Indian Institute of Technology Guwahati

Recent NOvA Results and Prospects

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(on behalf of NOvA Collaboration)

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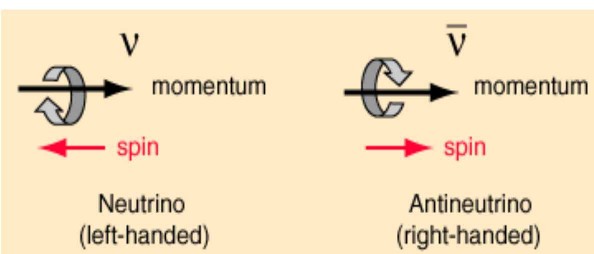
Neutrinos in the Standard Model

- Neutrinos
  - ✓ ν_e, ν_μ, ν_τ
  - ✓ $\bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau$
- Interacts only through weak force
  - ✓ Mediators: $W^{\pm}, Z^0$

✓ $m_\nu \approx 0$

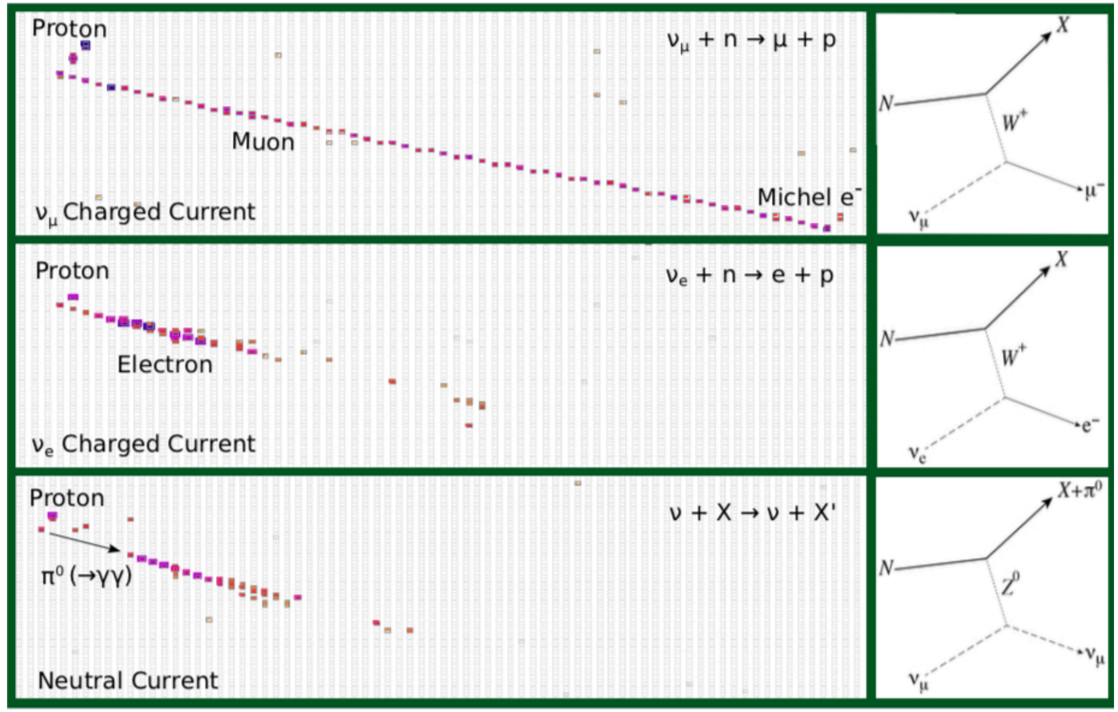
✓Neutrinos are left handed

- anti-neutrinos are right handed



✓ Neutrinos do not have electric charge. They only interact weakly.

- So, we see only the by products of the weak interactions.



✓ Neutrino interaction cross sections are small, $\mathcal{O}(10^{-38}\ cm^2/nucleon)$ at 1 GeV.

✓ Quite abundant: 100,000 billion pass through your body each second from the sun.

-Will stop ~1 neutrino which passes through it in a lifetime!

Neutrino: A new Identity in the last 25 years!

Standard Model

- Neutrinos interact through weak interaction.
- Lepton flavour is strictly conserved.
- Neutrino have zero mass.

Neutrino oscillations & Relative Neutrino Masses (confirmed by SNO, SuperKamiokande, T2K, NoVA etc.)

- Observed neutrino oscillation itself is a great triumph
  - Macroscopic manifestation of quantum effects.
- Indicates non-zero mass for neutrinos
  - Huge impact in particle physics & cosmology
- Neutrino mass states are different from flavor states.
  - As neutrinos travel, they change flavor
- Beyond standard model.

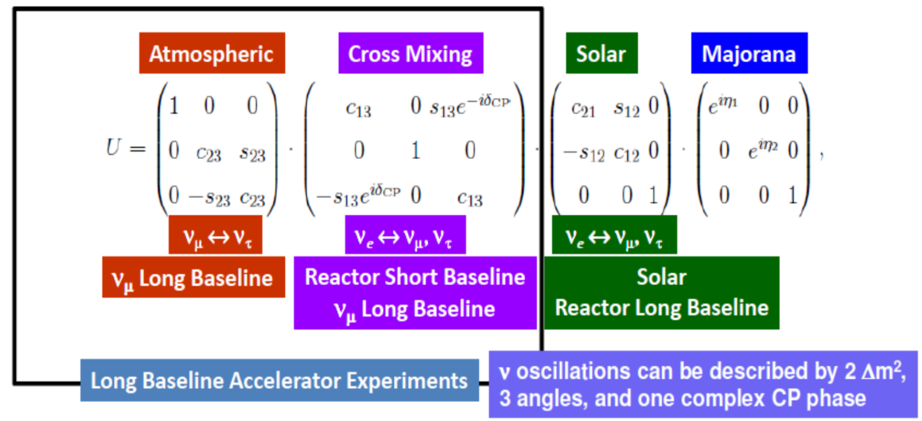
Neutrino Mixing

- Neutrinos mix, just like the quarks

$$|\nu_\alpha\rangle = \sum_k U^*_{\alpha k}\,|\nu_k\rangle$$

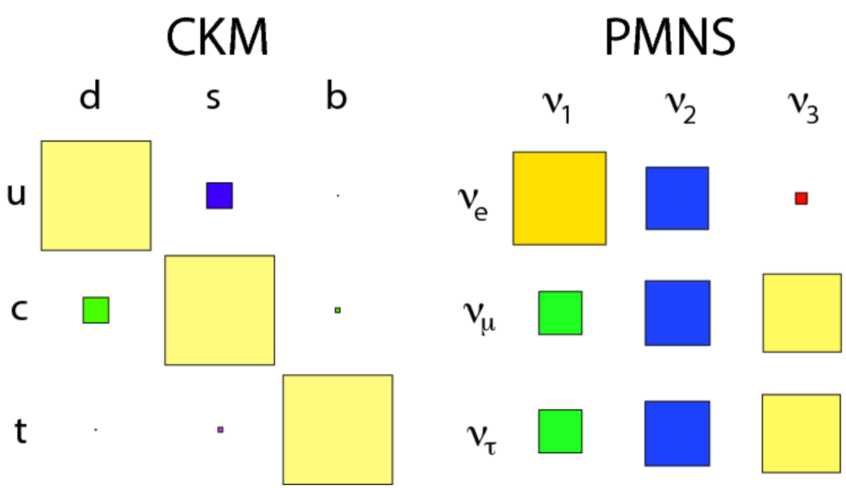
with $\alpha = e, \mu, \tau$ and $U^*_{\alpha k}$ is the unitary matrix.

- PMNS matrix. CKM matrix for quarks
- Unlike the quarks, mixings are large
  - All mixing angles and mass splitting have been measured.



Two flavor approximation:

$$P(\nu_\alpha \rightarrow \nu_\beta) \sim \sin^2(2\theta)\,\sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right)$$

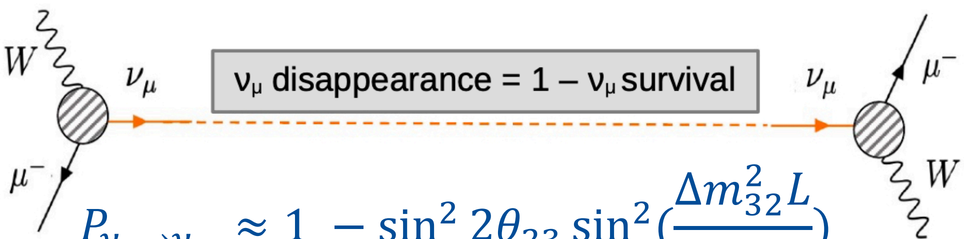


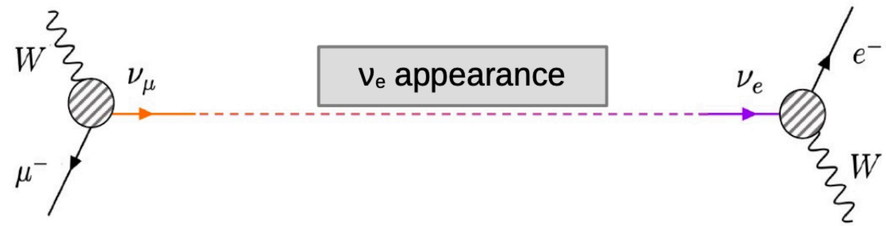
- Mixing results in oscillation; Probability of oscillation depends on:
  - ✓ Values of the parameters: $\delta_{CP}, \theta_{12}, \theta_{13}, \theta_{23}$
  - ✓ $\Delta m^2_{ij} = m^2_i - m^2_j$
  - ✓ Energy of the neutrino: E
  - ✓ Distance travelled (baseline): L

Neutrino Oscillation at LBL Experiments

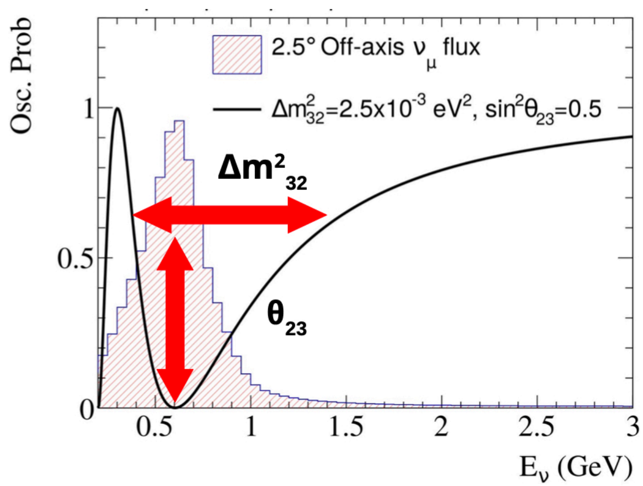
- Measure neutrino oscillations by sending neutrino beam across several hundreds of kms. Uses both ν_μ and $\bar{\nu}_\mu$ beam.

Study both $\nu_\mu/\bar{\nu}_\mu$ disappearance and $\nu_e/\bar{\nu}_e$ appearance in the Far detector.





$$P_{\nu_\mu \to \nu_x} \approx 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32} L}{4E_\nu}\right)$$



$$\begin{aligned} P_{\nu_\mu \to \nu_e} \approx\ & \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2((1-x)\Delta)}{(1-x)^2} \\ & - \alpha \sin 2\theta_{13} \sin\delta \sin 2\theta_{12} \sin 2\theta_{23} \sin\Delta \frac{\sin(x\Delta)}{x} \frac{\sin((1-x)\Delta)}{(1-x)} \\ & + \alpha \sin 2\theta_{13} \cos\delta \sin 2\theta_{12} \sin 2\theta_{23} \cos\Delta \frac{\sin(x\Delta)}{x} \frac{\sin((1-x)\Delta)}{(1-x)} \\ & + \alpha^2 \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(x\Delta)}{x^2} \end{aligned}$$

$$x = \frac{2\sqrt{2} G_F N_e E}{\Delta m^2_{31}} \qquad \Delta = \frac{\Delta m^2_{31} L}{4E} \qquad \alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$$

Leading order dependence on $\sin^2 2\theta_{23}, \Delta m^2_{32}$ *and* L/E

Sensitive to $\sin^2 2\theta_{13}$, $\sin^2\theta_{23}$, δ_{CP}, magnitude and sign of Δm^2_{32}

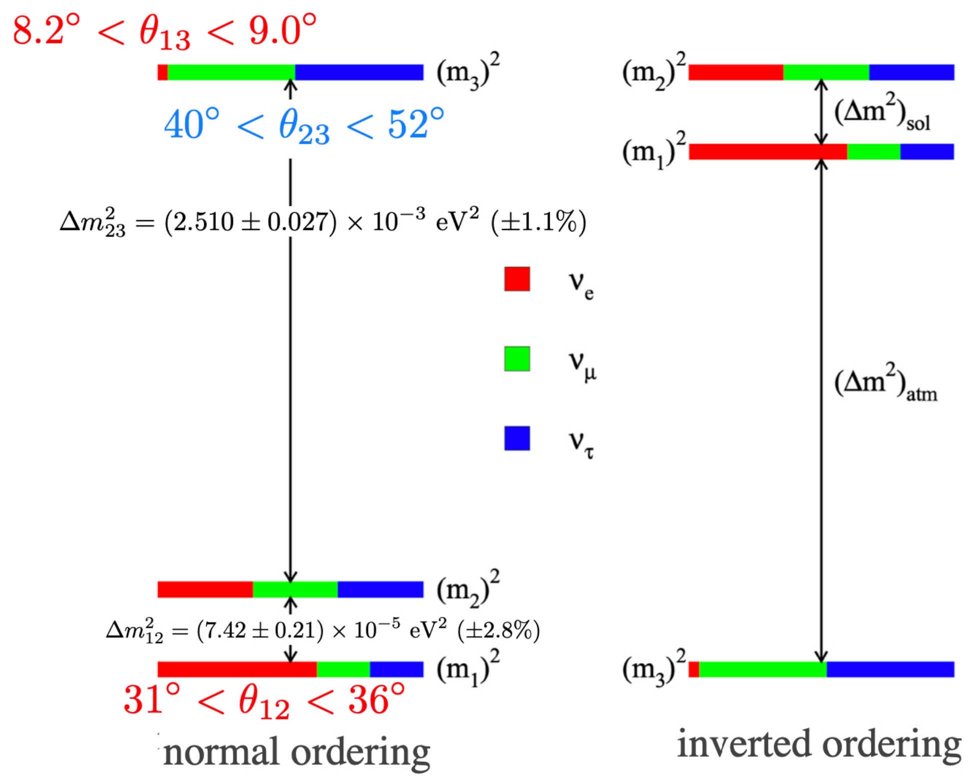
Matter effects modify oscillation probability.

Opposite impact of matter effects and δ_{CP} for ν and $\bar{\nu}$

- $\delta_{CP} = \frac{\pi}{2}$: fewer neutrinos, more anti-neutrinos
- $\delta_{CP} = \frac{3\pi}{2}$: more neutrinos, fewer anti-neutrinos.

Key Questions for LBL Experiments

- So far only the mass squared difference between neutrino mass states have been measured
  - Two states have similar mass, one is different
- Is it 2 light states + 1 heavy state or 2 heavy states + 1 light state?



arXiv:2102.00594 NuFit, arXiv:2111.03086

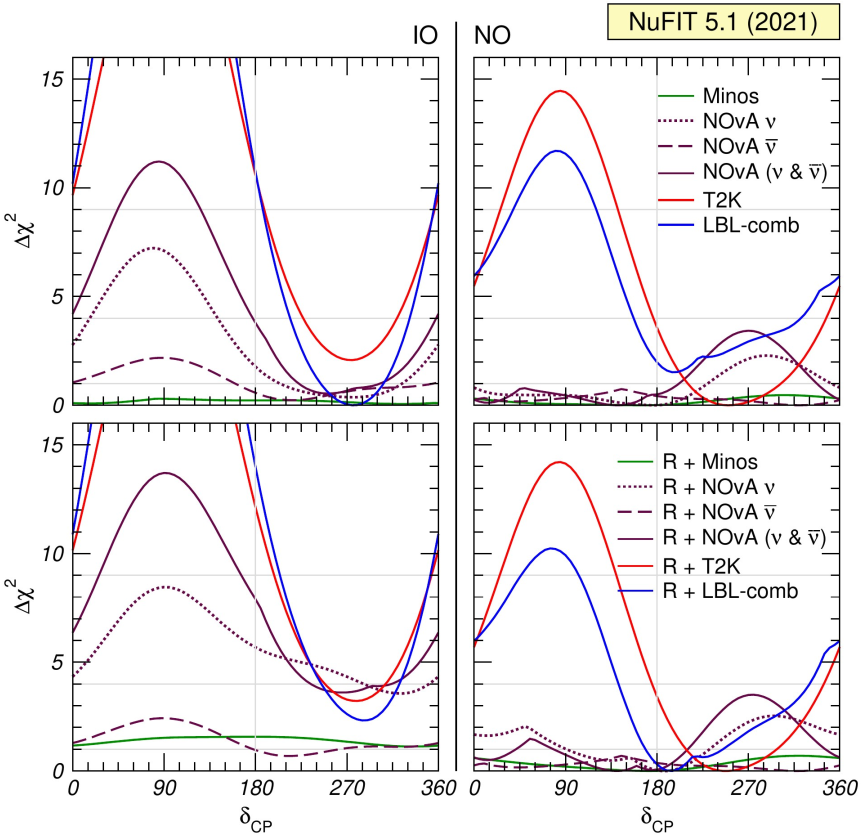
Important for Neutrino-less double beta decay searches.

Key Questions for LBL Experiments

- Discovery of CP violation in the lepton sector ($\delta_{CP} \neq 0\ or\ \pi$)
  - Important for theories of lepto-genesis.
  - The observed CP violation in the quark sector is too small to explain all the matter anti-matter asymmetry in the universe.
  - CP violation in the lepton sector will shed more light on the problem
    - Measurement of δ_{CP} is critical.

Some experiments slightly favor ($< 3\sigma$) $\delta_{CP} \sim 270° \ (-90°)$

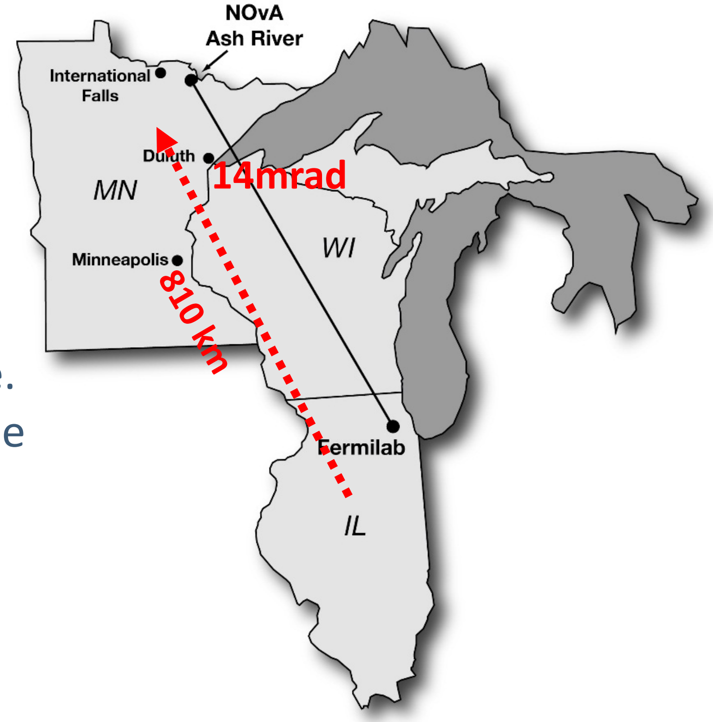
Combined results from Reactor +LBL Experiments is far from stable.



- Octant of θ_{23} ($\sin^2\theta_{23} > 0?$)
  - If $\theta_{23} = 45° \rightarrow |U_{\mu 3}| = |U_{\tau 3}|$

NuMI Off-Axis ν_e Appearance (NOvA) Experiment

- NOvA is a long baseline (810 km) neutrino oscillation experiment.
- Uses an artificial ν_μ beam of intensity ~900 kW mostly. **Recent NuMI record: 1.018 MW.**
- Near detector at Fermi Lab and the far detector at Ash River.
- Two functionally identical detector differing in size.
- The two detectors are located 14 mrad off from the on-axis.



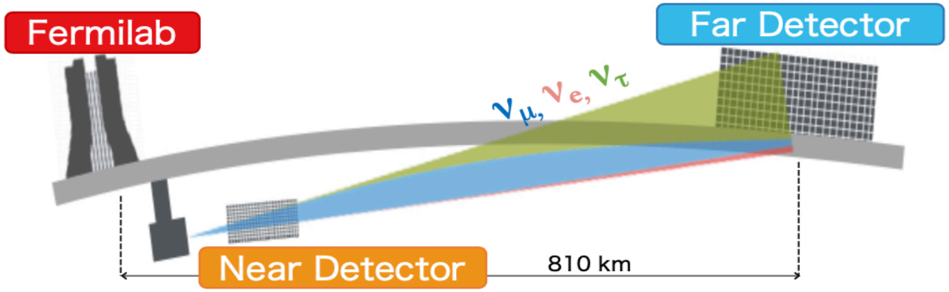
Experiment goals:

Using $\nu_\mu \rightarrow \nu_\mu$ $(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$

- ✓ Precise measurement of Δm^2_{32}
- ✓ Mixing angle θ_{23}

Using $\nu_\mu \rightarrow \nu_e$ $\left(\bar{\nu}_\mu \rightarrow \bar{\nu}_e\right)$

- ✓ Neutrino mass hierarchy
- ✓ CP violating phase
- ✓ Mixing angle θ_{23}



NOvA Detectors

Far Detector
14 kton
344k channels

2008: Construction starts

2014: Starts Operation

Near Detector
0.3 kton
20k channels

100 m underground
1 km baseline

The NOvA Collaboration

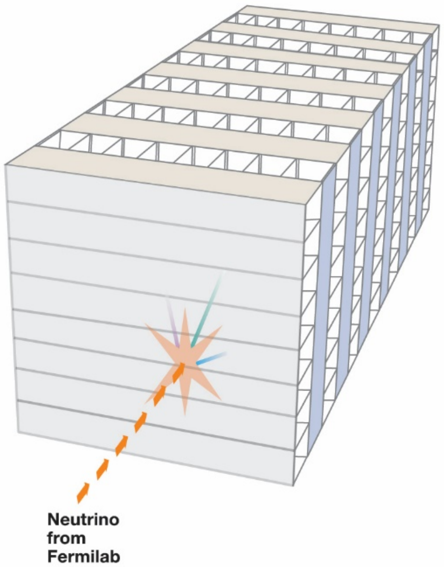
211 members from 50 institutions in 8 countries.

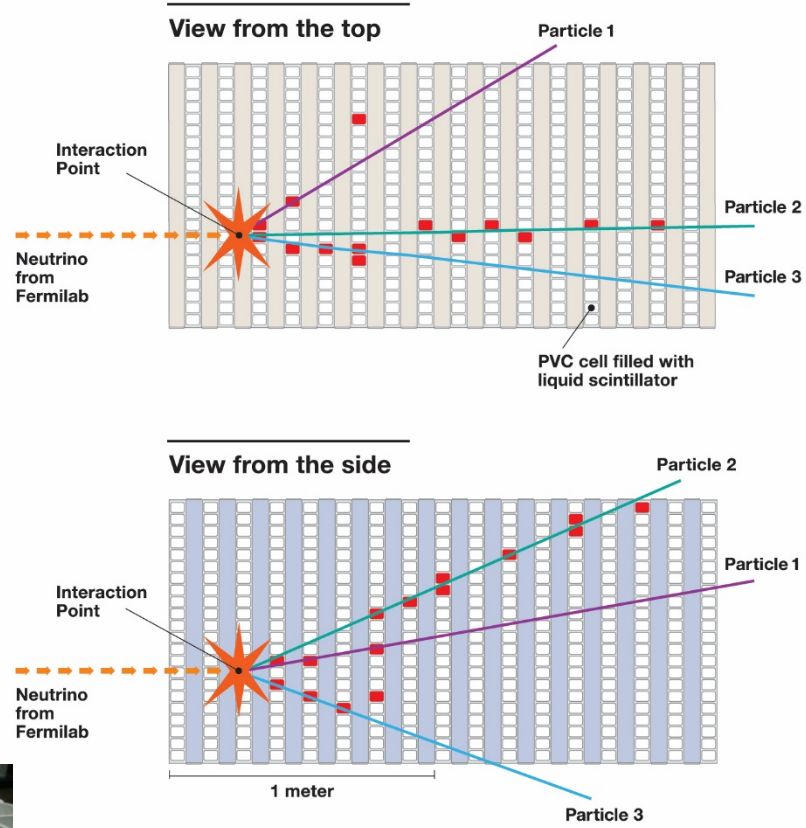
9 institutions from India.

- ✓ **Graduated 11 Ph.D. students**
- ✓ **8 Ph.D. students are currently on NOvA**

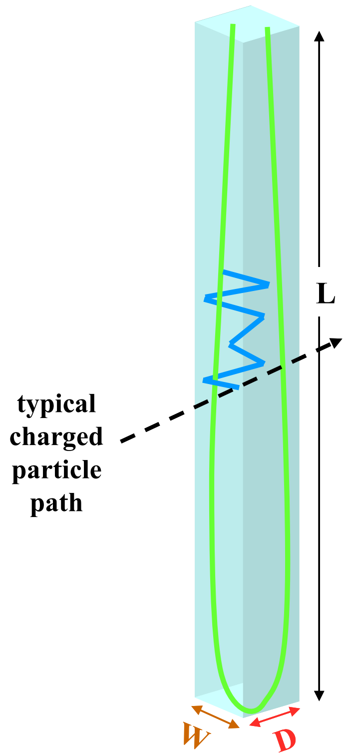
NOvA Detectors Capability

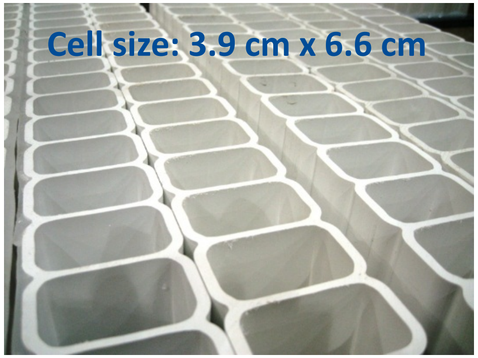
Detector elements:
PVC cells with 15% TiO_2, liquid scintillator, WLS fibers and APDs.





NOvA detectors are finely segmented (1 plane ~0.15 X0), which makes ***it well optimized for electromagnetic shower reconstruction.***

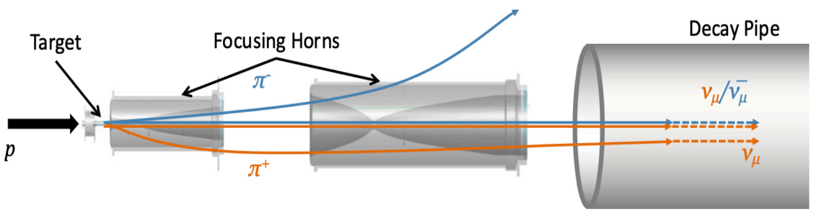


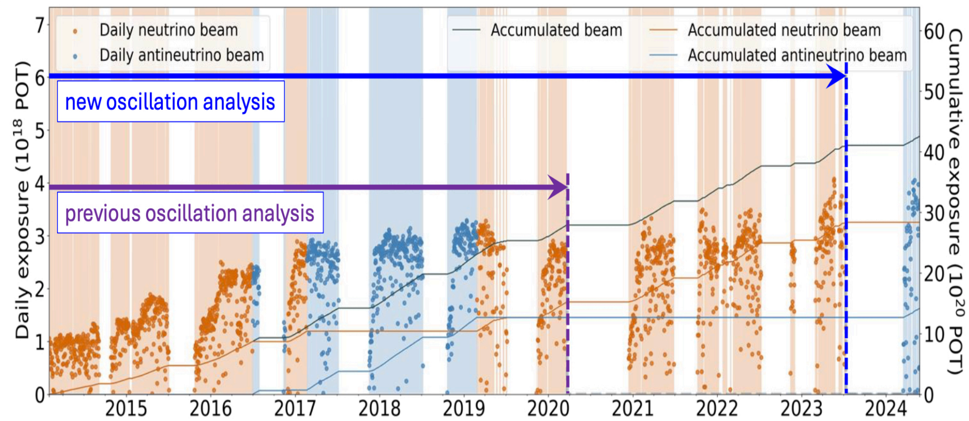


Fine-grained, low-Z, highly-active tracking calorimeter allows for differences between muons electrons, and π^0's to be seen.

Neutrino Beam and the Dataset

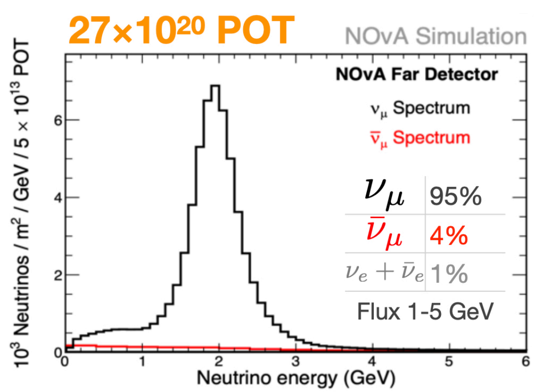
- 120 GeV protons on a carbon target, produce mesons which subsequently produces neutrinos through leptonic decays.

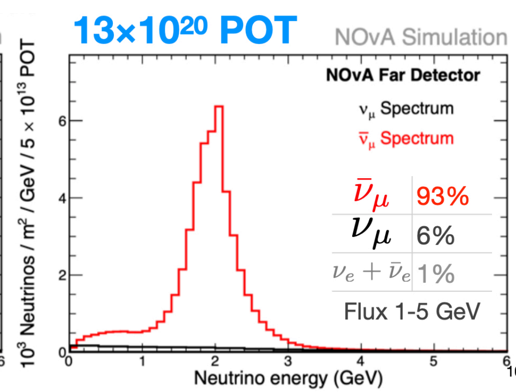




Cumulative Exposure (in units of 10^{20} POT)

	2020		2023
ν beam:	14	→	**27**
$\bar{\nu}$ beam:	13	→	13



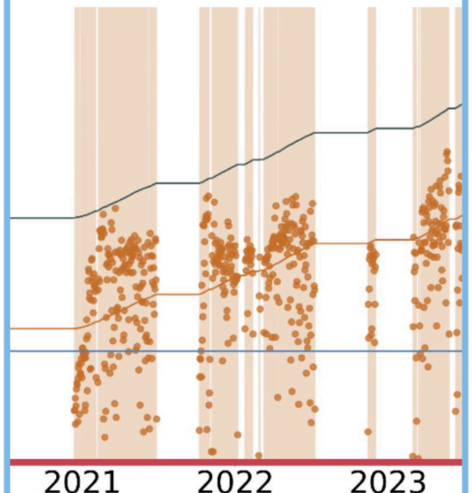


Now configured for $\bar{\nu}$ running.

Oscillation results from NOvA only with data collected till 2023. **Double the neutrino data since 2020.**

Improvements in the 2024 Analysis

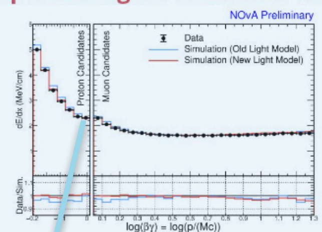
~2x Neutrino Mode Data



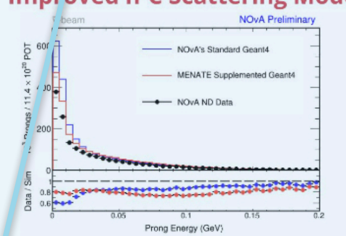
More statistics

Detector Characterization

Improved Light Production Model



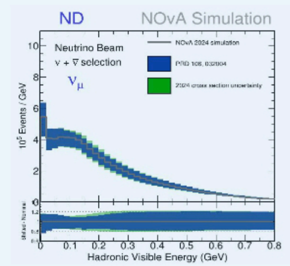
Improved n-C Scattering Model



Better data/MC agreement at high dE/dx.

Cross Section Modeling

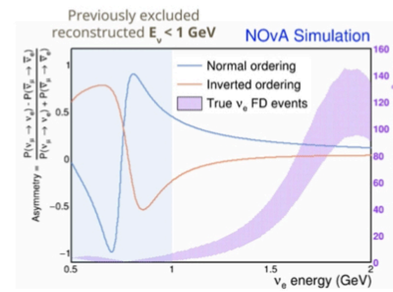
Additional Systematic Uncertainties for Pion Production



Simulation improvements

Low Energy ν_e Sample

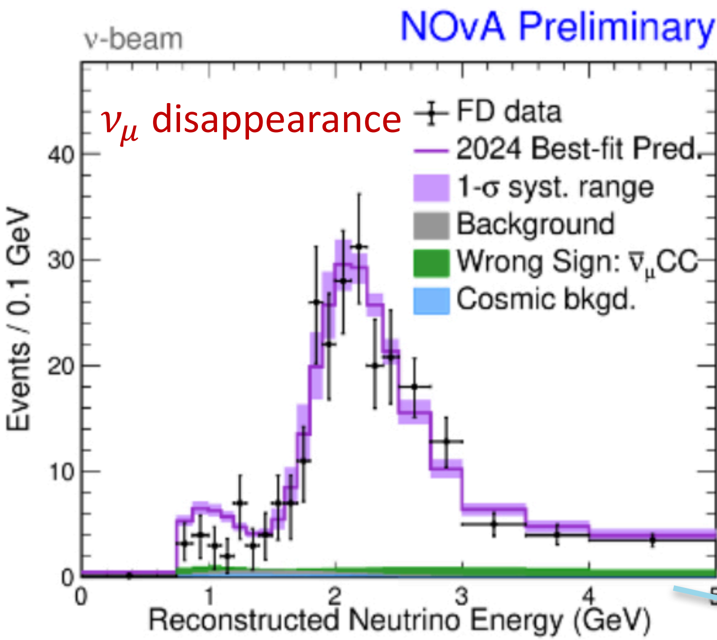
New Selection to Enhance Sensitivity

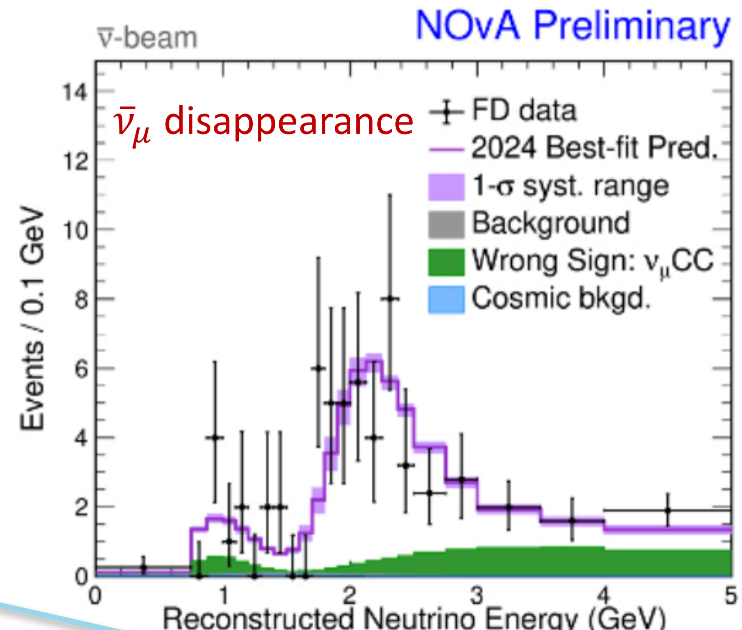


- New sample. Excluded reconstructed $E_\nu < 1\ GeV$ earlier.
- For now, ν only. Low energy $\bar{\nu}$ sample is too small currently.

$\nu_\mu \rightarrow \nu_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ at the Far Detector

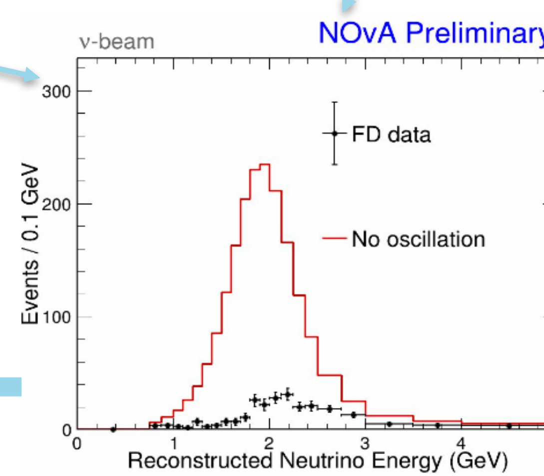
✓ Sensitive to the measurement of Δm^2_{32} and mixing angle θ_{23}





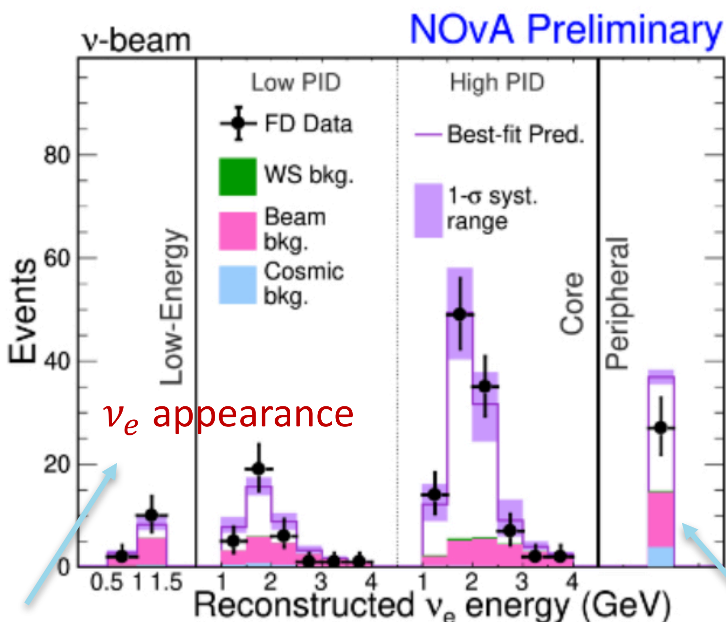
Clear oscillation signature as compared to no-oscillation prediction

	$\nu_\mu \rightarrow \nu_\mu$	$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$
Observed Events	384	106
Expected Background	11	2

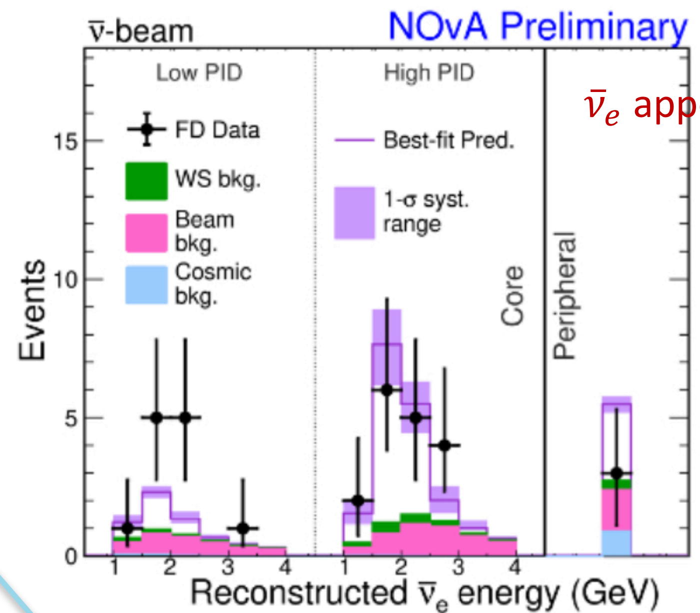


$\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ at the Far Detector

✓ Sensitive to the mass hierarchy, δ_{CP} and mixing angle θ_{23}



ν_e appearance



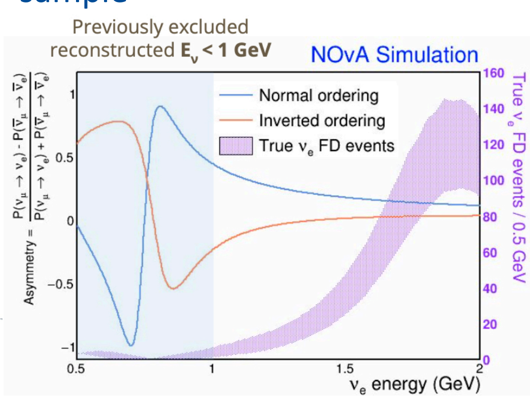
$\bar{\nu}_e$ appearance

The central value and uncertainties are constrained by near-far detector extrapolation.

New low energy ν_e sample

Fully contained, different PID

Partially contained

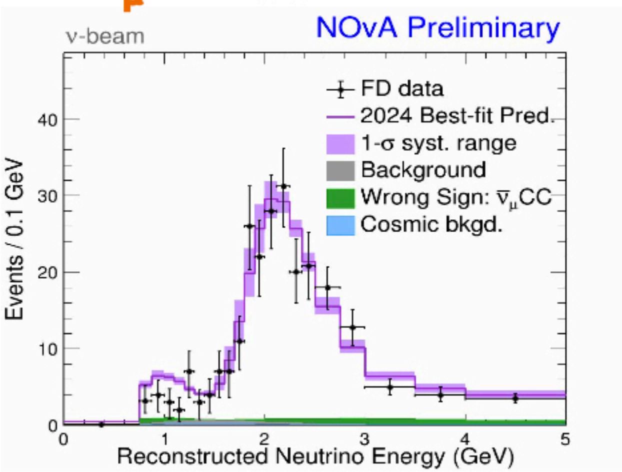


	$\nu_\mu \rightarrow \nu_e$		$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
Observed Events	169	12 (low energy)	32
Expected Background	55	7	12

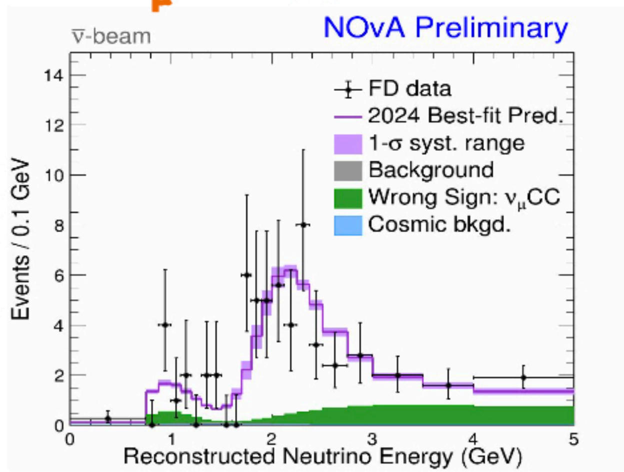
Low event rate but maximum ordering sensitivity from $\nu_e - \bar{\nu}_e$ asymmetry at low energy.

Fit to the Oscillation Parameters

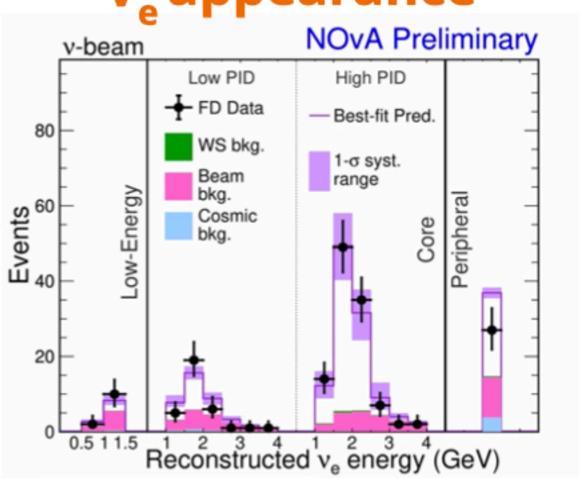
ν_μ disappearance



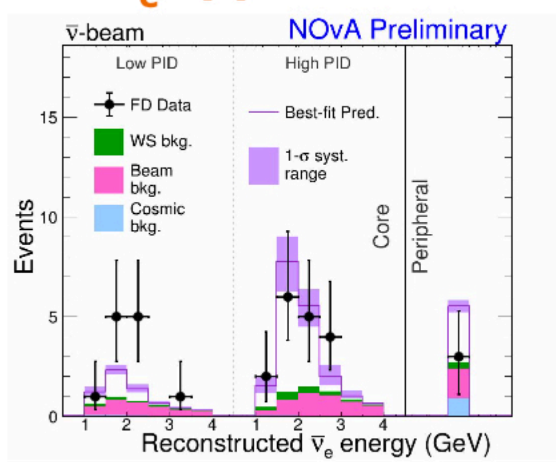
$\bar{\nu}_\mu$ disappearance



ν_e appearance



$\bar{\nu}_e$ appearance



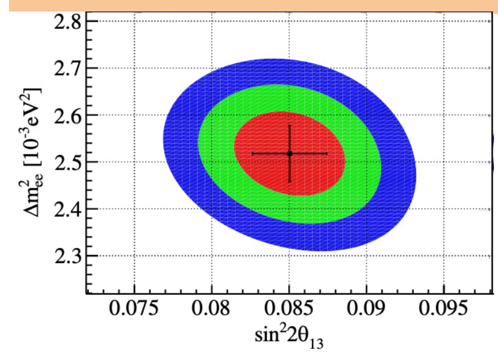
Simultaneous fit to $\Delta m^2_{32}, \sin^2\theta_{23}, \sin^2 2\theta_{13}, \delta_{CP}$

Consider three θ_{13} possibilities:

θ_{13} unconstrained (NOvA only)

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

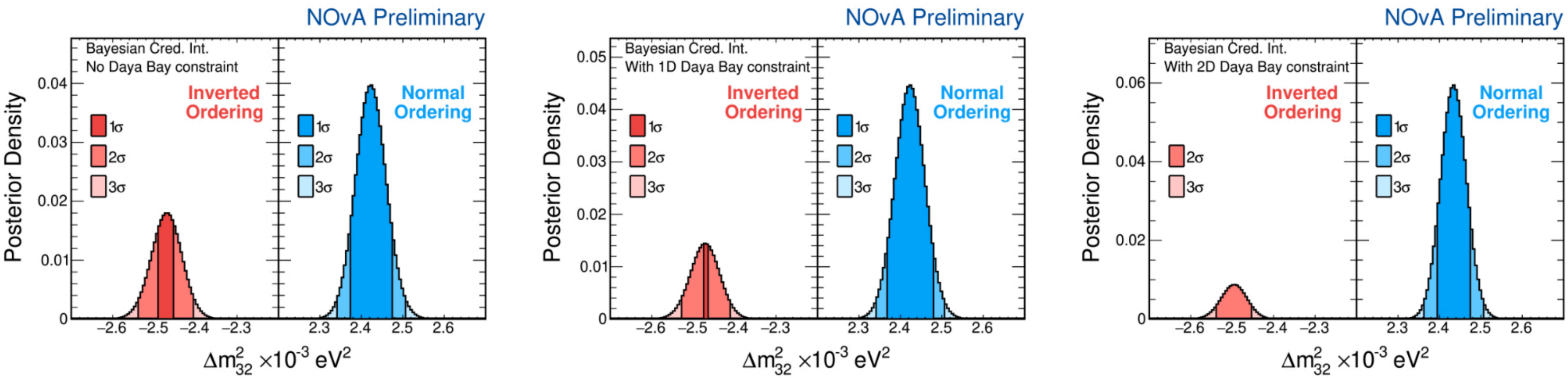
Daya Bay
2D $(\Delta m^2_{32}, \theta_{13})$ constraint



2024: Mass Ordering Preference, Δm^2_{32}

Preference for normal mass ordering is enhanced significantly by using the reactor constraint from Daya Bay.

Phys. Rev. Lett. 130, 161802 (2023)
Phys. Rev. D 72 013009 (2005)



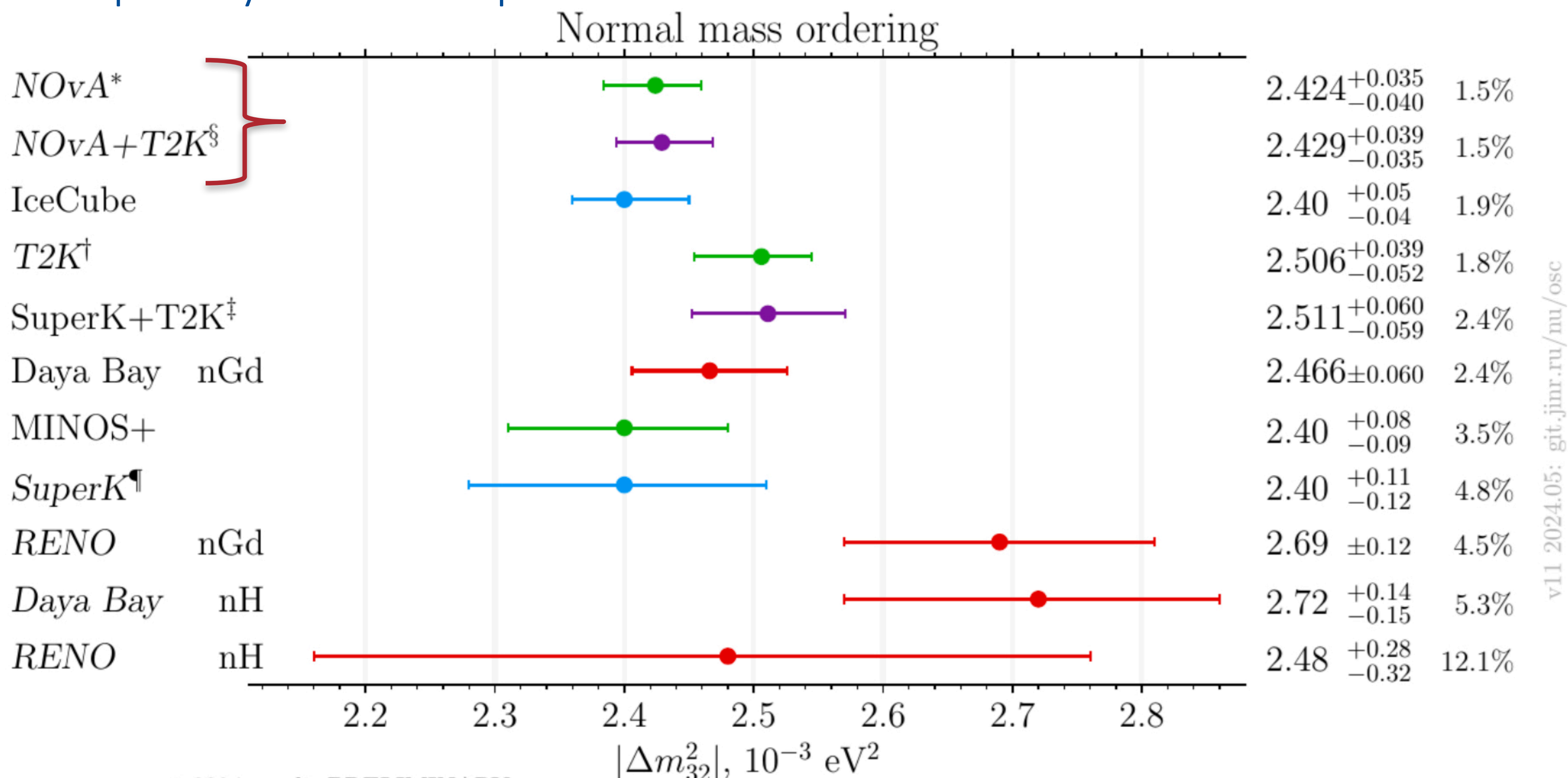
No reactor constraint	1D θ_{13} constraint	2D (θ_{13}, Δm^2_{32}) constraint

Normal ordering preference
(and Bayes factor)

69% (2.2)	**76%** (3.2)	**87%** (6.8)

Precision Measurement of Δm^2_{32}

NOvA presents the best single experiment and world leading precision of ~ 1.5% on $|\Delta m^2_{32}|$.
Most precisely known PMNS parameter.



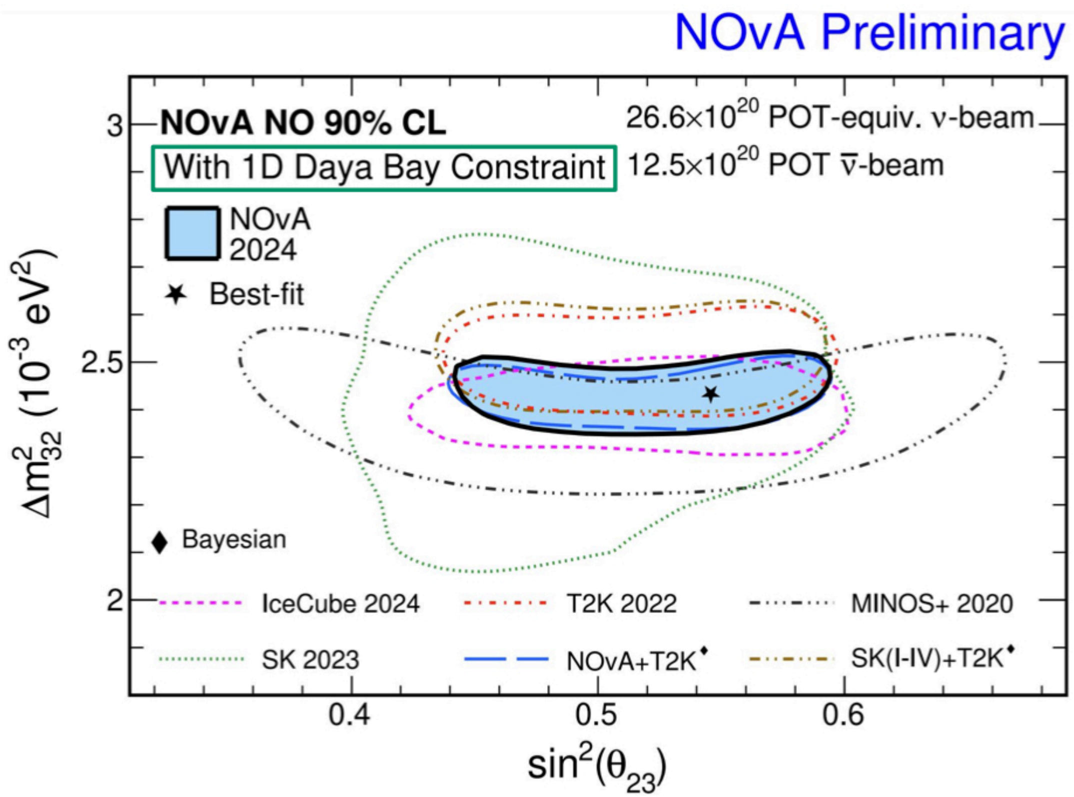
Preliminary
Published

* 2024 result, PRELIMINARY
§ based on 2020 ana.
† Neutrino-2022 result

¶ SKI-V result, arXiv:2311.05105
‡ based on SK IV and T2K 2020, arXiv:2405.12488

Measurement of $sin^2\theta_{23}$

Global consistency. NOvA measurements are consistent with accelerator, atmospheric and various joint results.

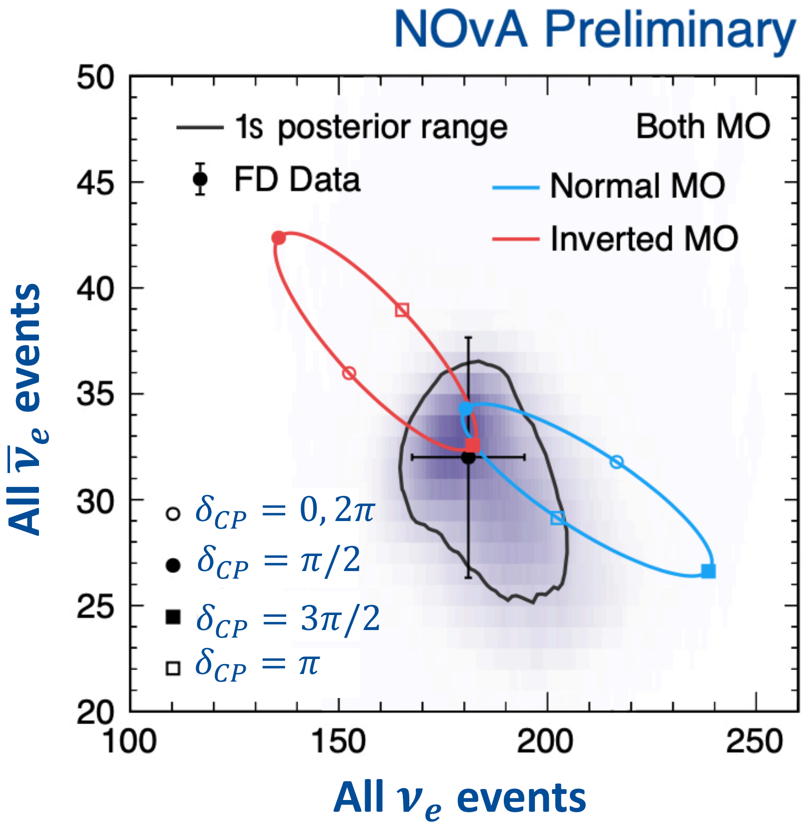


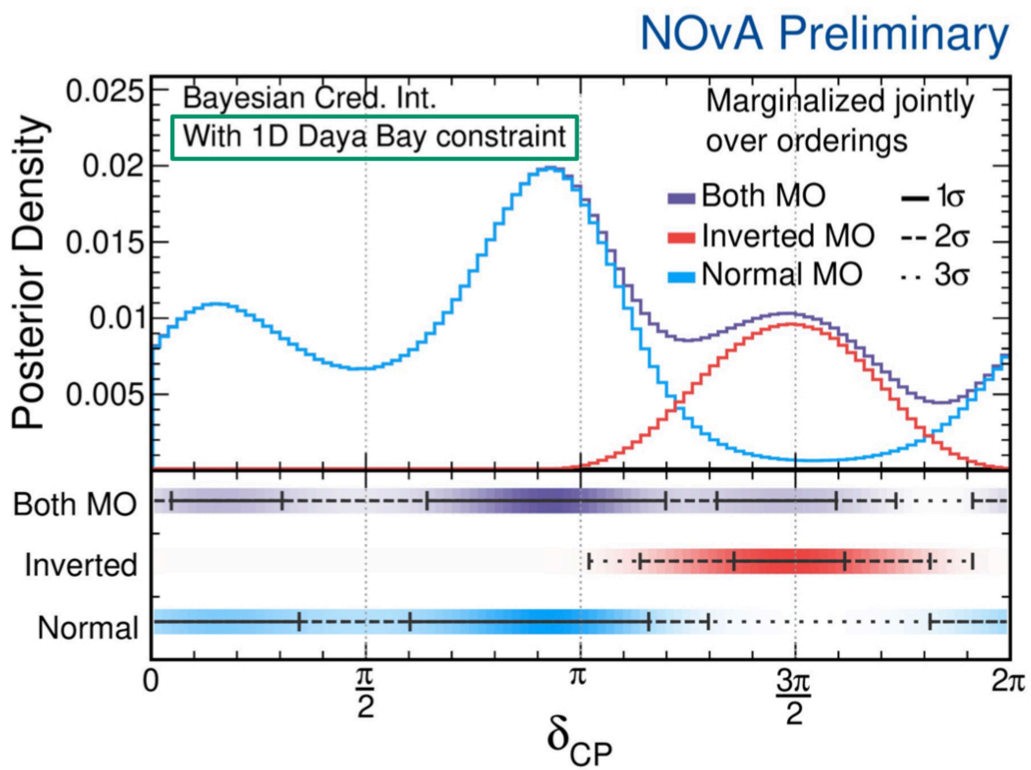
	Mass Ordering: Normal	Mass Ordering: Inverted
$\Delta m^2_{32}/10^{-3}\ \mathrm{eV}^2$	$+2.433^{+0.035}_{-0.036}$	$-2.473^{+0.035}_{-0.035}$
$\sin^2\theta_{23}$	$0.546^{+0.032}_{-0.075}$	$0.539^{+0.028}_{-0075}$
δ_{CP}	0.9π	1.5π

Maximal mixing ($\sin^2\theta_{23} = 0.5$) allowed within 1σ.

IceCube 2024: arXiv.2405.02163
T2K 2022: https://doi.org/10.5281/zenodo.6683821
MINOS+ 2020: PhysRevLett.125.131802
SK 2023: PhysRevD.109.072014
NOvA+T2K 2024: KEK IPNS Seminar, FNAL JETP Seminar
T2K+SK 2024: arXiv.2405.12488

Mass ordering and δ_{CP}

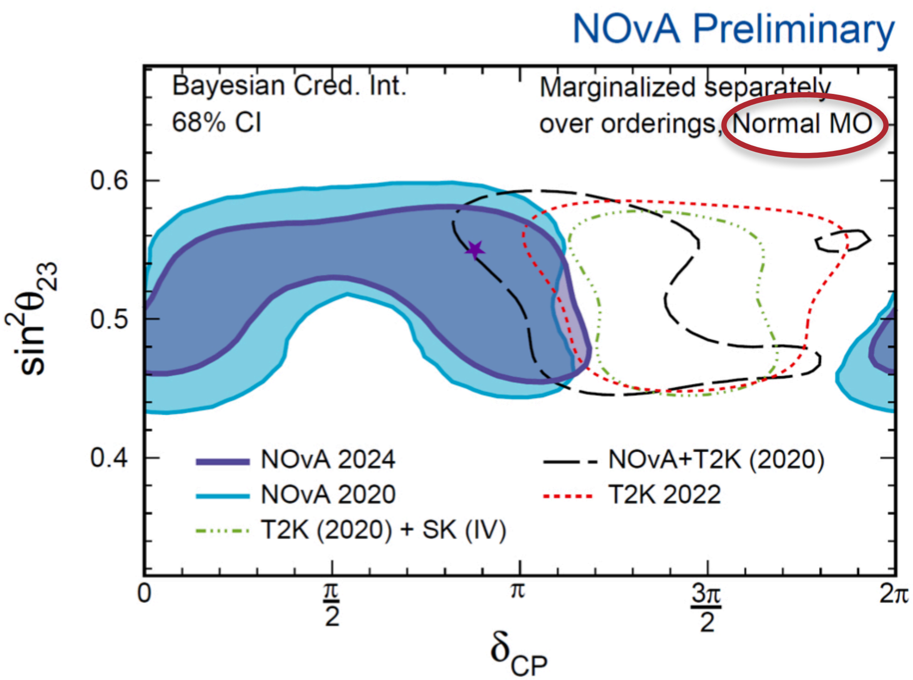


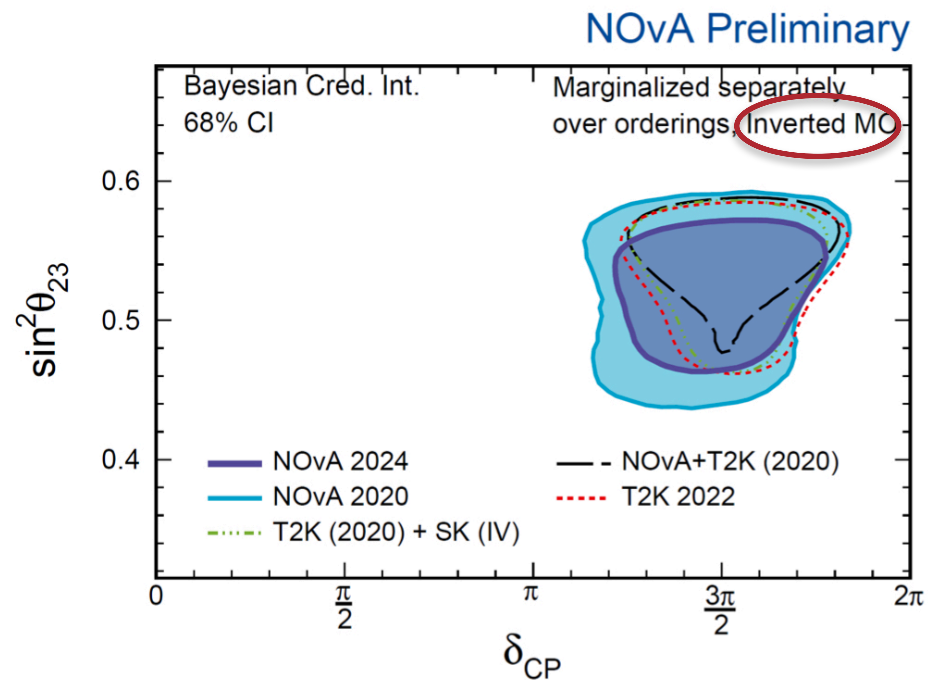


- NOvA data prefer regions where the effects of matter and CP phase cancel.
- Regions where these add (**NO, $\delta_{CP} = 3\pi/2$**) and **(IO, $\delta_{CP} = \pi/2$)** are largely ruled out.
- If the ordering is inverted, CP conserving values of $\delta(0, \pi, 2\pi)$ are ruled out at 3σ.

Comparison of 2020 and 2024 Results

- **Strong consistency between 2020 and 2024 results,** with improved constraint in the same regions.
- T2K, joint fits favor different regions in NO, same region in IO. **Joint fit results are based on 2020 dataset**





Individual experiments (**T2K** and **NOvA)** favor normal ordering, but in joint fit, there is a modest preference for IO.

	NOvA only	T2K only	NOvA+T2K
Bayes factor	2.07 Normal/Inverted ~67% : ~33% posterior	4.24 Normal/Inverted ~81% : ~19% posterior	1.36 Inverted/Normal ~58% : ~42% posterior

The two NOvA results use different choices of 1D reactor constraint.
NOvA 2020: 2019 PDG average θ_{13}
NOvA 2024: Daya Bay 2023 1D θ_{13}

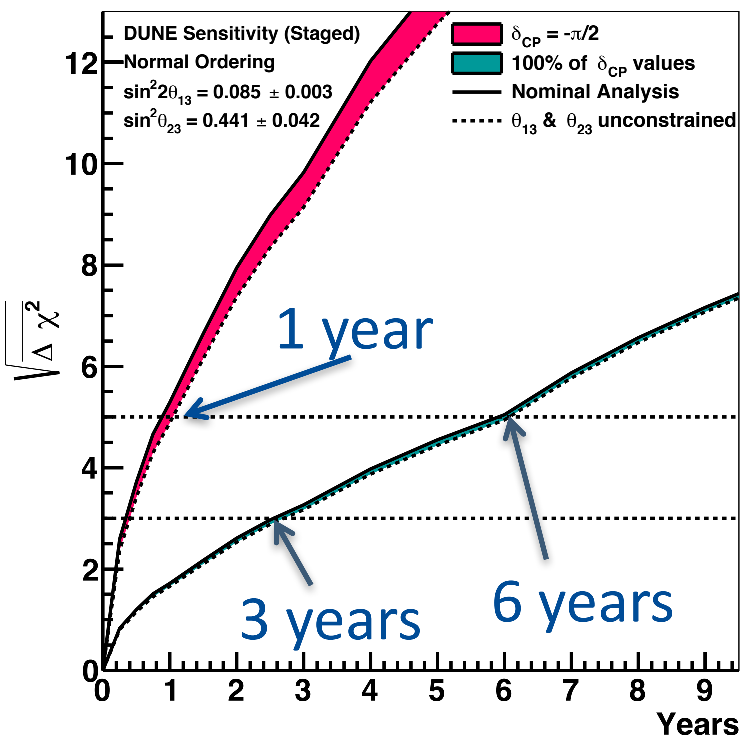
Summary

- NOvA experiment has released new data in 2024 doubling the neutrino data from the last dataset in 2020.
  - Major improvements in the new analysis including the addition of a new low energy sample.
  - Most precise measurement of Δm^2_{32} with a precision of ~1.5%. Good consistency with the previous results.
  - Slight preference for θ_{23} in the upper octant; maximal (μ/τ-symmetric) is a very good fit.
  - Data prefer oscillation parameters to be in region where effects of matter and CP phase cancel.
  - Interpretation of CP violation is strongly coupled to the resolution of the mass hierarchy problem.
- NOvA will collect data till the end of 2026.
  - **Goal is to double the anti-neutrino data.**
  - Broad physics program: Joint fits, Sterile searches, NSI, cross-section measurements, exotics, cosmic ray physics and many more.

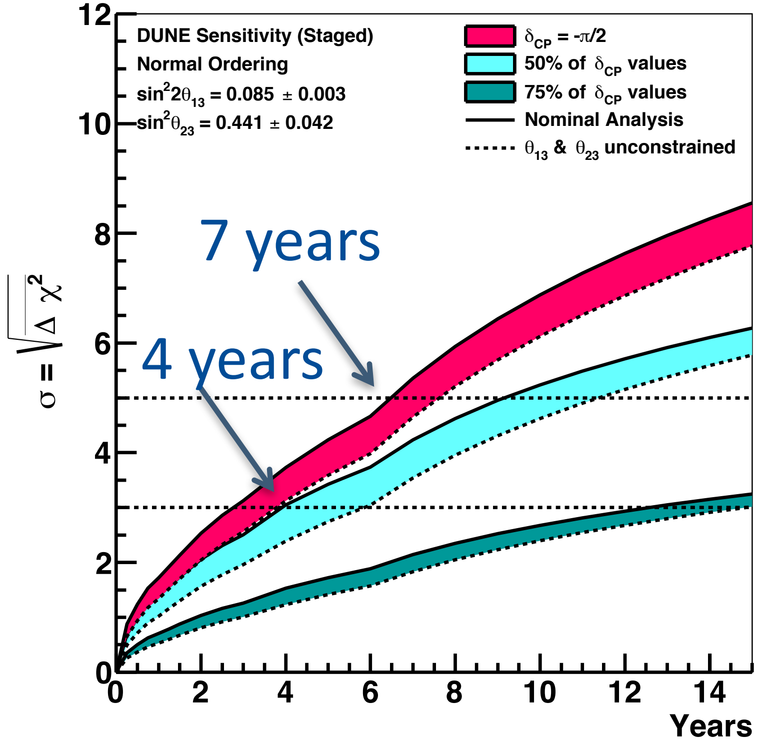
Backup

DUNE: Sensitivity vs. time

Mass Hierarchy Sensitivity



CP Violation Sensitivity



Important sensitivity milestones throughout beam physics program

NOvA+T2K Joint Fit Results: MO and δ_{CP}

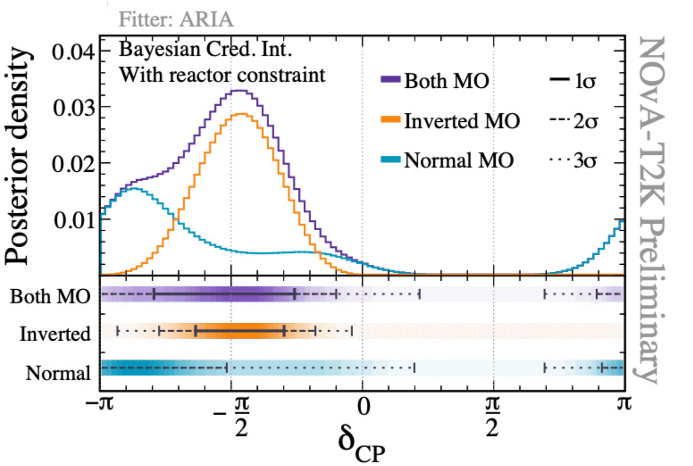
For both mass orderings, $\delta_{CP} = \frac{\pi}{2}$ lies outside the 3σ credible interval.

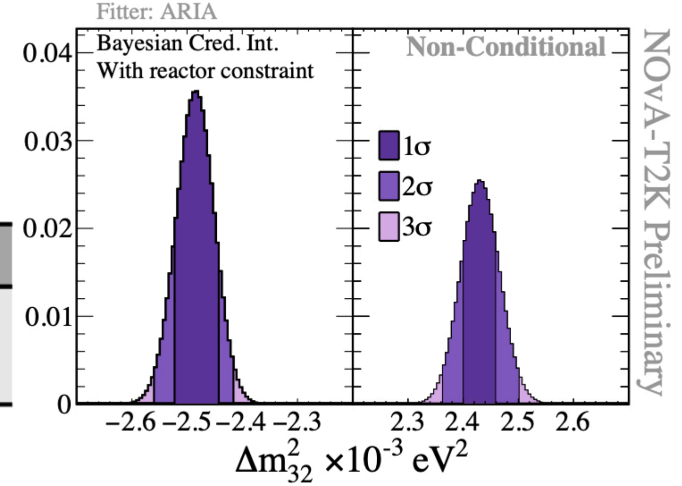
Normal Ordering allows for a broad range of permissible δ_{CP}.

For the Inverted Ordering, CP conserving values of $\delta_{CP}(0, \pi)$ lie outside the 3σ credible interval.

Including the Δm^2_{32} constraint from the Daya Bay, the mass ordering preference reverses back to **Normal Ordering**.

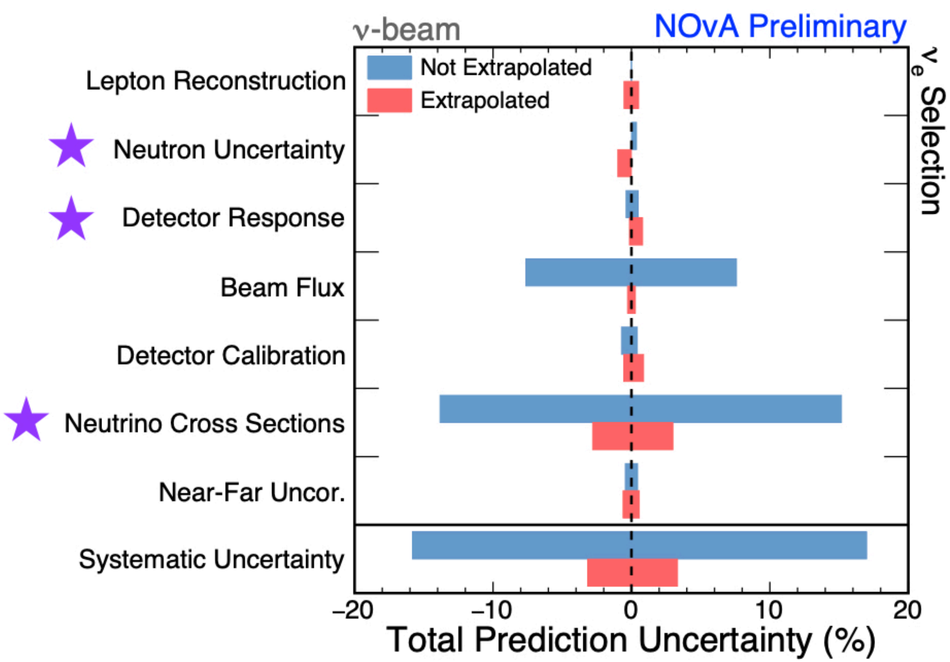
	NOvA - T2K w/o reactor	NOvA – T2K – 1D Daya Bay	NOvA - T2K - 2D Daya Bay
Bayes factor	2.47 Inverted/Normal ~71% : ~29% posterior	1.34 Inverted/Normal ~57% : ~43% posterior	1.44 Normal/Inverted ~59% : ~41% posterior

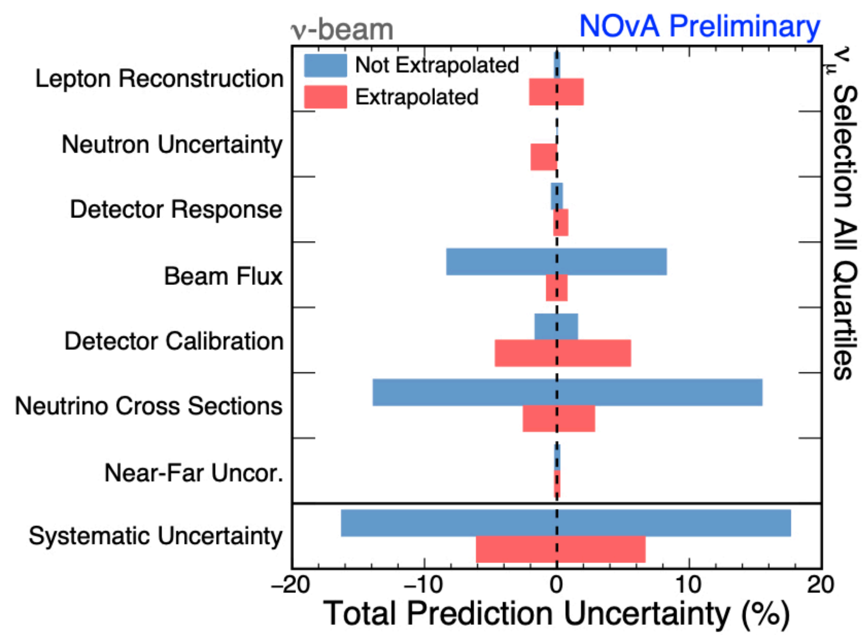




Systematic Uncertainties

- Improvements in the 2024 results: new pion-production systematic uncertainties, improved light response model and neutron propagation uncertainty.
- ND constraints reduce the systematic uncertainties in the FD predictions from ~15% to 4 - 5%.
- Statistical uncertainties are dominant in the oscillation measurement.





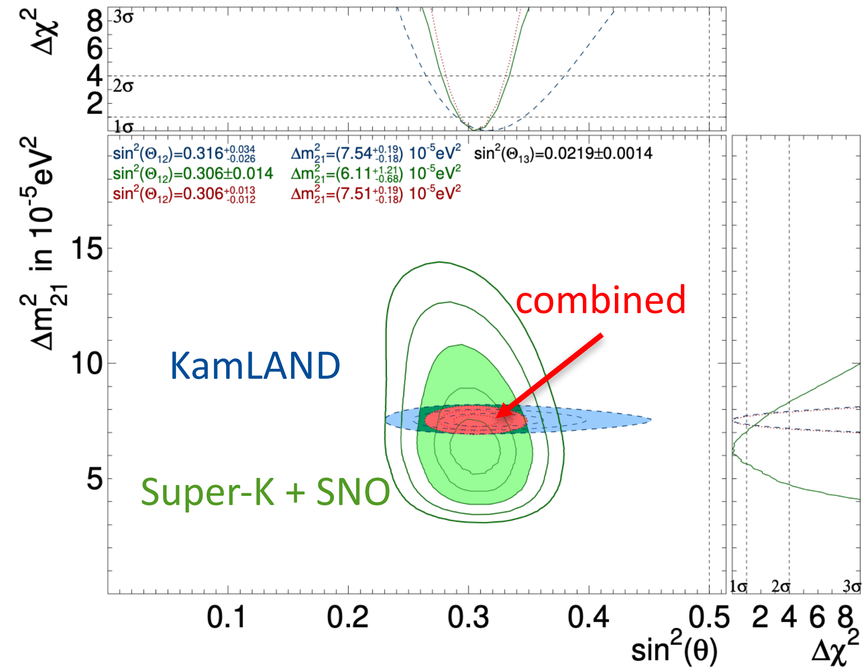
θ_{12} and Δm^2_{21}

- Solar neutrino measurements have the best sensitivity to constrain the so-called solar mixing angle θ_{12} and to a lesser degree, the Δm^2_{21} mass splitting.
  - Relies on the validity of the SSM predictions for solar neutrino fluxes.
  - Electron-neutrino survival probability (P_{ee}) of solar neutrinos is measured in the energy range of ~ 1 MeV to about 15 MeV.

High-precision measurements of 8_B solar neutrinos by Super-K and SNO dominate the combined fit to all solar neutrino data.

- Reactor anti-neutrino data from KamLAND provides complimentary measurements.
- Tension between solar and reactor result, **1.5 σ**

$$\sin^2(\theta_{12}) = 0.316^{+0.034}_{-0.026}$$
$$\Delta m^2_{21} = 7.54^{+0.19}_{-0.18} \times 10^{-5} eV^2$$
$$\sin^2(\theta_{12}) = 0.305 \pm 0.014$$
$$\Delta m^2_{21} = 6.10^{+1.04}_{-0.75} \times 10^{-5} eV^2$$
$$\sin^2(\theta_{12}) = 0.305^{+0.013}_{-0.012}$$
$$\Delta m^2_{21} = 7.49^{+0.19}_{-0.17} \times 10^{-5} eV^2$$



- **JUNO** can simultaneously measure Δm^2_{21} and θ_{12} using reactor anti-neutrinos and solar neutrinos
- **Hyper-K** will improve the solar results.

θ_{13} and Δm^2_{32}

- Reactor experiments use the inverse β −decay reaction with prompt and delayed γ signal to detect anti-neutrinos with liquid scintillator target

prompt — delayed

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

~180 μs: $\rightarrow + p \rightarrow d + \gamma\ (2.2\ \text{MeV})$

$\rightarrow + Gd \rightarrow Gd^*$ (~30 μs for 0.1% Gd) $\rightarrow Gd + \gamma\text{'s}\ (\sim 8\ \text{MeV})$

- Event rate without oscillation ~ 1 $(\text{ton.GW}_{th}.\text{day})^{-1}$
- Survival Probability: θ_{12} term is negligible at DayaBay baseline.

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - sin^2 2\theta_{13}\left[cos^2\theta_{12} sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + sin^2\theta_{12} sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)\right] - cos^4\theta_{13} sin^2 2\theta_{12} sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$

- New results from DayaBay using neutron-Gadolinium (nGd) capture.

$$\sin^2 2\theta_{13} = 0.0853^{+0.0024}_{-0.0024} \quad \text{(2.8\% precision)}$$

Normal hierarchy: $\Delta m^2_{32} = +\,(2.454^{+0.057}_{-0.057}) \times 10^{-3}\ \text{eV}^2$

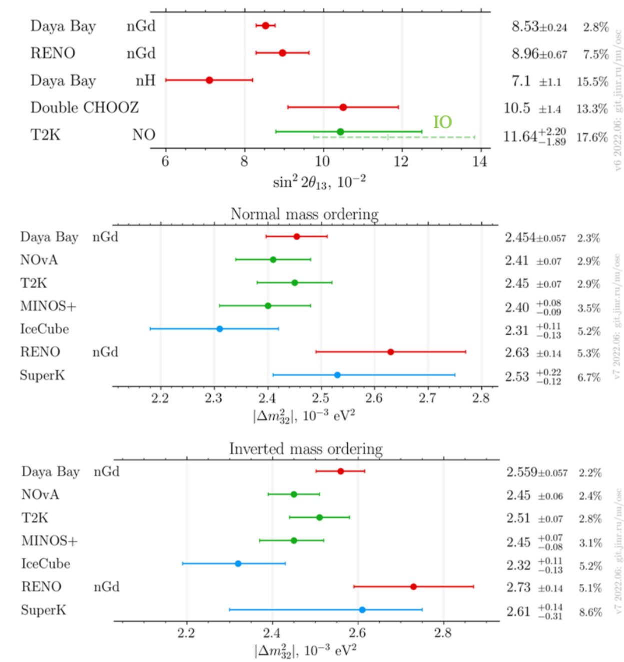
Inverted hierarchy: $\Delta m^2_{32} = -\,(2.559^{+0.057}_{-0.057}) \times 10^{-3}\ \text{eV}^2$

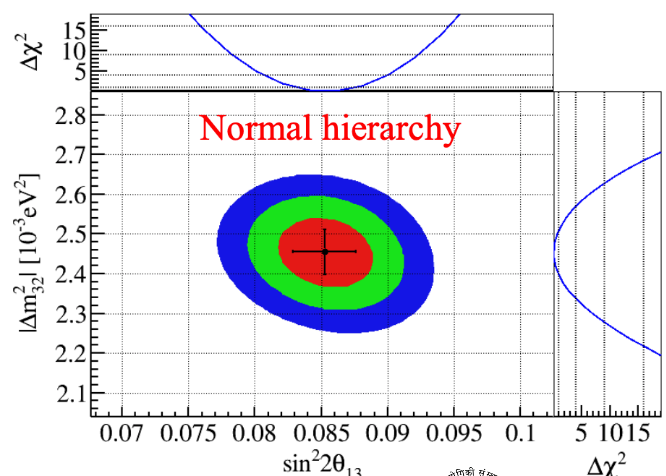
(2.3% precision)

$\sin^2 2\theta_{13}$

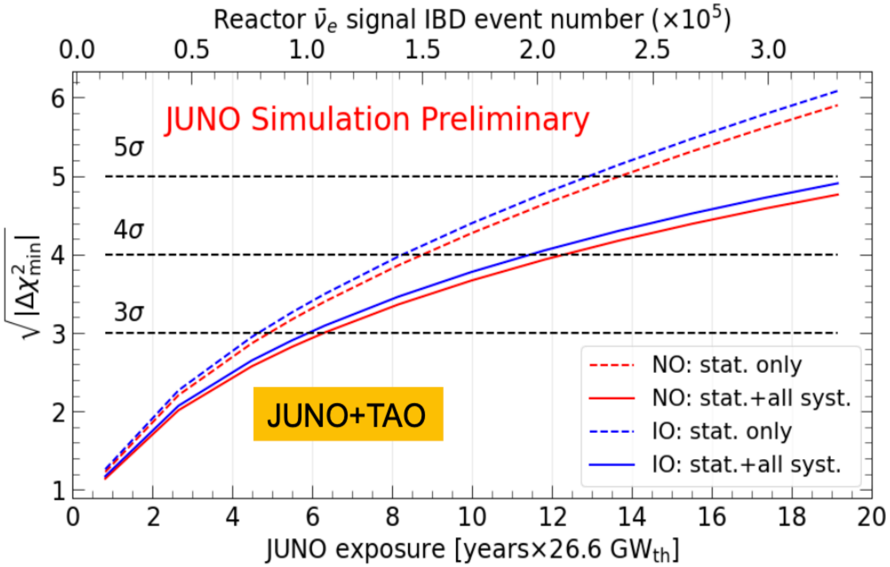
Δm^2_{32} (NO)

Δm^2_{32} (IO)





JUNO: Physics Outlook



Precision of $\sin^2 2\theta_{12}$, Δm^2_{21}, $|\Delta m^2_{32}|$ < 0.5% in 6 yrs

	Central Value	PDG2020	100 days	6 years	20 years
Δm^2_{31} ($\times 10^{-3}$ eV^2)	2.5283	±0.034 (1.3%)	±0.021 (0.8%)	±0.0047 (0.2%)	±0.0029 (0.1%)
Δm^2_{21} ($\times 10^{-5}$ eV^2)	7.53	±0.18 (2.4%)	±0.074 (1.0%)	±0.024 (0.3%)	±0.017 (0.2%)
$\sin^2\theta_{12}$	0.307	±0.013 (4.2%)	±0.0058 (1.9%)	±0.0016 (0.5%)	±0.0010 (0.3%)
$\sin^2\theta_{13}$	0.0218	±0.0007 (3.2%)	±0.010 (47.9%)	±0.0026 (12.1%)	±0.0016 (7.3%)

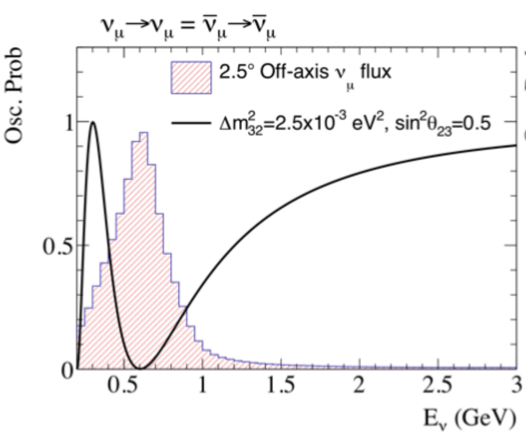
JUNO sensitivity on Neutrino MO: **3σ (reactors only) @~ 6 yrs * 26.6 GW$_{th}$ exposure**
MO sensitivity with reactor + Atmospheric neutrino analysis is expected soon.

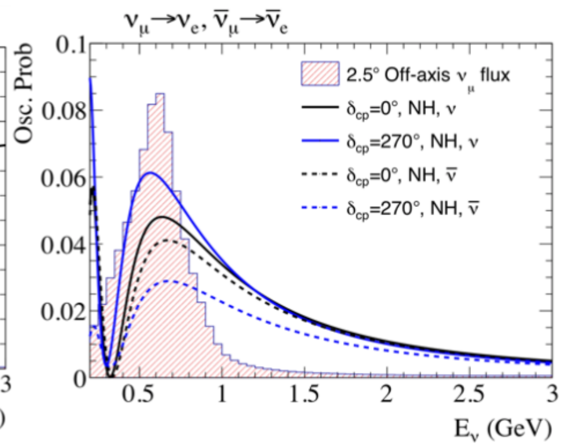
Physics	Sensitivity
Neutrino Mass Ordering	3σ (~1σ) in 6 yrs by reactor (atmospheric) $\bar{\nu}_e$
Neutrino Oscillation Parameters	Precision of $\sin^2\theta_{12}$, Δm^2_{21}, $|\Delta m^2_{32}|$ < 0.5% in 6 yrs
Supernova Burst (10 kpc)	~5000 IBD, ~300 eES and ~2000 pES of all-flavor neutrinos
DSNB	3σ in 3 yrs
Solar neutrino	Measure Be7, pep, CNO simultaneously, measure B8 flux independently
Nucleon decays ($p \to \bar{\nu}K^+$)	8.3×10^{33} years (90% C.L.) in 10 yrs
Geo-neutrino	~400 per year, 5% measurement in 10 yrs

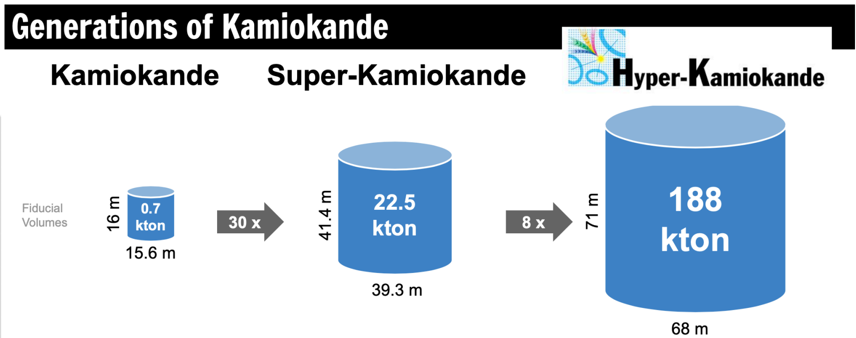
Hyper-K Experiment

Upcoming next generation neutrino physics expt. at J-PARC

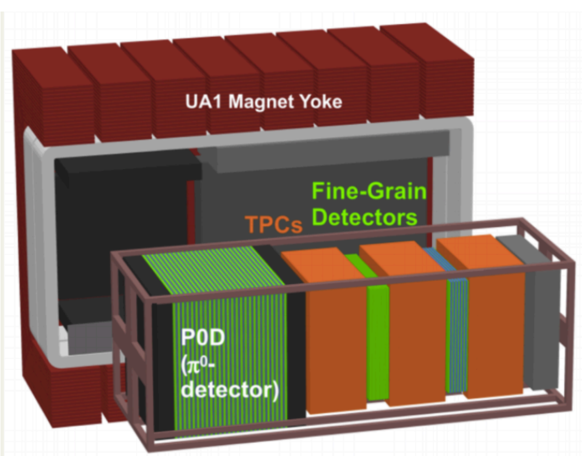
- 295 km baseline; ν_μ or $\overline{\nu}_\mu$ selected by horn current. 1.3 MW beam
- $2.5°$ off-axis $\nu/\overline{\nu}$ beam peaked at 0.6 GeV.







1983 - 1996	1996 - today (and beyond)	2027 - (and beyond)
Supernova 1987A 2002 Physics	Atmospheric ν Oscillation 2015 Physics	δ_{cp}, proton decay, indirect DM search, more SNs, ...



Will use the INGRID on-axis and upgraded magnetized ND280 off-axis detectors 280 m downstream as the ND system.

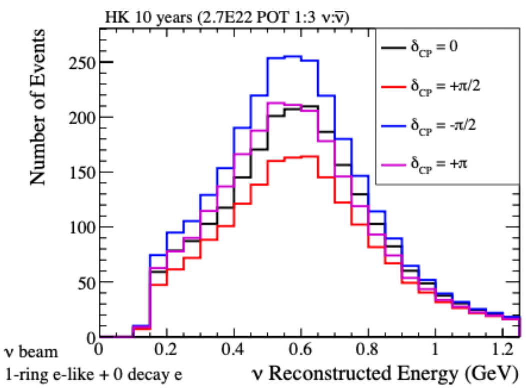
- Measurements constrain uncertainty on flux and neutrino interaction models.
- ND280: Active scintillator + passive water targets
  - Tracking with time projection chambers
  - Magnetized for charge & momentum measurement.

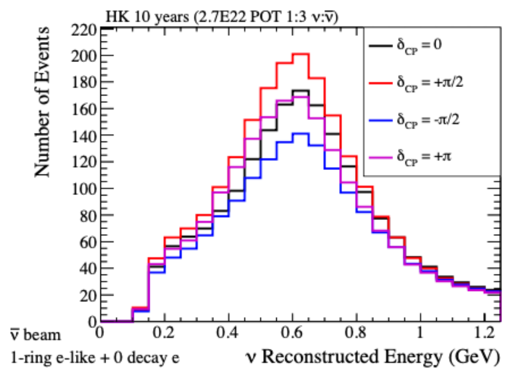
Hyper-K Experiment-δ_{CP} Sensitivity

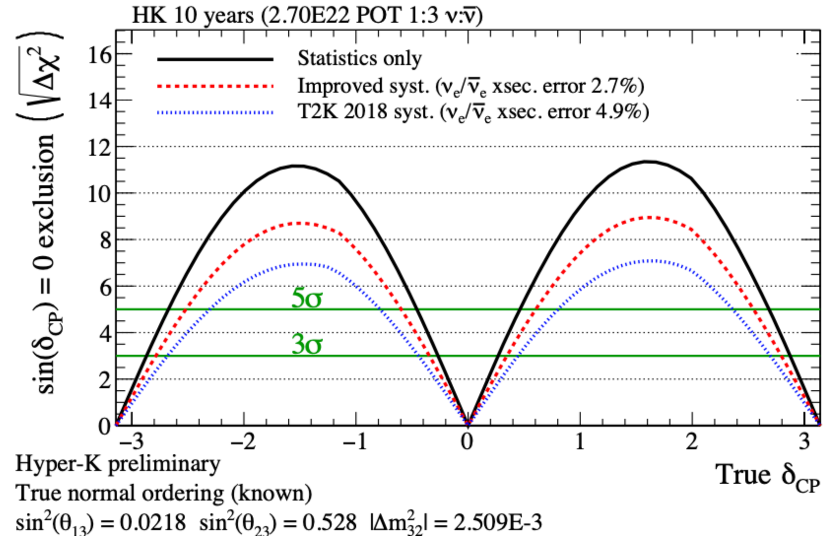
Measure CP-Violation through comparison of

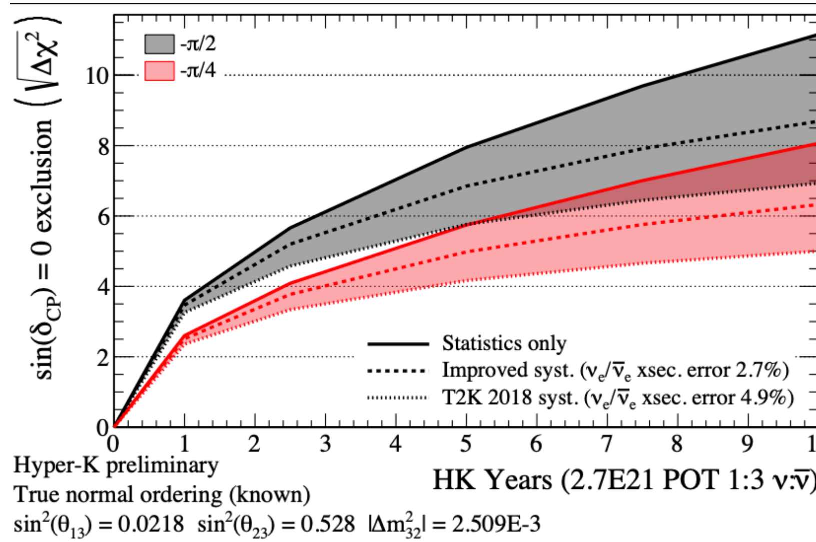
$$P(\nu_\mu \rightarrow \nu_e) \text{ and } P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$

- **Select 1 ring e-like events in the far detector**
- **10 years of running, 1:3 $\nu:\bar{\nu}$ run plan**
- **> 1000 ν_e and $\bar{\nu}_e$ signal events**







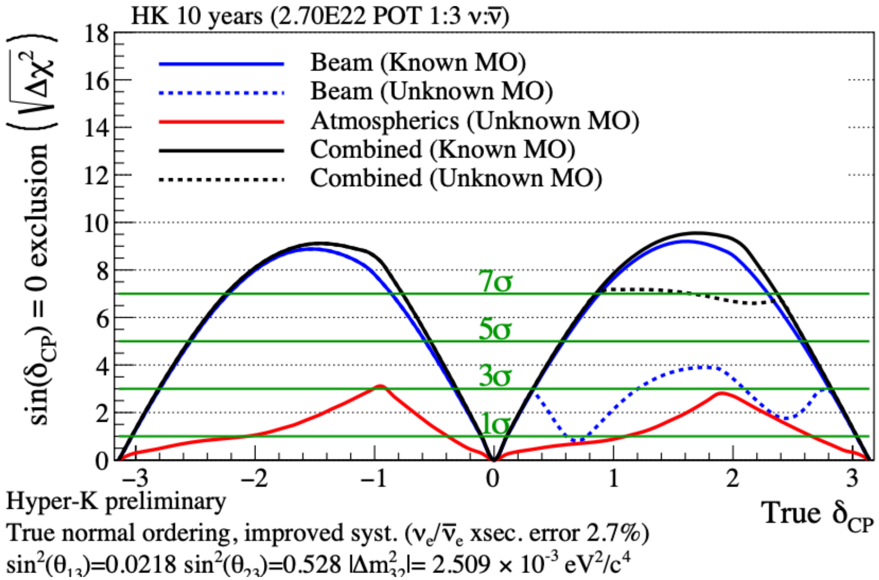


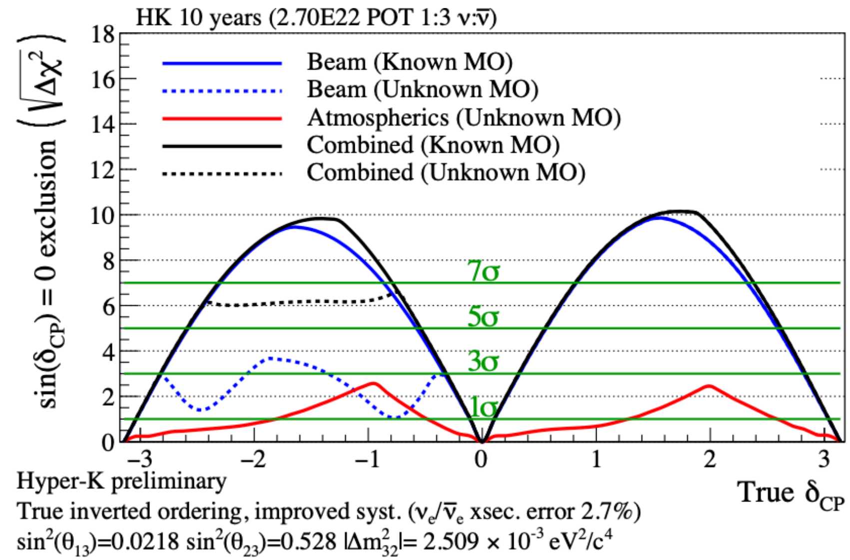
Projected sensitivity is based on T2K systematics and possible improvements for HK.

After 10 HK years, 61% of true δ_{CP} values Can be excluded at 5σ level.

Hyper-K Experiment- MO and $sin^2\theta_{23}$ Sensitivity

If the mass ordering is not known, combining the results from beam measurements and atmospheric neutrino observations will resolve the parameter degeneracy.

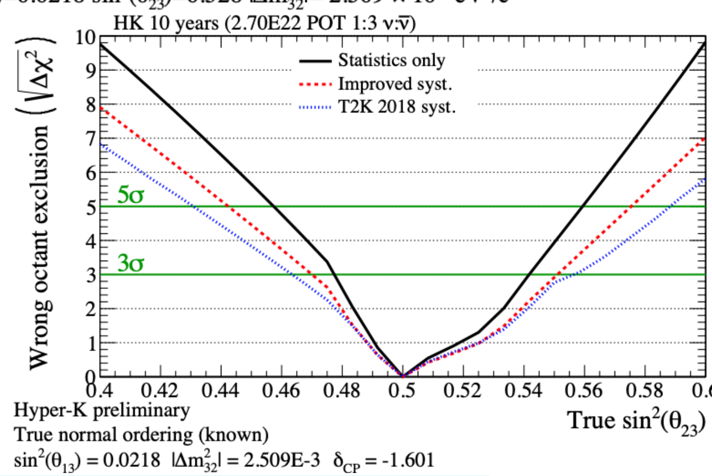




Probe 2-3 mixing through dip in

$$P(\nu_\mu \to \nu_\mu) \; and \; P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$$

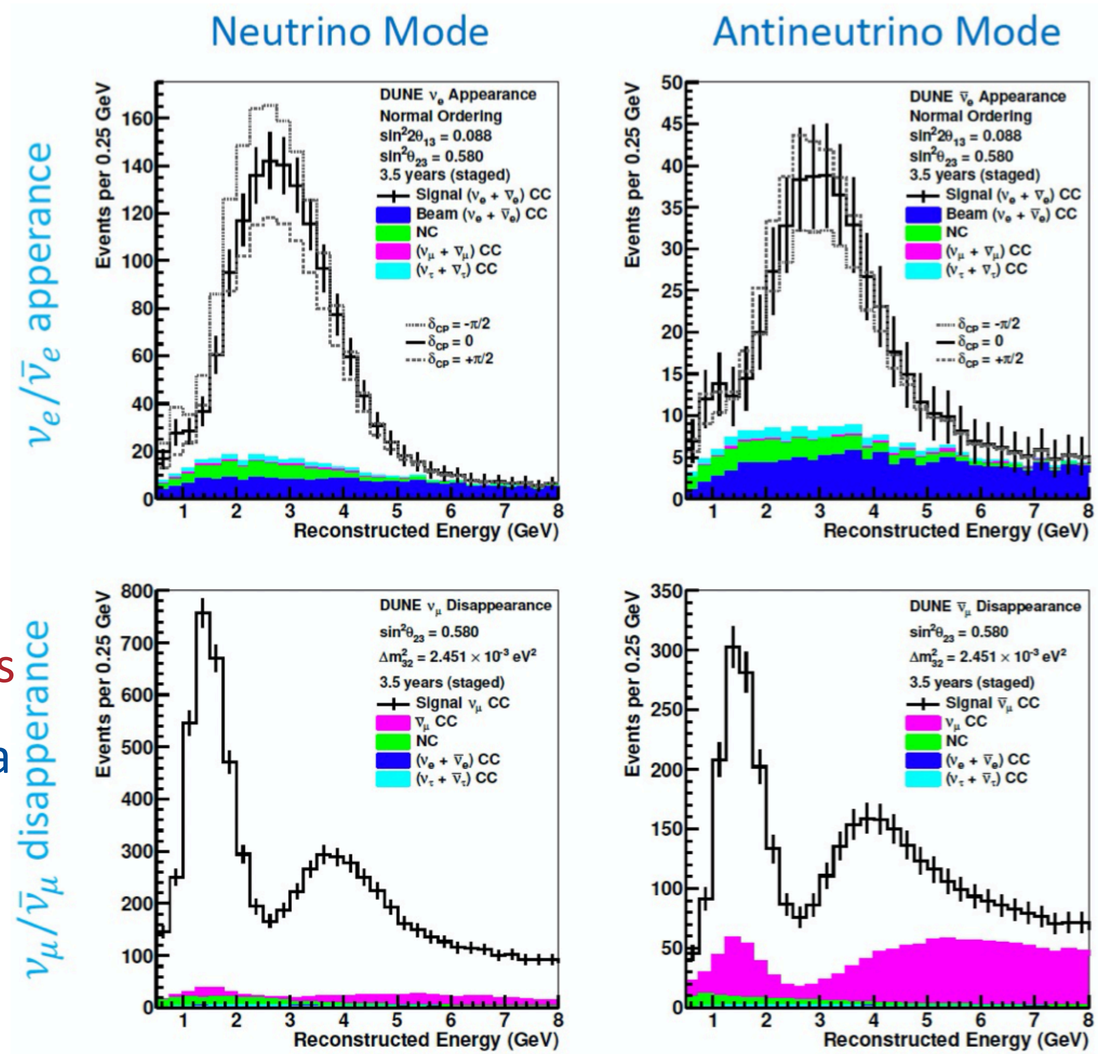
- **Select 1 ring μ-like events in the far detector**
- **10 years of running, 1:3 $\nu:\bar{\nu}$ run plan**



Wrong octant can be excluded at 3σ for true $sin^2\theta_{23} < 0.47$ and true $sin^2\theta_{23} > 0.55$.

Oscillation Sensitivity for DUNE

- Reconstructed spectra of selected CC-like events
- Includes full FD systematics
- 3.5 years neutrino beam mode
- 3.5 years anti-neutrino beam mode
- ~ 1000 $\nu_e/\overline{\nu_e}$ events in 7 years
- ~10,000 $\nu_\mu/\bar{\nu}_\mu$ events in 7 years
- Simultaneous fit to four spectra to extract oscillation parameters



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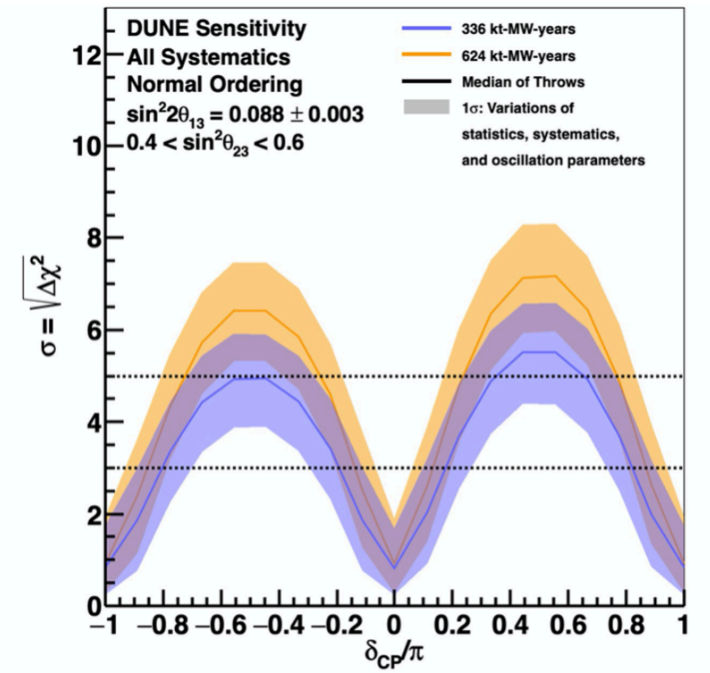
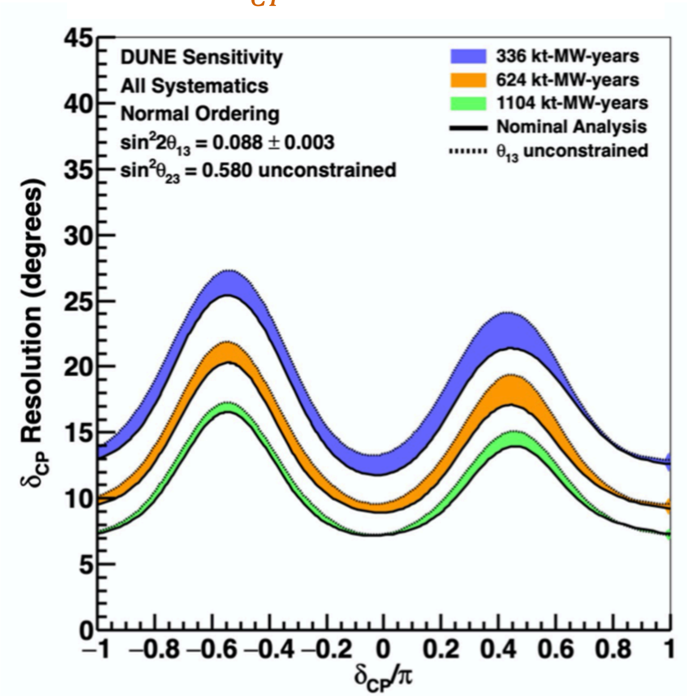
CP Violation Sensitivity

CP Violation Sensitivity



δ_{CP} Resolution

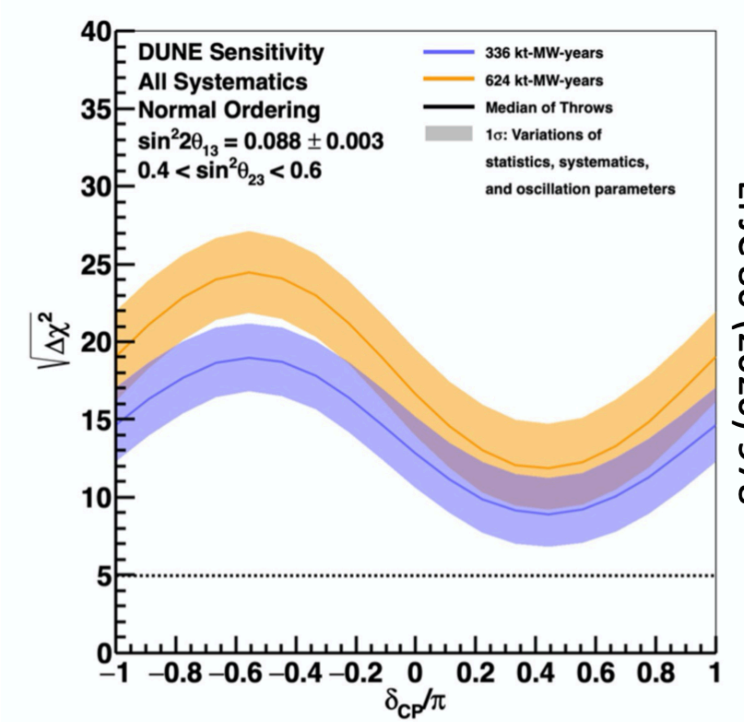


Width of the band indicates variation in the possible values of θ_{23}

- 5σ discovery potential for CP violation over > 50% of δ_{CP} values
- $7 - 16^{\circ}$ resolution to δ_{CP}, with external input only for solar parameters.
- Simultaneous measurement of neutrino mixing angles and δ_{CP}

Mass Hierarchy

Mass Hierarchy Sensitivity



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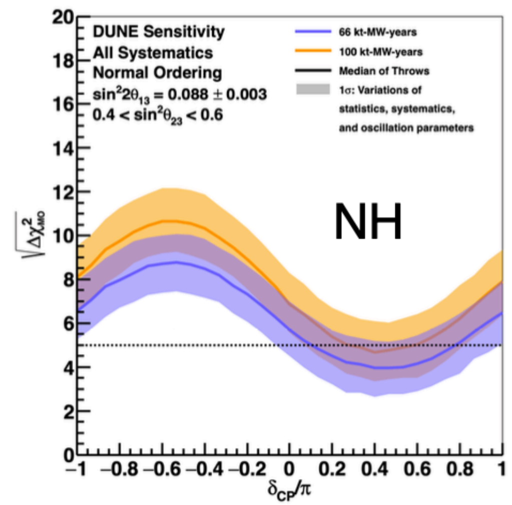
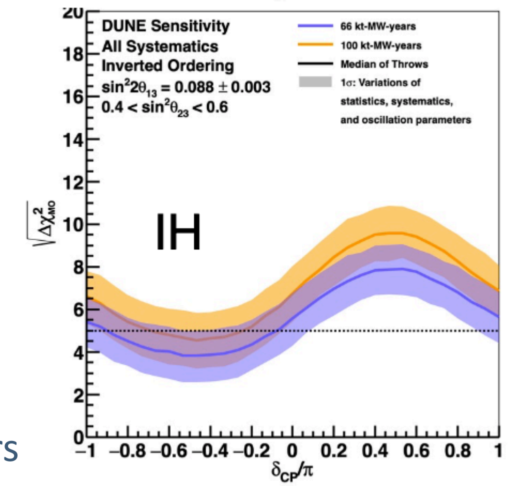
DUNE low exposure, PRD 105, 7, 072006 (2022)

100 kt

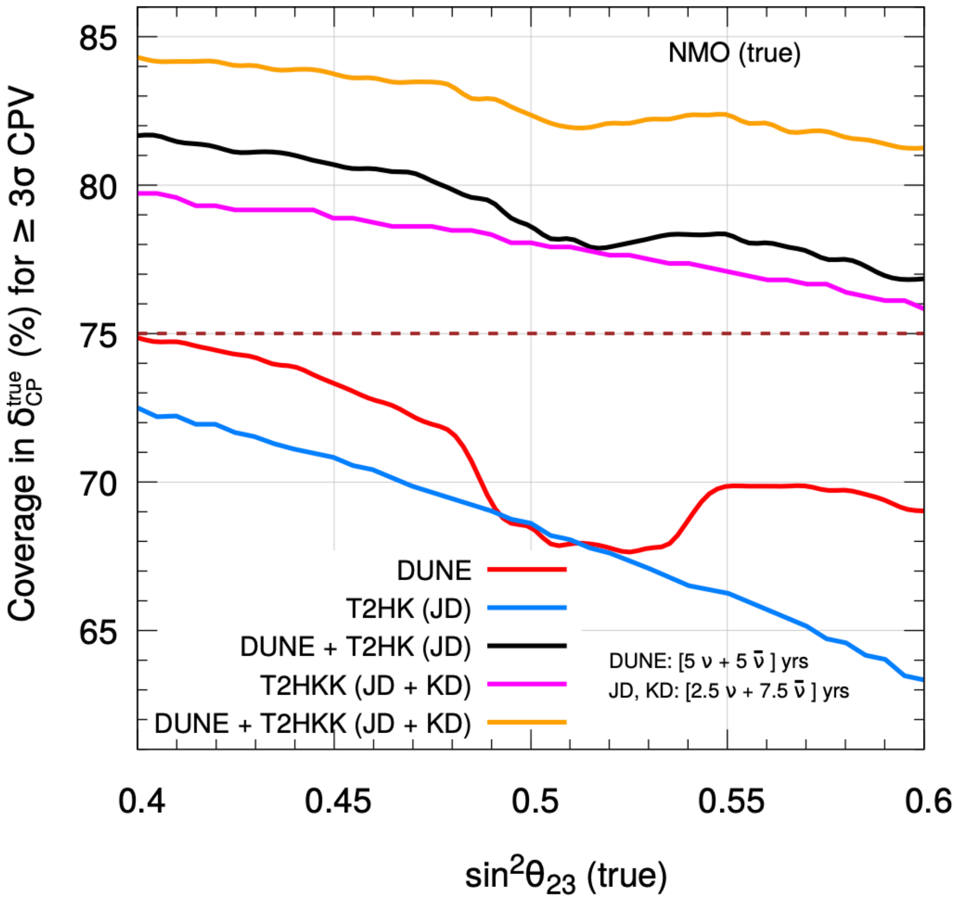
66 kt





- Mass hierarchy determination: > 5σ for all parameter values
- Even by exposure of 66 kt-MW-yr, probability to extract wrong ordering < 0.01
- With 1.2 MW beam running, DUNE will need only 1 -2 years to measure mass ordering definitely.

Complimentary between DUNE and Hyper-K



Characteristics	DUNE	JD/KD
Baseline (km)	1285	295 (1100)
ρ_{avg} (g/cm^3)	2.848	2.7 (2.8)
Beam	LBNF [16]	J-PARC [57]
Beam Type	wide-band, on-axis	narrow-band, 2.5° off-axis
Beam Power	1.2 MW	1.3 MW
Proton Energy	120 GeV	30 GeV
P.O.T./year	1.1×10^{21}	2.7×10^{22}
Flux peaks at (GeV)	2.5	0.6
1st (2nd) oscillation maxima for appearance channel (GeV)	2.6 (0.87)	0.6 (0.2) / 1.8 (0.6)
Detector mass (kt)	40, LArTPC	187 each, water Cherenkov
Runtime ($\nu + \bar{\nu}$) yrs	5 + 5	2.5 + 7.5
Exposure (kt·MW·yrs)	480	2431
Signal Norm. Error (App.)	2%	5%
Signal Norm. Error (Disapp.)	5%	3.5%

S.K. Agarwalla et. al. arXiv:2211.10620

Coverage in true δ_{CP} for achieving $\geq 3\sigma$ leptonic CPV as a function of true $sin^2\theta_{23}$

None of the experiments can achieve the milestone of 75%. However, their combination makes CP coverage For the entire canvas of $sin^2\,\theta_{23}$ above 75%.

Neutrino detector masses and sensitive energy ranges.