
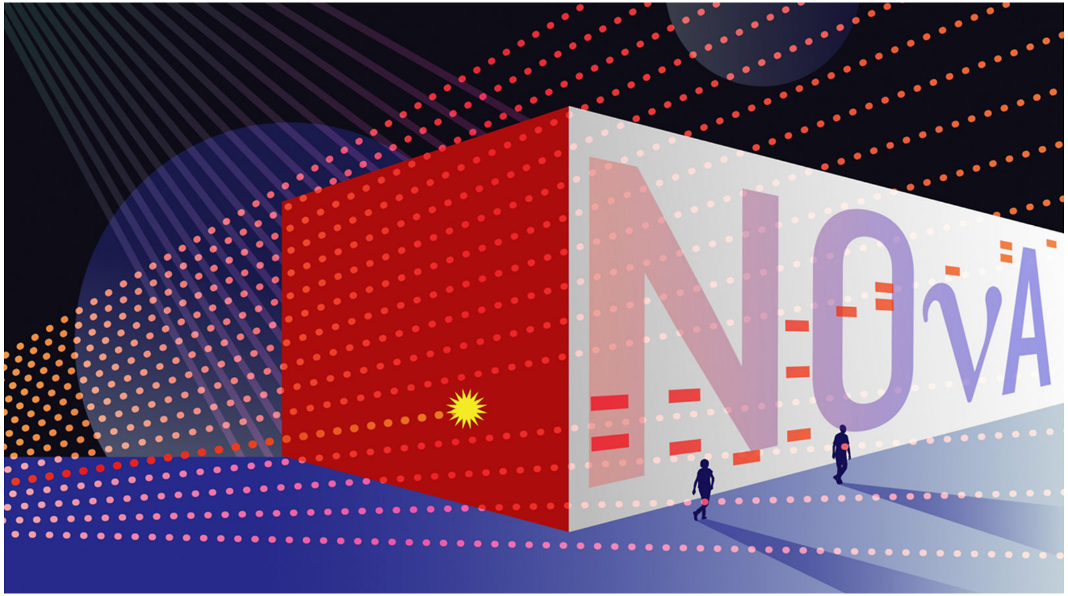

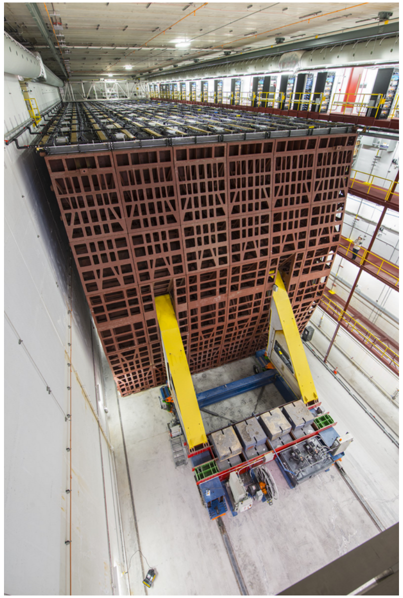

Latest Results from the NOvA Experiment

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For the NOvA Collaboration

XXV DAE-BRNS HEP SYMPOSIUM
12 - 16 DECEMBER 2022
IISER , Mohali

Standard Picture of 3 Flavor Mixing

Flavor Eigenstates (interact) — Mass Eigenstates (propagate)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\rm CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\rm CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$c_{ij}=\cos\theta_{ij}$
$s_{ij}=\sin\theta_{ij}$

Oscillation frequencies proportional to mass square splittings.

$$P_{\alpha\to\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}) \sin^2\left(1.27\frac{\Delta m^2_{ij}L}{E}\right) + 2\sum_{i>j} Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}) \sin\left(1.27\frac{\Delta m^2_{ij}L}{E}\right)$$

Current knowledge,
from global fit to oscillation data

$$\sin^2\theta_{23} = 0.573^{+0.018}_{-0.023}$$

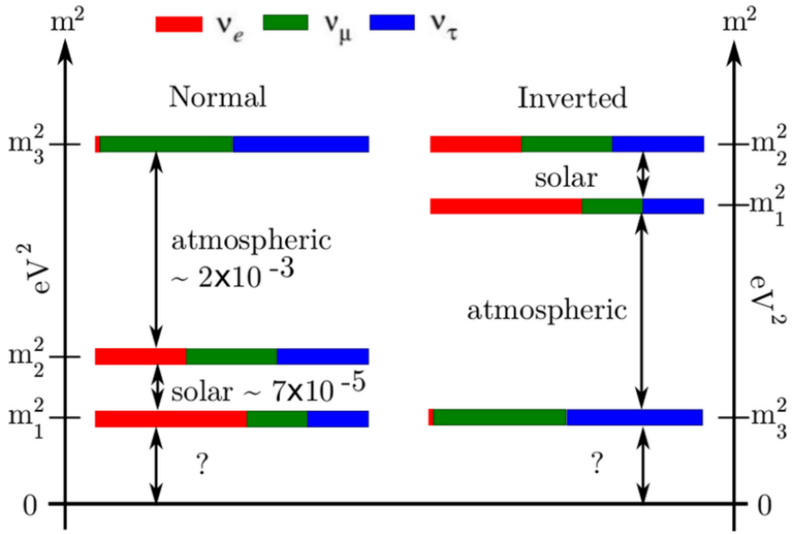
$$\sin^2\theta_{13} = 0.02220^{+0.00068}_{-0.00062}$$

$$\sin^2\theta_{12} = 0.304^{+0.013}_{-0.012}$$

NuFIT 5.1 (2021), www.nu-fit.org
JHEP 09 (2020) 178 [arXiv:2007.14792]

Questions Addressed in this Talk

- **What is the neutrino mass ordering**

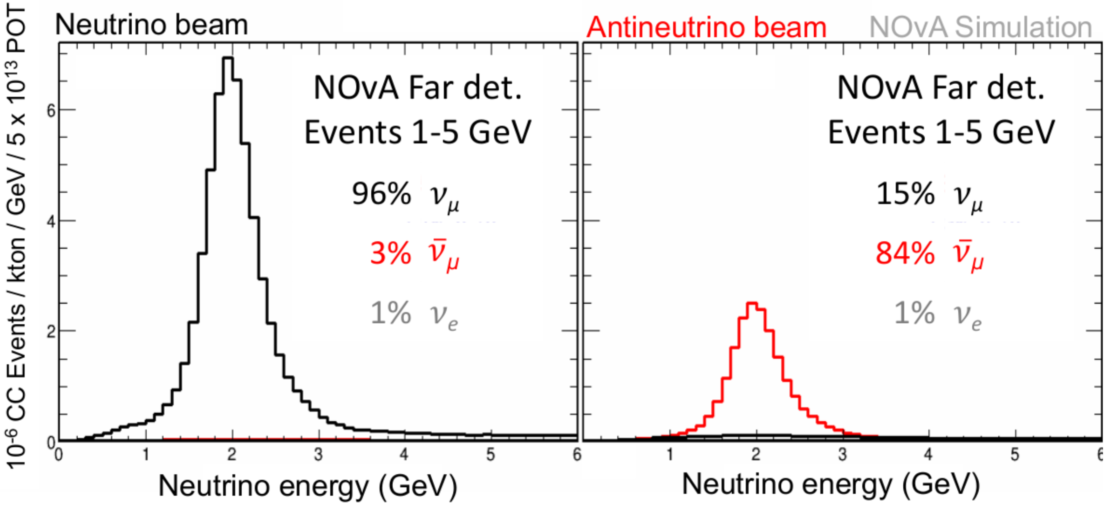


- **$\theta_{23} \neq 45°$? -** ν_μ or ν_τ couples more strongly to ν_3
- **$\sin(\delta_{CP}) = 0$ or $\neq 0$?** Do neutrinos exhibit CP violation?

- **Is the 3-flavour oscillation model the full picture?**
  - sterile neutrinos?

NUMI Off-Axis Narrow Band Beam

Far Detector simulated spectra assuming no oscillations



23.2×10^{20} (neutrino mode) + 12.7×10^{20} (antineutrino mode) protons on target

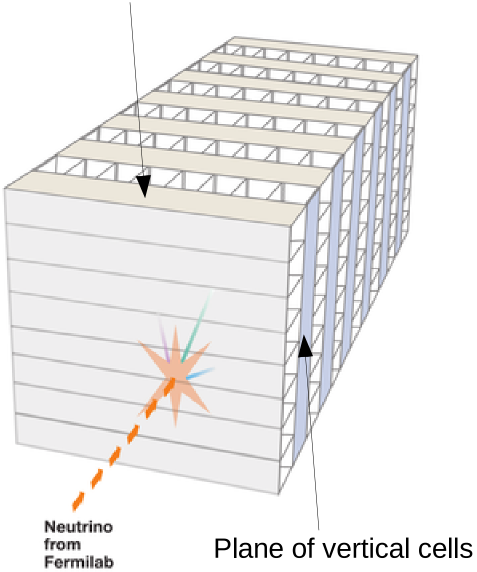
Two-detector experiment

Off-axis narrow band beam

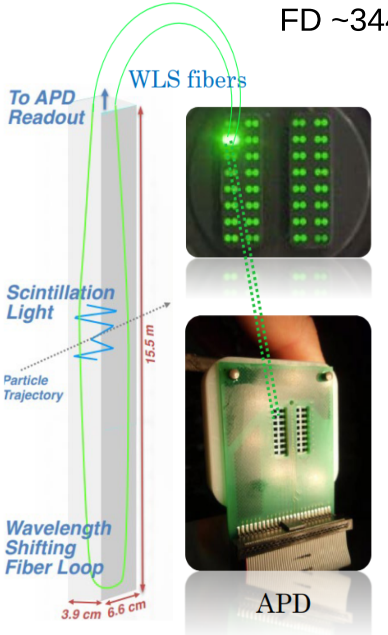
897 kW beam power demonstrated in 2022

NOvA Detectors

Far Detector 14 kton
896 planes



ND ~20,000 channels
FD ~344,000 channels

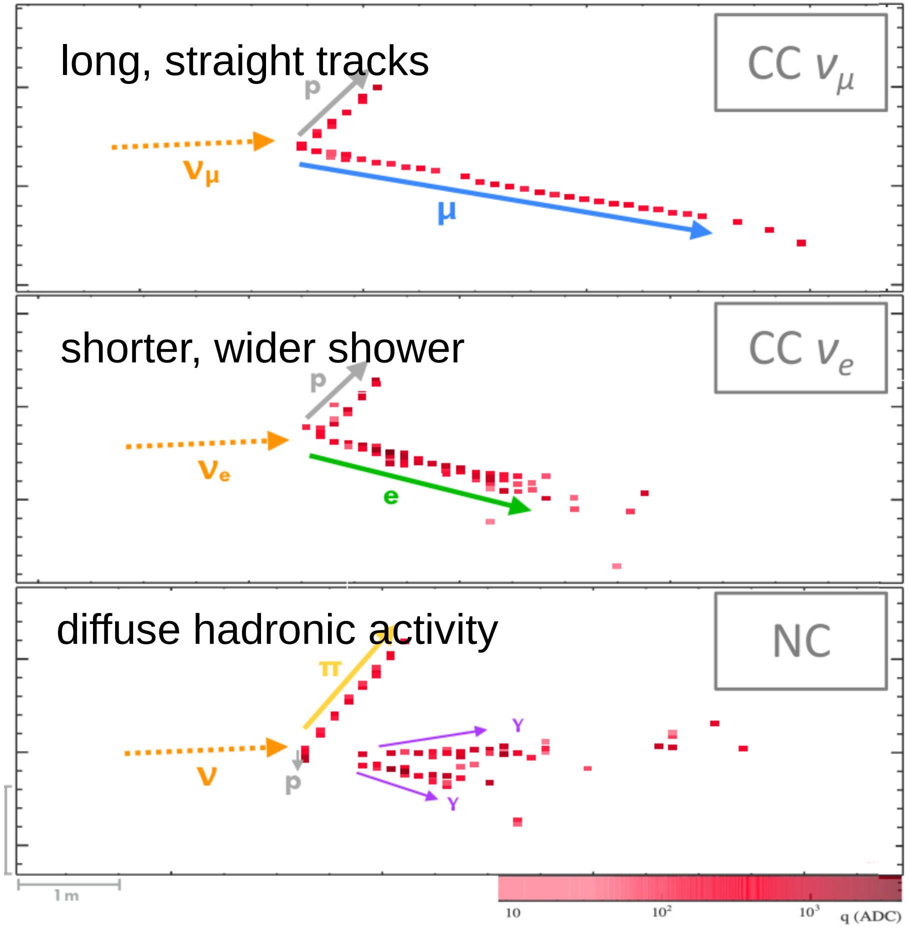


Near Detector 0.3 kton
214 planes

PVC extrusions filled with liquid scintillator(mineral oil + 5% pseudocumene)

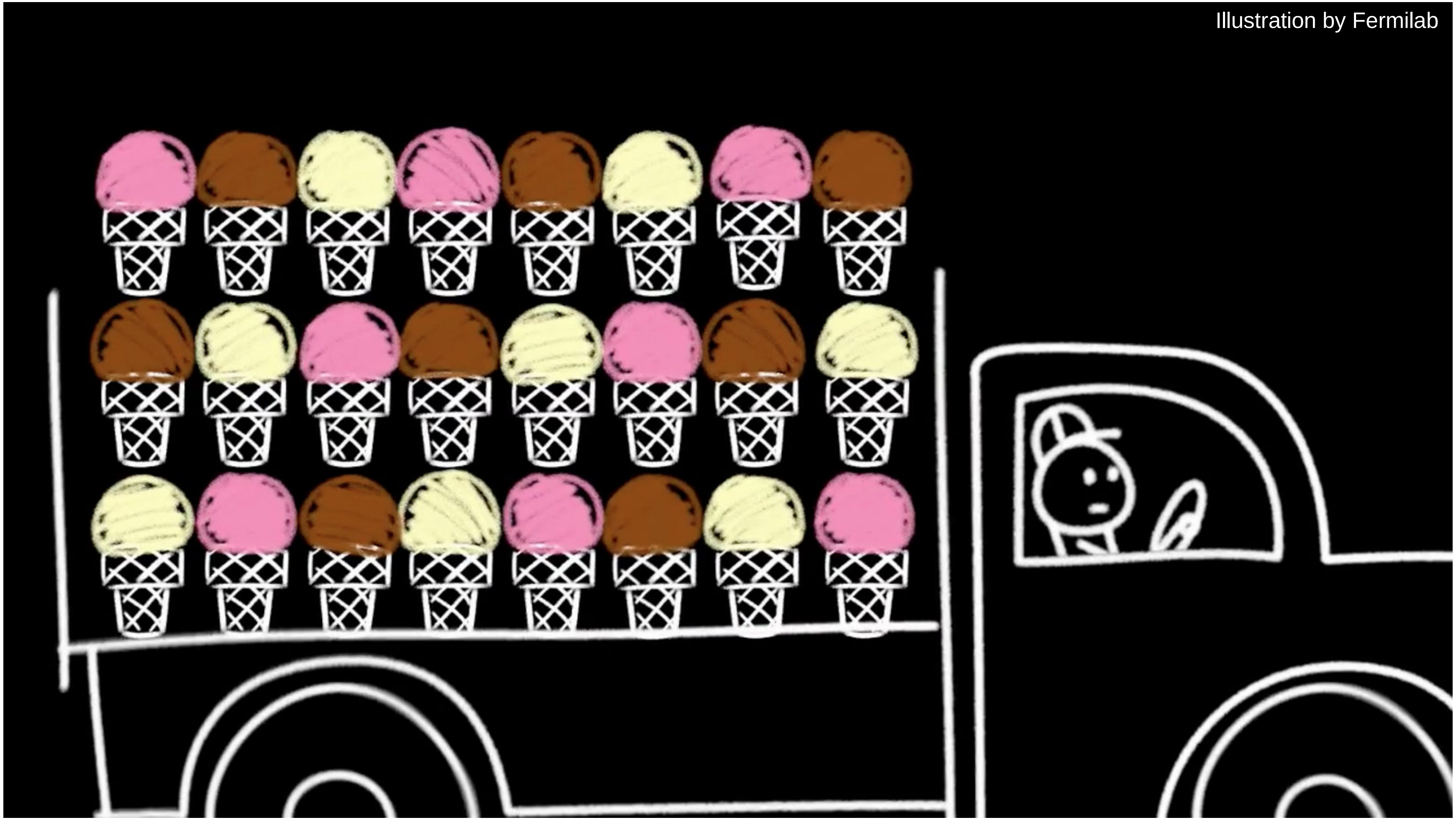
Each cell readout by a wavelength shifting fiber onto one pixel of a 32 pixel avalanche photodiode

Events in the Detectors



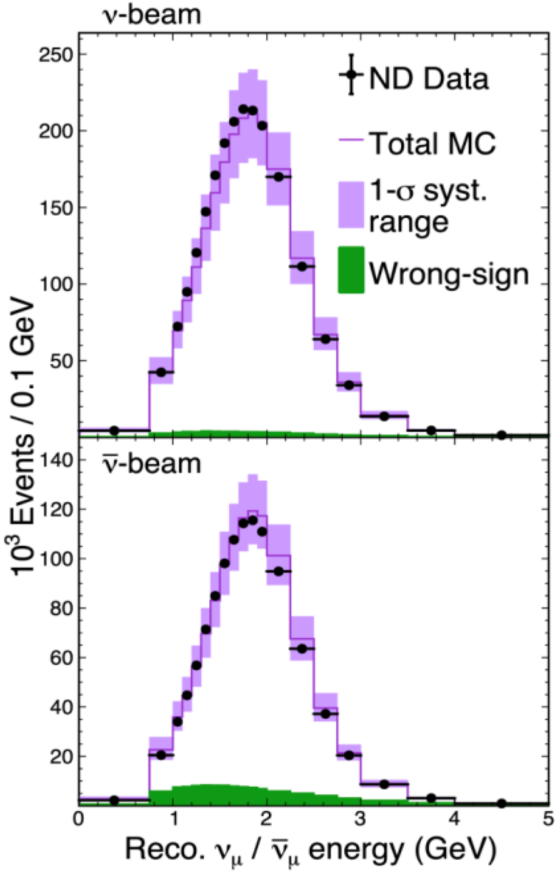
- NOvA uses Convolutional Visual Network (CVN) (implementation of Convolutional Neural Network (CNN)) to classify events:
  - classify events into **ν_e**CC, **ν_μ** CC, NC or cosmogenic.
  - The scores of the CNN are used to form two independent samples of neutrinos and antineutrino events.

Oscillation Analysis Results

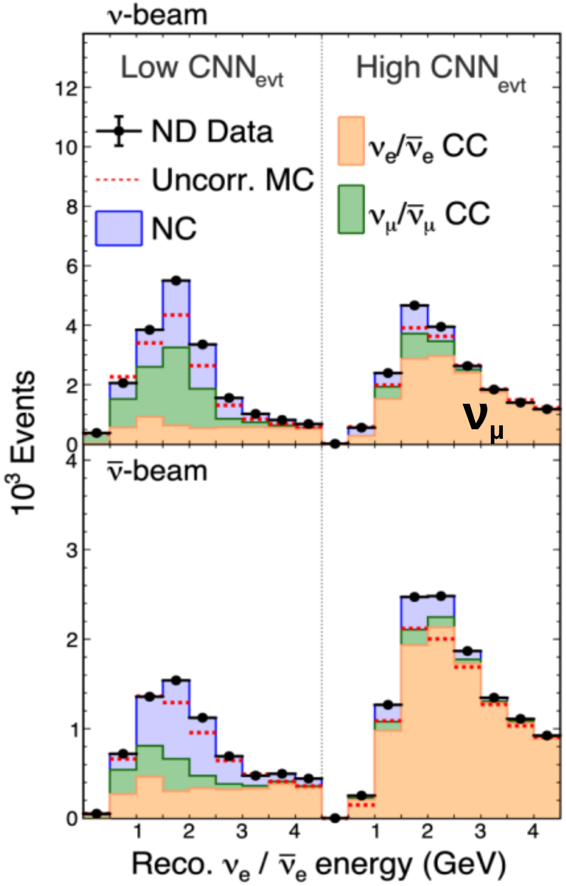


ND Data

ν_μ samples



ν_e samples



- Both neutrino and antineutrino mode data used. (Analysed Exposure:
  13.6×10^{20} neutrino mode
  12.5×10^{20} antineutrino mode (POT))

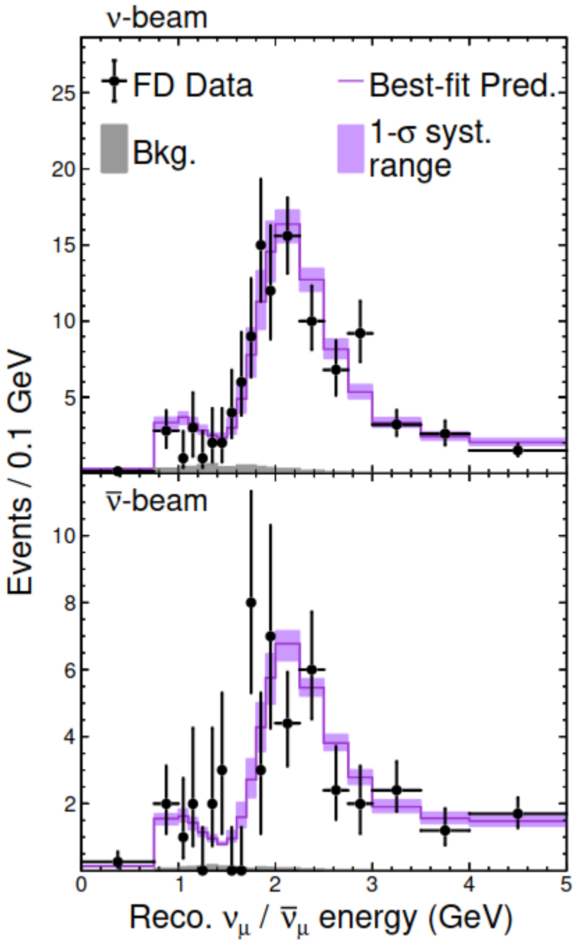
- Simulated ND spectra corrected to ND data and extrapolated to FD. Extrapolation accounts for
  - Energy Smearing
  - Acceptance and selection efficiency
  - Beam divergence

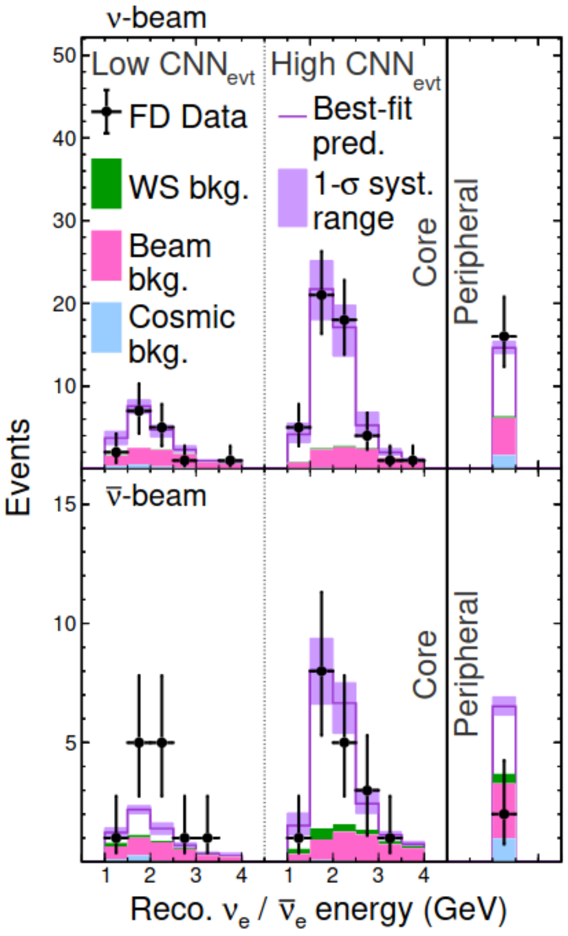
- Data-driven FD predictions for
  - ν_μ ($\bar{\nu}_\mu$) disappearance
  - ν_e ($\bar{\nu}_e$) appearance
  - Beam backgrounds

FD Data

211 ν_μ cand.
(8 bkgd)

105 $\bar{\nu}_\mu$ cand.
(2 bkgd)

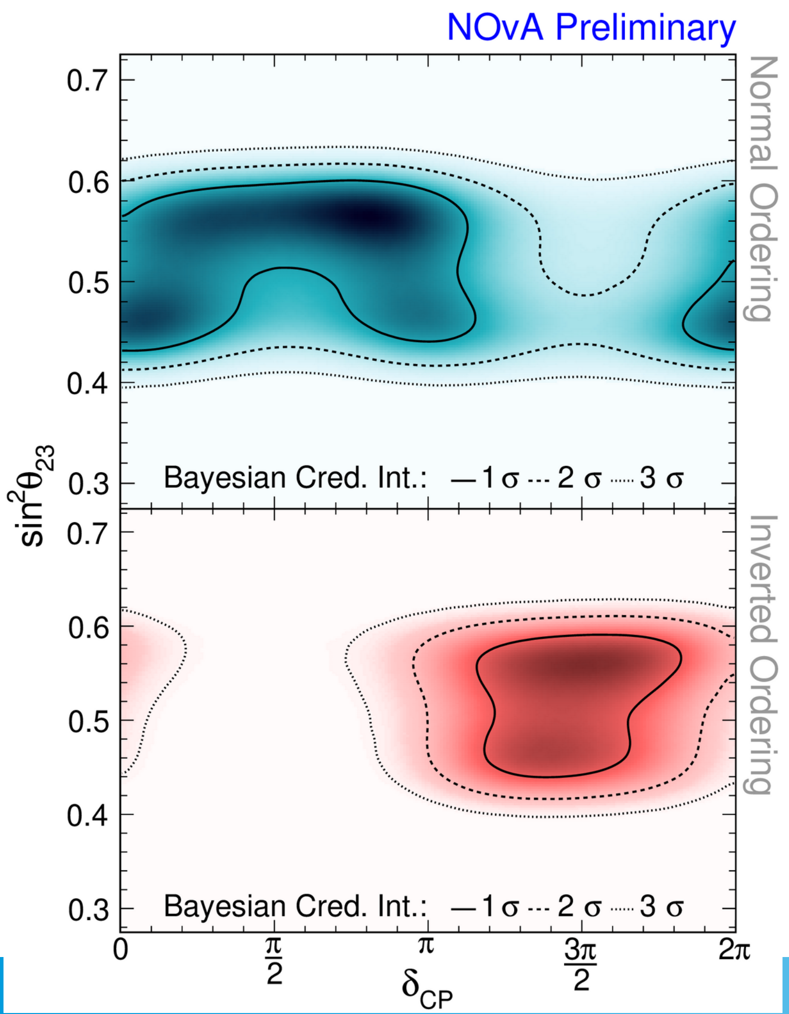




82 ν_e cand.
(27 bkgd)

33 $\bar{\nu}_e$ cand.
(14 bkgd)

Results



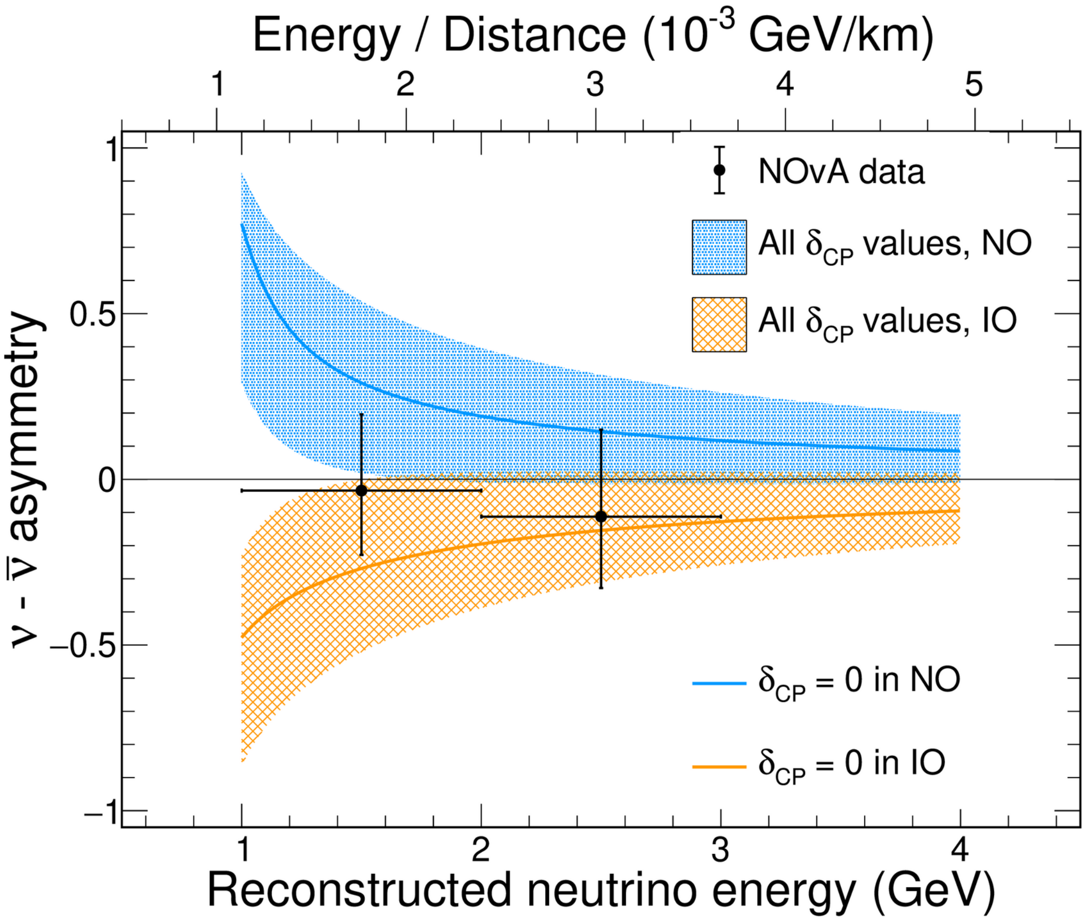
- **Markov Chain Monte Carlo Bayesian Analysis**
  - **Conclusions the same as frequentist results**

- **Weak preference for Normal Ordering, Upper θ_{23} Octant**

- **The inverted mass ordering with $\delta_{CP} = \pi/2$ is excluded at more than 3σ ;**

  normal ordering with $\delta_{CP} = 3\pi/2$ is disfavored at 2σ

Appearance Asymmetry



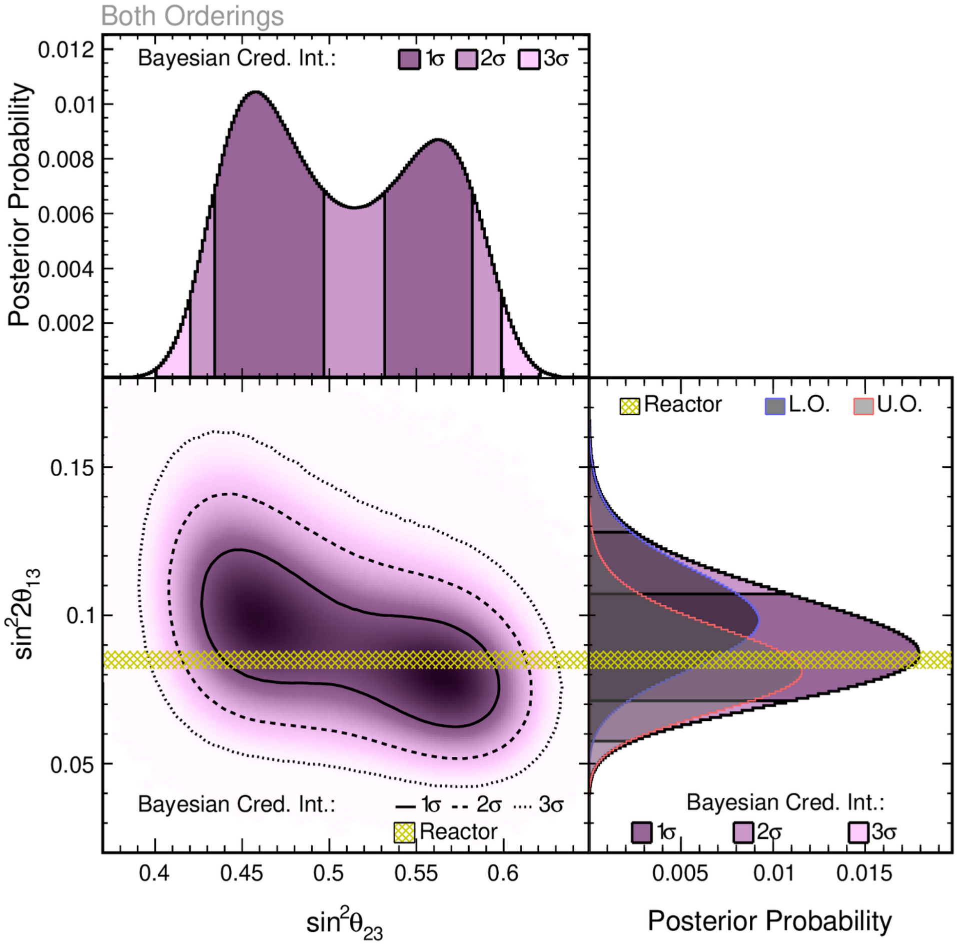
Defined as

$$\frac{P(\nu_e)-P(\bar{\nu}_e)}{P(\nu_e)+P(\bar{\nu}_e)}$$

No $\nu_e - \bar{\nu}_e$ asymmetry to 25% precision

Disfavour mass ordering-δ CP combinations with large asymmetry

NOvA-only θ_{13} vs θ_{23}

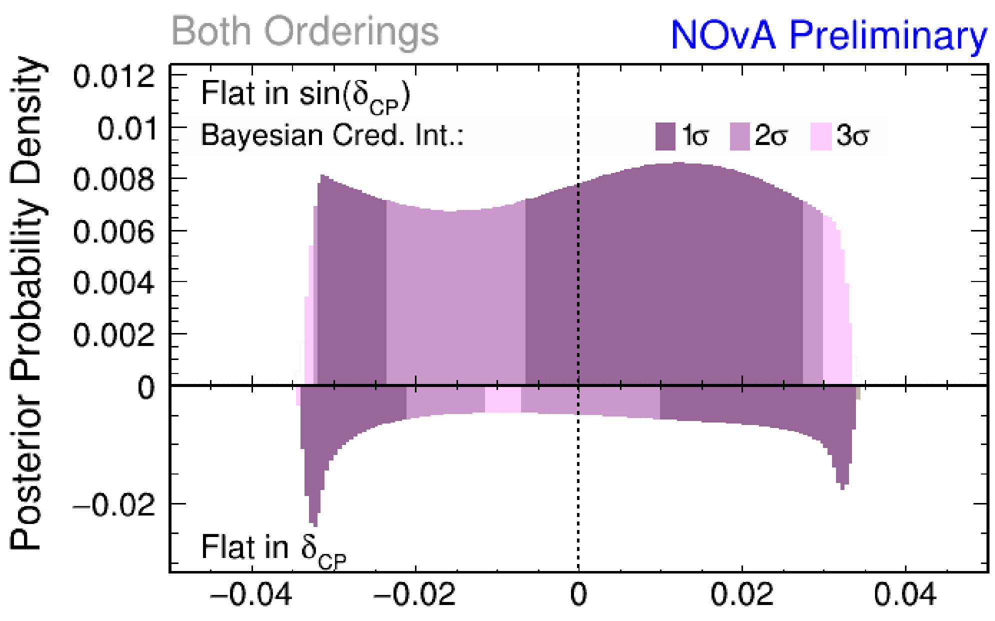


- Bayesian framework makes this type of analysis very easy.
- **Larger $_{13}$ would favour lower octant for $_{23}$ and vice versa**

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

- **Consistent with much more precise measurements from reactor experiments**

Jarlskog Invariant



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

- Jarlskog invariant: measures of CP-violation independent of parametrization of PMNS matrix
- Of interest to theorists
- J=0: CP-Conservation. J≠0: CP-Violation

Sterile Neutrino Search

Artwork by Sandbox Studio, Chicago

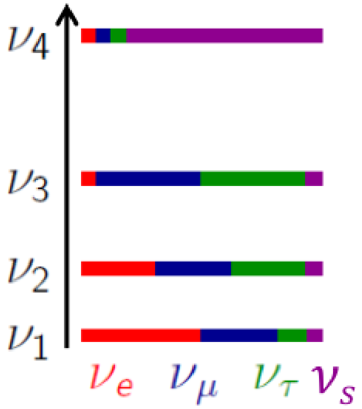
Sterile Neutrino Oscillations at NOvA

ν_μ CC disappearance:

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

NC disappearance:

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



- add 4th mass eigenstate
- 3+1 model

Additional mixing driven by two angles and one phase
NC disappearance allowed, inconsistent with standard oscillations

Sterile Neutrino Search

- New sterile ν search using neutrino beam data
- Can probe a wide Δm^2_{41} range

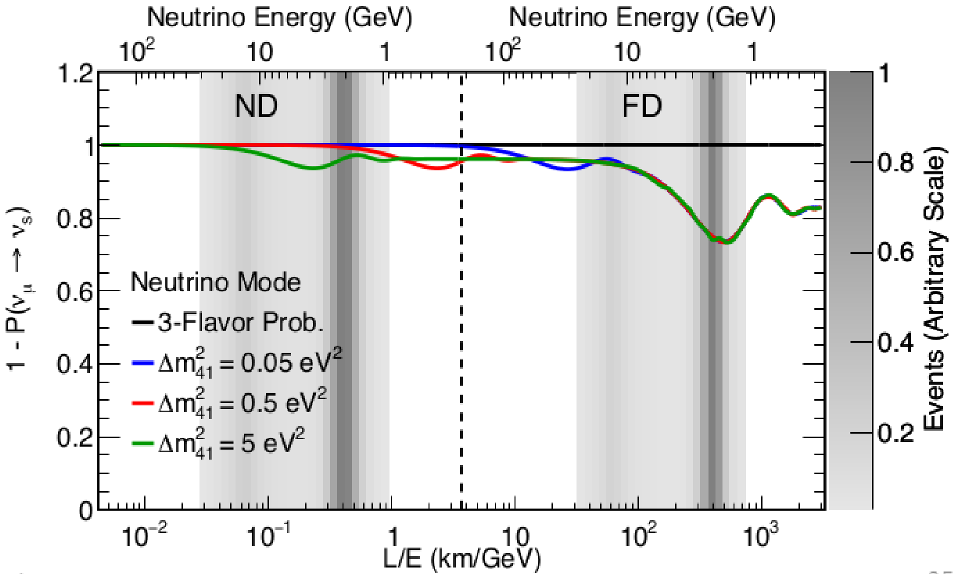
  Oscillations allowed in both detectors simultaneously

- Include new neutrino interaction type, neutral current + ν_μ charged current

  - Fit ND and FD simultaneously

  – Covariance matrix fit to 3+1 sterile ν model

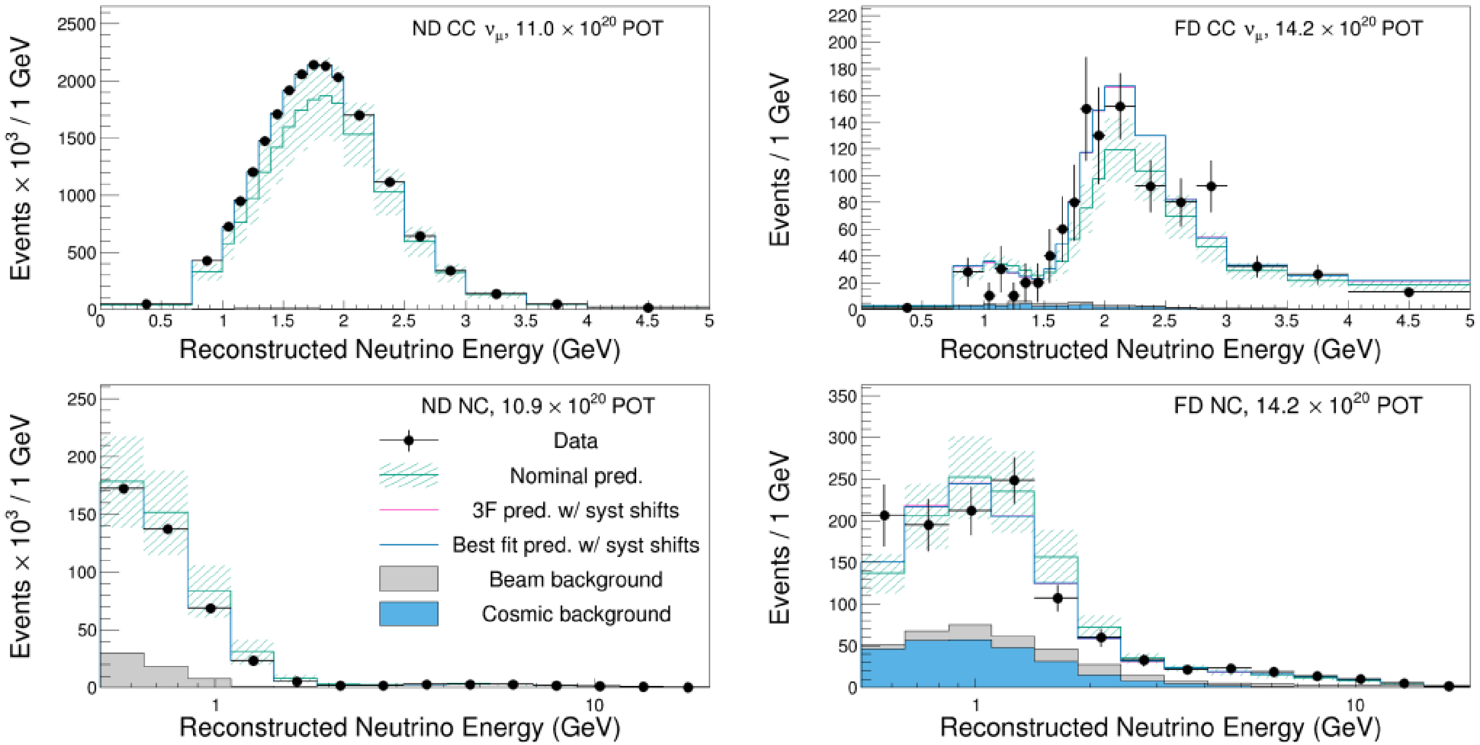
  – Dedicated systematics to reduce dependence on (possibly oscillated) neutrino data



Data used in Sterile Neutrino Search

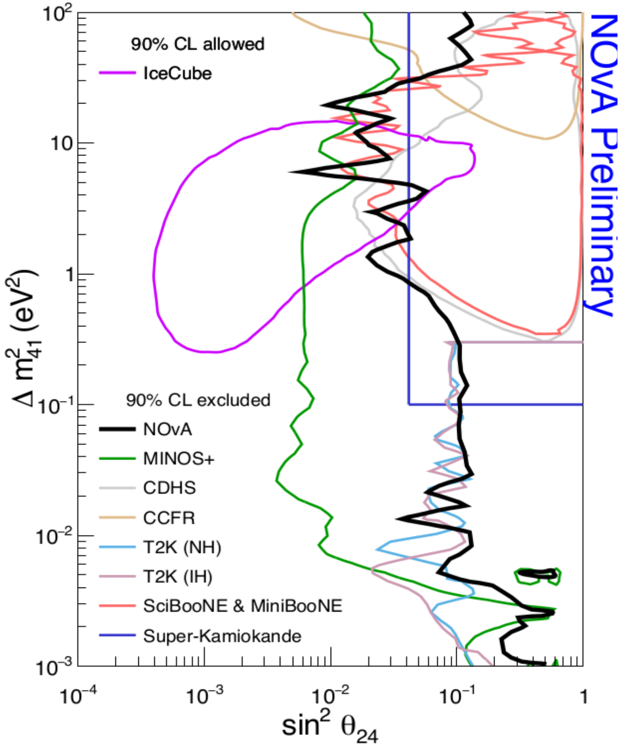
Neutrino Beam

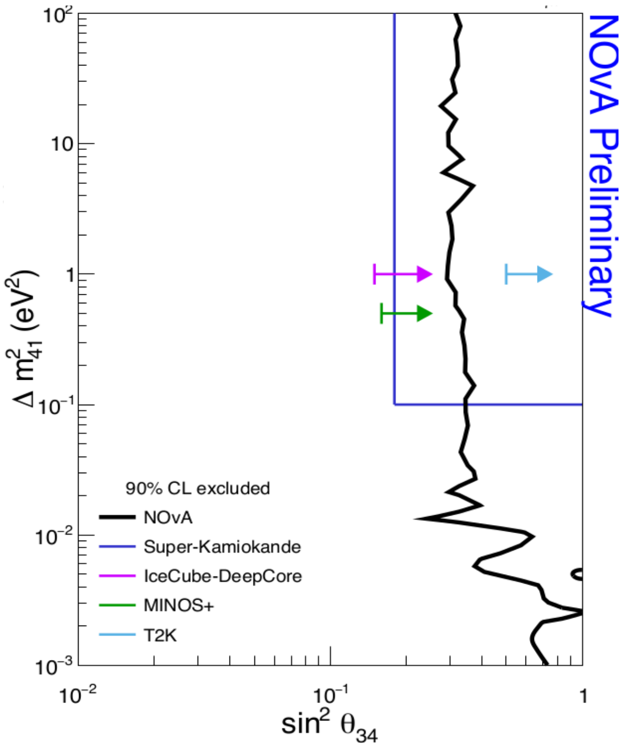
NOvA Preliminary



Nearly identical best fits to 3-flavor and 3+1 models

Sterile Neutrinos - Results





Data shows no evidence for sterile neutrinos

- Competitive limits on θ_{24} for $\Delta m^2_{41} \sim 10$ eV^2

New constraints on θ_{34}

(sensitivity mainly via NC channel)

Summary

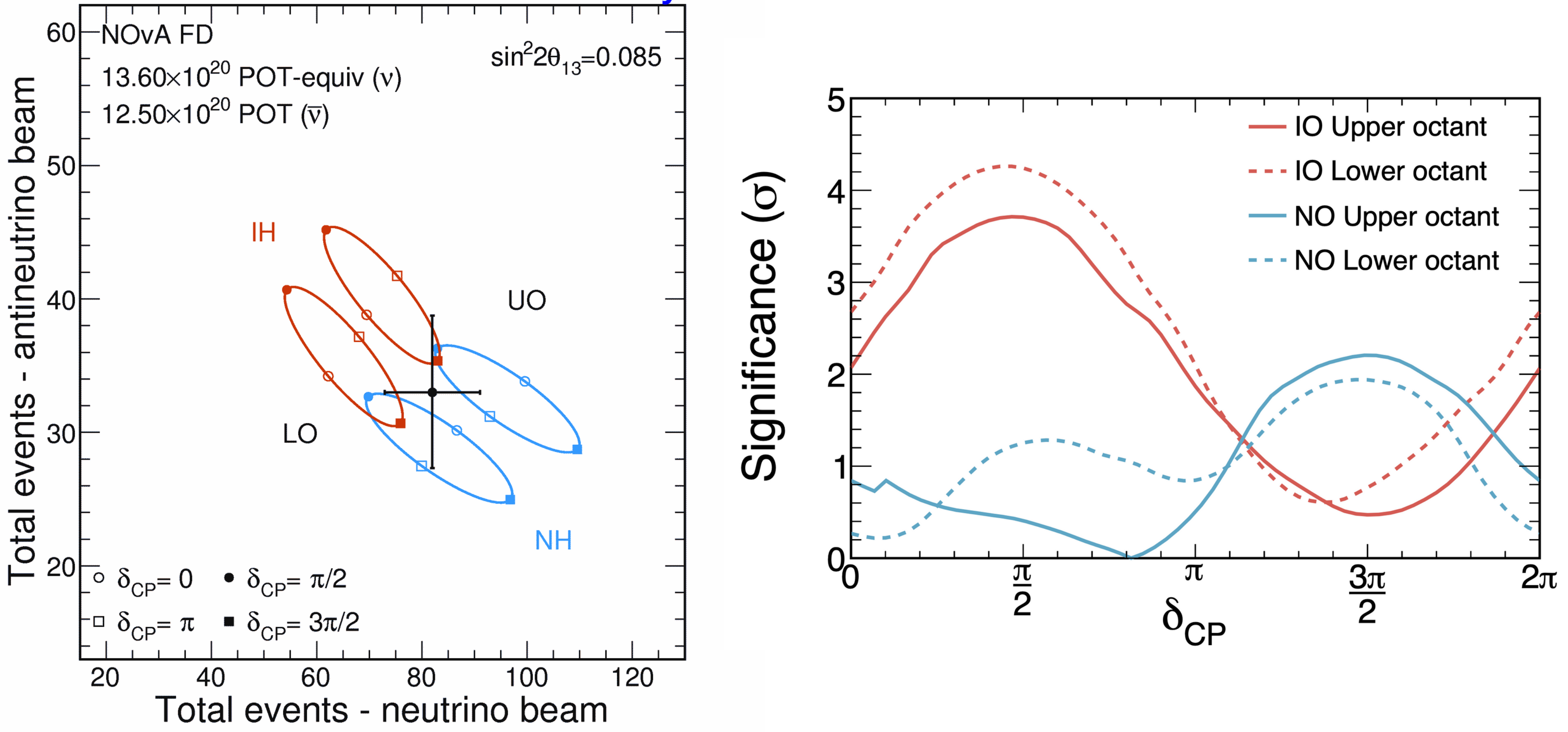
- Measured $\sin^2\theta_{13} = 0.085^{+0.020}_{-0.016}$
  - Consistent with reactor experiments
- Appearance symmetry consistent with zero to 25% precision.
- No preference for CP conservation or violation
- Data shows no evidence for a sterile neutrino
- More to come:
  - NOvA – T2K joint fit in progress
  - We've already taken a lot more data
  - continue to take data through 2026.
  - Many improvements to oscillation analyses, new cross section measurements & exotic searches in progress!

The NOvA Collaboration

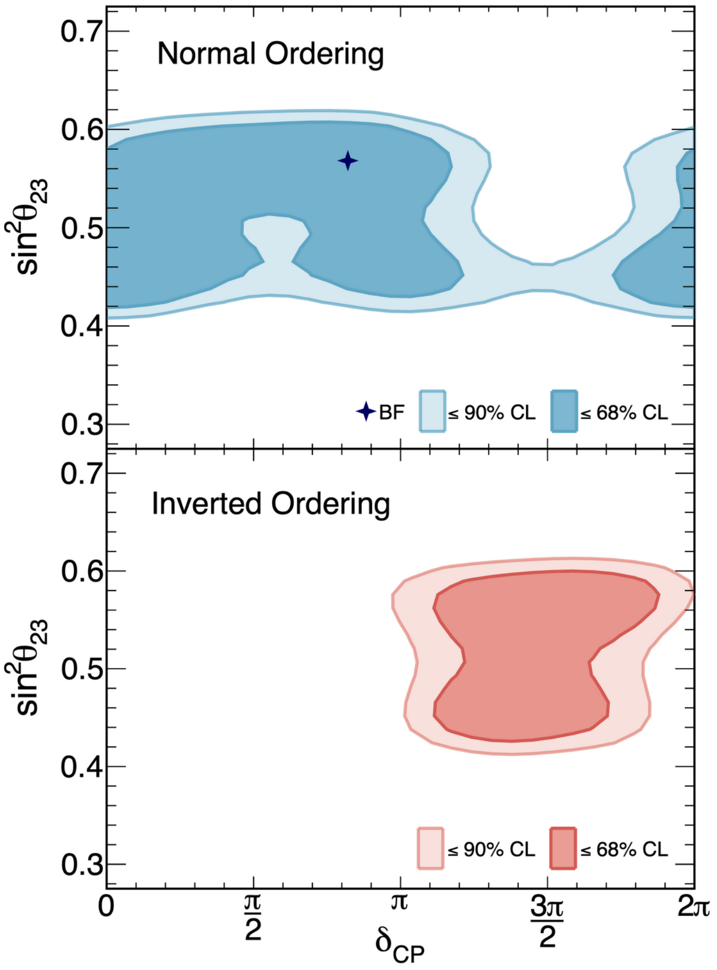
Thank You!

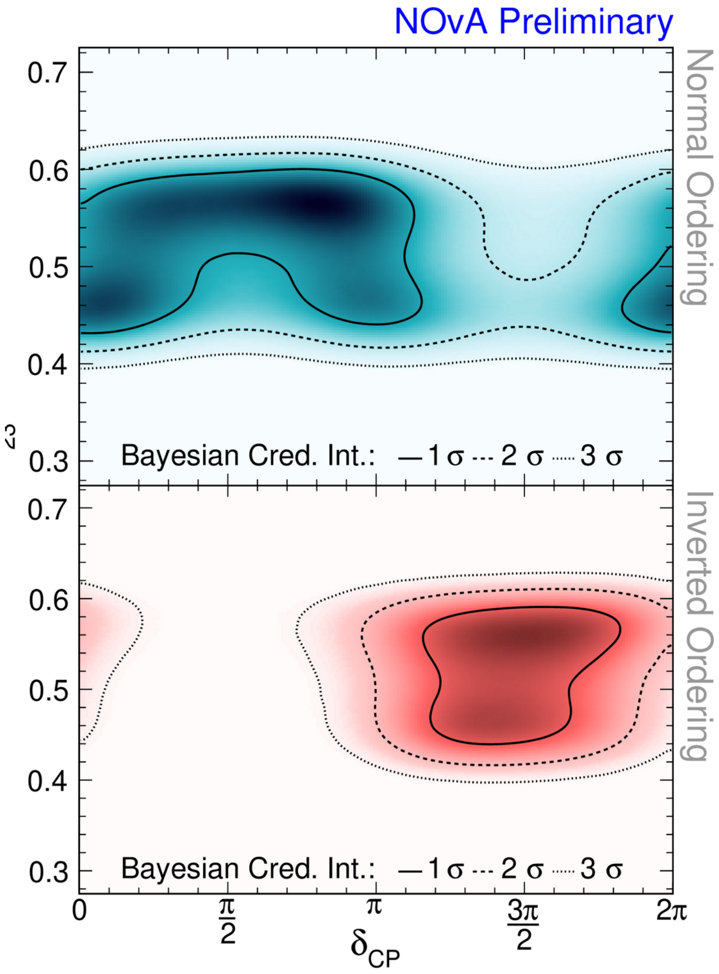
Backup

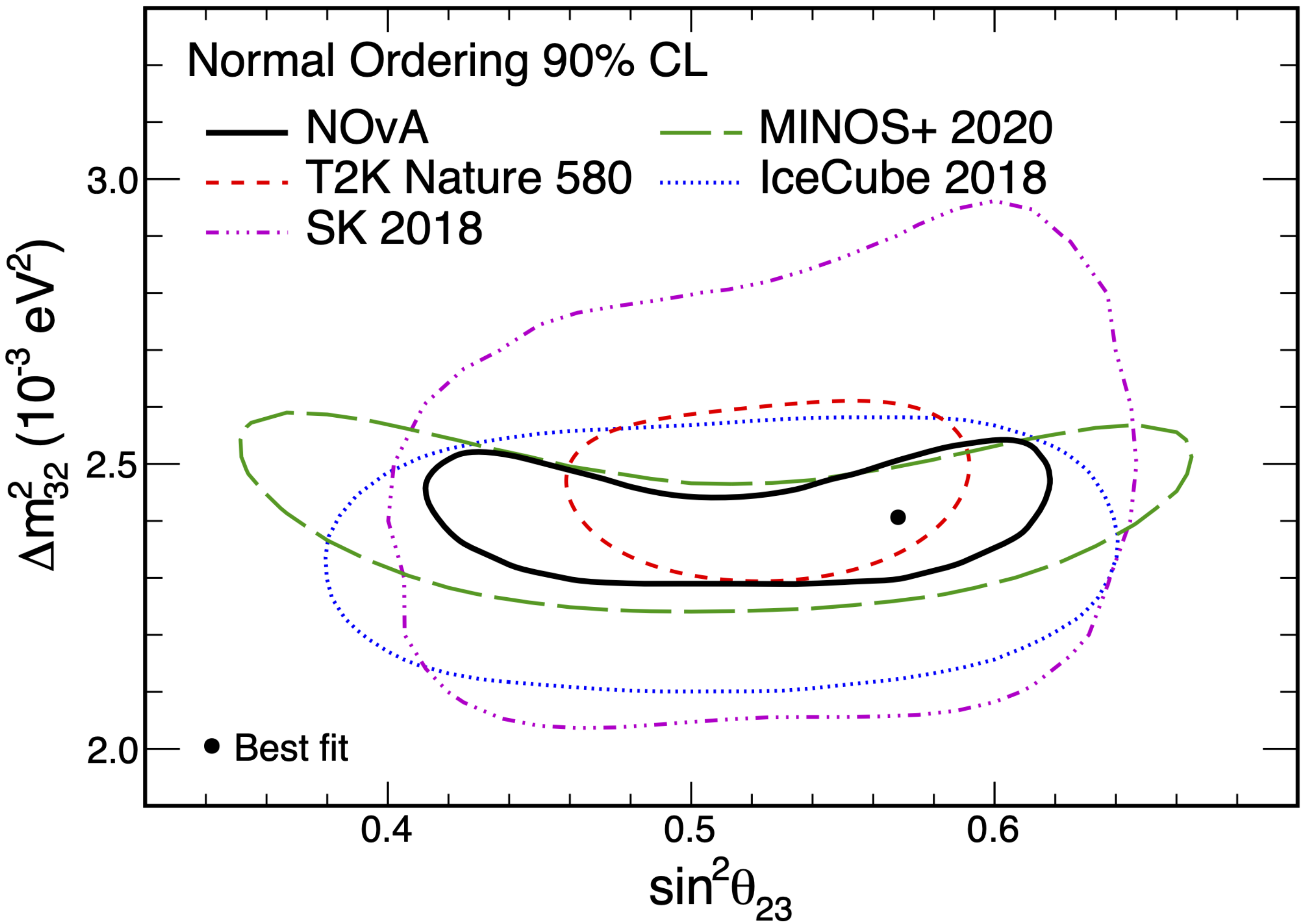
NOvA Preliminary



Frequentist vs Bayesian

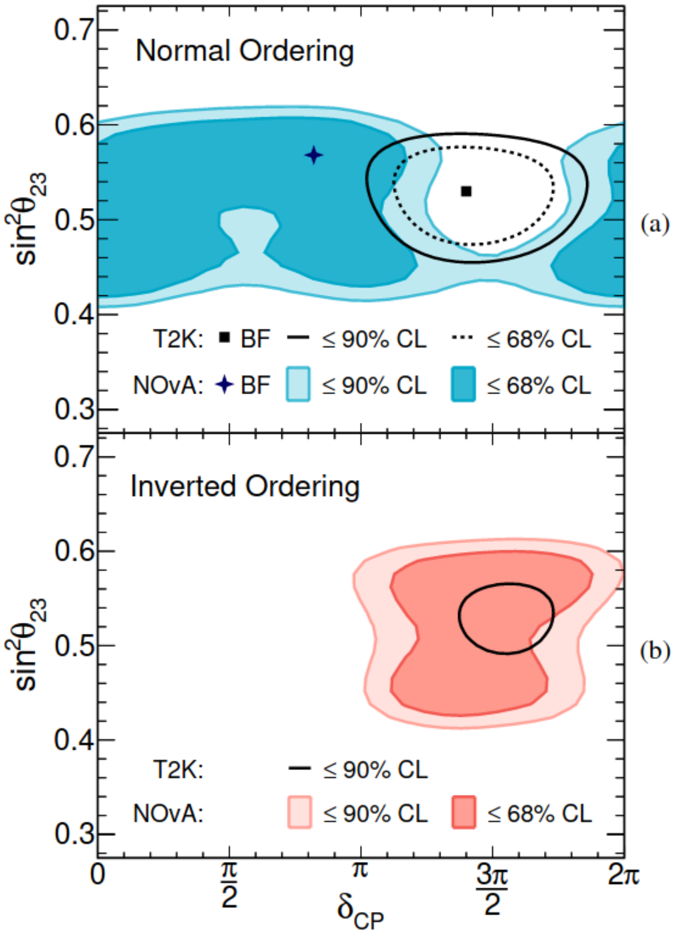


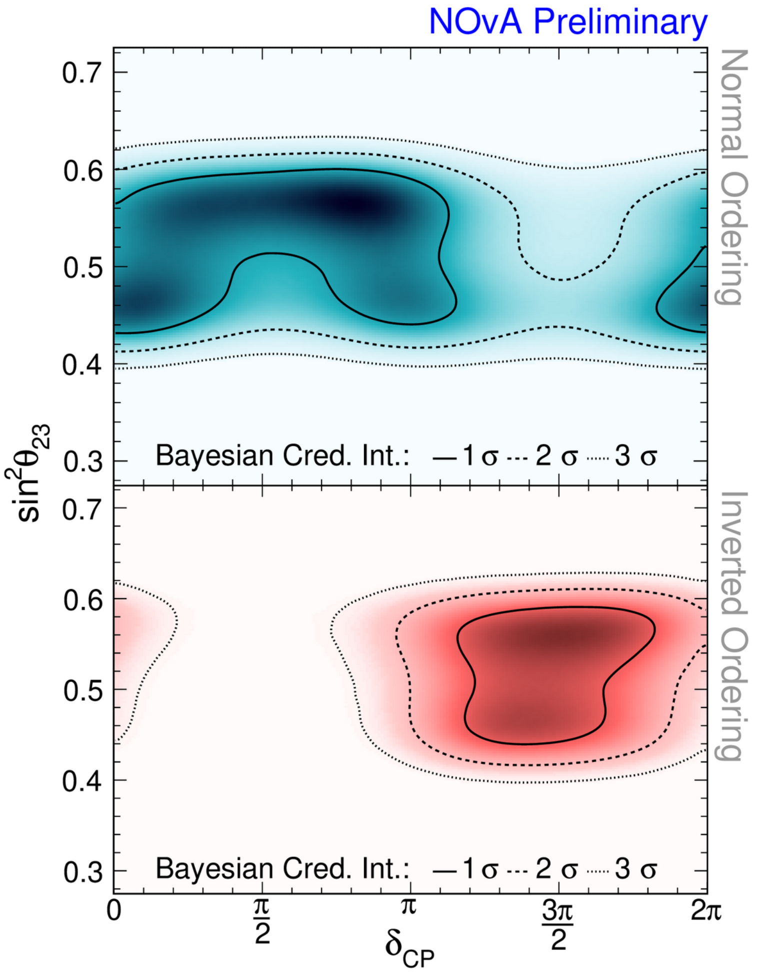




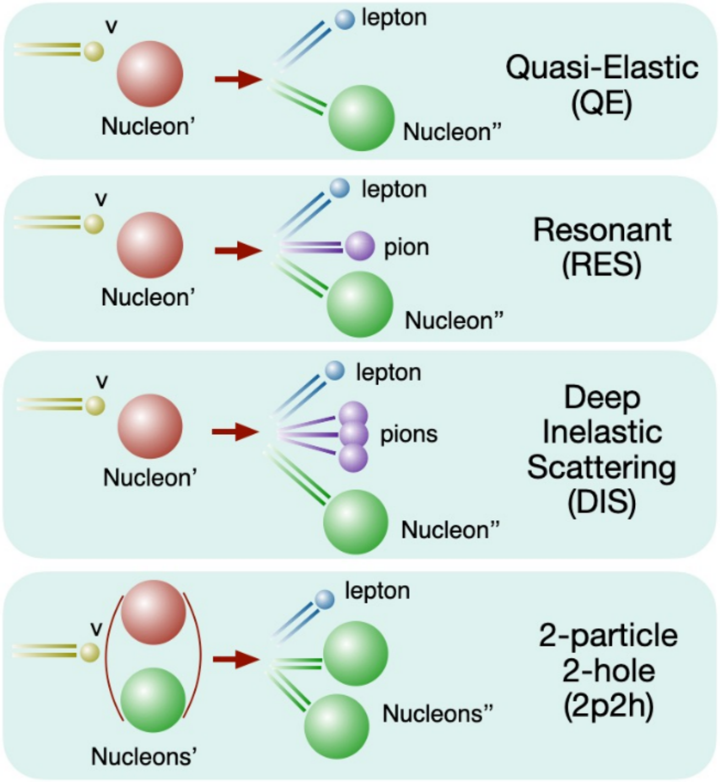
Normal Ordering 90% CL
NOvA
MINOS+ 2020
T2K Nature 580
IceCube 2018
SK 2018
Best fit
3.0
2.5
2.0
0.4
0.5
0.6
Δm^2_{32} (10^{-3} eV^2)
$\sin^2\theta_{23}$

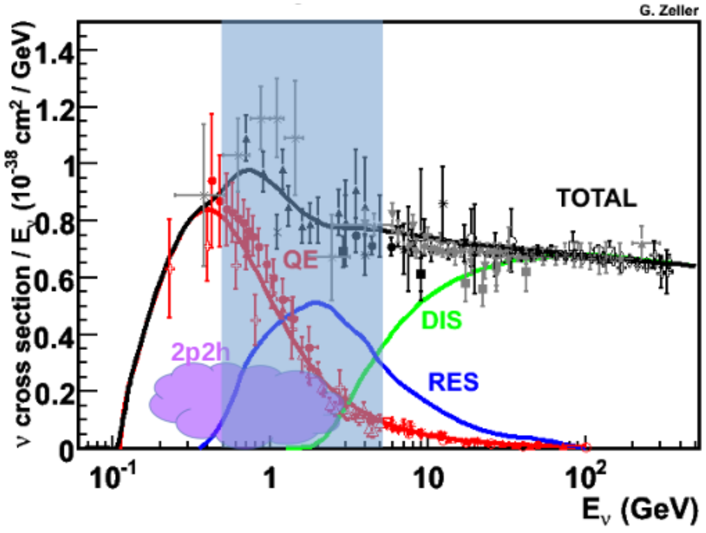
Frequentist vs Bayesian





Neutrino Interaction Types





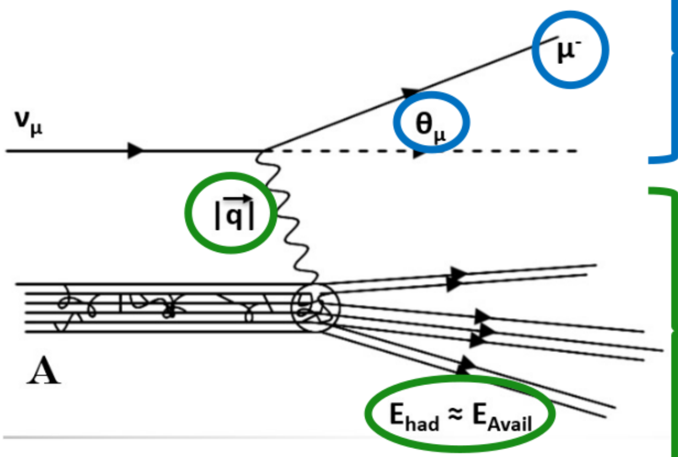
NovA can study all interaction types with huge statistics

- Nuclear effects are significant
– Contribution of axial part of weak interaction can only be studied with neutrinos

- Better understanding important for in reducing systematics on oscillation measurements

Two new ν_μ CC Cross Section Results

Both double differential

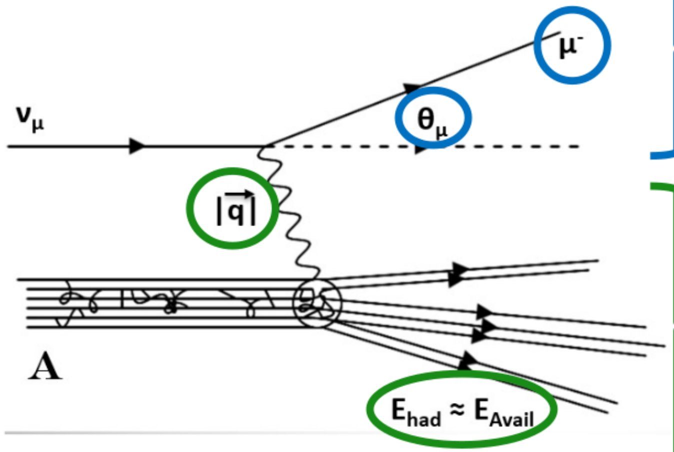


Muon System ⇨ Energy **vs** angle

Hadronic System ⇨ 3-momentum transfer $|\vec{q}|$ **vs** energy

Two new ν_μ CC Cross Section Results

Both focus on sensitivity to 2p2h / MEC events



Muon System

Exclusive
Select only events with low hadronic energy

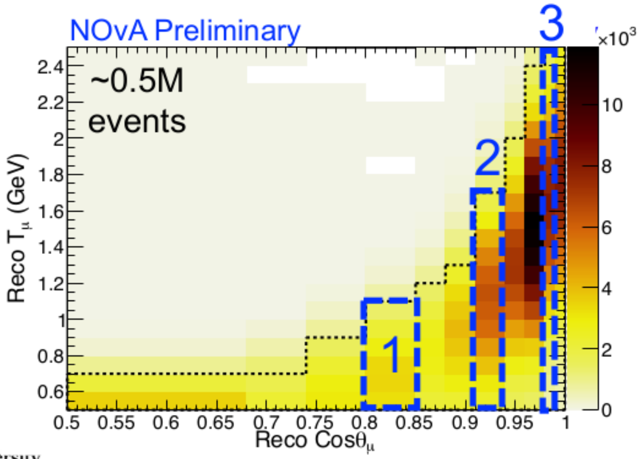
Hadronic System

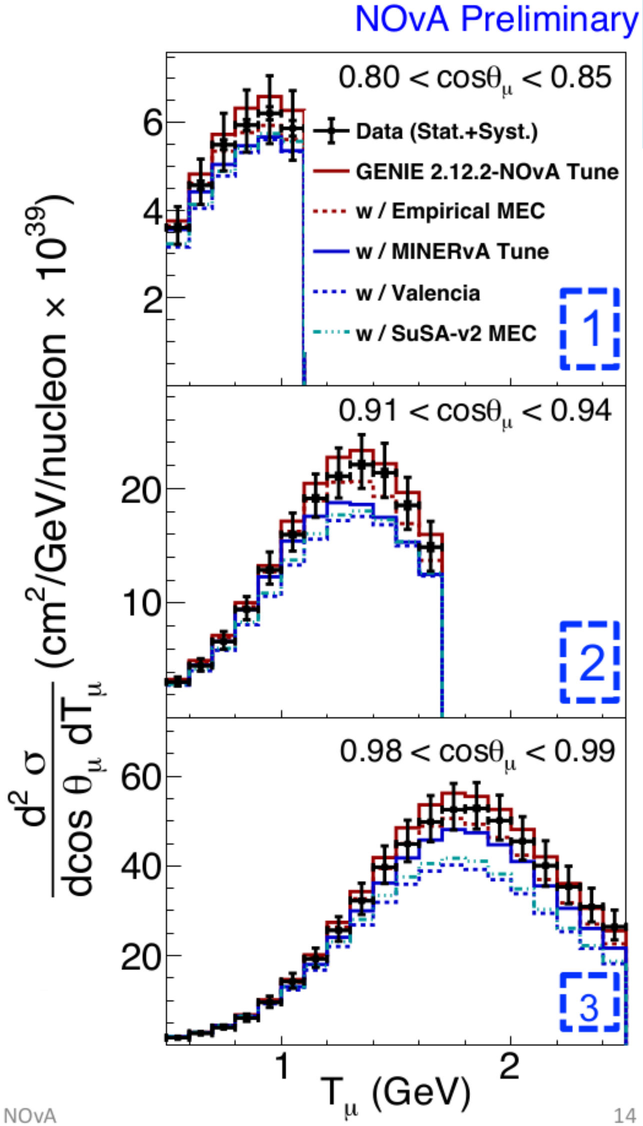
Inclusive
Select all ν_μ CC events

Both build on previous ν_μ CC inclusive meas. (arXiv:2109.12220)

Muon System

- Events must have exactly one reconstructed track (low E_{had})
  - **Boosts 2p2h,** reduces DIS and RES
- Cross section reported at 115 kinematic points
  - 12-15% uncertainty typically
  - dominated by flux systematic





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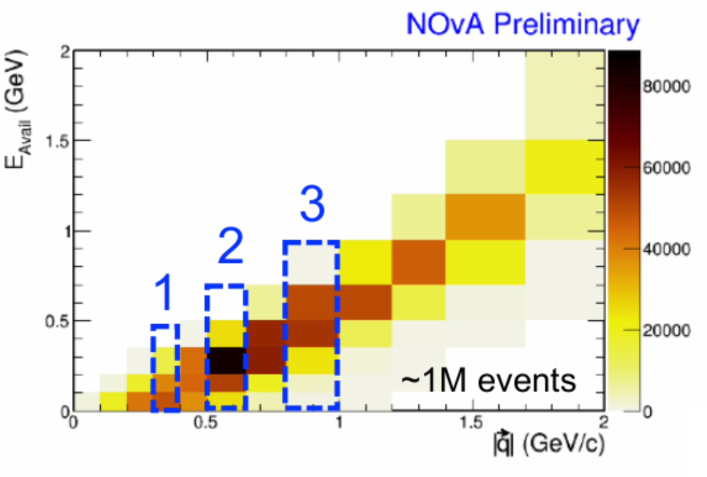
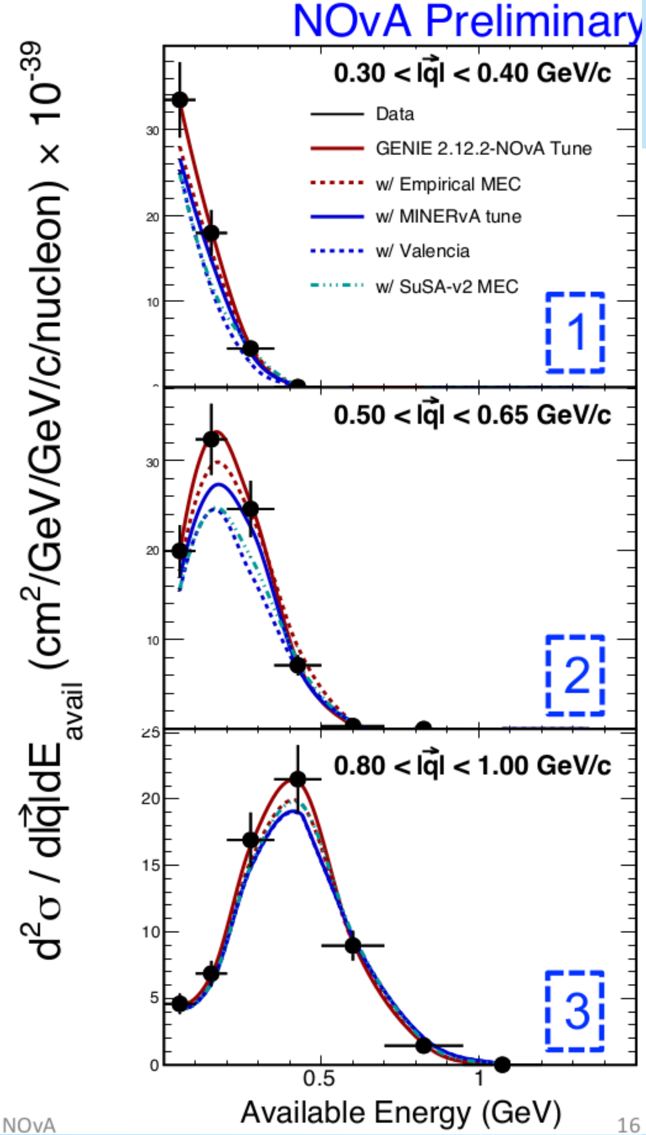
Hadronic System

- NOvA's first measurement in $|\vec{q}|$ and E_{Avail}
  - **2p2h concentrated at low values**
- Cross section reported at 67 kinematic points
  - ~12% uncertainty typically
  - dominated by flux systematic





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Comparison of 2p2h Models to Data

- Large χ^2 values seen for all 2p2h models/tunes
- Tuned models match data better than Valencia/SuSA-v2

Muon System

2p2h Model	χ^2 (115 d.o.f.)	
GENIE v2-12.2 NOvA Tune	200	Tuned models
Empirical MEC	190	Tuned models
Valencia w/ MINERvA Tune	340	Tuned models
Valencia	630	Theoretical models
SuSA - v2	620	Theoretical models

- Hadronic System analysis suggests similar conclusions
- χ^2 calculated for data vs. simulation with the various 2p2h models using full covariance matrix
- Correlations between bins are dominant contribution to χ^2
- Data release for these high-statistics analyses coming soon
  - Can explore many aspects of generator models beyond 2p2h with this data