Fermilab U.S. DEPARTMENT OF ENERGY | Office of Science

NOvA Current Status and Future Prospects

Teresa Lackey

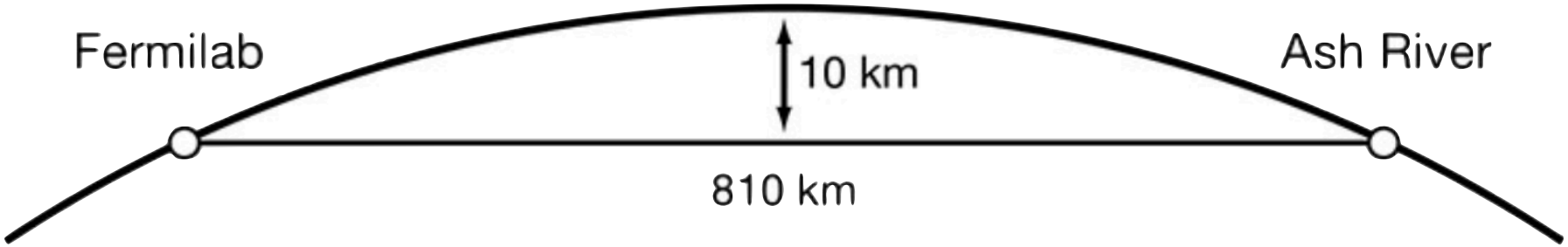
for the NOvA collaboration

7 December 2023

December 4-8 2023

NOvA —NuMI Off-axis ν_e Appearance experiment

- Long baseline neutrino oscillation experiment;
- Designed to detect ν_e, ν_μ, $\bar{\nu}_e$, and $\bar{\nu}_\mu$ originating from the primarily muon (anti)neutrino NuMI beam at Fermilab.



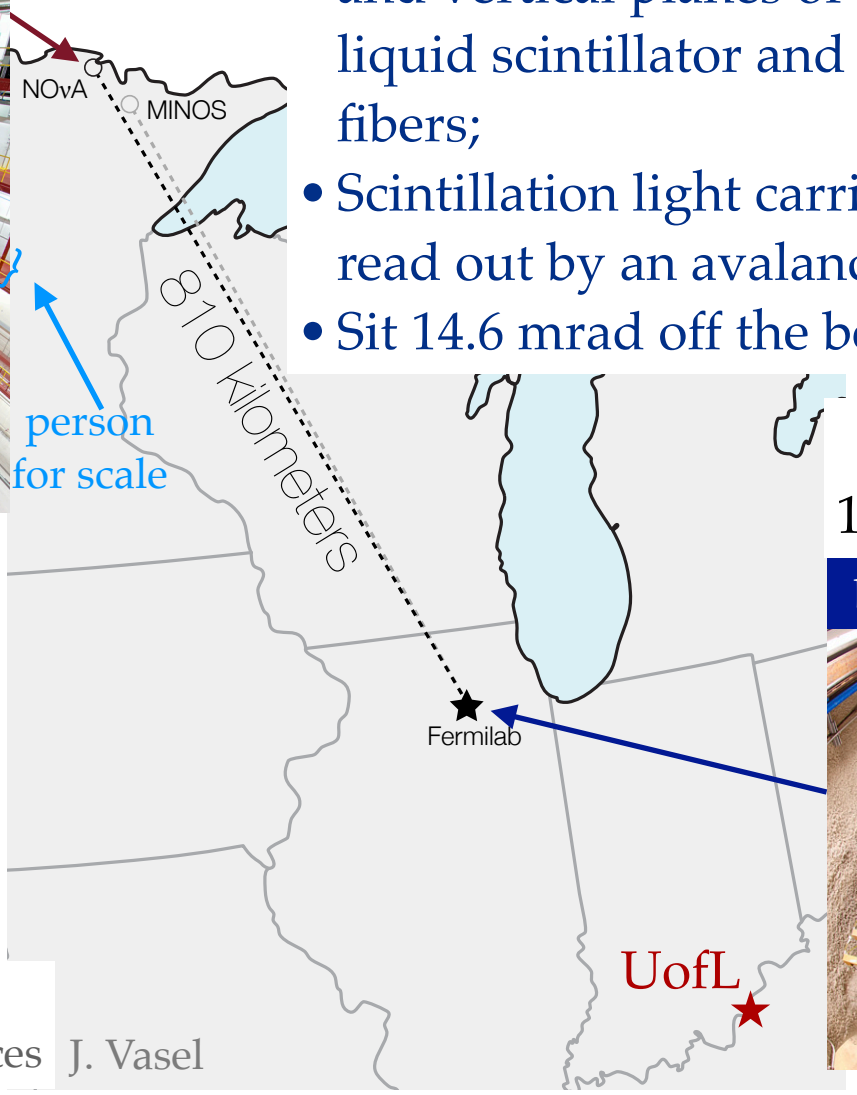
Primary experiment goals

- measure Δm^2_{32}
  - determine mass ordering
- determine octant/value of θ_{23}
  - have some sensitivity to $\sin^2 2\theta_{13}$
- measure δ_{CP}

The NOvA detectors

front-view of Far Detector

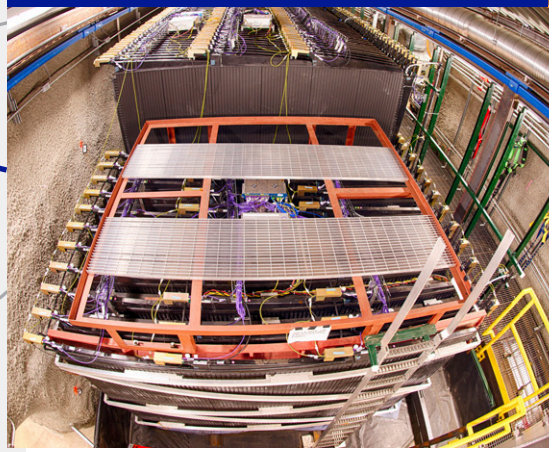
Far Detector, 14 kT
810 km from beam target



- Detectors composed of alternating horizontal and vertical planes of PVC cells, filled with liquid scintillator and wavelength shifting fibers;
- Scintillation light carried down the fiber and read out by an avalanche photodiode;
- Sit 14.6 mrad off the beam axis.

Near Detector, 293 T
1 km from beam target

back-view of Near Detector



detector photos from Fermilab Creative Services J. Vasel

Near Detector cross-section analyses

- We study cross sections to gain a better understanding of neutrino-nucleus interactions.
- In NOvA's case, this helps us inform our systematic uncertainties on oscillation and other non-cross-section results.
- Dataset contains millions of neutrino interactions in the Near Detector.

- Analyses in progress:
  - Inclusive measurements:
    - $\overline{\nu}_\mu$ CC, triple differential in T_μ, $\cos\theta_\mu$, E_{Avail}
    - $\overline{\nu}_e$ CC, double differential in E_e, $\cos\theta_e$
    - $\overline{\nu} : \nu$ ratios
  - Along with many exclusive measurements.

Pro Tip:
There is no such thing as Quantum Mechanics.

https://www.smbc-comics.com/?id=1452

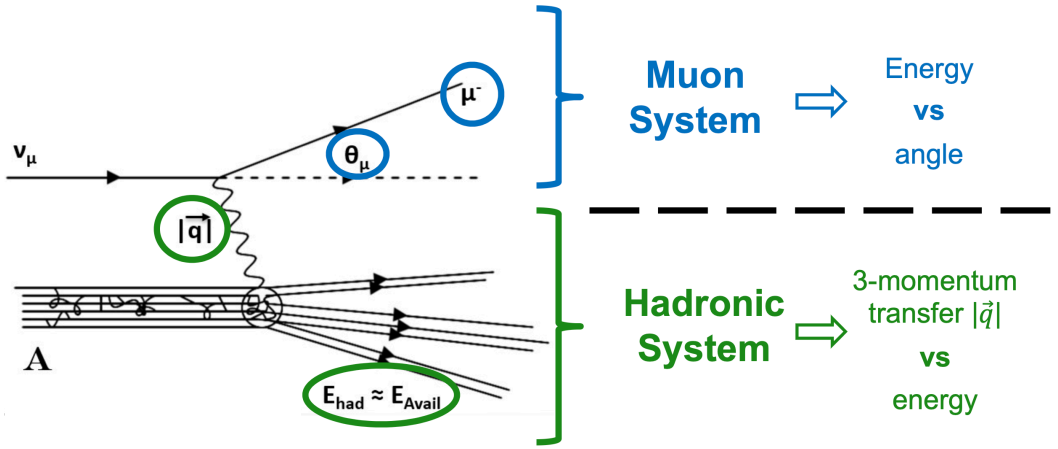
Near Detector cross-section analyses

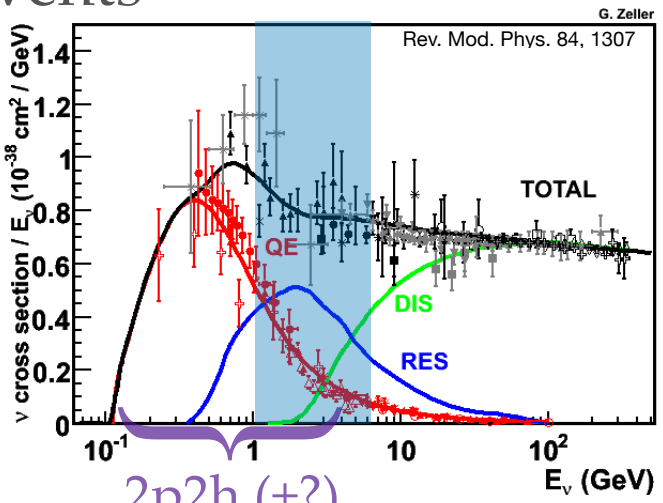
- We study cross sections to gain a better understanding of neutrino-nucleus interactions.
- In NOvA's case, this helps us inform our systematic uncertainties on oscillation and other non-cross-section results.
- Dataset contains millions of neutrino interactions in the Near Detector.

Latest results:

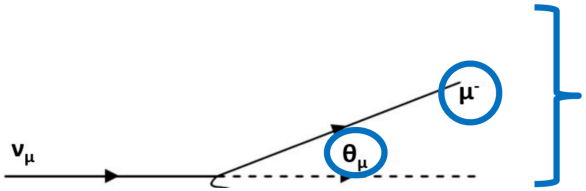
ν_μ CC cross-section measurements - two double differential analyses

Focussing on sensitivity to 2p2h/MEC events





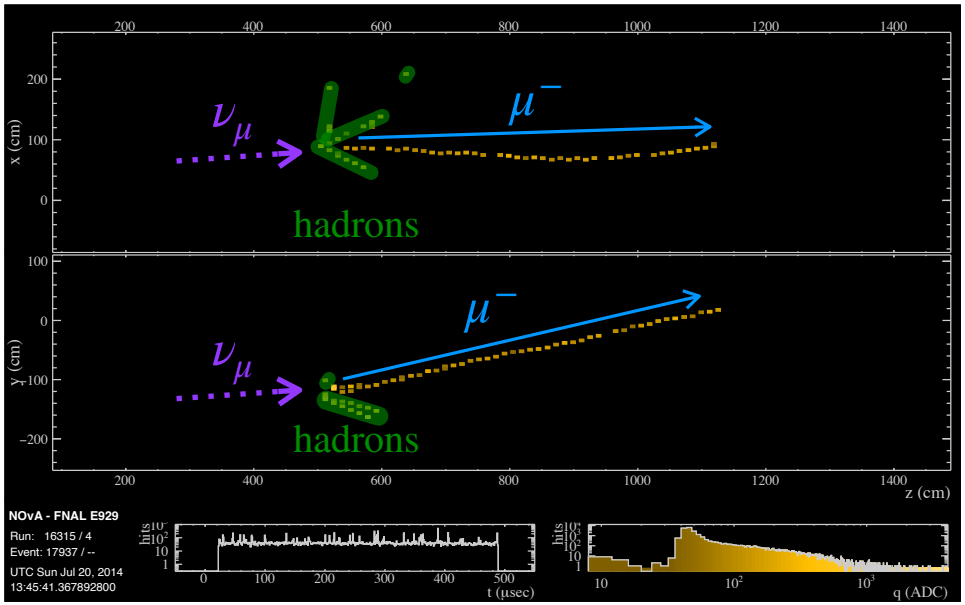
Muon system



Muon System ⇨ Energy **vs** angle

signal definition:

- Only one reconstructed track (low hadronic activity)
- Interaction contained within fiducial volume of detector
- $T_p \leq 200$ MeV
  $T_\pi \leq 175$ MeV
- Measurement in bins of
  T_μ - kinetic energy of muon,
  $\cos\theta_\mu$ - scattering angle of muon



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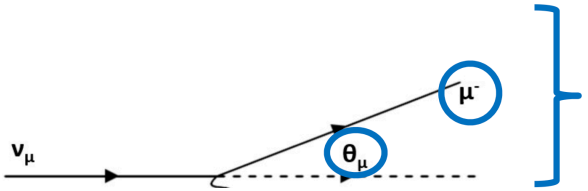

Muon System ⇨ Energy **vs** angle

- 115 kinematic bins
- Uncertainty of 12-15%

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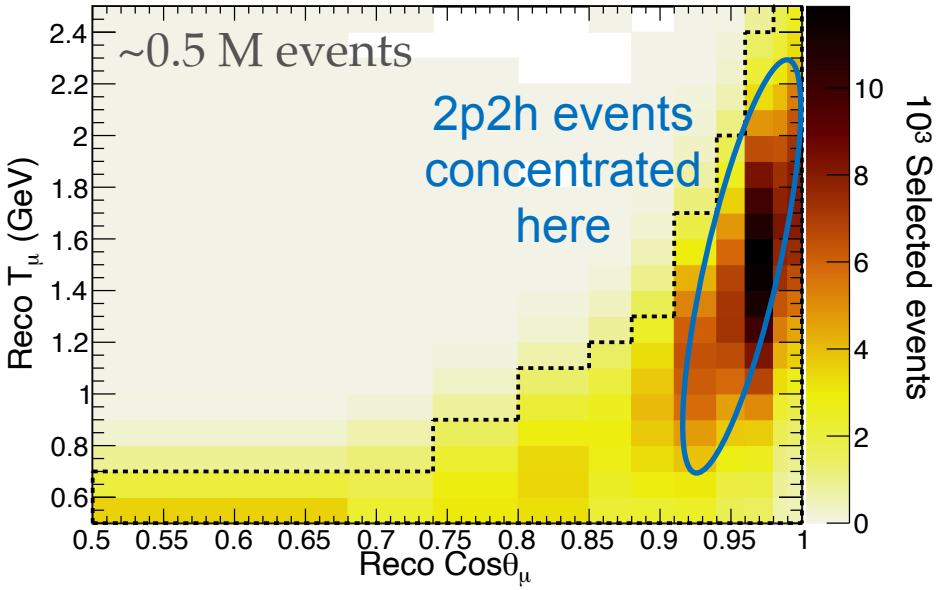
QE	MEC	RES	DIS	COH
39.7%	33.7%	23.0%	2.5%	1.1%

NOvA Preliminary



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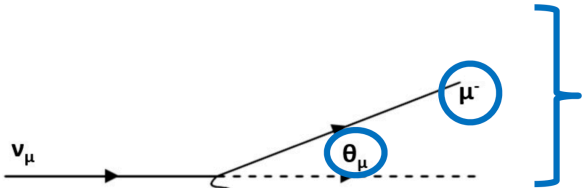

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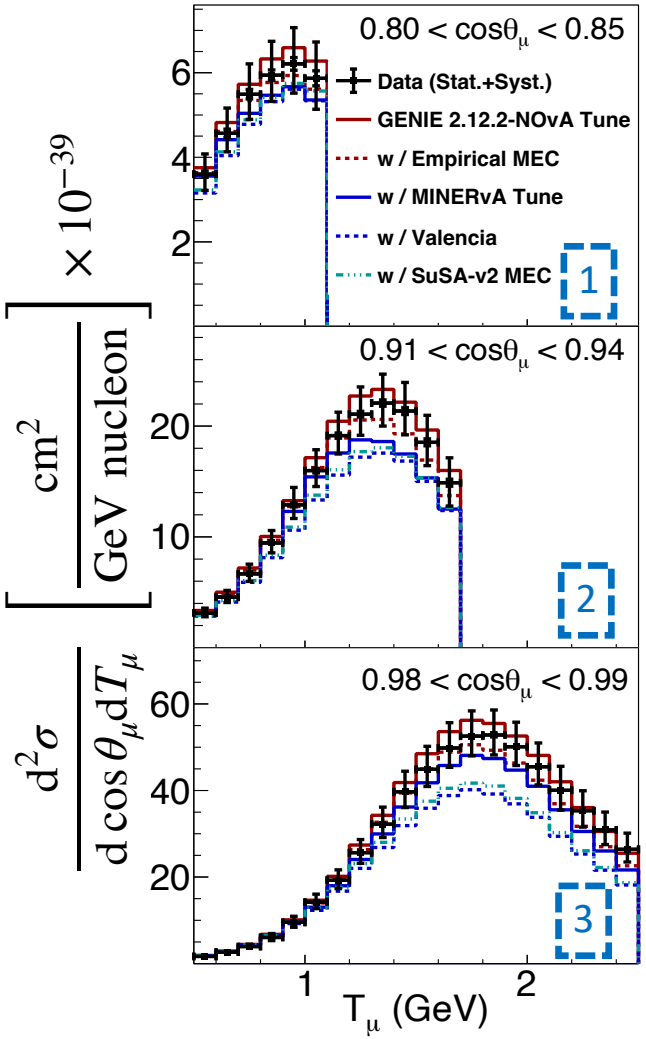

- Models underestimate cross section in 2p2h region

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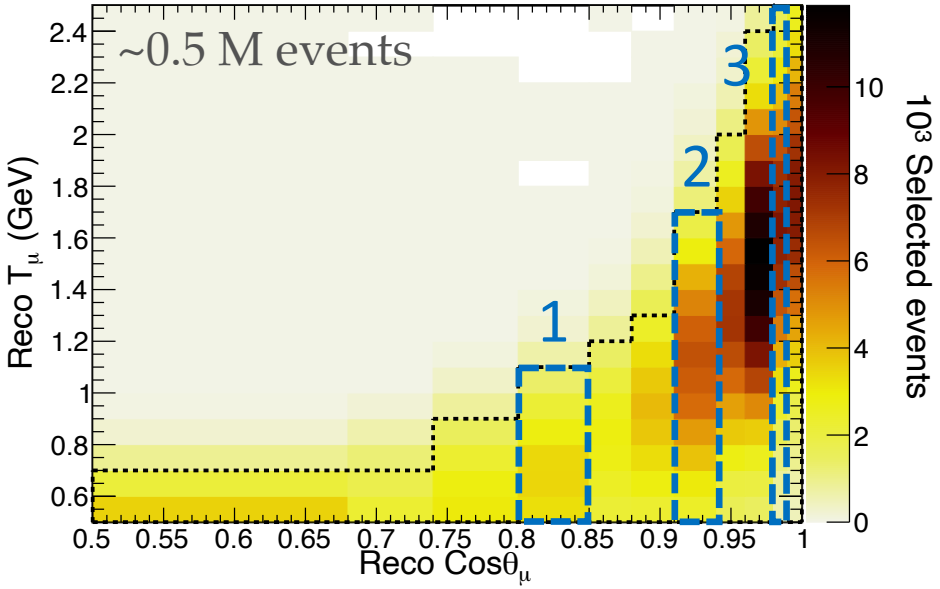
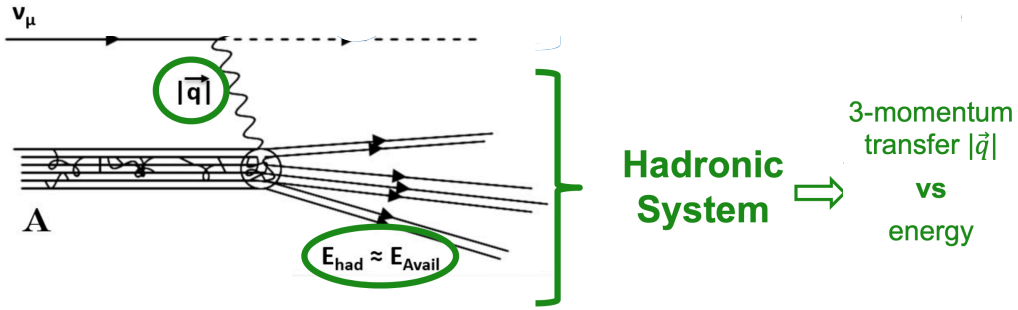
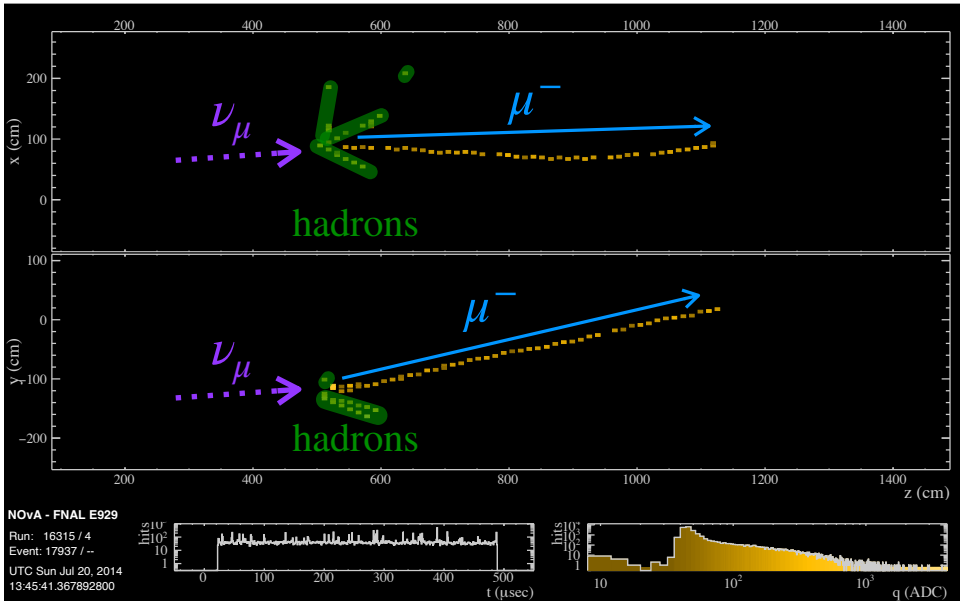


Hadron system

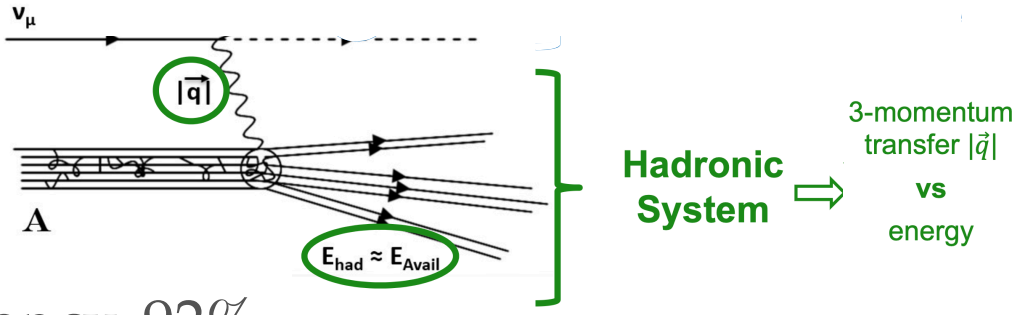




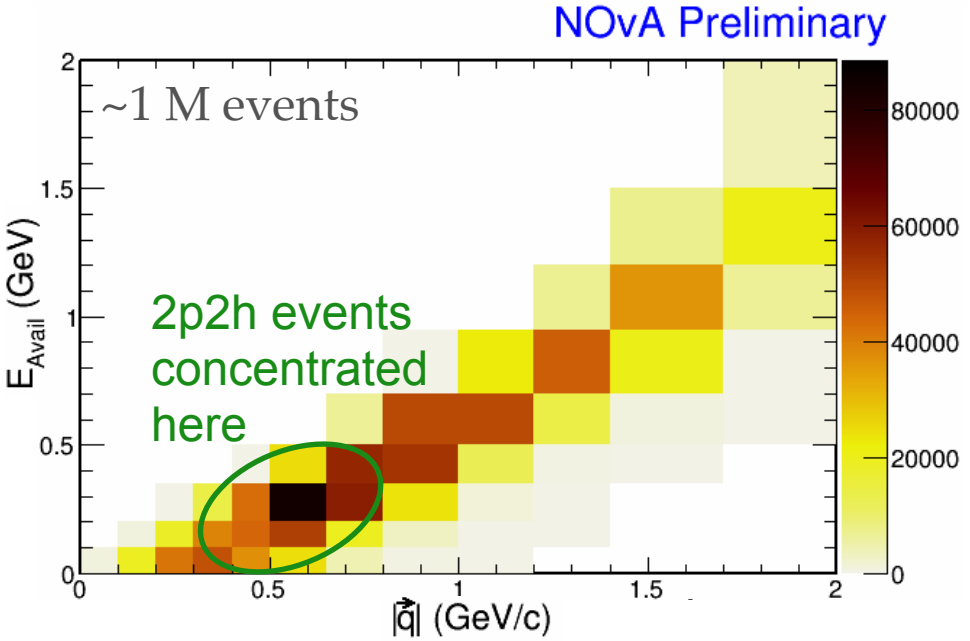
signal definition:

- Interaction contained within fiducial volume of detector
- $0.5 < T_\mu < 2.5\text{GeV}$
  $\cos\theta_\mu > 0.5$
- Measurement in bins of
  $|\vec{q}|$ - three momentum transfer
  E_{Avail} - visible hadronic energy

Hadron system



- 27% selection efficiency, 92% purity
- 67 kinematic bins
  - Average uncertainty of 12%



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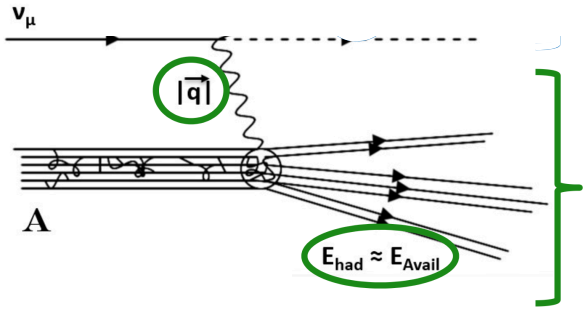

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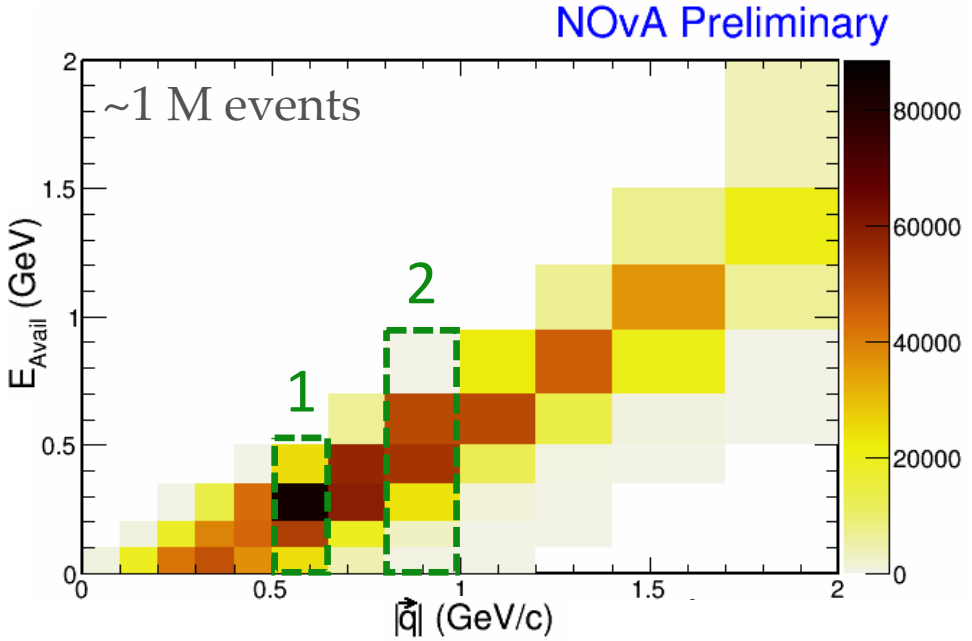
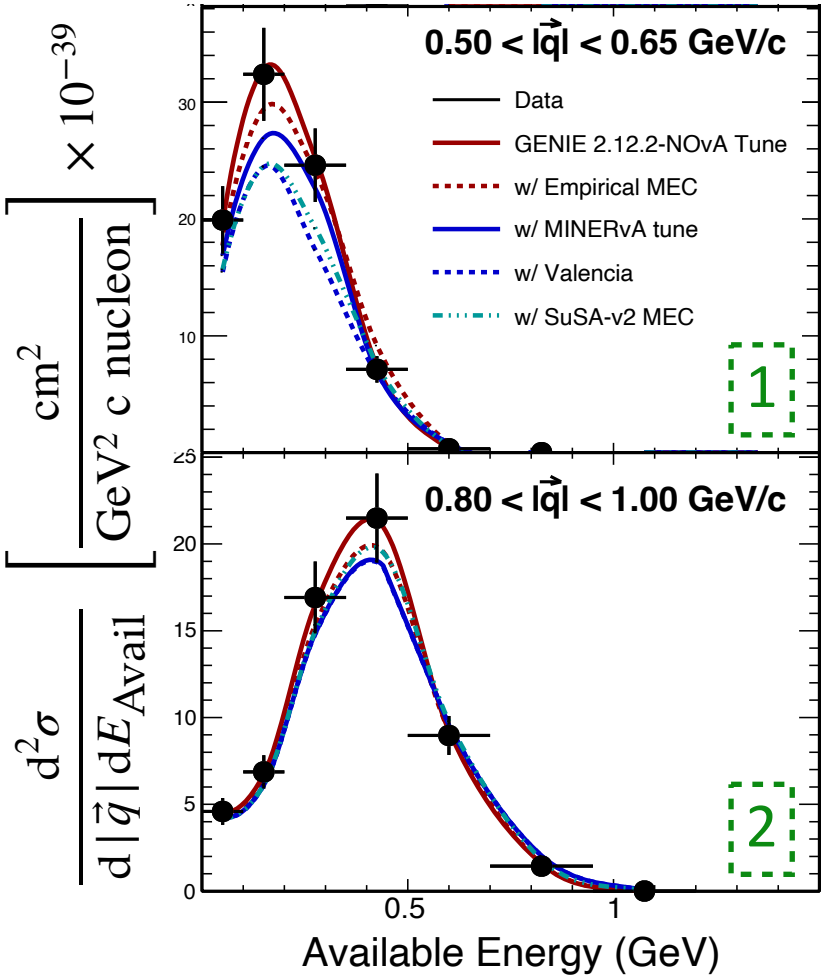




ν_μ CC cross-section measurements summary

- Overall, models underestimate the cross sections in both muon and hadron systems.

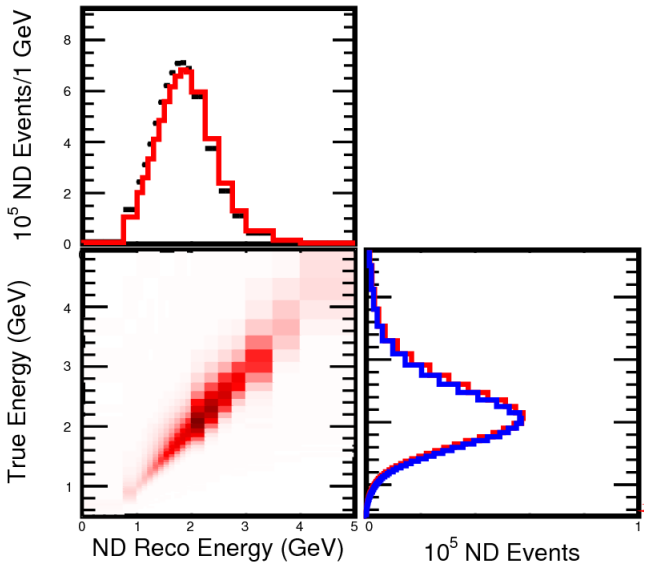
	model	χ^2 − 115 DOF (Muon system)	χ^2 − 67 DOF (Hadron system)
tuned to data	GENIE v2-12.2 + NOvA Tune	200	560
	Empirical MEC	190	910
	Valencia + MINERvA Tune	340	970
purely theoretical	Valencia	630	1900
	SuSA - v2	620	1000

- Poor agreement with all models; data is in closer agreement with tuned models.
- Future analyses will continue probing the 2p2h/MEC region.

Long-baseline neutrino oscillation results

Predicting energy spectra for the Far Detector

- Using the spectrum of neutrino events in the Near Detector, we can predict the ν_μ and ν_e energy spectra we expect to see at the Far Detector, varying Δm^2_{32}, $\sin^2\theta_{23}$, and δ_{CP}.



ND data
Base Simulation
Data-Driven Prediction

Start with the reconstructed energy of events in the Near Detector, convert to true energy using simulation.

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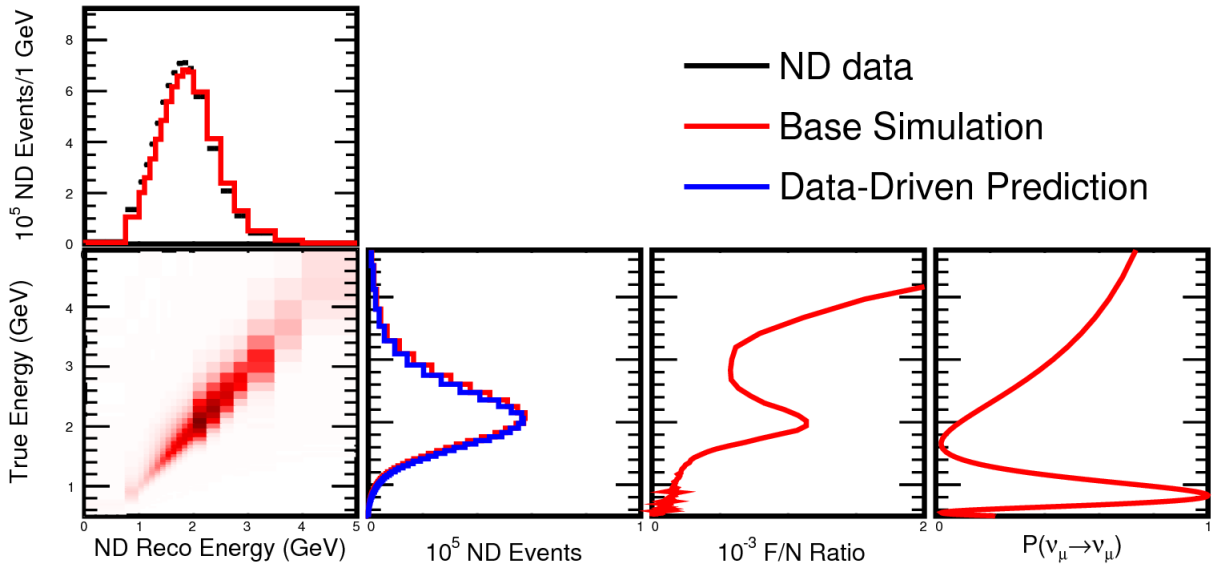

Account for different acceptances in the two detectors and apply oscillations.

Predicting energy spectra for the Far Detector

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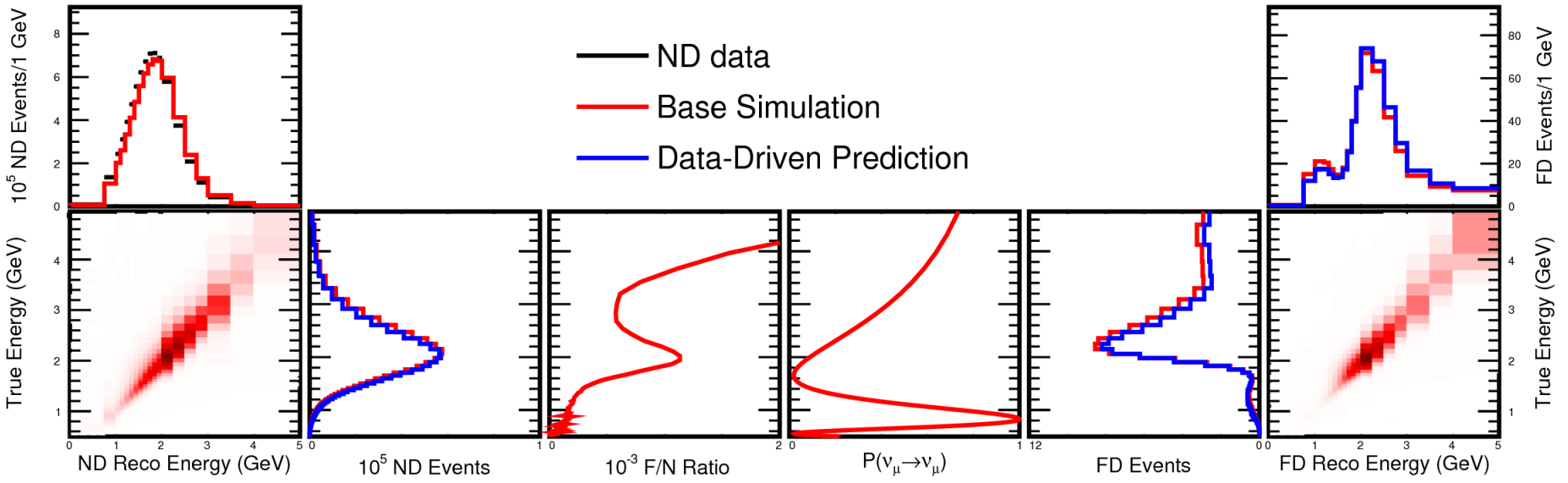
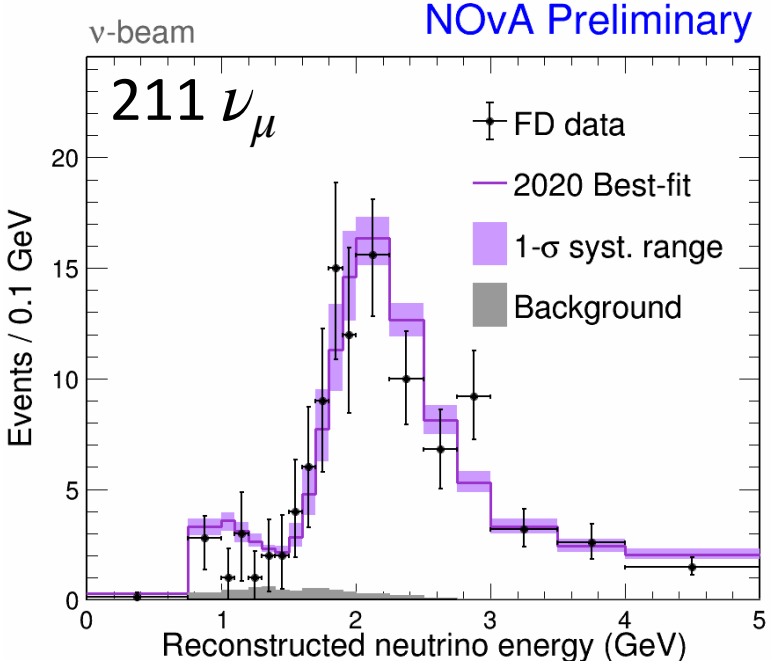
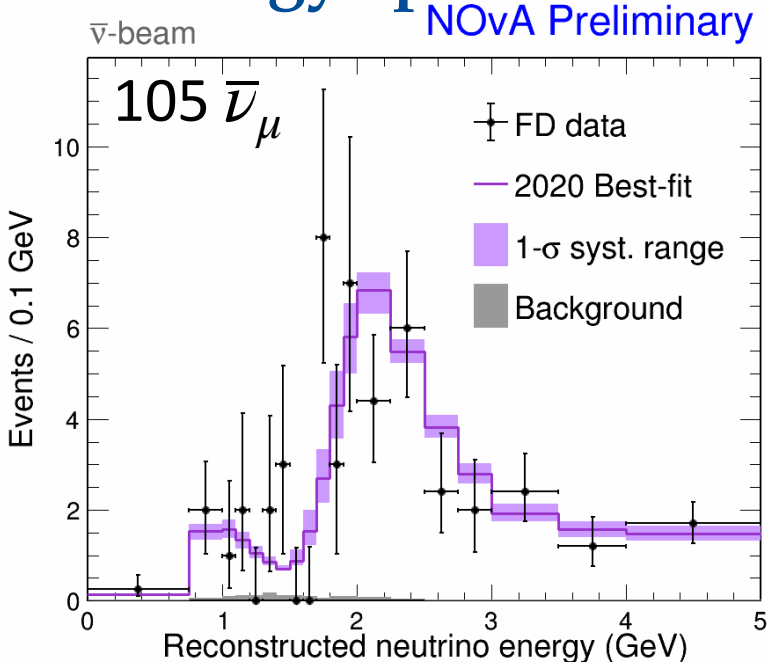
Convert the expected Far Detector true energy spectrum to reconstructed energy and compare with data.



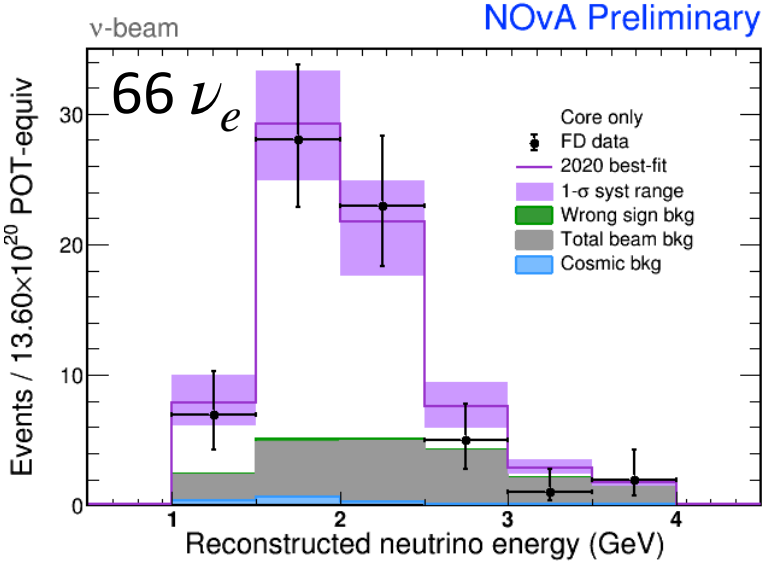
Measured Far Detector neutrino energy spectra

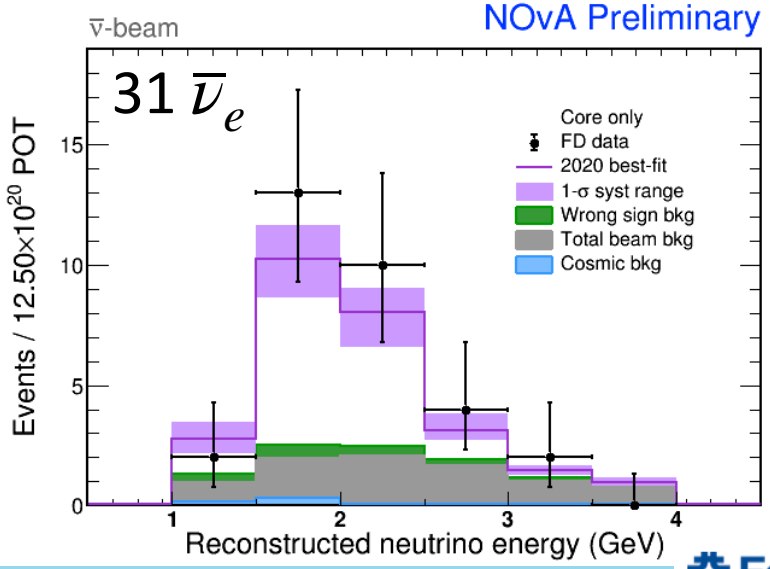
ν_μ





ν_e

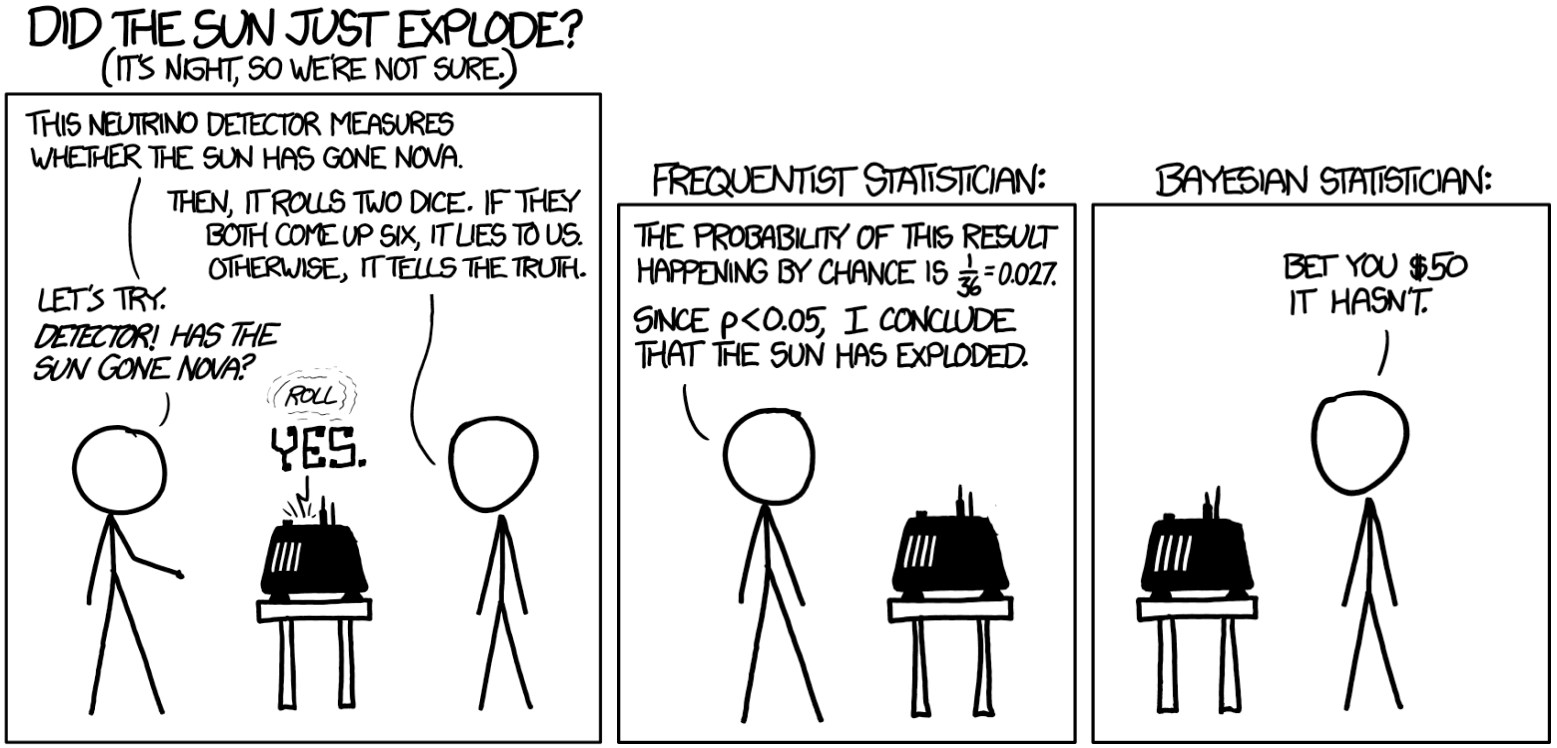




and 16 ν_e, 2 $\bar{\nu}_e$ w/o known energy

Interpreting the results - two analysis methods

- Data selection and prediction remain the same.
- Results for ~equal ν-enhanced and $\bar{\nu}$-enhanced beam modes.
  - 13.6×10^{20} protons-on-target in ν-enhanced beam
  - 12.5×10^{20} protons-on-target in $\bar{\nu}$-enhanced beam



https://xkcd.com/1132/

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Frequentist

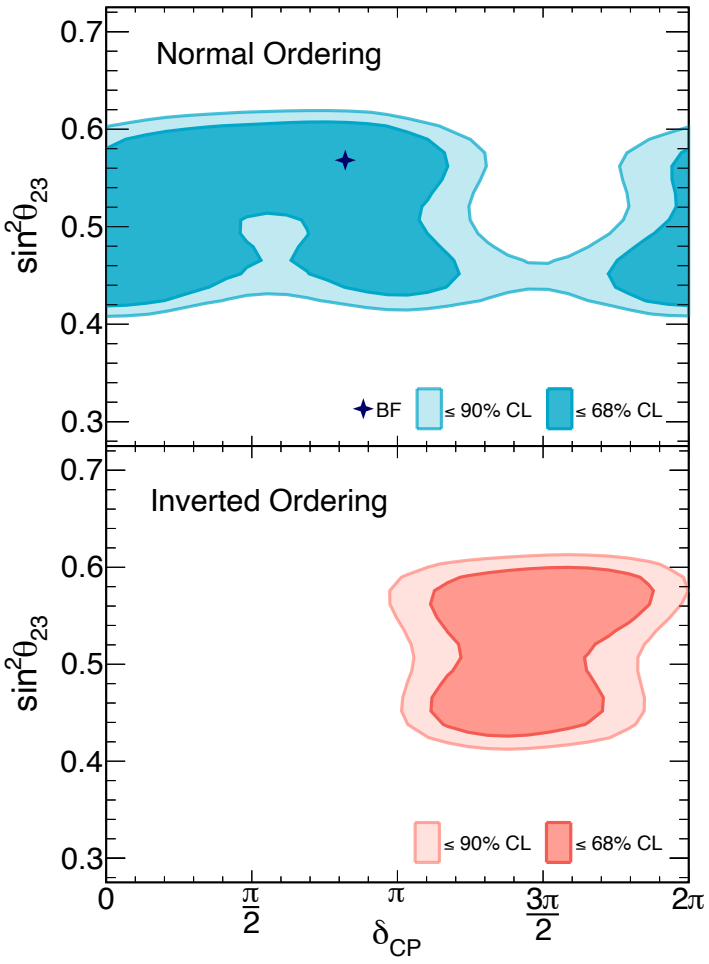
- Requires Feldman-Cousins for correct confidence regions
  - computationally intensive and time-consuming.
- Profiling – maximizes parameters not shown.
- Confidence Regions: χ^2

Bayesian

- Faster to look at other parameters like $\sin^2 2\theta_{13}$, Jarlskog-Invariant
  - can also look at the effect of systematics in more detail.
- Utilizes Markov Chain Monte Carlo which uses marginalization – integrates over parameters not shown.
- Credible Regions: posterior probability densities

more details here: arxiv.org/abs/2311.07835, indico.fnal.gov/event/55483/

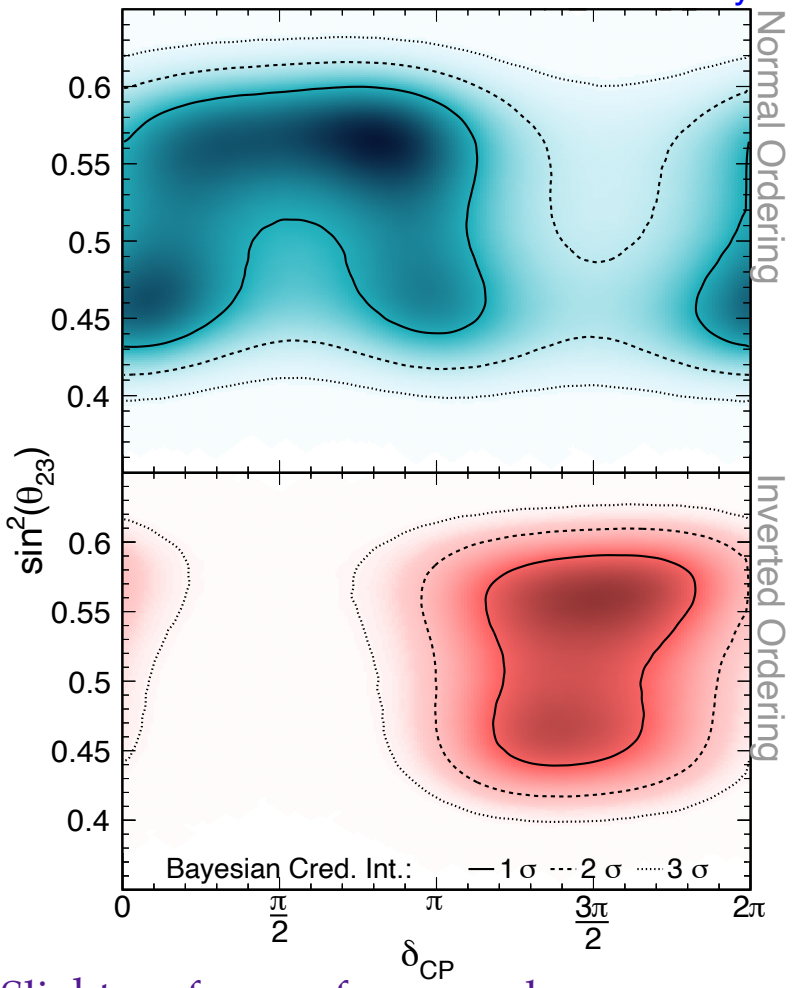
Frequentist



- Slight preference for normal ordering, upper octant.
- $\Delta m^2_{32} = (2.41 \pm 0.07) \times 10^{-3}$ eV^2
- $\sin^2\theta_{23} = 0.57^{+0.04}_{-0.03}$
- $\delta_{CP} = 0.82^{+0.27}_{-0.87}\pi$

Bayesian

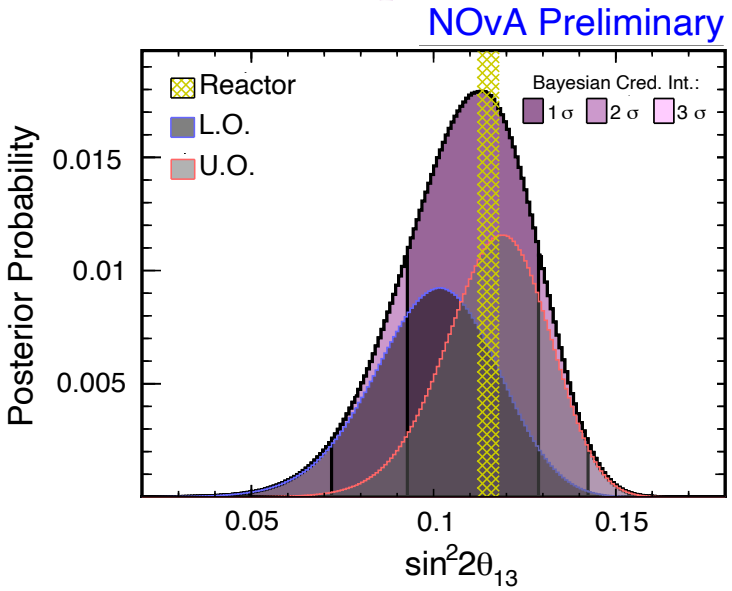
NOvA Preliminary



- Slight preference for normal ordering, upper octant.
- $\Delta m^2_{32} = (2.39 \pm 0.07) \times 10^{-3}$ eV^2
- $\sin^2\theta_{23} = 0.56^{+0.03}_{-0.12}$
- $\delta_{CP} = 0.89\pi$ $[-0.01\pi, 0.48\pi] \cup [0.54\pi, 1.07\pi]$

Other measurements now possible with Bayesian analysis

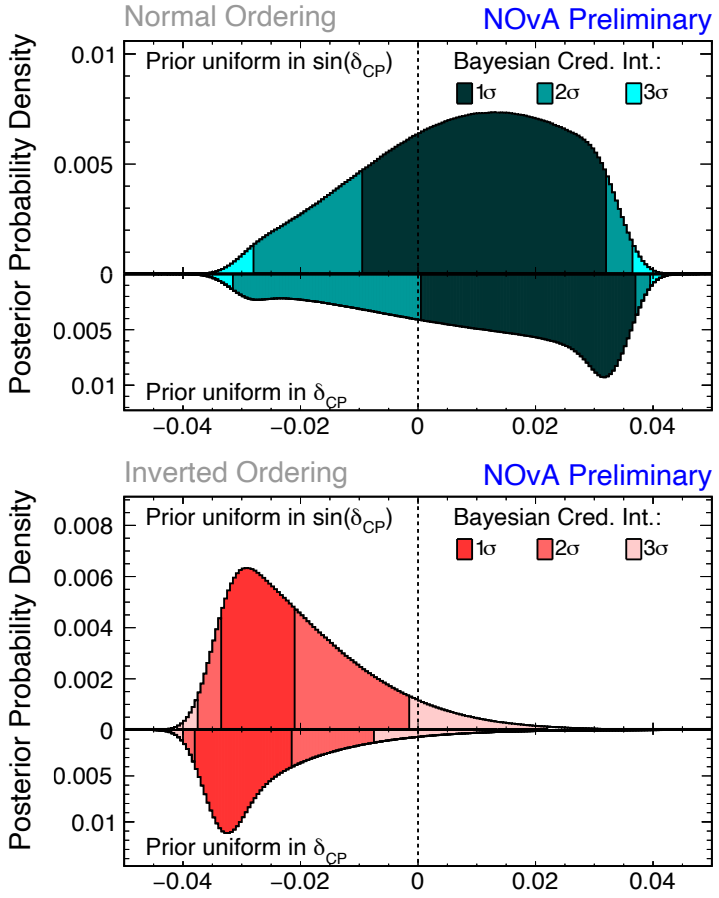
- NOvA-only measurement of $\sin^2(2\theta_{13})$
  - usually use constraint from reactor and solar experiments



- **NOvA result:** $\sin^2(2\theta_{13}) = 0.087^{+0.010}_{-0.016}$
- 2019 PDG value: $\sin^2(2\theta_{13}) = 0.085 \pm 0.003$

- Jarlskog-Invariant

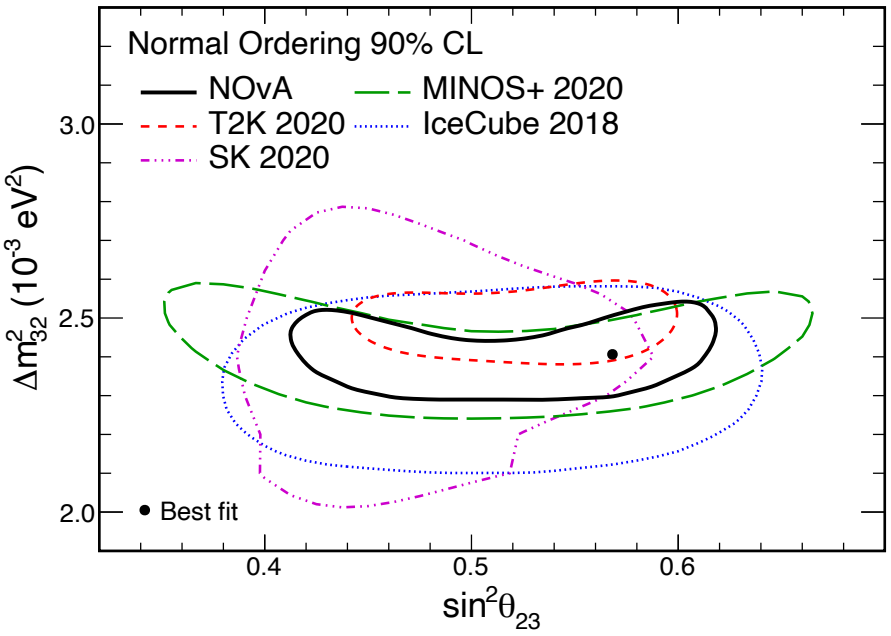
$$J \equiv \cos\theta_{12}\cos\theta_{13}^2\cos\theta_{23}\sin\theta_{12} \times \sin\theta_{13}\sin\theta_{23}\sin\delta_{CP}$$

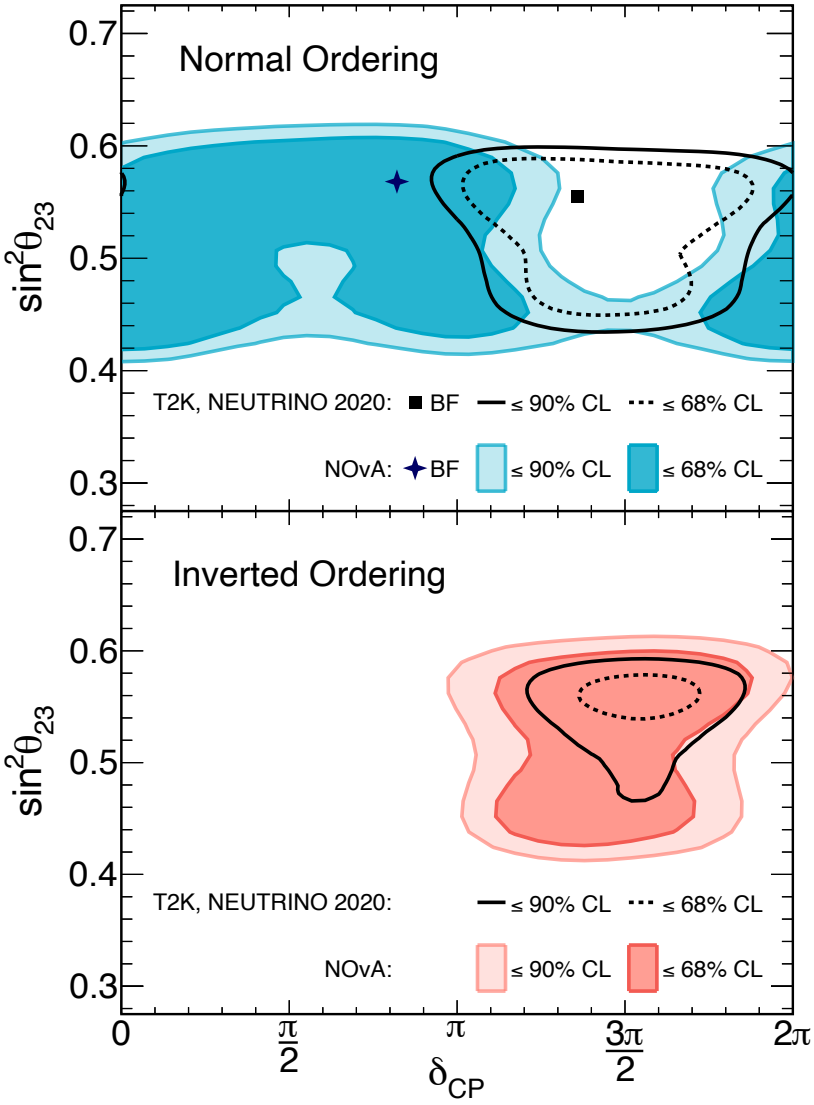


$J \neq 0 \rightarrow$ CP violation

Joint Fit with T2K in progress

- NOvA and T2K have general agreement, but there are different preferences for δ_{CP} values in normal ordering.
- Results expected early next year.

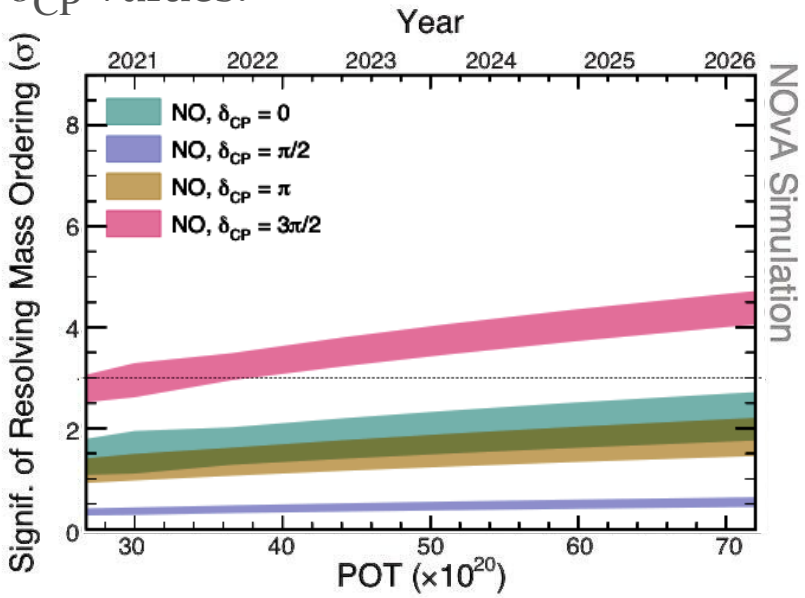




Future prospects

More data

- Continuing to collect (anti)neutrino data.
  - Already have an additional 10-13 × 10^{20} protons-on-target from ν-enhanced beam.
  - Plan to collect beam data until the beginning of 2027.
- $> 3\sigma$ mass-ordering sensitivity for 30-40% of δ_{CP} values.



More analyses

- Recent results (talks linked):
  - sterile neutrinos in the 3+1 model,
  - non-standard-interactions (NSI).
- Many cross-section analyses in the pipeline, with first inclusive antineutrino results from NOvA imminent.
- Ongoing joint analysis with T2K, results expected early next year.
- Analyzing data from our Test Beam detector to better understand some of our systematic uncertainties.
- Other non-cross-section and non-neutrino-oscillation results.

Questions?

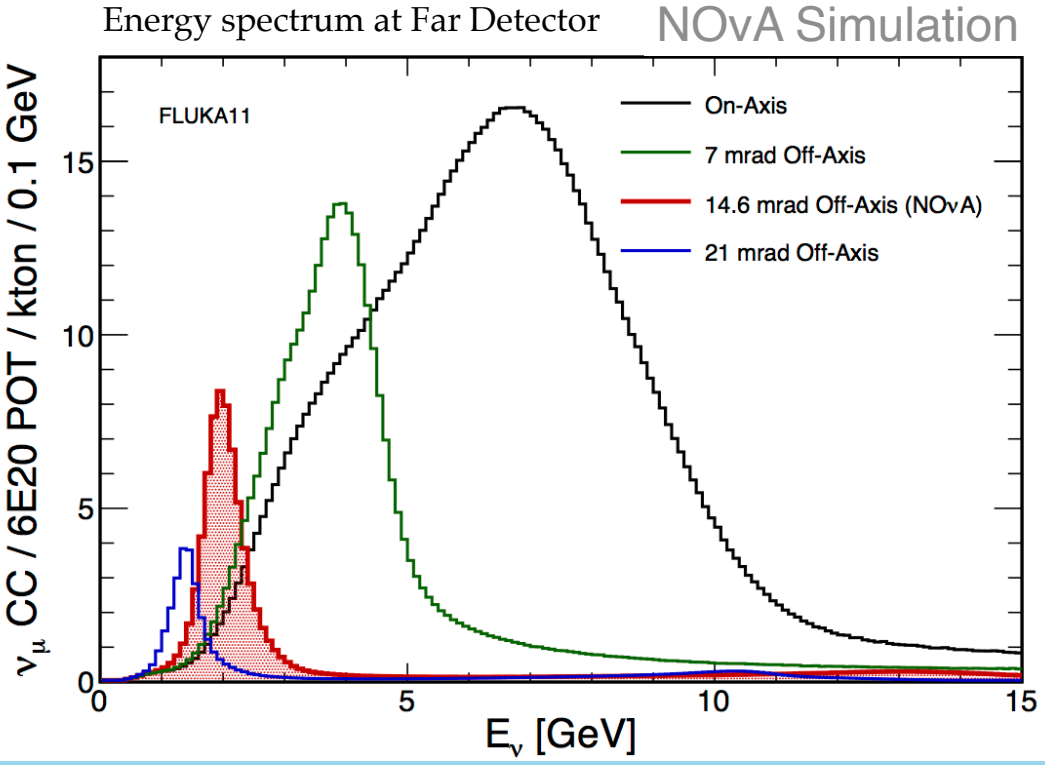
NOvA Collaboration Meeting at Fermilab — October 2023

lackey32@fnal.gov


The Evening Herald
EXTRA!

Why off-axis?

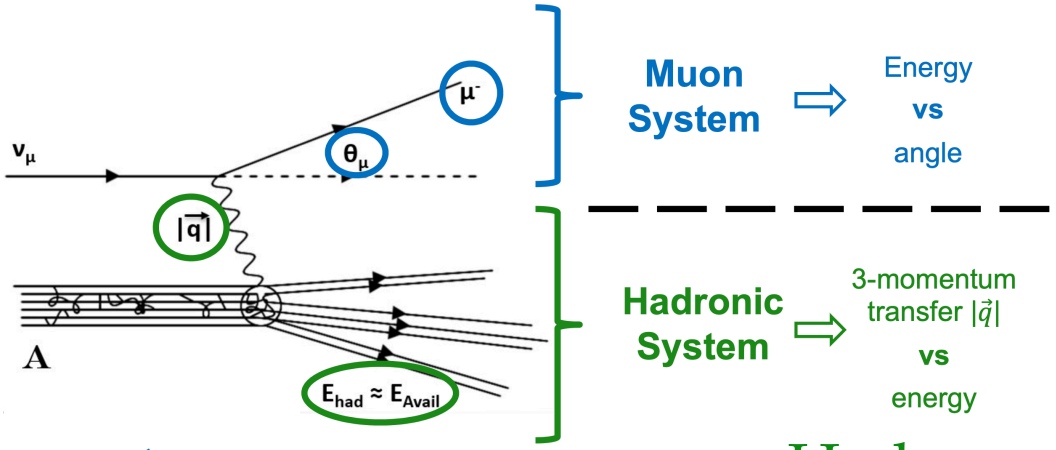
- At 14.6 mrad off-axis, the beam peaks around 2 GeV, which is close to the location of the first oscillation maximum for our baseline.
- We see more ~2 GeV neutrinos at this off-axis location than if we were on-axis. It has the additional benefit of reducing backgrounds from higher energy NC events which can mimic ν_e events.



Other cross-section analyses in progress

- Inclusive measurements:
  - $\overline{\nu}_\mu$ CC, triple differential in T_μ, $\cos\theta_\mu$, E_{avail}
  - $\overline{\nu}_e$ CC, double differential in E_e, $\cos\theta_e$
  - $\nu : \overline{\nu}$ ratios
- Exclusive measurements:
  - $\overline{\nu}_\mu$ CC π^0
    - and $\nu : \overline{\nu}$ ratio
  - $\overline{\nu}_\mu$ CC zero meson
  - ν_μ CC one π
  - $\nu - e$ elastic scattering
  - ν_μ CC $\pi^\pm$
  - $\nu_\mu + N \rightarrow \nu_\mu, \mu^+, \mu^-$ (neutrino trident)

ν_μ CC cross-section measurements - two double differential analyses



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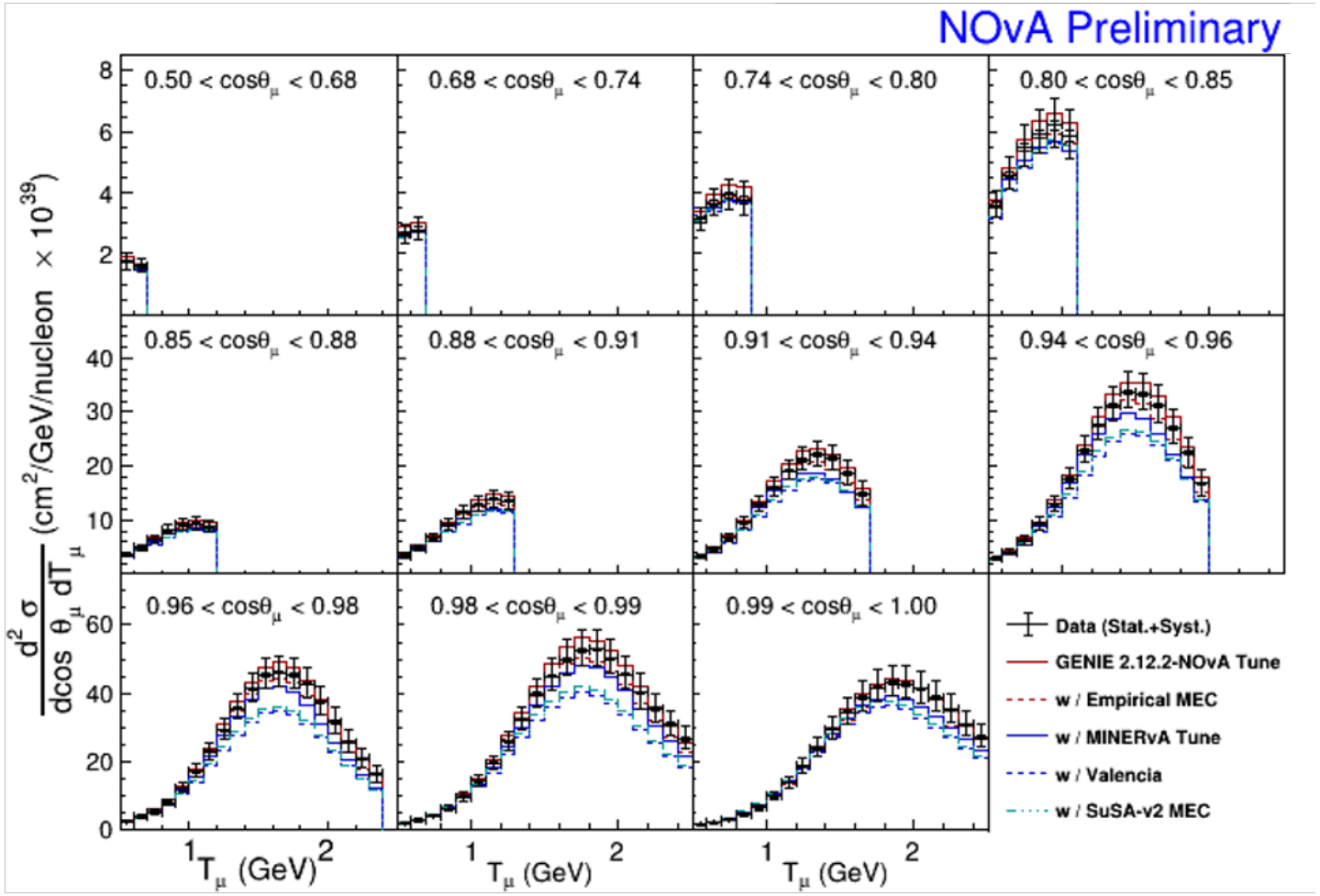
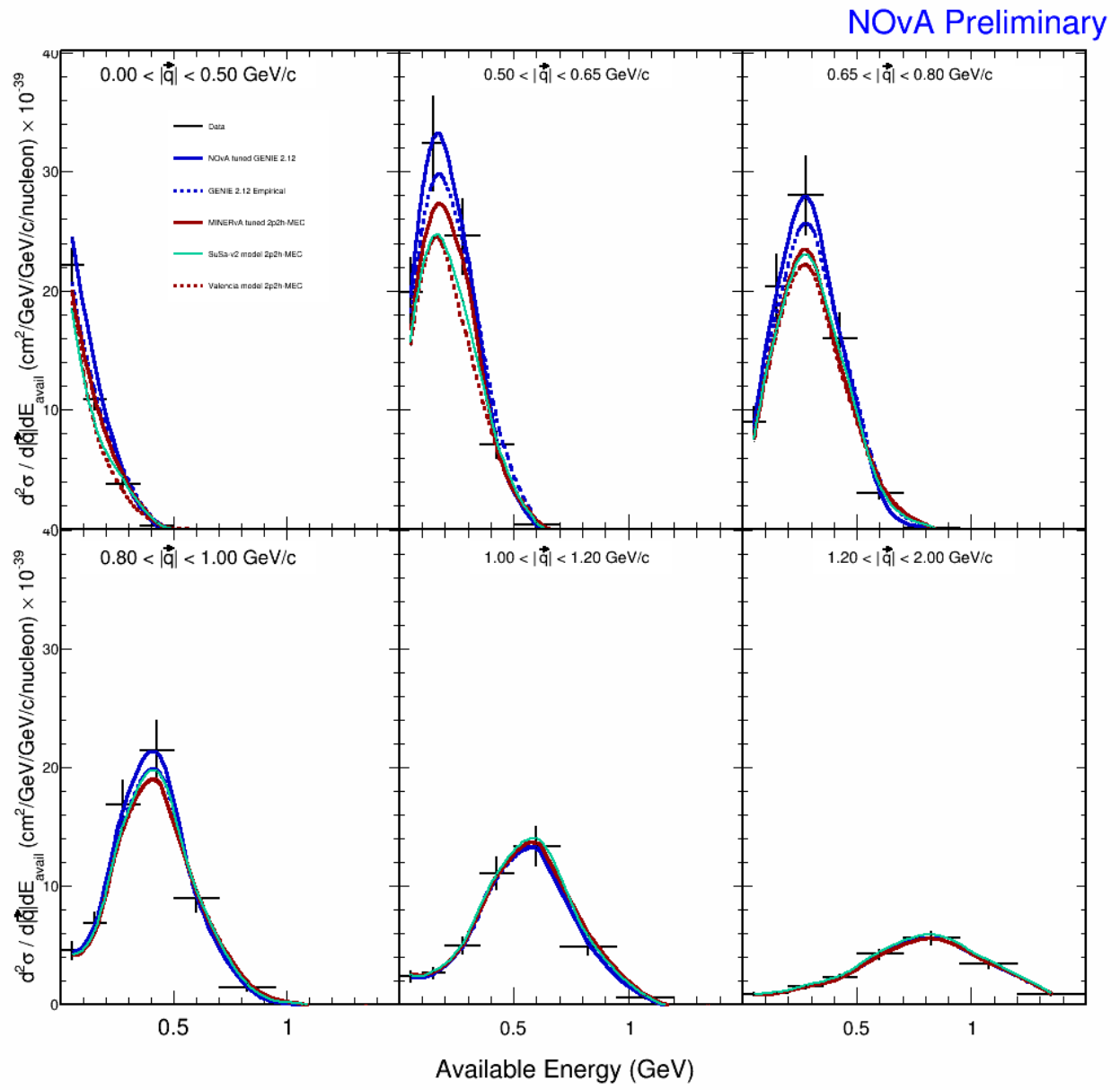
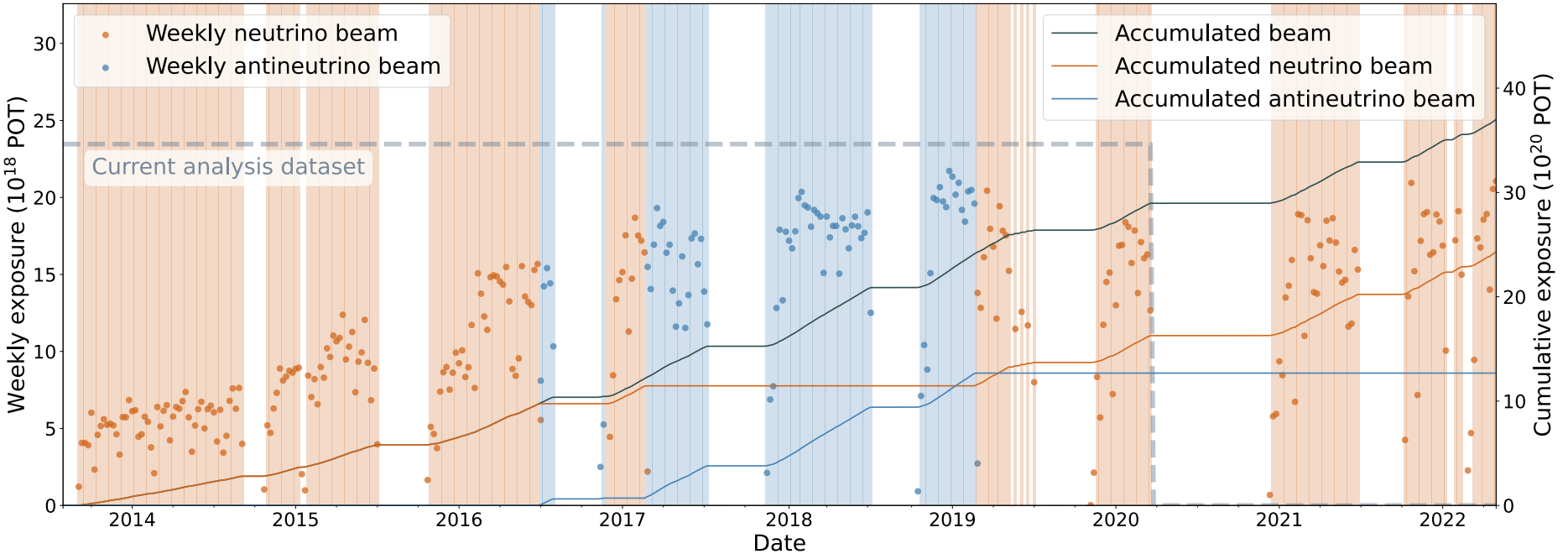
muon-system model comparisons



hadron-system model comparisons



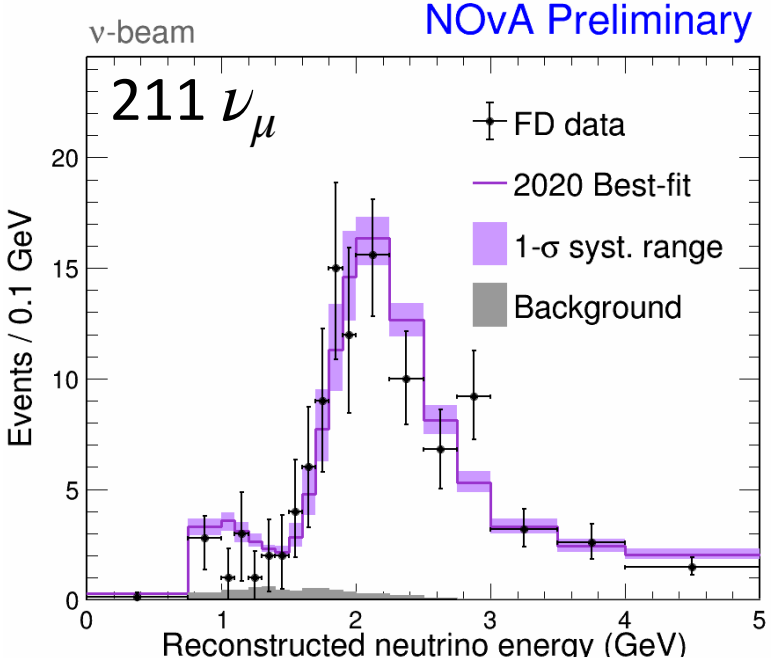
POT vs. time

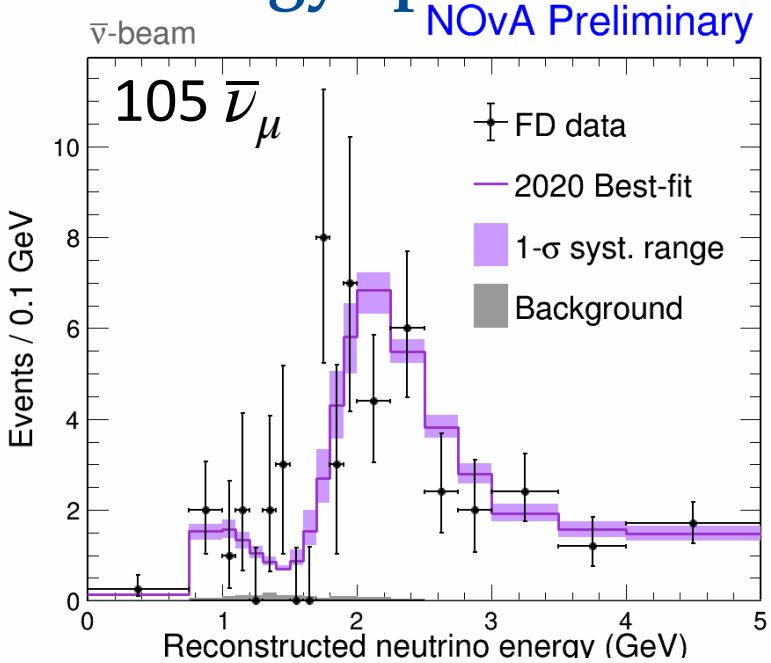


- 13.6×10^{20} protons-on-target in ν-enhanced beam
- 12.5×10^{20} protons-on-target in $\bar{\nu}$-enhanced beam

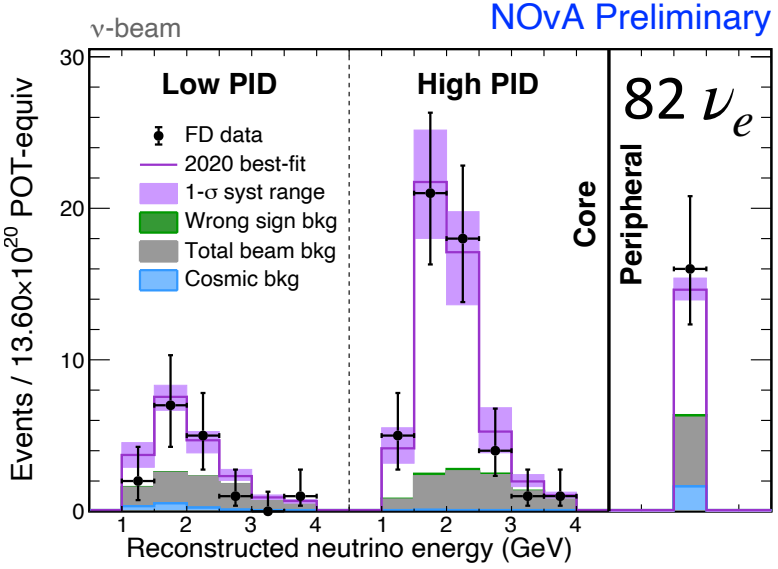
Measured Far Detector neutrino energy spectra

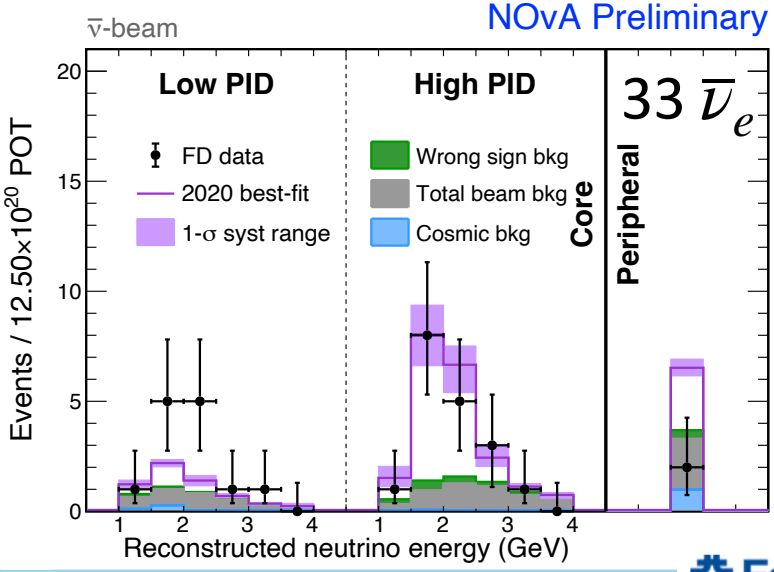
ν_μ



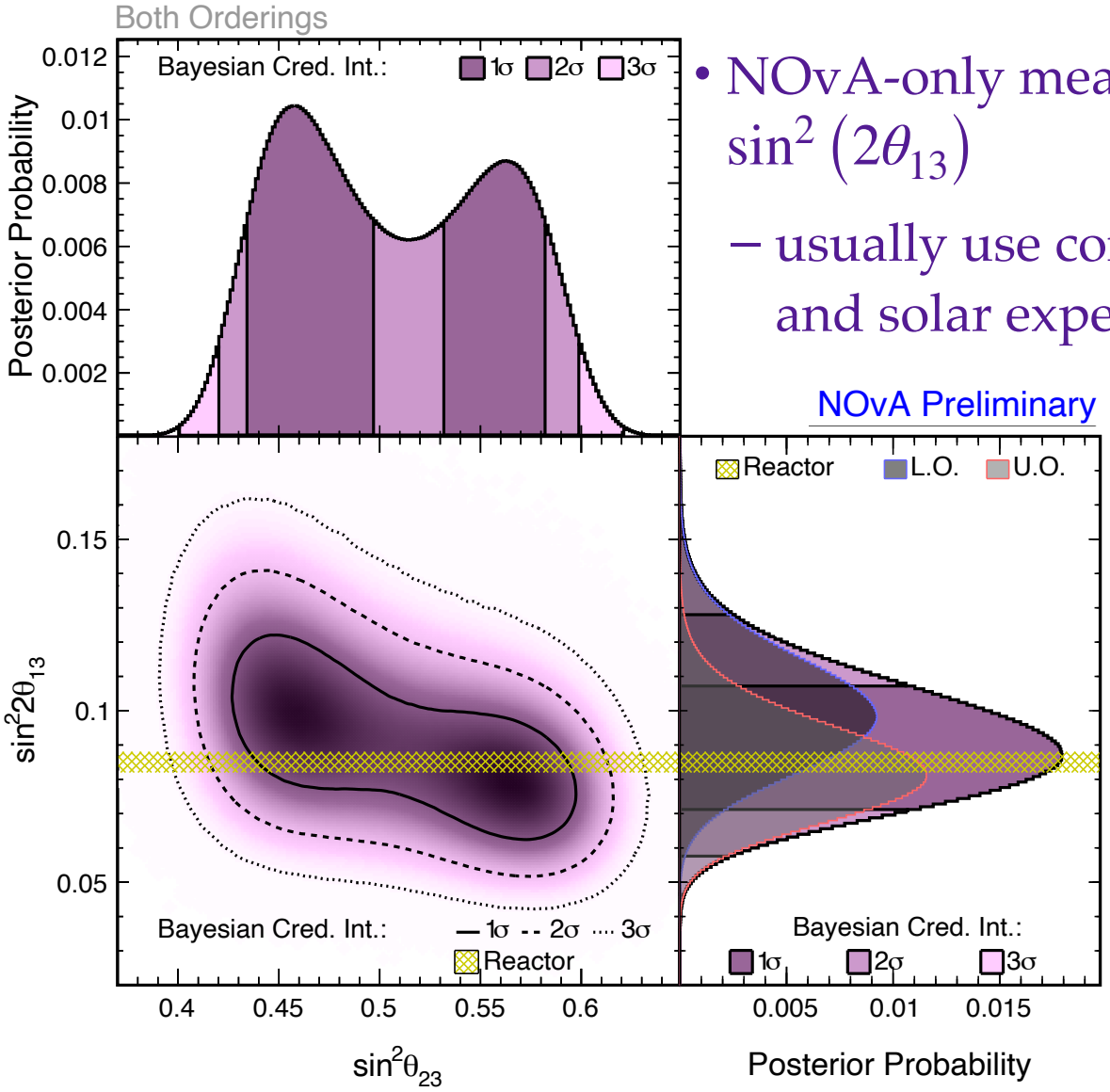


ν_e





Other measurements now possible with Bayesian analysis

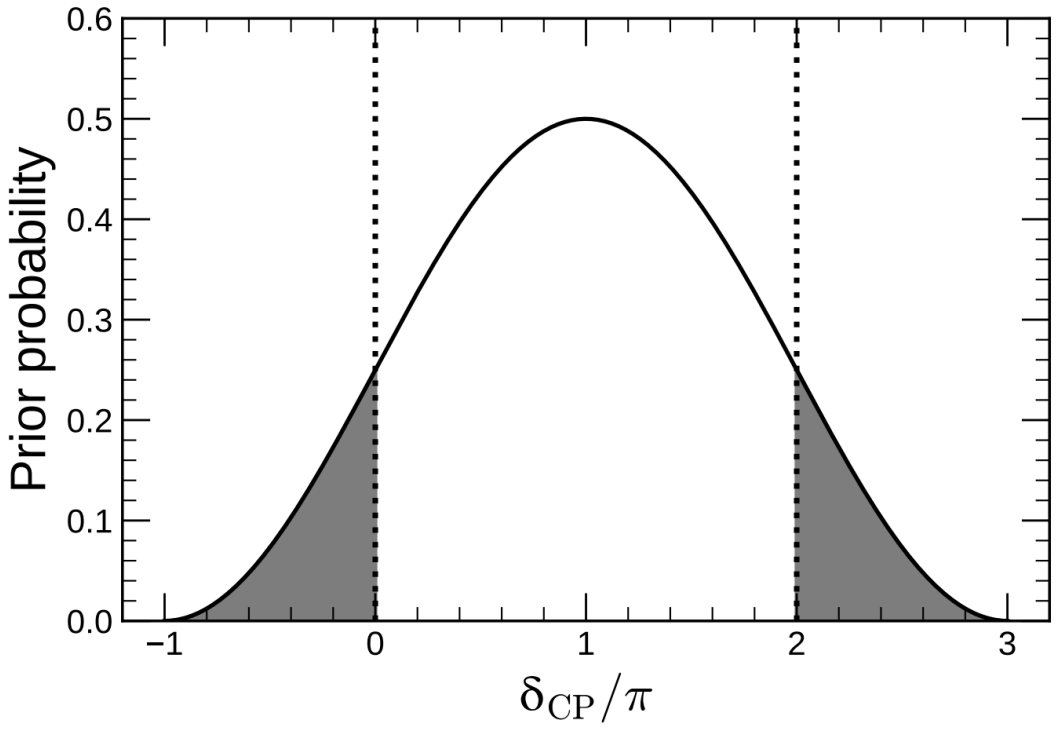


- NOvA-only measurement of $\sin^2(2\theta_{13})$
  - usually use constraint from reactor and solar experiments

- **NOvA result:** $\sin^2(2\theta_{13}) = 0.085^{+0.020}_{-0.016}$

- 2019 PDG value: $\sin^2(2\theta_{13}) = 0.085 \pm 0.003$

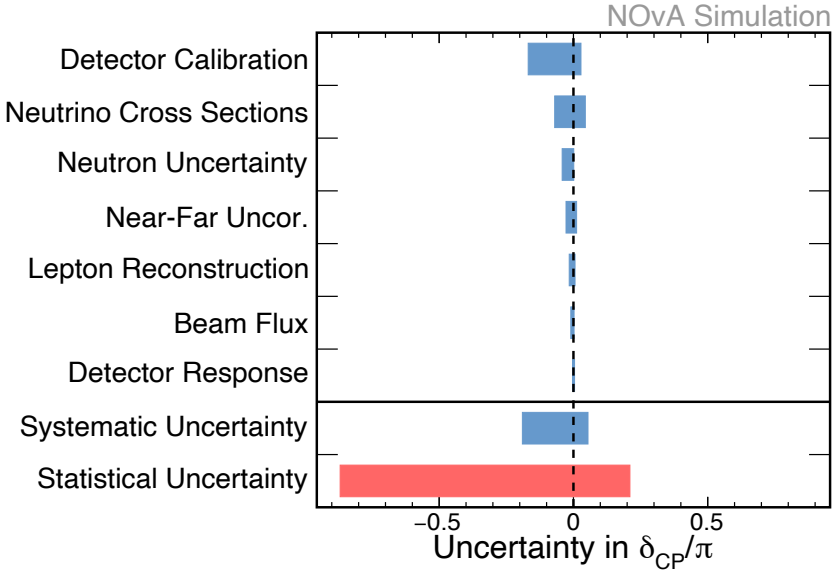
prior uniform in $\delta_{\rm CP}$

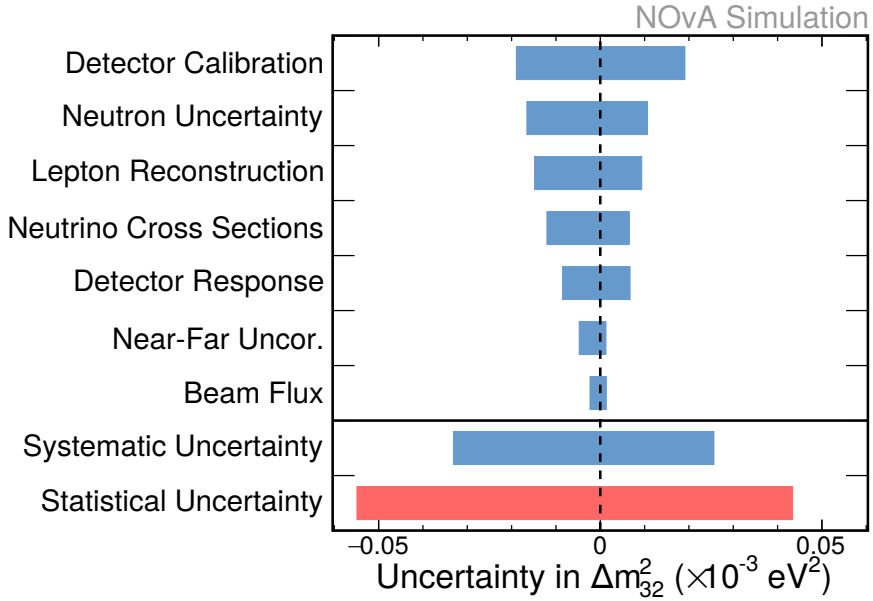


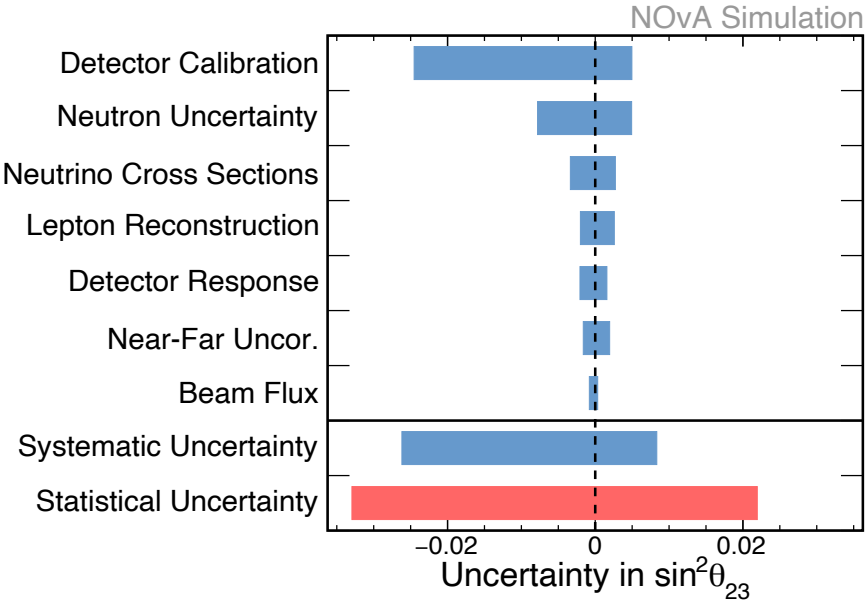
$$\Pi(\delta_{\rm CP}) = \begin{cases} \frac{1}{2}\sin^2\left(\frac{1}{4}(\delta_{\rm CP}+\pi)\right), & -1 \le \delta_{\rm CP}/\pi \le 3 \\ 0, & \text{otherwise.} \end{cases}$$

3-Flavor Oscillation Systematics

Source of Uncertainty	$\sin^2\theta_{23}$	δ_{CP}/π	$\lvert\Delta m^2_{32}\rvert$ ($\times 10^{-3}$ eV^2)
Beam Flux	+0.00034 / -0.0008	+0.0023 / -0.0099	+0.0014 / -0.0023
Detector Calibration	+0.005 / -0.025	+0.028 / -0.17	+0.019 / -0.019
Detector Response	+0.0016 / -0.0021	+0.0041 / -0.0035	+0.0067 / -0.0085
Lepton Reconstruction	+0.0026 / -0.002	+0.006 / -0.016	+0.0094 / -0.015
Near-Far Uncor.	+0.002 / -0.0016	+0.012 / -0.028	+0.0013 / -0.0048
Neutrino Cross Sections	+0.0027 / -0.0034	+0.044 / -0.07	+0.0066 / -0.012
Neutron Uncertainty	+0.0049 / -0.0078	+0.0012 / -0.042	+0.011 / -0.017
Systematic Uncertainty	+0.0083 / -0.027	+0.054 / -0.19	+0.024 / -0.028
Statistical Uncertainty	+0.022 / -0.033	+0.21 / -0.87	+0.043 / -0.055







Exotic analyses

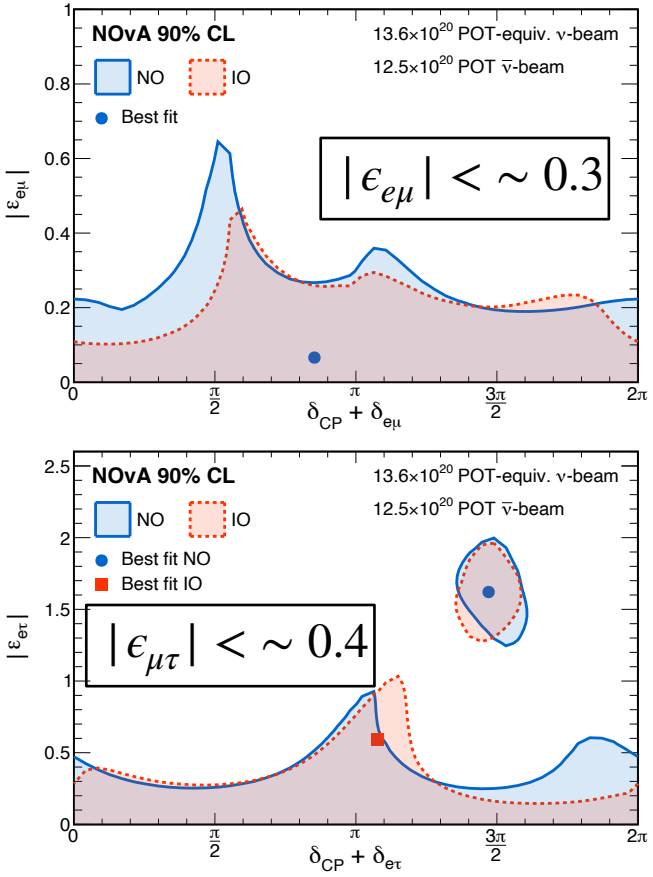
- Many 'exotic' analyses in progress.
  - Exotic = any non-cross-section or non-neutrino-oscillation result

- slow / fast magnetic monopoles
- neutrino magnetic moment
- light dark matter
- upward-going muons
- microscopic black holes
- seasonal variation of cosmic rays
- sidereal variations
- high-energy muons
- ultra-high-energy showers
- atmospheric neutrinos

Other analyses with results in the past couple of years

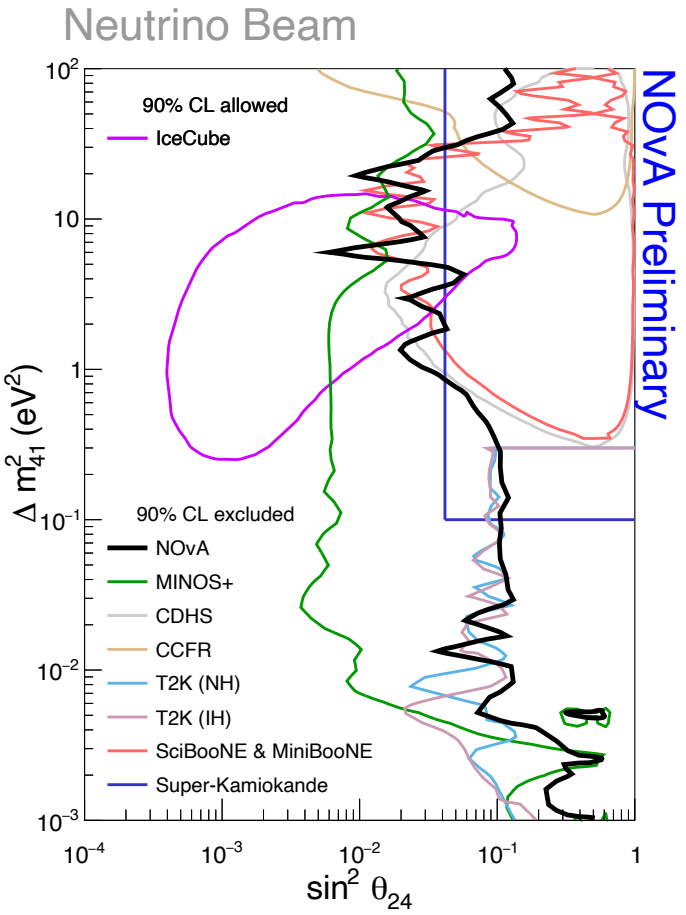
Non-Standard Interactions (NSI)

Allow for non-zero, off-diagonal components in matter potential matrix.



Sterile Neutrinos in 3+1 model

No evidence for sterile neutrinos, also have limits for θ_{34}.



Sensitivities

- Continuing to collect (anti)neutrino data.
  - Already have an additional 10-13 $\times 10^{20}$ protons-on-target from ν-enhanced beam.
- $> 3\sigma$ mass-ordering sensitivity for 30-40% of δ_{CP} values