LONG-BASELINE NEUTRINO EXPERIMENTS

PATRICIA VAHLE

WIN, JUNE, 2025

NEUTRINOS HAVE MASS!

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \mathbf{U}^\dagger \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

$$P(\nu_\alpha \rightarrow \nu_\beta) = \left| \sum_j U^*_{\beta j} e^{-i\frac{m_j^2 L}{2E}} U_{\alpha j} \right|^2$$

$\nu_e, \nu_\mu, \nu_\tau \leftrightarrow \nu_1, \nu_2, \nu_3$

- Flavor States: creation and detection
- Mass States: propagation

A neutrino created as one flavor can later be detected as another flavor, depending on:

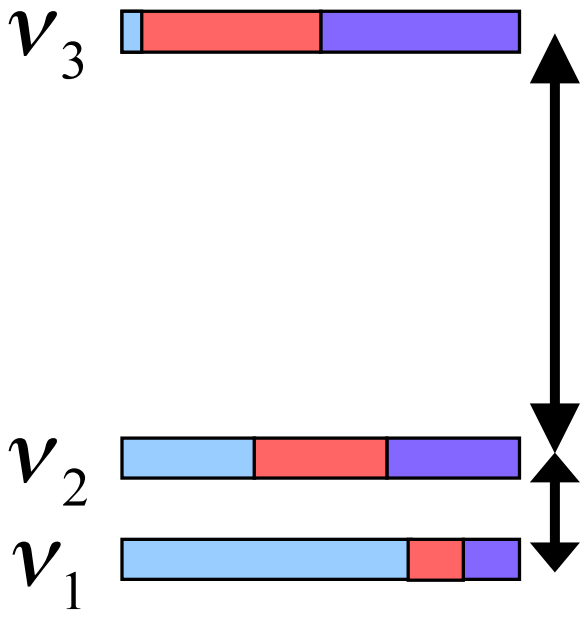
- distance traveled (L) and neutrino energy (E)
- difference in the squared masses ($\Delta m^2_{ij} = m^2_i - m^2_j$)
- The mixing amplitudes ($U_{\alpha j}$)

Seagull art created by MihiMihi
From Noun Project

THE PMNS MIXING MATRIX

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\theta_{23} \approx 45^\circ \qquad \theta_{13} \approx 9^\circ \qquad \theta_{12} \approx 34^\circ$$



What we know

All known to a few %

$$\square m^2_{\text{atm}} \approx 2 \times 10^{-3}\text{eV}^2$$

$$\square m^2_{\text{sol}} \approx 8 \times 10^{-5}\text{eV}^2$$

THE PMNS MIXING MATRIX

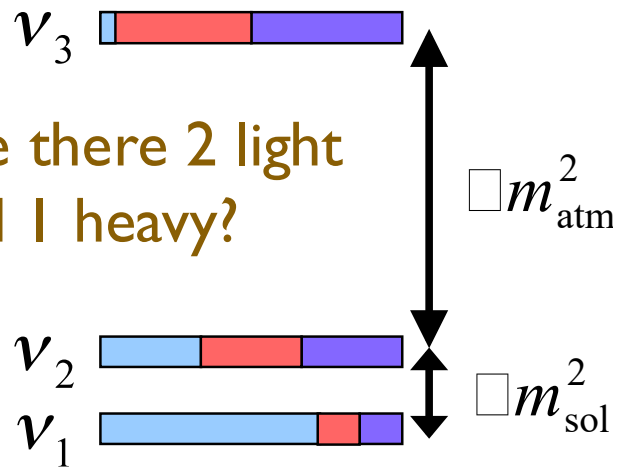
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Is it really 45°?

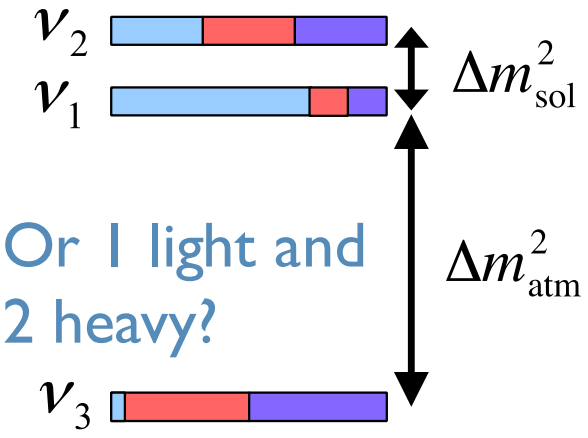
Is there CP violation?

What we don't know

The Mass Ordering



Are there 2 light and 1 heavy?



Or 1 light and 2 heavy?

Can CP violation in neutrinos help understand the matter-antimatter asymmetry?

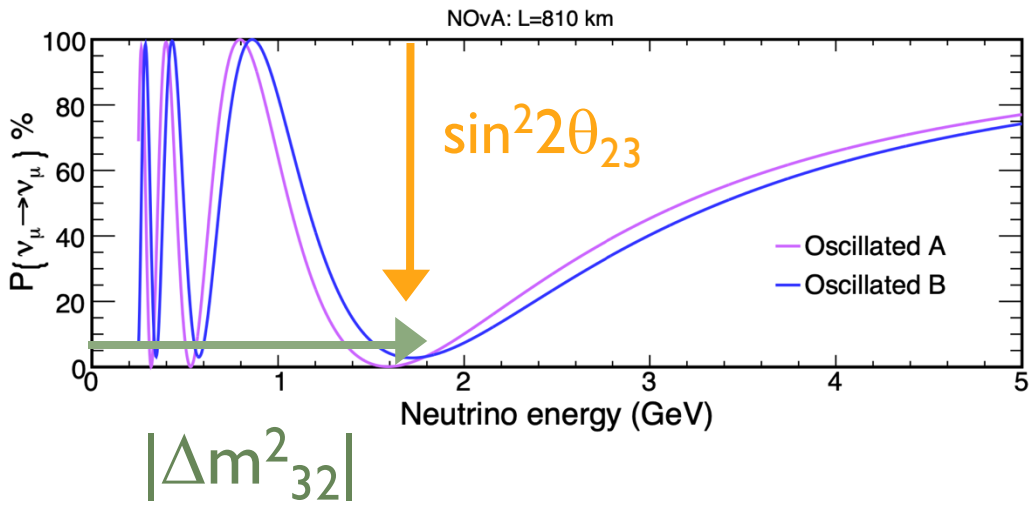
How do massive neutrinos fit into the Standard Model?

Does PMNS Mixing tell the whole story?

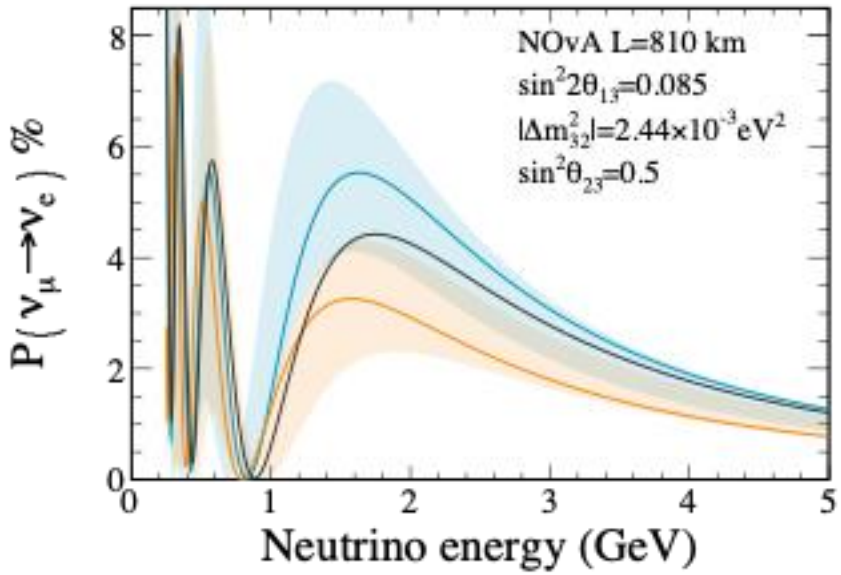
LONG-BASELINE OBSERVABLES

Oscillation probabilities at L/E~500km/GeV are sensitive to most of the remaining unknowns

Muon Neutrinos disappear



Electron Neutrinos appear

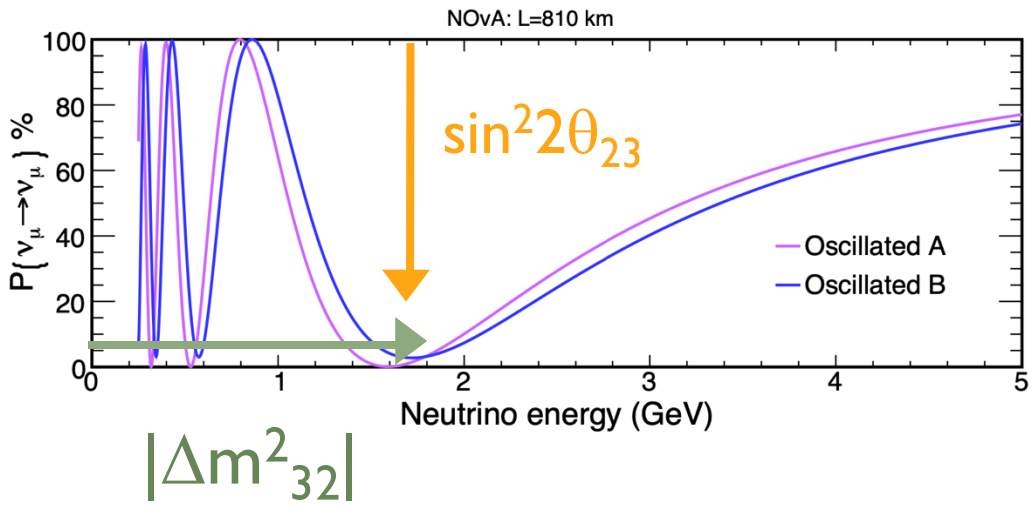


Depends on Mass Ordering (NO, IO), δ_{cp} (bands), and octant of θ_{23}

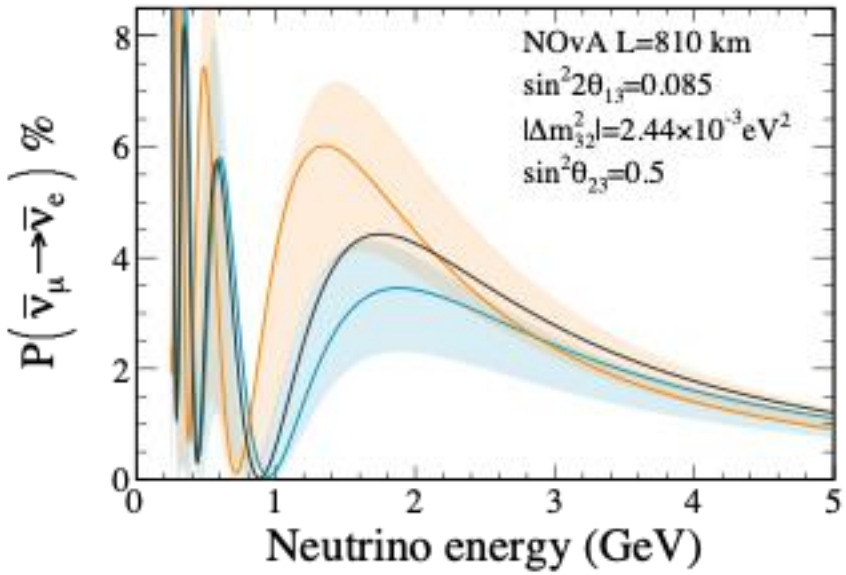
LONG-BASELINE OBSERVABLES

Oscillation probabilities at L/E~500km/GeV are sensitive to most of the remaining unknowns

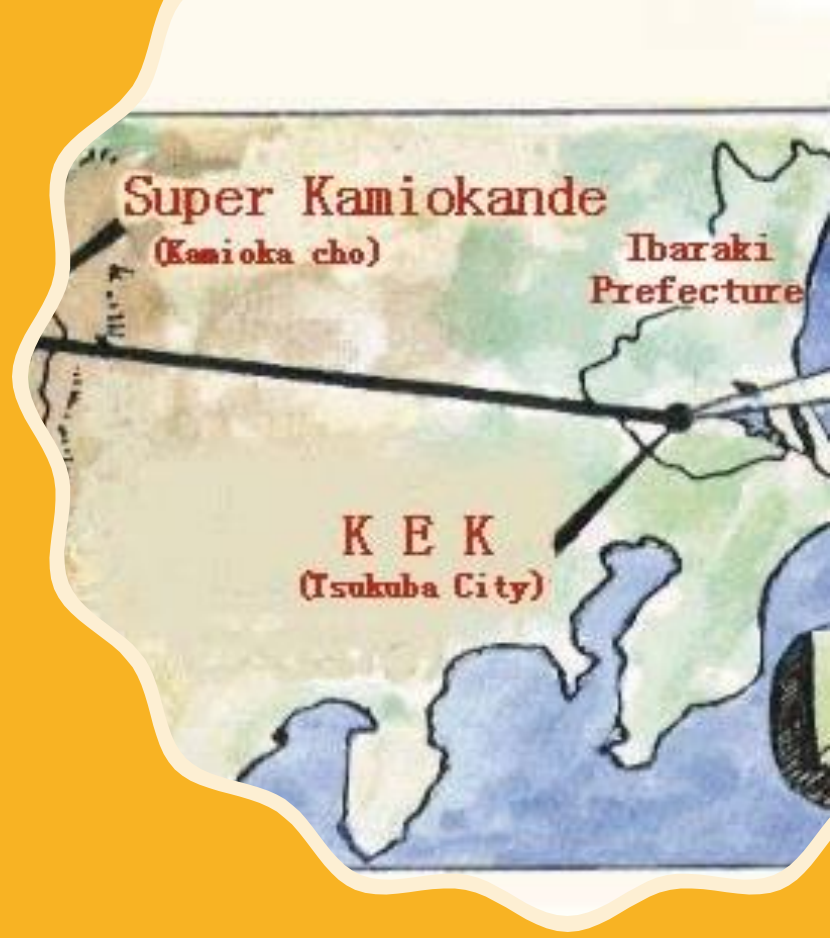
Muon Neutrinos disappear



Electron Neutrinos appear



AND could be different between neutrinos and antineutrinos!



THREE GENERATIONS OF ACCELERATOR LONG-BASELINE EXPERIMENTS

THREE GENERATIONS

MINOS
K2K
Opera

NOvA

T2K

Hyper-Kamiokande

DUNE
DEEP UNDERGROUND
NEUTRINO EXPERIMENT

Past
~2000-2015

Present
2015-2025

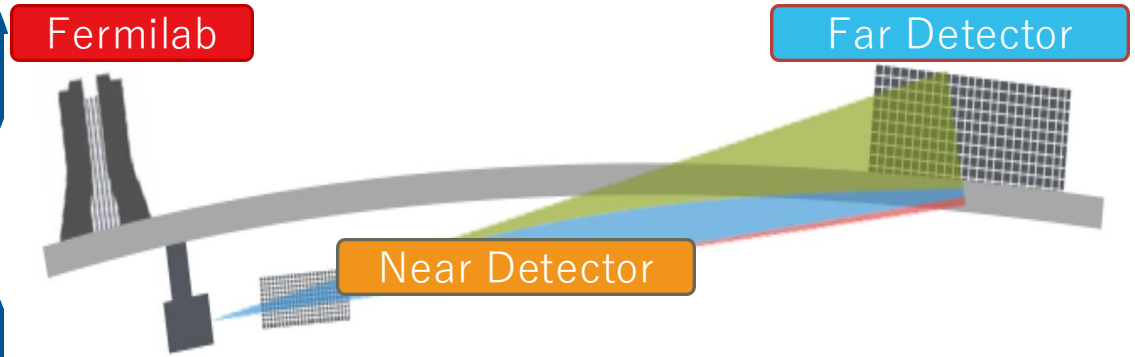
Future
2030+

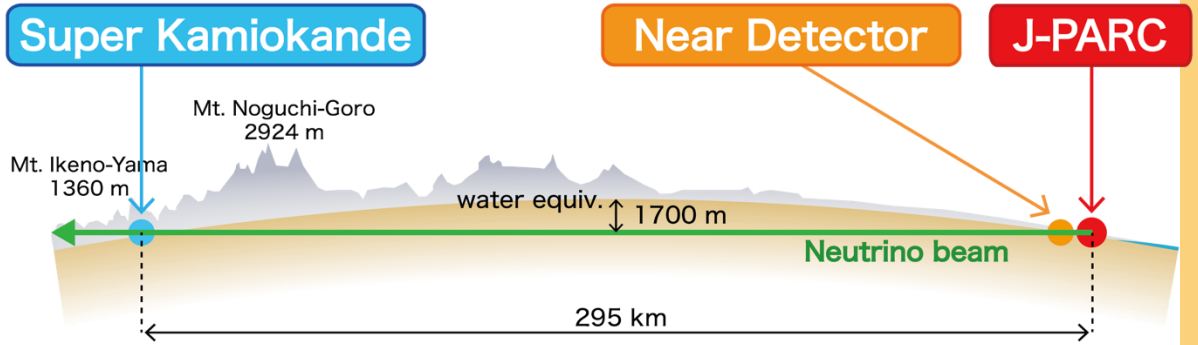
LONG-BASELINE EXPERIMENTS

Two experiments at different baselines and energies compliment each other and could help resolve degeneracies in parameters

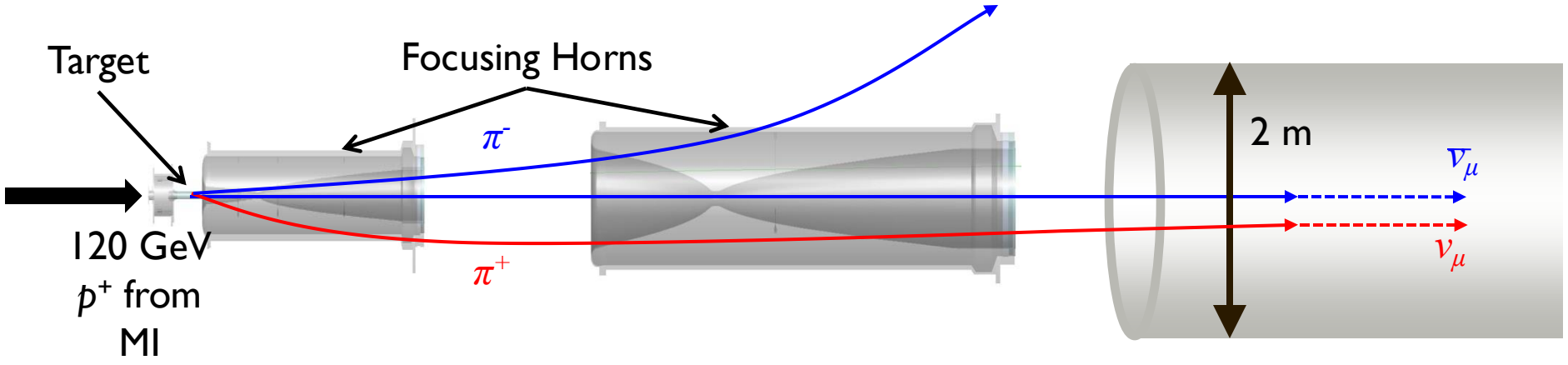
NOvA

T2K





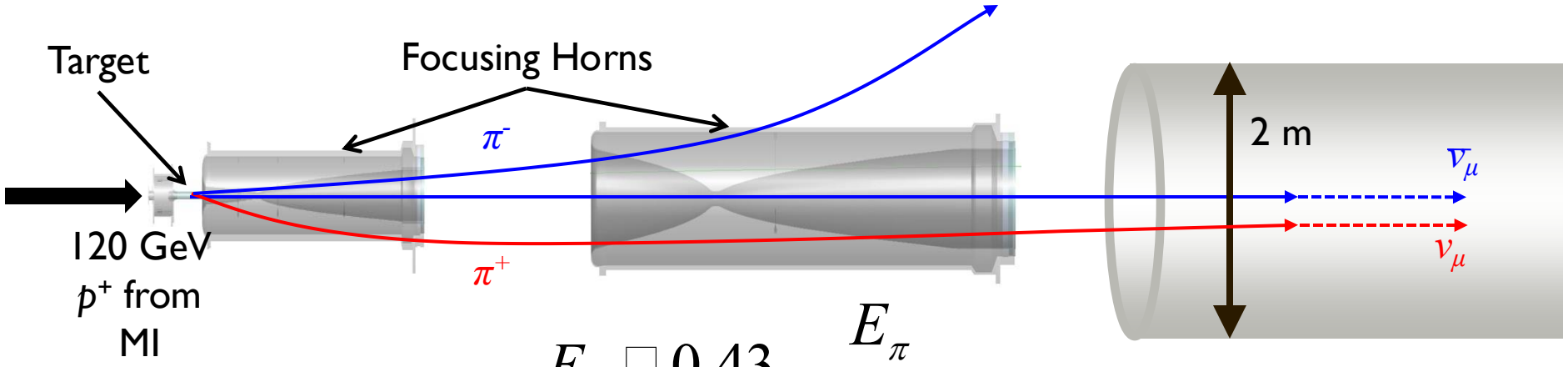
MAKING A NEUTRINO BEAM



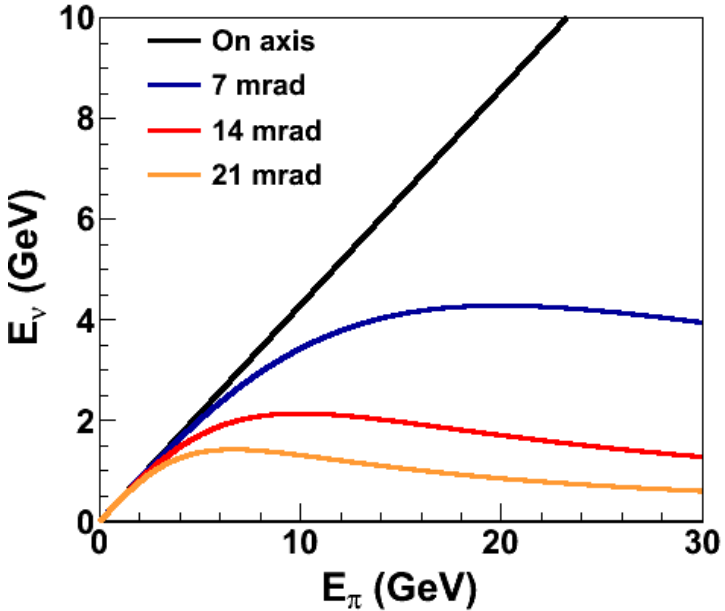
Both experiments use conventional, horn focused neutrino beams and have achieved high power:

- T2K uses 30 GeV protons, achieved 760 kW in 2024
- NOvA uses 120 GeV protons, set new neutrino beam power record of 1MW in 2024

MAKING A NEUTRINO ~~BEAM~~ ~~Flashlight~~ Torch

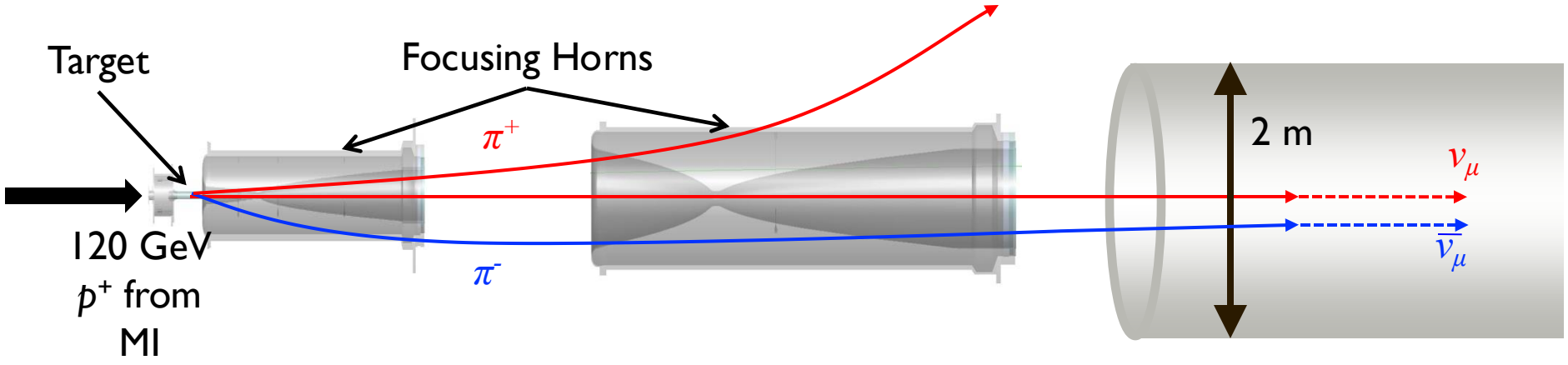


$$E_\nu \square 0.43 \frac{E_\pi}{1+\gamma^2\theta_\nu^2}$$



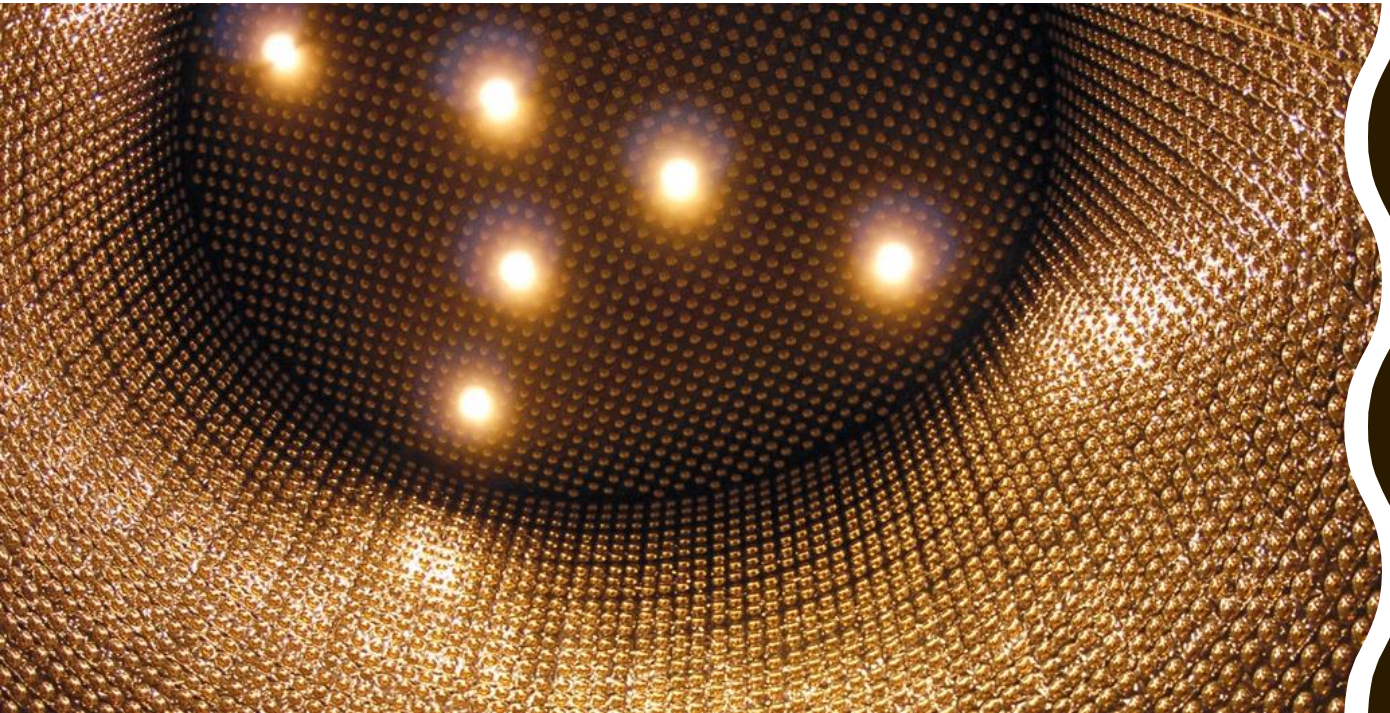
- Off-axis beam means less neutrino energy dependence on parent energy
- Neutrino spectrum becomes a narrow peak
  - NOvA: 14 mrad, sees 2GeV beam
  - T2K: 2.5° (43mrad), sees 600 MeV beam
- Suppressed high energy tail: fewer neutral current backgrounds at low visible energy

MAKING A ^anti- NEUTRINO ~~BEAM~~ ~~Flashlight~~ Torch



Off Axis the experiments see high purity muon neutrino/antineutrino beams:

- ~1% electron neutrino contamination
- Wrong sign flux less than 10% in both neutrino and antineutrino beams

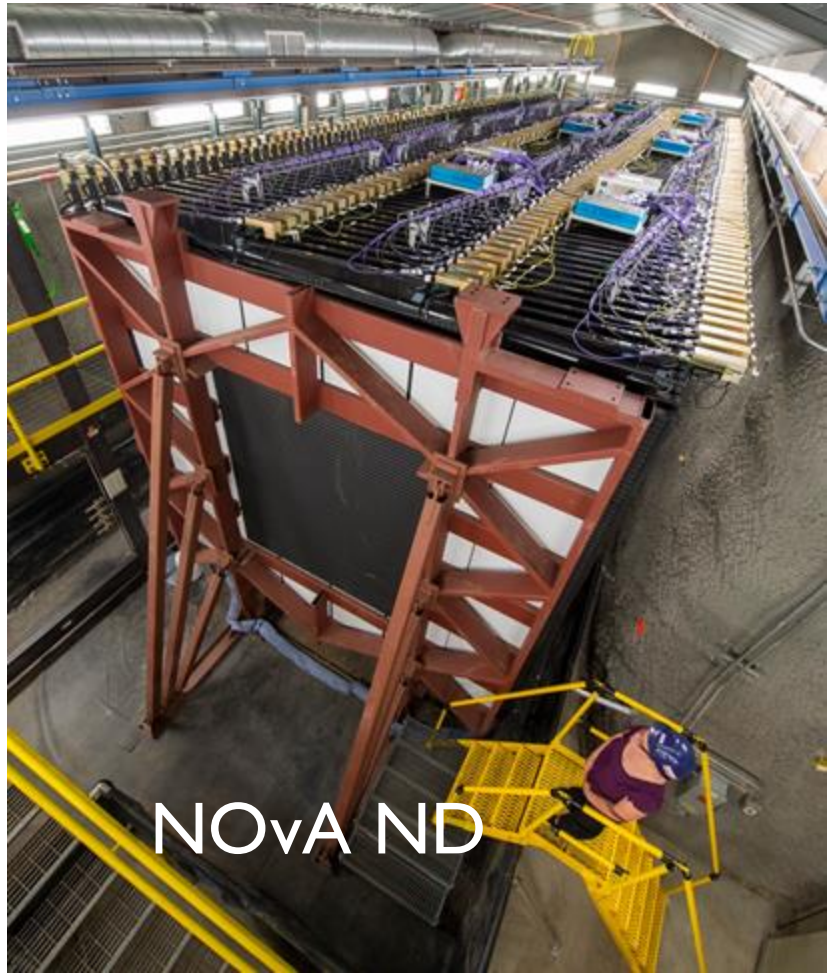


FAR DETECTORS

- T2K uses SuperK detector
  - 50 kton Water Cherenkov
- NOvA FD
  - 14 kton PVC and liquid scintillator

TWO DETECTOR TECHNIQUE

Near detectors used to predict far detector expectations and control systematics



NOvA ND is functionally identical to FD. Same technology and materials, smaller size

To make FD prediction:

- Adjust flux and cross section models guided by external data, then further adjust to account for multi-nucleon processes
- extrapolate remaining discrepancies in bins of energy resolution and transverse momentum using F/N ratio
- Systematic uncertainties cancel in F/N ratio

C. Giganti, Neutrino 2024

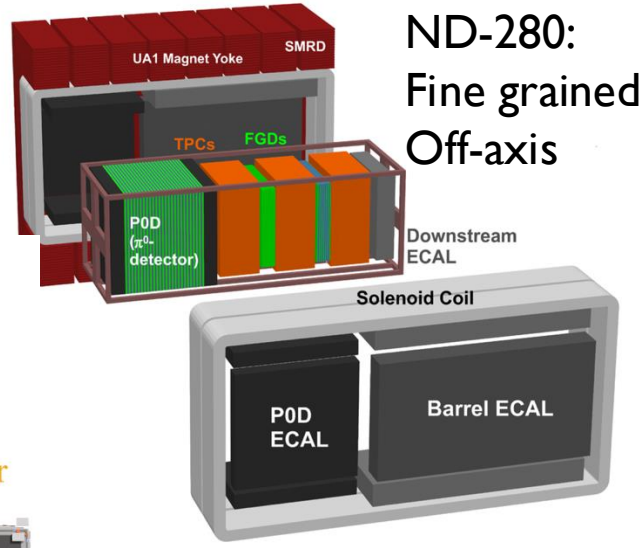
TWO DETECTOR TECHNIQUE

Near detectors used to predict far expectations and control systematics

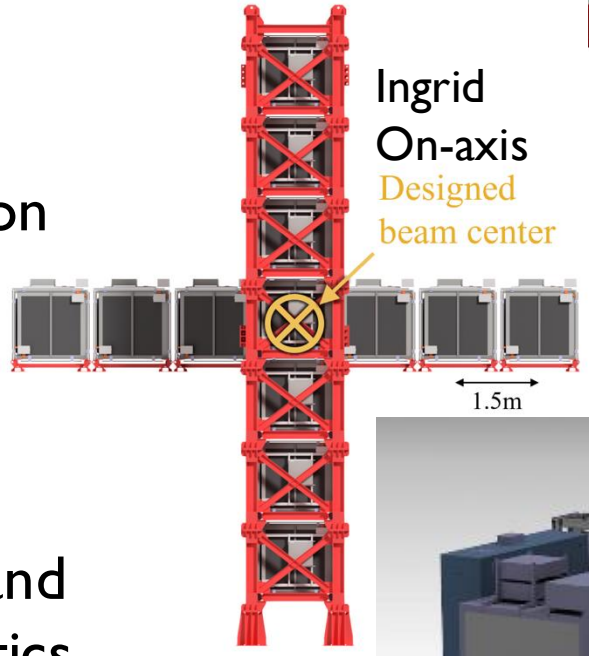
T2K has ND suite (on axis + 2 off-axis)

To make FD prediction:

- Using external data constraints, build parameterized model of flux, cross section and detector response
- Simultaneously fit 22 different ND280 samples and FD samples for model parameters and oscillations
- The fit makes sure the model is "right," and high stat ND samples constrain systematics.



ND-280:
Fine grained
Off-axis



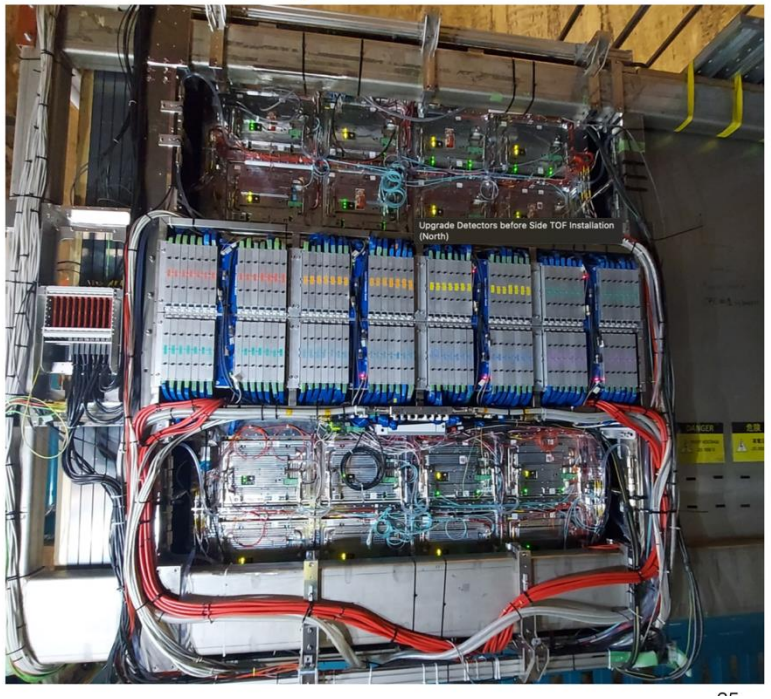
Ingrid
On-axis

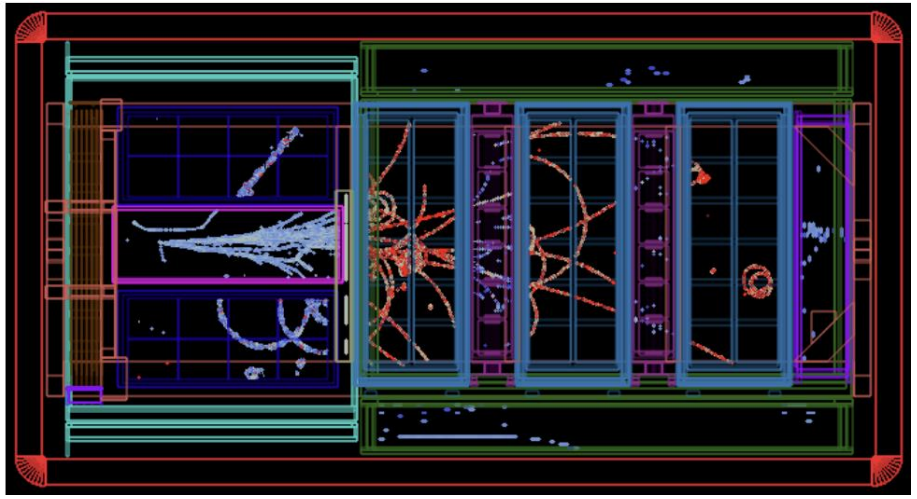
Bottom line: ~15% errors on FD predictions are reduced to ~4% in both experiments

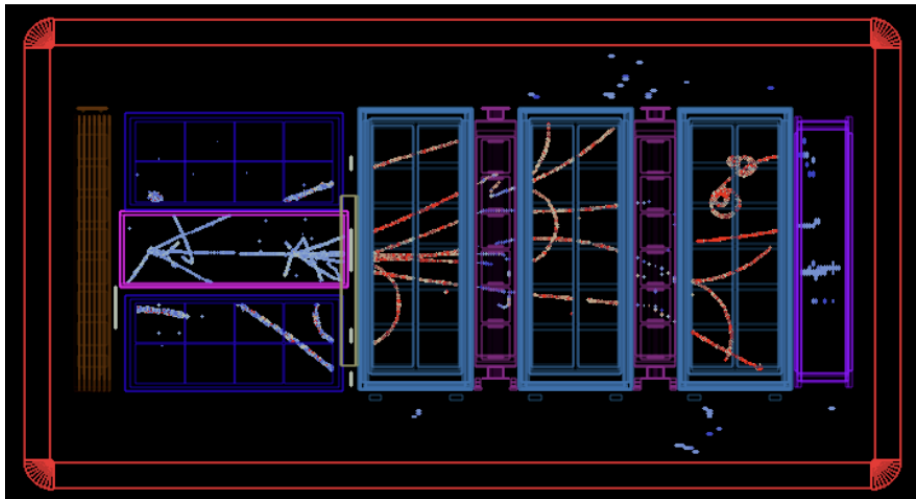
TWO DETECTOR TECHNIQUE

New T2K ND online!

April 2024







- Improves low energy proton and neutron reco
- Increased angular acceptance to better match SK
- Better e/γ discrimination

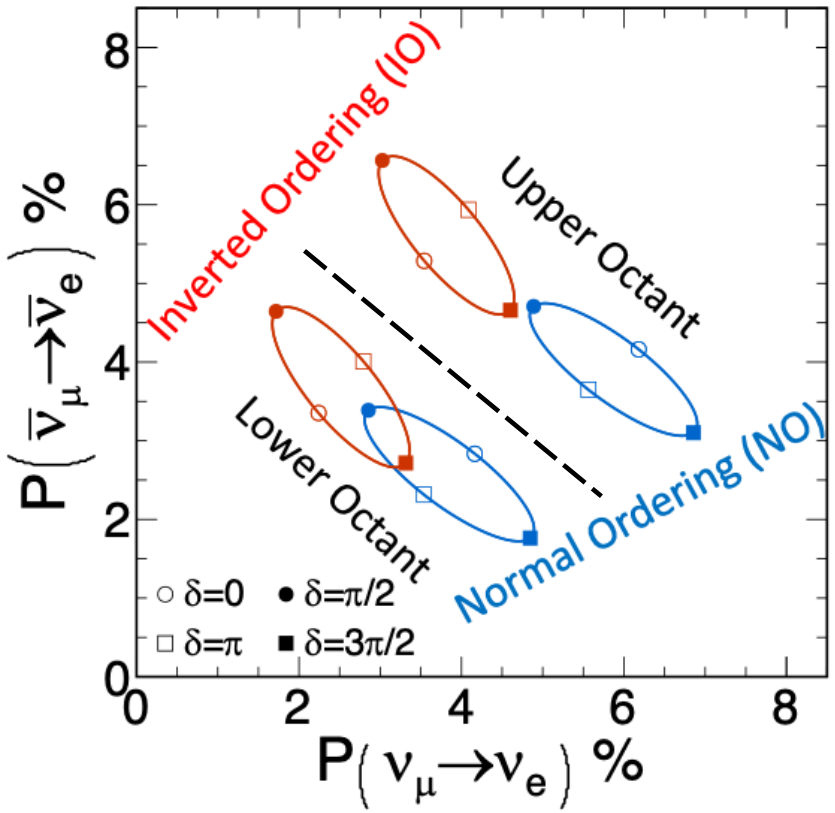
arXiv:1901.03750

T.Vladisavljevic, J-PARC Symposium, Oct. 2024

3 FLAVOR OSCILLATION ANALYSIS

Image Credit: Symmetry Magazine

ANALYSIS BASICS



Compare electron-neutrino appearance probability in neutrinos to antineutrinos

- In vacuum with no CP violation, neutrino and antineutrino appearance probabilities the same
- CP violation enhances appearance probability for neutrinos while suppressing it for antineutrinos, or vice-versa
- Matter effects also introduce mass ordering dependent neutrino vs. antineutrino differences
- Upper octant enhances both neutrino and antineutrino appearance probability, while lower octant suppresses both

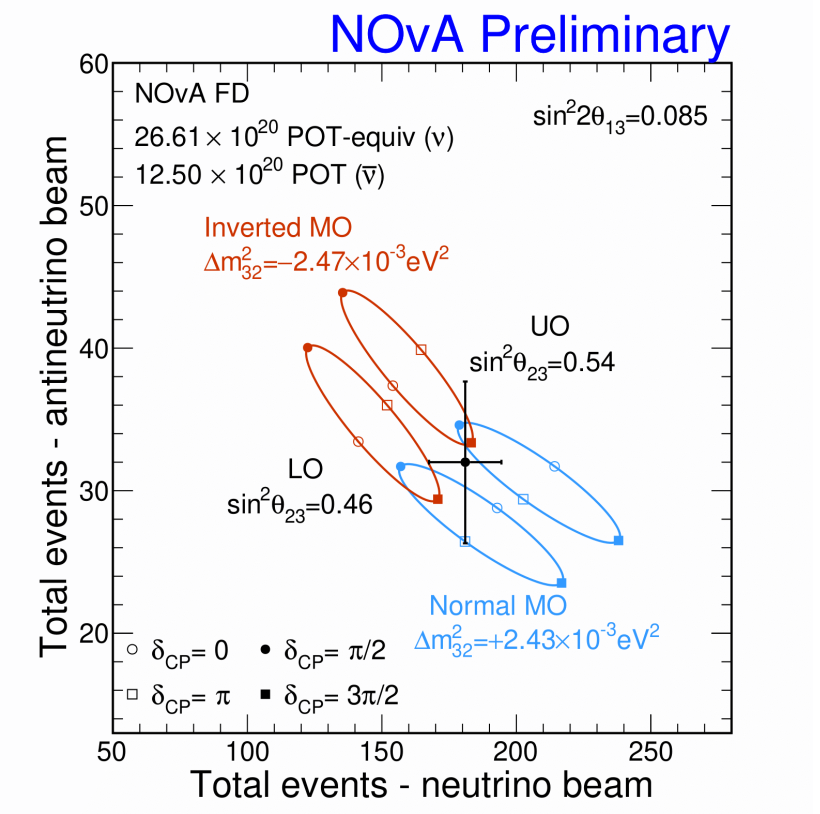
NOVA RESULTS

J. Wolcott, Neutrino 2024

- Results feature double the exposure of previously published neutrino data set.
  - Exposure: (26.6, 12.5)x10^{20} POT (neutrinos, antineutrinos)
  - New low energy electron neutrino sample enhances mass ordering sensitivity, among other analysis updates.

10 years of NOvA FD Data

	ν_μ	$\bar{\nu}_\mu$	ν_e	$\bar{\nu}_e$	Low Energy ν_e
Observed	384	106	169	32	12
Pred. BG	11.3	1.7	54.9	12.2	6.8



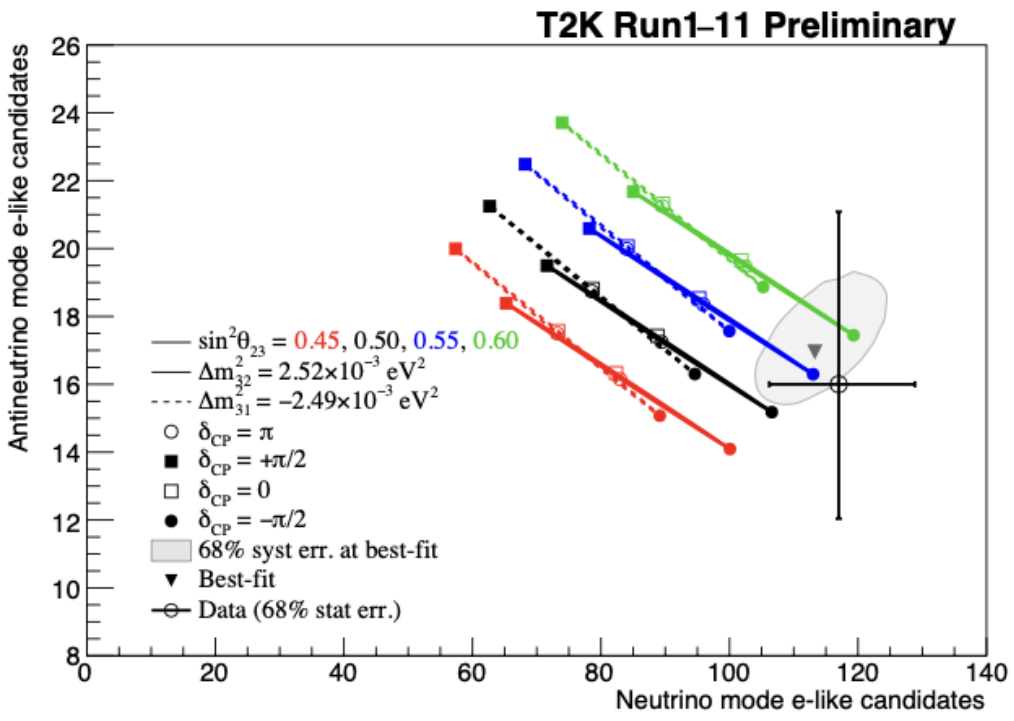
Data land in region of overlap, meaning either ordering with different values of δ_{CP} can adequately describe data

C. Giganti, Neutrino 2024

T2K RESULTS

Results feature ~38e20 POT

- 11 years of data
- SK doped with Gd in last run period
- ND280 only



Sample	$\delta_{CP}=-\pi/2$	$\delta_{CP}=0$	$\delta_{CP}=\pi/2$	$\delta_{CP}=\pi$	Data
ν-mode 1Rμ	417.2	416.3	417.1	418.2	357
ν-mode MR	123.9	123.3	123.9	124.4	140
$\bar{\nu}$-mode 1Rμ	146.6	146.3	146.6	147.0	137
ν-mode 1Re	113.2	95.5	78.3	96.0	102
$\bar{\nu}$-mode 1Re+d.e.	10.0	8.8	7.2	8.4	15
$\bar{\nu}$-mode 1Re	17.6	20.0	22.2	19.7	16

Neutrino

Anti-neutrino

Neutrino

Anti-neutrino

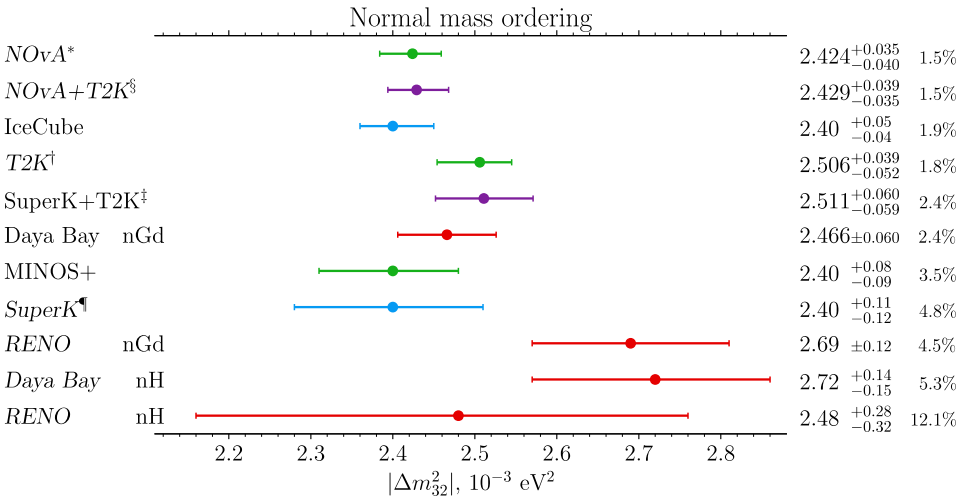
Disappearance

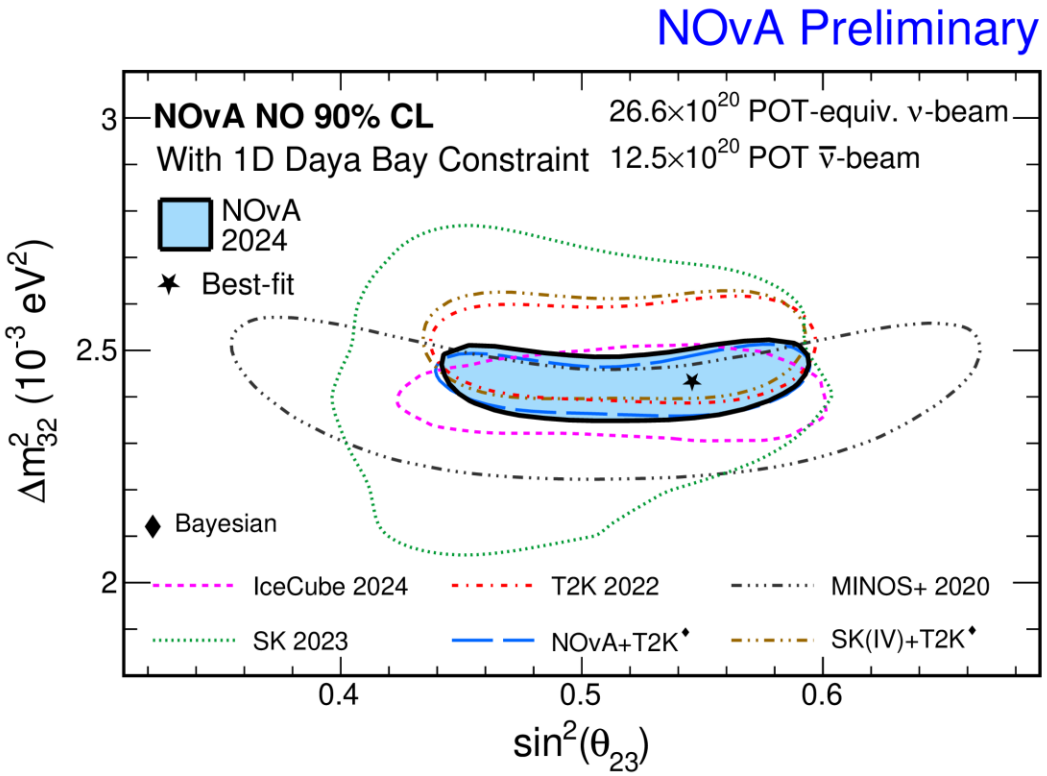
Appearance

J. Wolcott, Neutrino 2024

32 SECTOR RESULTS

Good agreement among experiments in the 32-sector





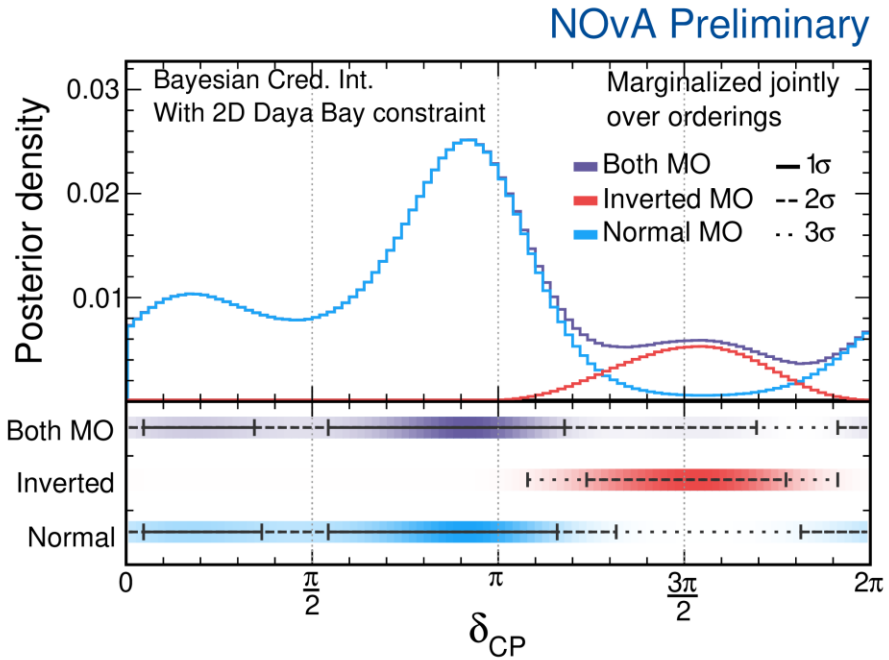
NOvA Frequentist best fit:

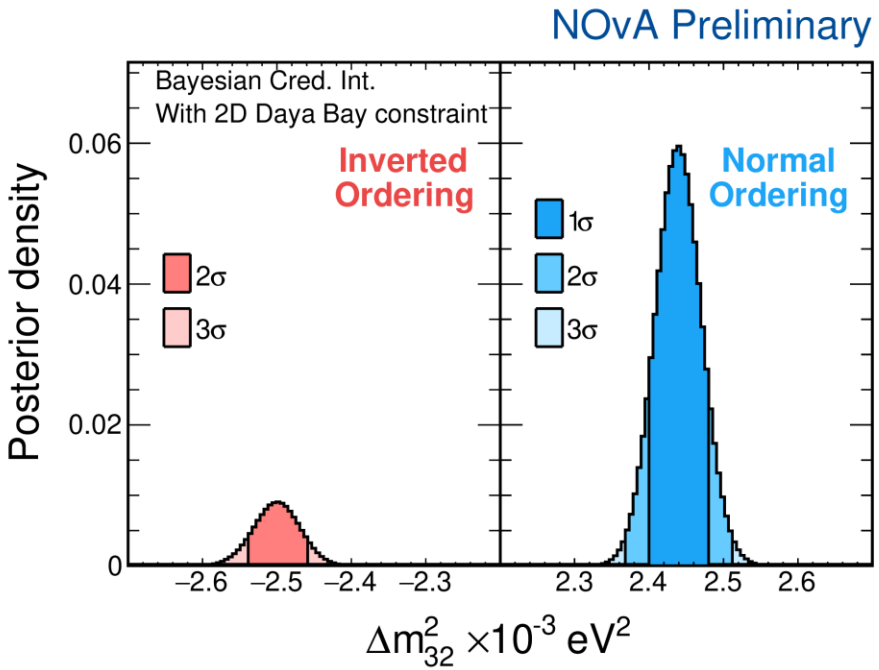
$\Delta m^2_{32} = +2.43^{+0.035}_{-0.036} \times 10^{-3}$ eV²

$\sin^2\theta_{23} = 0.546^{+0.032}_{-0.075}$

J. Wolcott, Neutrino 2024

NOVA RESULTS—MO AND CP





Normal MO: data prefer CP-conserving δ_{CP} values
Inverted MO: data prefer maximal CP-violation, δ_{CP}=0,π not in 3σ allowed interval

Using Daya Bay to constrain both θ_{13} and Δm^2, NOvA data favor Normal MO by ~7:1 odds (Bayes factor of 6.8).

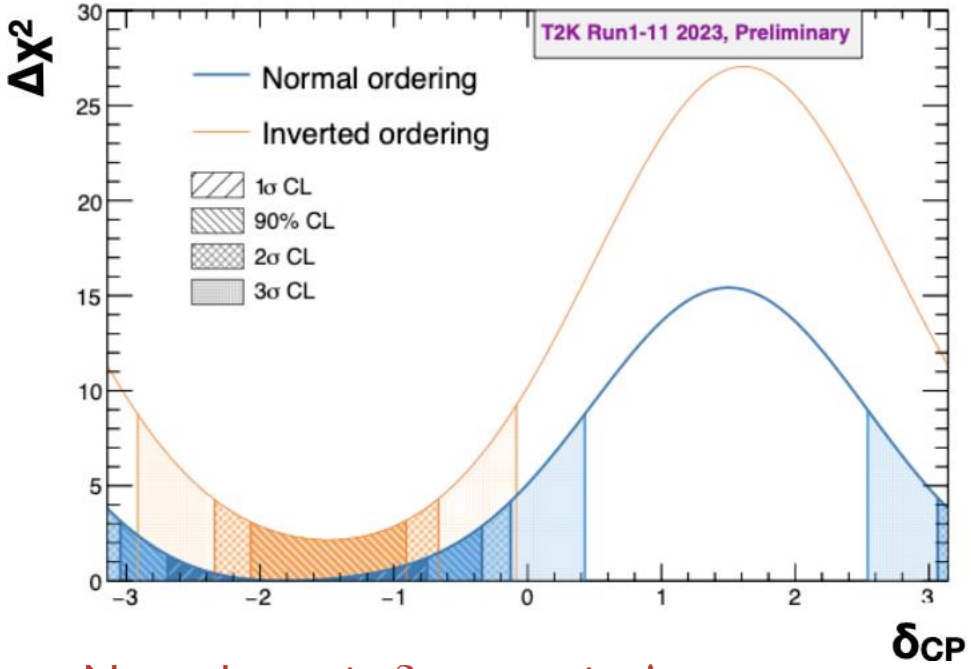
NOvA Frequentist best fit:
Normal ordering, Upper Octant
$\delta_{CP} = 0.875\pi$

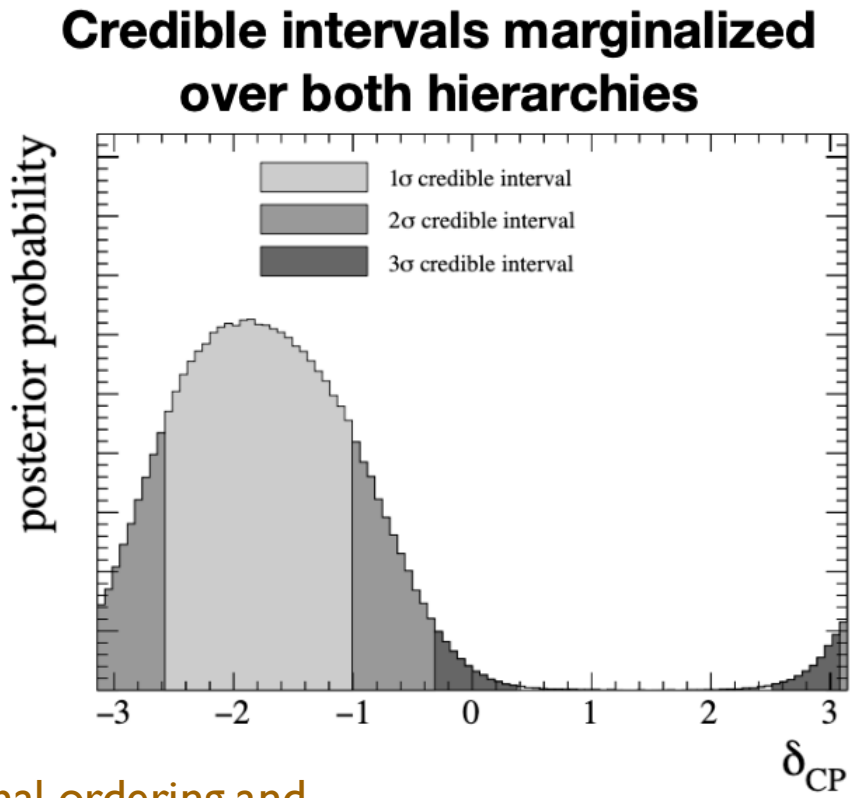
Disfavors Inverted MO at 1.6σ
Maximal mixing allowed at ~1σ

T2K RESULTS—CP

C. Giganti, Neutrino 2024
†N. Latham, WIN 2025

T2K prefers maximal CP violation (-π/2, aka 3π/2), but CP conserving values are allowed at 2σ
After conducting pseudo—data studies, T2K quotes CP conservation is allowed at just below 90% C.L.†





Note change in δ convention!

T2K also prefers normal ordering and upper octant, at low significance
Bayes Factor NO/IO = 3.3
Bayes Factor UO/LO = 2.6

JOINT FIT

Complimentary experiment design break degeneracies

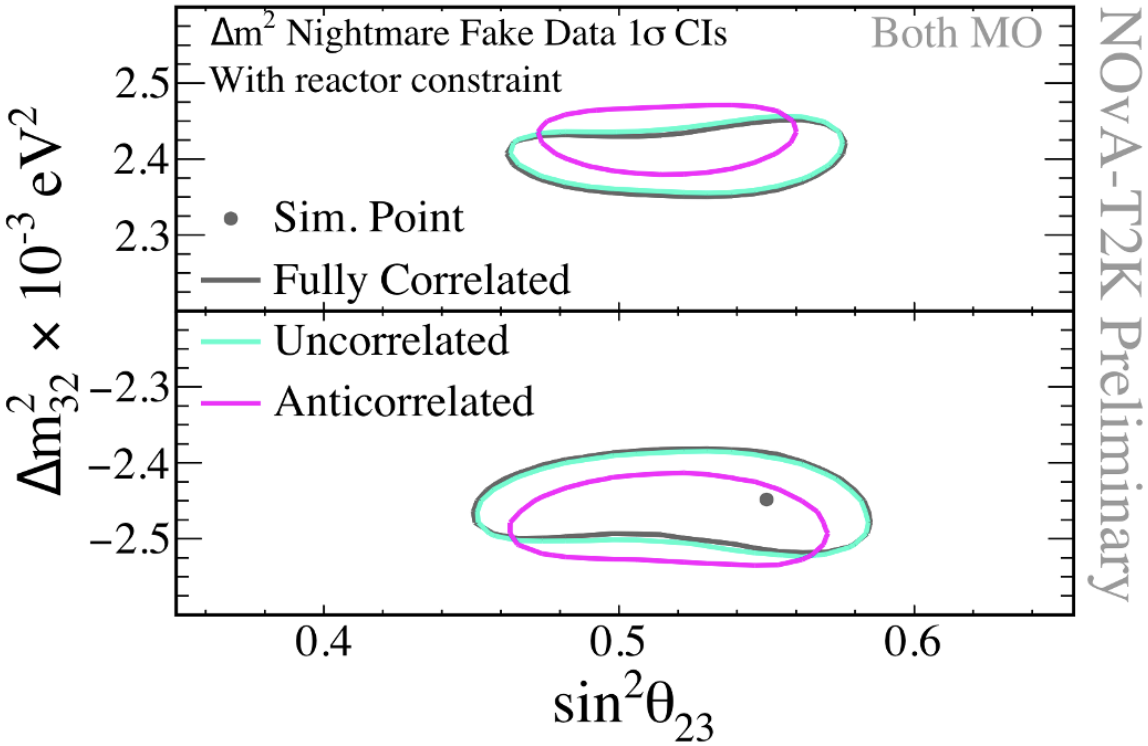
NOVA/T2K HAVE DIFFERENT:

- L/E
- Amounts of matter effect
- Interaction processes
  - T2K mostly QE/2p2h
  - NOvA a mix of QE/2p2h/RES/DIS
- Detector technologies
- Systematic uncertainties
- Analysis approaches

BENEFITS OF JOINT FIT:

- Fit includes full details of
  - Energy reconstruction and detector response
  - Likelihood in all fitted dimension
  - Consistent statistical inference
- Together we conducted an in-depth review of the models, systematics, and correlations

JOINT FIT



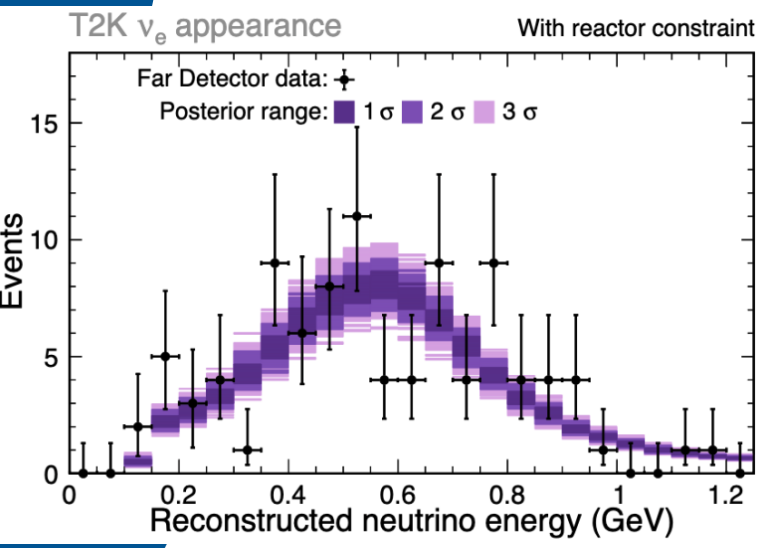
- Detector response and flux systematic uncertainties have no correlation between the experiments
- Cross section uncertainties likely are correlated, but there is no direct mapping between the model parameters from each experiment
- Constructed extreme scenarios where artificially large systematic uncertainties induce an effect like oscillations
- Leaving parameters uncorrelated is a better strategy than getting the correlation wrong

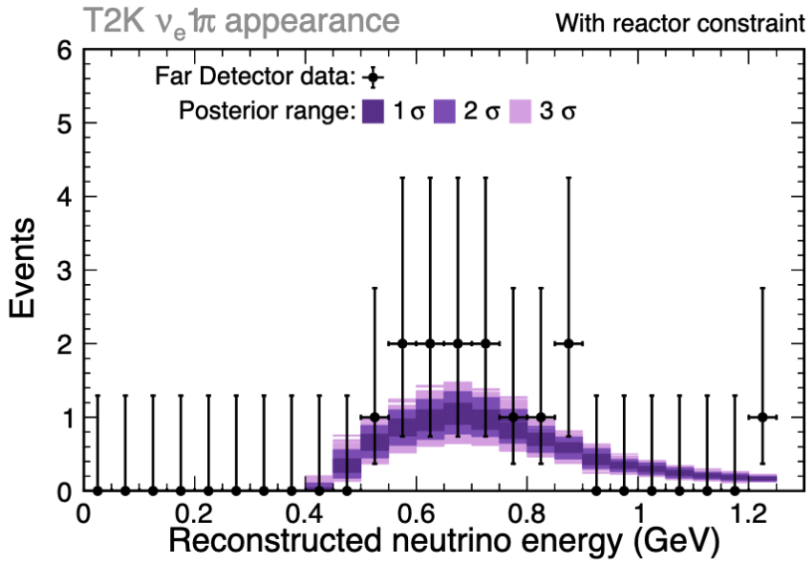
After extensive studies, both experiments were satisfied that leaving systematics uncorrelated was appropriate for the exposure of the first analysis

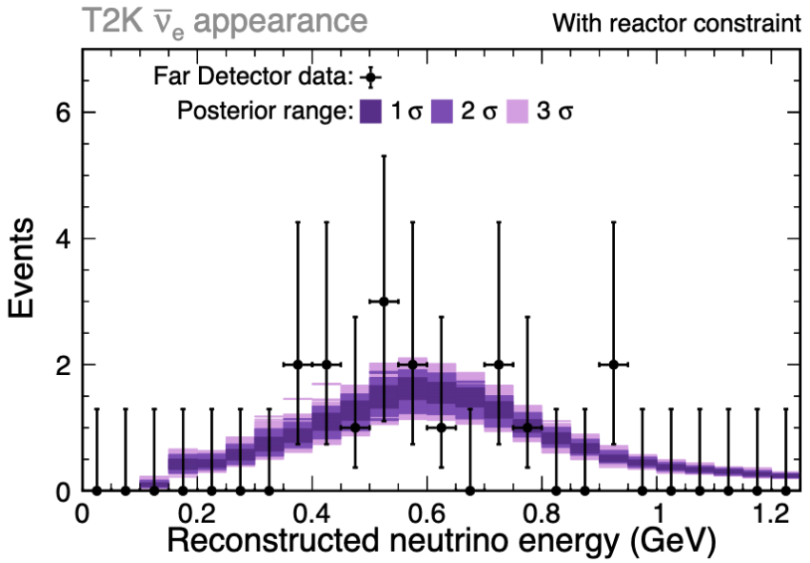
JOINT FIT RESULTS

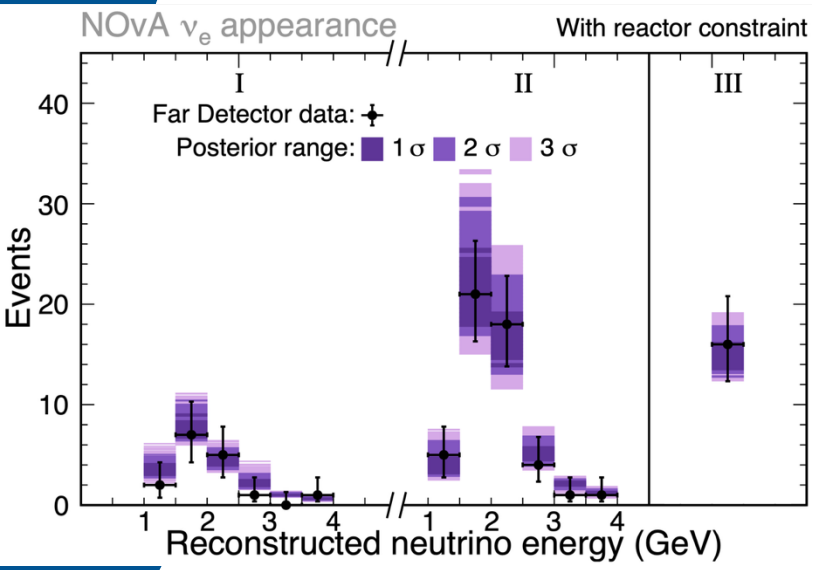
Z.Vallari, JETS, Feb. 2024

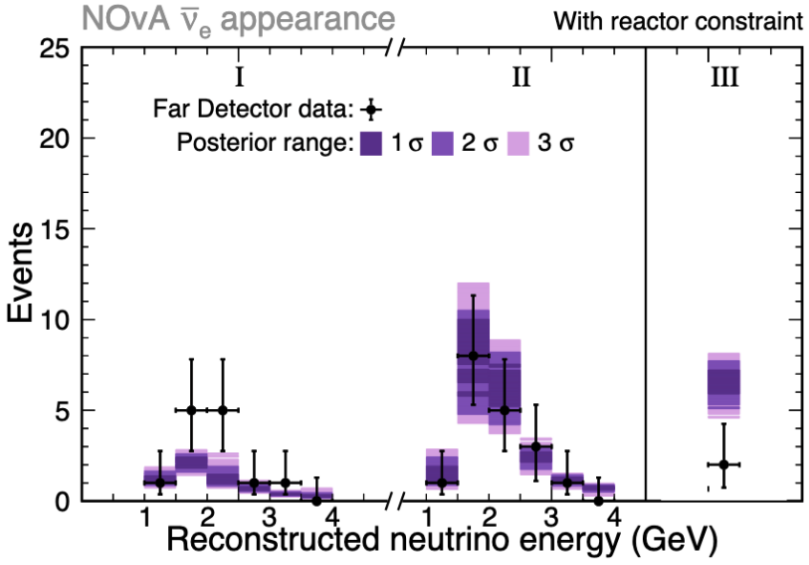
Note: Joint fit results based on smaller data sets than the individual results











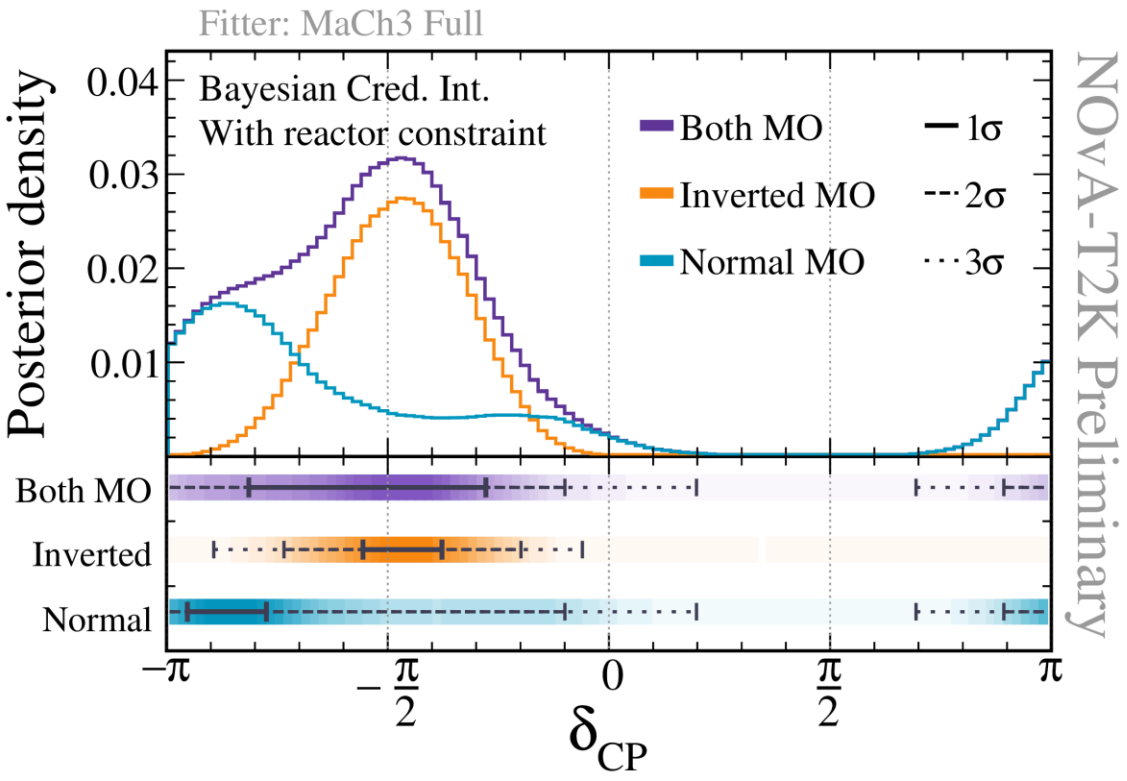
	NOvA	T2K	Combined
ν_e	0.90	0.19 (ν_e) 0.79 ($\nu_e 1\pi$)	0.62
$\bar{\nu}_e$	0.21	0.67	0.40
ν_μ	0.68	0.48	0.62
$\bar{\nu}_\mu$	0.38	0.87	0.72
Total	0.64	0.72	0.75

Posterior predictive p-value
(~0.5 is good compatibility)

Z. Vallari, JETS, Feb. 2024

JOINT FIT—CP

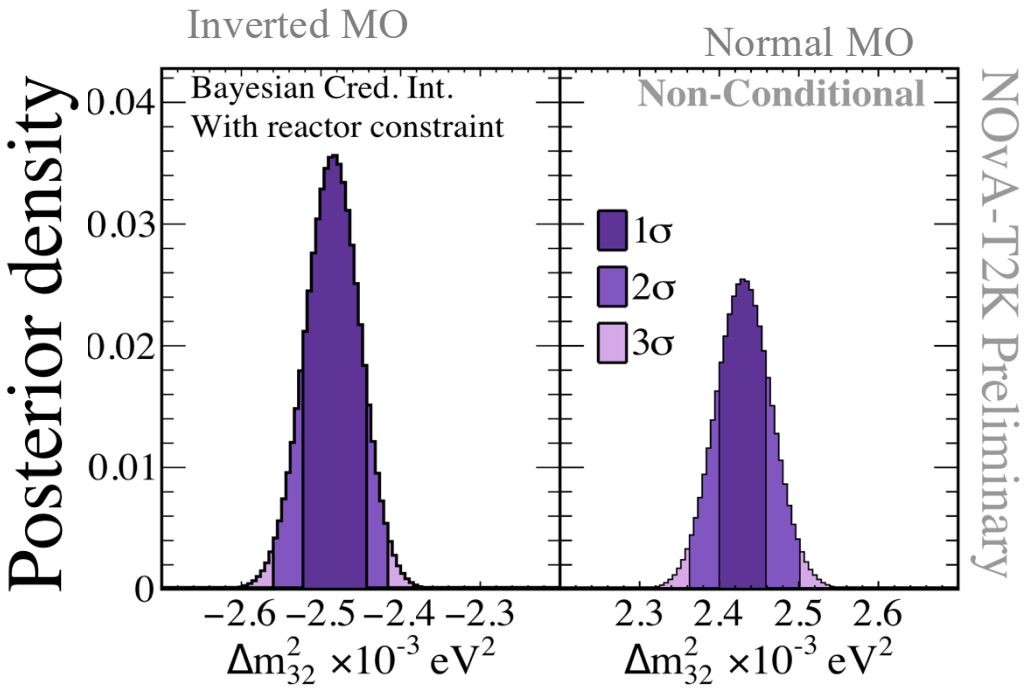
- For both mass orderings, $\delta_{CP} = \pi/2$ lies outside 3-sigma credible interval.
- Normal Ordering allows for a broad range of permissible δ_{CP}
- For the Inverted Ordering, CP conserving values of δ_{CP} $(0, \pi)$ lie outside the 3-sigma credible interval.



Note change in δ convention!

Z.Vallari, JETS, Feb. 2024

JOINT FIT—MO



Another possible way to determine the Neutrino Mass Hierarchy

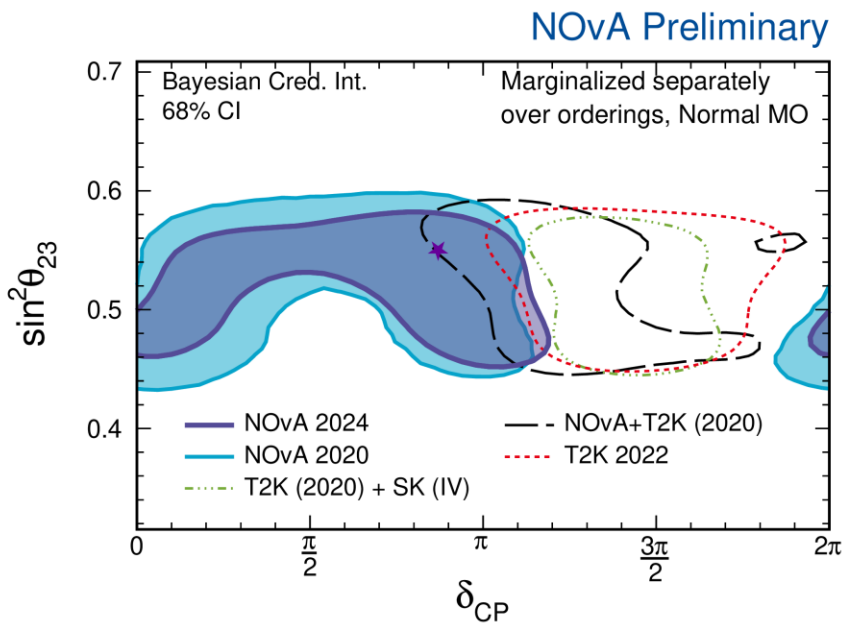
Hiroshi Nunokawa[1],* Stephen Parke[2],† and Renata Zukanovich Funchal[3]‡

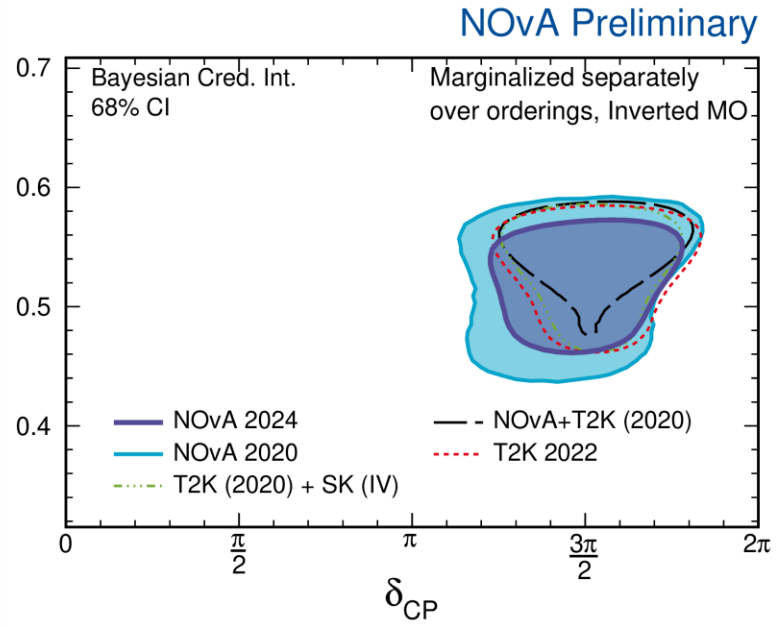
In the true mass ordering, reactor extraction of Δm_{32}^2 should be consistent with long-baseline value

	Preferred Ordering	Bayes Factor	Odds
No Reactor	Inverted	2.47	71% : 29%
Daya Bay θ_{13}	Inverted	1.34	57% : 43%
Daya Bay 2D	Normal	1.44	59% : 41%

NOvA+T2K Joint fit has a modest preference for the Inverted Ordering, but flips depending on what reactor constraints are used.

FINAL COMPARISONS





T2K also does joint fit with SK
Phys.Rev.Lett. 134 (2025) 1, 01180

- Prefers NO with 1.2σ exclusion of IO
- 1.9σ exclusion of CP conservation (J_{cp}=0)

External Global fits see similar trends
(I. M. Soler, WIN2025, JHEP 12 (2024) 216)

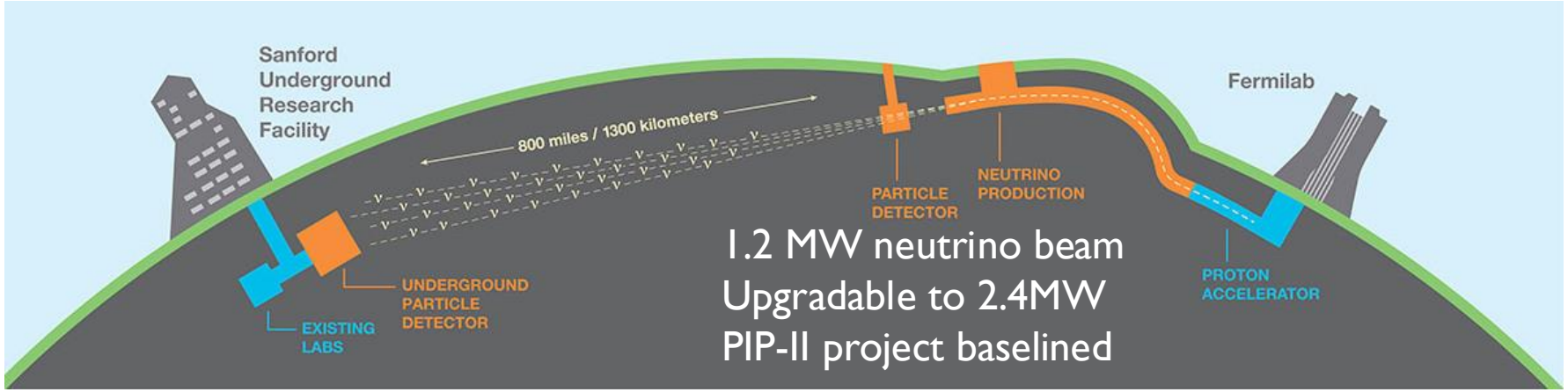
- Fit to LBL+Ice Cube+Reactor falls in NO, but fit is almost equally good in either ordering
- Adding SK Atmospherics disfavors IO with $\Delta\chi^2$=6.3
- Consistent with CP conservation at 1σ

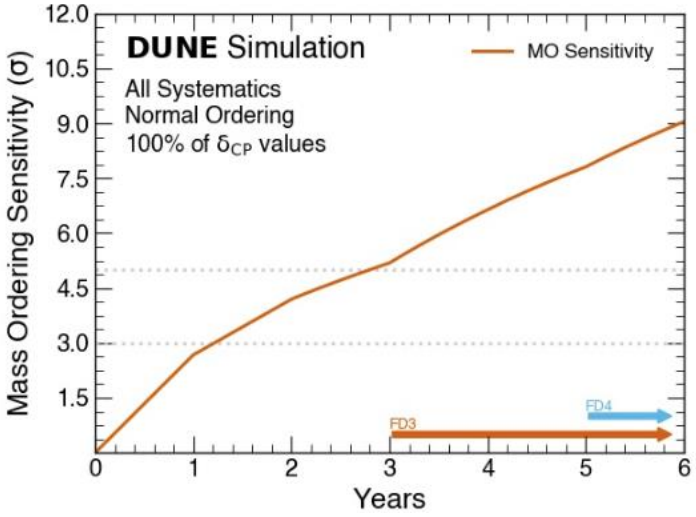
Stay tuned for more joint NOvA+T2K results

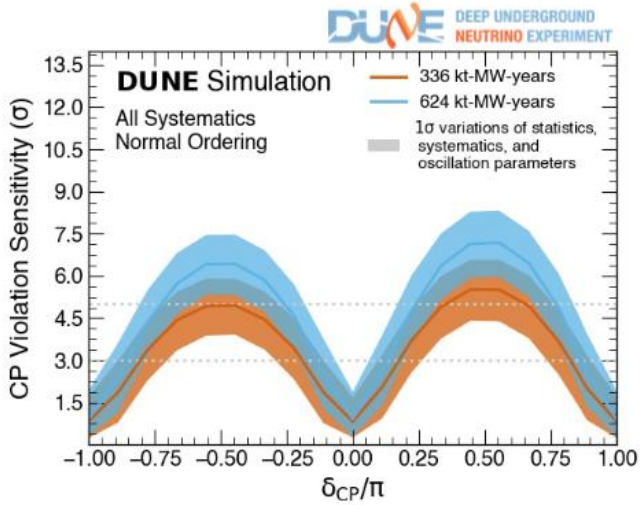
FUTURE LONG-BASELINE EXPERIMENTS

Image Credit:
New York Times

THE FUTURE LONG-BASELINES



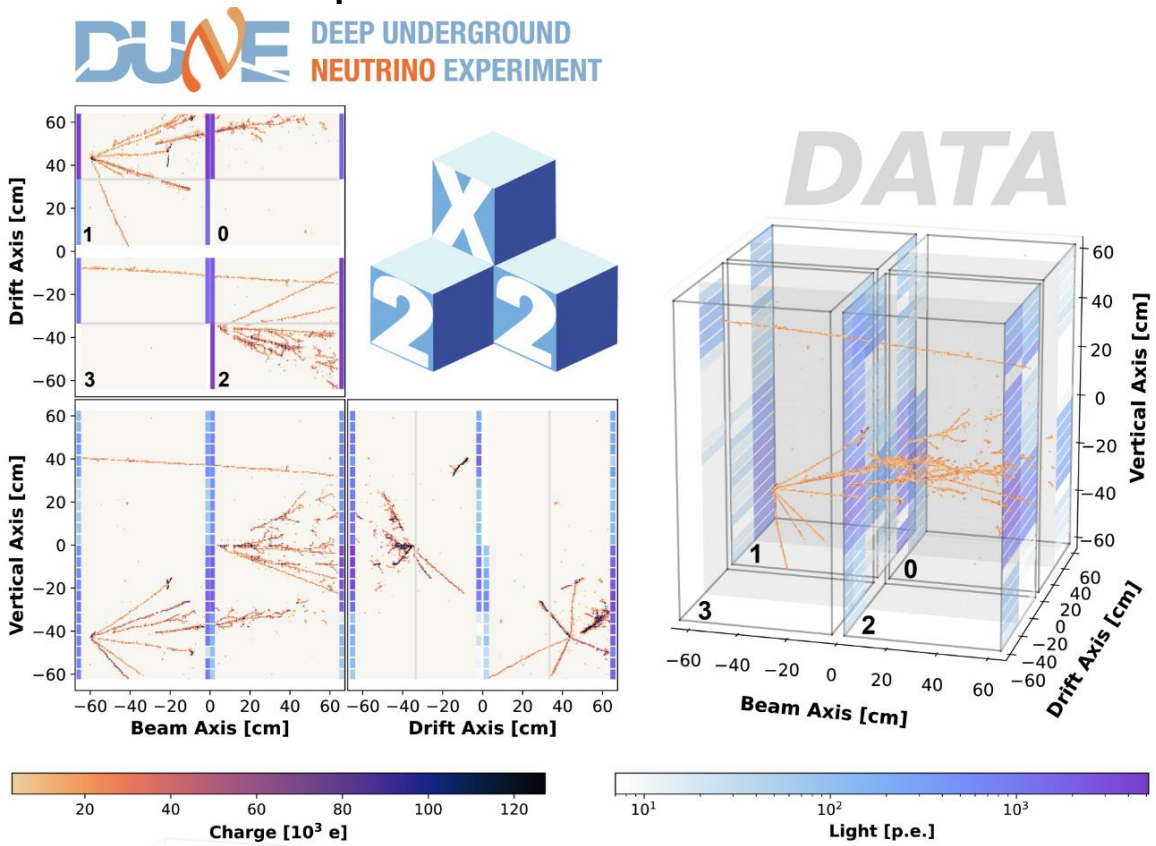


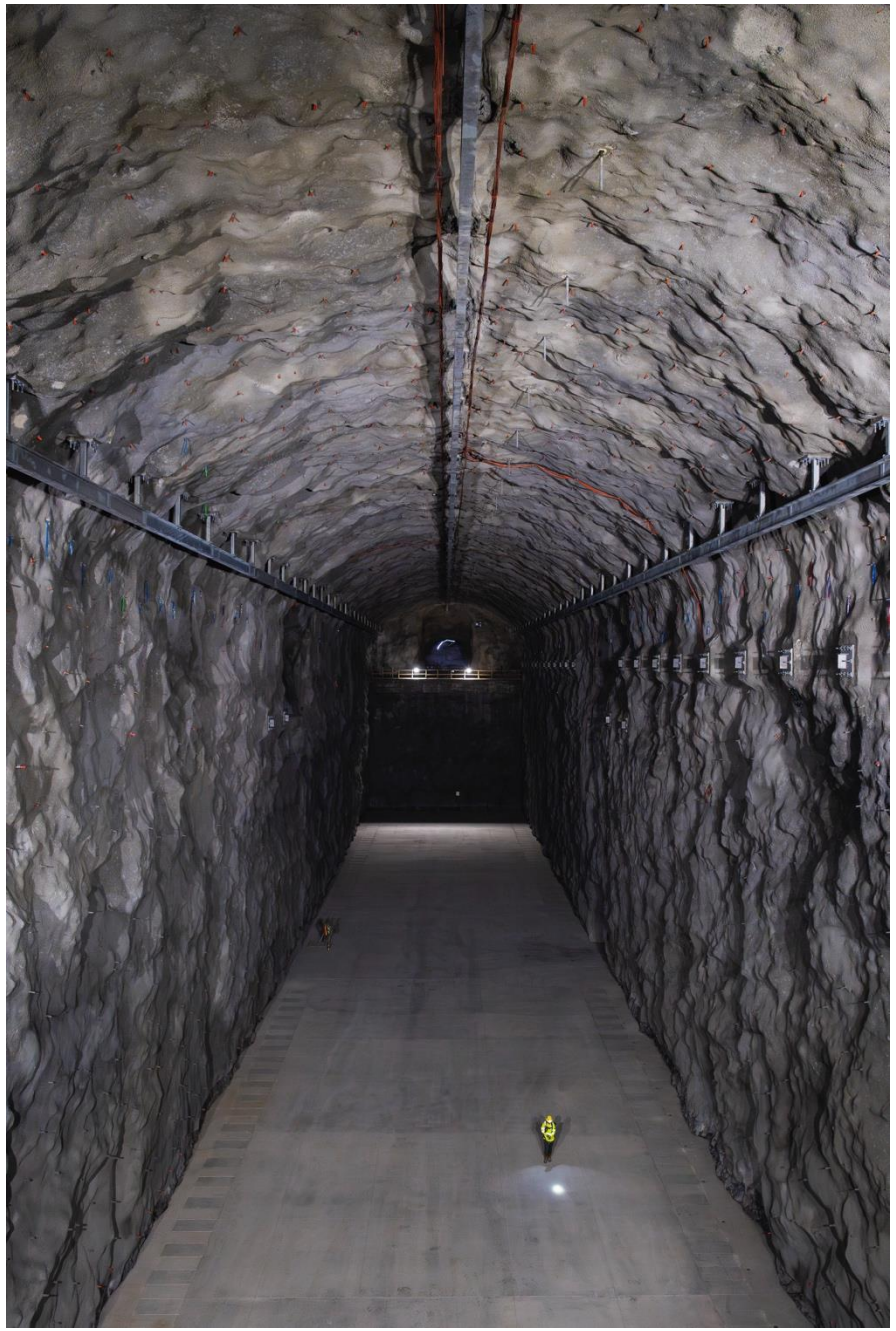


- 5 sigma mass ordering resolution after 3 years running with nominal detector design and beam configuration
- CP violation for 50% of delta values
  - 3 sigma in 5 years
  - 5 sigma in 10 years
- Expected start 2031

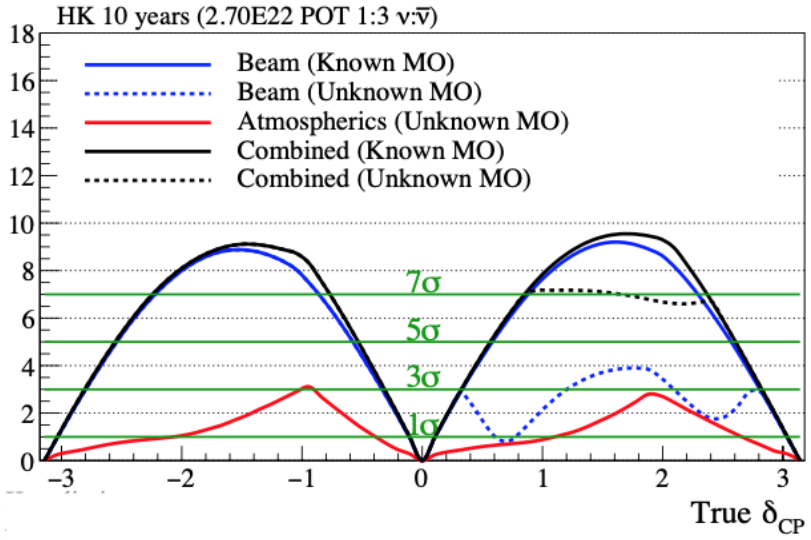
DUNE STATUS

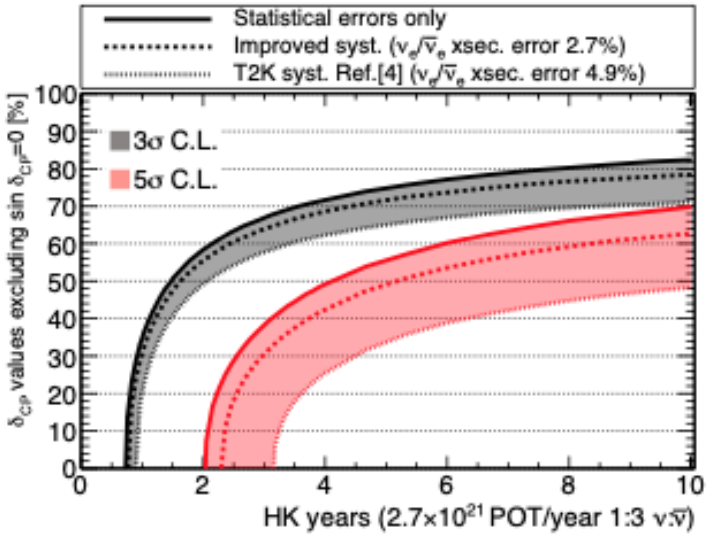
- Excavation of FD Caverns completed April 2024
- Cavern occupancy expected in Jan 2026
- Cryostat steel in South Dakota
- Vertical drift prototype commissioning at CERN
- 2x2 LAr det. w/ pixelated readout run in NuMI in 2024



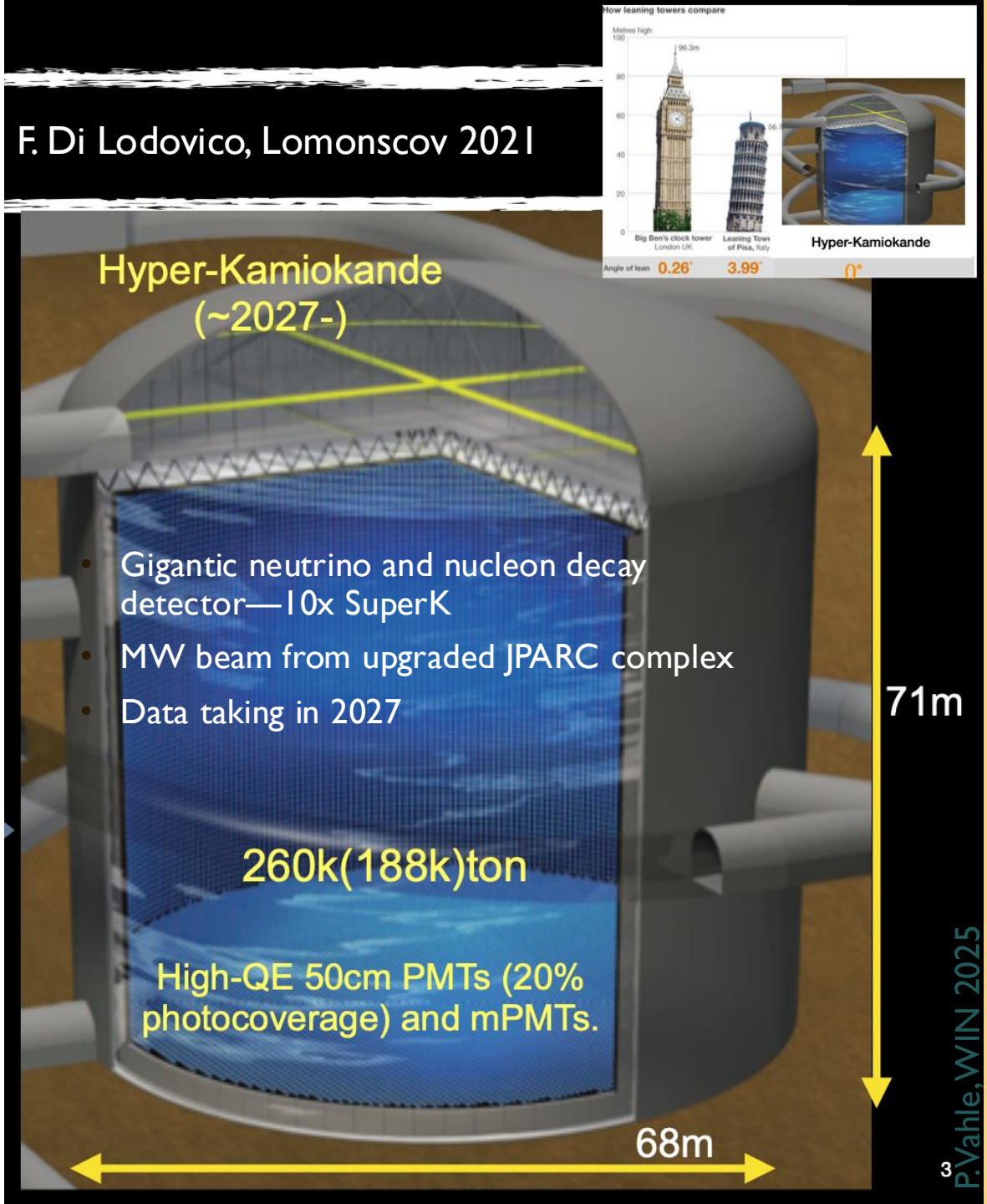


HYPER-K





F. Di Lodovico, Lomonscov 2021



HYPER-K STATUS

T. Katori, JETS May, 2025

Operation start expected 2028

- Site excavation completed
- R&D is concluding
- 10K+ of 20K PMTs are delivered and have had QA tests
- Working towards 1.3 MW beam in 2028 by reducing cycle time

SUMMARY

- In 25+ years of long-baseline accelerator neutrino oscillations, we've measured many parts of PMNS mixing of massive neutrinos.
- Important open questions remain:
  - Individual experiments tend to favor the NO at 1-2σ, but combinations weaken the significance or even flip the preference!
  - CP conserving values of δ_{cp} are allowed by T2K data at 2σ, 1σ in NOvA
  - In T2K+NOvA joint fit, the CP conserving values are outside the 3σ interval in the IO.
- The 2nd generation long-baseline experiments are nearing end of data taking.
- DUNE and Hyper-K promise exciting results just over the horizon!

BACKUP

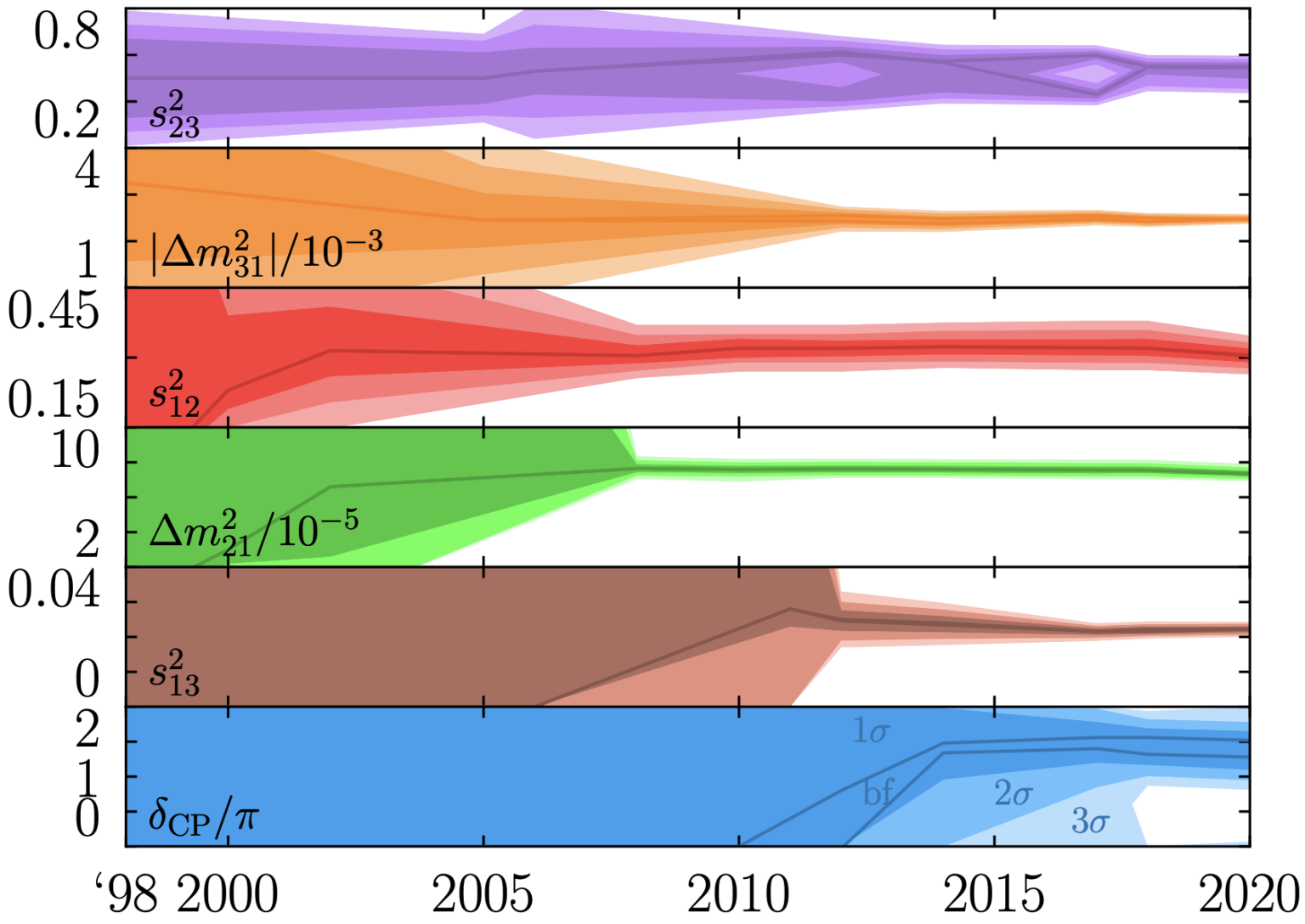


Figure 1: The six oscillation parameters listed in the order they were first measured, and the evolution of our understanding of them. Data comes from [8, 31–40].

LONG-BASELINE OBSERVABLES

Oscillation probabilities at L/E~500km/GeV are sensitive to most of the remaining unknowns

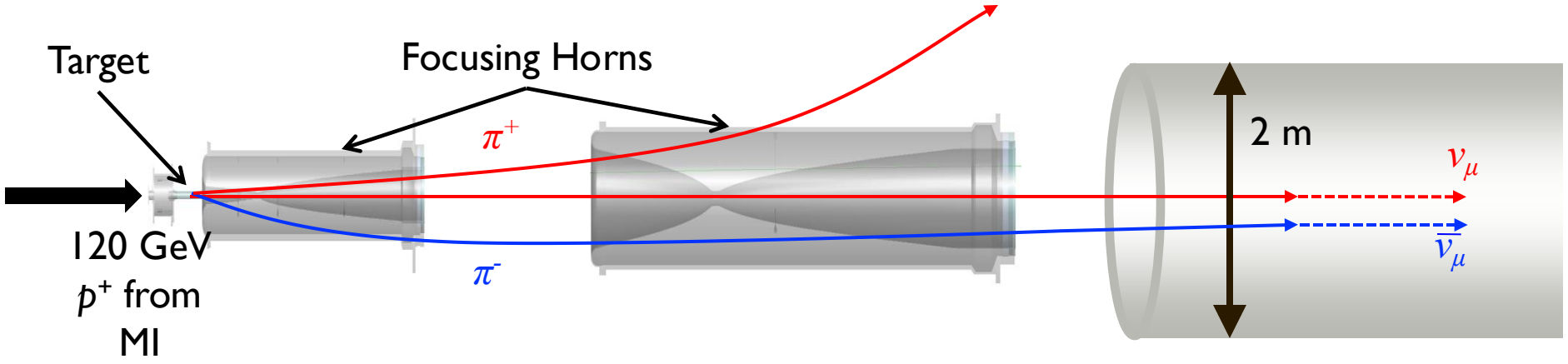
Muon Neutrinos disappear

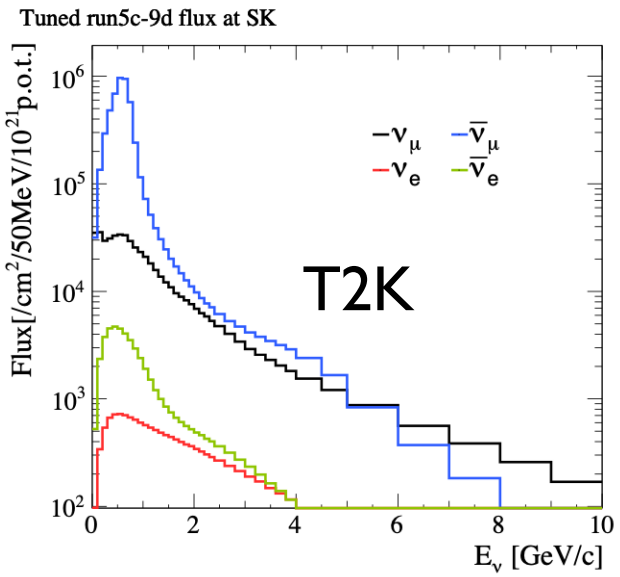
$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\theta)\sin^2(1.27\Delta m^2 L/E)$$

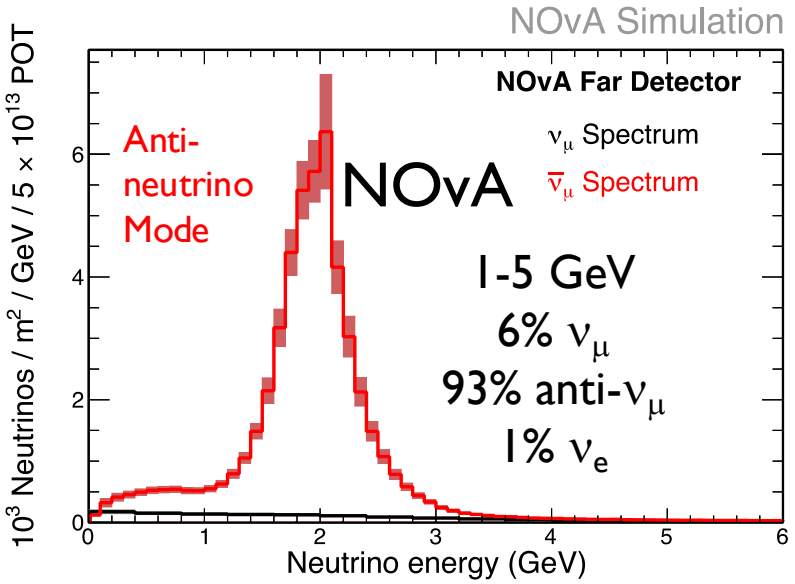
Electron Neutrinos appear

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

MAKING A ^anti- NEUTRINO ~~BEAM~~ ~~Flashlight~~ Torch



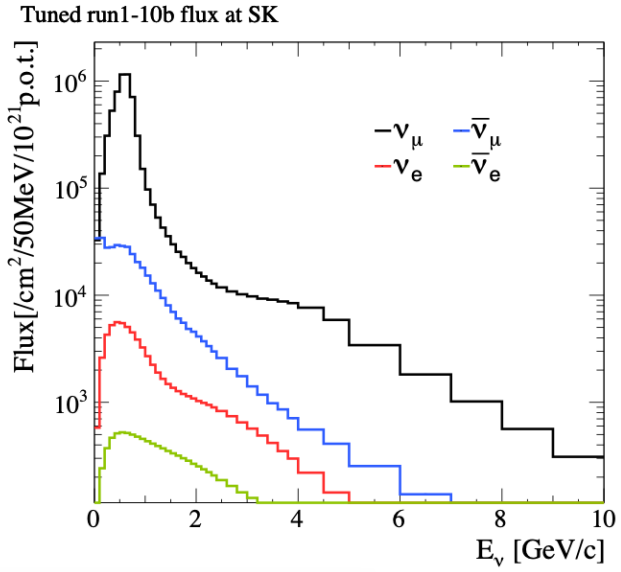


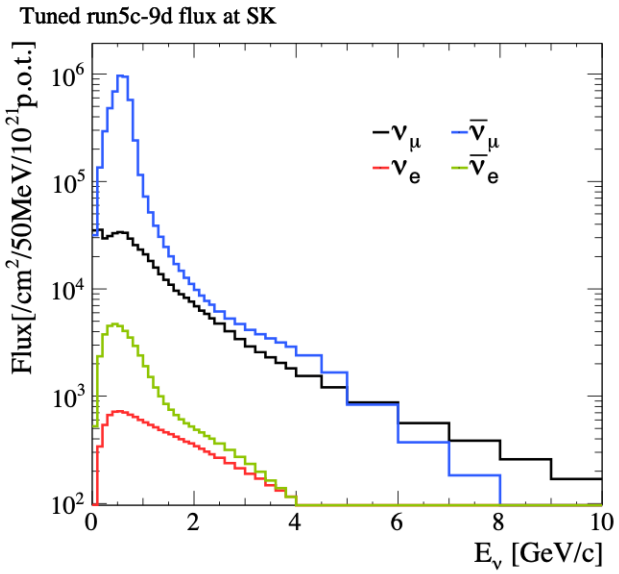


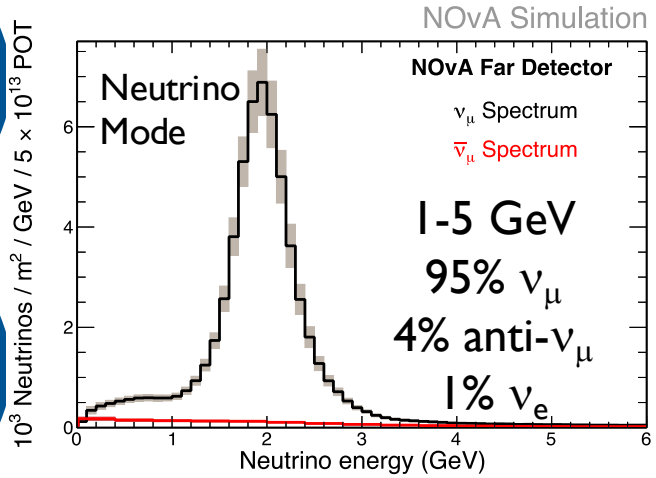
Wrong sign flux less than 10% in both neutrino and antineutrino beams

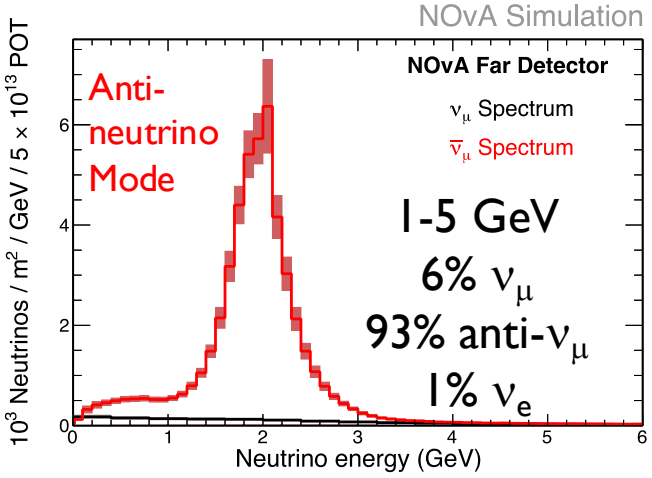
FLUX SPECTRA

P. Dunne, Neutrino 2020
L. Berns, Moriond EW 2021





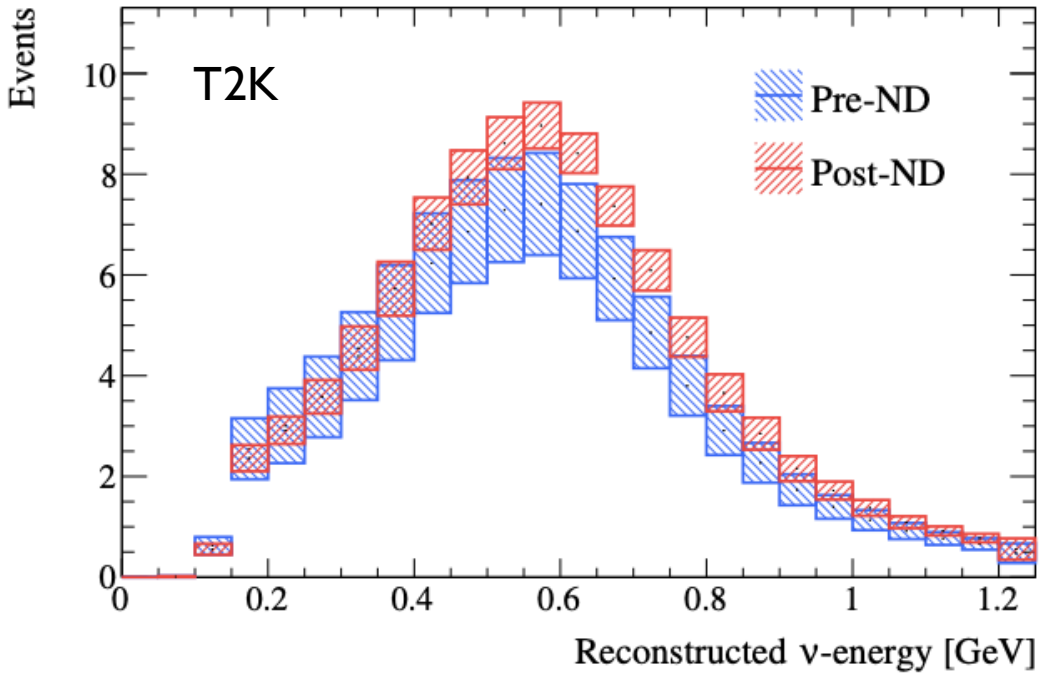




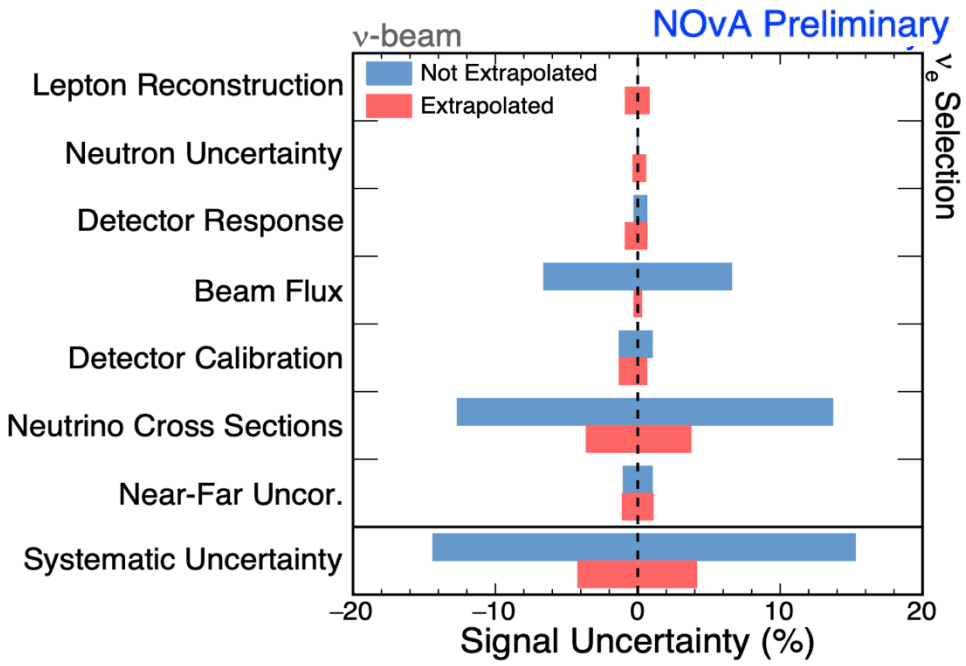
- External Hadron Production data constrains flux uncertainty to ~10%
- Wrong sign flux less than 10% in both neutrino and antineutrino beams
- Small electron neutrino contamination

TWO DETECTOR TECHNIQUE

Near detectors used to predict far expectations and control systematics

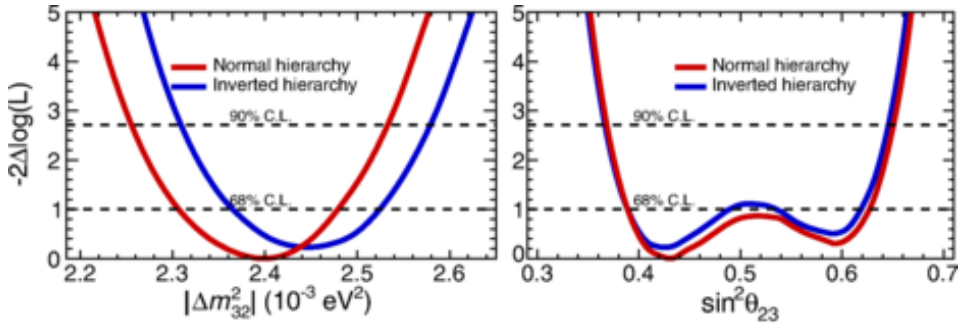


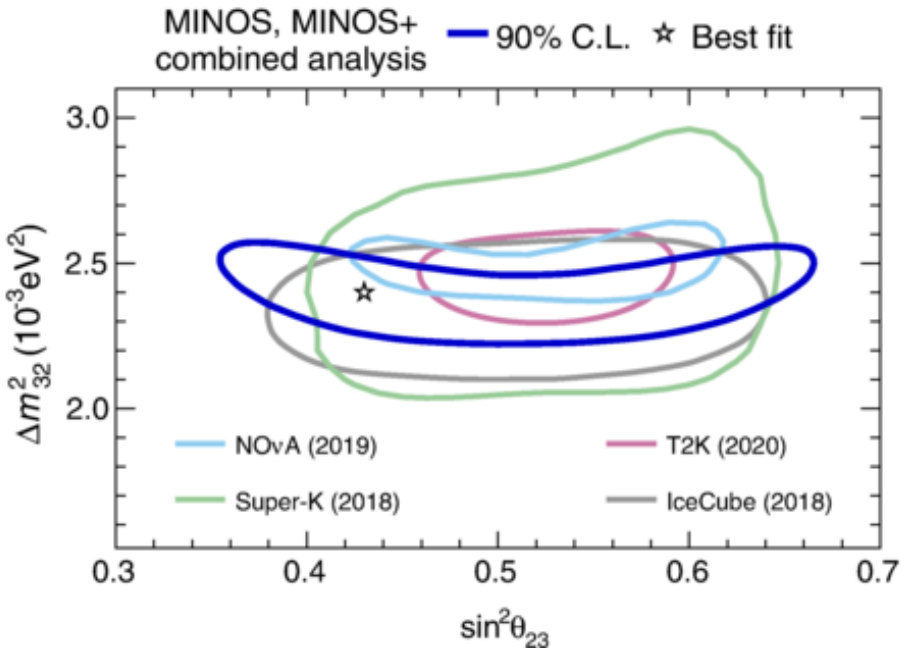
T2K: Systematic uncertainty on number of expected 1-ring e-like FD events drops from 13% to 5%



NOvA: Systematic uncertainty on predicted number of FD electron neutrino events drops from 15% to 4%

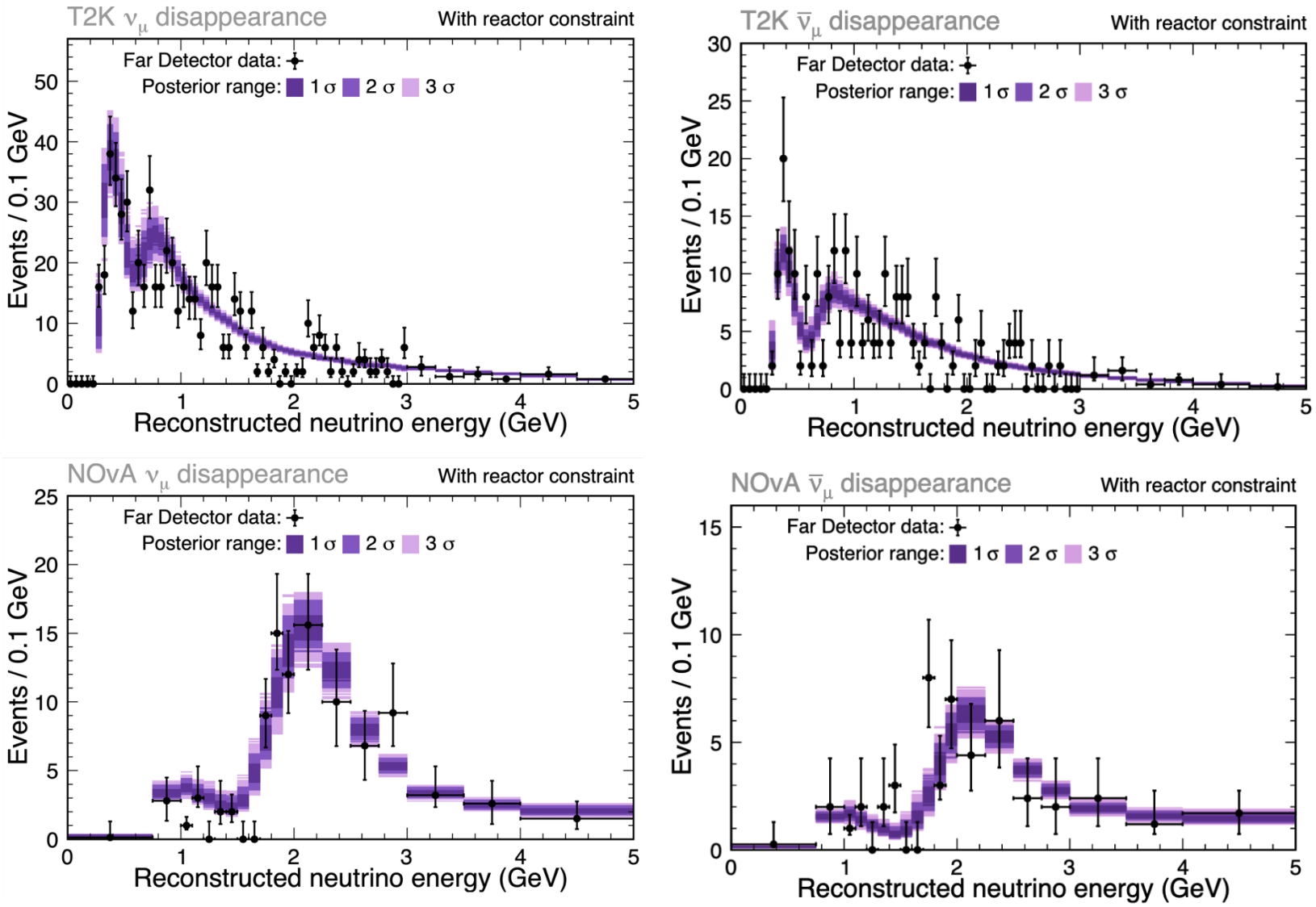
MINOS/MINOS+





MINOS+
PRL 125, 131802 (2020)

NOVA+T2K DISAPPEARANCE DATA SAMPLES:



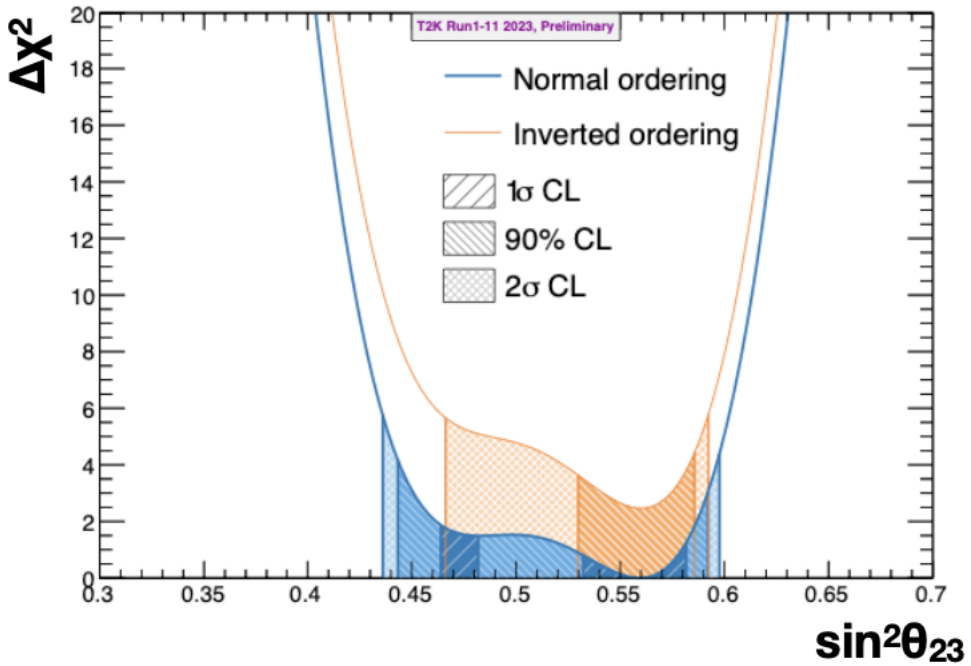
C. Giganti, Neutrino 2024

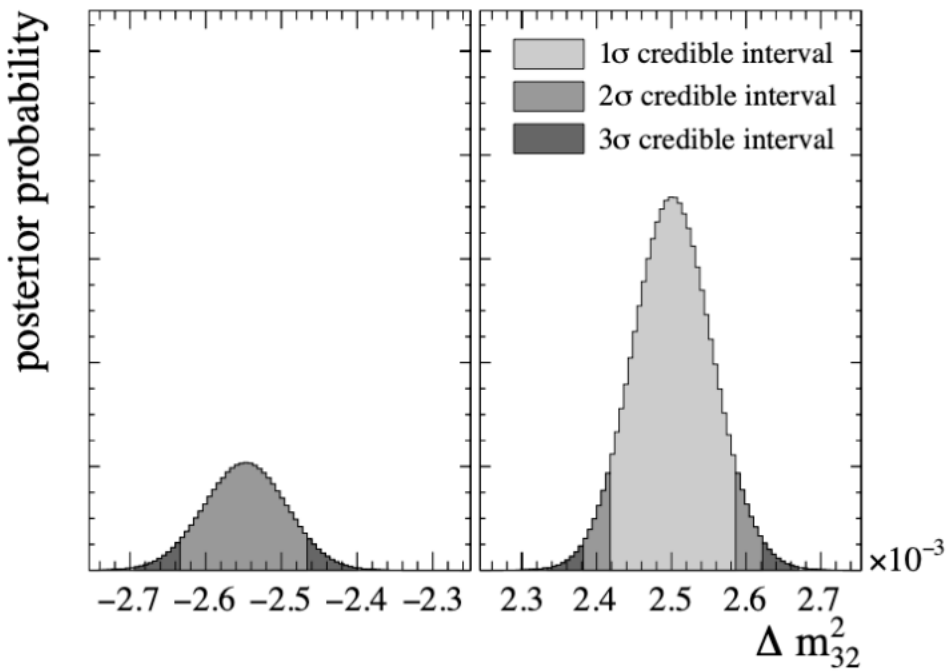
T2K RESULTS— 23 SECTOR

T2K prefers normal ordering and upper octant, at low significance

Bayes Factor NO/IO = 3.3
Bayes Factor UO/LO = 2.6

	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NH ($\Delta m^2_{32} > 0$)	0.23	0.54	0.77
IH ($\Delta m^2_{32} < 0$)	0.05	0.18	0.23
Sum	0.28	0.72	1.00

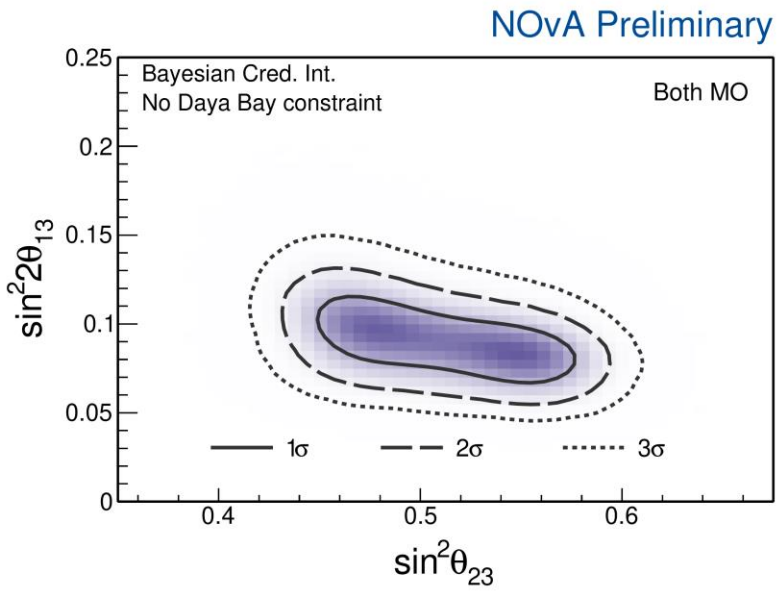


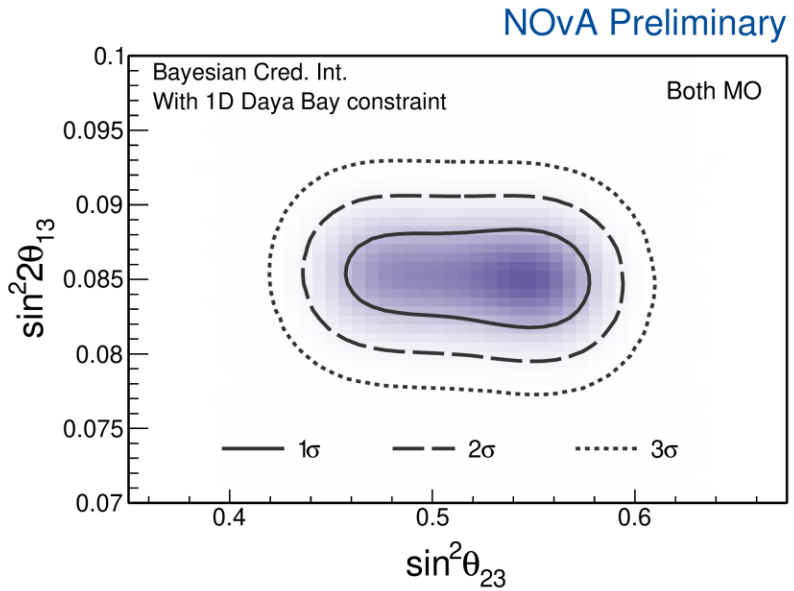


MIXING ANGLES: θ_{23} & θ_{13}

- Without any external constraint from reactor experiments, long-baseline measurements have a degeneracy in $\sin^2\theta_{23}$ and $\sin^2 2\theta_{13}$ parameters.

- Using the average constraint on $\sin^2 2\theta_{13} = 0.085 \pm 0.0027$ [PDG 2020], restricts us to a narrow posterior in θ_{13} and lifts this degeneracy.

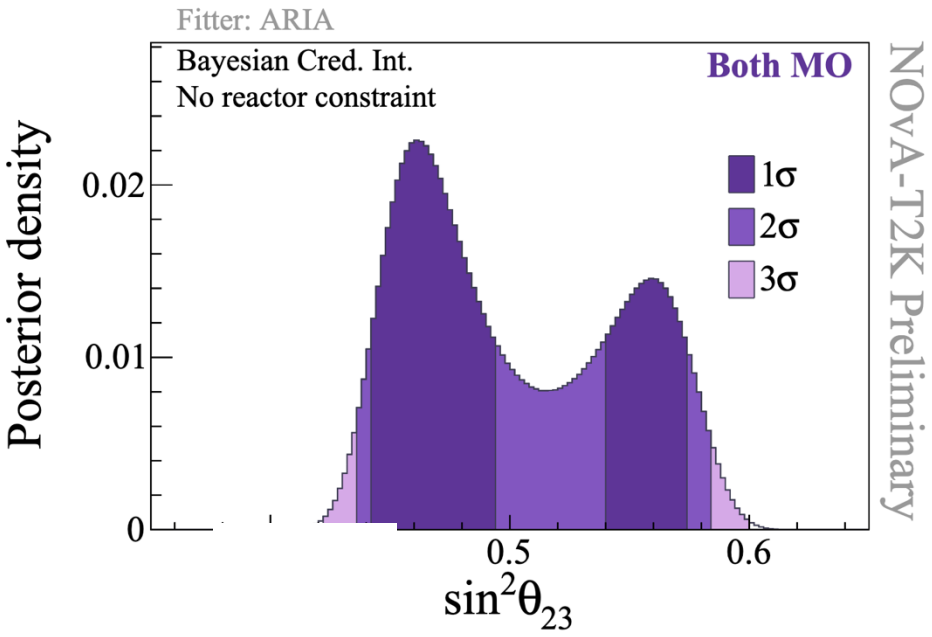


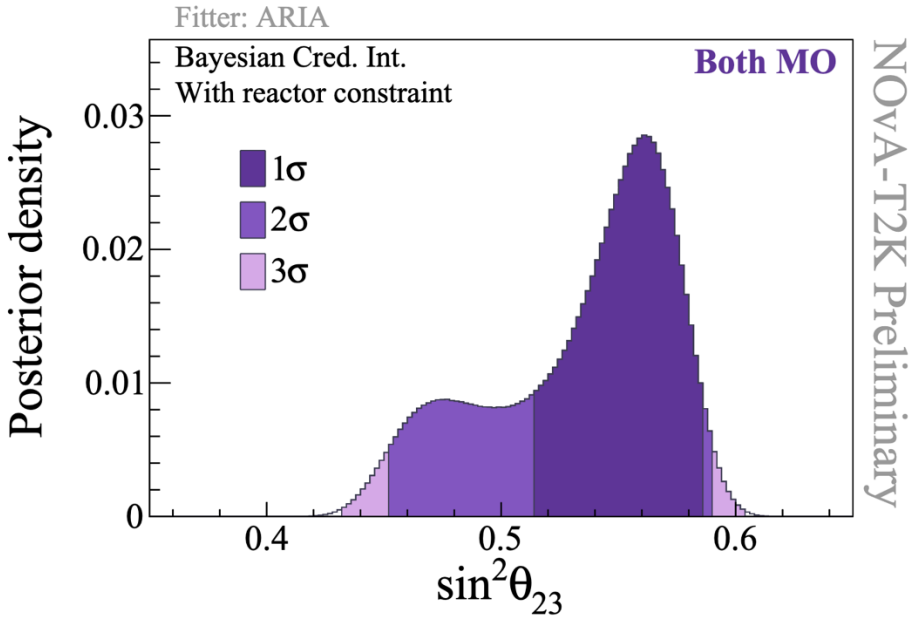


Mixing angles: θ_{23} & θ_{13}

- Modest preference for lower octant from the joint-analysis.
- This preference shifts to a small preference for the upper octant when the reactor constraint on θ_{13} is applied.

	NOvA - T2K w/o reactor	NOvA – T2K – w/ reactor
Bayes factor	1.17 Lower Octant/Upper Octant ~54% : ~46% posterior	3.59 Upper Octant/Lower Octant ~78% : 22% posterior





THREE GENERATIONS

MINOS Groundbreaking, 1999

Dune Groundbreaking, 2017

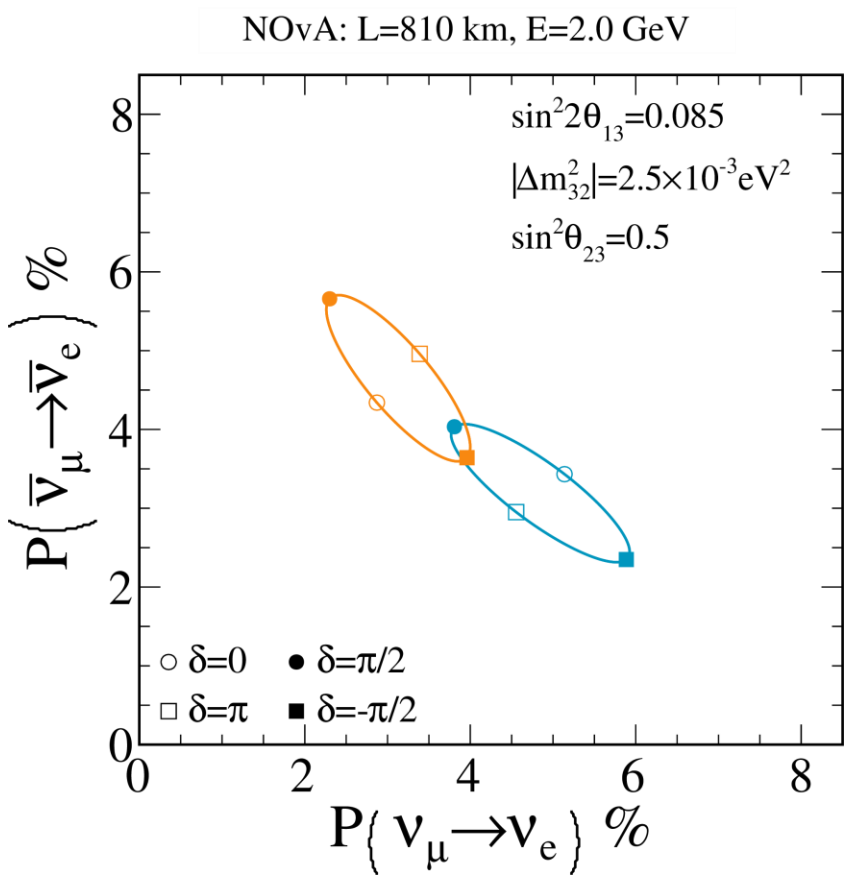
Past
~2000-2015

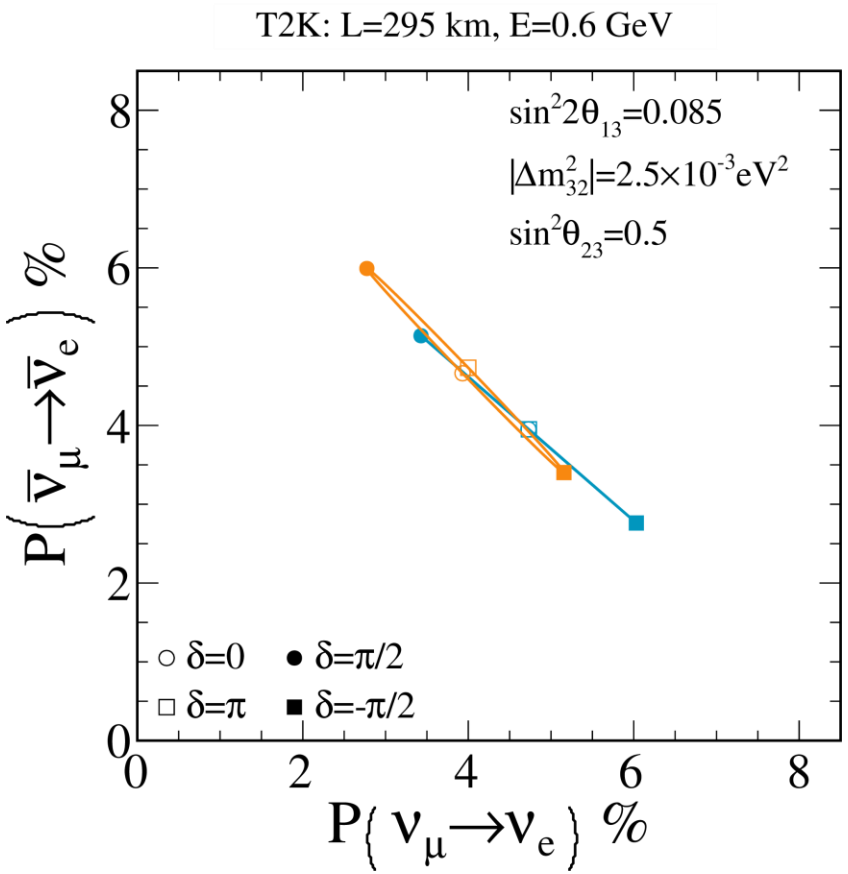
Present
2015-2025

Future
2030+

NOvA Groundbreaking, 2009

ANALYSIS BASICS



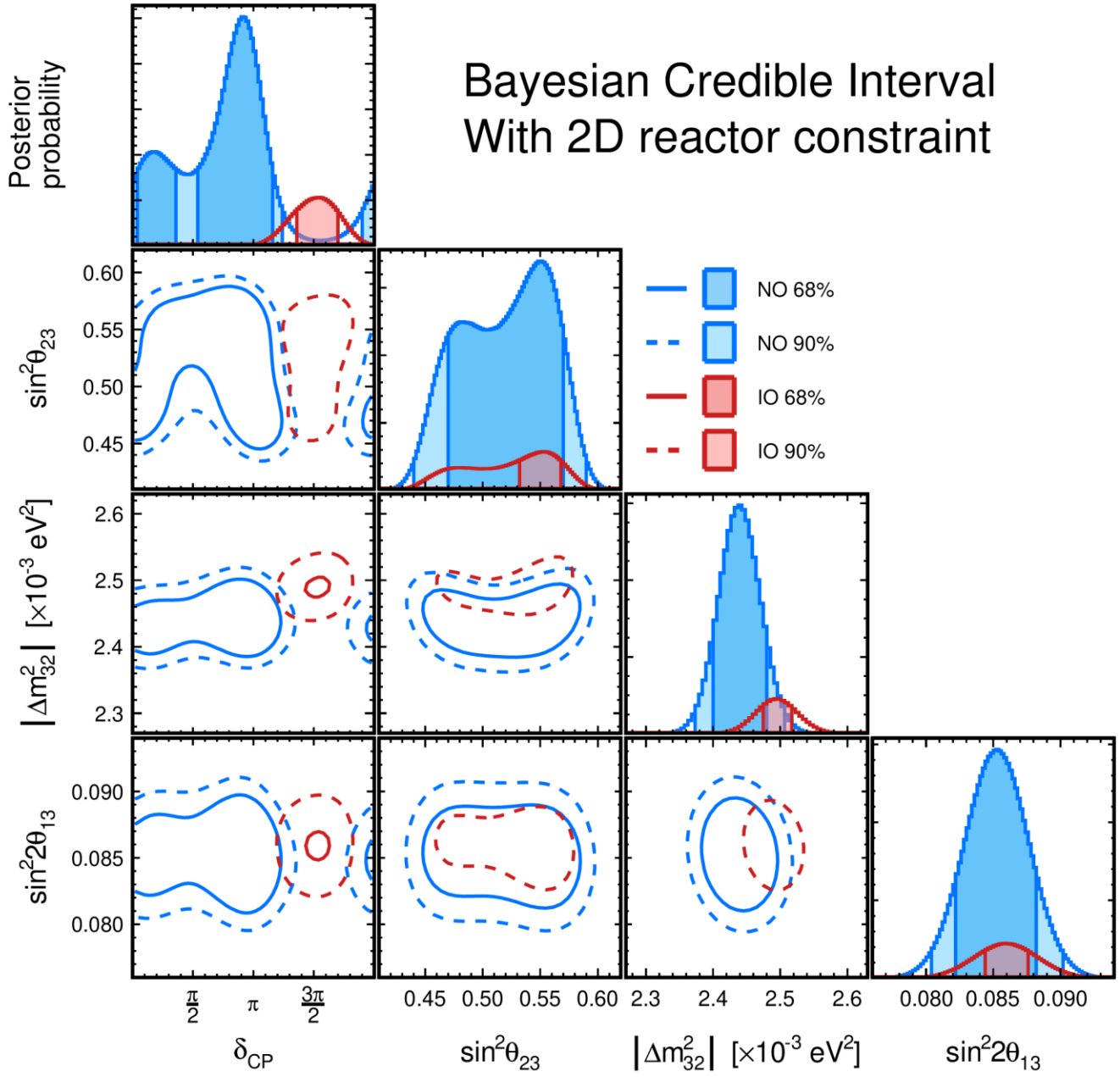


NOvA's longer baseline means mass ordering makes a big difference: ±20% NOvA compared to ±10% T2K

T2K's L/E optimizes CP violation differences: ±30% T2K compared to ±22% NOvA (NOvA runs a bit above oscillation max to optimize MO determination)

NOvA Preliminary

NOvA Results in all Parameters
With 2d reactor constraint



It is possible to reduce tension!

Tension: Apparent excess in

(see U. Rahaman et.al. Universe **8** (2022) n

Explanation:

⇒ Decrease $P(\nu_\mu \to \nu_e)$

⇒ Preferably: act differe

Attempts to reduce the

Non-Standard interaction (matter): P. Denton et al. PRL **12** 5, 051802, and R. Majhi et al. EPJC **82** (2022) no.10, 919

Non-unitarity (matter+ baseline): Pedro Pasquini et al. Eur. Ph

Lorentz Invariance Violation (energy): U. Rahaman EPJC **81** (2021) no.9,

Sterile neutrinos (baseline): A. de Gouvêa et. al.PRD **106** (2022) no.5, 055025

TENSION?

Are NOvA and T2K hinting at different conclusions about δ_{CP}?

Significance of differences is <2σ

NSI in Matter?
NSI in Production?
Sterile Neutrinos
Non-unitarity?
Lorentz Invariance?

Also see NOvA NSI analysis in A. Lister, WIN2025

P.Vahle, WIN 2025

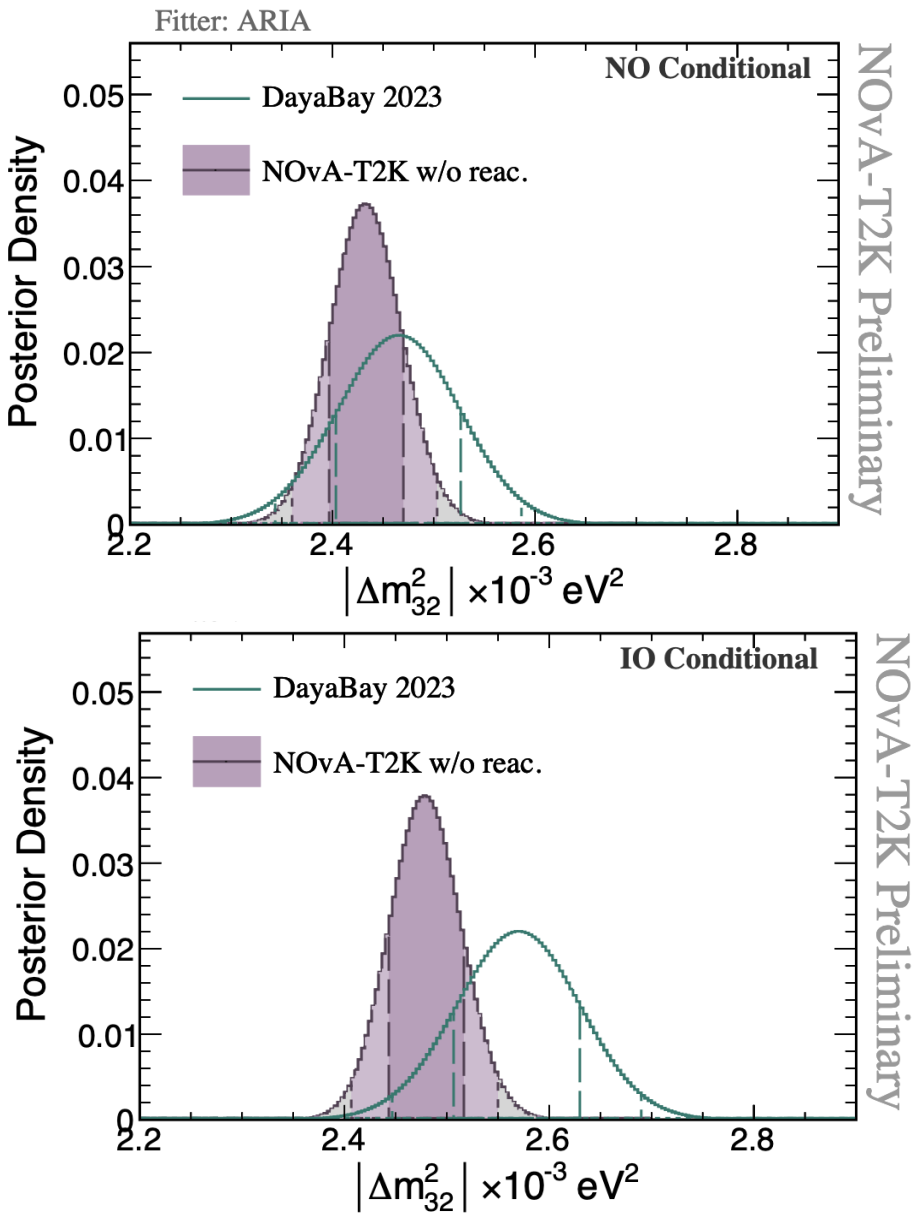
Z.Vallari, JETS, Feb. 2024

JOINT FIT—MO

Another possible way to determine the Neutrino Mass Hierarchy

Hiroshi Nunokawa[1],* Stephen Parke[2],† and Renata Zukanovich Funchal[3‡]

In the true mass ordering, reactor and long-baseline measurements of Δm_{32}^2 should be consistent

2-d Daya Bay result (Δm_{ee}^2 vs. θ_{13}) adds additional information on the mass ordering

	Preferred Ordering	Bayes Factor	Odds
No Reactor	Inverted	2.47	71% : 29%
Daya Bay θ13	Inverted	1.34	57% : 43%
Daya Bay 2D	Normal	1.44	59% : 41%