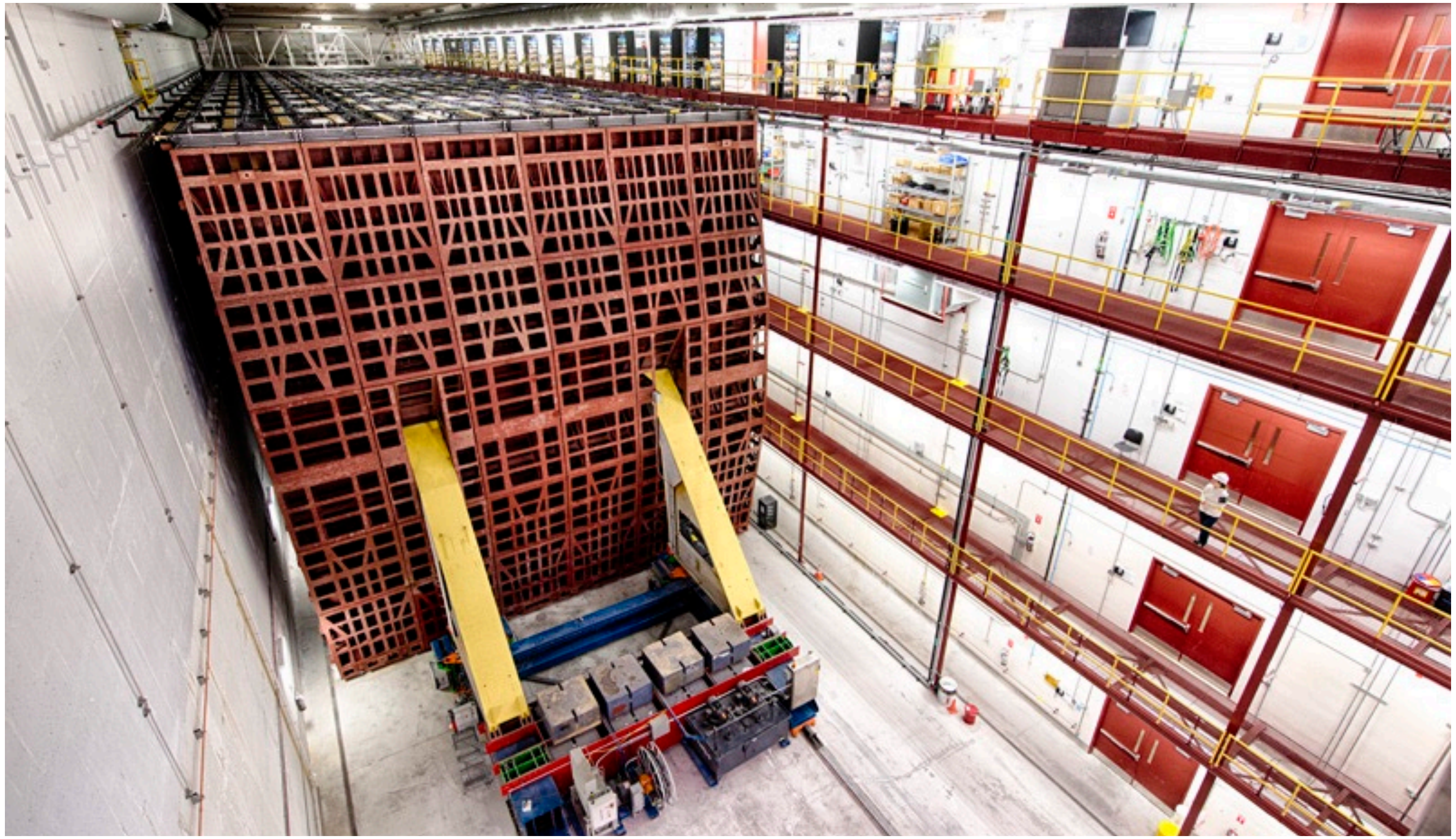
New 3-flavor neutrino oscillation results from NOvA



Erika Catano-Mur

William & Mary

NOvA Collaboration

Fermilab JETP

June 28th, 2024

2024 marks the 10th anniversary of NOvA's data collection, and the first analysis adding new data since 2020

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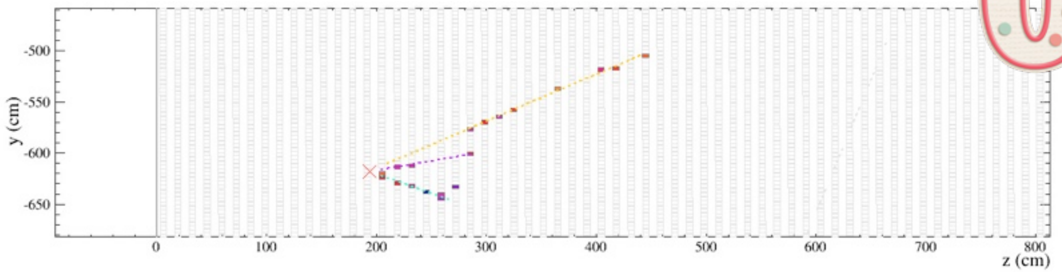
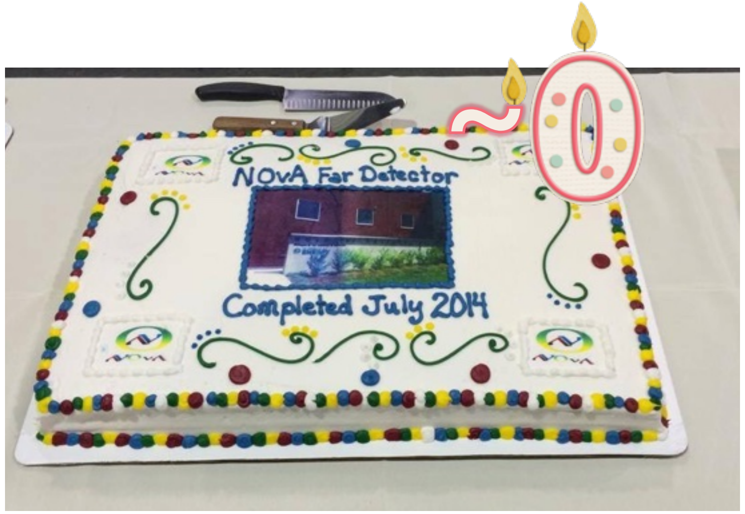
February 5th, 2014 – NOvA's Period 1 data taking began with run 12941 at 11:57 pm



February 11, 2014 - NOvA "1st Neutrino Event" Celebration in the Main Control Room

(No evidence of cake at this event)

10 years, many milestones, a few cakes…

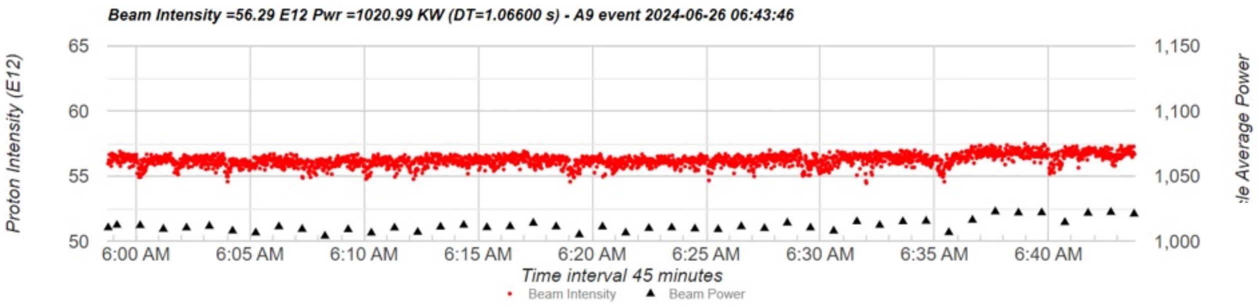


July 2014 –
FD completed

April 2015 –
"Gary-fest"

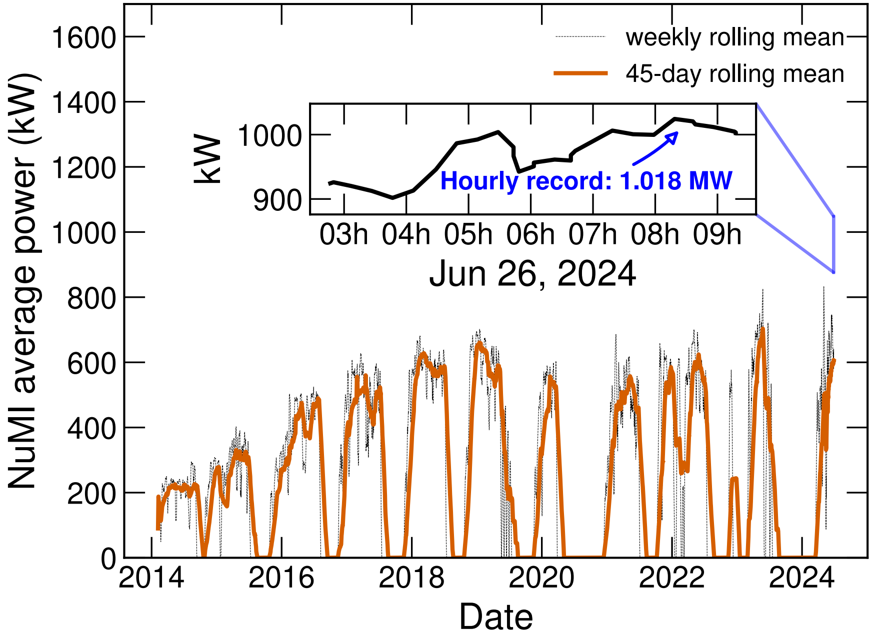
February 2017 –
NuMI 700 kW

Earlier this week (Wednesday, June 26th) the power delivered to NuMI surpassed 1MW for ~3 hrs!!!



New one-hour power record is

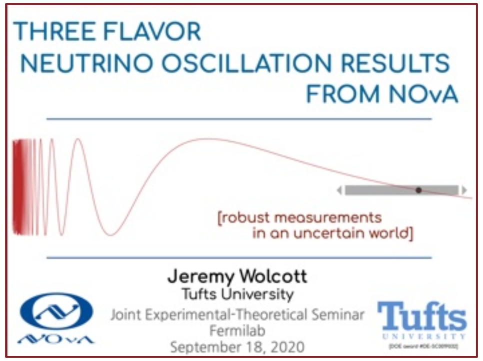
1.018 MW!



The NOvA collaboration currently consists of more than 200 scientists and engineers from 50 institutions in eight countries.

The NOvA collaboration currently consists of more than 200 scientists and engineers from 50 institutions in eight countries. Many more have contributed over the years…

The “2020” dataset - with 6 years of NOvA data - has generated many interesting results

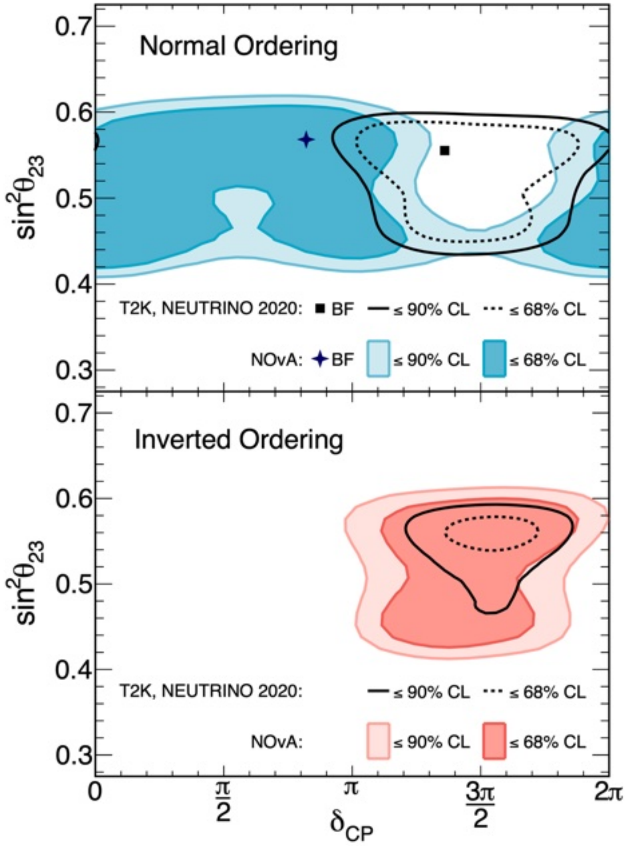


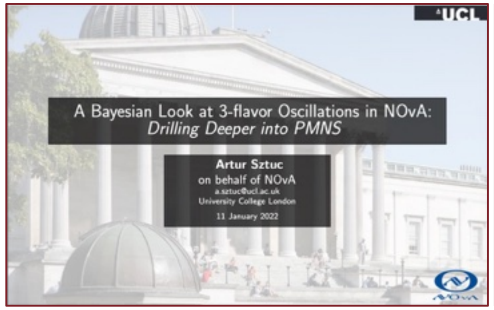
2020 analysis

Neutrino 2020, July 2nd, 2020

JETP Sept. 18, 2020

PhysRevD.106.032004

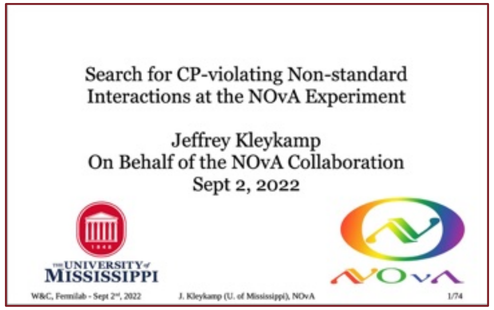




Bayesian analysis

JETP Jan. 11, 2022

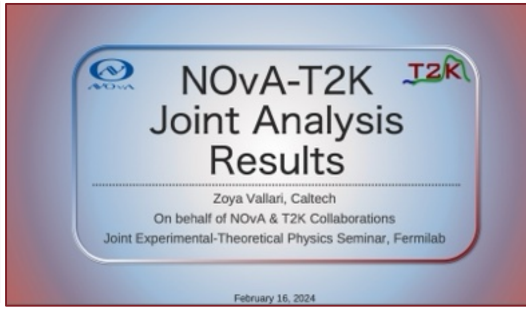
arXiv:2311.07835



NSI analysis

JETP Sept. 2, 2022

arXiv:2403.07266

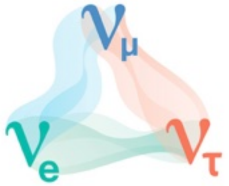


NOvA-T2K joint analysis

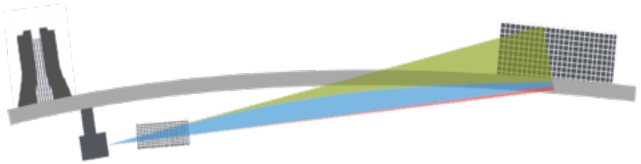
JETP Feb. 16, 2024

Today: we'll discuss NOvA's 3-flavor neutrino oscillation analysis, and the new results with 10 years of data

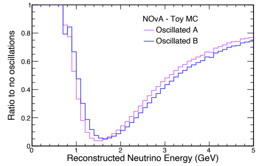
1. 3-flavor neutrino oscillations



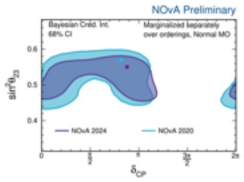
2. The NOvA Experiment



3. Building an oscillation analysis

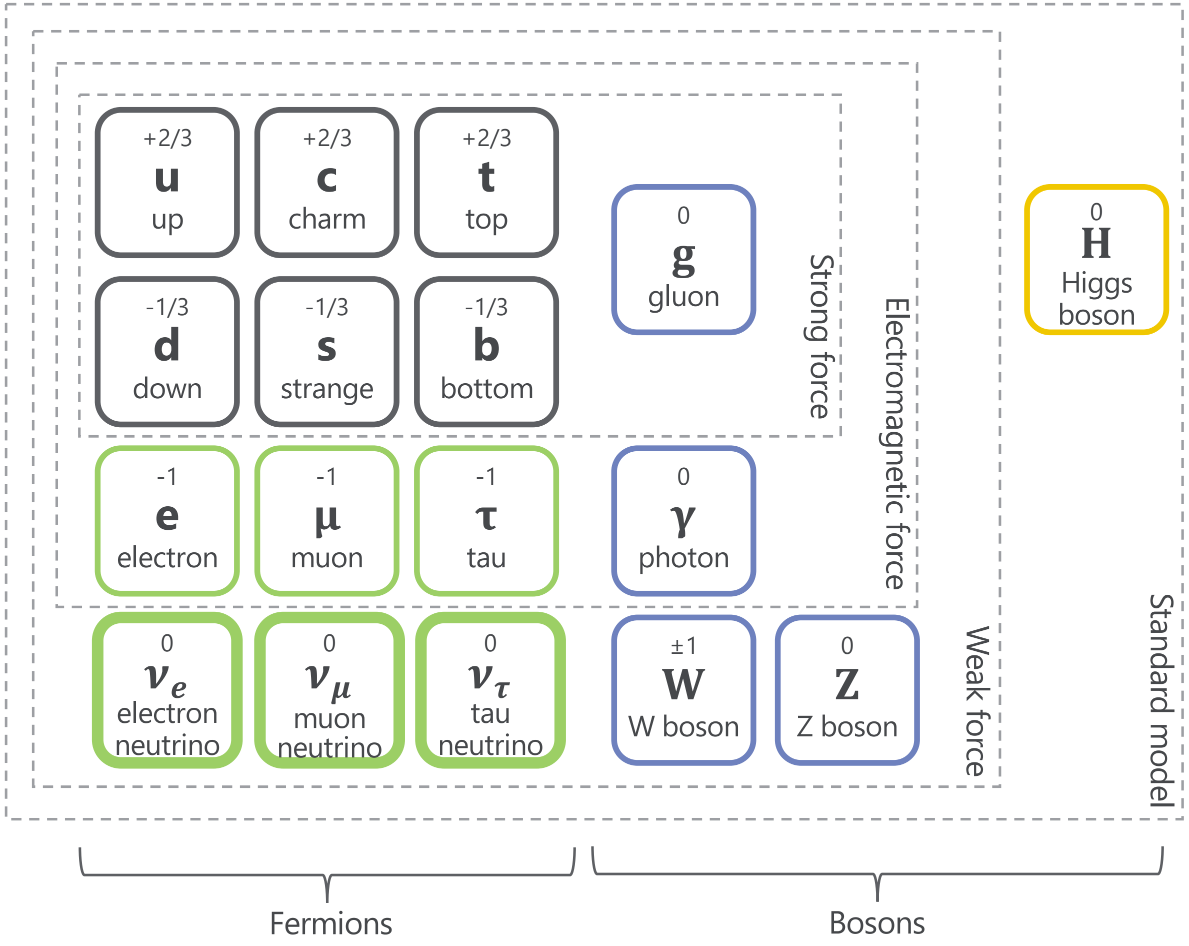


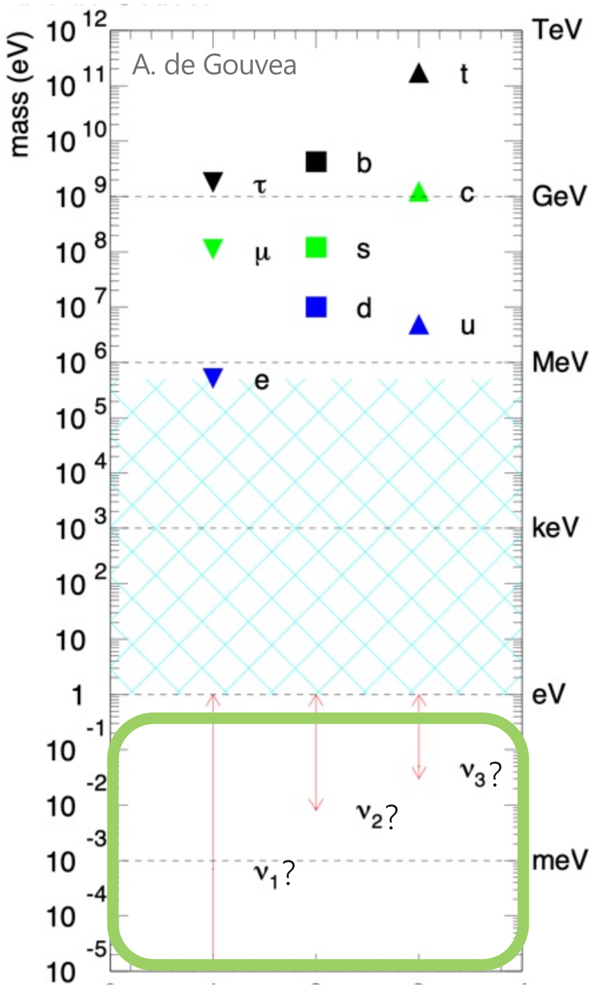
4. New results!



3-flavor neutrino oscillations

Neutrinos are fundamental particles. They are fermions that do not have strong nor electromagnetic interactions, and have unusually small masses relative to their charged partners





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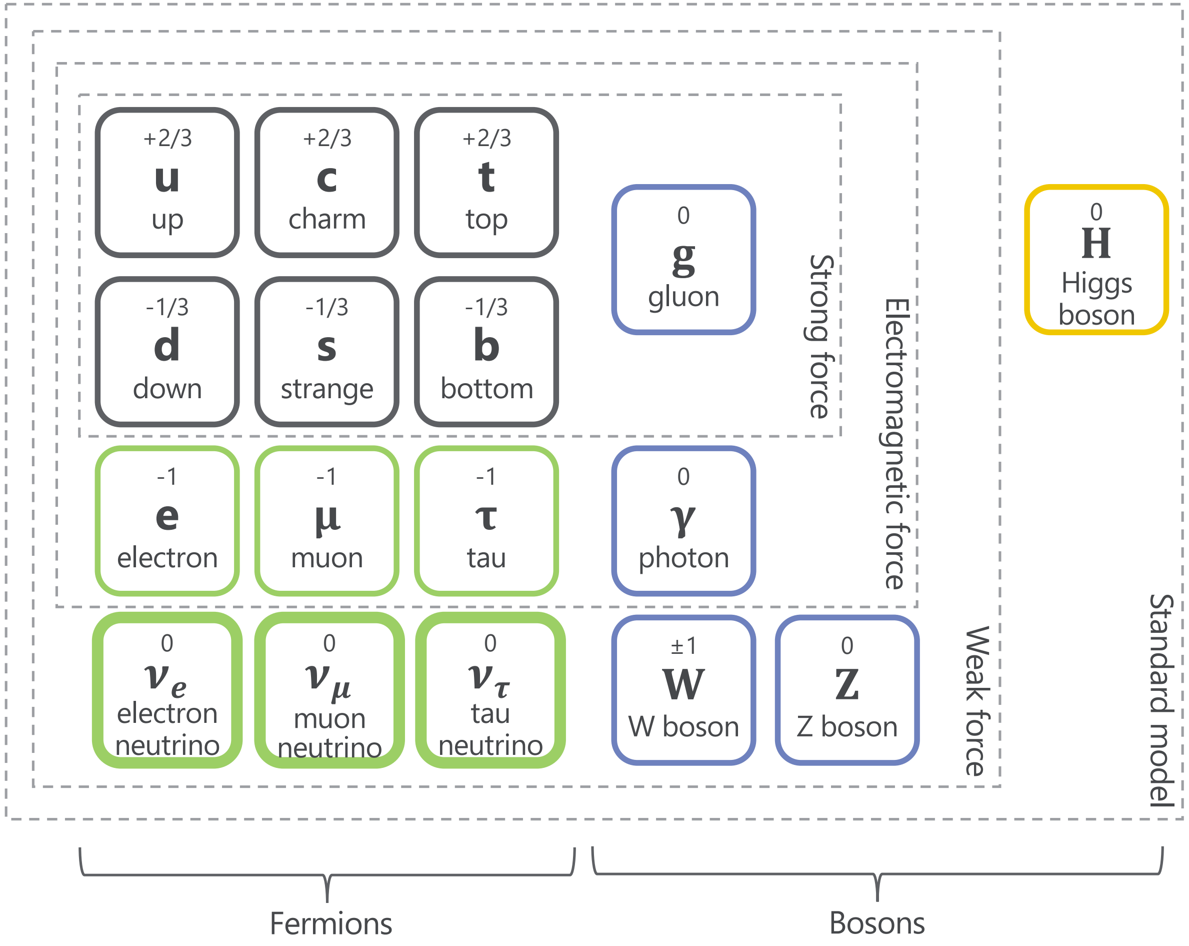
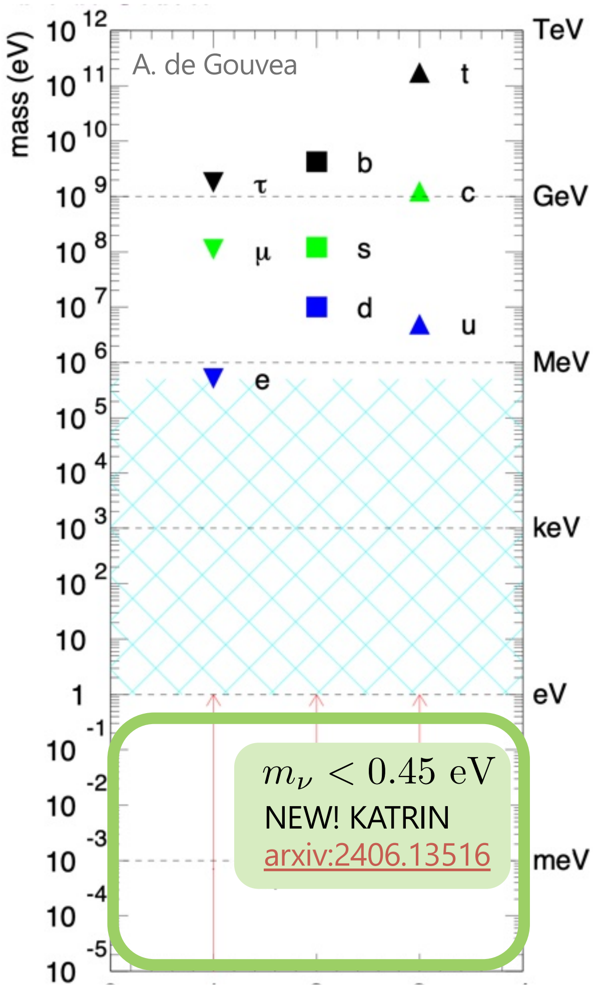
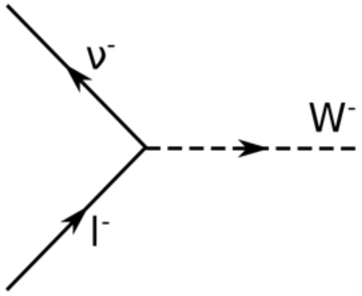


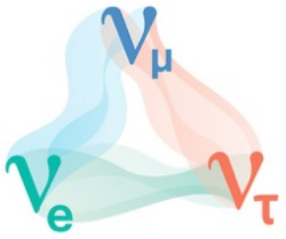


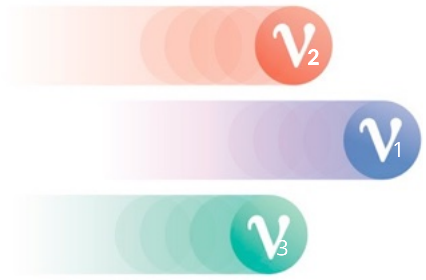
The neutrino flavor eigenstates are related to the mass eigenstates by the PMNS unitary mixing matrix

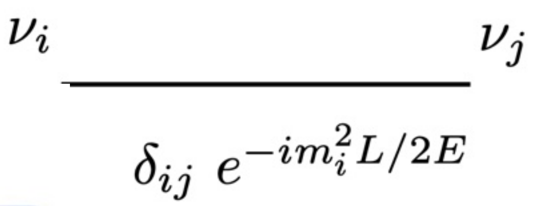
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Flavor states (interaction) | Mixing matrix | Mass states (propagation)

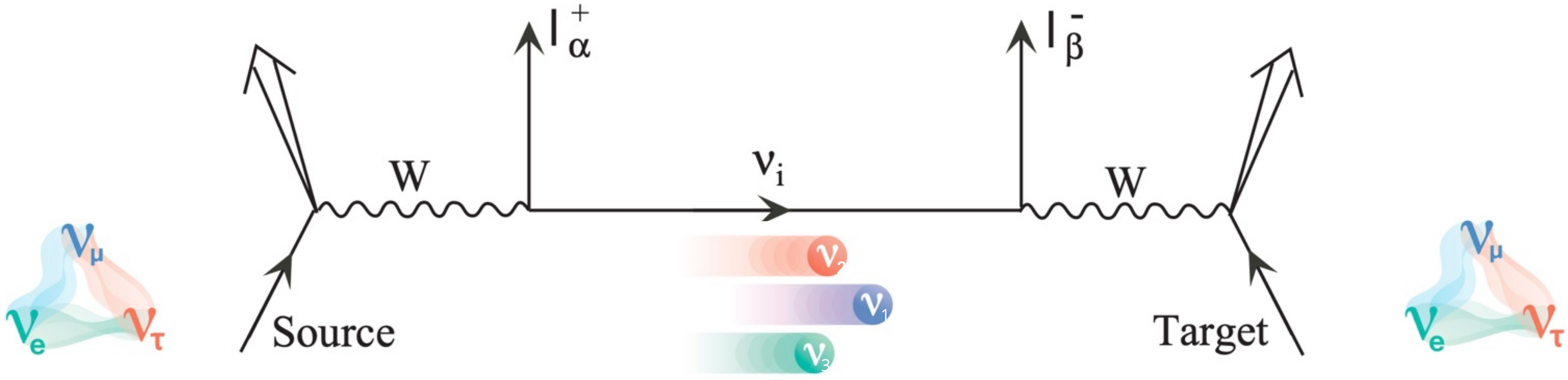








3-flavor neutrino oscillations are transitions in-flight between the flavor neutrinos, caused by non-zero neutrino masses and neutrino mixing

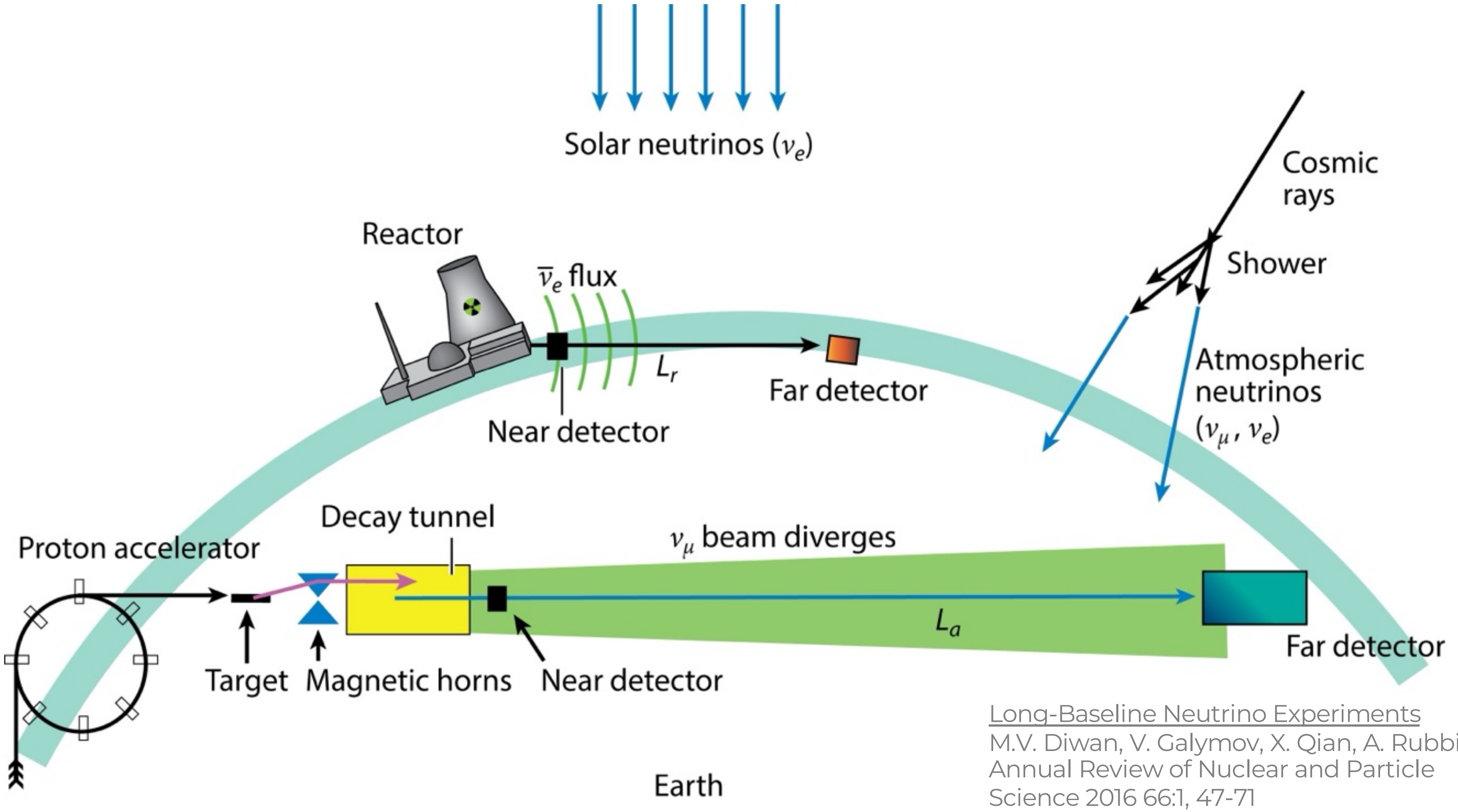


$$P(\nu_\alpha \to \nu_\beta) = \left| \sum_i U^*_{\alpha i} e^{-i\frac{m_i^2 L}{2E}} U_{\beta i} \right|^2$$

Oscillatory in distance $L^{\text{osc}}_{0,ij} = \frac{4\pi E}{|\Delta m^2_{ij}|}$

Amplitudes proportional to products of elements in the mixing matrix

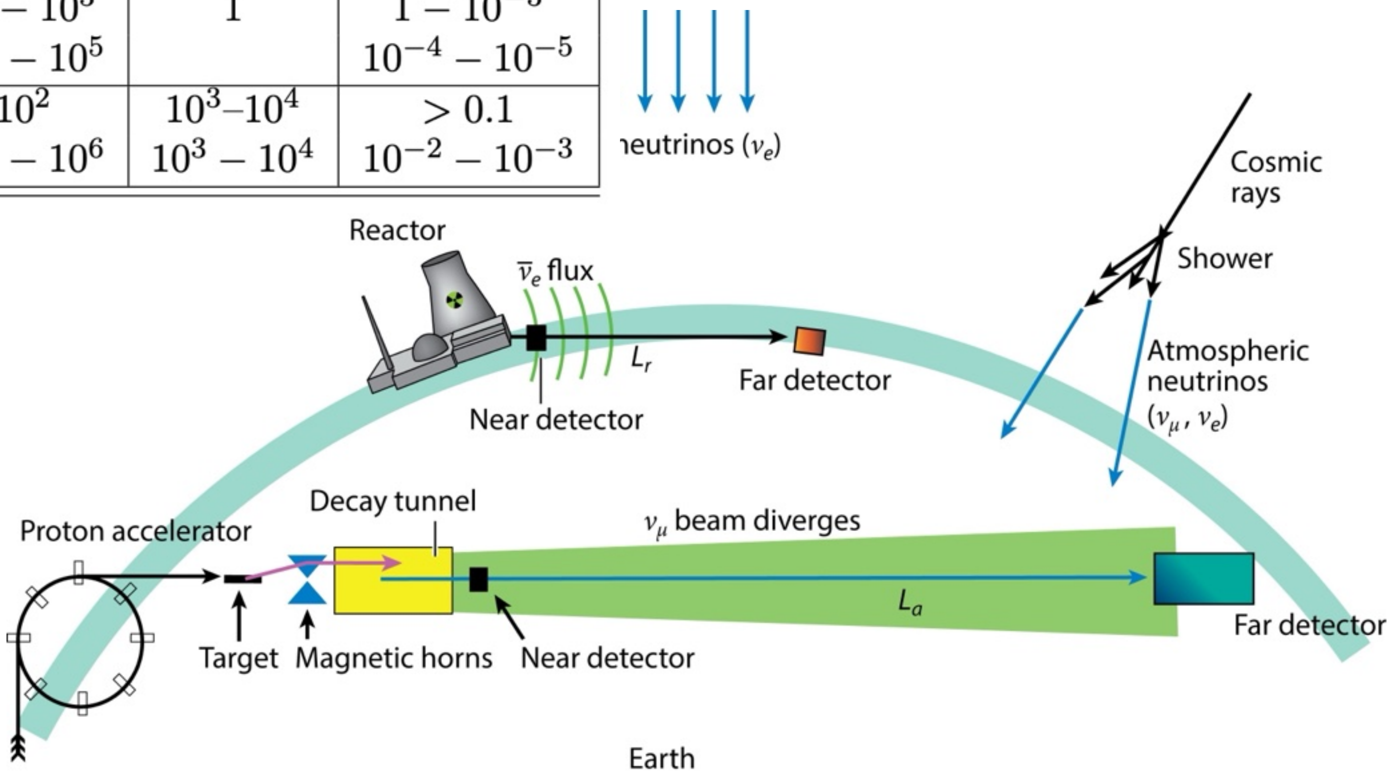
Different neutrino sources + experiments have typical L/E, and correspondingly ranges of Δm_{ij}^2 to which they can be most sensitive



Long-Baseline Neutrino Experiments
M.V. Diwan, V. Galymov, X. Qian, A. Rubbia
Annual Review of Nuclear and Particle Science 2016 66:1, 47-71

Different neutrino sources + experiments have typical L/E, and correspondingly ranges of Δm_{ij}^2 to which they can be most sensitive

Experiment		L (m)	E (MeV)	$\lvert\Delta m^2\rvert$ (eV^2)
Solar		10^{10}	1	10^{-10}
Atmospheric		$10^4 - 10^7$	10^2–10^5	$10^{-1} - 10^{-4}$
Reactor	VSBL–SBL–MBL	$10 - 10^3$	1	$1 - 10^{-3}$
	LBL	$10^4 - 10^5$		$10^{-4} - 10^{-5}$
Accelerator	SBL	10^2	10^3–10^4	> 0.1
	LBL	$10^5 - 10^6$	$10^3 - 10^4$	$10^{-2} - 10^{-3}$



A phenomenologically-useful parametrization of the mixing matrix reflects the sensitivity of different types of experiments

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{+i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha} & 0 \\ 0 & 0 & e^{i\beta} \end{pmatrix}$$

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

θ_{ij} : the mixing angles

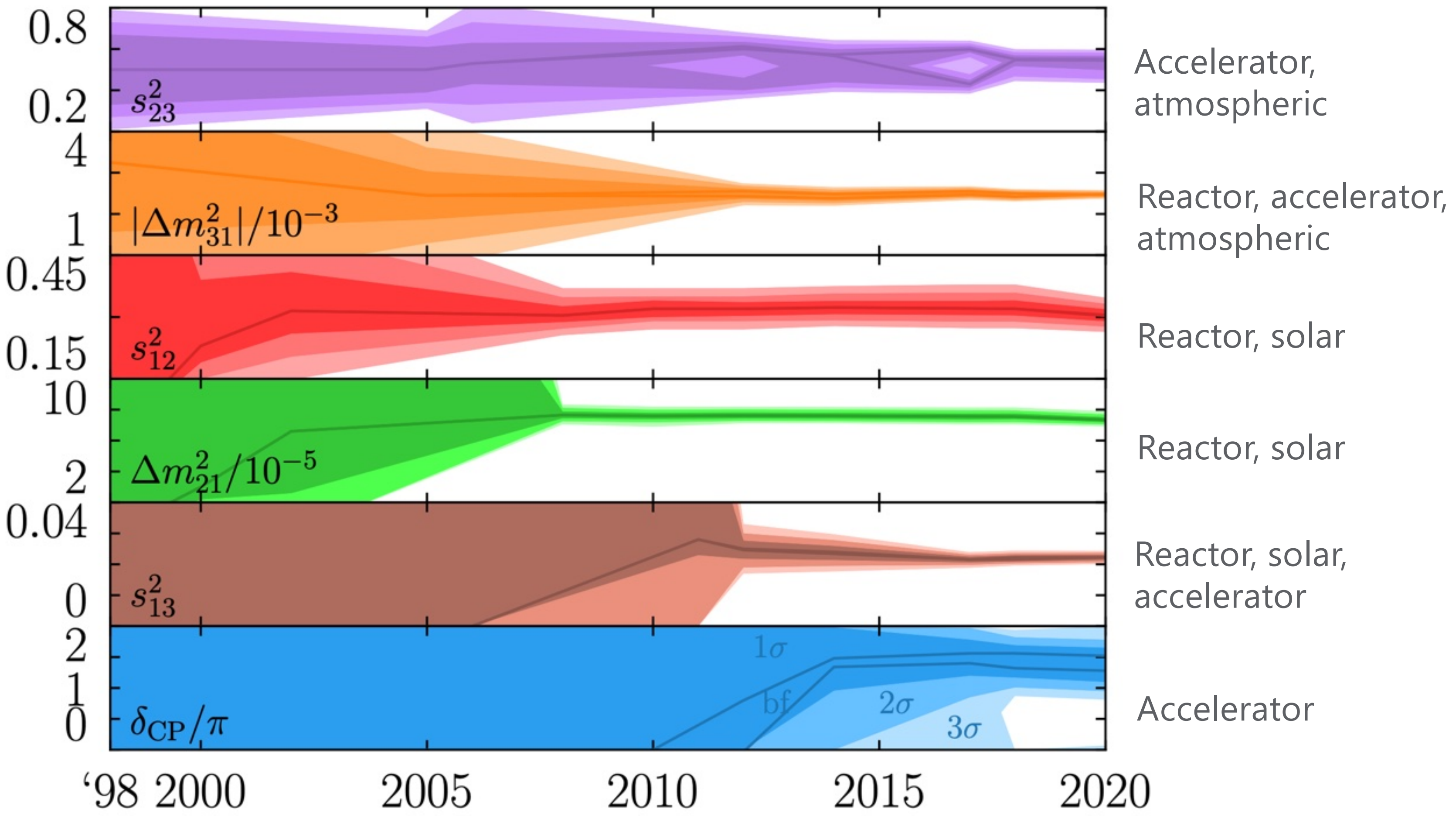
δ : CP-violating phase

α, β : Majorana phases

Atmospheric/LBL	Reactor/LBL	Reactor/Solar
$\theta_{23} \sim 45^o$	$\theta_{13} \sim 8.5^o$	$\theta_{12} \sim 33^o$
$\Delta m^2_{32} \sim \pm 2.5 \times 10^{-3} eV^2$	$\delta_{CP}???$	$\Delta m^2_{12} \sim 7.5 \times 10^{-5} eV^2$

L. Cremonesi

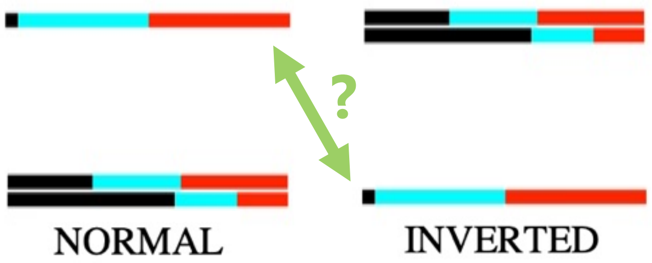
Our understanding of the neutrino oscillation parameters has evolved over the past 25 years.



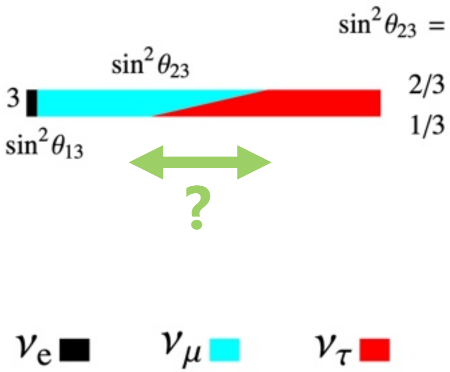
Snowmass NF01 report
P.B. Denton et al
arXiv:2212.00809

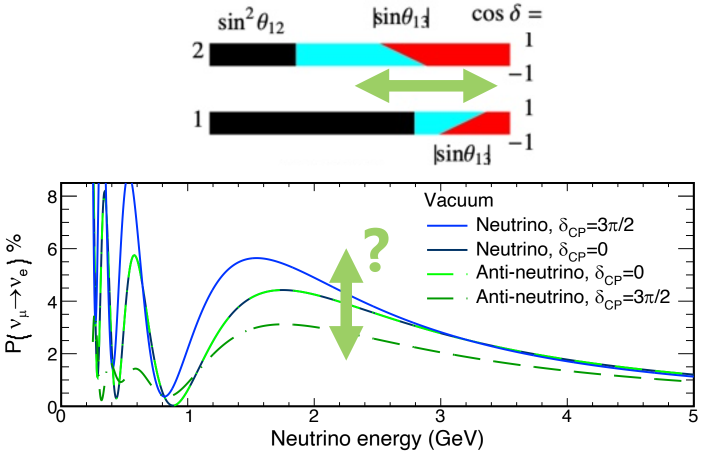
Open questions in the 3-flavor paradigm include the neutrino mass ordering, the octant of θ_{23}, and CP violation

Symmetry Magazine / Sandbox Studio, Chicago

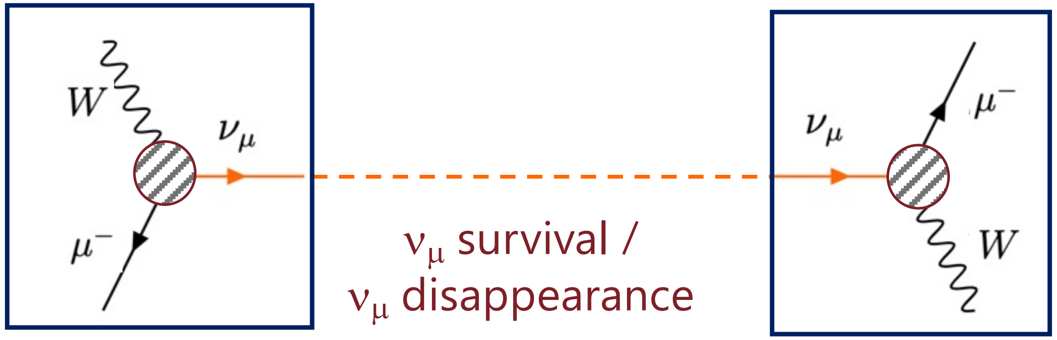


arXiv:hep-ph/0312131





Accelerator experiments have the potential to answer those questions, by measuring muon (anti)neutrino disappearance and electron (anti)neutrino appearance

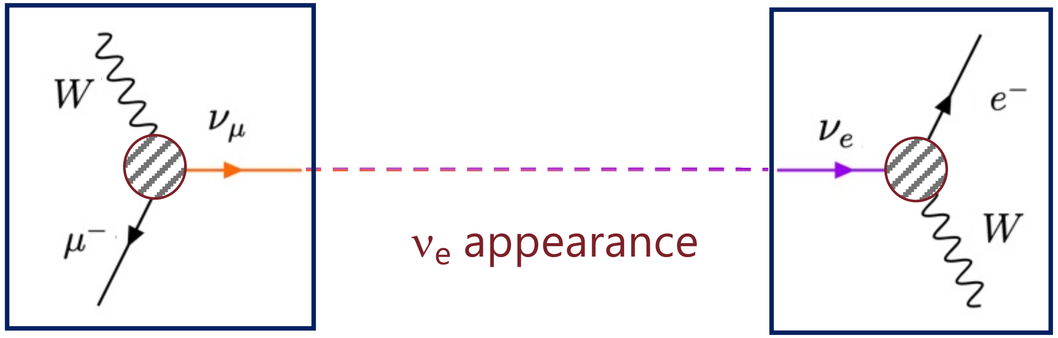


$$P\left(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_\mu\right) \approx 1 - \sin^2 2\theta_{23} \sin^2\left(\Delta m^2_{32} \frac{L}{4E}\right)$$

Mass Ordering and $|\Delta m^2_{32}|$

Mixing angles

CP Phase δ_{CP}



$$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2$$
$$+\sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}$$
$$\times\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}\pm\delta_{CP})$$
$$+\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2,$$

Z. Vallari

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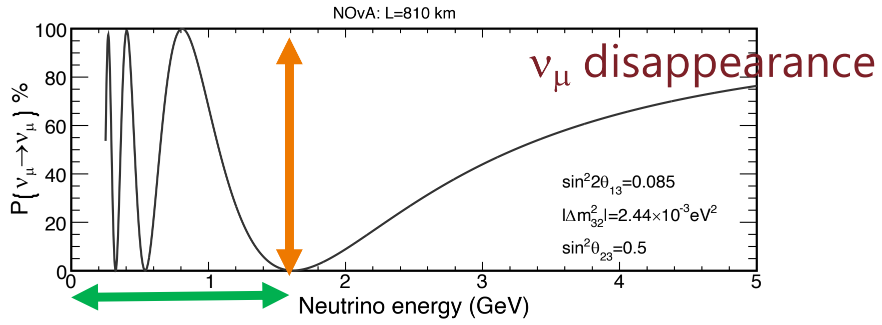

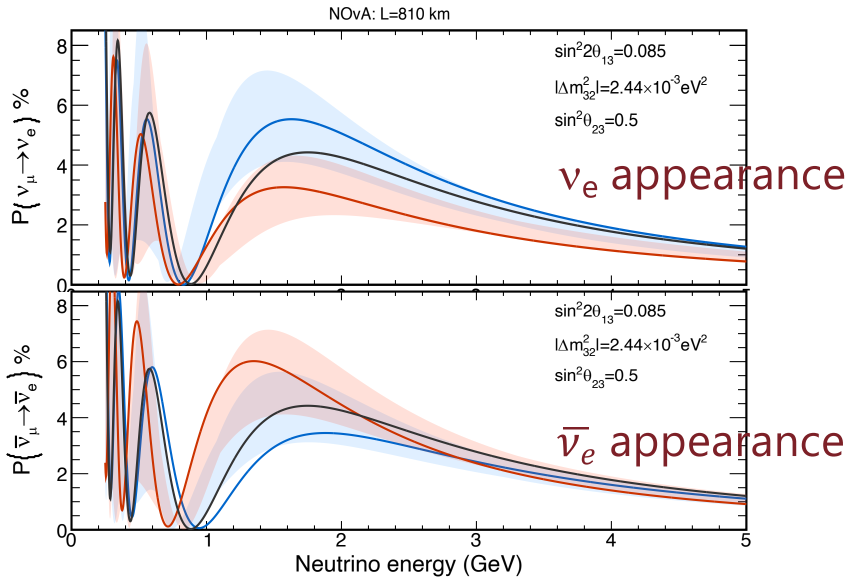

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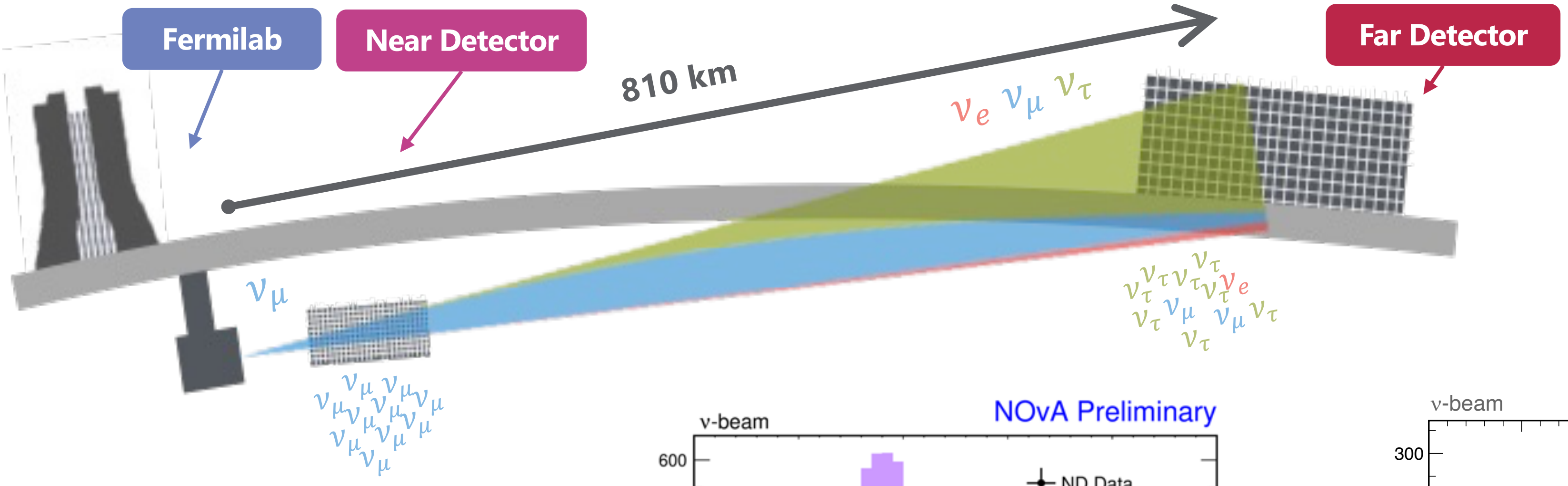
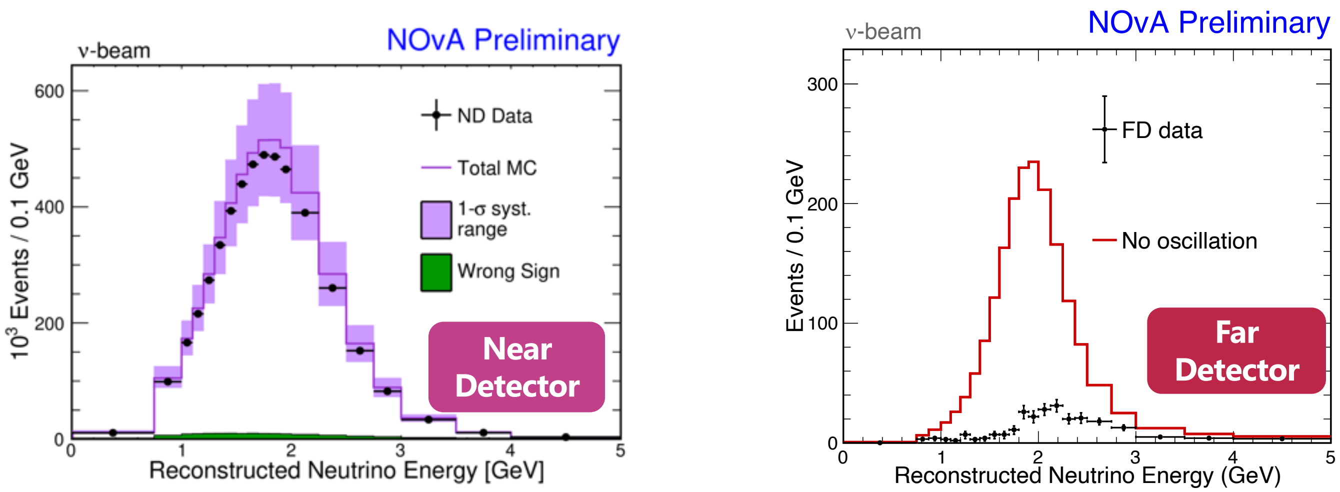
$$+ \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}$$
$$\times \frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31} \pm \delta_{CP})$$
$$+ \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2,$$

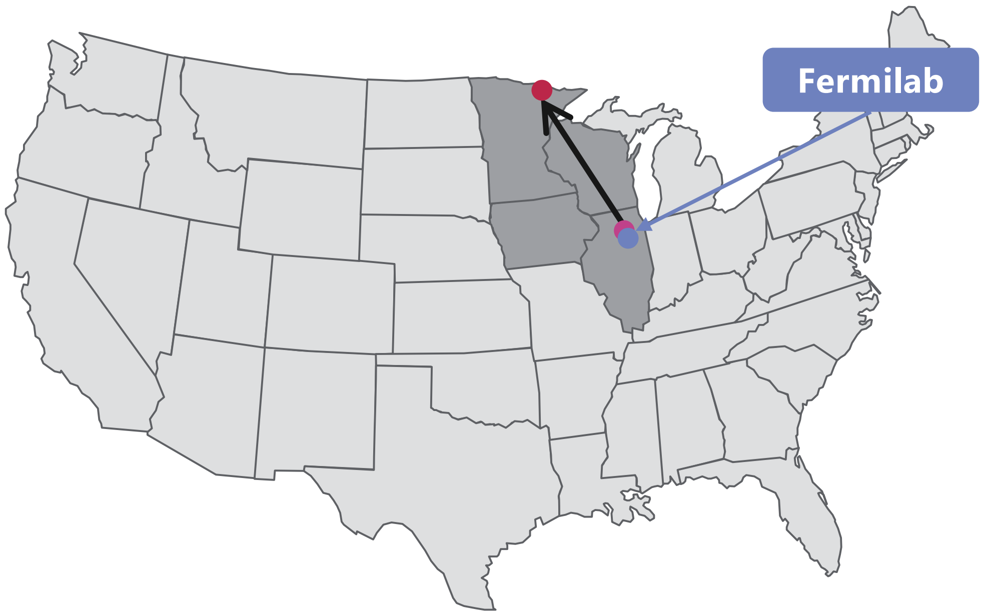
The NOvA experiment

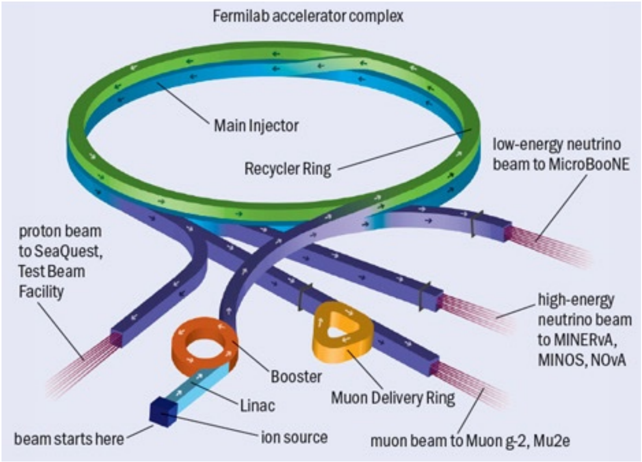
Long-baseline experiments like NOvA use neutrinos produced by a particle accelerator. Neutrinos before (after) oscillations are measured with a Near (Far) Detector





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





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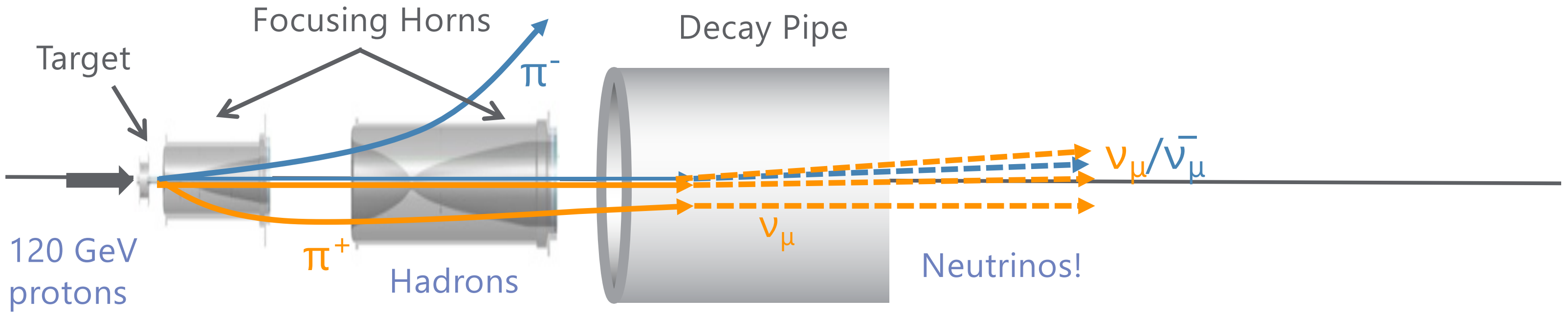
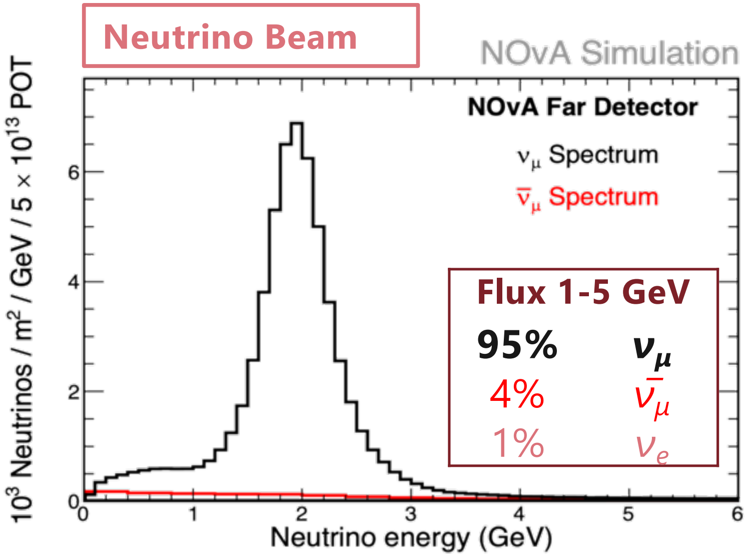
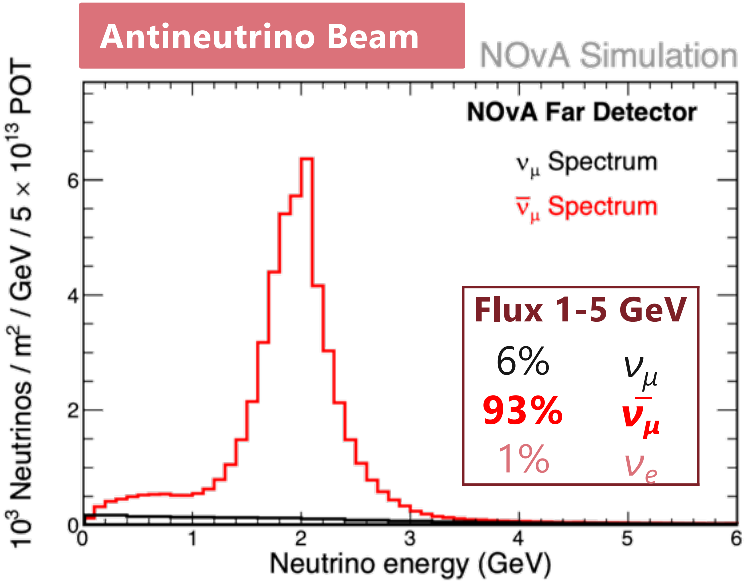
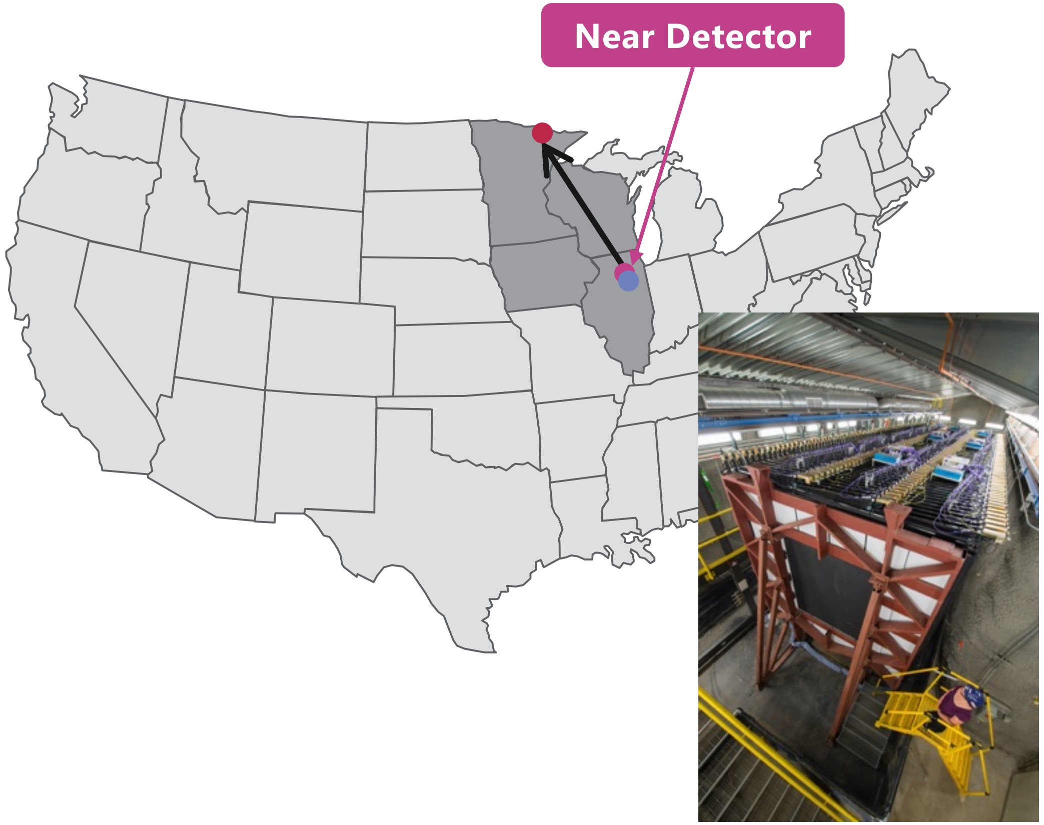
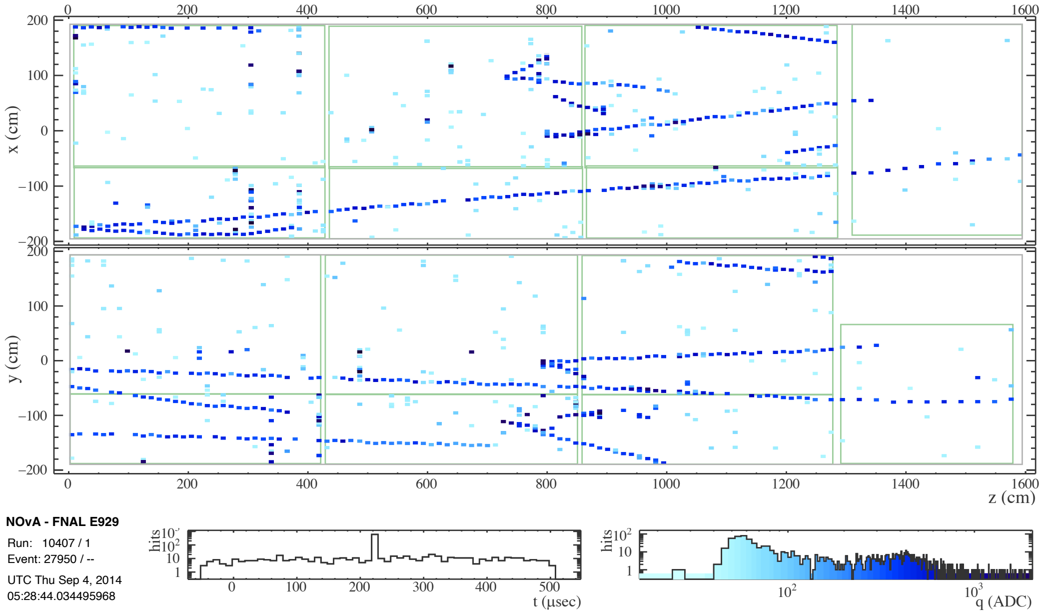




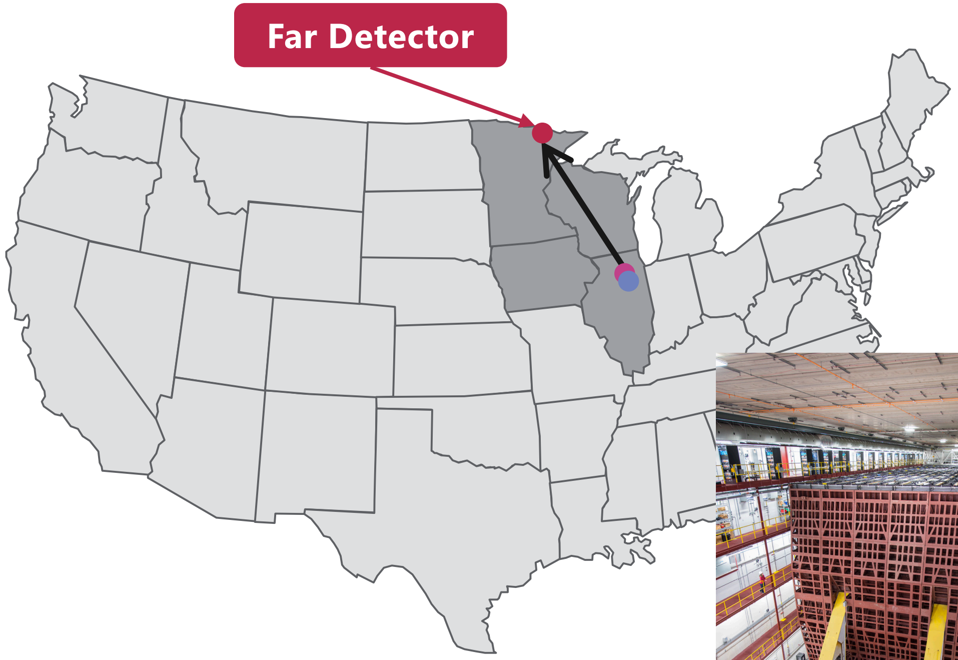


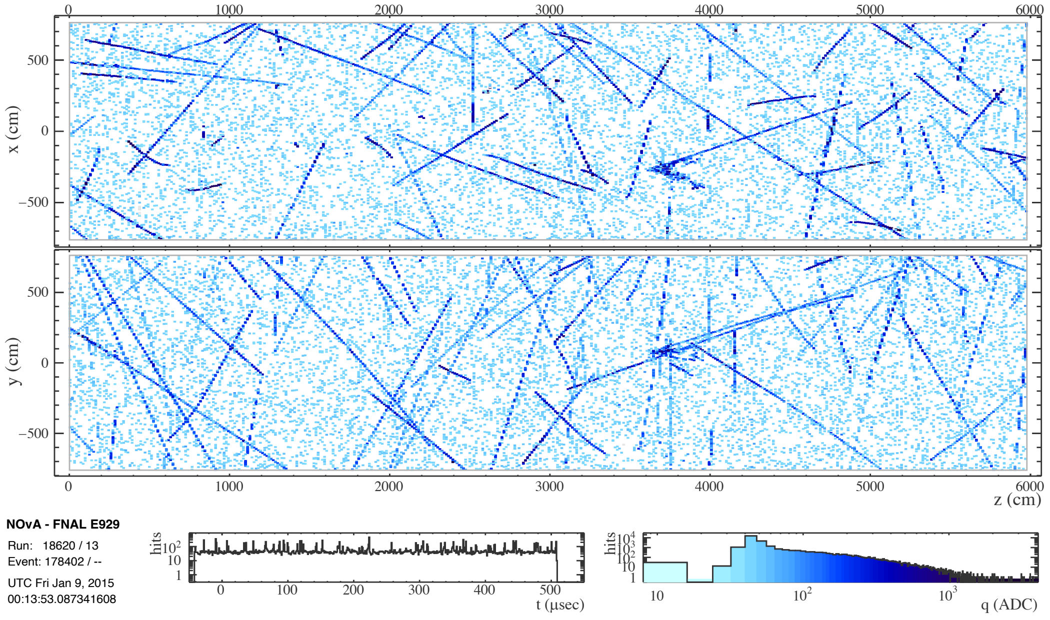
The NOvA near detector is 1km from the beam source, 100 m underground, with a mass of 0.3 kton



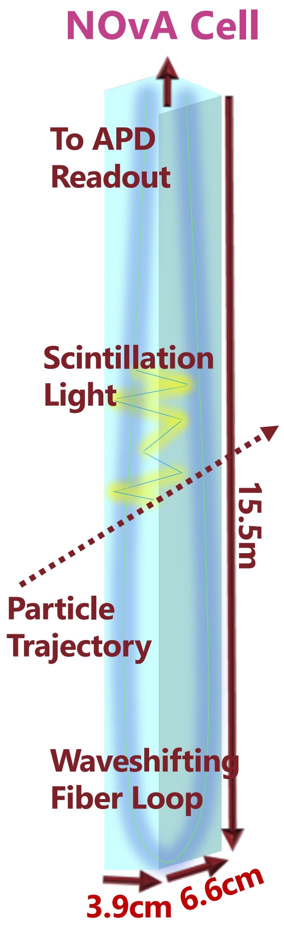


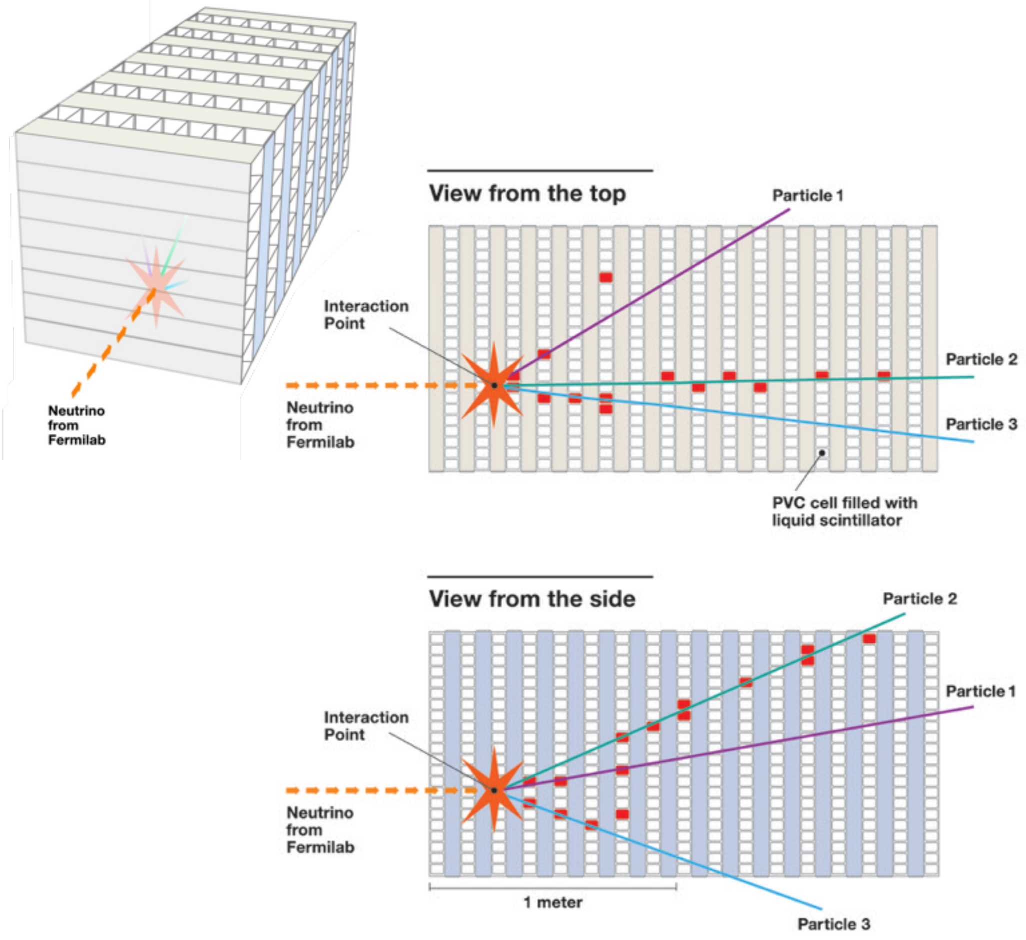
The NOvA far detector is 810 km from the beam source, on the surface, with a mass of 14 kton





The NOvA detectors are segmented liquid scintillator detectors. Orthogonal layers of cells provide top and side views for each event





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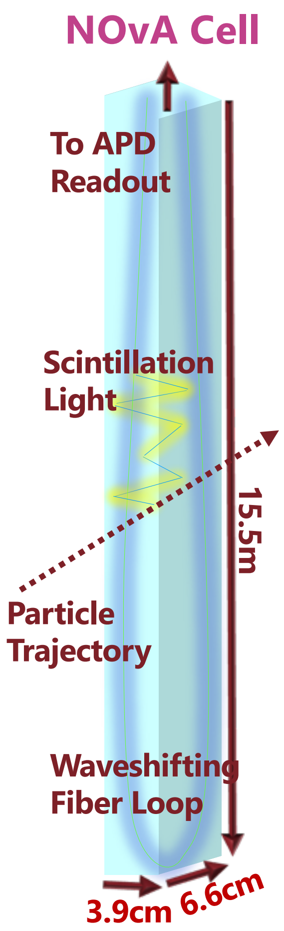
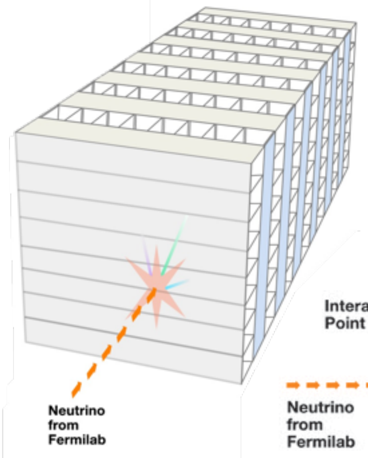
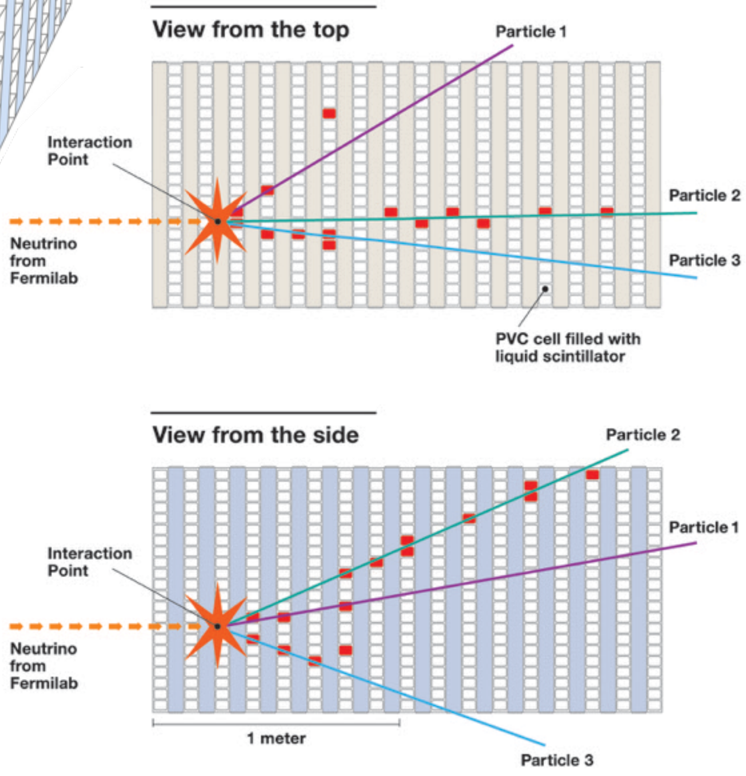
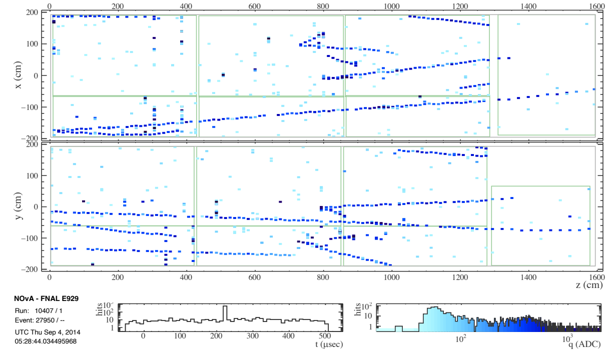


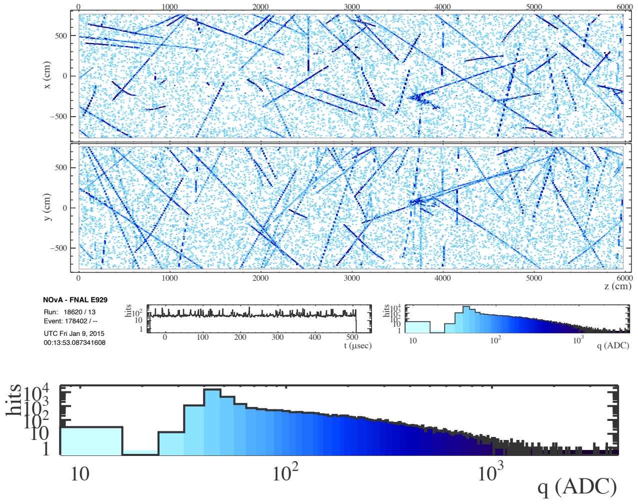




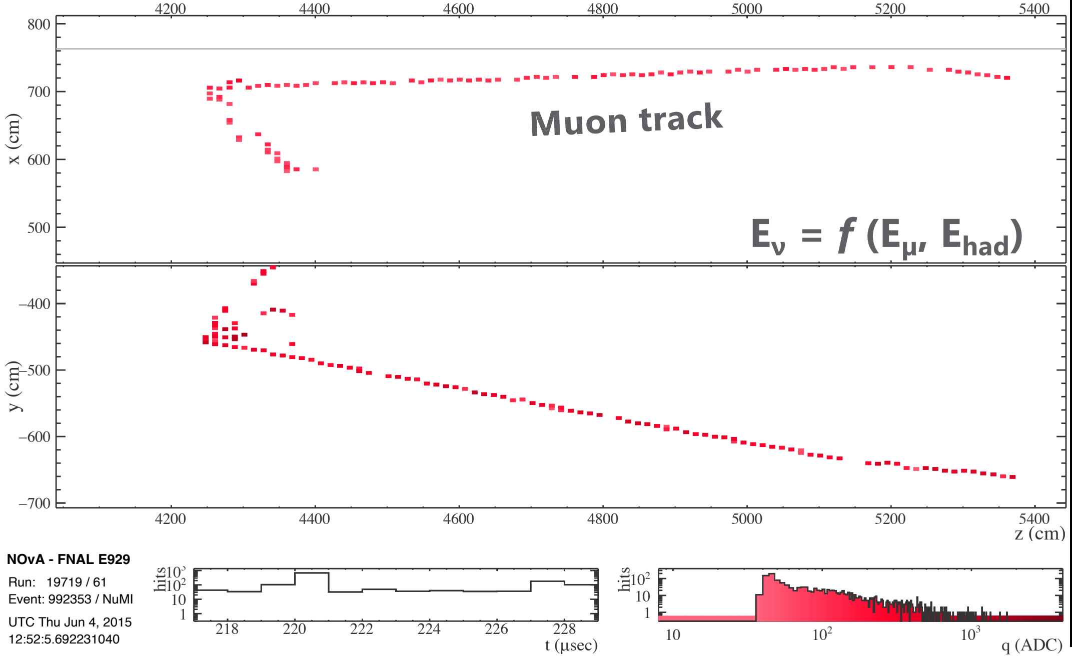
ND: 20 193 channels



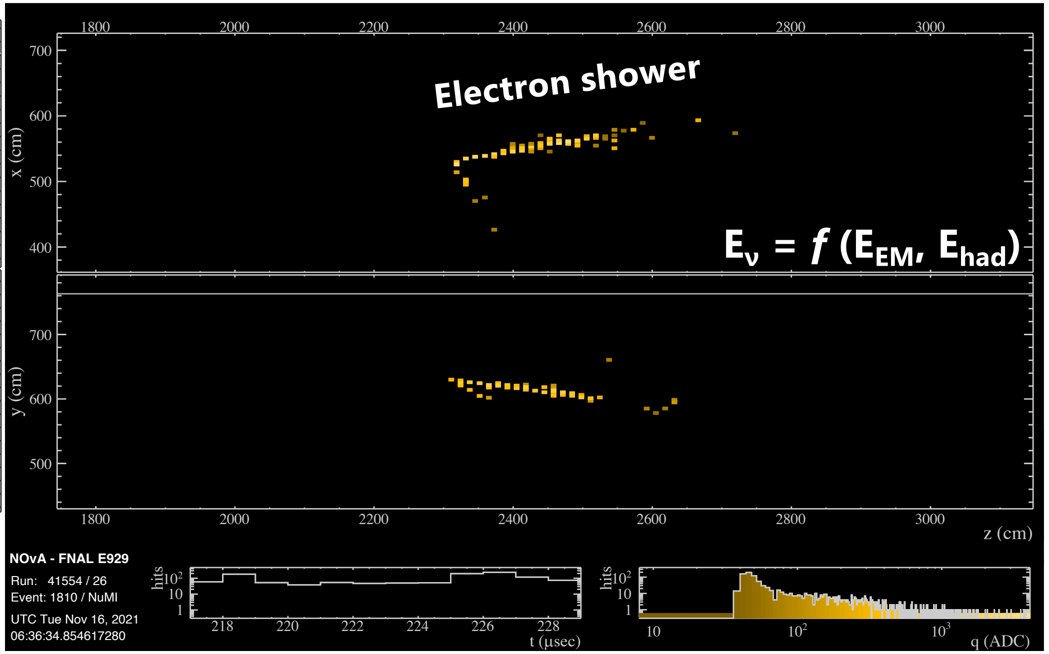
FD: 344 064 channels



Event candidates comprise hits clustered in space and time and matched across views. Energy is reconstructed via tracking (muon) and calorimetry (electromagnetic, hadronic)



3.8 GeV numu candidate



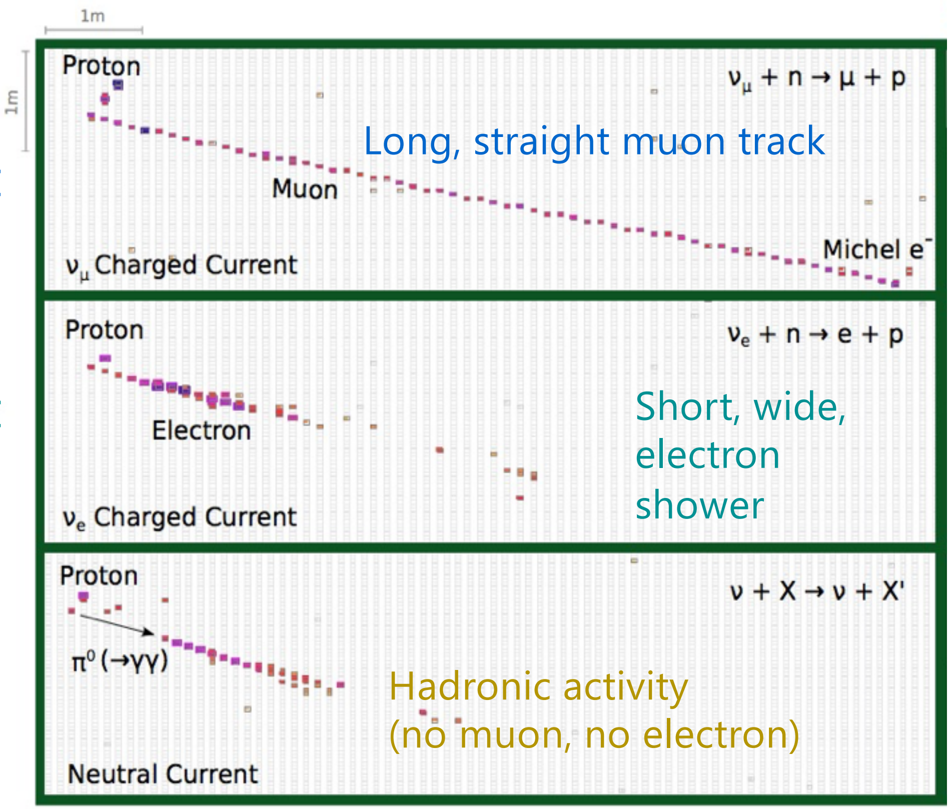
2 GeV nue candidate

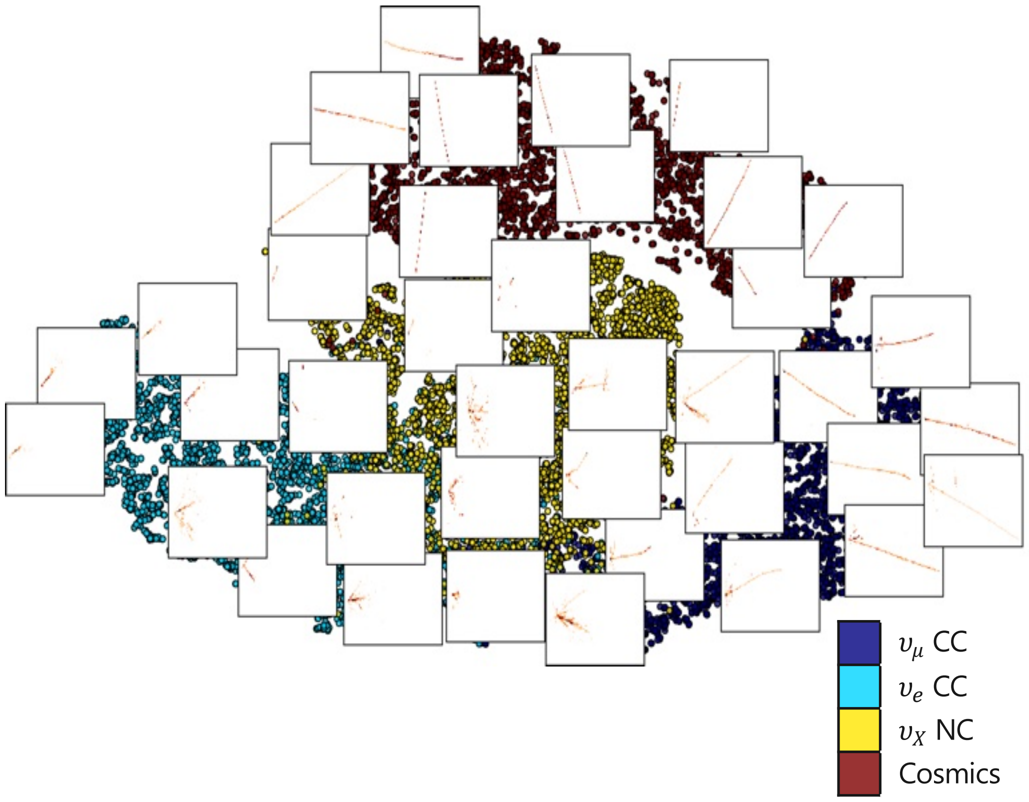
Neutrino interaction candidates are identified using a convolutional neural network (CNN)

ν_μ CC

ν_e CC

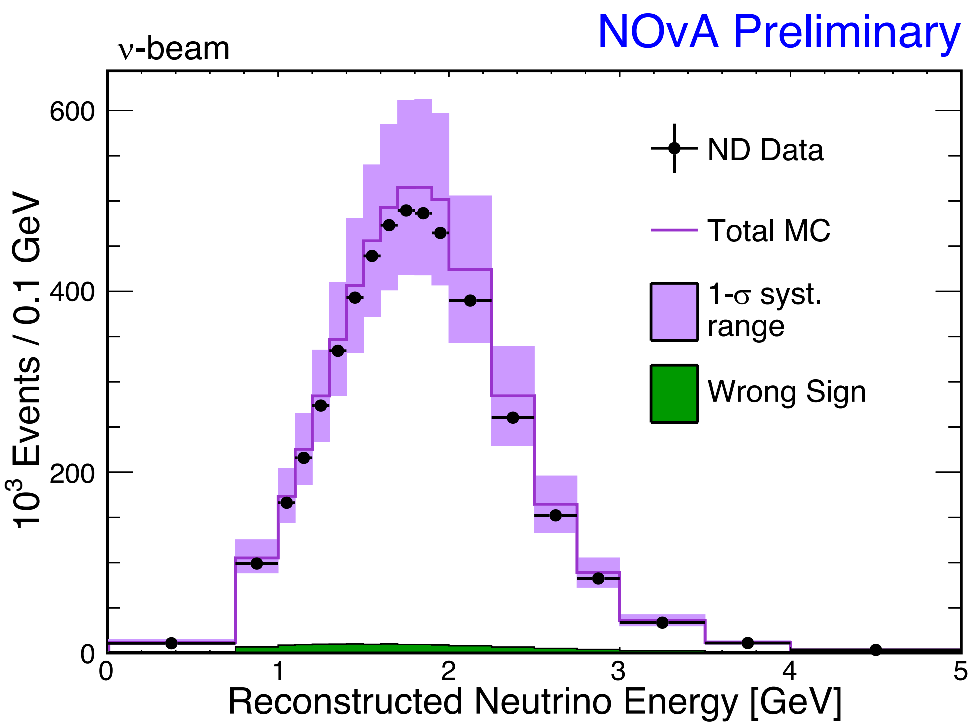
NC



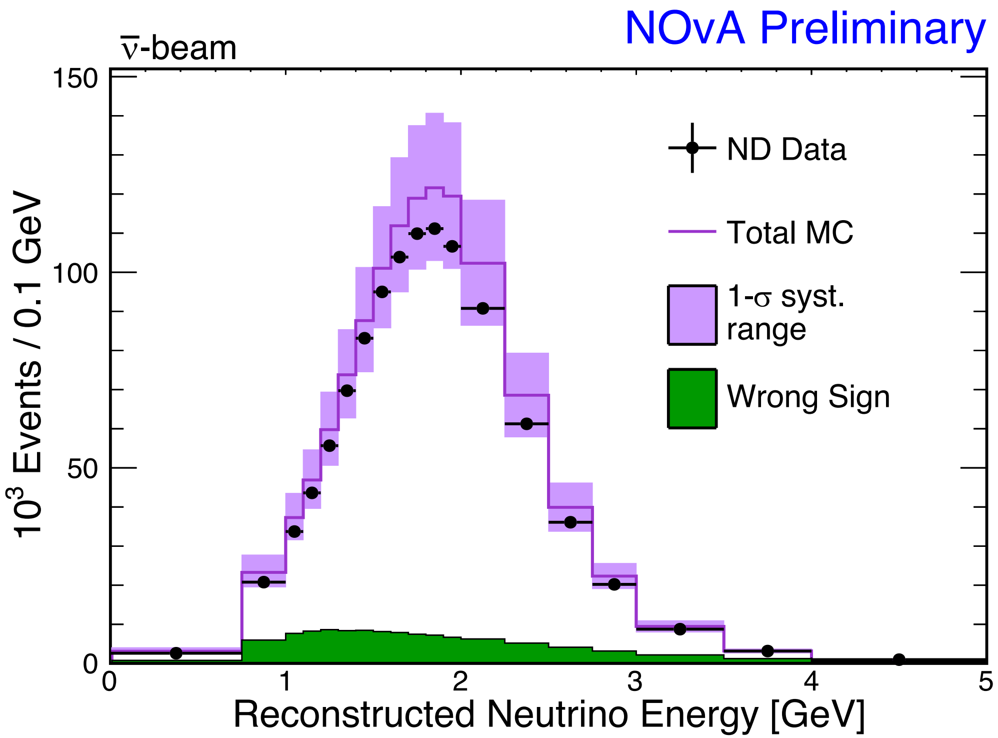


We select millions of muon neutrinos and anti-neutrinos in the near detector

~6.5 M candidates

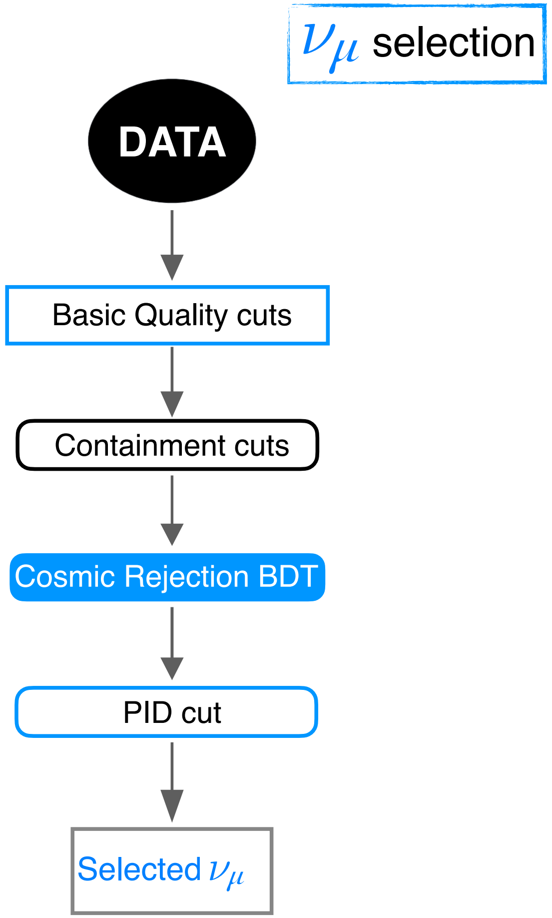


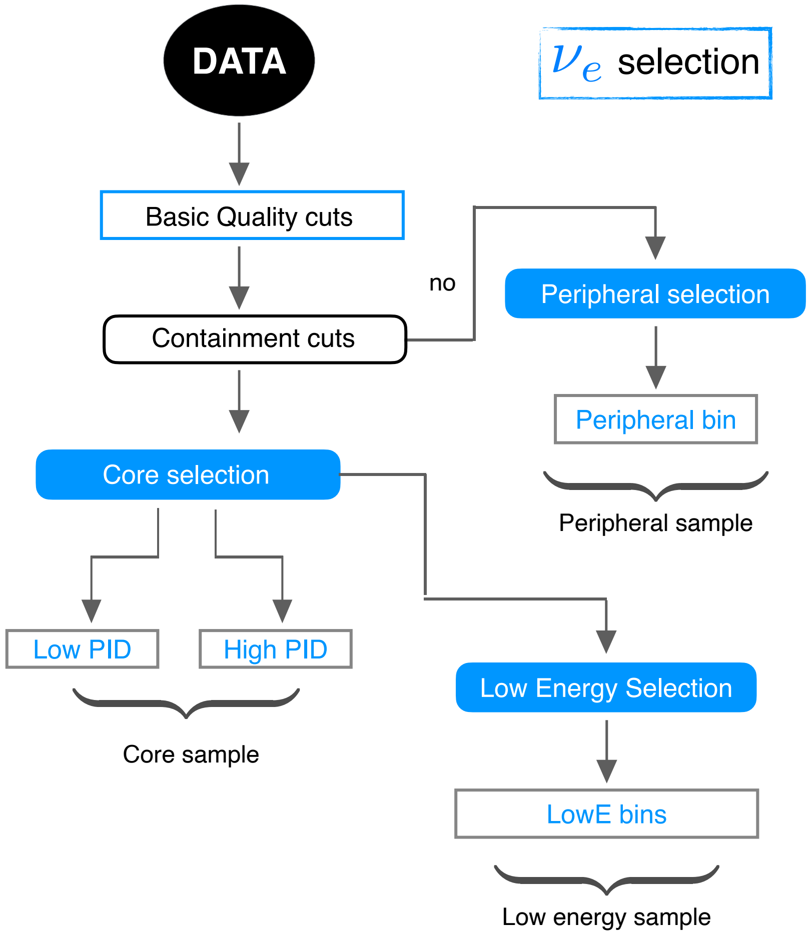
~1.5 M candidates



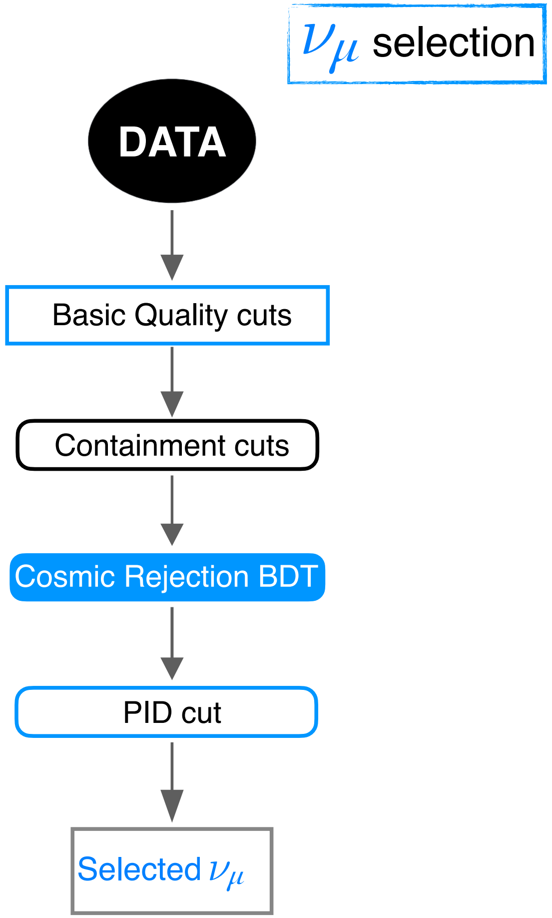
Building an oscillation analysis

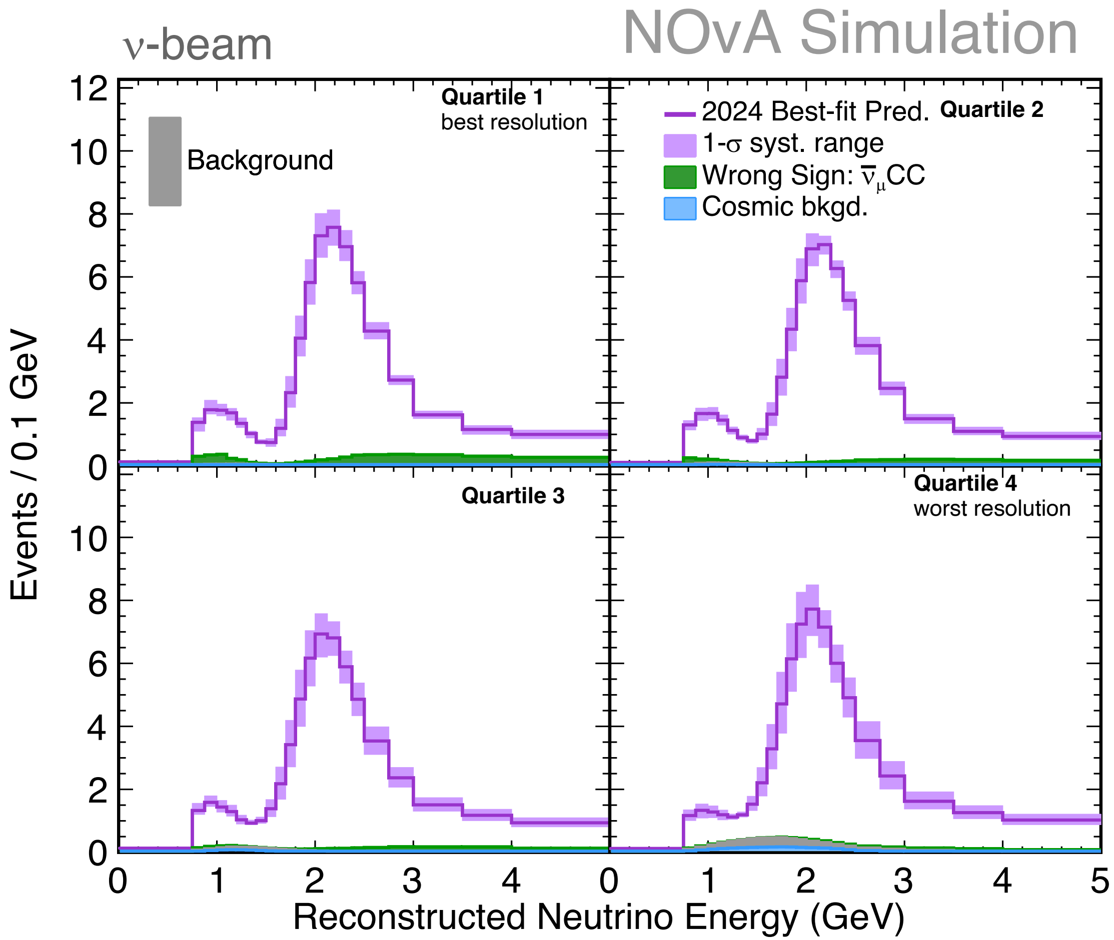
The full FD selection includes quality, containment, cosmic rejection, and the event-classifier (CNN) cuts. Sensitivity can be enhanced by further splitting the samples



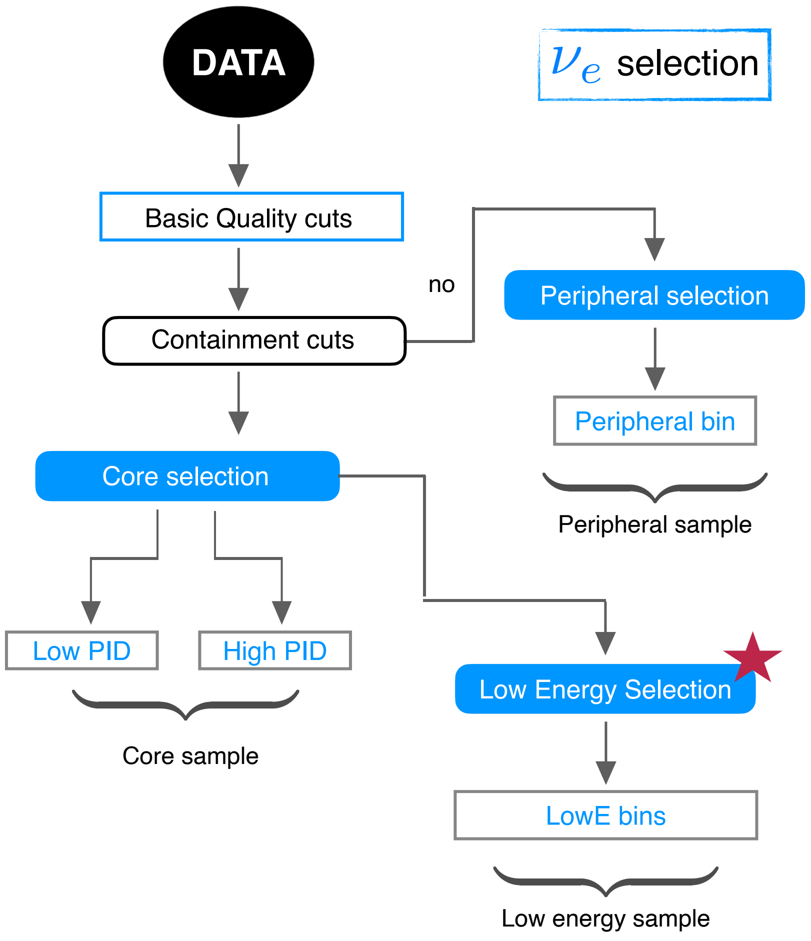


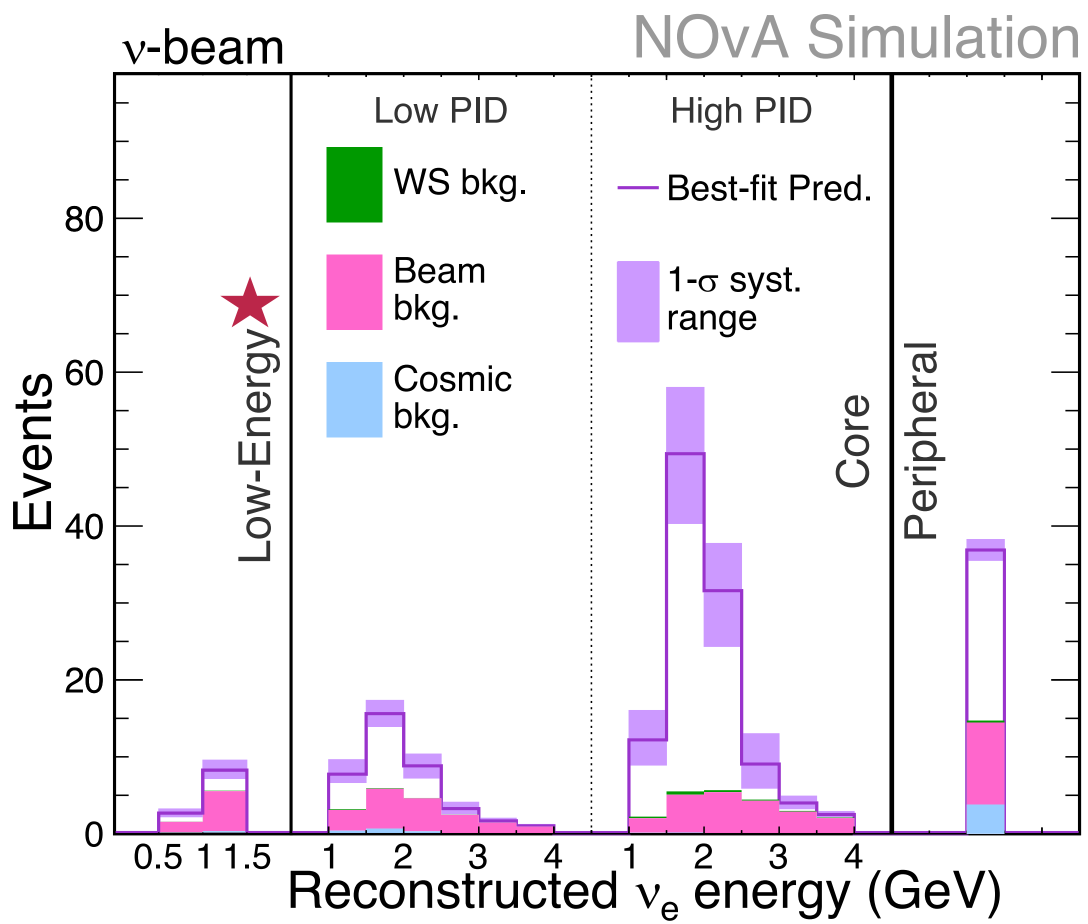
For the ν_μ sample, the sensitivity depends primarily on the shape of the energy spectrum. We bin by hadronic energy fraction, as a proxy for binning by energy resolution



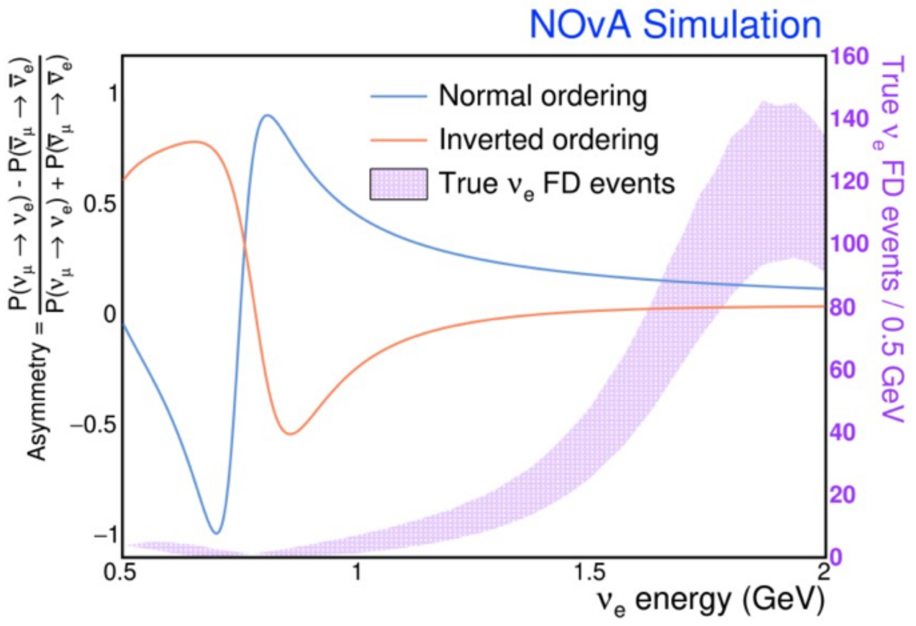


For the ν_e sample, the sensitivity depends primarily on separating signal from background. We bin by "purity" with bins of low & high PID

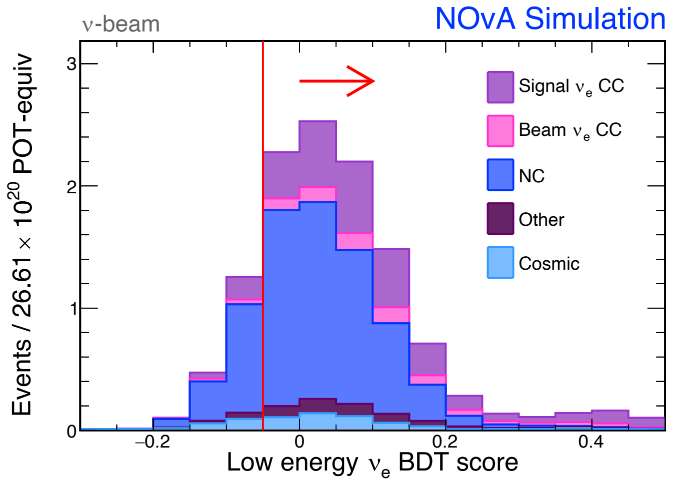


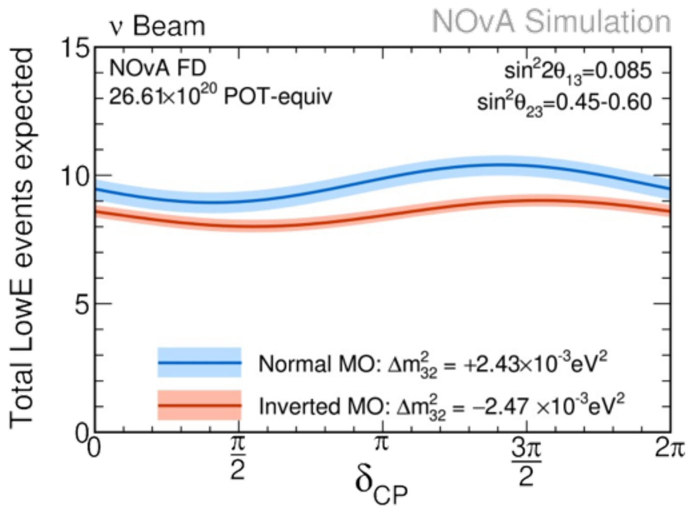


A new selection was developed to retain lower-E ν_e candidates. It increases the mass ordering sensitivity by ~few %(depending on oscillation parameters)

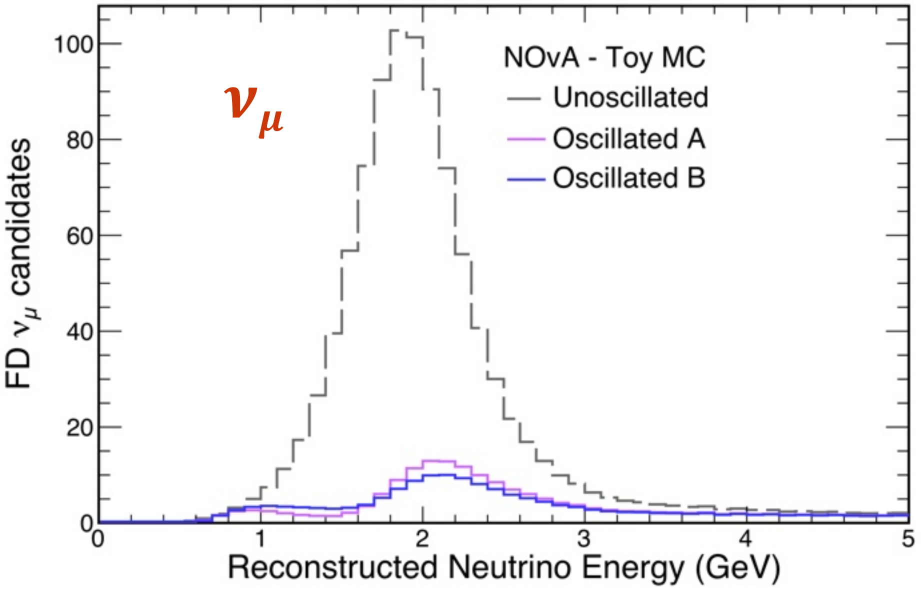


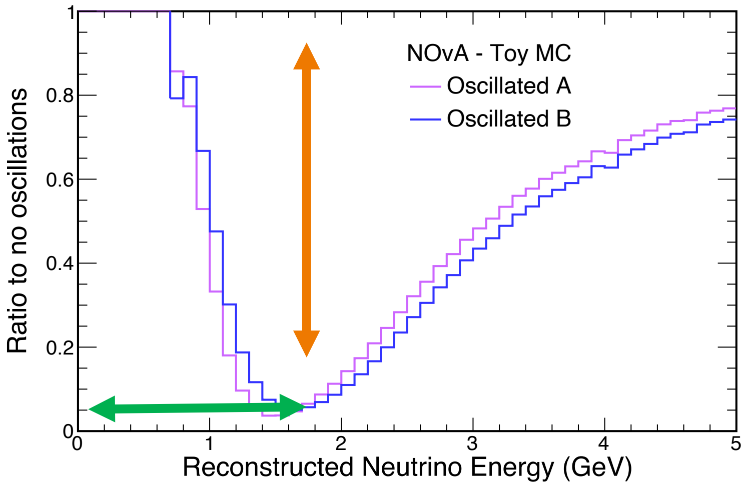
Maximum ordering sensitivity from νe–νe asymmetry at lower Eν
(previous analysis had a cut reco. Eν ≥ 1 GeV)

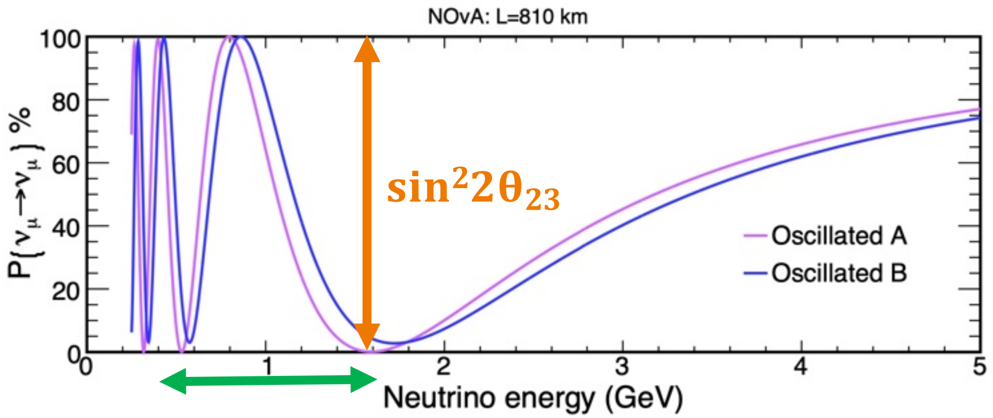




We make inferences about the oscillation parameters by measuring neutrino candidates in the FD and comparing our observations to simulated predictions

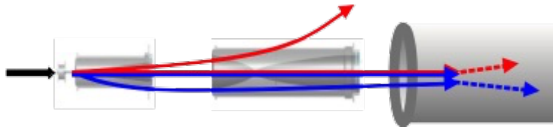




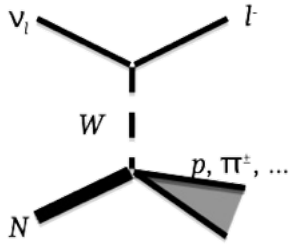


Simulating events in the detector is a multi-stage process. We also use data-driven techniques to improve the predictions.

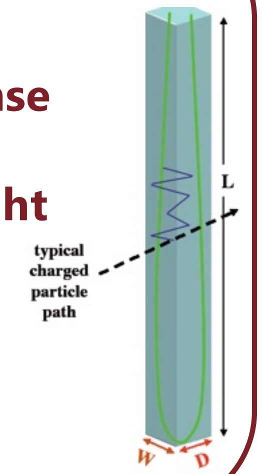
Neutrino flux



Neutrino interactions on detector materials

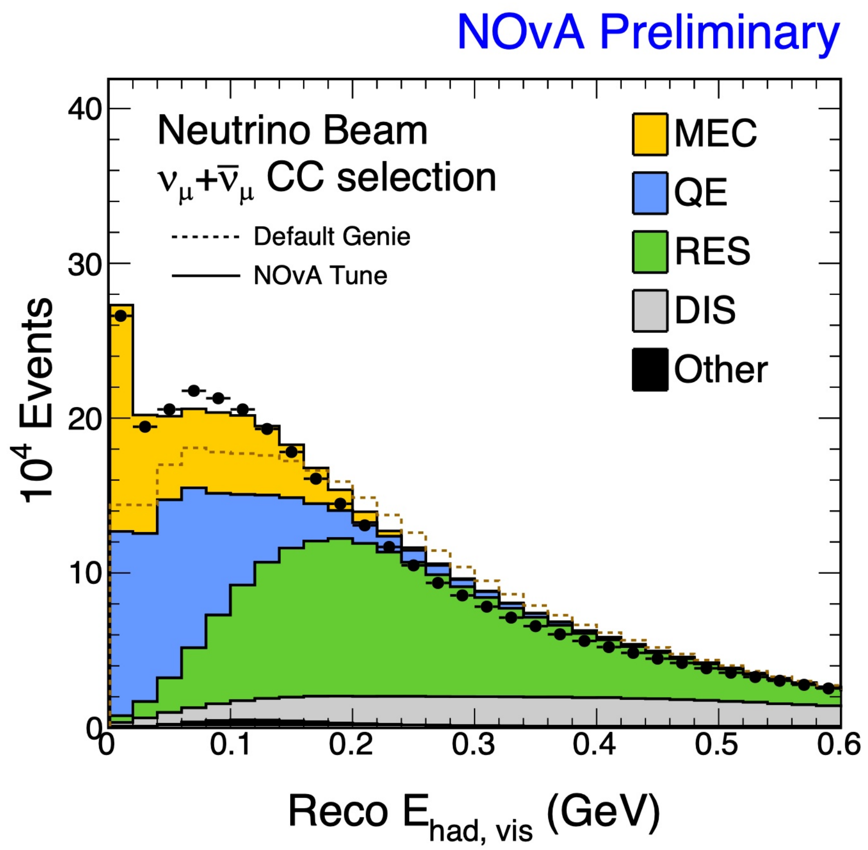


Detector response to charged particles and light propagation

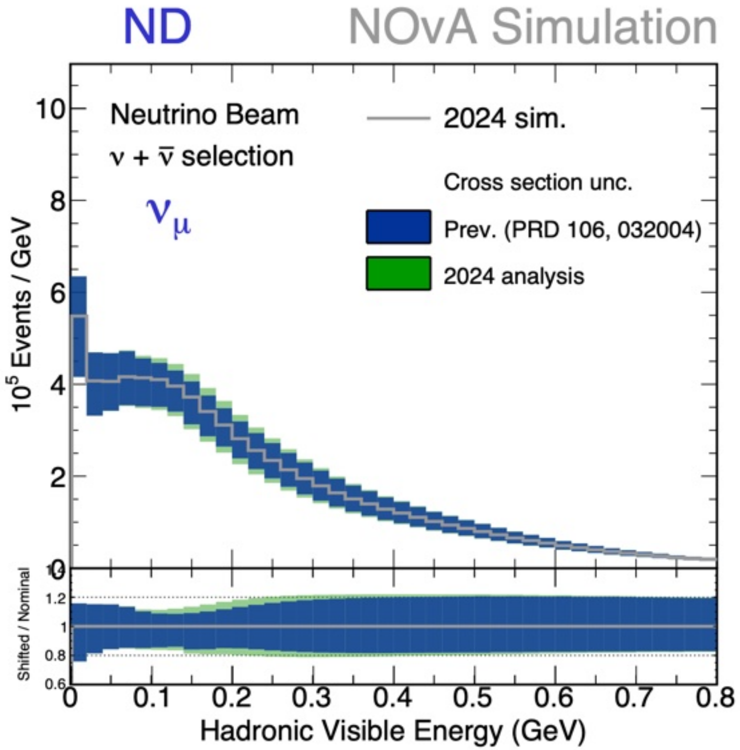


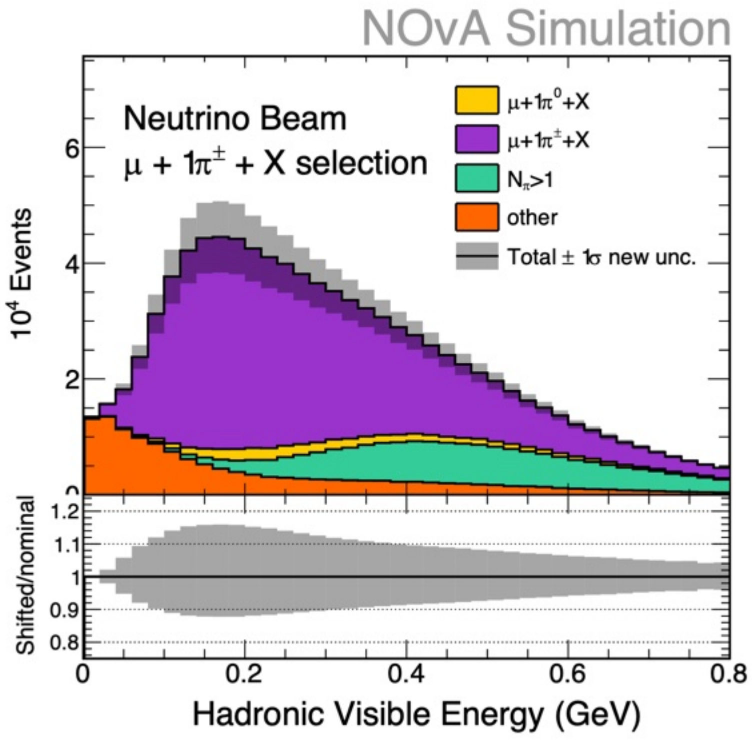
The cross-section model is largely unchanged from previous analysis: GENIE 3.0.6 Custom configuration and tuned to external data and NOvA ND Data.

Neutrino - free nucleon interactions	
Quasi-Elastic (QE)	Valencia 1p1h Z-expansion axial form facror
Resonance (RES)	Berger-Sehgal
Deep inelastic Scattering (DIS)	Bodek-Yang
Multinucleon interactions	
Meson exchange current (MEC)	Valencia MEC custom adjustment to NOvA data for 2p2h
Interactions with the nuclear environment	
Final State Interactions (FSI)	hN Semi Classical Cascade Custom fit to external pion scattering data.



New for 2024: extra systematic uncertainties treating pion production.

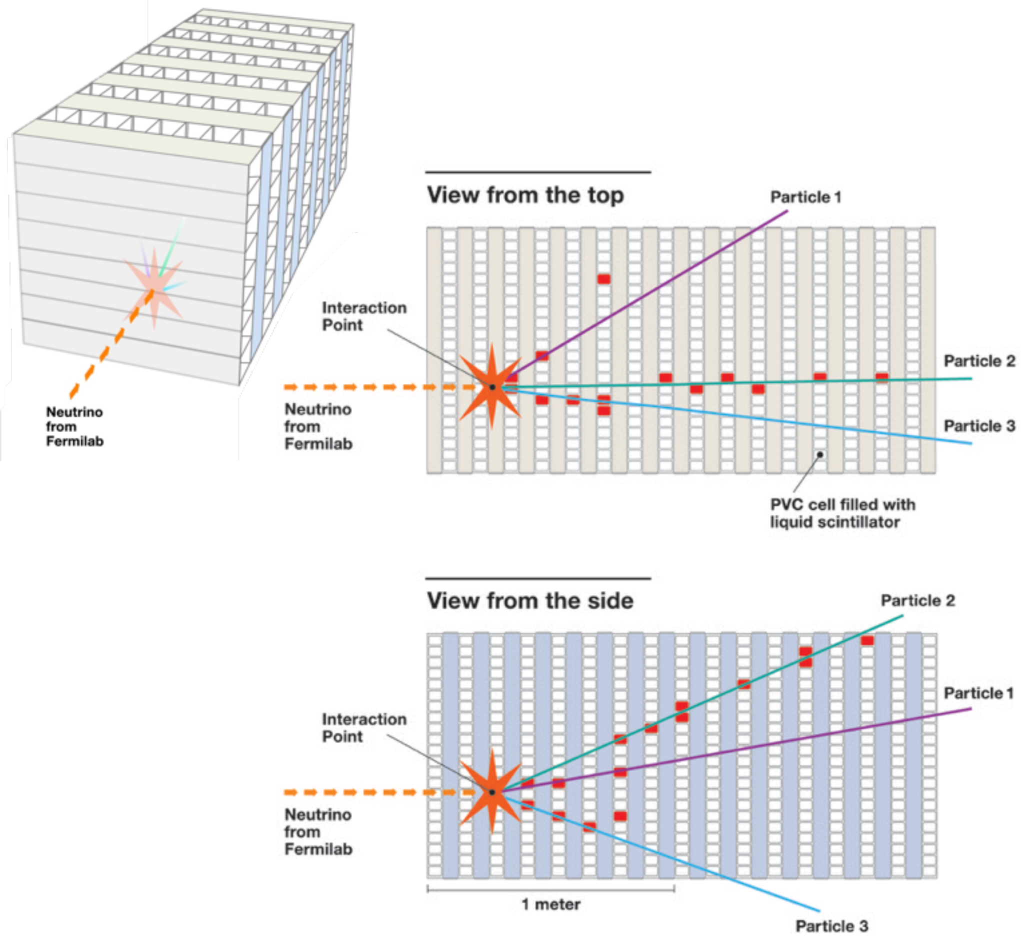


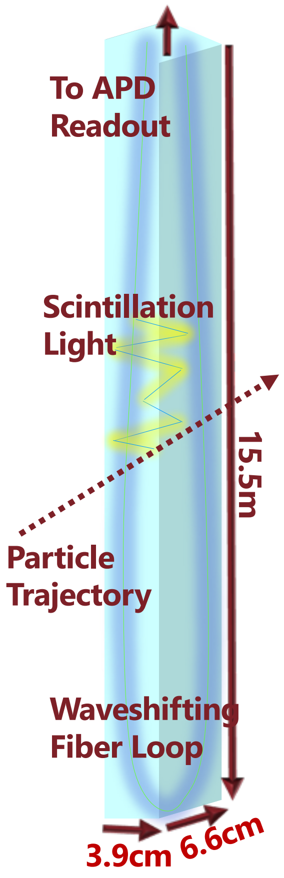


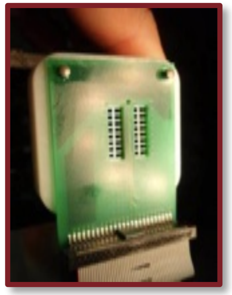
- RES: relative ratio of Delta vs. non-Delta resonances
- RES & DIS: rates of charged vs neutral hadron production

- Modest effect on the inclusive sample
- These uncertainties will prove important contributions to pion-sensitive cross section measurements

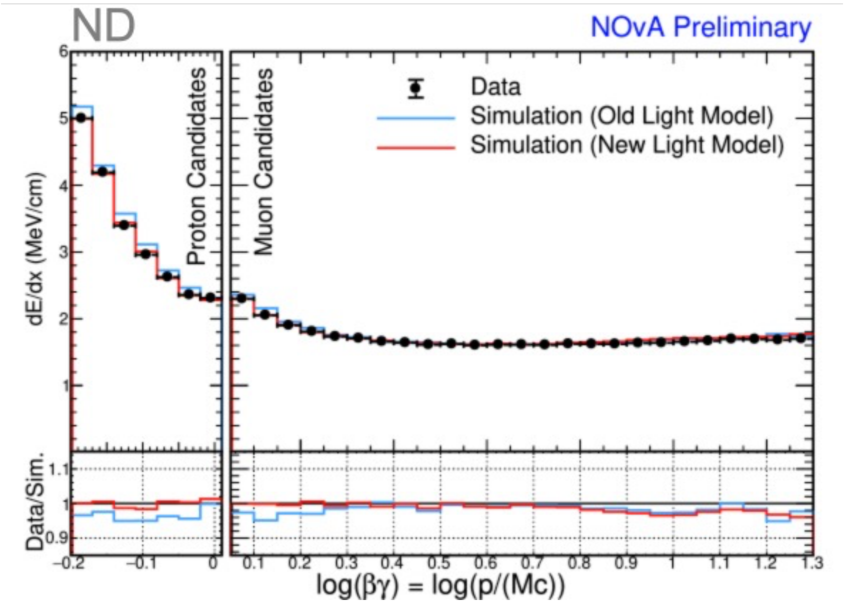
The propagation of final state particles is simulated with GEANT4. Light readout and front–end electronics use a custom simulation.



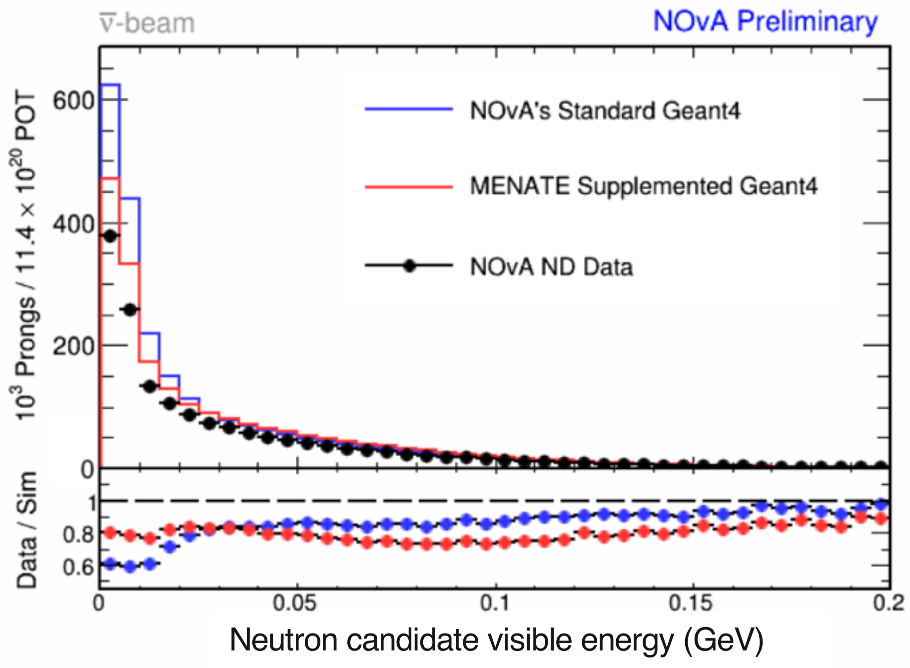




Updates to the simulation include an improved light response model and neutron propagation uncertainty



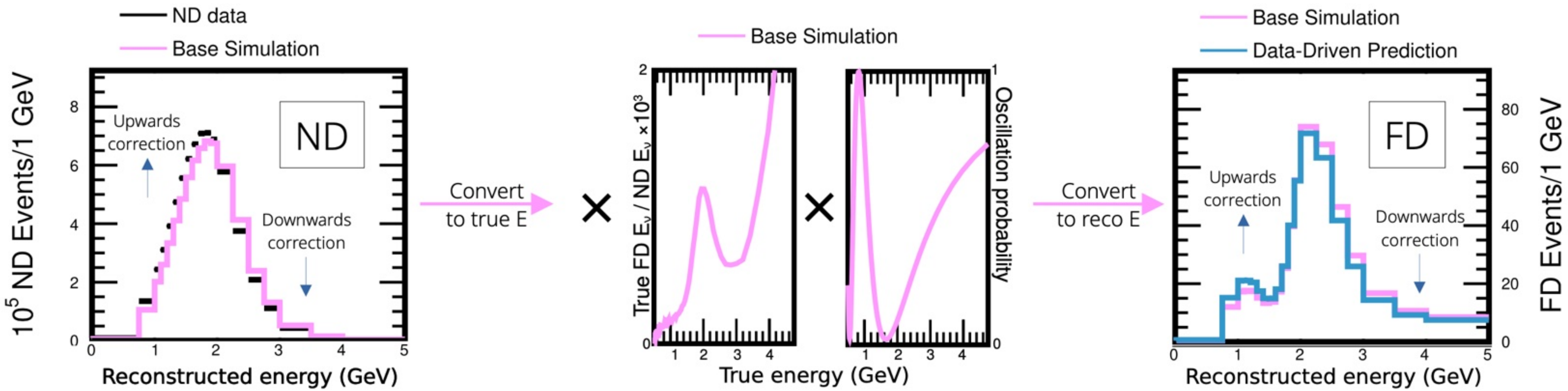
Improved light production model
(Cherenkov & scintillation)
in both detectors, from dedicated bench measurements
& in situ stopping muon and proton tracks



Improved n-^{12}C inelastic scattering model
Difference between MENATE_R* and default Geant4.10.4 informs systematic uncertainty

* P. Désesquelles, et al., NIM A307 366-373 (1991), Z. Kohley, et al., NIM A682 59-65 (2012)

Data-MC differences observed at the ND can be used to modify the FD MC. "Extrapolation" constrains the nominal prediction and the effect of systematic uncertainties



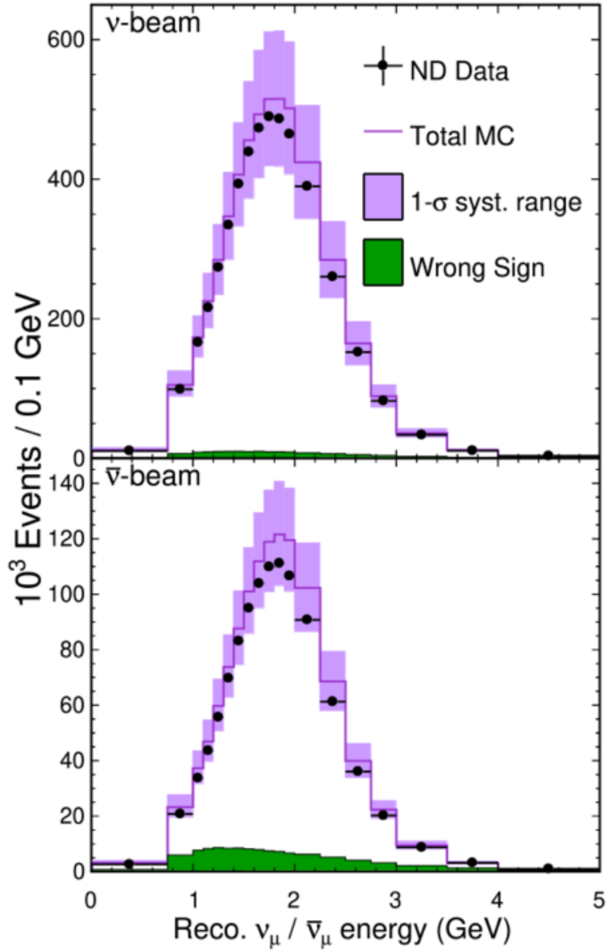
Correcting ND simulation to agree with data in reco E_ν...

... via **Far/Near transformation** that comprises **well understood effects** (beam divergence, detector acceptance) + **oscillations**

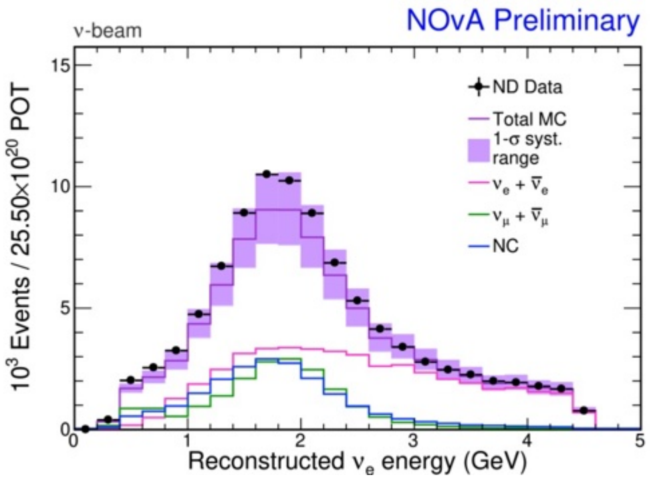
... results in **constrained FD E_ν prediction** highly correlated with ND correction

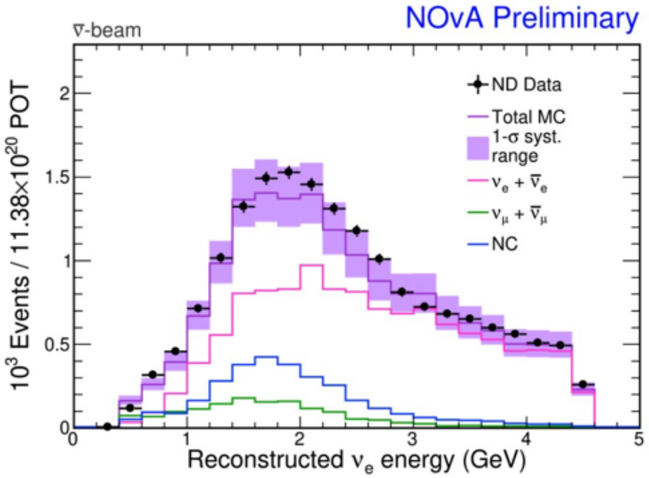
J. Wolcott

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



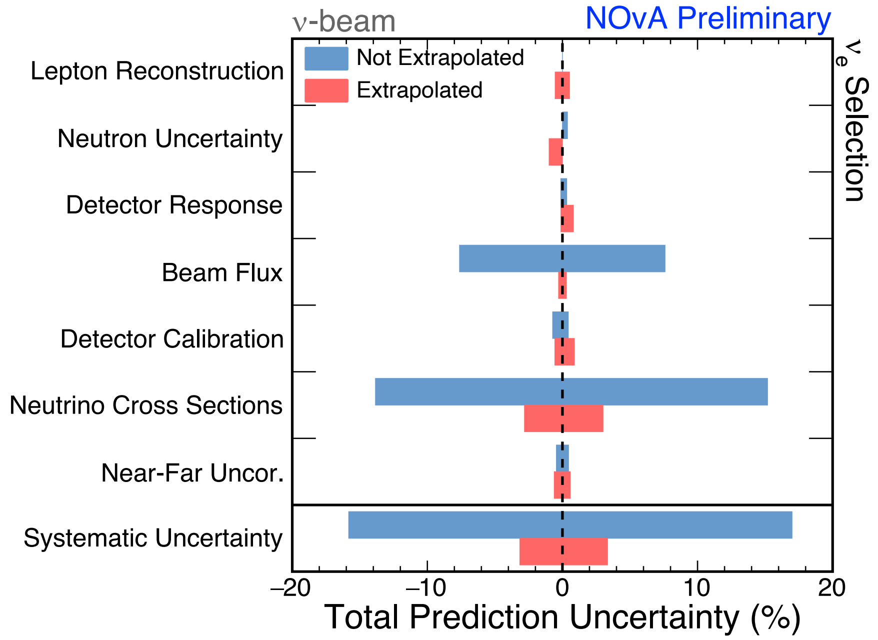
ND ν_μ-like samples are used to correct the FD $\nu_\mu \rightarrow \nu_\mu$ and $\nu_\mu \rightarrow \nu_e$ **signal** predictions





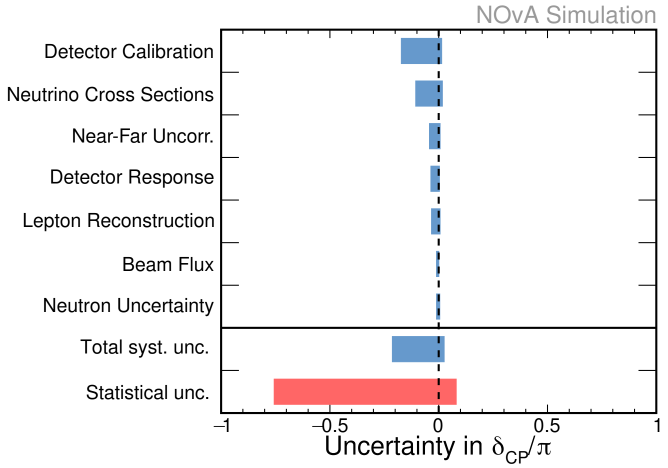
ND ν_e-like samples are used to correct the FD ν_e **background** predictions

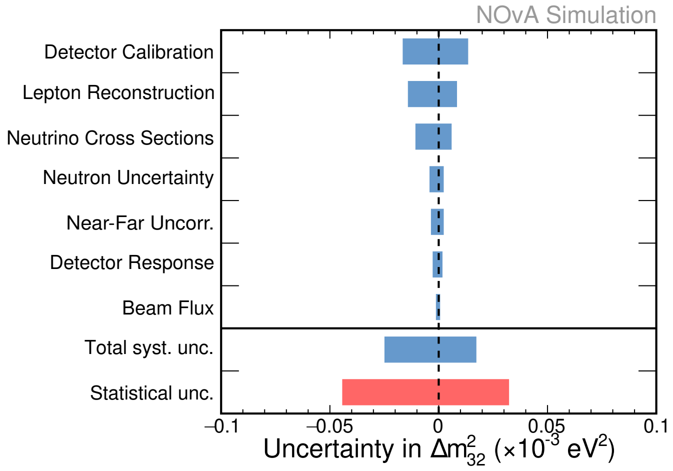
ND constraints reduce the systematic uncertainties in the FD predictions from ~15% to 4-5%. Statistical uncertainties are dominant in the oscillation measurement.



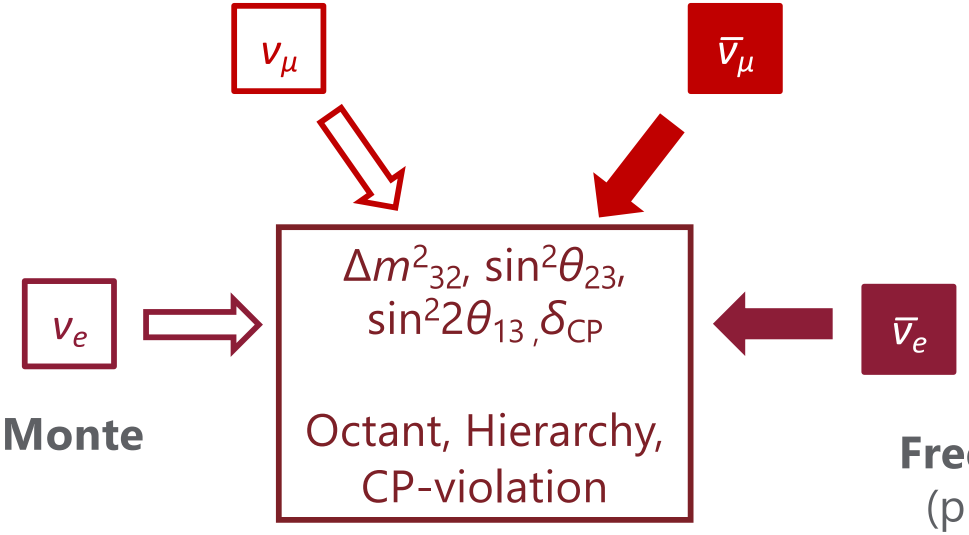
Example: Systematic uncertainties on the nue candidate count: a-priori vs improved predictions

Uncertainties on the oscillation parameters: statistical vs systematic





We perform a simultaneous fit of all samples, using Bayesian or frequentist techniques. External constraints are used for the solar parameters and optionally reactor constraint on θ_{13}



Bayesian Markov Chain Monte Carlo
(marginalization)
(technique described in arXiv:2311.07835)

Bayesian credible regions

Frequentist χ^2 minimization
(profiled Feldman-Cousins)
(technique described in arXiv:2207.14353)

Frequentist confidence regions

Other mixing parameters:

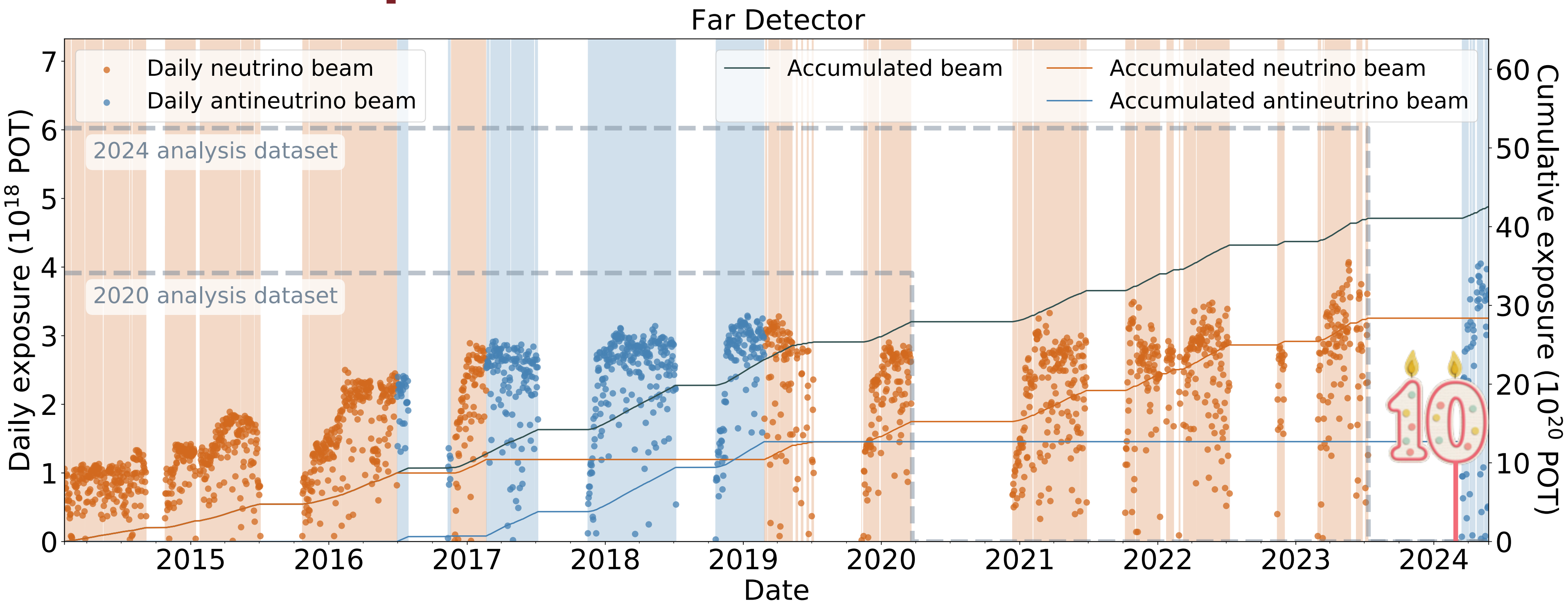
$\sin^2\theta_{12}$	= 0.307	(PDG 2023)
Δm^2_{21}	= 7.53×10^{-5} eV^2	(PDG 2023)
ρ	= 2.74 g/cm^3	(CRUST1.0)

Daya Bay 1D θ_{13} constraint
$\sin^2 2\theta_{13} = 0.0851 \pm 0.0024$

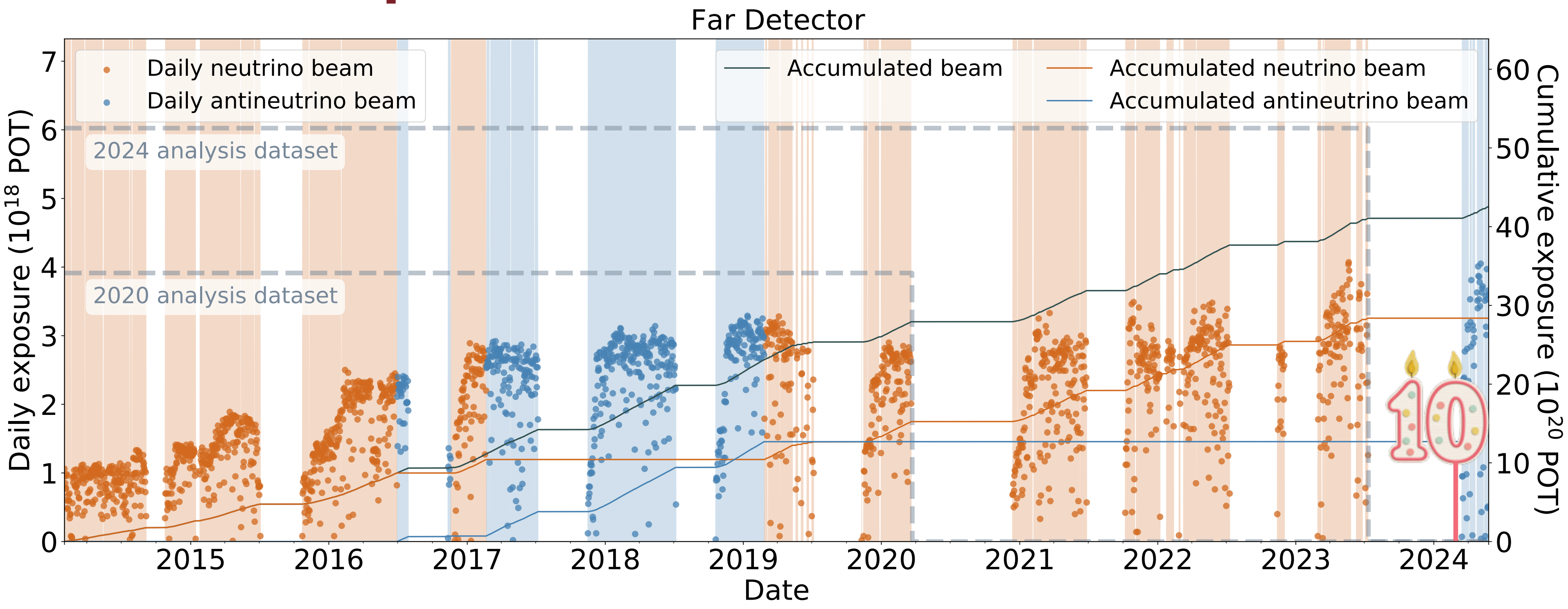
Daya Bay 2D (Δm^2_{32}, θ_{13}) constraint
(PRL 130, 161802)

New results

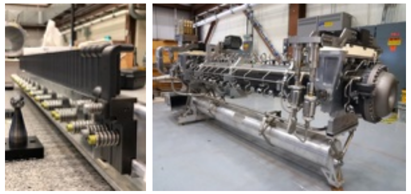
This analysis uses 26.6×10^20 POT neutrino + 12.5×10^20 POT antineutrino beam mode data. A 96% increase in neutrino-beam data compared to 2020



This analysis uses 26.6×10²⁰ POT neutrino + 12.5×10²⁰ POT antineutrino beam mode data. A 96% increase in neutrino-beam data compared to 2020



Fermilab's NuMI beam reached design power of 700 kW in 2017

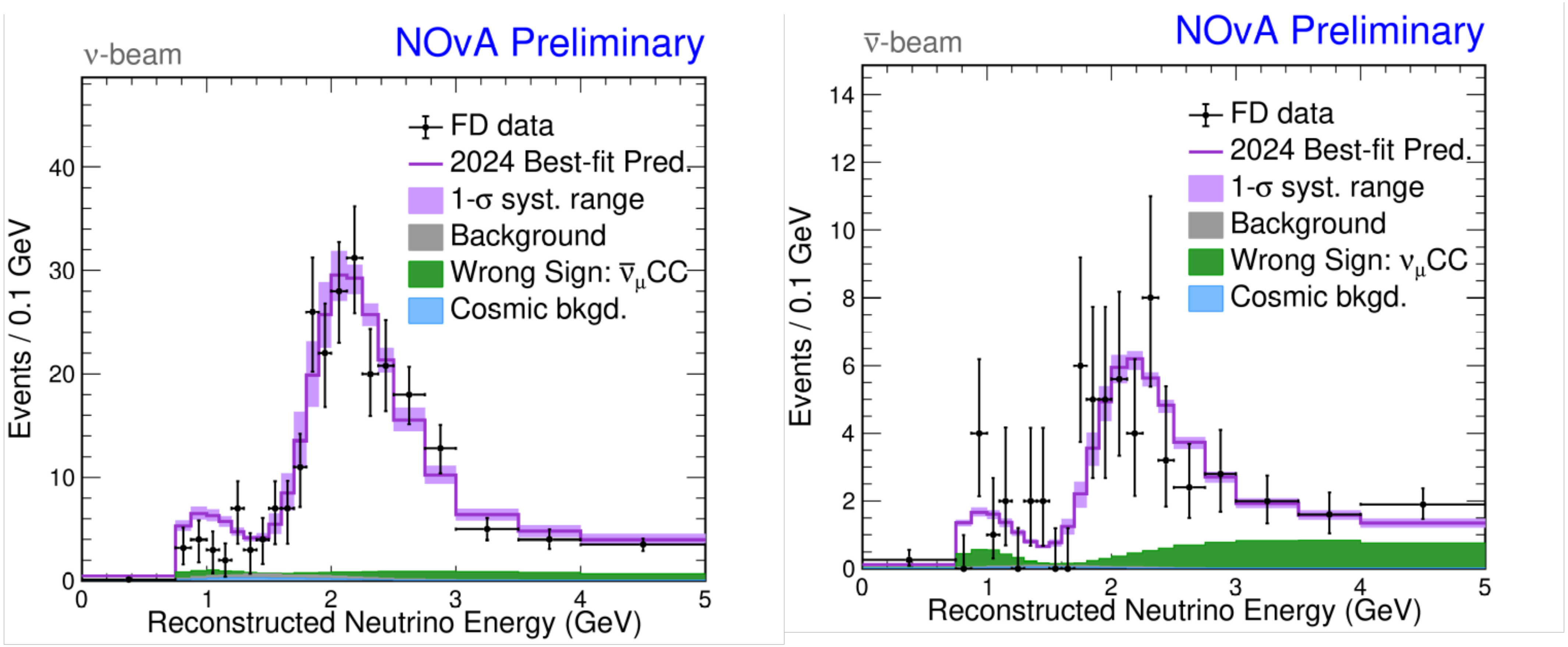


MW capable target, horn installed in 2019-2020

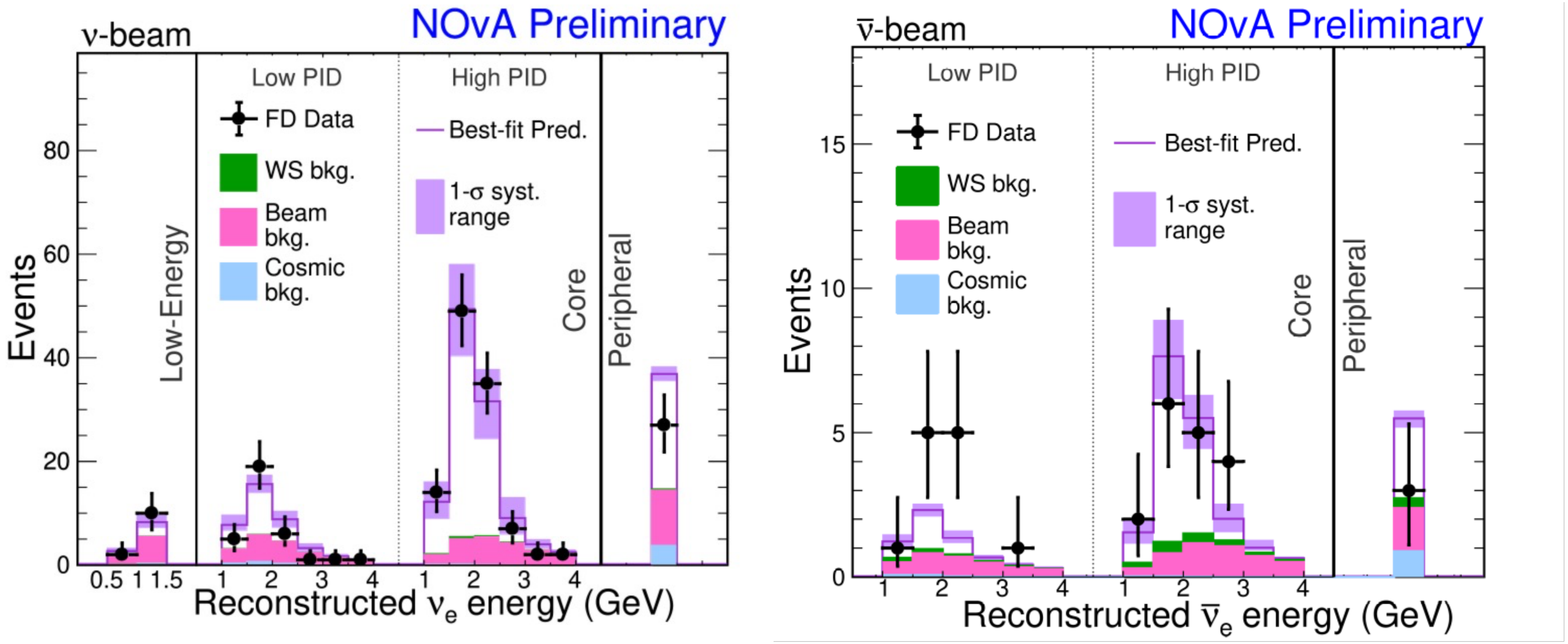
Typical NuMI beam power ~900kW, with record 959 kW in 2023

Achieved 1.018 MW record in June 2024!

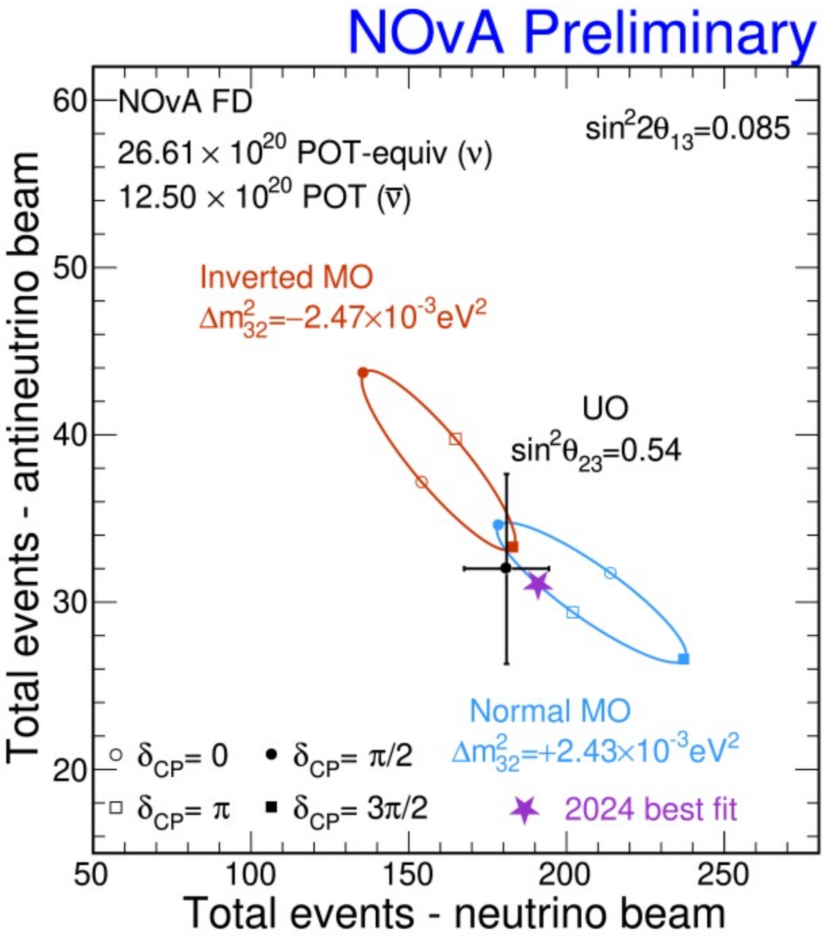
We observe 384 ν_μ and 106 $\bar{\nu}_\mu$ candidates in the FD. In the absence of oscillations, we'd expect ~2100 and ~500.



We observe 181 ν_e and 32 $\bar{\nu}_e$ appearance candidates in the FD. The predicted backgrounds are 62 and 12 respectively.

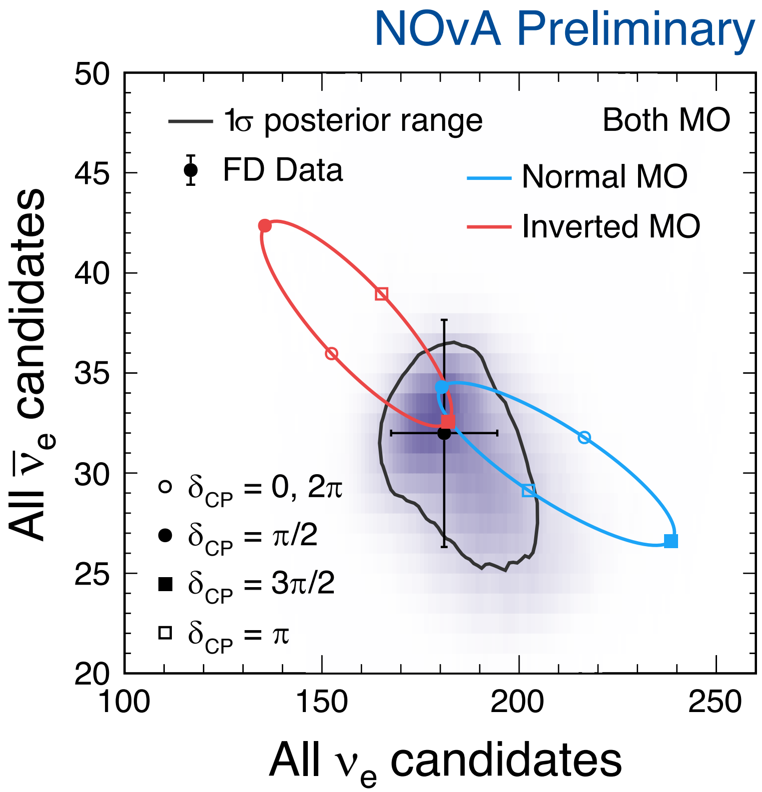


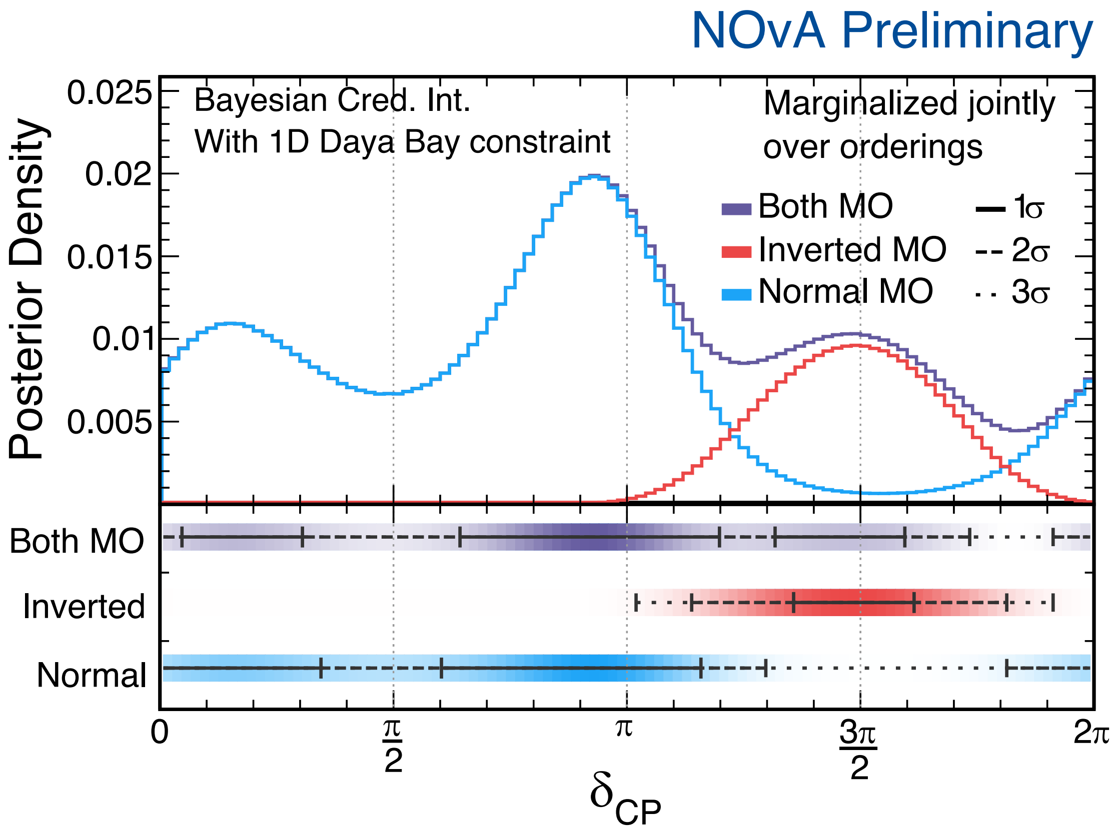
The appearance data favor a region where matter and CP violation effects are highly degenerate



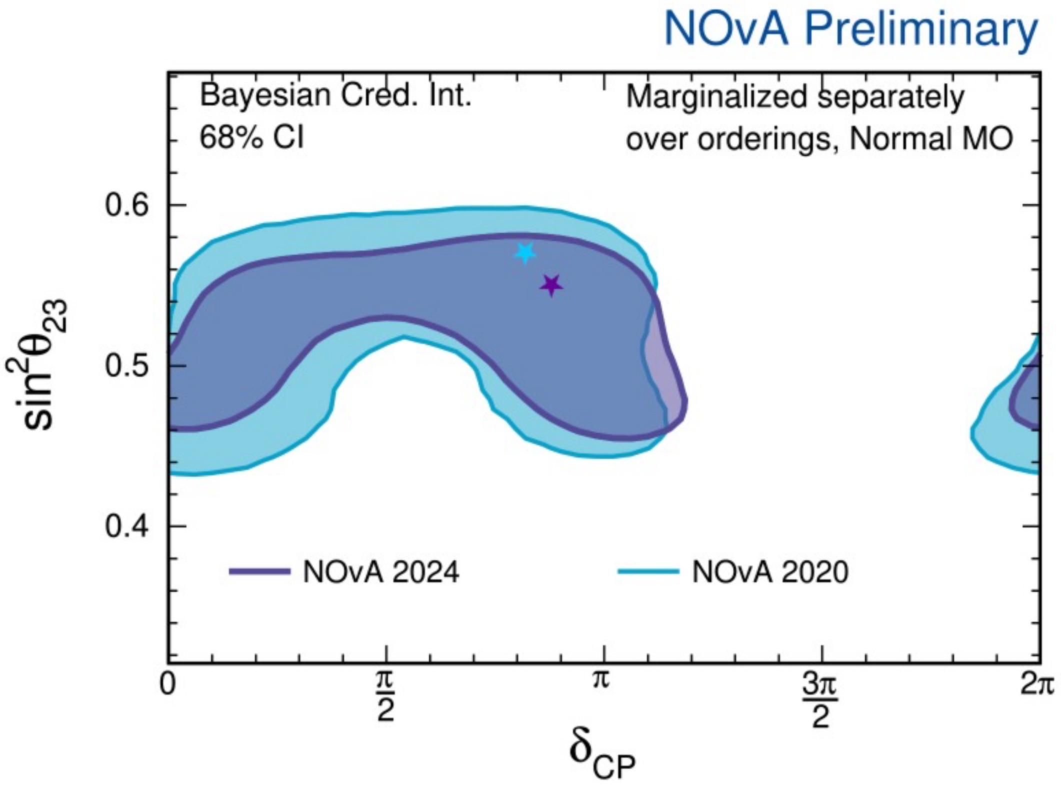
	Frequentist results (w/ Daya Bay 1D θ_{13} constraint)			
	Normal MO		Inverted MO	
Δm^2_{32} / 10^{-3} eV^2	+2.433	$^{+0.035}_{-0.036}$	−2.473	$^{+0.035}_{-0.035}$
$\sin^2\theta_{23}$	**0.546**	$^{+0.032}_{-0.075}$	0.539	$^{+0.028}_{-0.075}$
δ_{CP}	**0.88 π**		1.51 π	
Rejection significance (σ)			1.36	

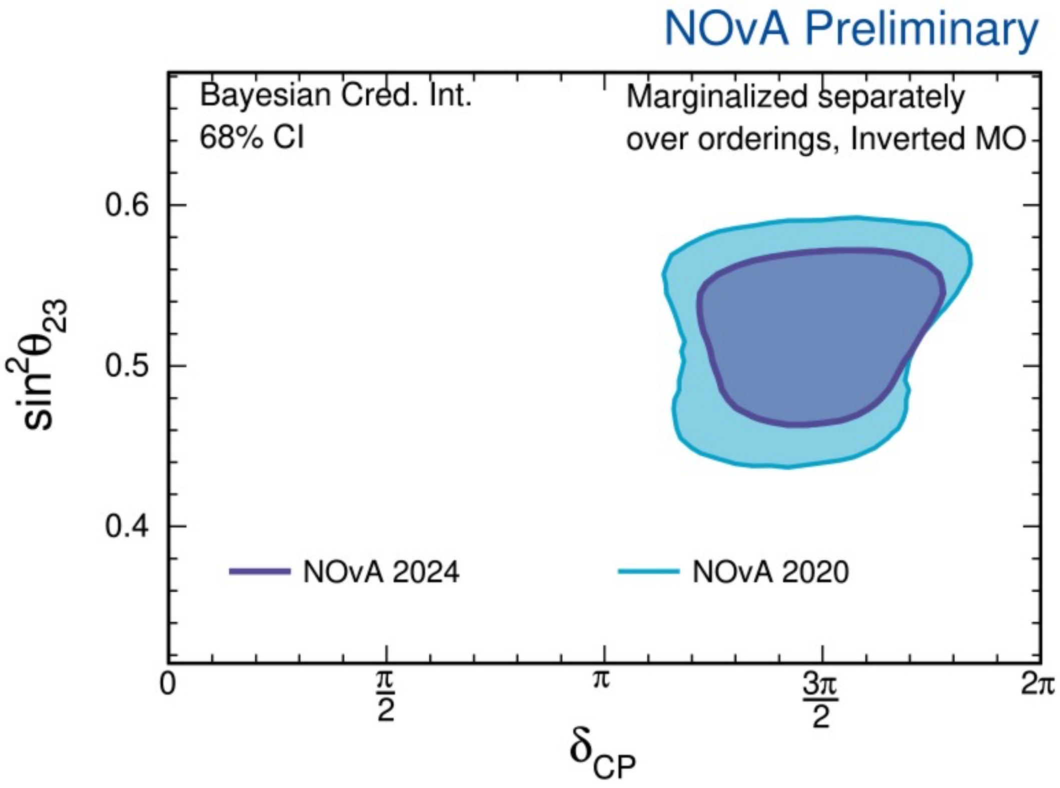
The data disfavor "extreme" asymmetry combinations: (IO, δ = π/2) and (NO, δ = 3π/2). CP-conserving points outside 3σ interval in IO





The new NOvA result is consistent with our previous analysis: improved constraints lie in ~ the same regions

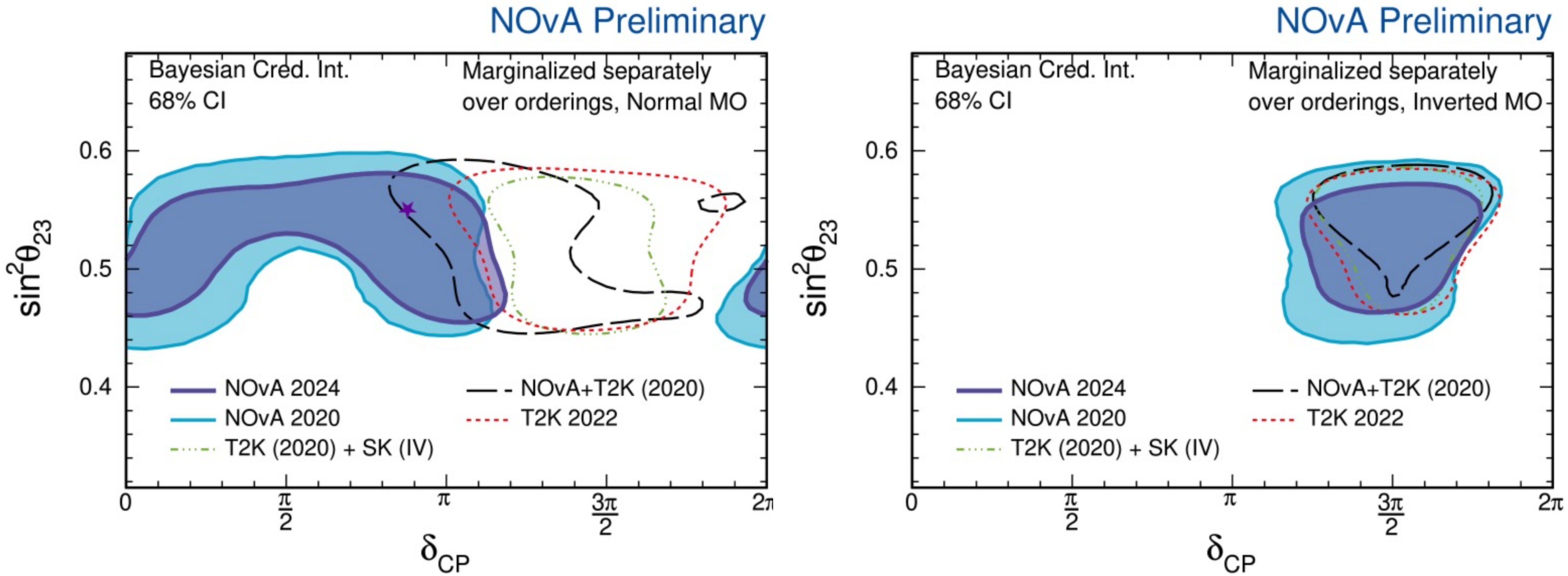




Note: results use different choices of reactor constraint

NOvA 2020 2019 PDG avg θ13
NOvA 2024: Daya Bay 2023 1D θ13

The new NOvA result is consistent with its previous analysis. T2K, joint fits, favor different regions in NO, same region in IO

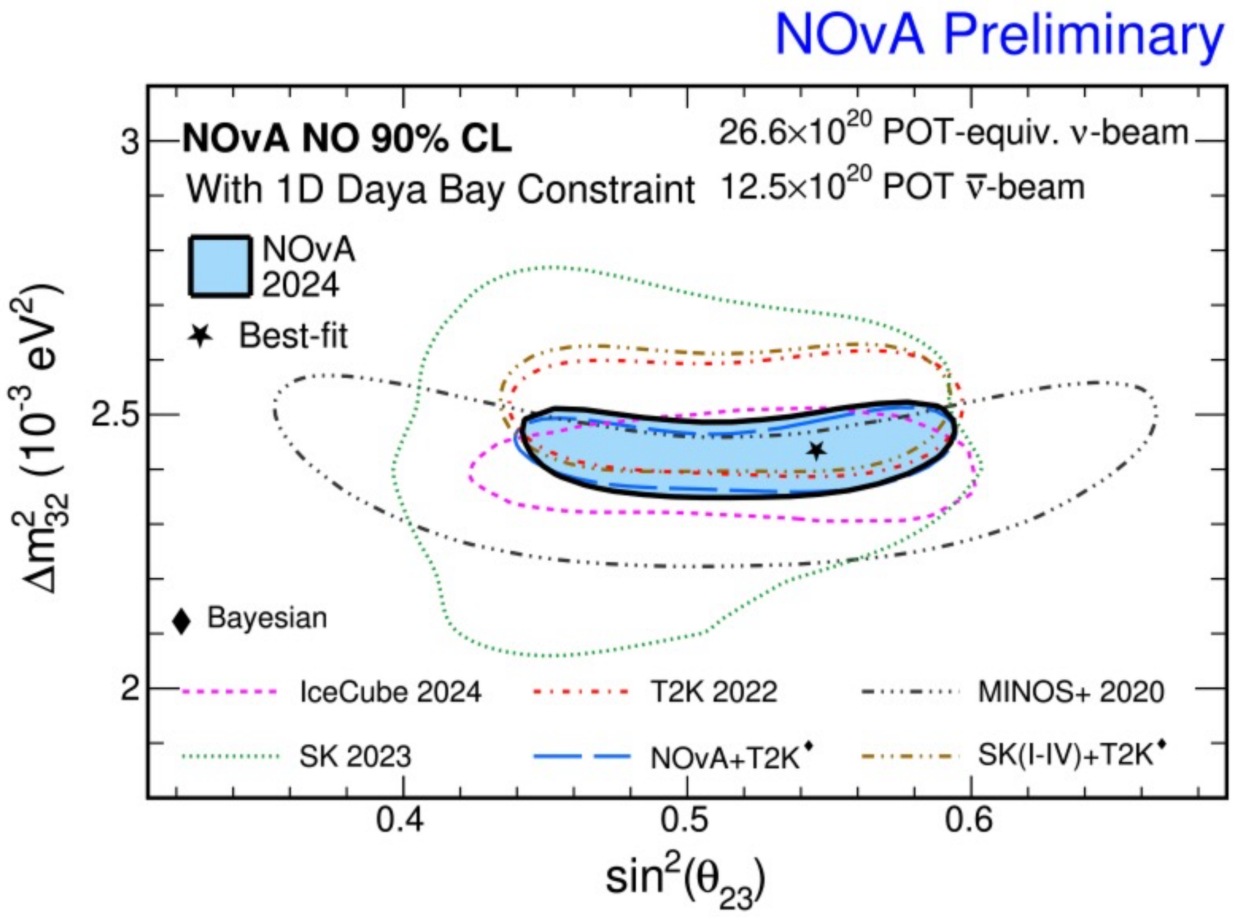


Note: results use different choices of reactor constraint

NOvA 2020 2019 PDG avg θ13
NOvA 2024: Daya Bay 2023 1D θ13

T2K 2019 PDG avg θ13
NOvA+T2K Daya Bay 2023 1D θ13
T2K+SK 2019 PDG avg θ13

In the ν2 – ν3 sector, our measurements are consistent with accelerator, atmospheric, and joint results



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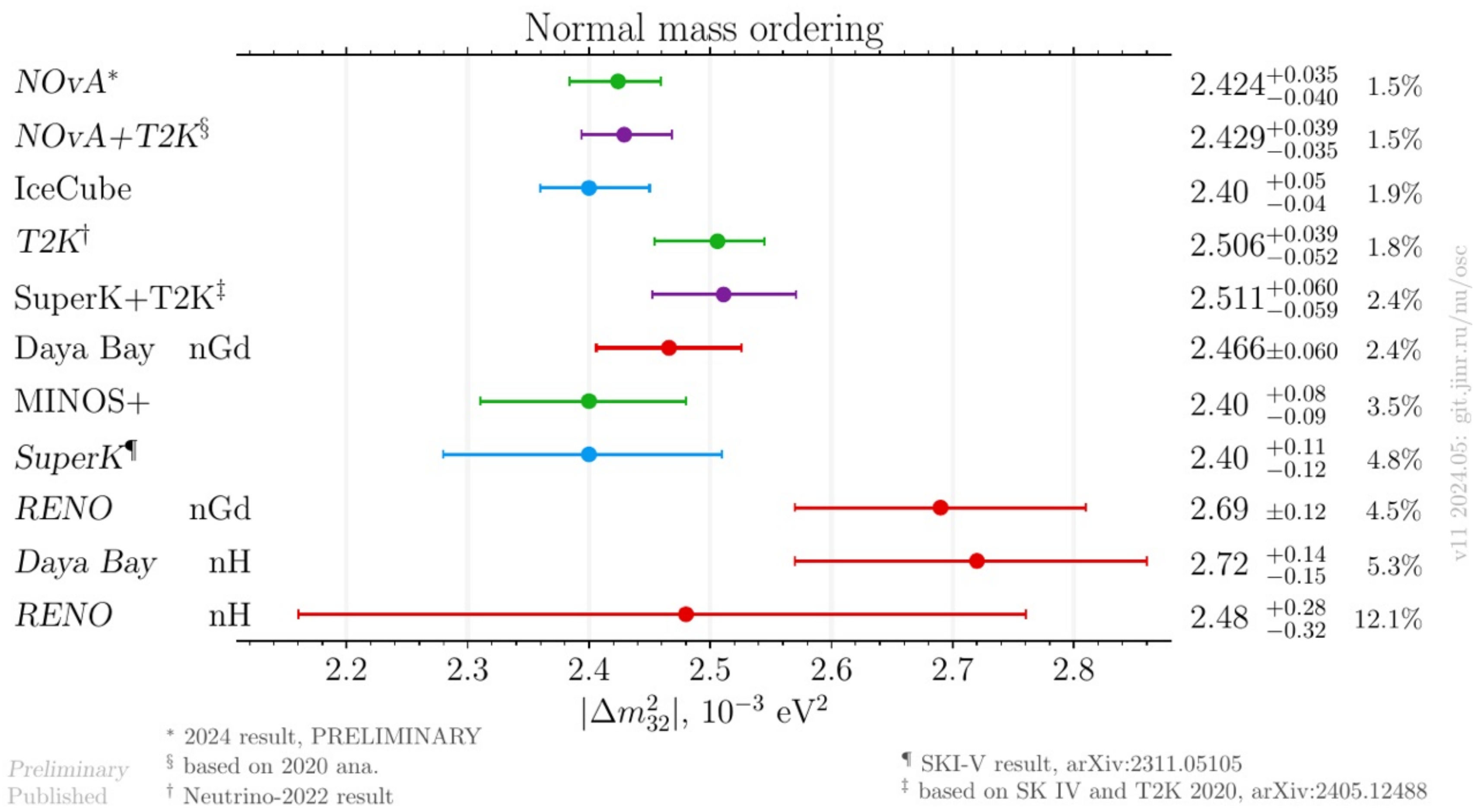
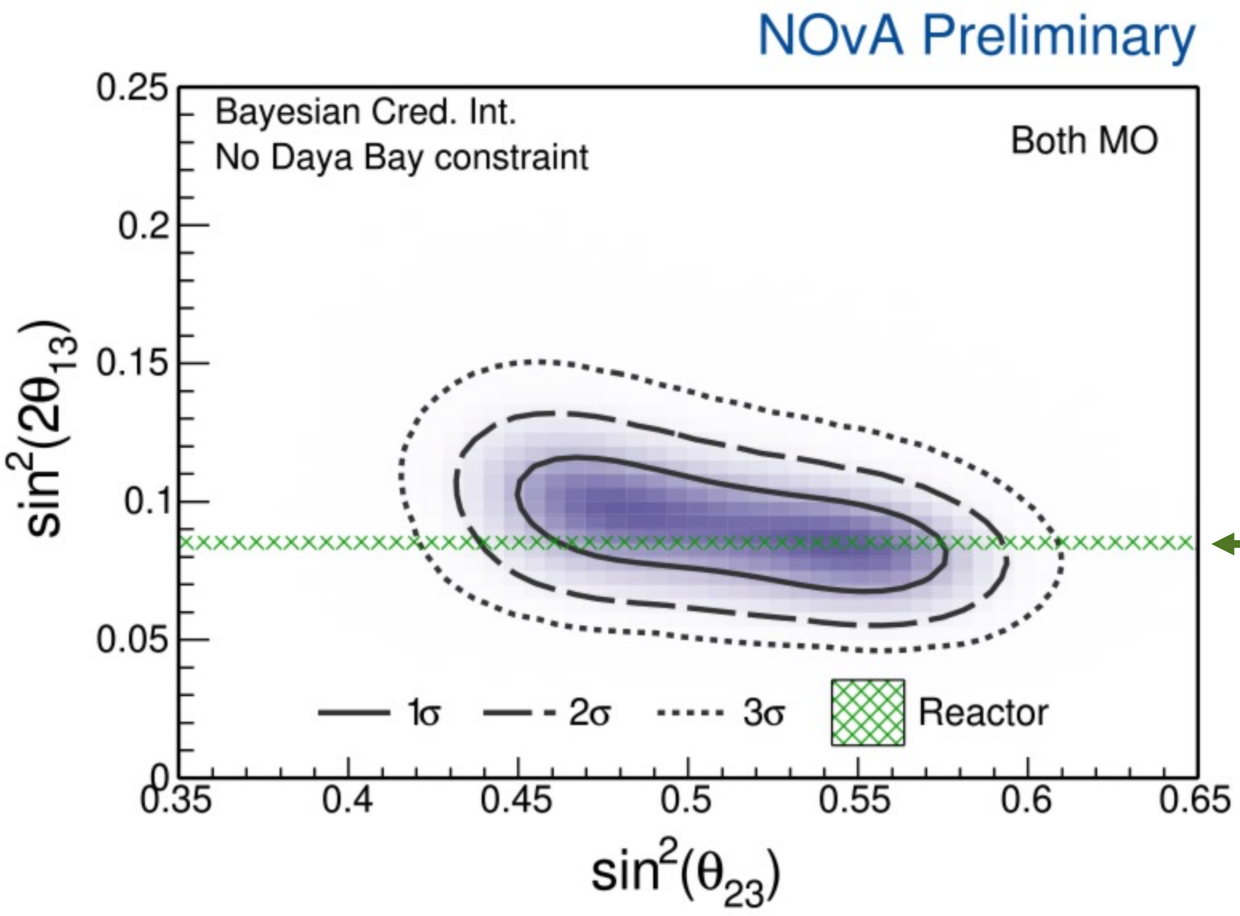
Rejection significance (σ)			1.36	

IceCube 2024: arXiv:2405.02163
T2K 2022: 10.5281/zenodo.6683821
MINOS+ 2020: Phys. Rev. Lett. 125, 131802
SK 2023: Phys. Rev. D109, 072014
NOvA+T2K 2024: KEK IPNS seminar, FNAL JETP seminar
T2K+SK 2024: arXiv:2405.12488

Δm^2_{32} is now the most precisely known PMNS parameter. NOvA's new result achieves a precision of 1.5%



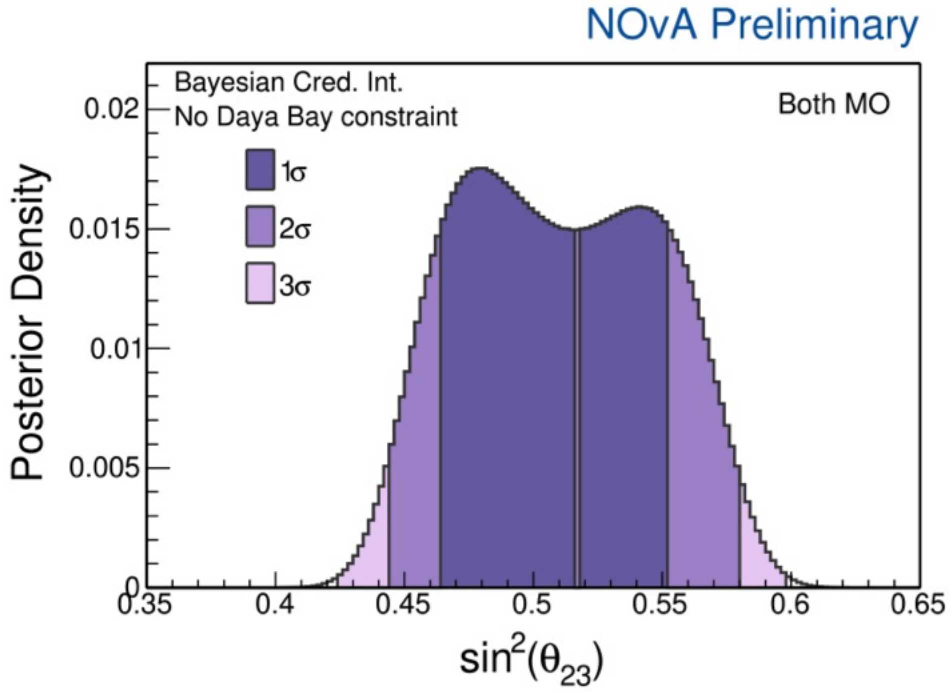
Without any external constraint from reactor experiments, there's a degeneracy between $\sin^2\theta_{23}$ and $\sin^2 2\theta_{13}$

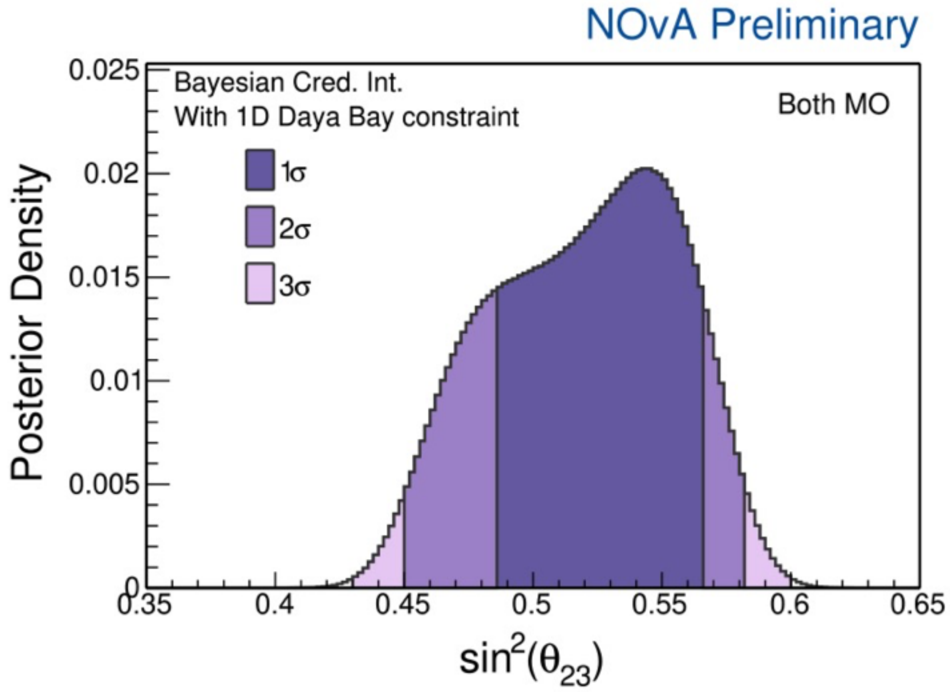


θ_{13} unconstrained
(NOvA only)

Daya Bay 1D θ_{13} constraint
$\sin^2 2\theta_{13} = 0.0851 \pm 0.0024$

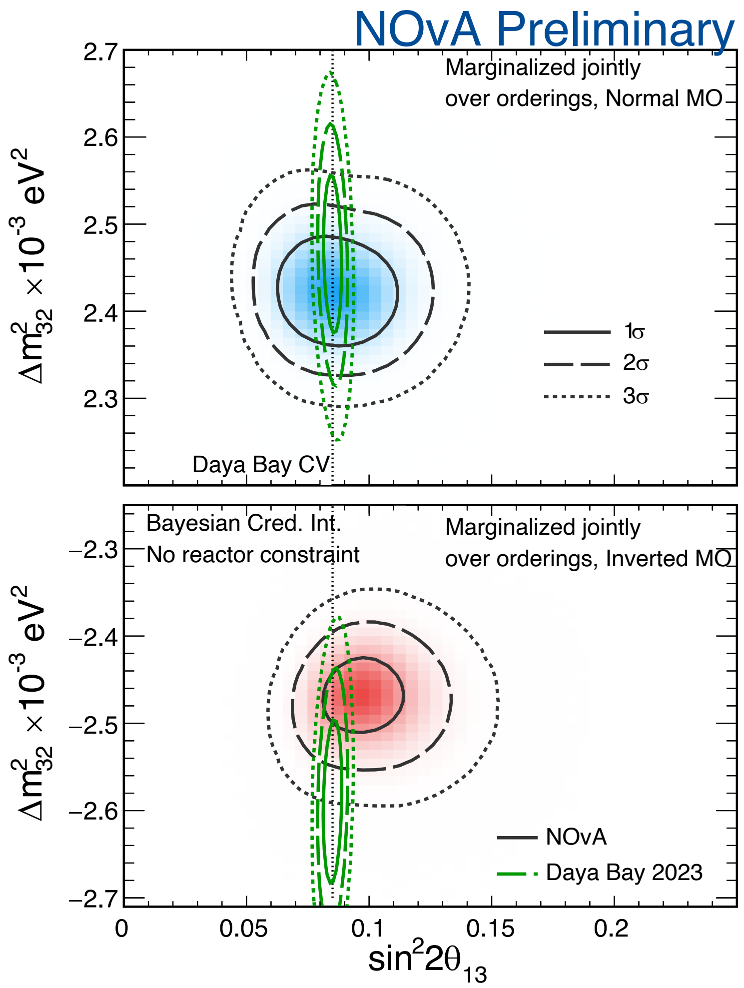
The NOvA results show a mild preference for the upper octant that emerges from applying the reactor constraint. Maximal mixing is allowed at <1σ





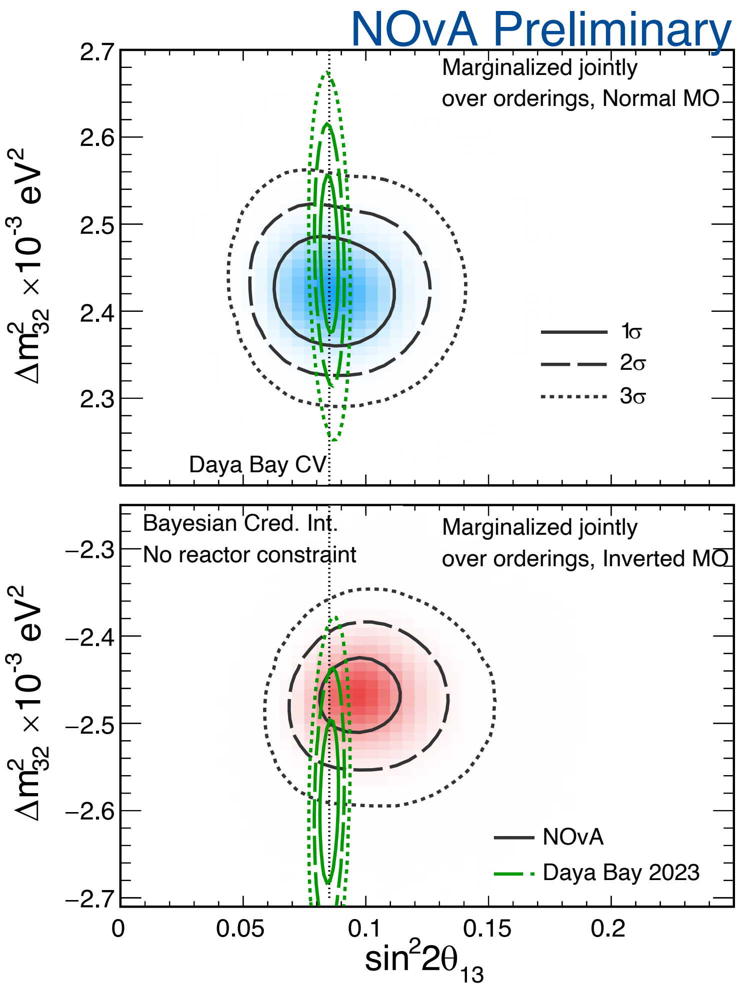
	No constraint		Daya Bay 2023 1D θ13	
	Probability	Bayes Factor	Probability	Bayes Factor
Upper Octant preference	**57%**	1.3	**69%**	2.2

Precision measurements of Δm^2_{32} in both accelerator and reactor experiments offer more ways to resolve degeneracies



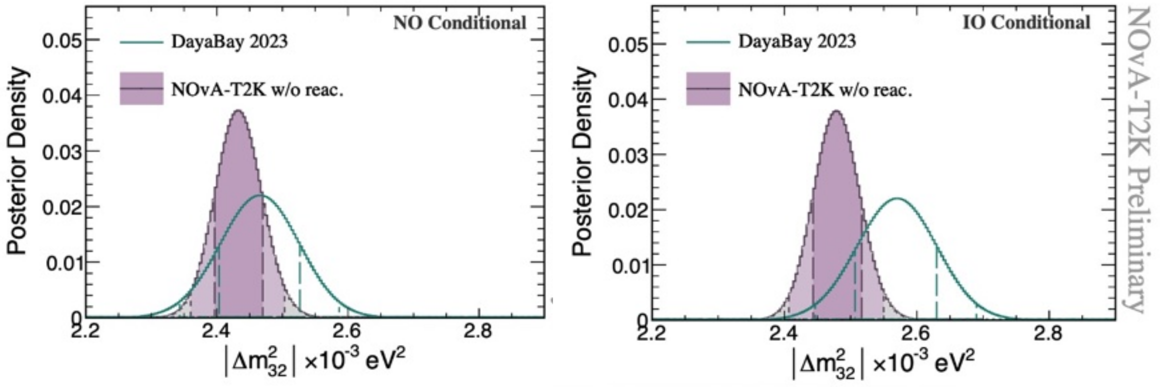
Daya Bay
2D (Δm^2_{32}, θ_{13})
constraint
(PRL 130, 161802)

Precision measurements of Δm^2_{32} in both accelerator and reactor experiments offer more ways to resolve degeneracies



Daya Bay
2D (Δm^2_{32}, θ_{13})
constraint
(PRL 130, 161802)

Z. Vallari



- In the true mass ordering, reactor and long-baseline measurements of Δm^2_{32} would be consistent but in the incorrect mass ordering would be wrong by different amounts.

See: Stephen Parke W&C, 2023 *Phys. Rev. D 72: 013009, 2005

Another possible way to determine the Neutrino Mass Hierarchy

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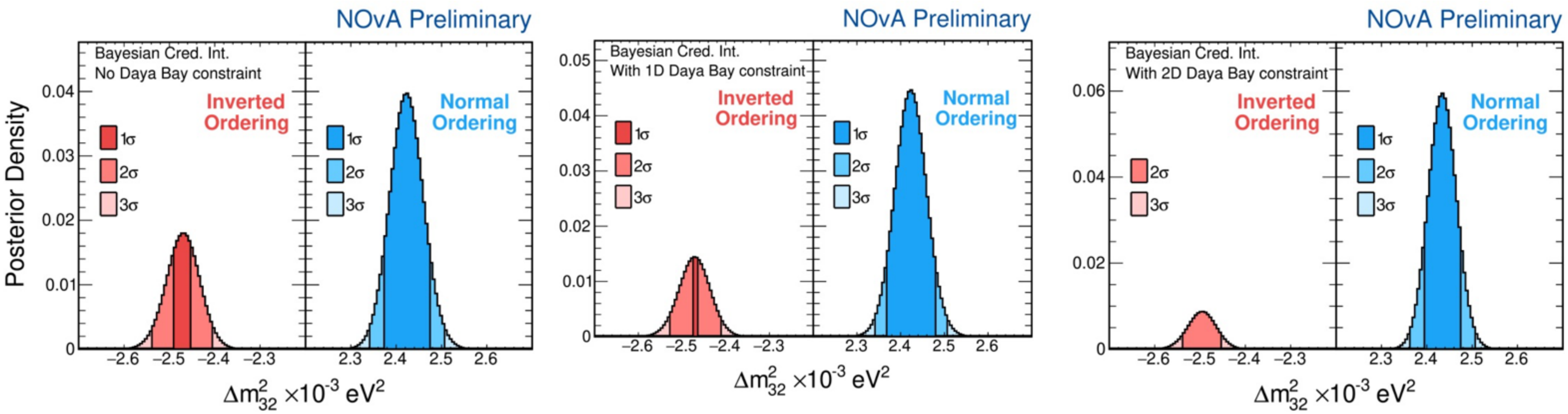
NOvA data prefer the normal mass ordering. This preference is enhanced by applying reactor constraints (1D and 2D)



	No constraint		Daya Bay 2023 1D $\sin^2 2\theta_{13}$		Daya Bay 2023 2D $(\sin^2 2\theta_{13}, \Delta m_{32}^2)$	
	Probability	Bayes Factor	Probability	Bayes Factor	Probability	Bayes Factor
Normal MO preference	**69%**	2.2	**76%**	3.2	**87%**	6.8

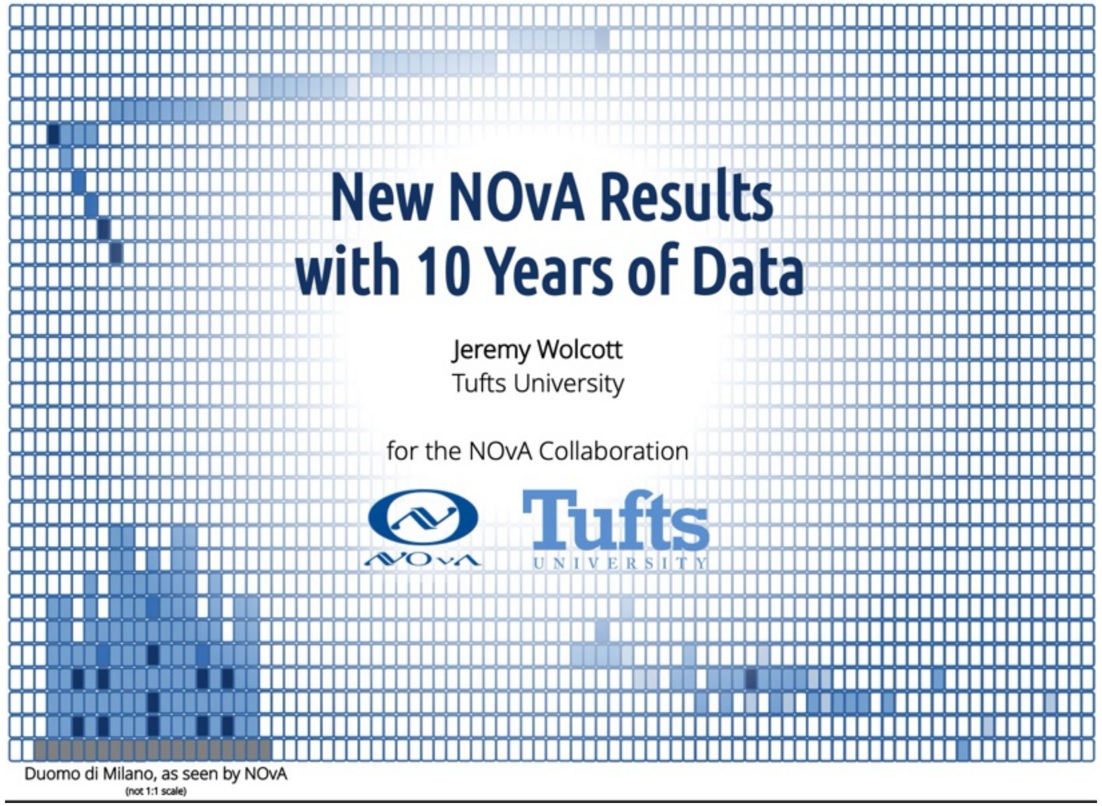
Summary

Summary and Outlook

- **The NOvA 2024 analysis is the first large update since 2020**
  - Doubled neutrino-mode dataset with 10 years of neutrino & antineutrino data
  - Updated simulation, including improved light response model and neutron propagation uncertainty
  - New low-energy νe candidate sample
- **NOvA's most recent oscillation analysis results:**
  - Most precise single-experiment measurement of Δm^2_{32} (1.5%)
  - Data favors region where matter, CP violation effects are degenerate
- **Strong synergy with reactor measurements**
  - Constraint on θ_{13} enhances Upper Octant preference (69% odds)
  - Constraint on Δm^2_{32} enhances Normal Ordering preference (87% odds)
- **NOvA has a bright future ahead**
  - Goal of doubling antineutrino dataset → Increased precision measurements of the osc. parameters, disentangle mass ordering / CPV?
  - Test beam results could address some of the largest systematic uncertainties in NOvA
  - Sterile searches, NSI, cross section measurements, cosmic ray physics, exotics… and more!

Backup

https://agenda.infn.it/event/37867/contributions/233955/




IIT Armour @ Rice

Beyond the standard 3-flavor picture... is there undiscovered physics impacting neutrino mixing and oscillations?

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

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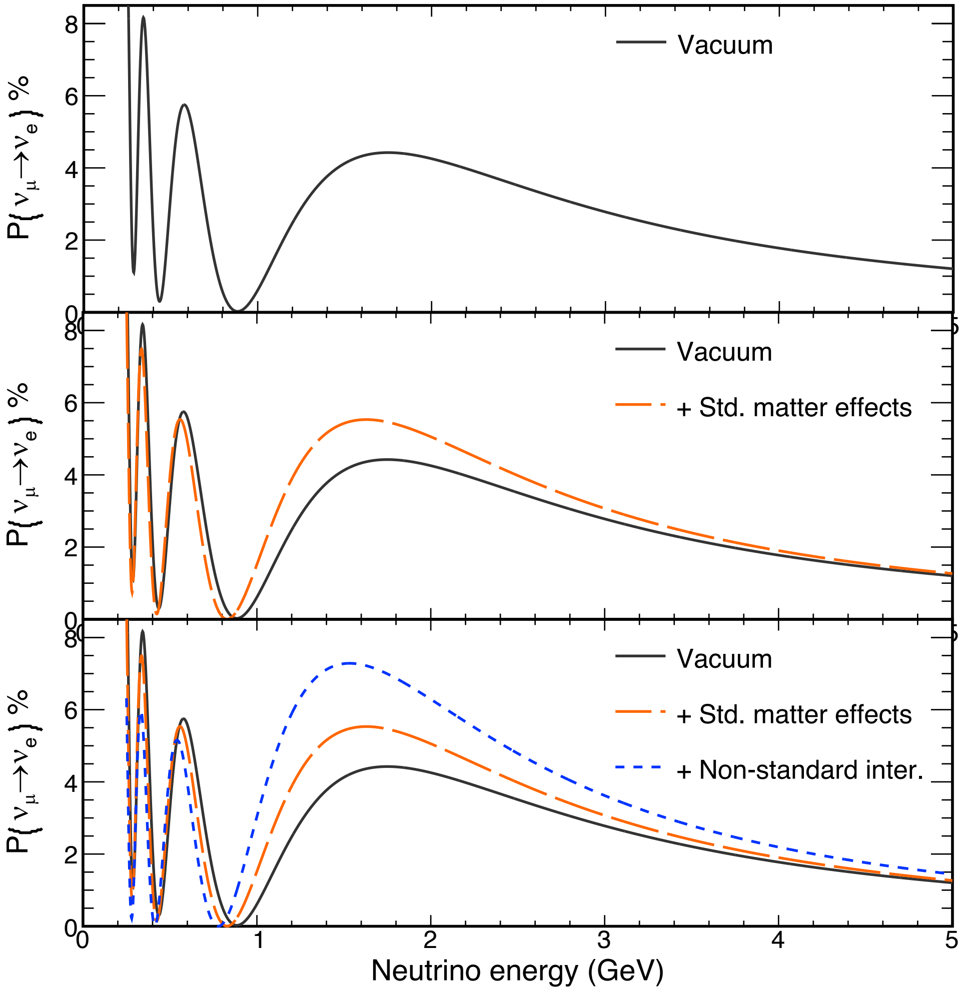
flavor-conserving

flavor-changing

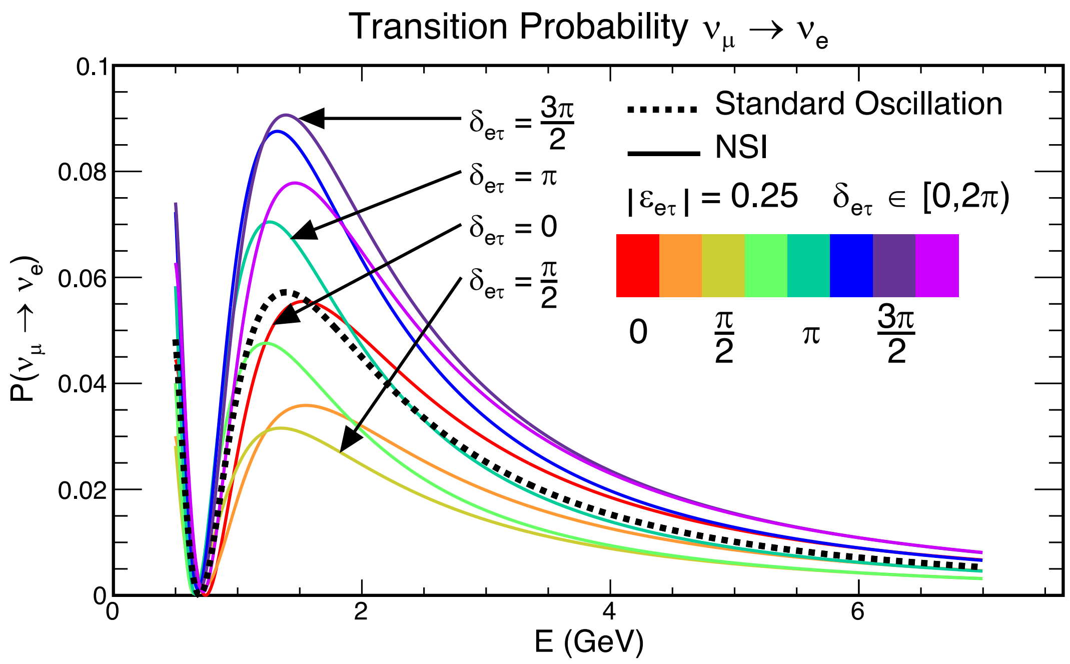


The off-diagonal complex terms introduce CP-violating phases. NOvA's $\nu_\mu \rightarrow \nu_e$ channel is sensitive to $\varepsilon_{e\mu}$ and $\varepsilon_{e\tau}$

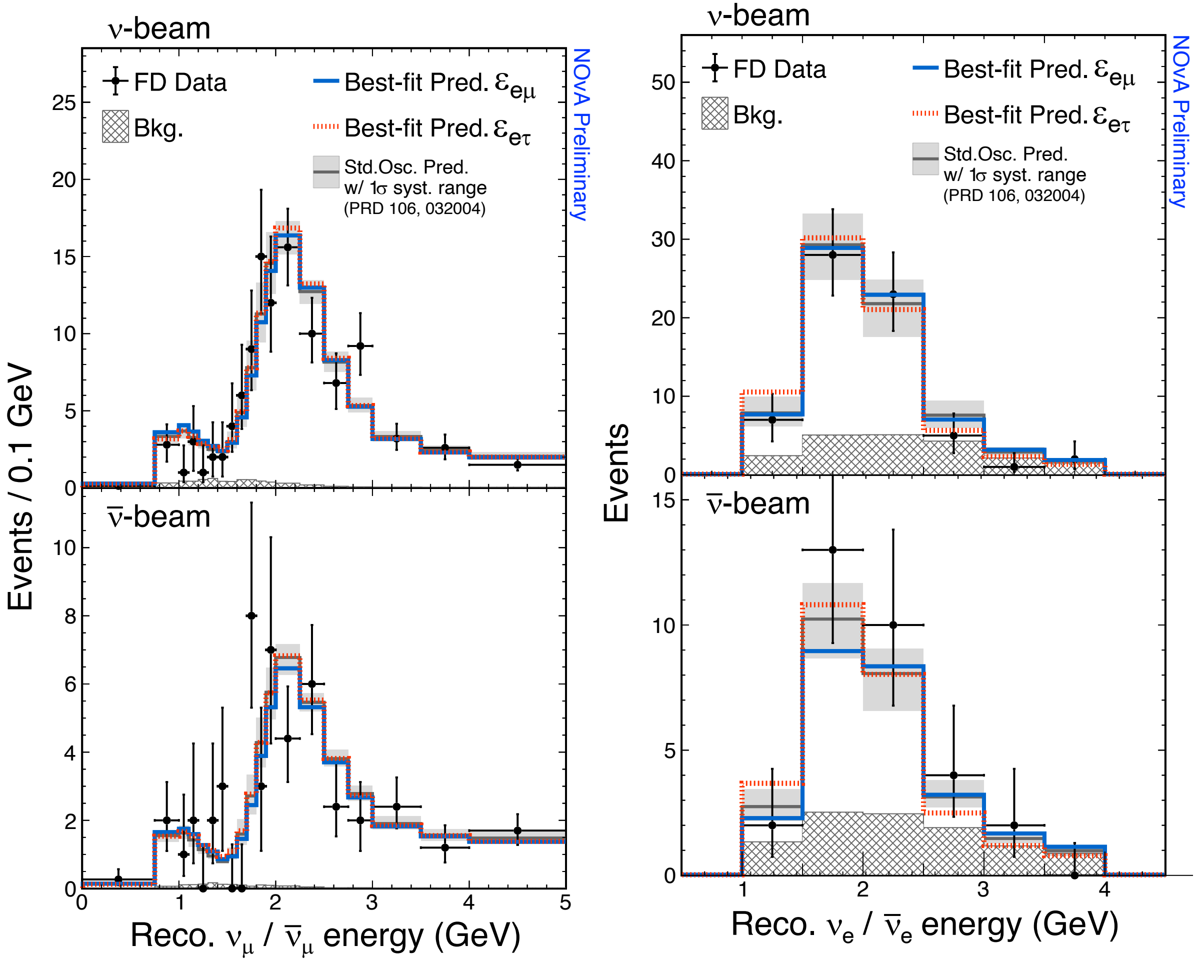
$$\varepsilon_{\alpha\beta} = \left|\varepsilon_{\alpha\beta}\right| e^{i\delta_{\alpha\beta}}$$

	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)



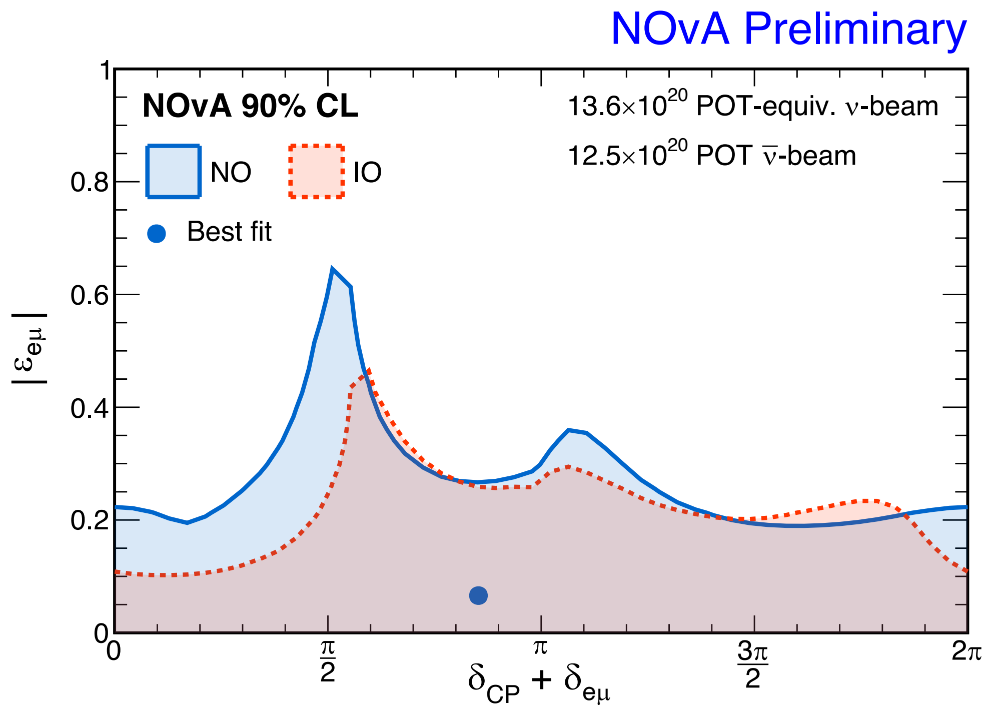
We re-analyze the data with added degrees of freedom to estimate the effect of non-zero NSI parameters $\varepsilon_{e\mu}$ and $\varepsilon_{e\tau}$

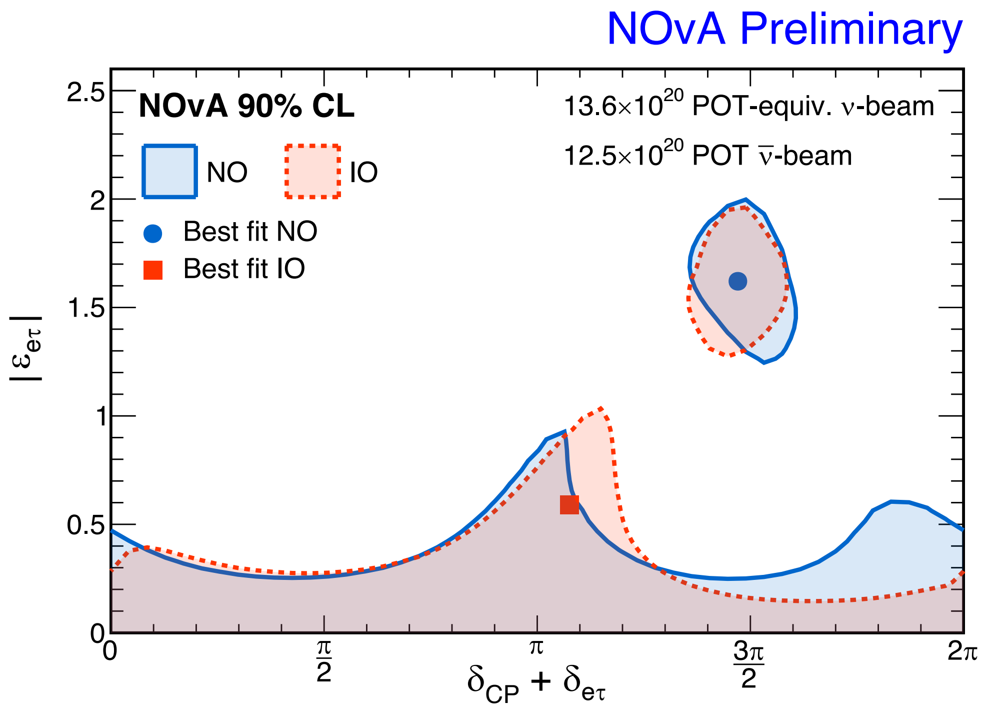


The NSI parameters $\boldsymbol{\varepsilon_{e\mu}}$ and $\boldsymbol{\varepsilon_{e\tau}}$ are added separately to the oscillation fit.

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})