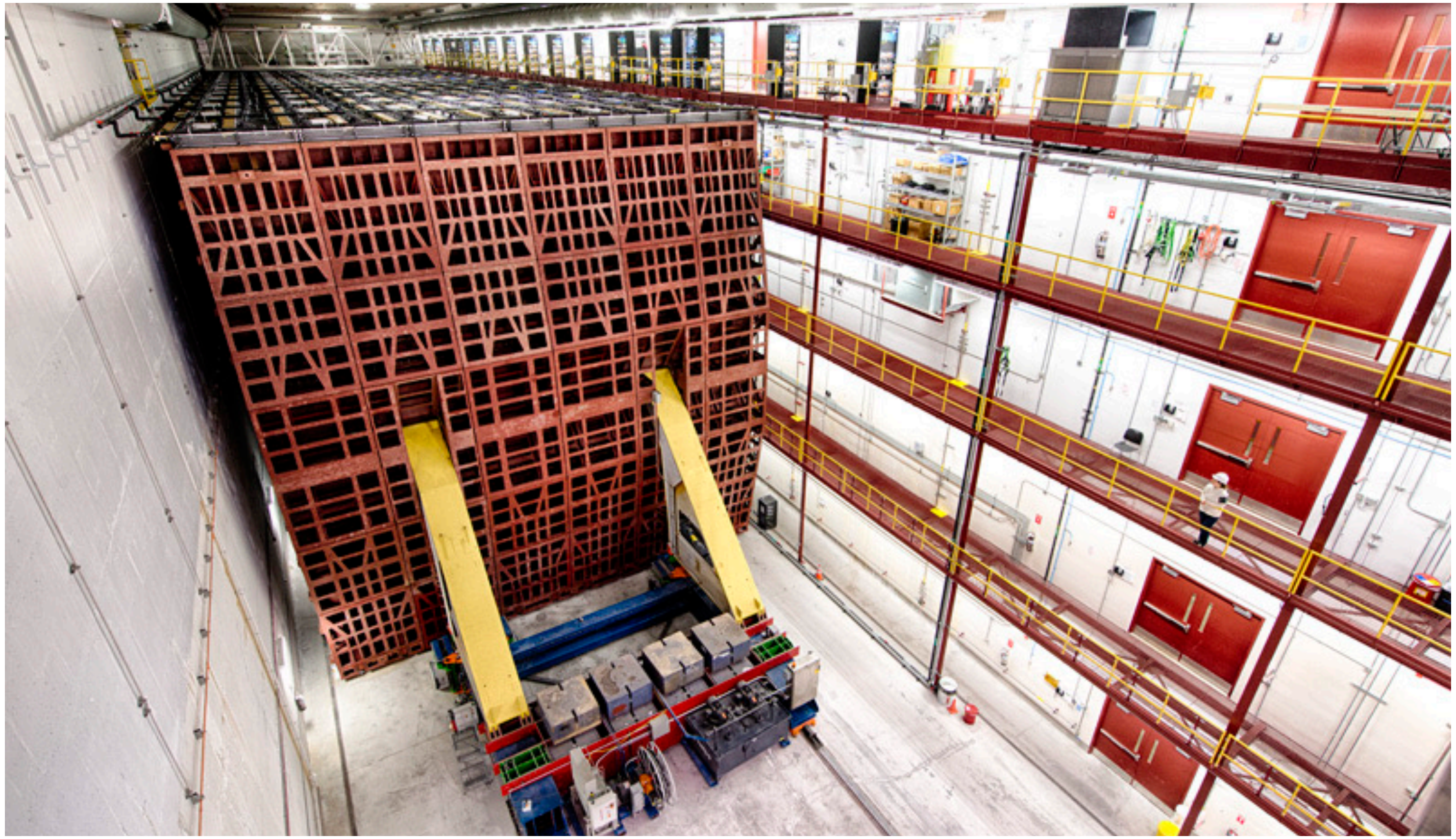
Status of the NOvA experiment
3-flavor neutrino oscillation measurements



Erika Catano-Mur

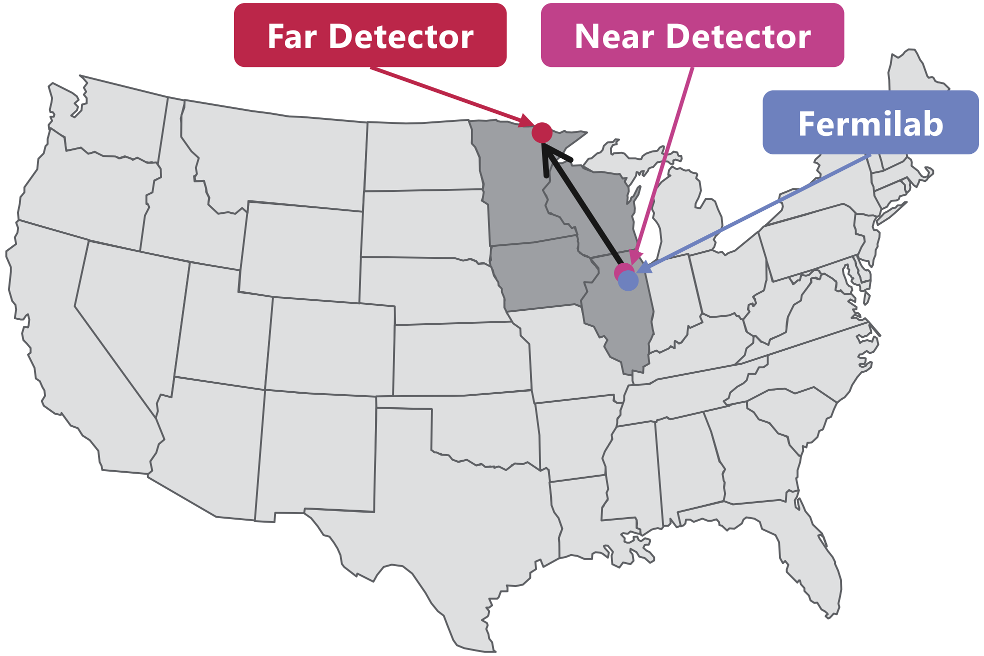
William & Mary

NOvA Collaboration

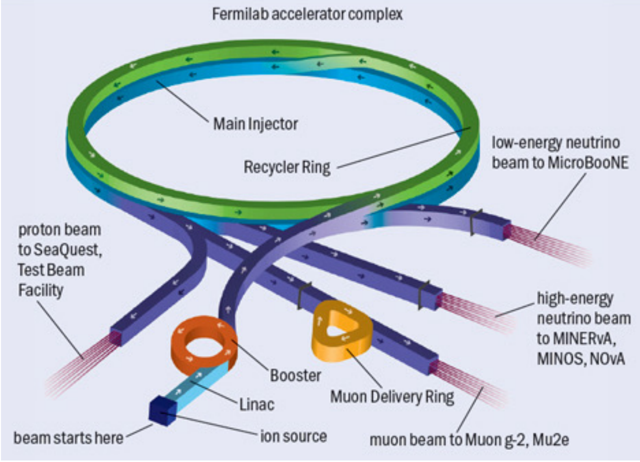
NNN23, October 11th, 2023

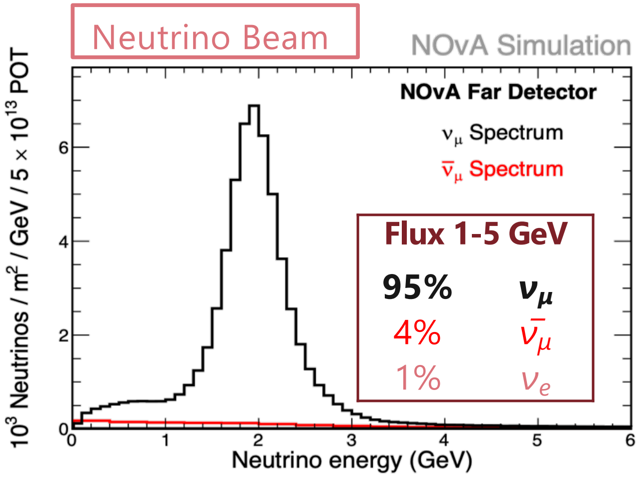
Procida, IT

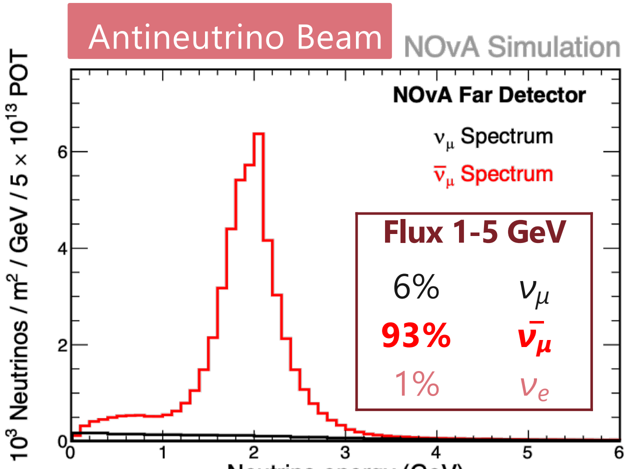
NOvA is a long-baseline accelerator neutrino oscillation experiment based in the US



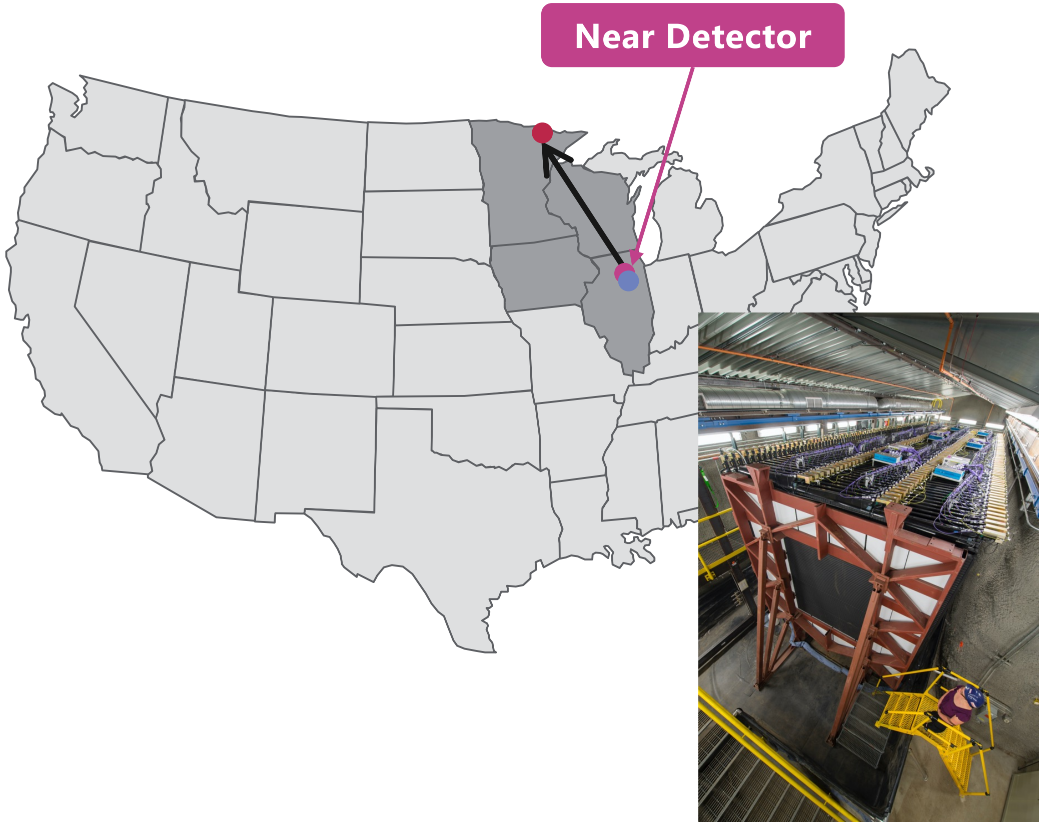
Fermilab's NuMI muon (anti)neutrino beam provides NOvA a narrow-band, highly pure neutrino flux peaked at ~2 GeV

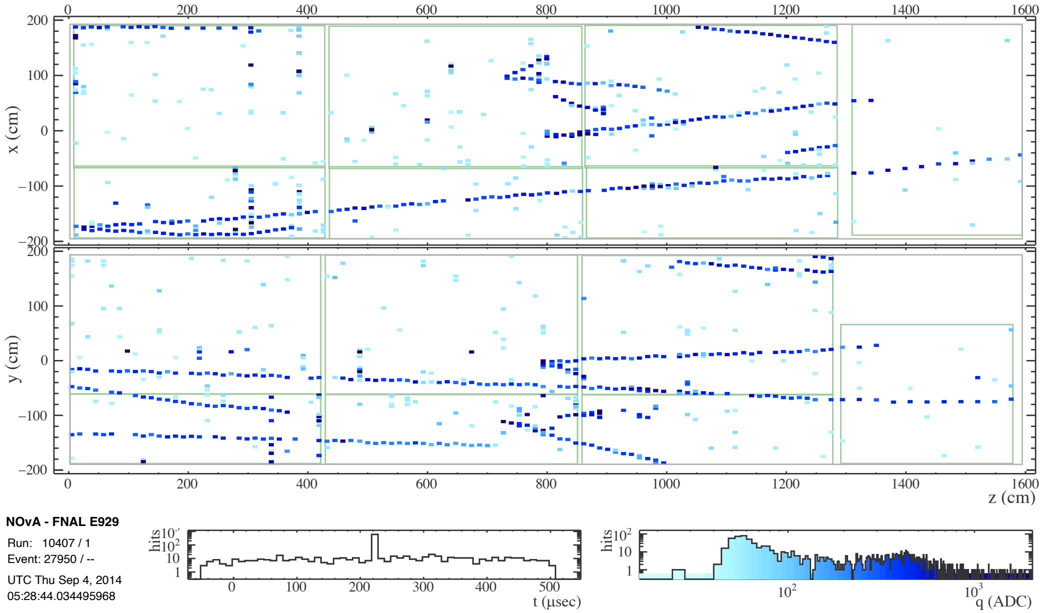




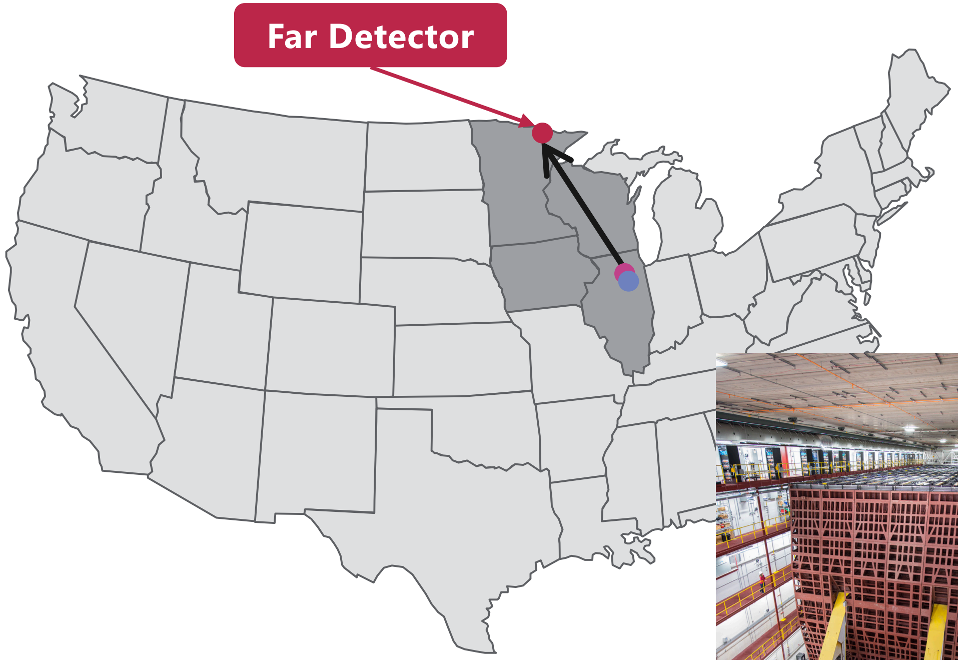


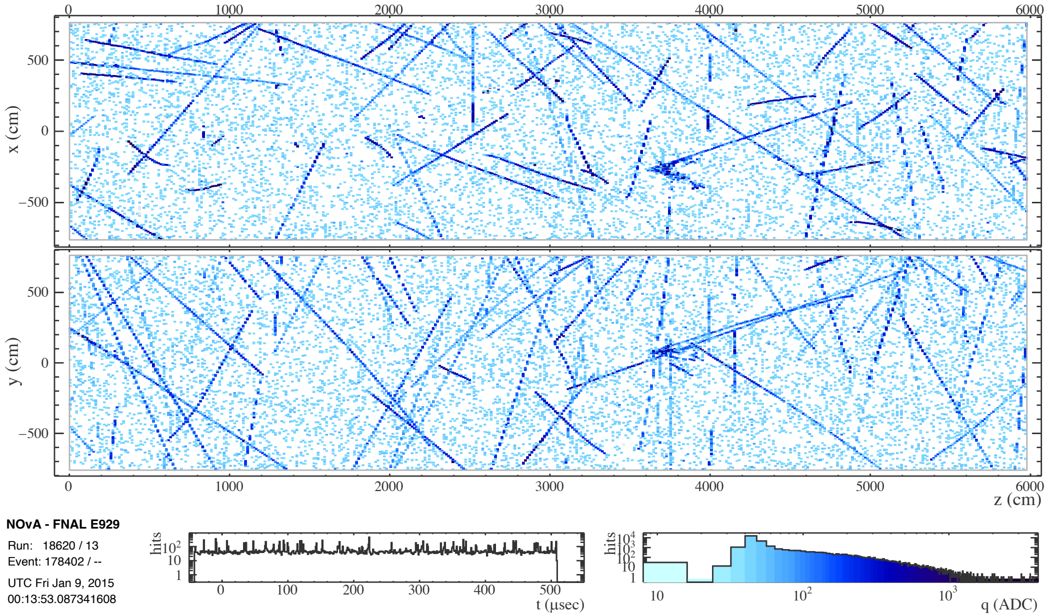
The NOvA near detector is 1km from the beam source, 100 m underground, with a mass of 0.3 kton



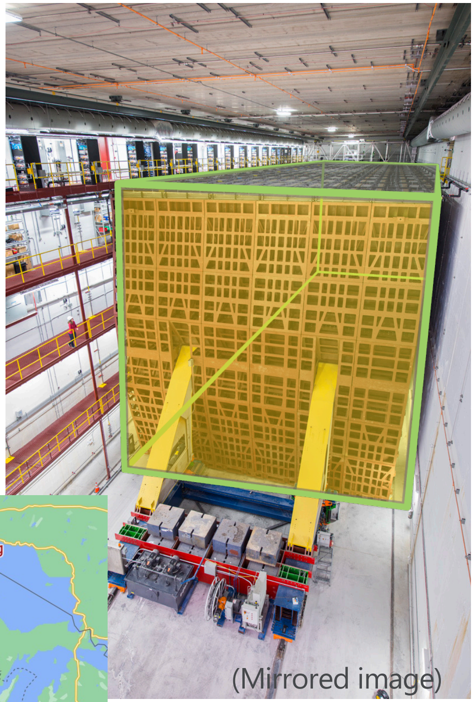


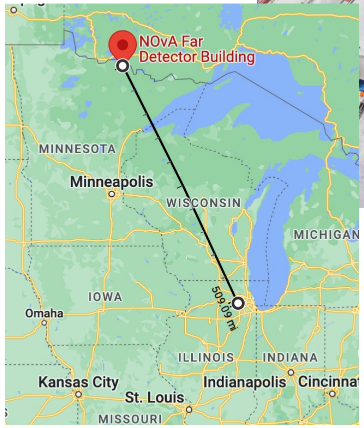
The NOvA far detector is 810 km from the beam source, on the surface, with a mass of 14 kton

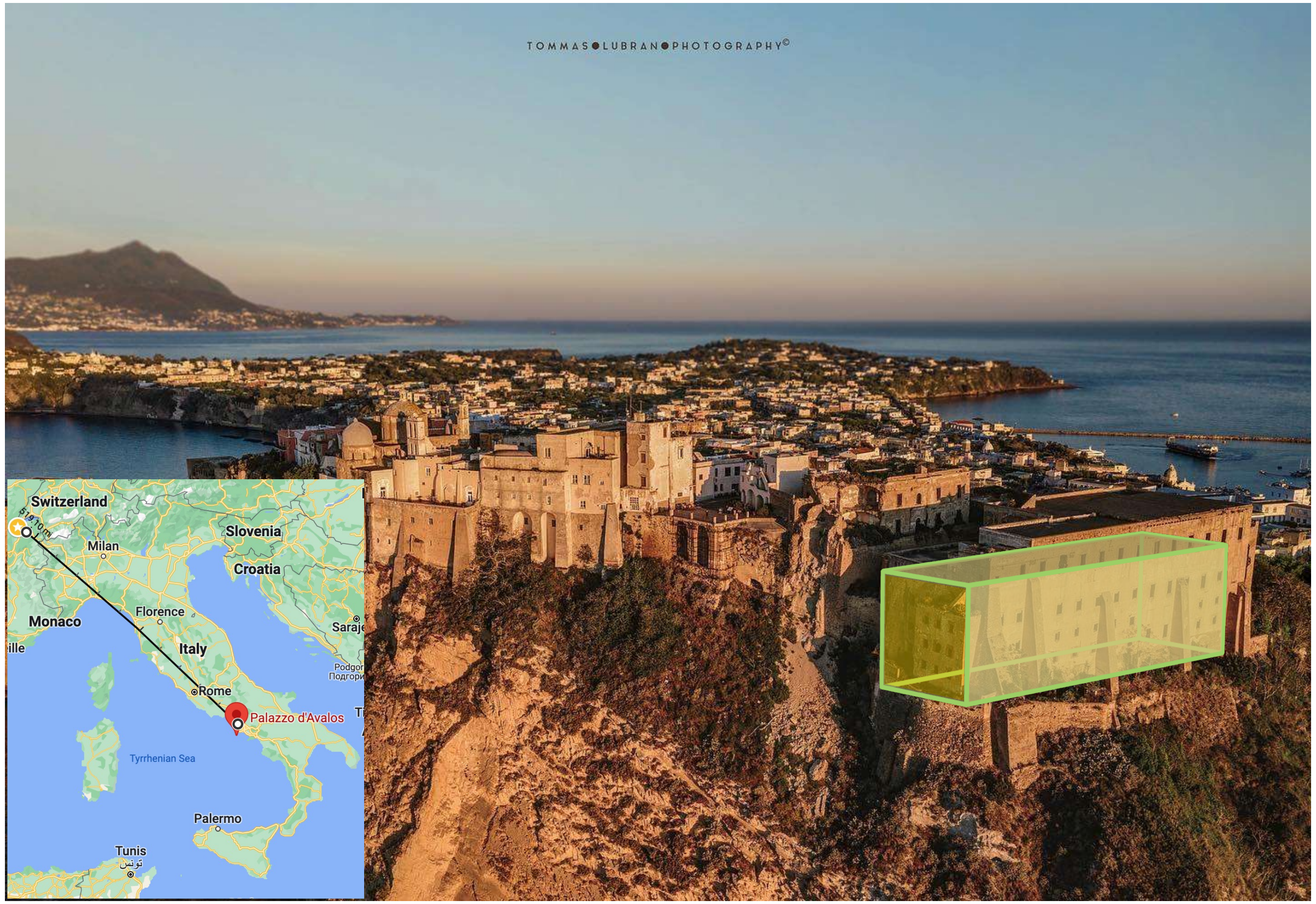




The Far Det. is ~ the size of the large Palazzo d'Avalos building.
The baseline is ~ the distance between Procida and CERN

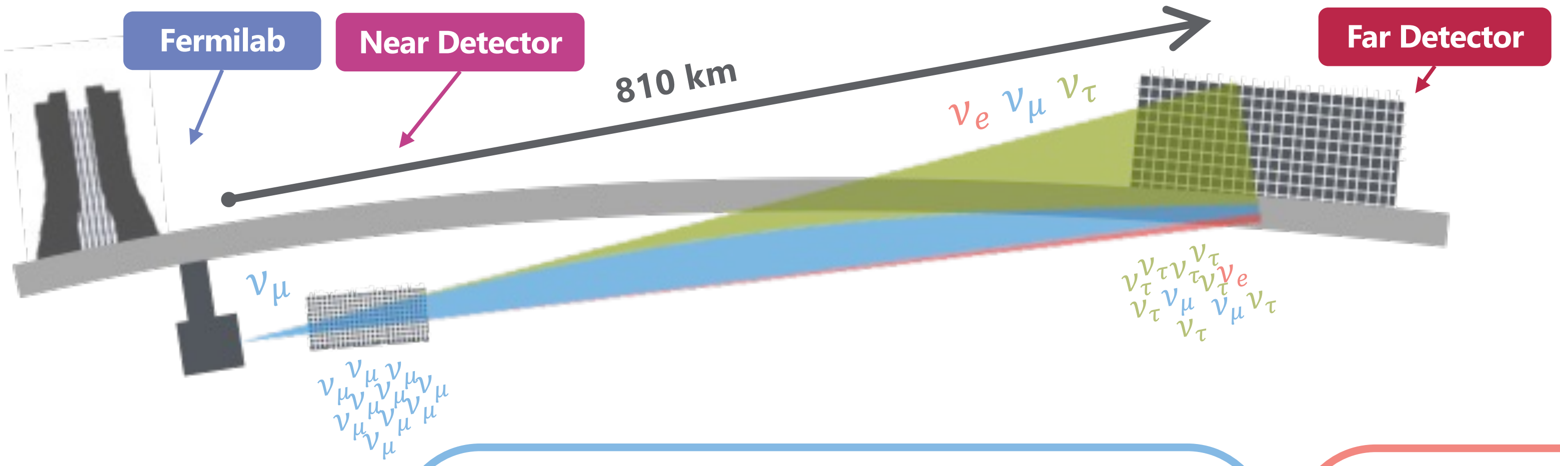




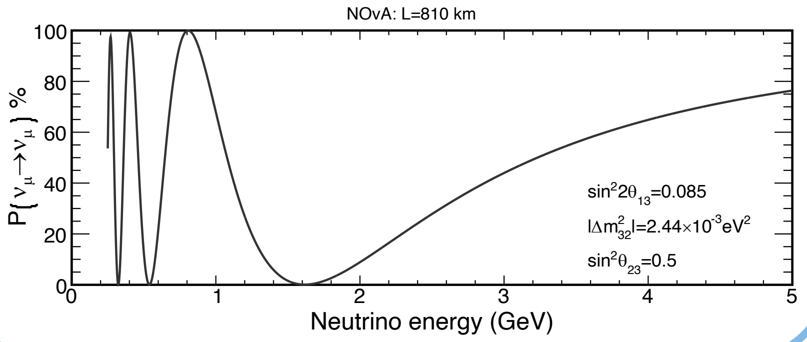


https://www.visitprocida.com/en/places/places-of-interest/palazzo-davalos/

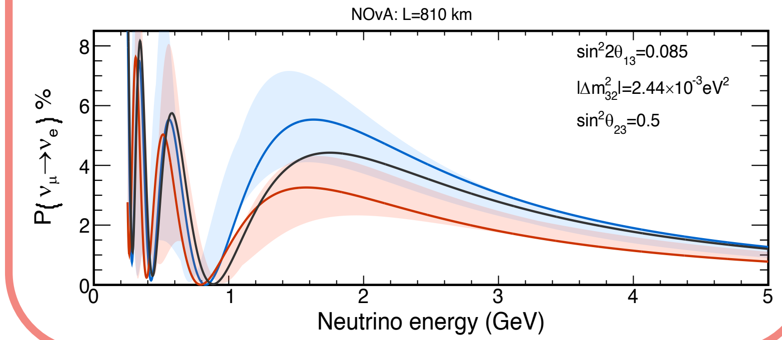
The FD measures the oscillated beam in two channels: muon neutrino disappearance and electron neutrino appearance



$\nu_\mu \to \nu_\mu$ and $\bar{\nu}_\mu \to \bar{\nu}_\mu$ disappearance depend on **$\sin^2 2\theta_{13}$,$\sin^2 2\theta_{23}$ and $|\Delta m^2{}_{32}|$**

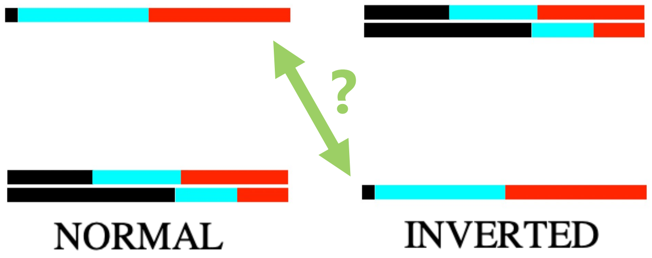


$\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ appearance depend on **$\sin^2 2\theta_{13}$, $\sin^2\theta_{23}$, $\Delta m^2{}_{32}$ and δ_{CP}**

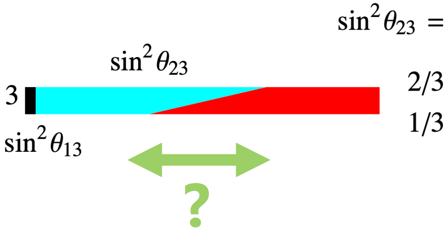


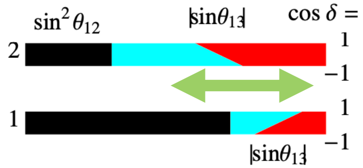
Open questions in the 3-flavor paradigm include the neutrino mass ordering, the octant of θ_{23}, and CP violation

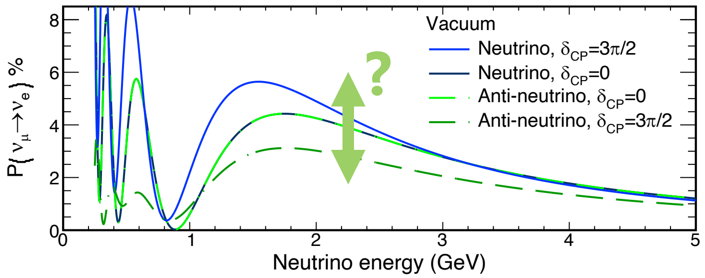
Symmetry Magazine / Sandbox Studio, Chicago



arXiv:hep-ph/0312131



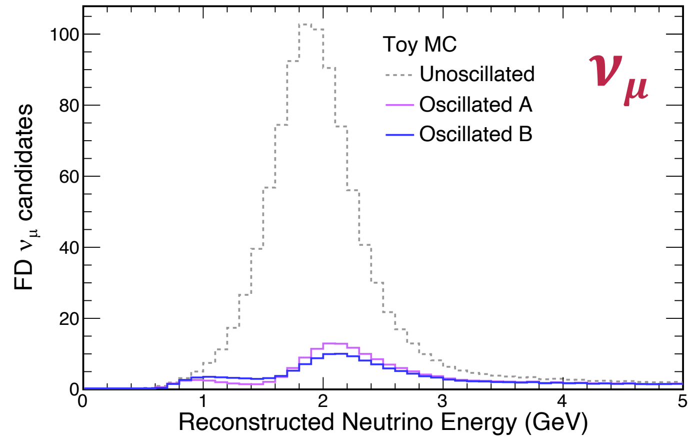


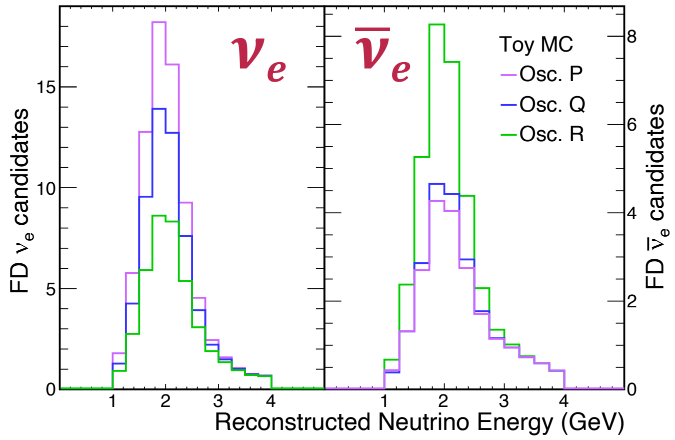


ν_e ■ ν_μ ■ ν_τ ■

3-flavor oscillation measurements

We make inferences about the oscillation parameters by measuring neutrino candidates in the FD and comparing our observations to simulated predictions.



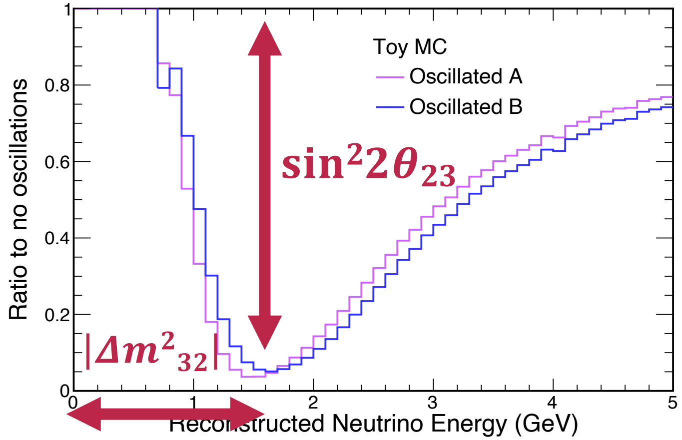


Measurement

Detection

Identification

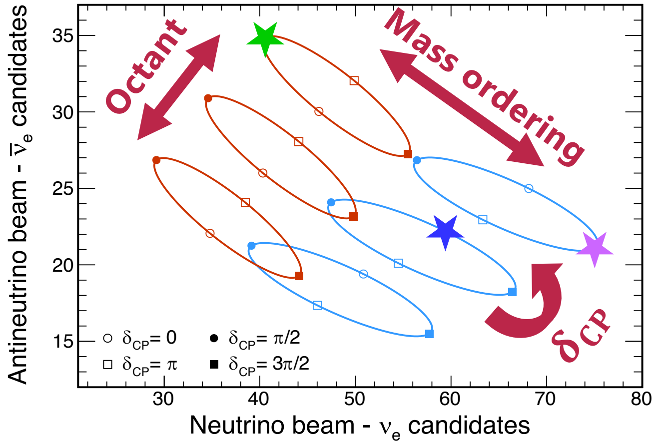
Energy estimation



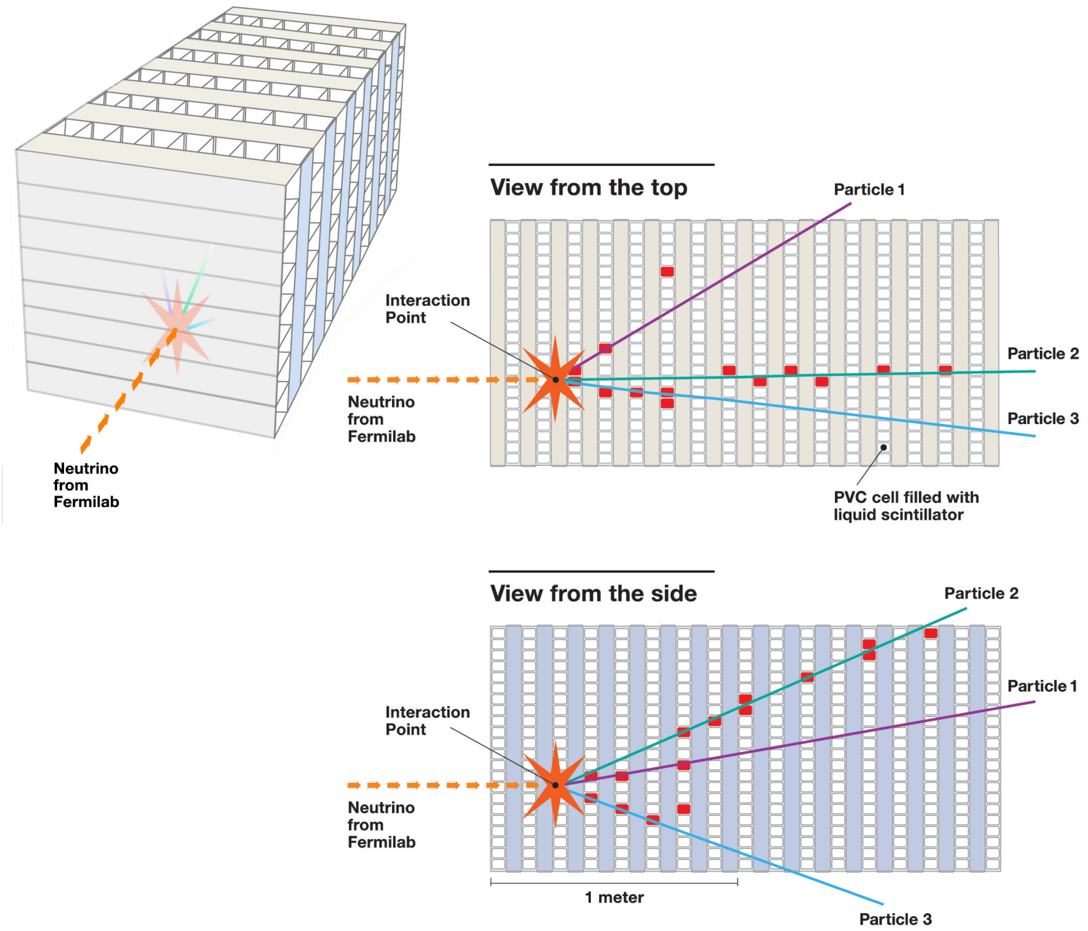
Inference

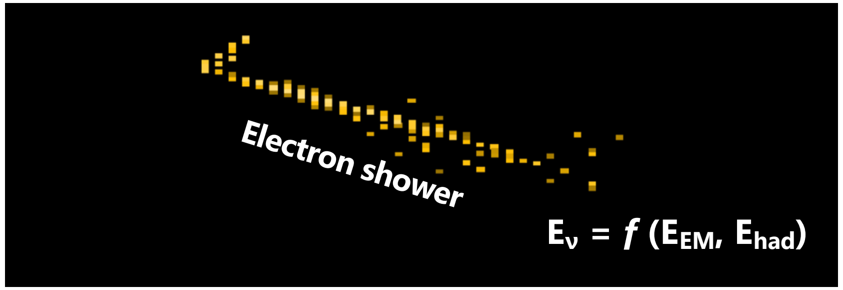
Compare to no-osc.

Combine info. from multiple channels



NOvA has segmented liquid scintillator detectors. Energy is reconstructed via tracking (muon) and calorimetry (EM, had.)



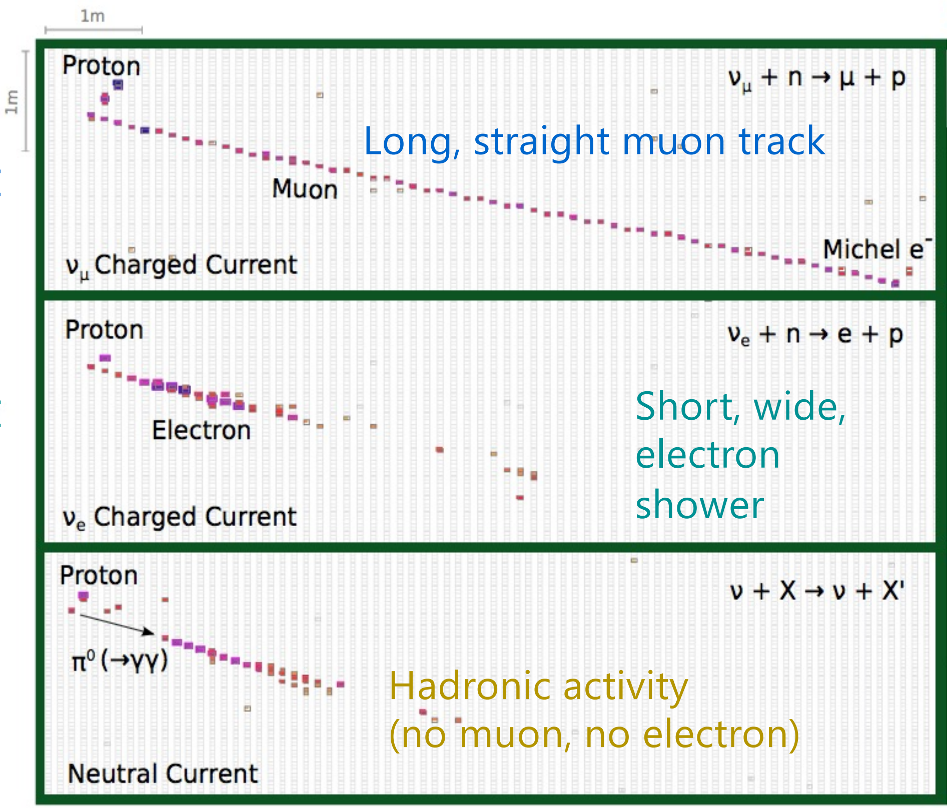


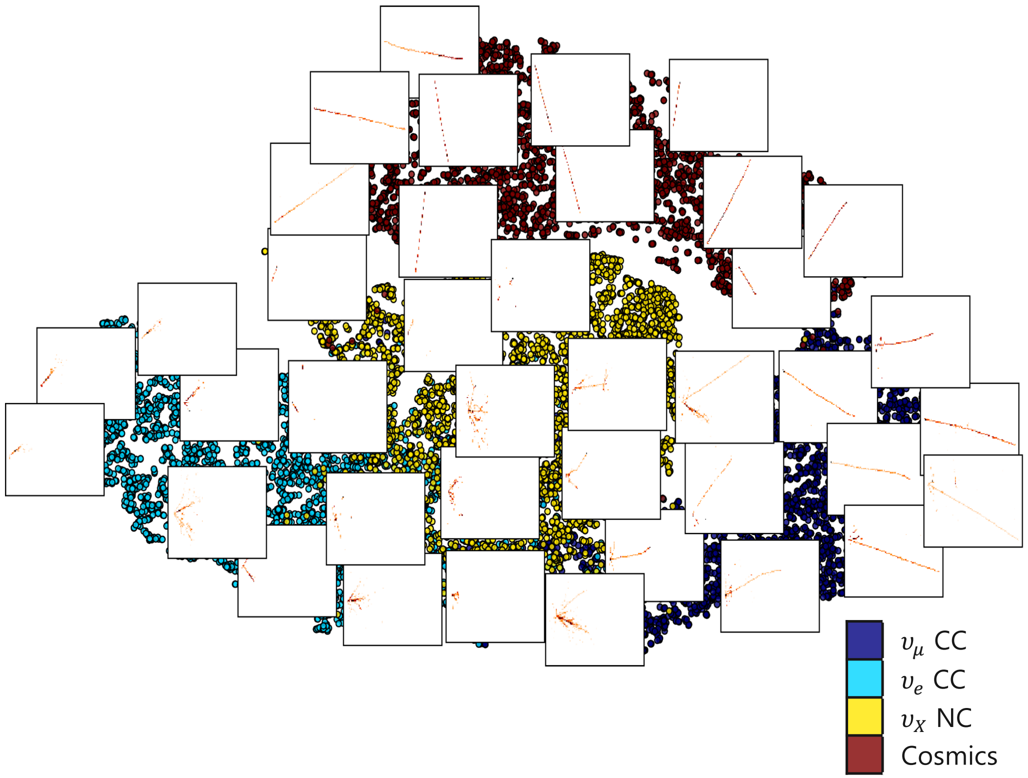
Neutrino interaction candidates are identified using a convolutional neural network (CNN)

ν_μ CC

ν_e CC

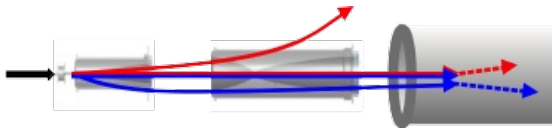
NC





Simulating events in the detector is a multi-stage process. We also use data-driven techniques to improve the predictions.

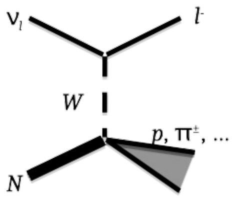
Neutrino flux



GEANT4-based simulations of particle production and transport.

Reweighted to incorporate external measurements ("PPFX")

Neutrino interactions on detector materials



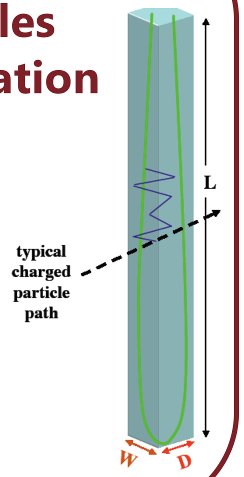
Simulated with GENIE 3.0.6.

Use a custom configuration, tuned to external data and NOvA ND Data.

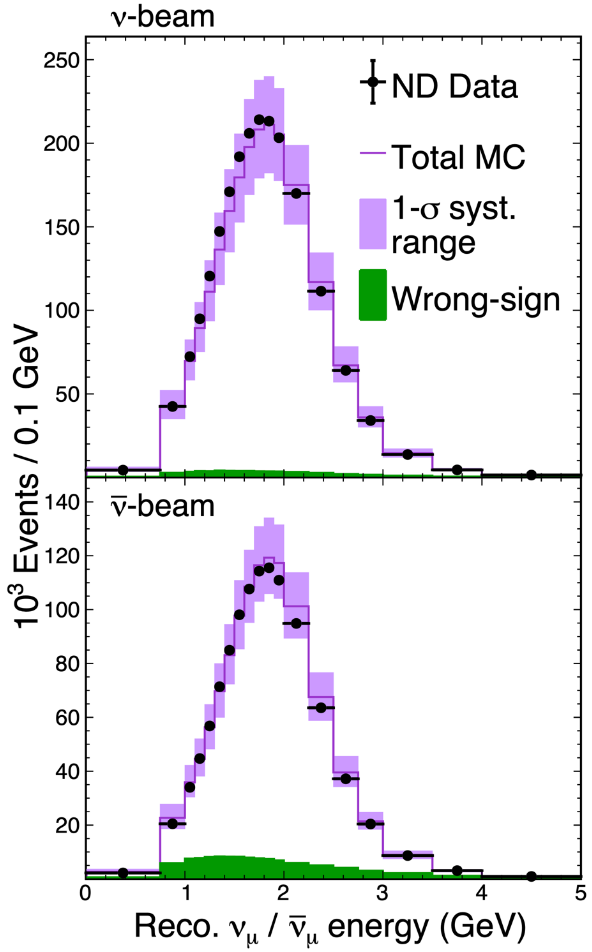
Detector response to charged particles and light propagation

Propagation of final state particles simulated with GEANT4.

Light readout and front–end electronics use a custom simulation.

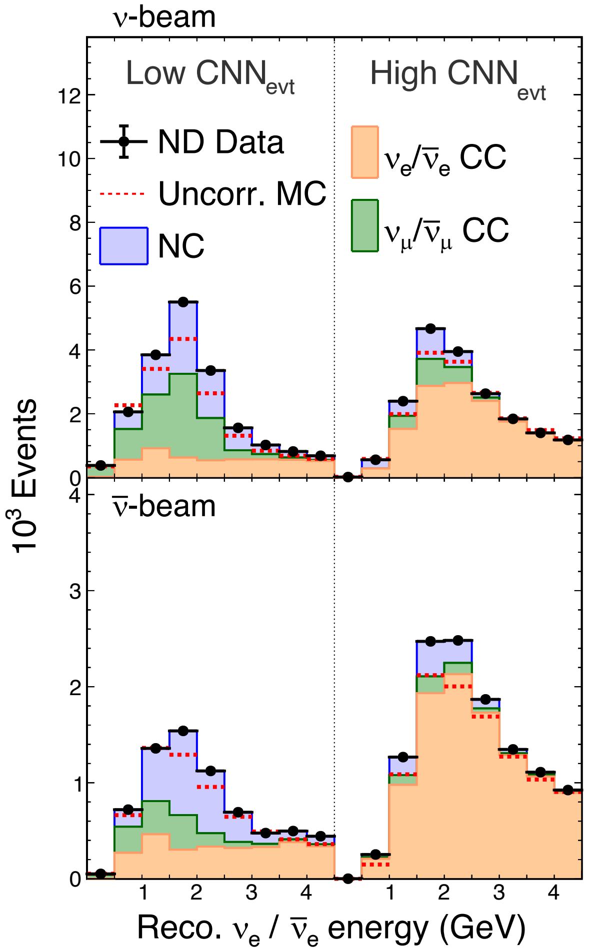


ν_μ-like and ν_e-like ND data samples are used to correct the a-priori simulated predictions of FD signal and backgrounds.

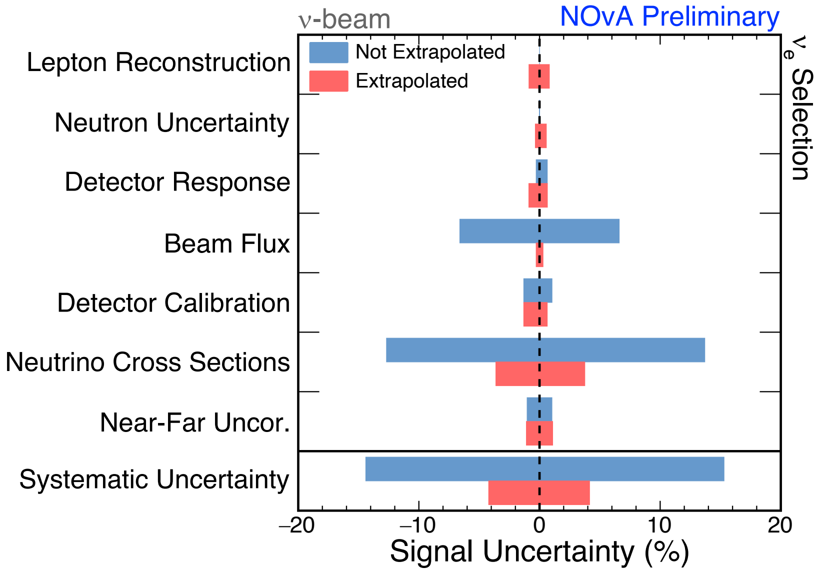


ND ν_μ-like samples are used to correct the FD $\nu_\mu \rightarrow \nu_\mu$ and $\nu_\mu \rightarrow \nu_e$ **signal** predictions

ND ν_e-like samples are used to correct the FD ν_e **background** predictions

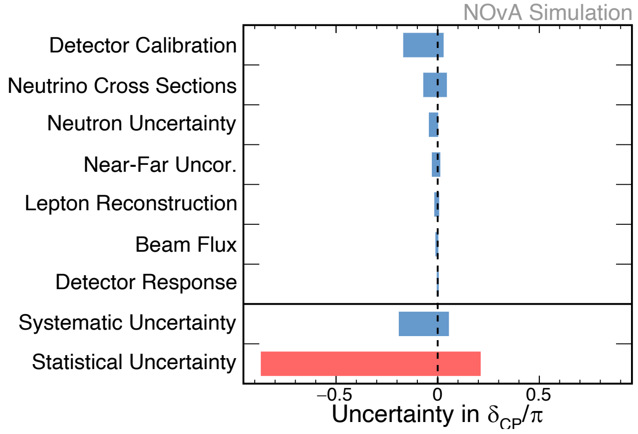


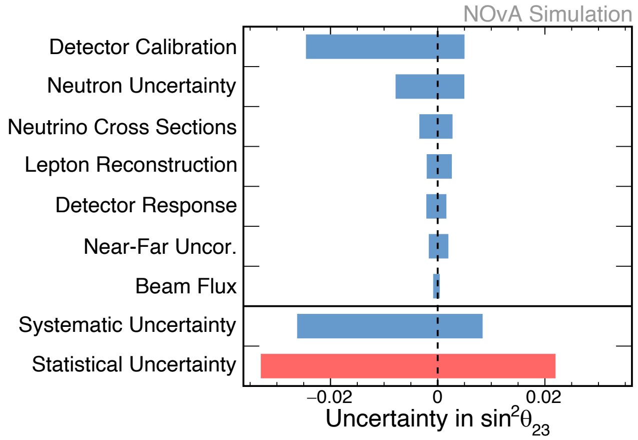
ND constraints reduce the systematic uncertainties in the FD predictions from ~15% to 4-5%. Statistical uncertainties are dominant in the oscillation measurement.



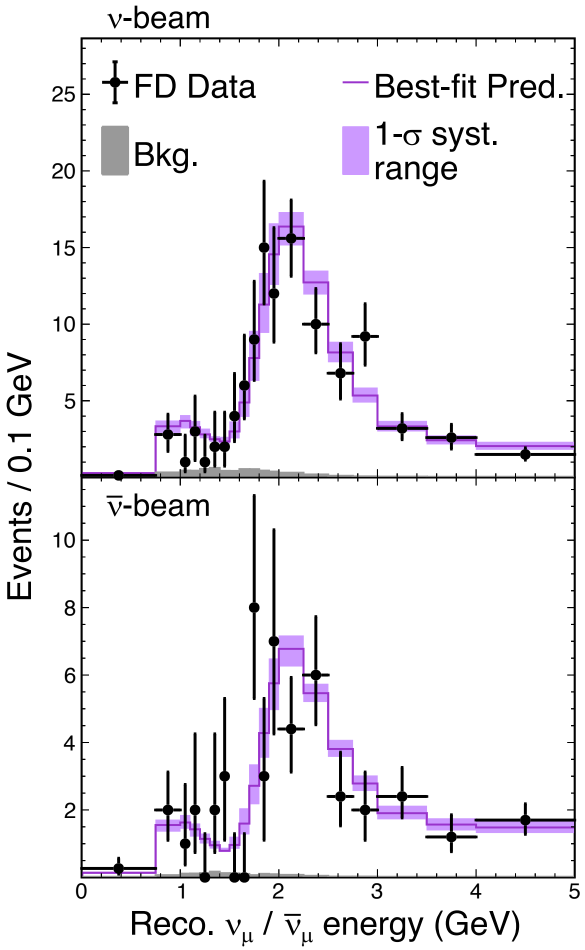
Example: Systematic uncertainties on the nue FD signal: a-priori vs improved predictions

Uncertainties on the oscillation parameters: statistical vs systematic

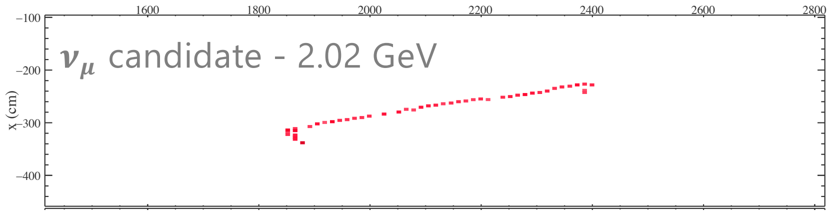


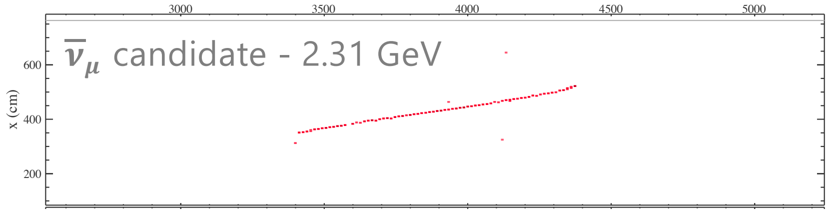


We observe 211 ν_μ and 105 $\bar{\nu}_\mu$ candidates in the FD. In the absence of oscillations, we'd expect 1153 and 488.

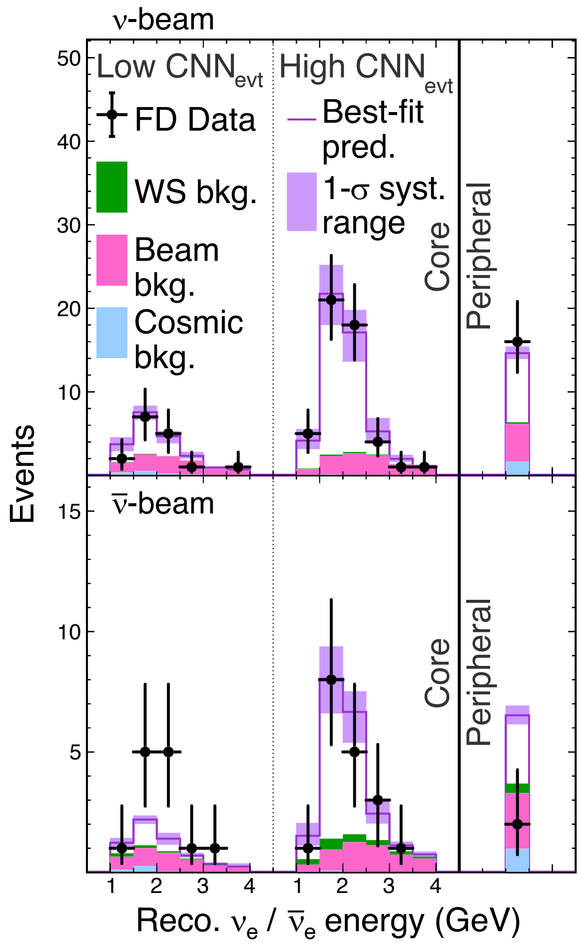


Observed	211 ν_μ	105 $\bar{\nu}_\mu$
Best fit pred.	222.3	105.4
Signal	$214.1^{+14.4}_{-14.0}$	$103.4^{+7.1}_{-7.0}$
Background	$8.2^{+1.9}_{-1.7}$	$2.1^{+0.7}_{-0.7}$

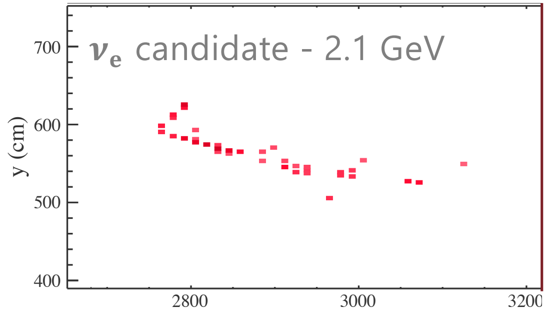




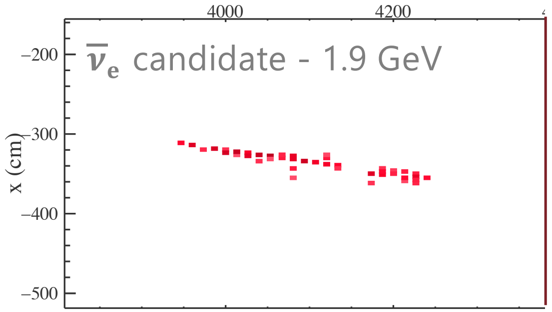
We observe 82 ν_e and 33 $\bar{\nu}_e$ appearance candidates in the FD. The predicted backgrounds are 27 and 14 respectively.



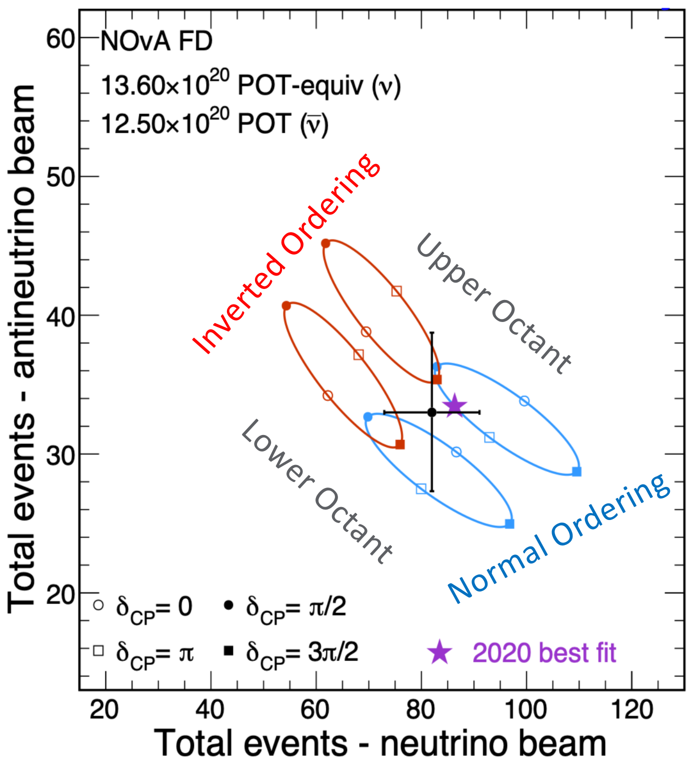
Observed	82 ν_e	33 $\bar{\nu}_e$
Best fit prediction	85.8	33.2
Signal	$59.0^{+2.5}_{-2.5}$	$19.2^{+0.6}_{-0.7}$
Background	$26.8^{+1.6}_{-1.7}$	$14.0^{+0.9}_{-1.0}$



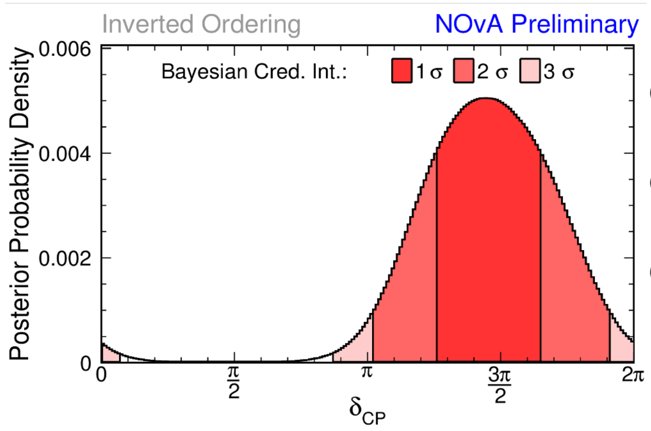
>4σ evidence of electron anti-neutrino appearance

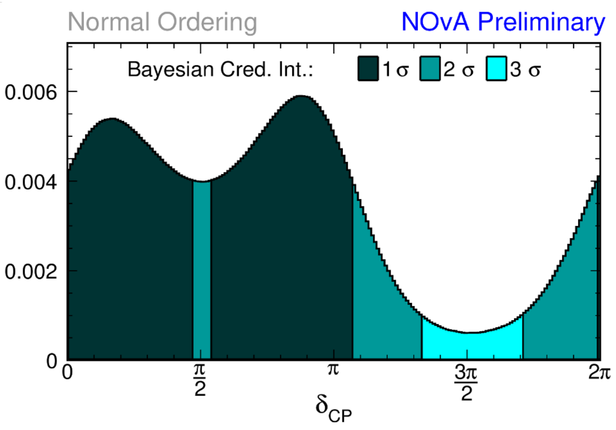


We don't see a strong asymmetry between ν_e and $\bar{\nu}_e$ appearance rates



Disfavor "extreme" asymmetry combinations:



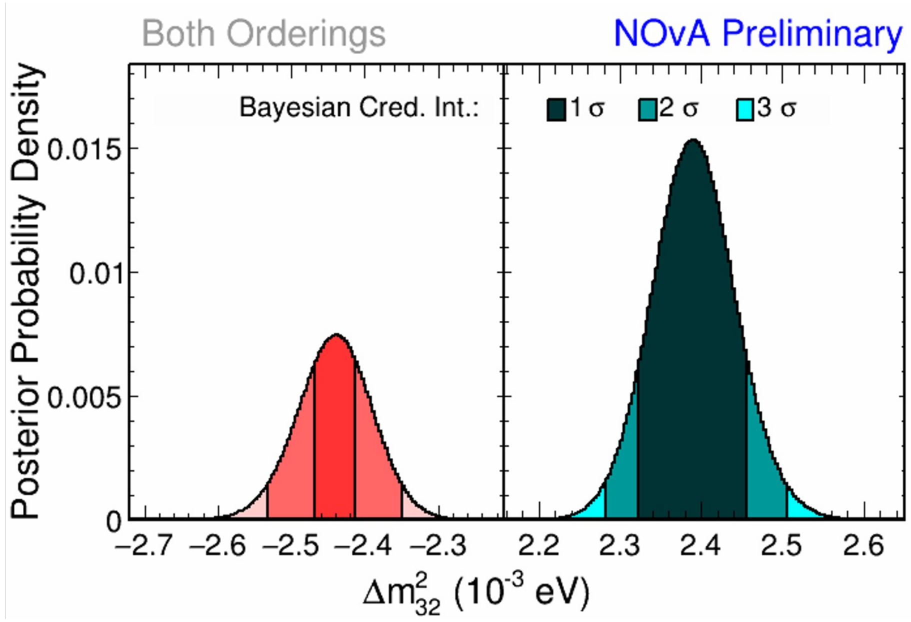


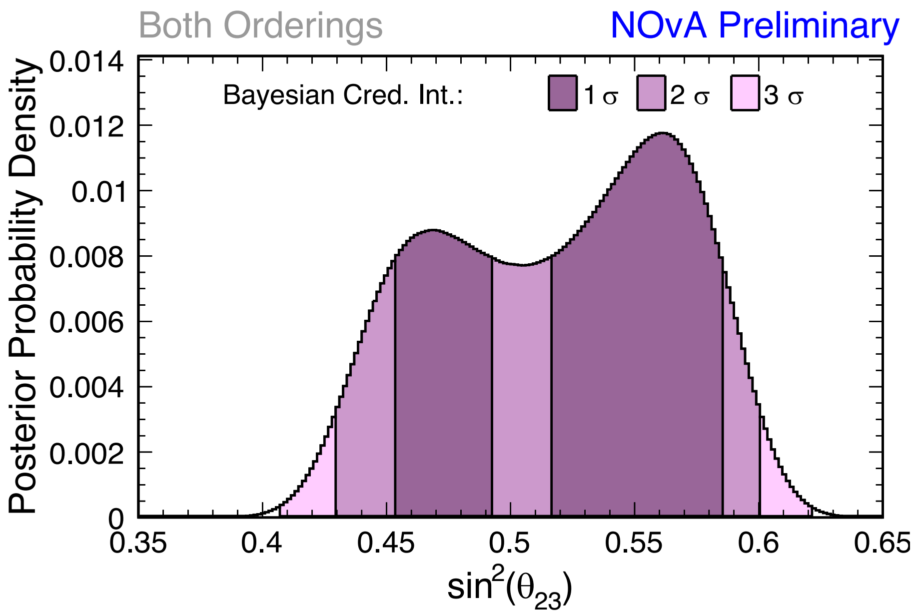
δ = π/2 outside of 3σ credible intervals (Inverted Ordering)

δ = 3π/2 outside of 2σ credible intervals (Normal Ordering)

CP violation more probable in the Inverted Mass Ordering.

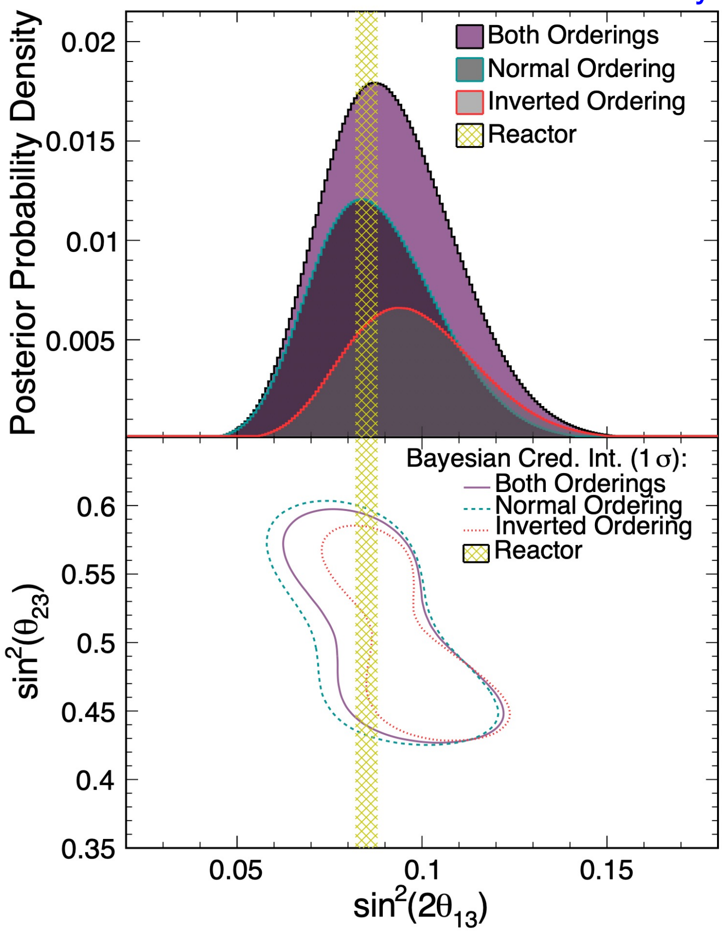
Results show a weak preference for the normal mass ordering and the upper octant of θ_{23}



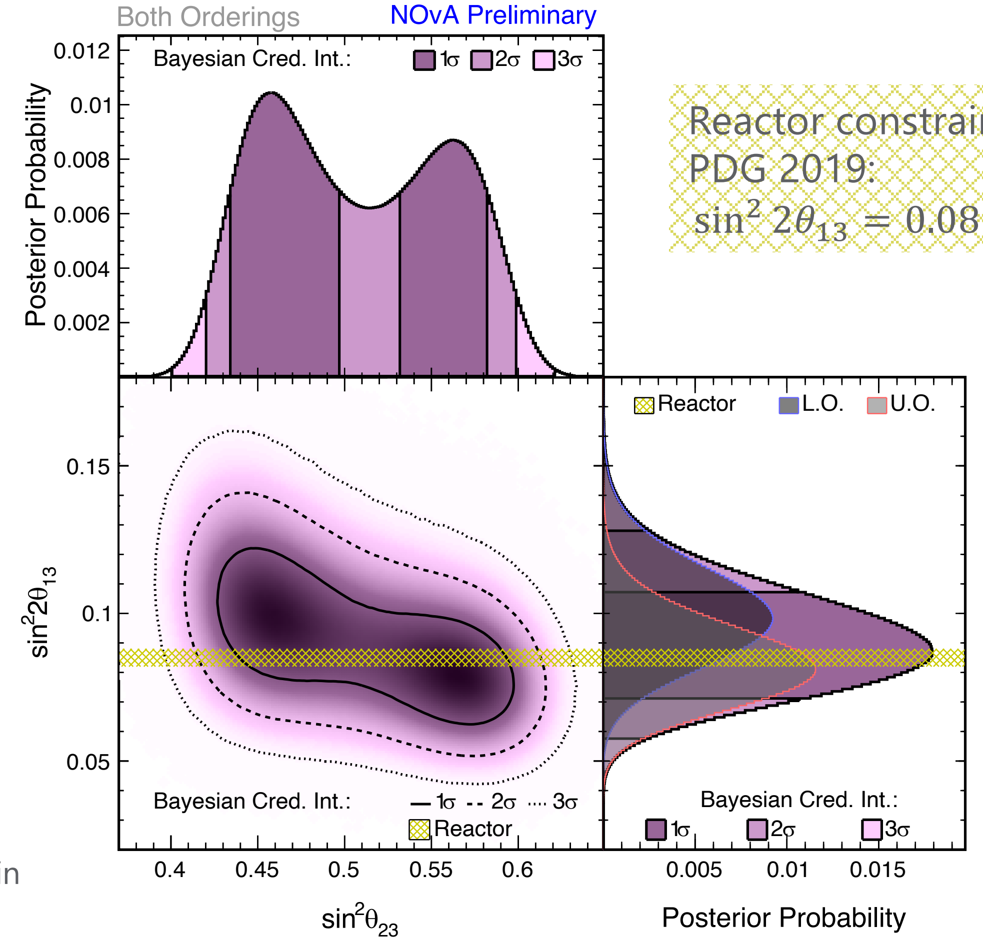


Posterior Probability	**Lower Octant**	**Upper Octant**	**Sum**
Normal Ordering	0.26	0.42	0.68
Inverted Ordering	0.11	0.21	0.32
Sum	0.37	0.63	1.00

First NOvA-only measurement of θ_{13}: $\sin^2 2\theta_{13} = 0.087^{+0.020}_{-0.016}$. The preferred value slightly changes for different {ordering, octant} combinations



Prior uniform in $\sin^2 2\theta_{13}$



Reactor constraint from PDG 2019:
$\sin^2 2\theta_{13} = 0.085 \pm 0.003$

3-Flavor+NSI analysis

Non-standard interactions (NSI) are a BSM extension of the matter effect. The phenomenology is enclosed via effective parameters $\varepsilon_{\alpha\beta}$

$$H = UH_0U^\dagger + H_{\text{matter}} + H_{\text{NSI}}$$

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

flavor-conserving

flavor-changing

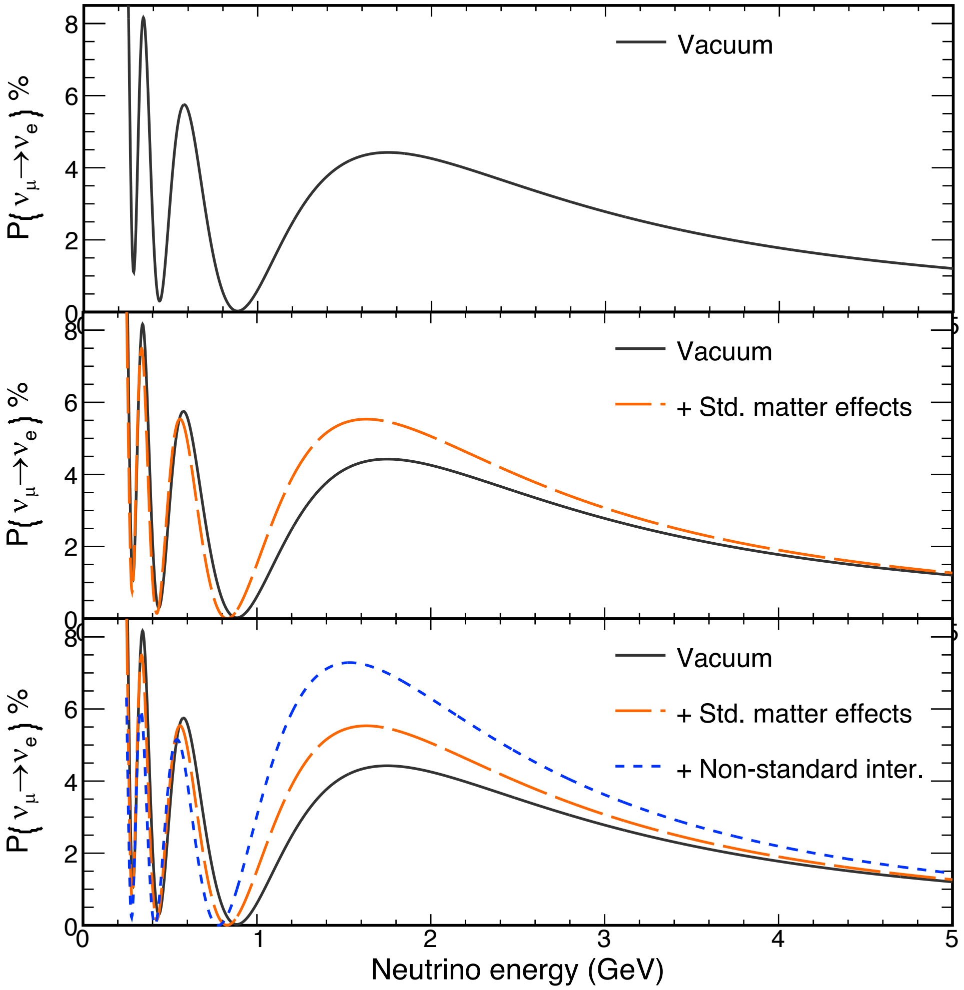
Non-standard interactions (NSI) are a BSM extension of the matter effect. The phenomenology is enclosed via effective parameters $\varepsilon_{\alpha\beta}$

$$H = U H_0 U^\dagger + H_{\text{matter}} + H_{\text{NSI}}$$

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

flavor-conserving

flavor-changing

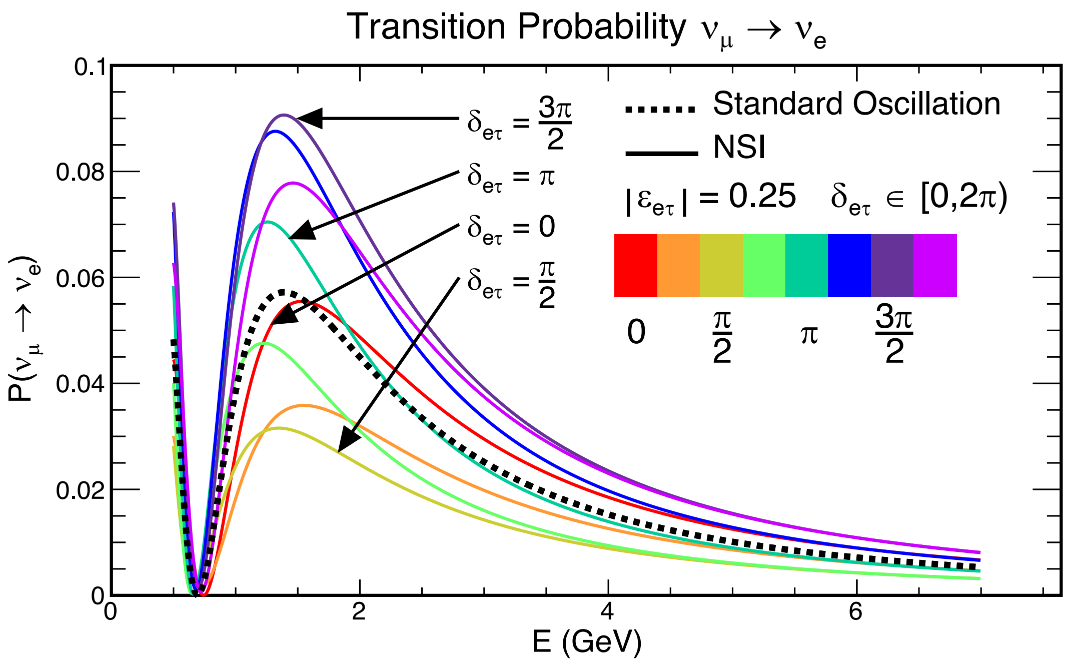


The off-diagonal complex terms introduce CP-violating phases. NOvA's $\nu_\mu \rightarrow \nu_e$ channel is sensitive to $\varepsilon_{e\mu}$ and $\varepsilon_{e\tau}$

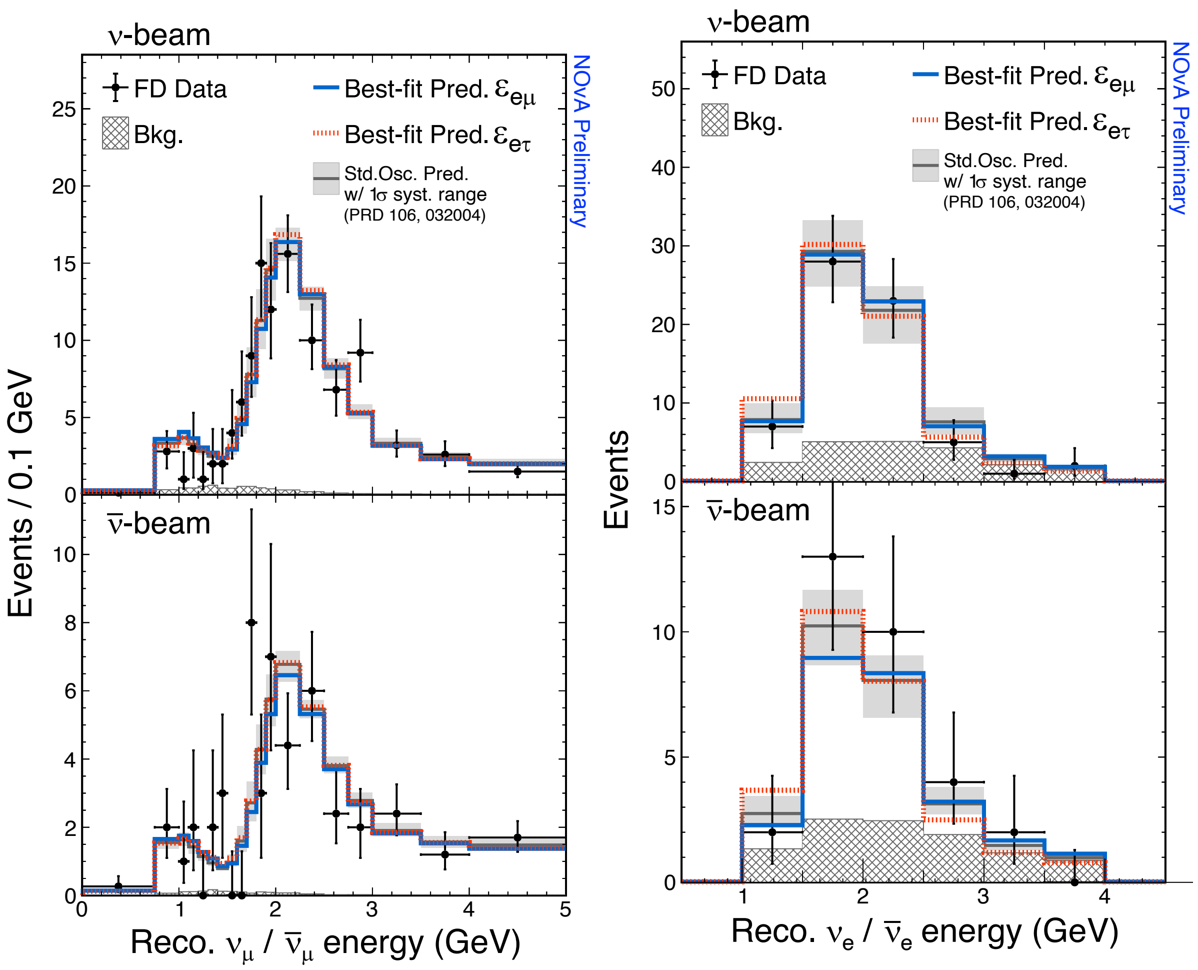
$$\varepsilon_{\alpha\beta} = |\varepsilon_{\alpha\beta}|\, e^{i\delta_{\alpha\beta}}$$

	Magnitude	Phase
$\varepsilon_{\mu\tau}$	$\lvert\varepsilon_{\mu\tau}\rvert$	$\delta_{\mu\tau}$
$\varepsilon_{e\mu}$	$\lvert\boldsymbol{\varepsilon_{e\mu}}\rvert$	$\boldsymbol{\delta_{e\mu}}$
$\varepsilon_{e\tau}$	$\lvert\boldsymbol{\varepsilon_{e\tau}}\rvert$	$\boldsymbol{\delta_{e\tau}}$

New degrees of freedom
(one row at a time)



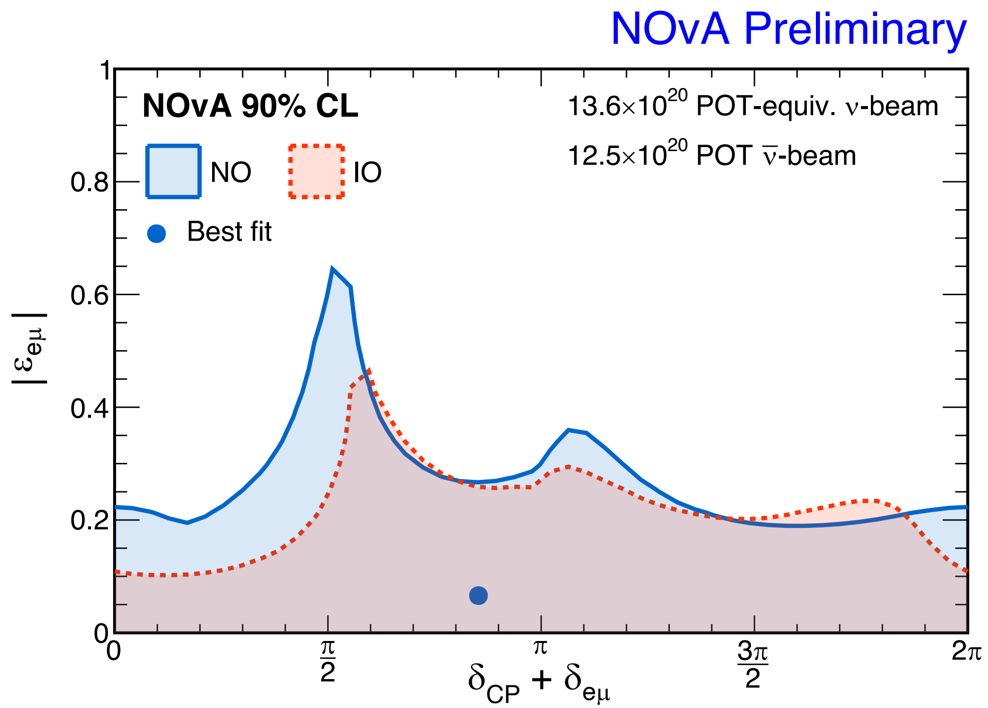
We re-analyze the data with added degrees of freedom to estimate the effect of non-zero NSI parameters $\varepsilon_{e\mu}$ and $\varepsilon_{e\tau}$

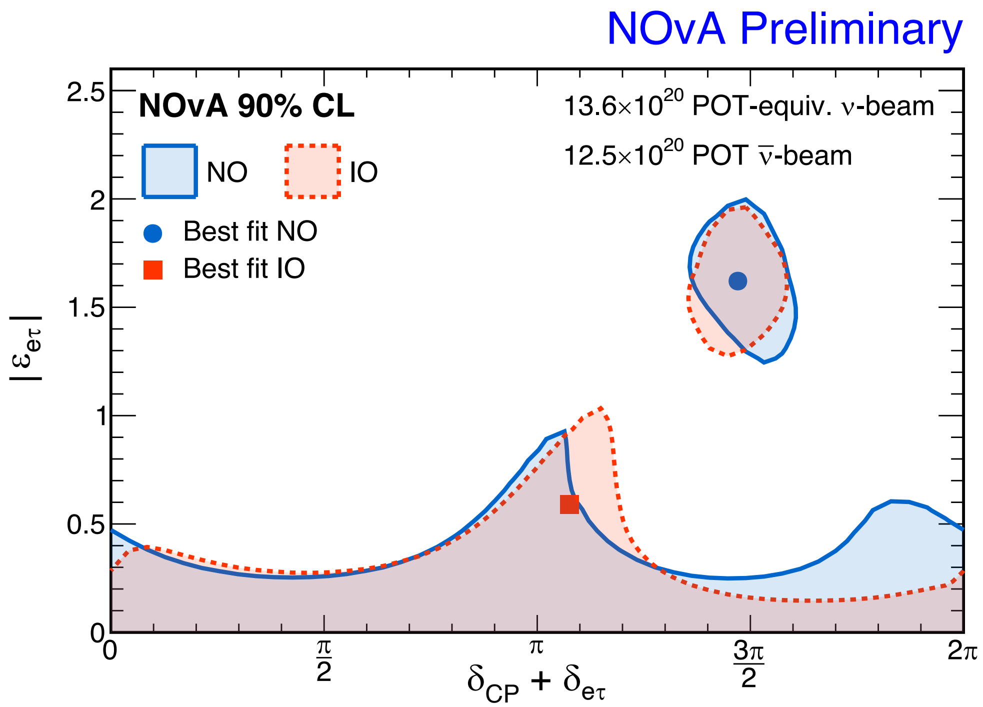


The NSI parameters $\varepsilon_{e\mu}$ and $\varepsilon_{e\tau}$ are added separately to the oscillation fit.

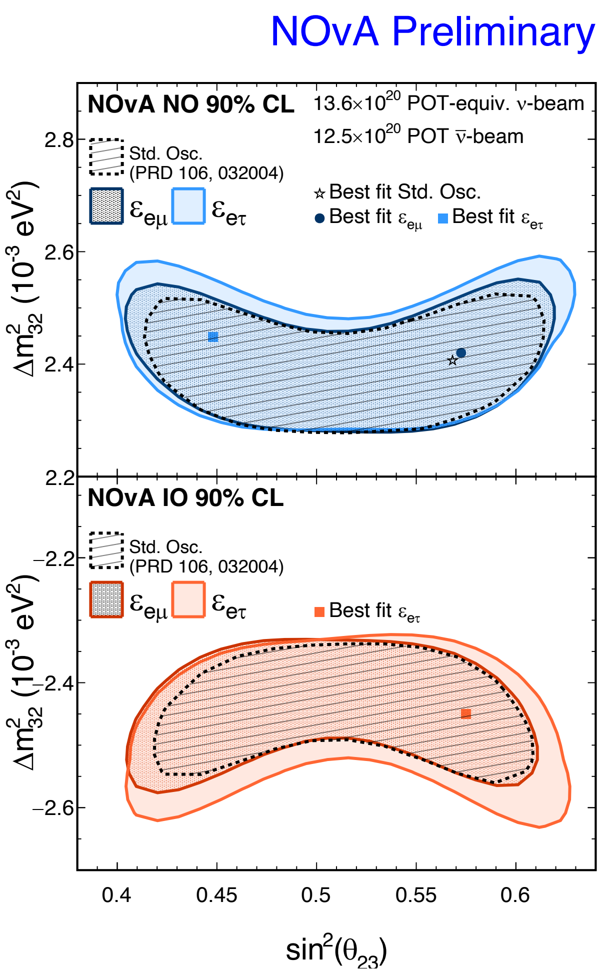
These fits to data are not significantly better than the standard oscillation result.

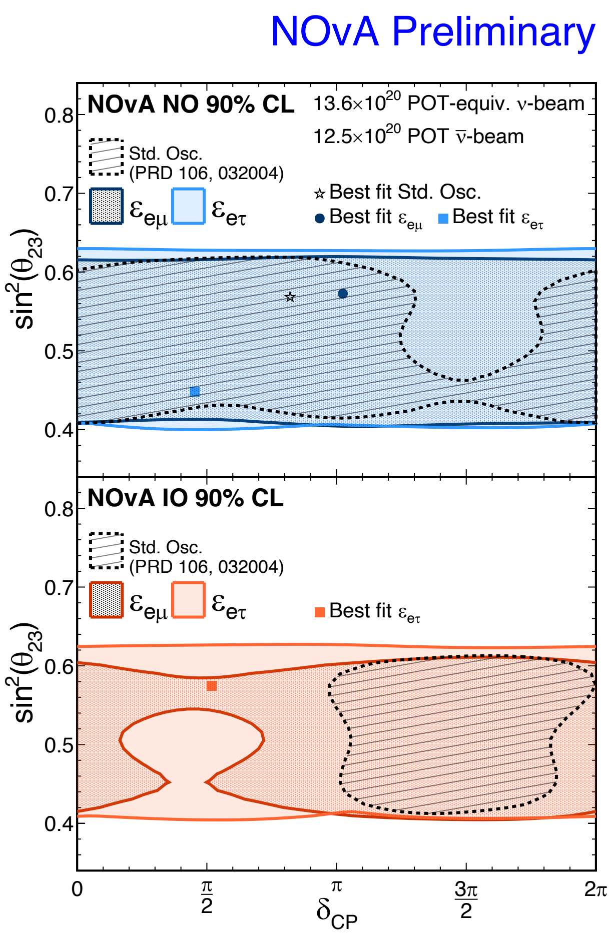
This analysis constrains the NSI parameters $|\varepsilon_{e\mu}| \lesssim 0.4$ and $|\varepsilon_{e\tau}| \lesssim 0.8$, $1.4 \lesssim |\varepsilon_{e\tau}| \lesssim 2$





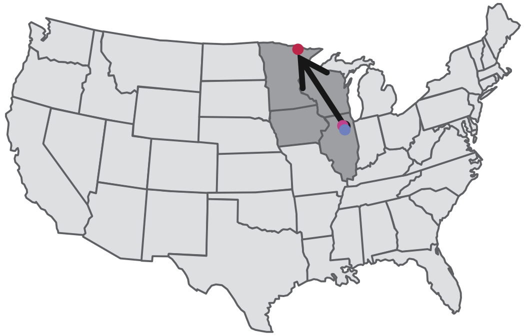
Allowing non-zero NSI parameters $\varepsilon_{e\mu}$ and $\varepsilon_{e\tau}$ can significantly affect the measurement of the standard parameters (esp. δ_{CP})



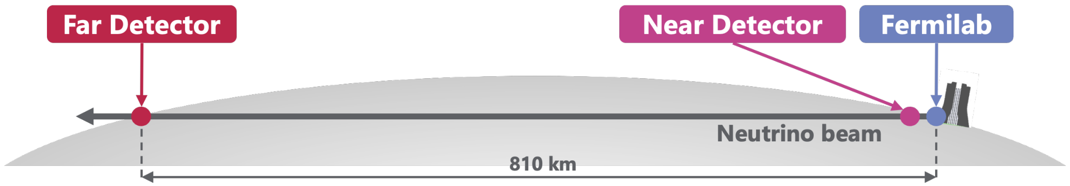


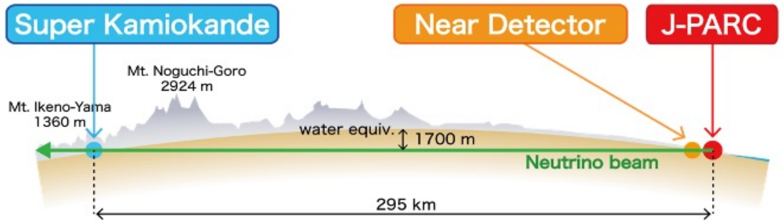
NOvA-T2K joint analysis

NOvA and T2K are accelerator neutrino experiments currently running in the US and Japan



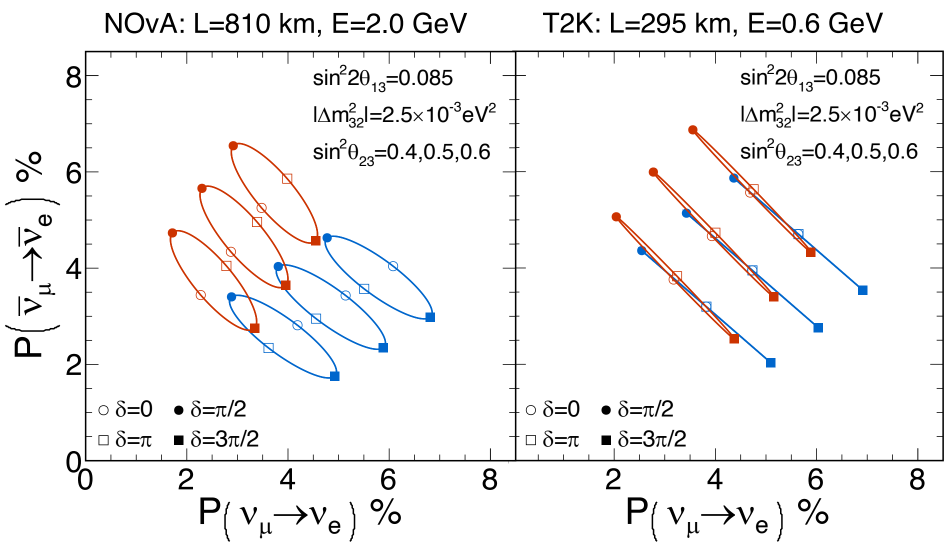
Learn about T2K in Lorenzo Magaletti's talk (today)

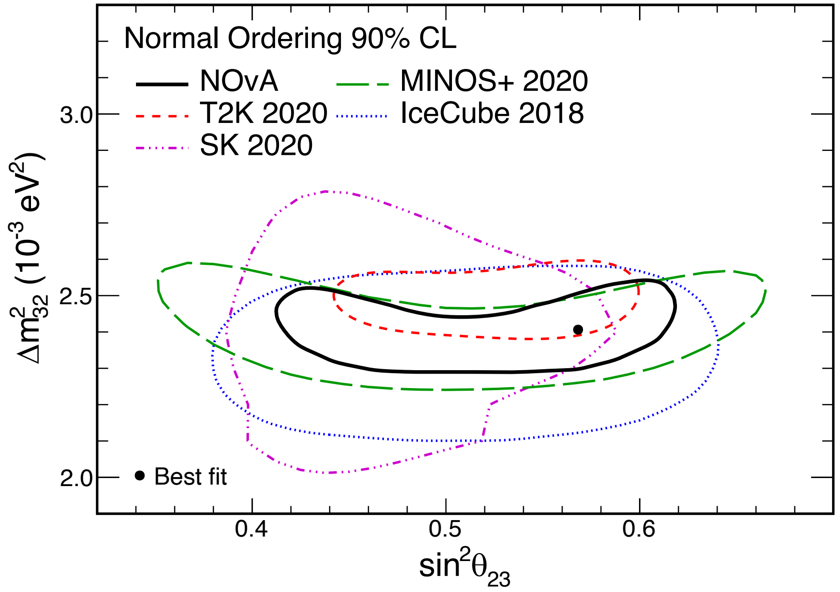




	NOvA	T2K
Baseline	810 km	295 km
Peak neutrino energy	~2 GeV	~0.6 GeV
Far Det. mass	14 kton	50 kton
Detector technique	Segmented liquid scint. cells	Water Cherenkov

NOvA and T2K have natural complementarity due to their difference in beam energies, baselines, and detector technologies.





Factor	Type	Inverts for $\bar{\nu}$?	NOvA	T2K
Matter effect (mass ordering)	Binary	Yes	±19%	±10%
CP violation	Bounded, continuous	Yes	[-22…+22]%	[-29…+29]%
θ_{23} octant	Unbounded, continuous	No	[-22…+22]%	[-22…+22]%

M. Messier. HEPAP 2017
https://science.osti.gov/hep/hepap/Meetings/201709

Our collaborations are working on a combined analysis to constrain PMNS neutrino oscillations

HUMANS OF NOvA

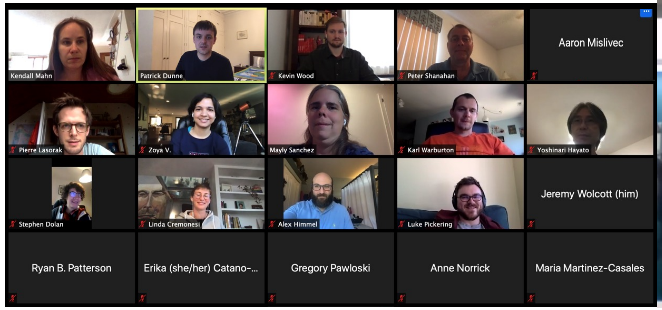
>250 collaborators
50 institutions
8 countries

HUMANS OF T2K

>500 collaborators
78 institutions
12 countries

NOvA-T2K workshop, Fermilab, Feb. 2019

WG @NOvA Collaboration Meeting, London, Feb 2023

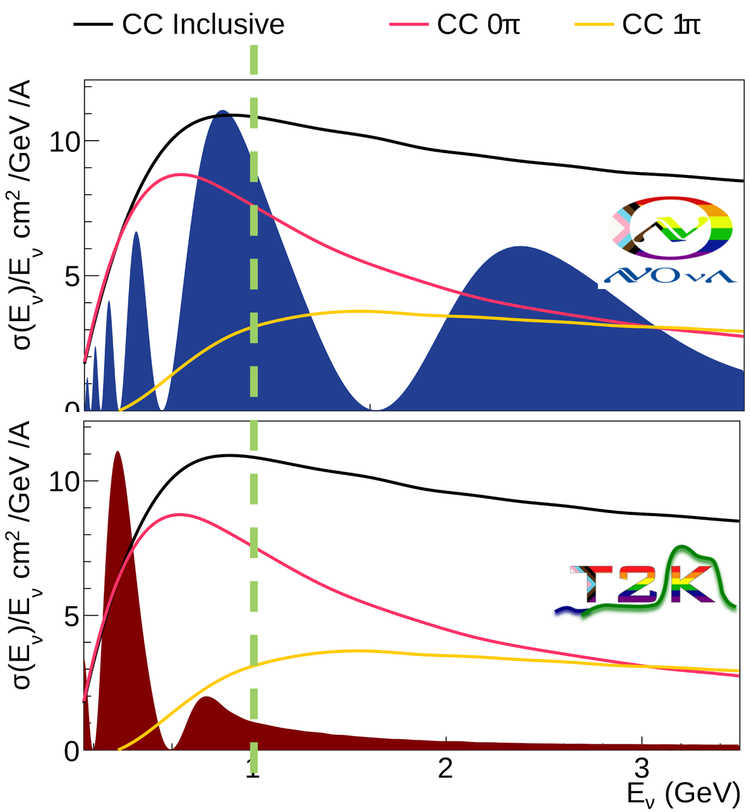


NOvA-T2K workshop, Oct. 2020

Working Group meeting, Caltech, Aug. 2022

WG @ DUNE Meeting, Sta. Marta, Sept. 2023

Advantages of a joint fit include access to each experiment’s infrastructure (e.g., model and uncertainties), and use of a consistent statistical treatment.



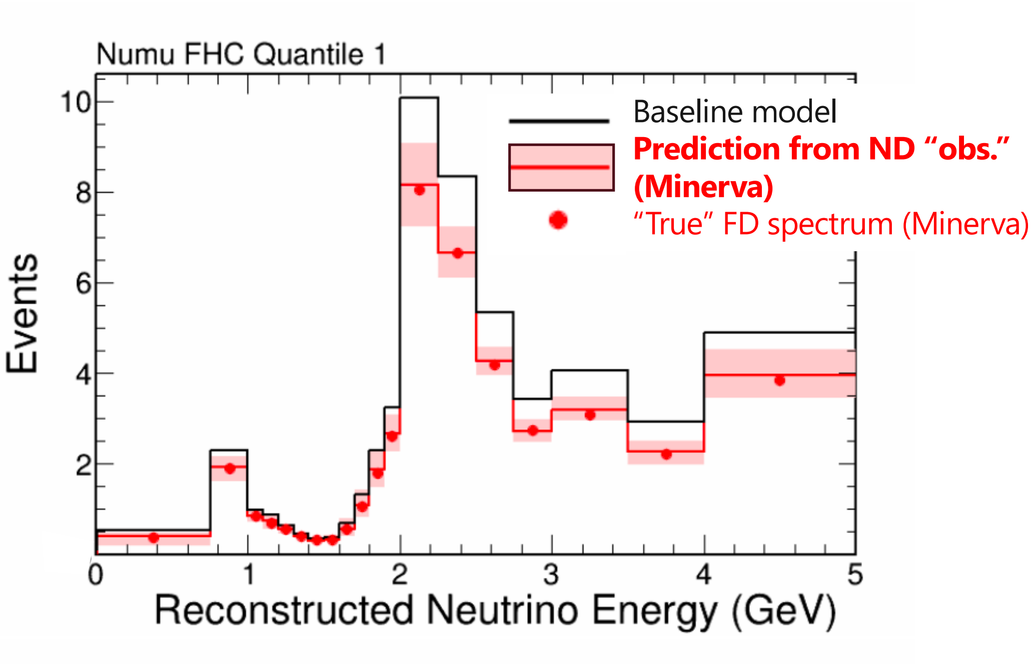
- Example surviving muon neutrino flux
- NEUT 5.3.3 predicted topological cross-sections

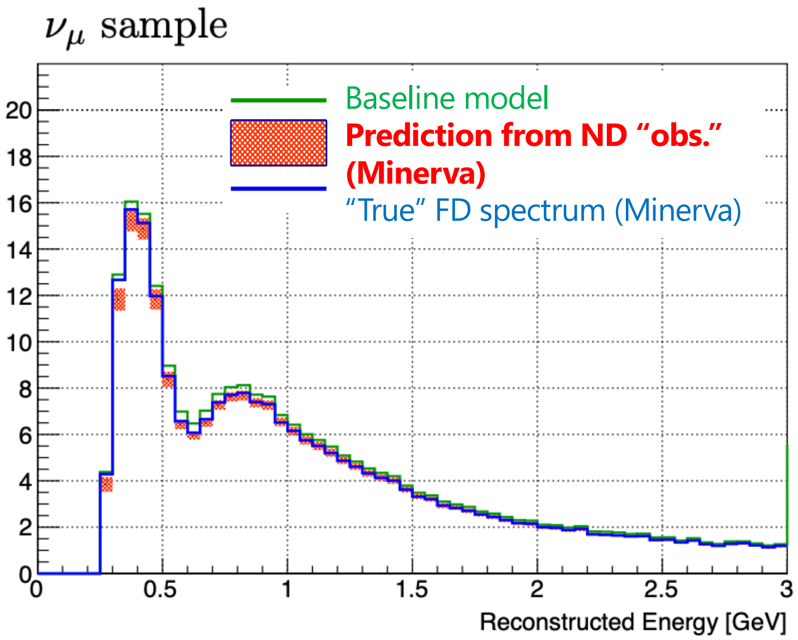
Cateogry	NOvA Parameters	T2K Parameters
CCQE	ZNormCCQE ZExpAxialFFSyst2020_EV1 ZExpAxialFFSyst2020_EV2 ZExpAxialFFSyst2020_EV3 ZExpAxialFFSyst2020_EV4 RPAShapeenh2020 RPAShapesupp2020	M_A QE Q2_norm_0 Q2_norm_1 Q2_norm_2 Q2_norm_3 Q2_norm_4 Q2_norm_5 Q2_norm_6 Q2_norm_7 EB Dial C nu EB Dial C nubar EB Dial O nu EB Dial O nubar
MEC	MECEnuShape2020Nu MECEnuShape2020AntiNu MECShape2020Nu MECShape2020AntiNu MECInitStateNPFrac2020Nu MECInitStateNPFrac2020AntiNu	2p2h Norm nu 2p2h Norm nubar 2p2h C to O 2p2h Shape C 2p2h Shape O 2p2h Edep low Enu 2p2h Edep high Enu 2p2h Edep low Enubar 2p2h Edep high Enubar

Examples of systematic knobs used by two experiments for their QE and MEC models.

See discussion by Zoya Vallari and Luke Pickering at the Neutrino Generator Workshop (March 2023)
https://indico.fnal.gov/event/57388/#30-novat2k-systematics

NOvA and T2K use their ND data to predict oscillated spectra at the FD. The robustness of the joint fit has been tested by using alternative interaction models to generate pseudo-data.



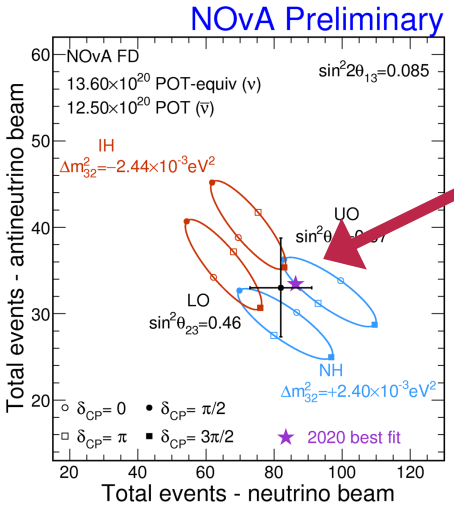


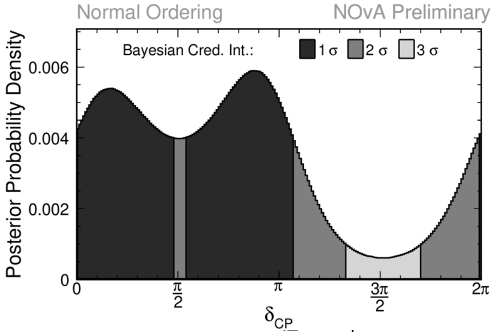
Example: tune of 1π production by the MINERvA experiment (https://doi.org/10.1103/PhysRevD.100.072005).

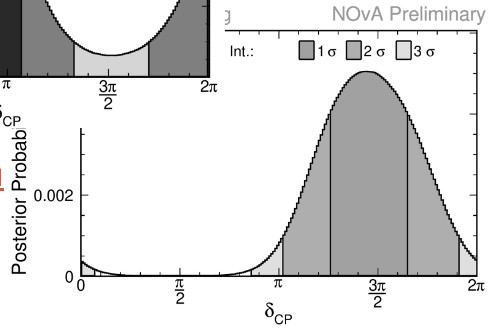
This would test a correlated change in the cross-section model impacting one topology.

Note how the ND "obs." pseudo-data pull the model toward the "true" spectrum

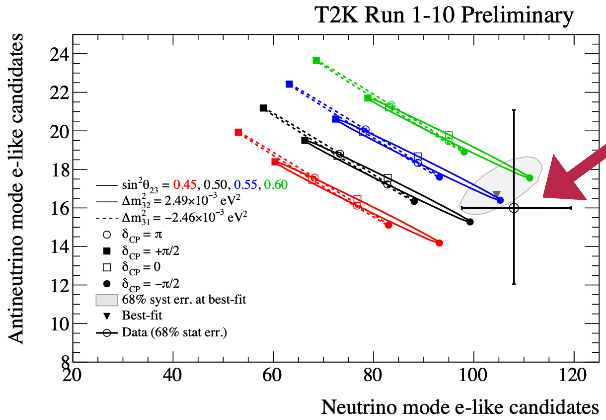
We can expect improvements in sensitivity beyond the increase in statistics from the resolved degeneracies and systematic constraints.

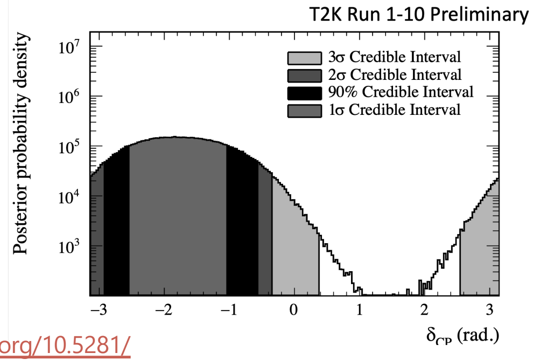






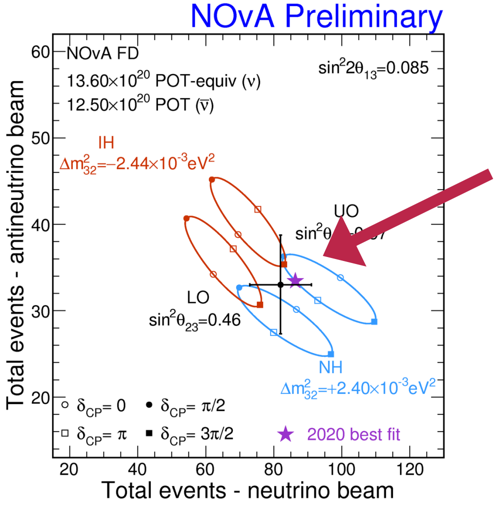
https://doi.org/10.5281/zenodo.6683827

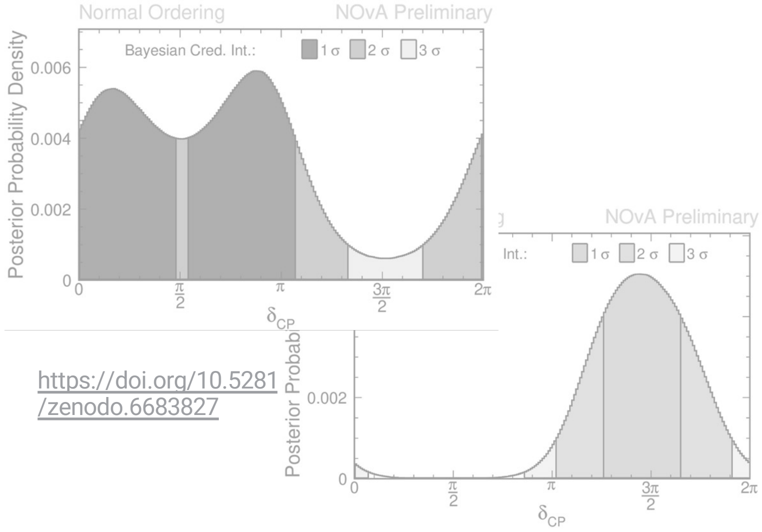




https://doi.org/10.5281/zenodo.3959558

We can expect improvements in sensitivity beyond the increase in statistics from the resolved degeneracies and systematic constraints. Stay tuned!





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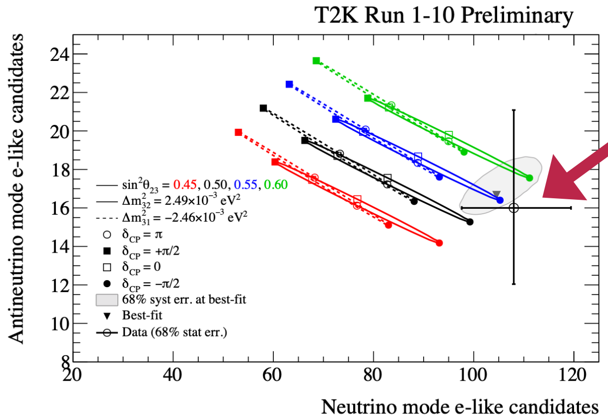

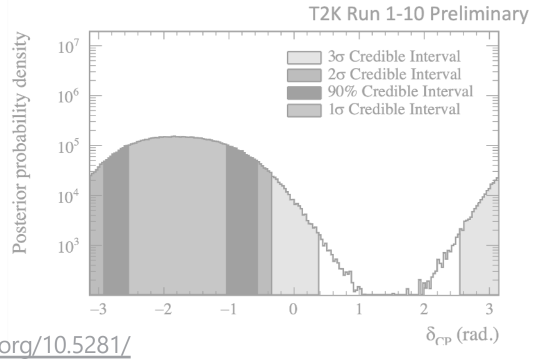

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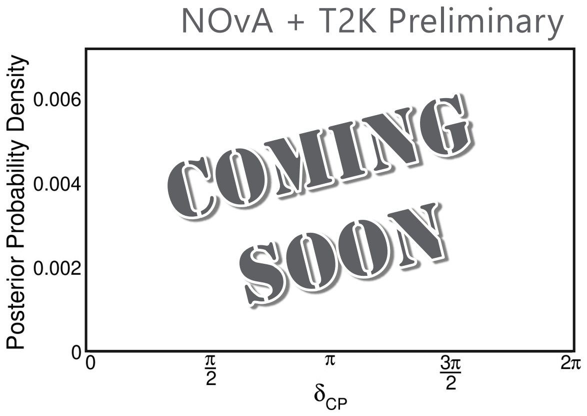

Summary

Status of NOvA's 3-flavor neutrino oscillations measurements

3F frequentist analysis	Precision measurements of Δm^2_{32} (3%) and $sin^2\,\theta_{23}$ (6%). No strong asymmetry between ν_e and $\overline{\nu}_e$ appearance rates	Neutrino 2020, JETP	10.1103/PhysRevD.106.032004
3F Bayesian analysis	First NOvA measurements of the reactor mixing angle θ_{13} and the Jarlskog invariant	Neutrino 2022, JETP	In preparation
3F+NSI	Limits on flavor-changing NC-NSI parameters $\lvert\varepsilon_{e\mu}\rvert \lesssim 0.4$ and $\lvert\varepsilon_{e\tau}\rvert \lesssim 0.8,\ 1.4 \lesssim\ \lvert\varepsilon_{e\tau}\rvert \lesssim 2$	ICHEP 2022, JETP	In preparation
NOvA-T2K	Expected increase in sensitivity from the combination of two experiments' datasets	TBD	TBD
Upcoming 3F analysis	Expected increase in sensitivity from 2X more neutrino-beam exposure	TBD	TBD
	Switching back to anti-neutrino beam mode in 2024. NOvA will continue running through 2026.		

Even more from NOvA! cross-section analyses, sterile neutrino searches, non-beam physics, Test Beam program

Grazie!

NOvA Collaboration Meeting
UC Irvine, February 2023

NOvA-T2K Working Group Meeting
Caltech, August 2022