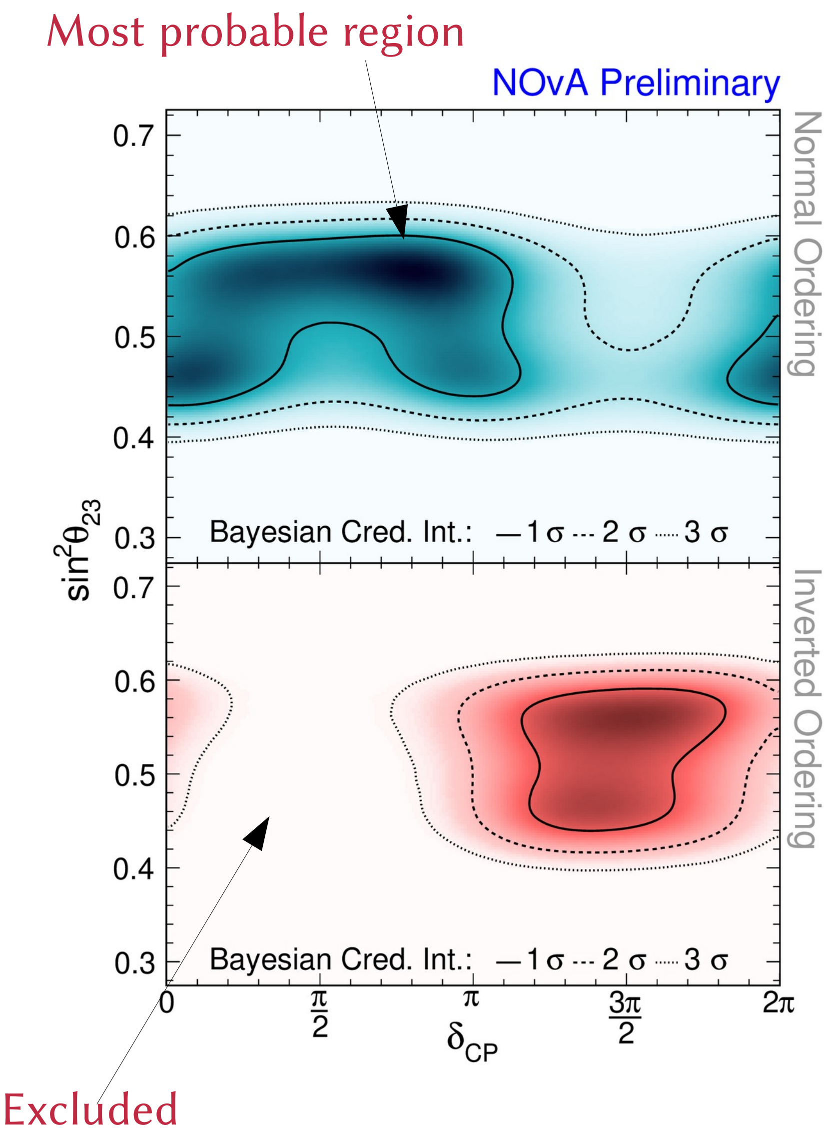
- Introducing NSI via $\varepsilon_{e\tau}$ into three flavor oscillations profoundly affects sensitivity to CP violation
- Much sensitivity to δ_{CP} in the three flavor interpretation is lost when introducing NSI, due to degeneracy with $\delta_{e\tau}$ phase

NSI Takeaways

- Addition of NSI does not improve description of NOvA data
- Large NSI parameter values excluded at 90% CL
  - $|\varepsilon_{e\mu}| > 0.6$
  - $1.0 < |\varepsilon_{e\tau}| < 1.2$ and $|\varepsilon_{e\tau}| > 2.0$
  - All values of phases compatible with current data
- Allowing the possibility of NSI affects standard oscillation parameter inferences
  - Minor weakening of atmospheric parameter measurements
  - Mass ordering and δ_{CP} sensitivity effectively wiped out

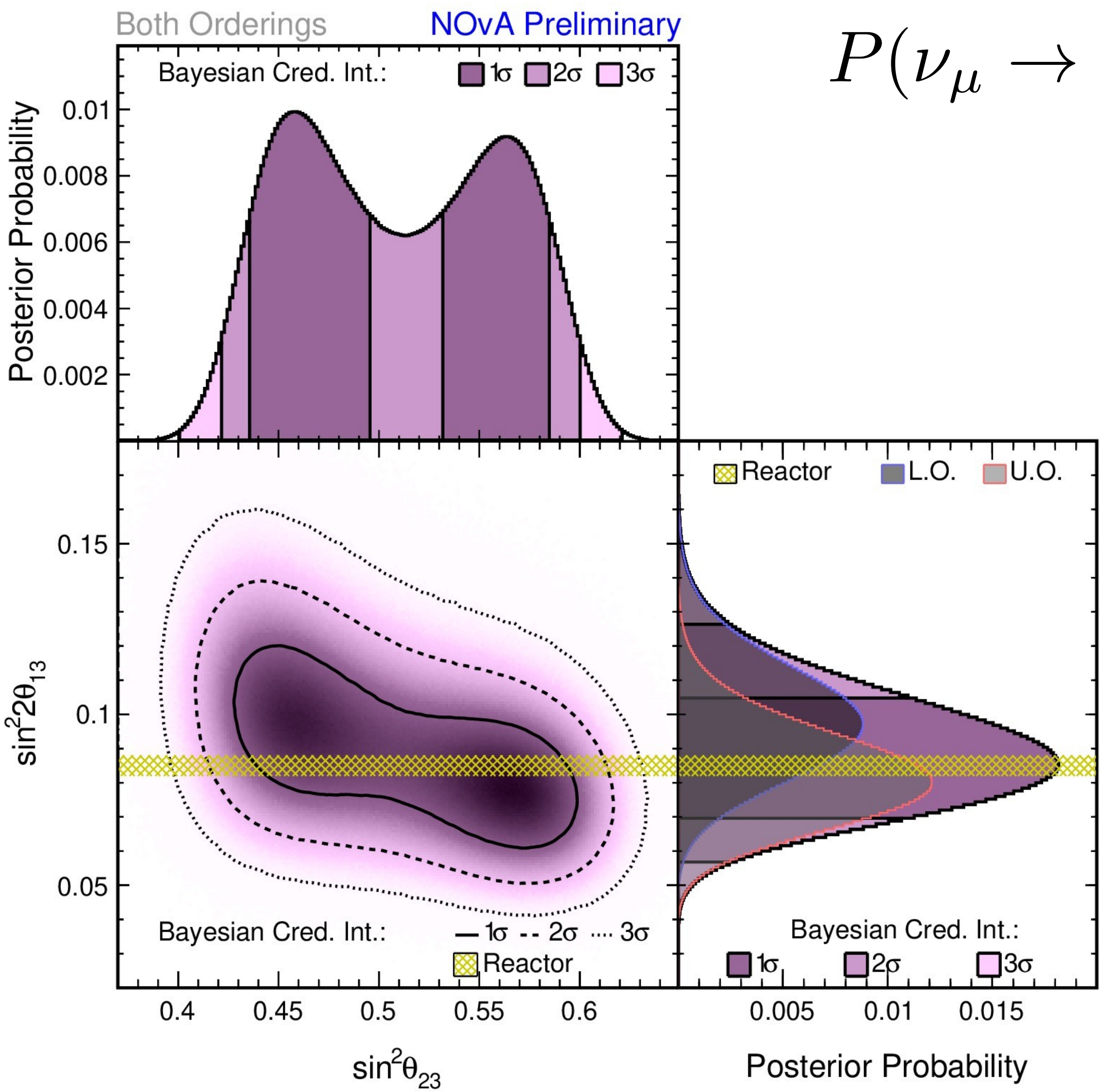
Three-Flavor Oscillations

Three-Flavor Oscillations



- New Bayesian analysis has similar top-line conclusions as previous
  - Phys. Rev. D 106 (2022) 032004
- Weak preferences for normal ordering and upper θ_{23} octant
- Rule out (>3σ) combination (IO, $\delta_{CP} = \pi/2$)
- Allows us to drill deeper

θ_{13} Constraints



LBL experiments can't measure θ_{23} octant alone:

$$P(\nu_\mu \to \nu_e) \approx \sin\theta_{23}\sin 2\theta_{13}\sin\Delta_{31}$$

- Bayesian analysis enables first NOvA-only measurement of θ_{13}:
  - Strong correlations with θ_{23} (as expected)
  - Very good agreement with reactor values
  - Weak θ_{23} octant preference driven by reactor constraint

$$\sin^2 2\theta_{13} = 0.085^{+0.020}_{-0.016}$$

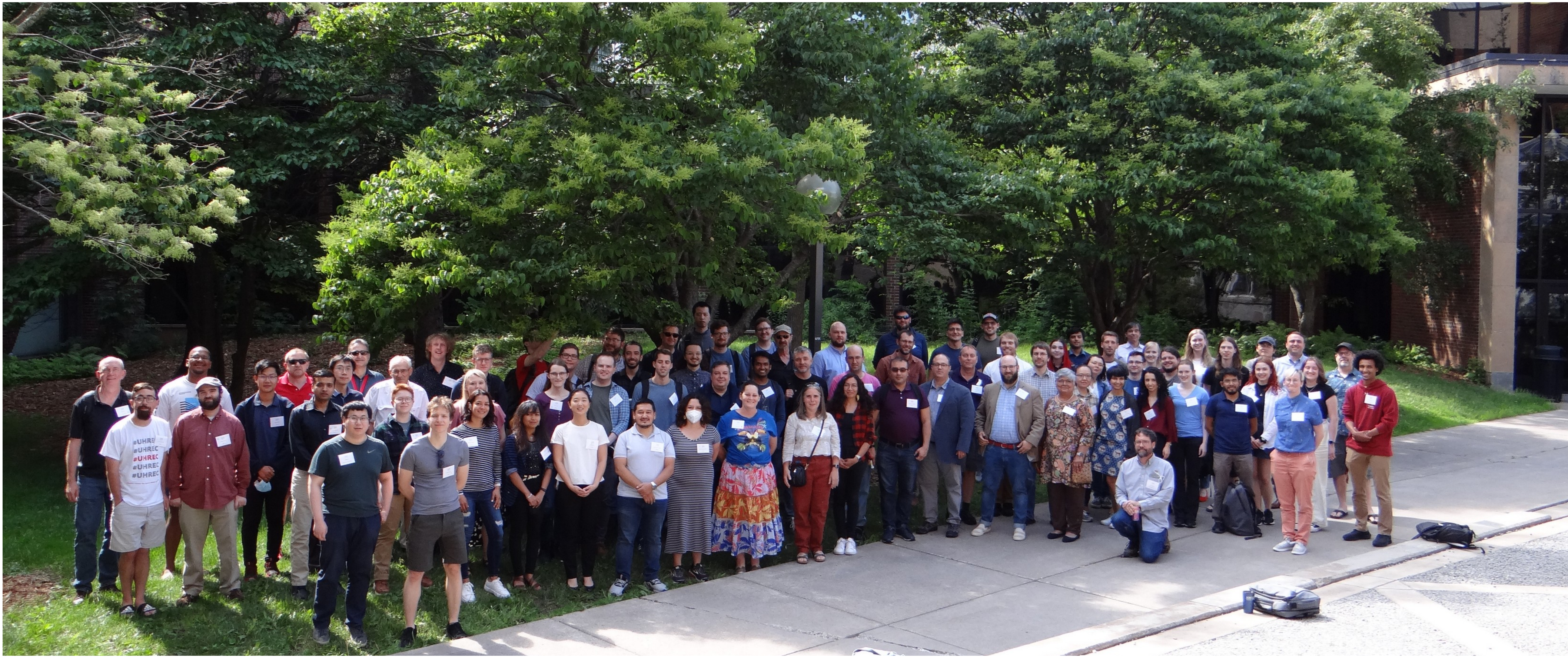
Three Flavor Takeaways

- Weak indications for upper θ_{23} octant and normal ordering
- PMNS model holding up well to deeper scrutiny
  - First NOvA only θ_{13} result is consistent with reactors
  - NOvA and T2K have broadly compatible three flavor results
  - Bayesian result enables other new inferences too, like Jarlskog invariant
- More details from Juan Miguel Carceller on Wednesday

Summary

- NOvA embarking on a program of more deeply probing the consistency of the PMNS model
  - Holding up well under increased scrutiny
    - No sign of sterile neutrinos
    - NSI do not improve description of data
    - Good agreement with other three flavor measurements (reactors, T2K)
- Official NOvA-T2K combination expected later in 2022
- About 50% of expected data collection is still to come
- Stay tuned!

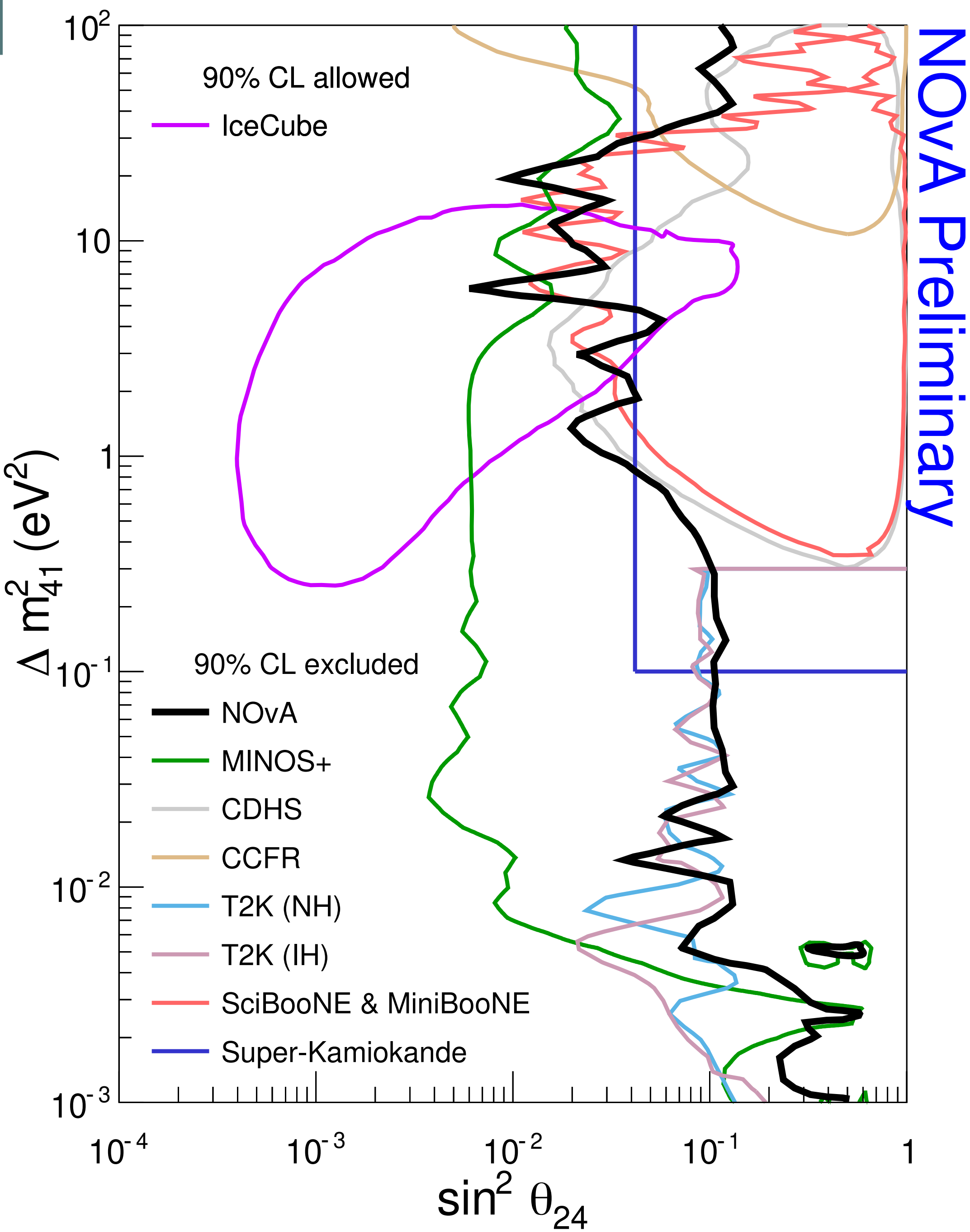
Thank You!



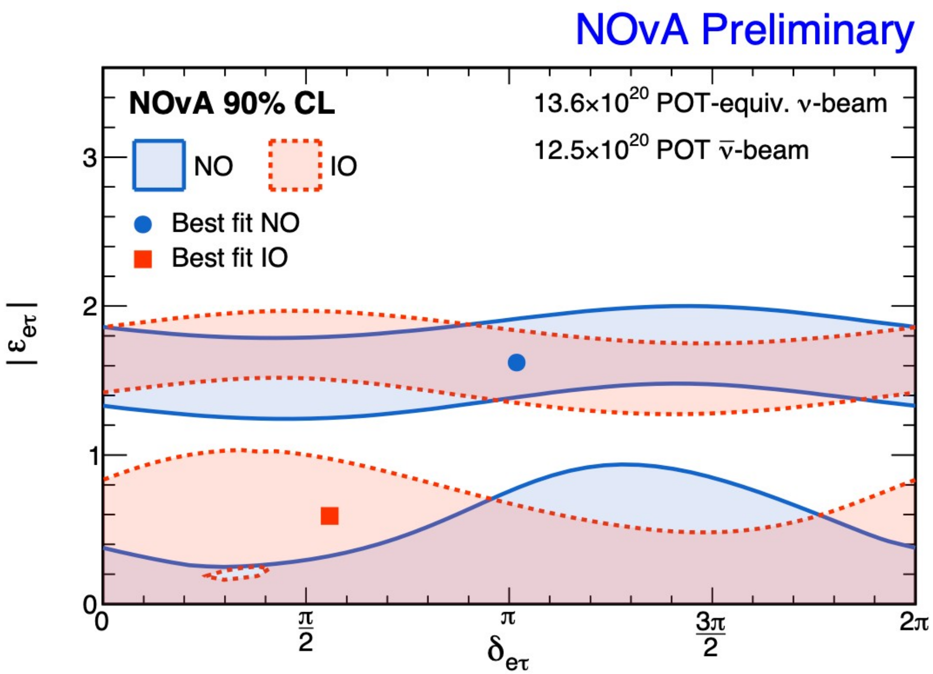
Backup Slides

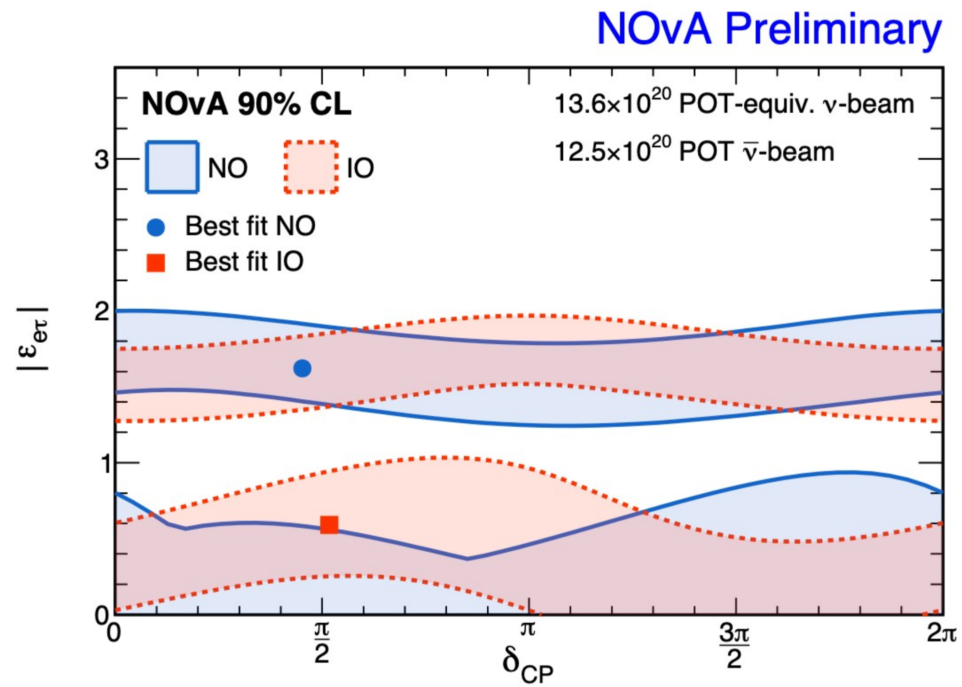
Sterile Neutrino References

- Citations:
  - SK: K. Abe et al. (Super-Kamiokande), Phys. Rev. D 91, 052019 (2015)
  - CDHS: F. Dydak et al. (CDHSW), Phys. Lett. B 134, 281 (1984)
  - CCFR: I.E. Stockdale et al. (CCFR), Phys. Rev. Lett. 52, 1384 (1984)
  - SciBooNE: K. B. M. Mahn et al. (SciBooNE, MiniBooNE), Phys. Rev. D 85, 032007 (2012)
  - MINOS+: P. Adamson et al. (MINOS+) Phys. Rev. Lett. 122, 091803 (2019)
  - T2K: K. Abe et al. (T2K) Phys. Rev. D 99, 071103(R) (2019)
  - IceCube: M. G. Aartsen et al. (IceCube), Phys. Rev. Lett. 125, 141801 (2020)



The Upper Band





The oscillation probability has terms proportional to

$$|\epsilon_{e\tau}|\cos(\delta_{CP}+\delta_{e\tau})$$

This term dominates in the intermediate $|\varepsilon_{e\tau}|$ region,

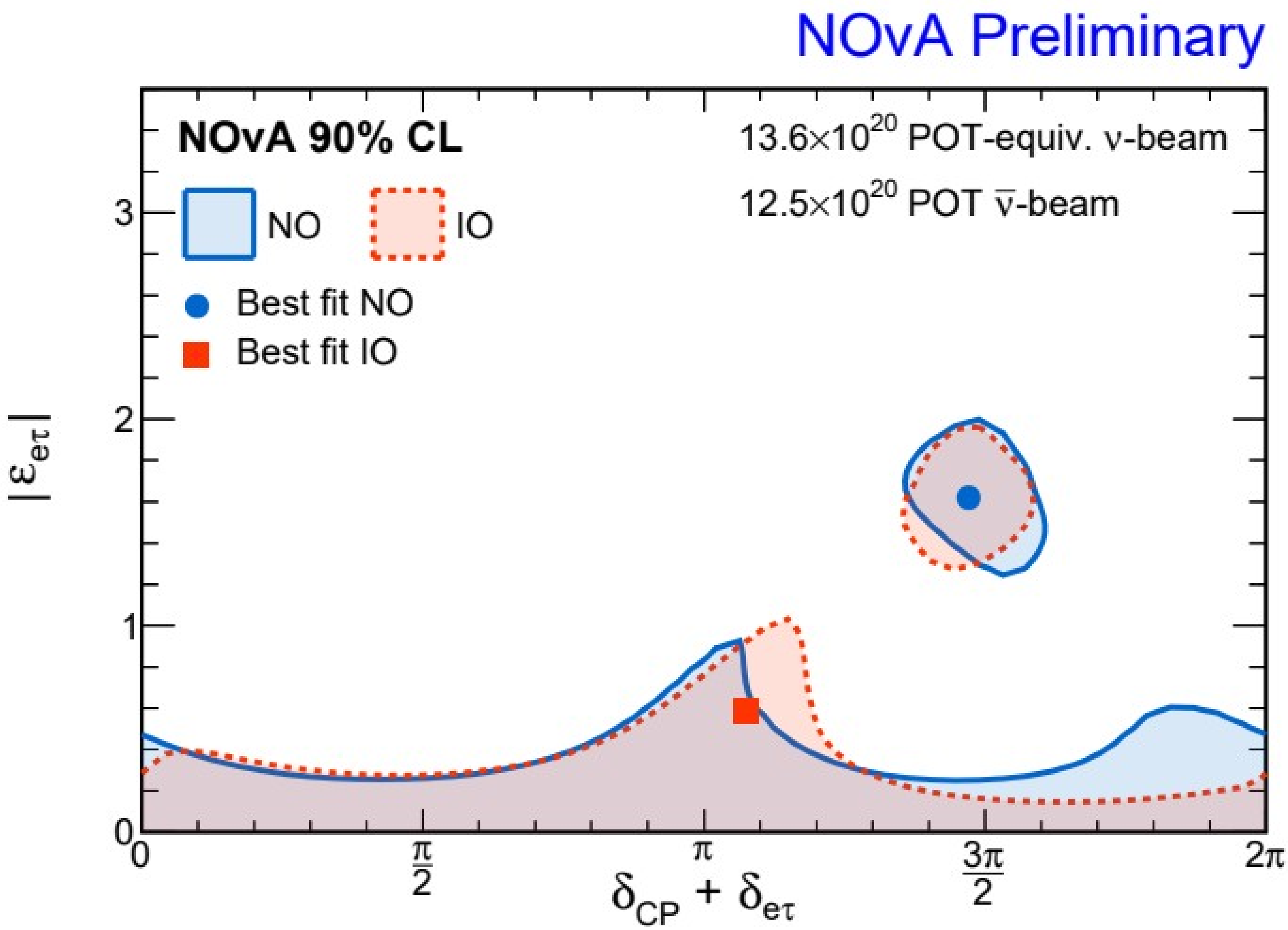
but **$(\delta_{CP} + \delta_{e\tau})=n\pi/2$ makes the cosine term vanish,**

which makes prob reduce to ~3-flavor.

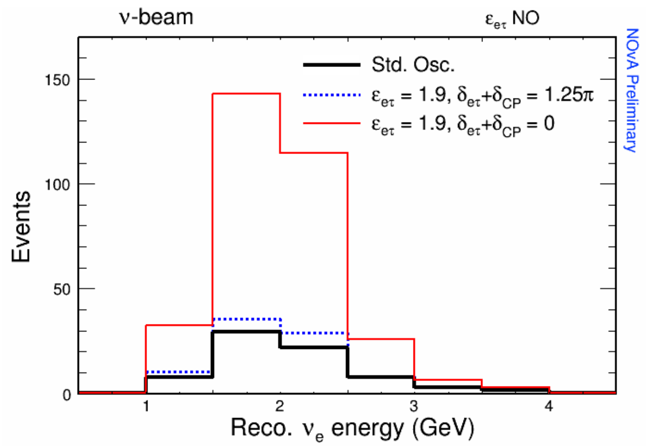
When we profile over one of the two δs, the best-fit for the other δ always forces their sum to nπ/2, in order to be compatible with the data (which is compatible with 3-flavor-only).

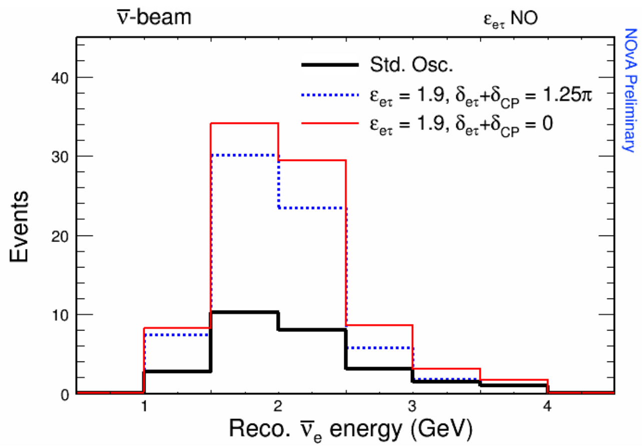
At lower and higher $|\varepsilon_{e\tau}|$, other terms in the probability dominate (and are not reducible to the 3-flavor-only case even at $(\delta_{CP} + \delta_{e\tau})=n\pi/2$).

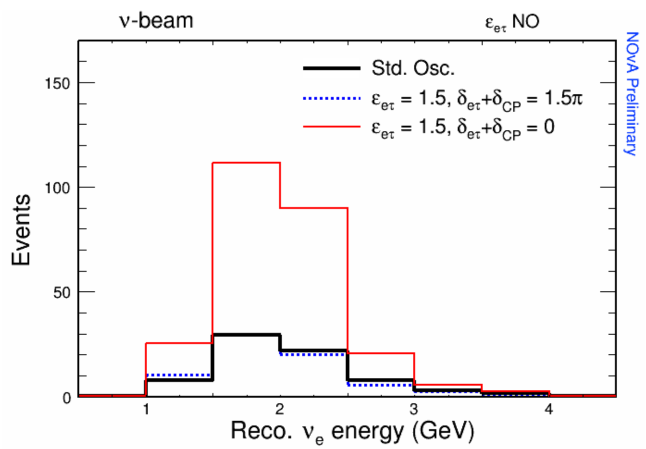
$\varepsilon_{e\tau}$ Limit, Combined Phase

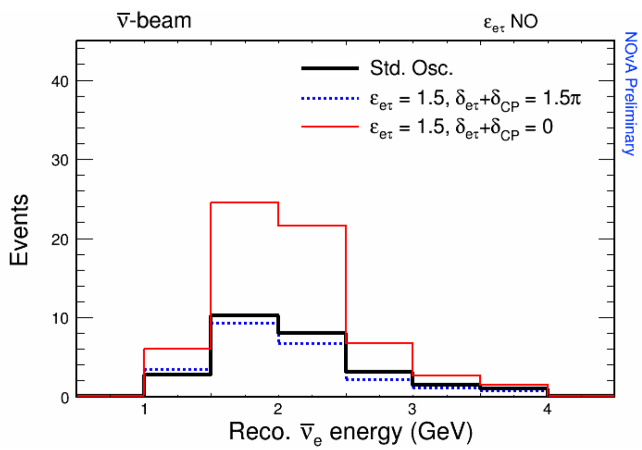


Understanding the Degeneracy

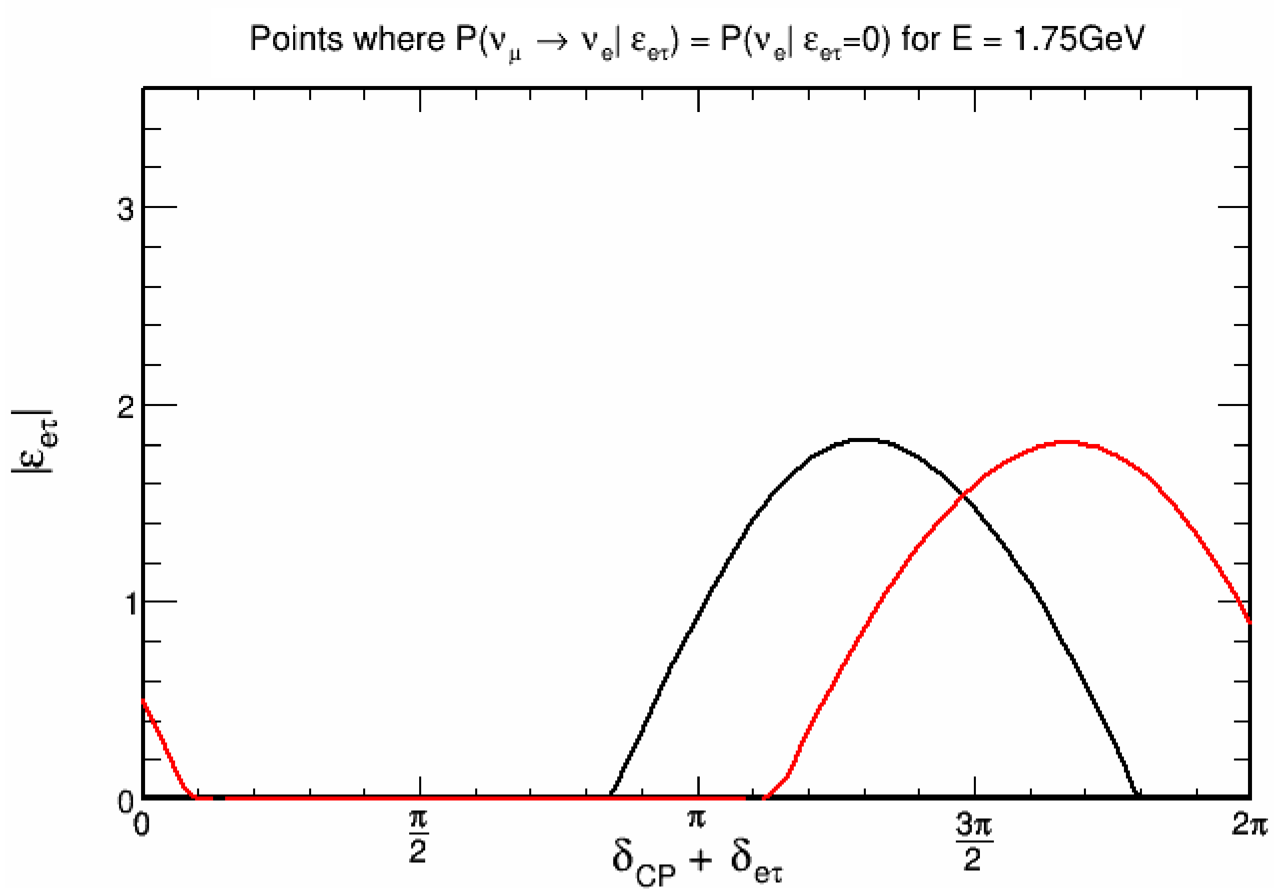




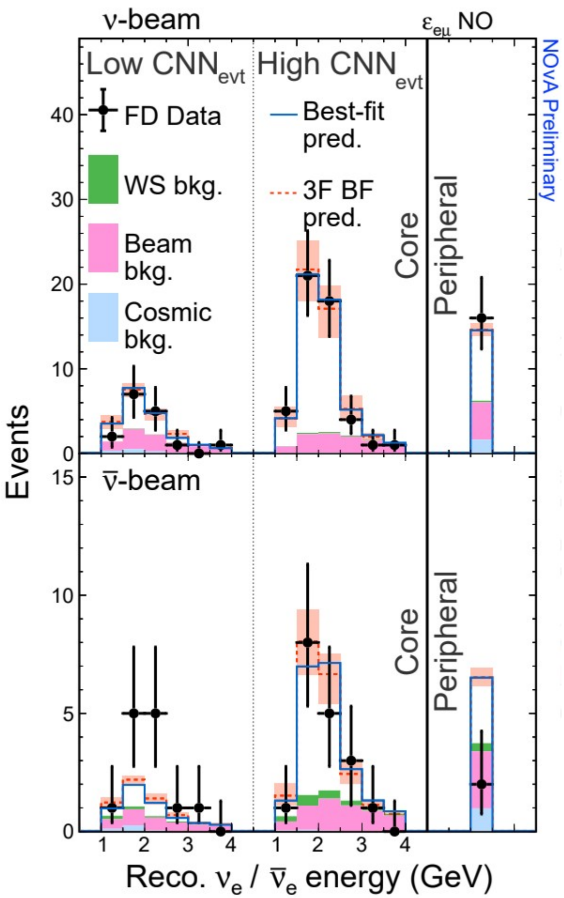


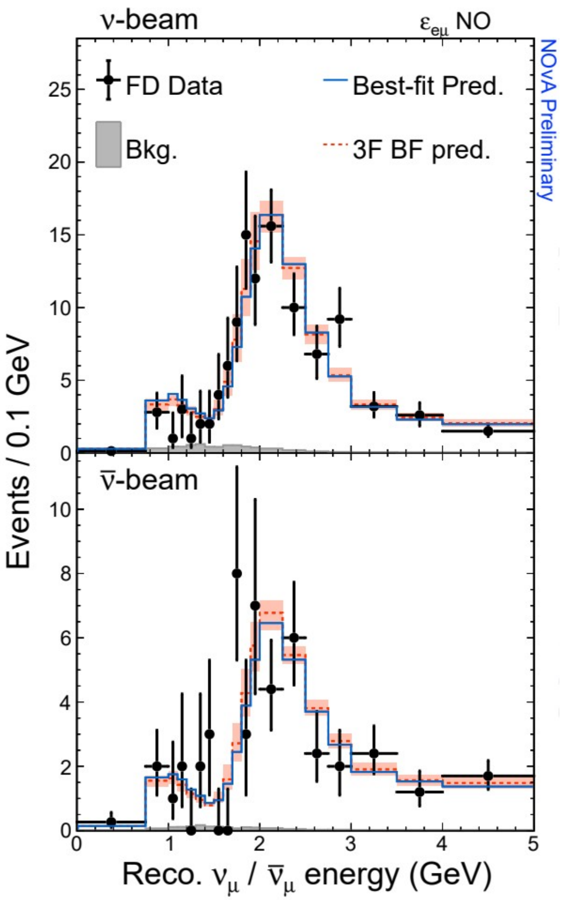


Understanding the Degeneracy

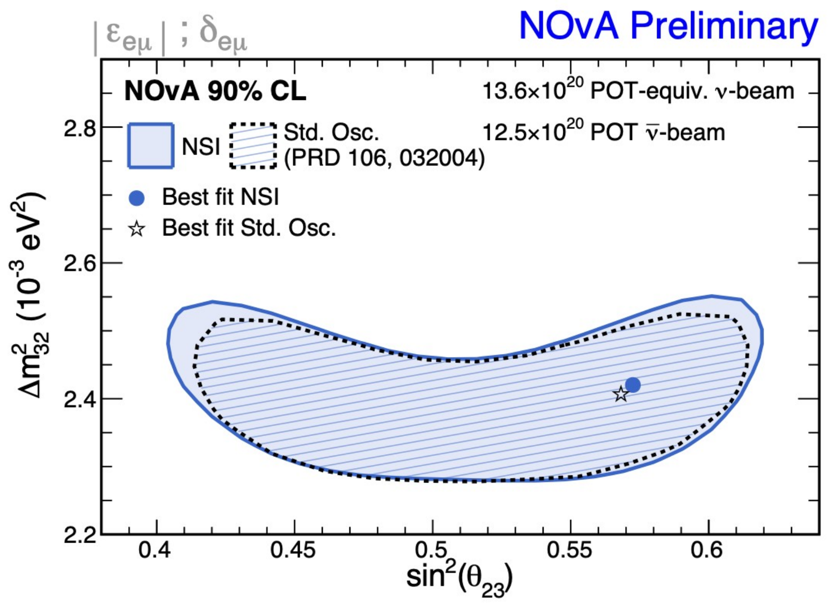


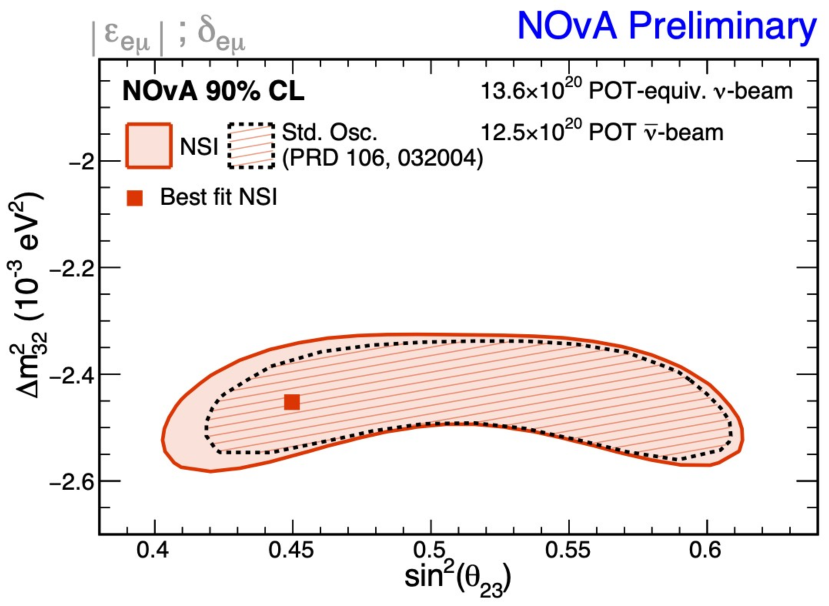
$\varepsilon_{e\mu}$ Spectra



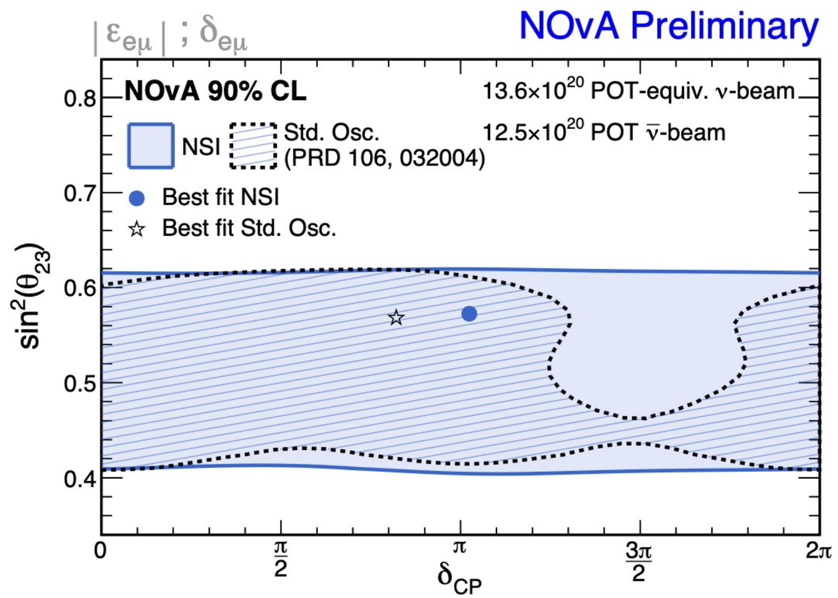


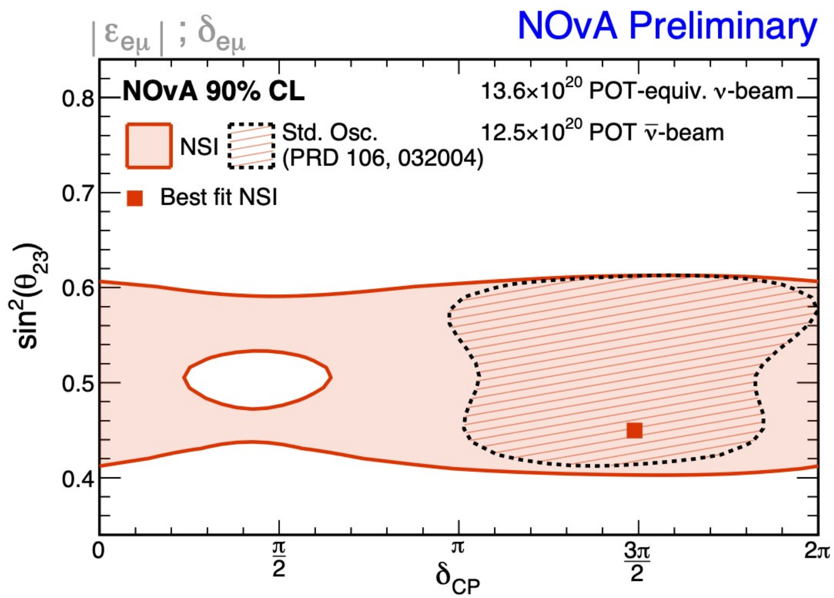
$\varepsilon_{e\mu}$



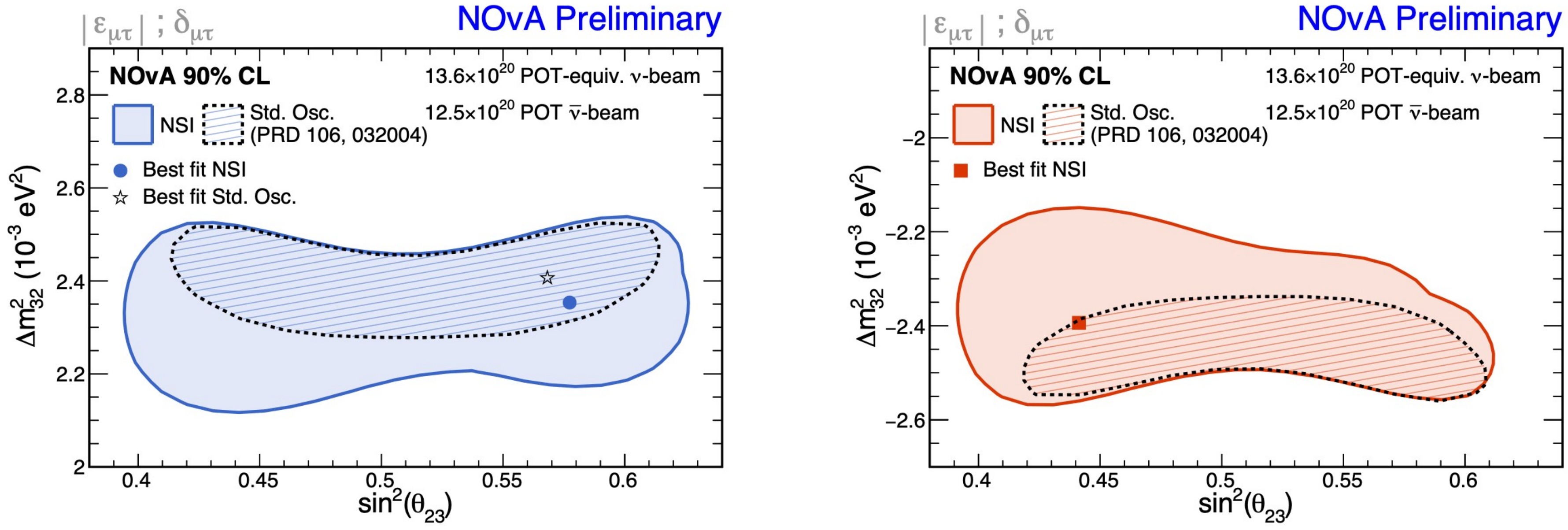


$\varepsilon_{e\mu}$





$\varepsilon_{\mu\tau}$



$\varepsilon_{\mu\tau}$