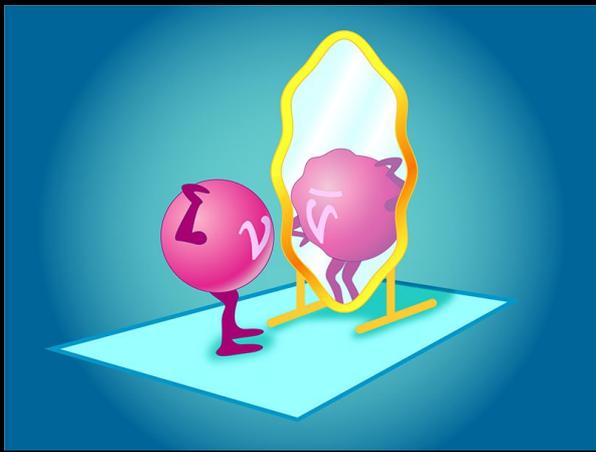


NOvA-T2K joint analysis

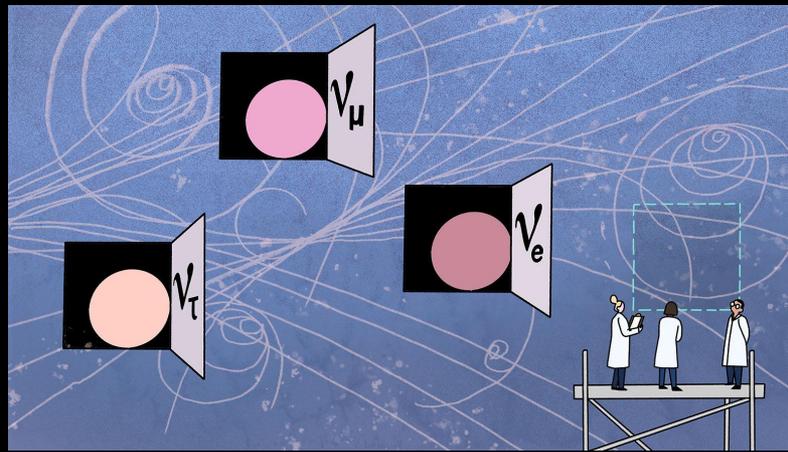
Dr. Artur Sztuc, University College London

Rencontres de Moriond 2026: Electroweak Interactions & Unified Theories

17 March 2026



Do neutrinos violate Charge-Parity?



Is there a light, sterile neutrino?



How are the neutrino mass states ordered?

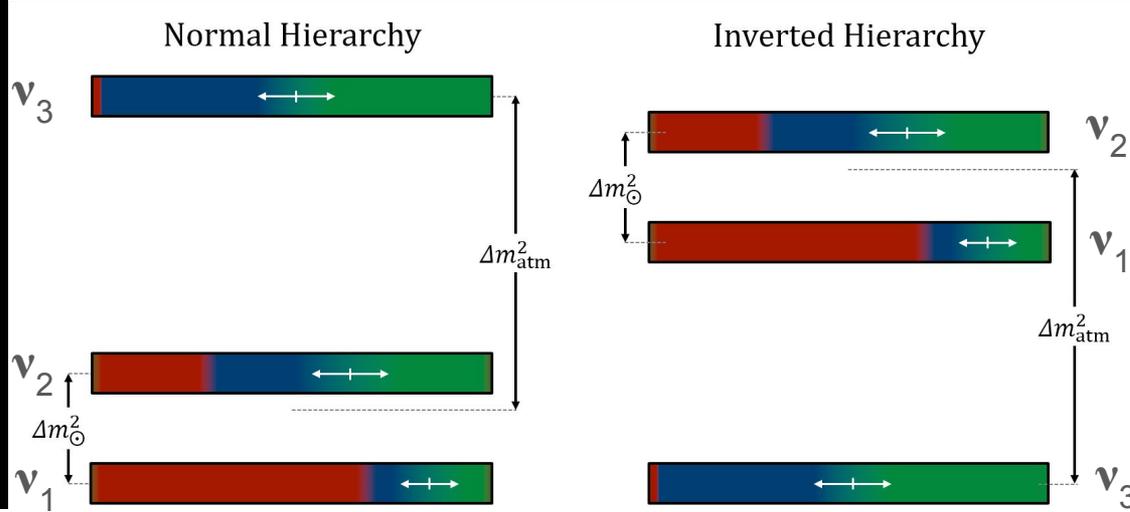


Do we understand neutrino propagation in matter?



How do ν_μ/ν_τ mix into the mass states?

Neutrino oscillations



Flavour eigenstates: ν_e, ν_μ, ν_τ (ν_4 ?)

Mass eigenstates: ν_1, ν_2, ν_3 (ν_4 ?)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\begin{aligned}
 s_{ij} &= \sin\theta_{ij} \\
 c_{ij} &= \cos\theta_{ij}
 \end{aligned}$$

atmospheric, beam
Super-Kamiokande, IceCube,
Opera, T2K, NOvA

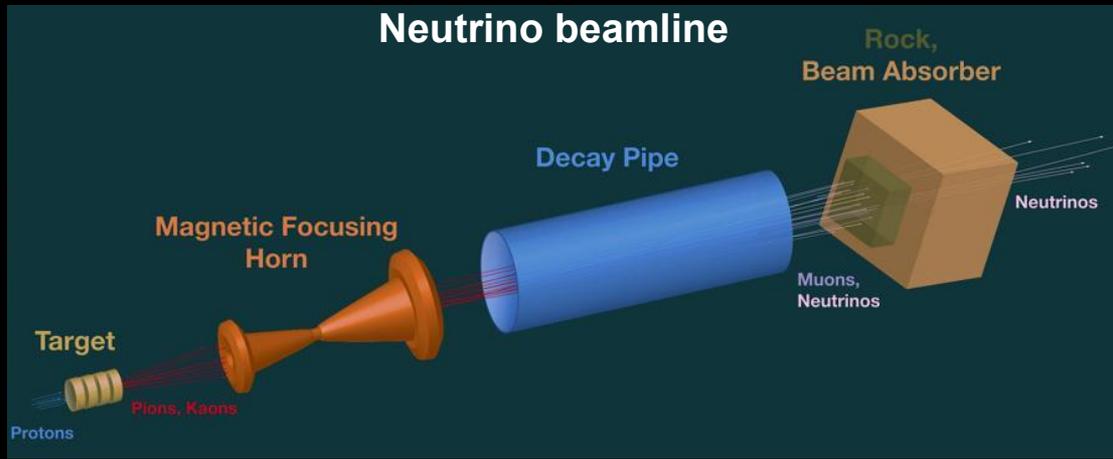
reactor, beam
Double Chooz, Daya Bay,
RENO, NOvA, T2K

solar, reactor
Super-Kamiokande, SNO,
KamLAND

- θ_{23} : 45° , larger, or smaller than 45° ? Important for $\nu_\tau - \nu_\mu$ symmetries.
- δ_{CP} : Potential contribution to matter-antimatter asymmetry in the universe.
- $\pm\Delta m_{32}^2$: Symmetries in neutrino physics, consequences for other measurements.

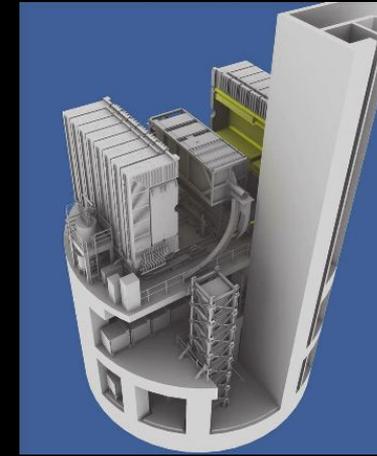
Accelerator neutrino experiment template

- Protons directed on target, producing charged pions.
- Focusing horns direct positive/negative mesons, selecting neutrino/antineutrino beam.
- Near Detector to measure neutrinos in their un-oscillated state.
 - Constrain neutrino flux and interaction uncertainties.
- Far Detector detects neutrinos in their oscillated state: deficit of muon neutrinos, excess of electron neutrinos.



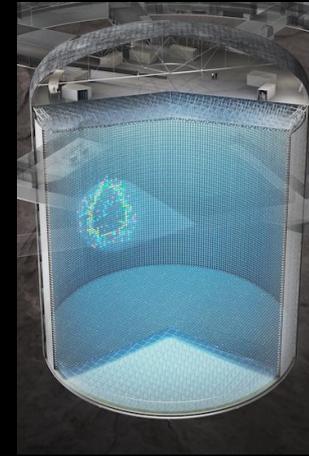
Includes beam monitoring devices

Near Detector



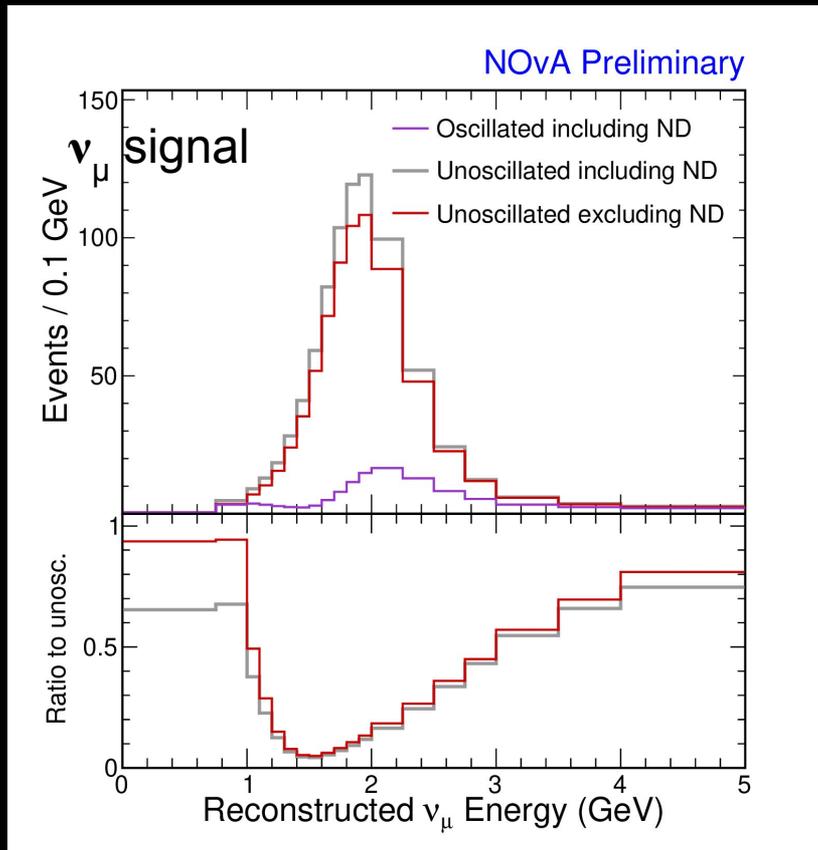
O(0.1-1)km
baseline

Far Detector



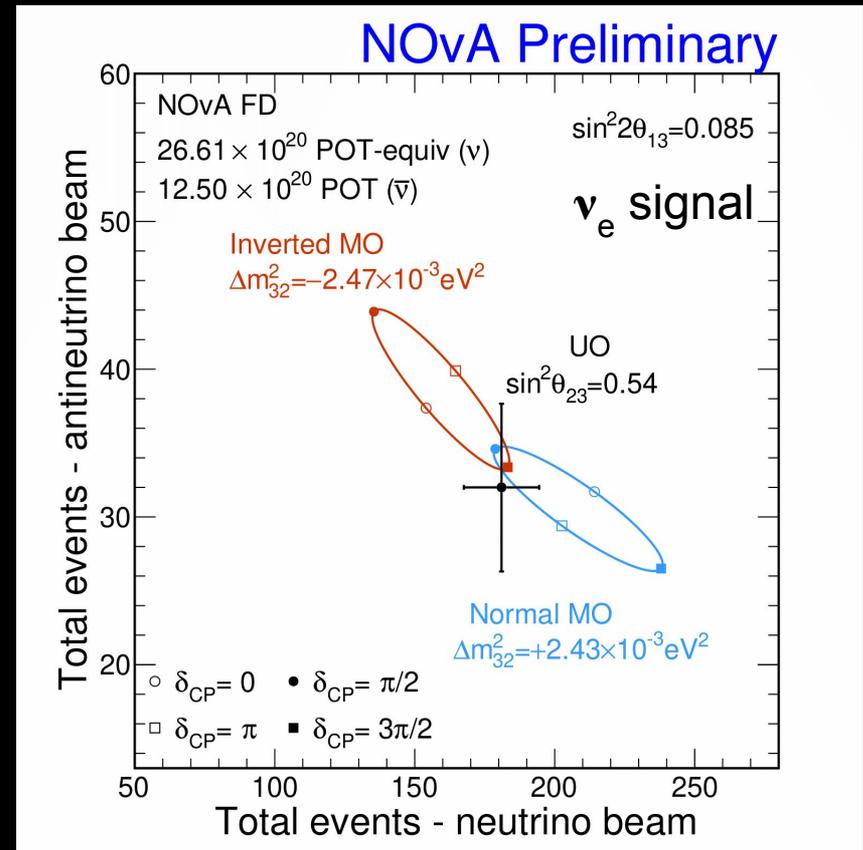
O(100-1000)km
baseline

Three Flavour Oscillations with Accelerators



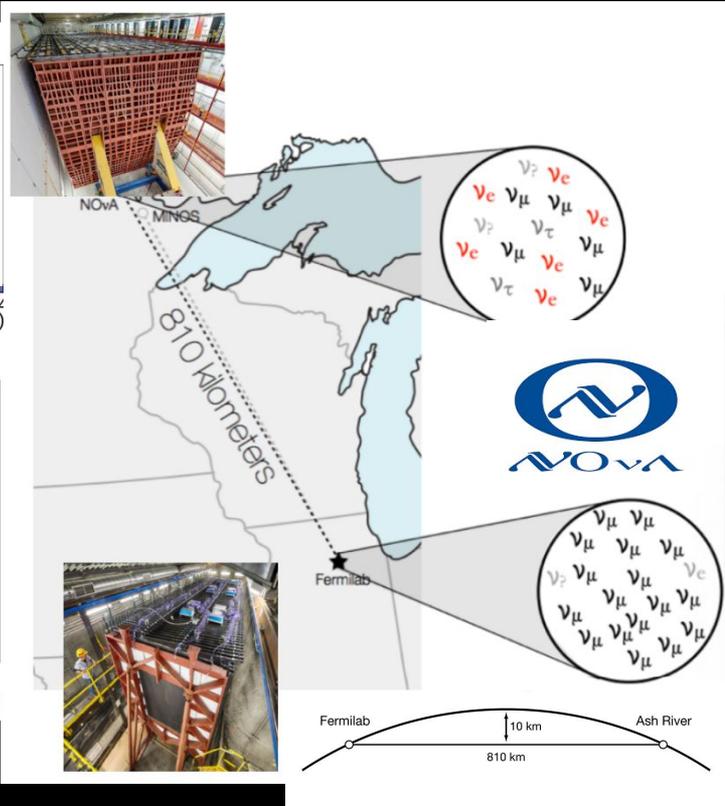
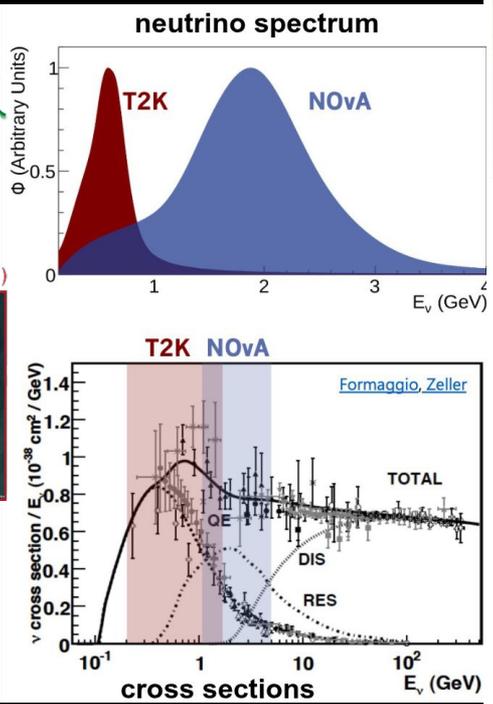
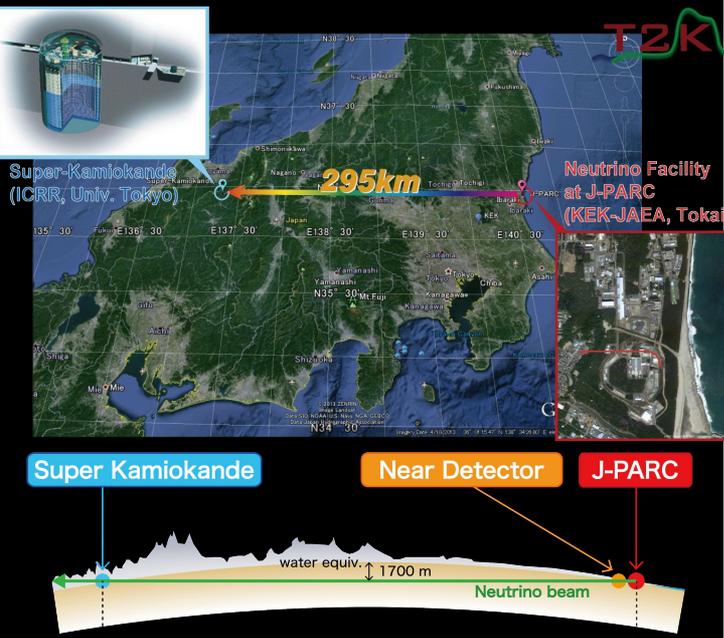
Location of the dip: $|\Delta m_{32}^2|$
(does not depend on the sign)

Depth of the dip: $\sin^2(2\theta_{23})$
Cannot to separate $\theta_{23} > 45$ and $\theta_{23} < 45$
Is $\nu_\mu = \nu_\tau$ in ν_3 mass state?



Combination of ν_e & $\bar{\nu}_e$ excess:
 $\sin^2(\theta_{23}), \sin^2(\theta_{13}), \delta_{CP}$
 Good dependance on Δm_{32}^2 sign
 Channel for CP violation

NOvA and T2K

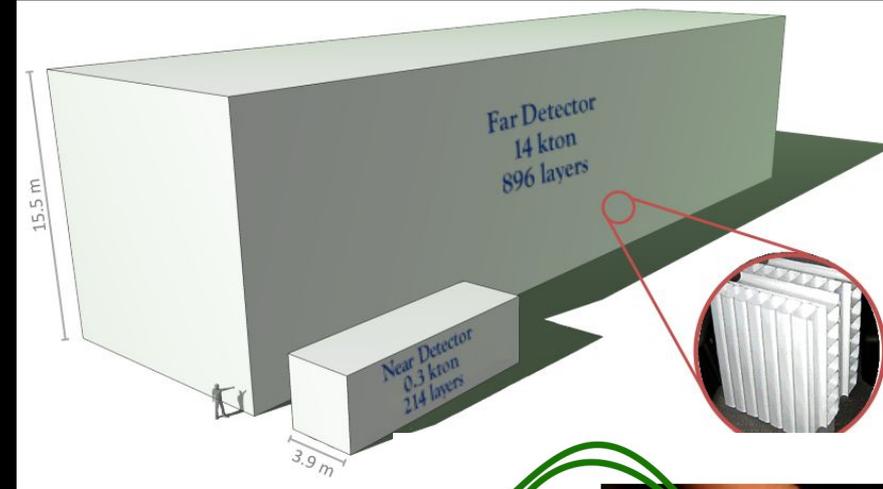


	NOvA	T2K
Baseline	810 km	295 km
Peak Energy	2 GeV	0.6 GeV
Near Det.	Liquid Scintillator in extruded plastic cells	Multi-purpose, TPCs, FGDs, ECAL, magnet
Far Det.	Liquid Scintillator in extruded plastic cells	Water Cherenkov, PMTs

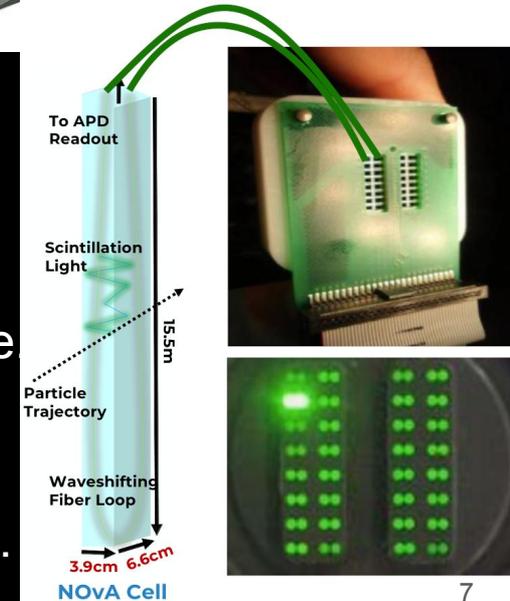
Artur Sztuc

- Two currently leading long-baseline accelerator neutrino experiments.
- Completely different baselines, neutrino energies & detector designs.

NOvA Experiment



- Functionally identical Near & Far detectors.
- Extruded cells filled with liquid scintillator, 62% active volume
- Wavelength-shifting fibre collects & transports light to Avalanche photodiode.
- Alternating horizontal & vertical planes for 3D reconstruction.

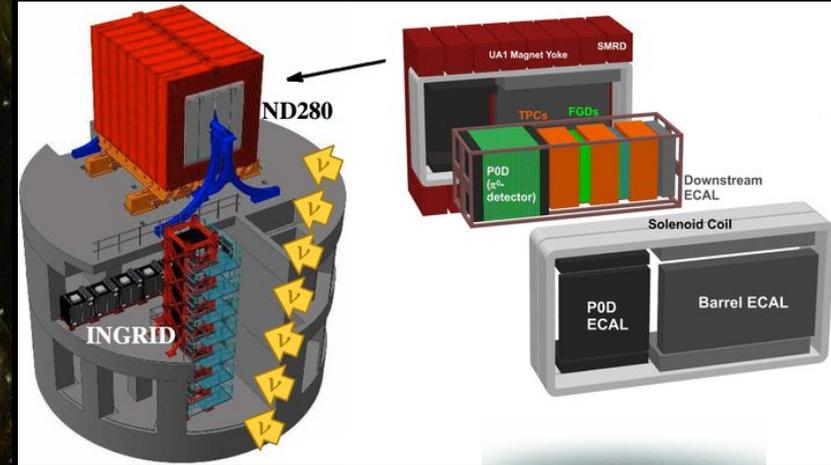


T2K Experiment

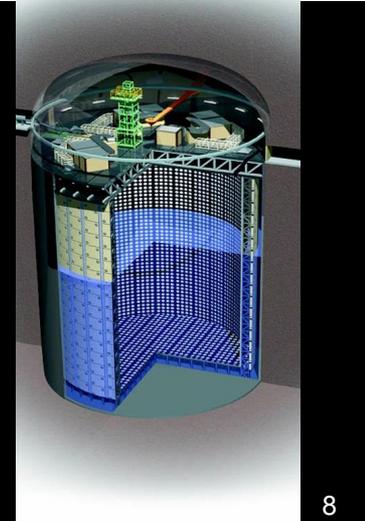
SK talk from Benda Xu next



In the picture:
Dr. Lauren Anthony
Dr. Artur Sztuc (me!)

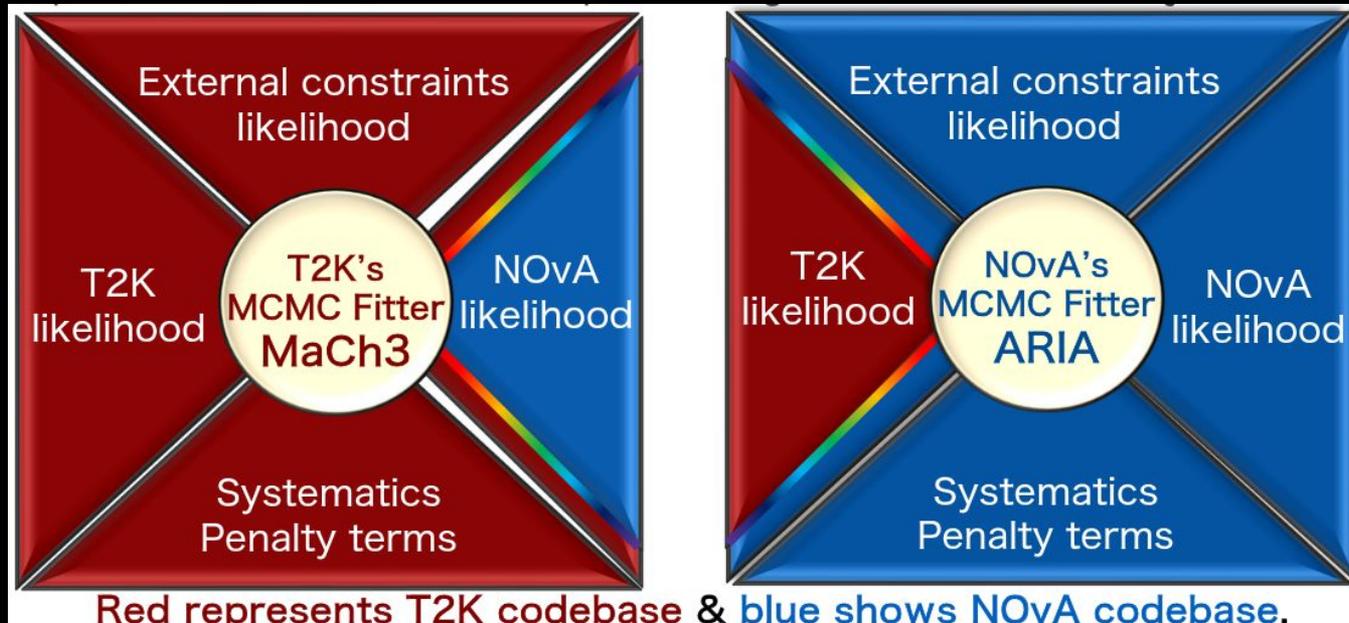


- A suite of near detectors:
 - ND280 made of TPCs for tracking & PID, FGDs as Carbon/Water target, P0D for detecting π^0 (upgraded to SuperFGD & High-Angle TPCs).
 - INGRID measures the beam profile.
- Far detector: Super-Kamiokande, 50 kton water Cherenkov tank.
 - 11k 20" PMTs in the Inner Detector, ~2k 8" PMTs in the Outer Detector
 - Gd-loaded since 2020 for antineutrino tagging.



NOvA-T2K Joint Analysis Approach

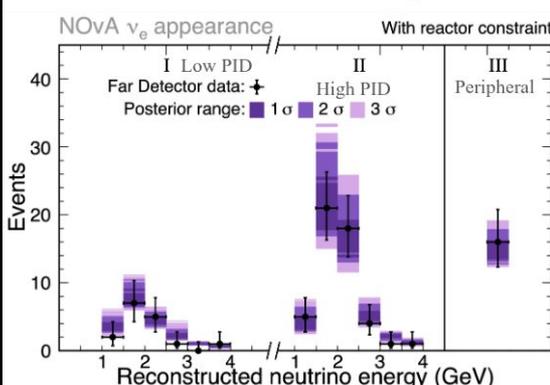
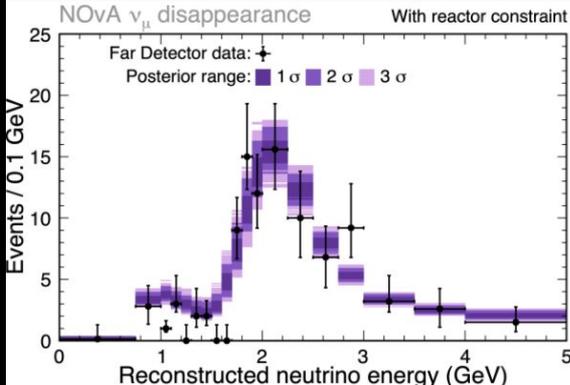
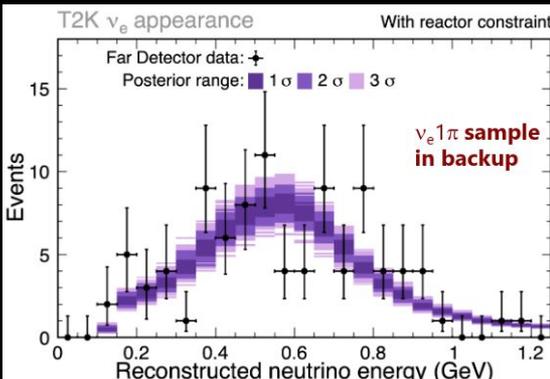
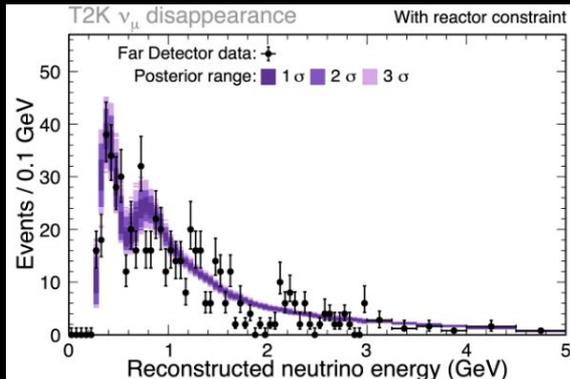
- Different experimental design mean different analysis approaches:
 - T2K: Fit neutrino interaction/flux/detector model to the Near detector data, extract parameters, use them in the Far detector fit (or simultaneous fit with MCMC).
 - NOvA: Correct FD Monte Carlo with ND MC-Data differences before FD fits.
- Both end up reducing systematic uncertainties from ~10% to 4-5%.
- Containerised our likelihoods to provide them to each-other's frameworks.
 - Shared oscillation parameters, priors, external constraints.
- Independent frameworks provided robust validation of the joint fits.
 - No correlations between the experiments' systematic models, apart from ν_{μ}/ν_{e} correction uncertainties.



NOvA-T2K Data

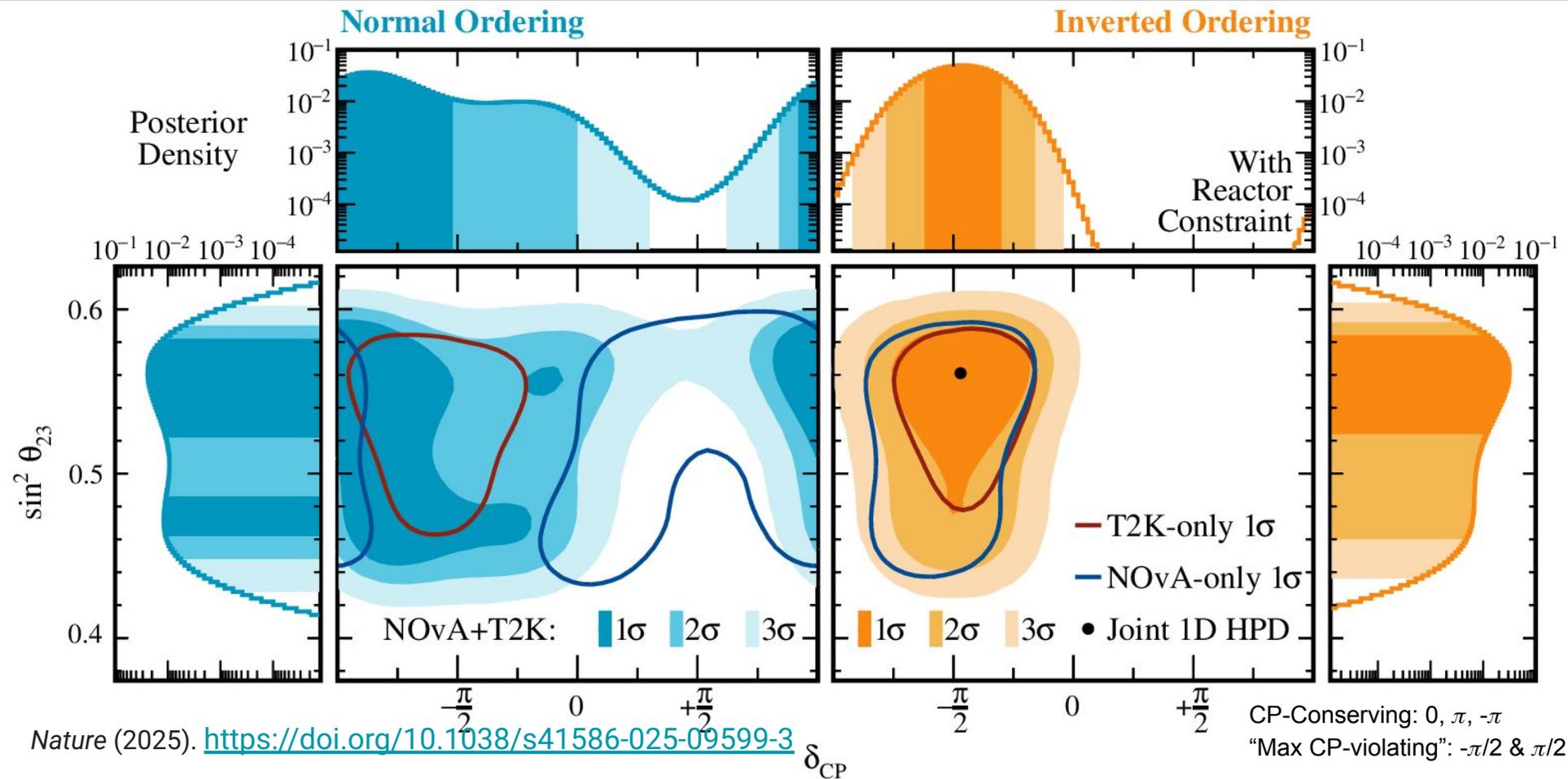
Channel	NOvA	T2K
ν_e	82	94 (ν_e) 14 ($\nu_e 1\pi$)
$\bar{\nu}_e$	33	16
ν_μ	211	318
$\bar{\nu}_\mu$	105	137

Channel	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



- Data collected up to 2020 from both experiments.
- Roughly doubles the Far detector statistics.
- Posterior-predictive p-values from the joint fit reasonable for all the data samples.
 - A good posterior-predictive p-value: 0.5
 - Sampled model predictions describe the data well.

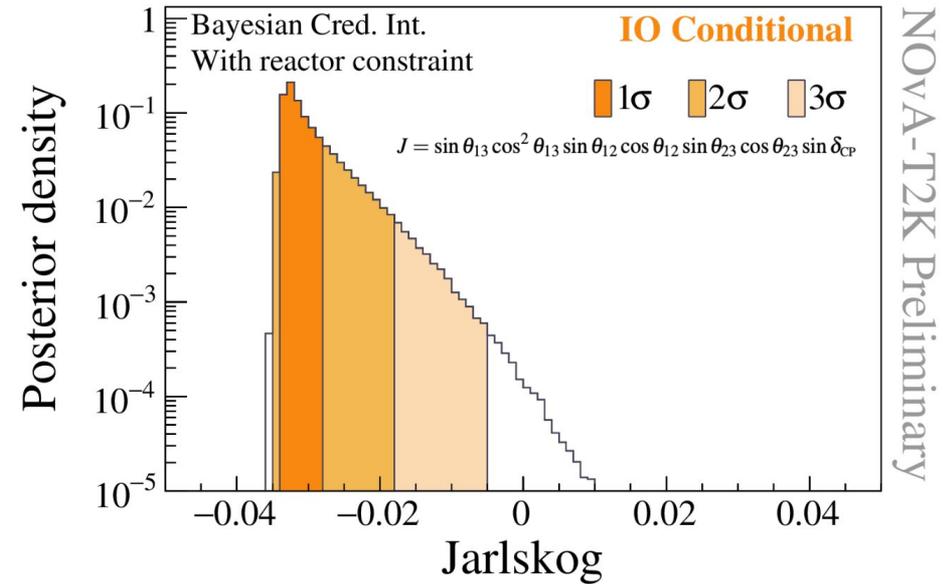
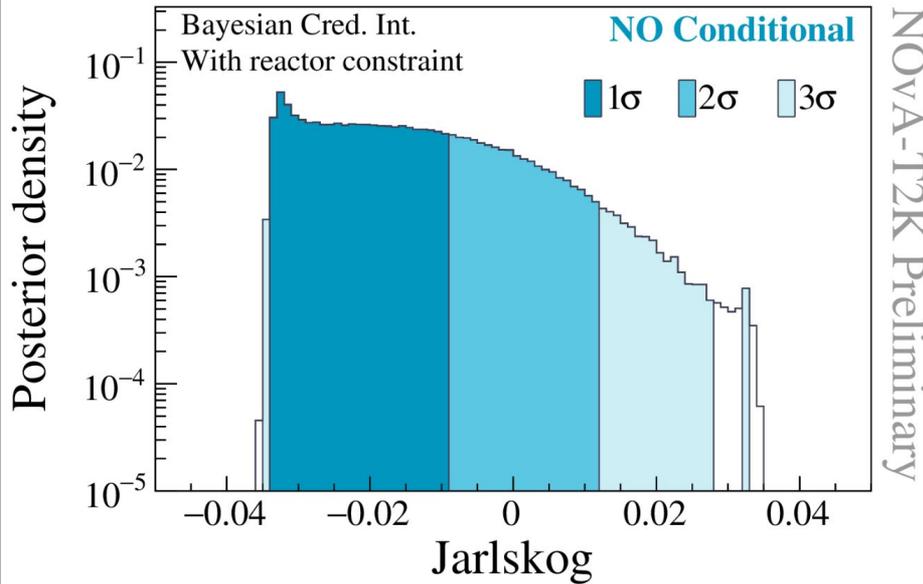
NOvA-T2K Results: CP Violation



Nature (2025). <https://doi.org/10.1038/s41586-025-09599-3>

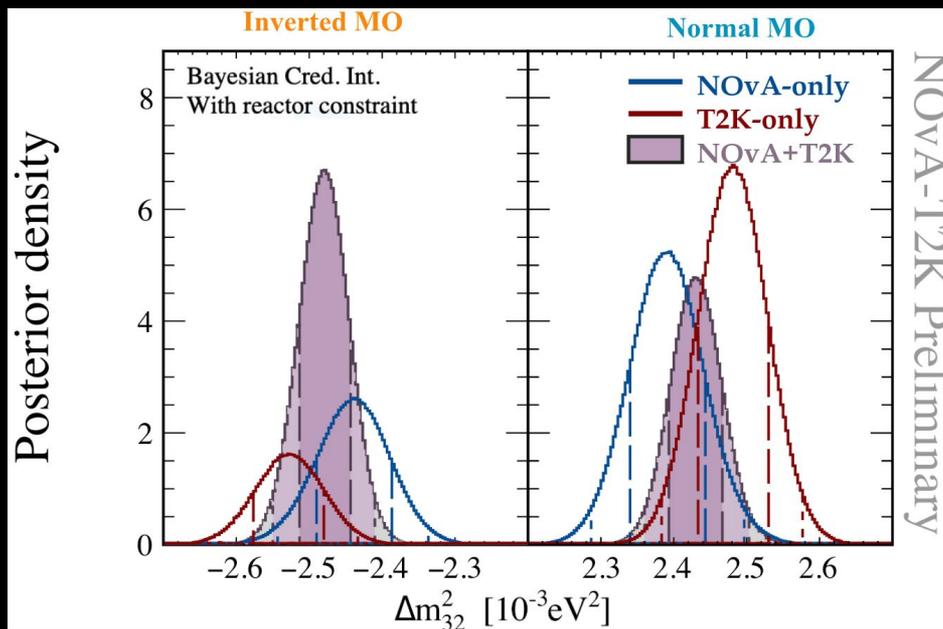
- δ_{CP} of $\pi/2$ outside of 3-sigma intervals regardless of MO.
- CPV preferred in the IO.
- No preference for CPV or CPC in NO.

NOvA-T2K Results: CP Violation

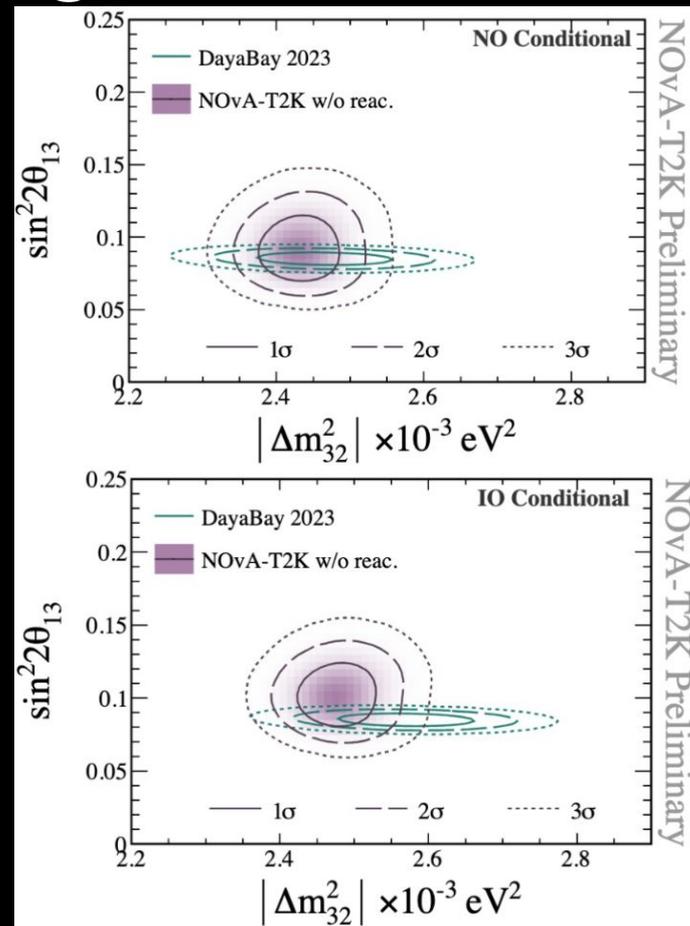


- Jarlskog-Invariant: measure invariant under different PMNS parameterisations.
 - 0 = CP conservation.
- In IO, Jarlskog of 0 lies outside of 3-sigma interval: high preference for CP violation.
- No preference either way in NO.
- Both statements true for priors uniform in δ_{CP} and $\sin(\delta_{CP})$

NOvA-T2K Results: Mass Ordering



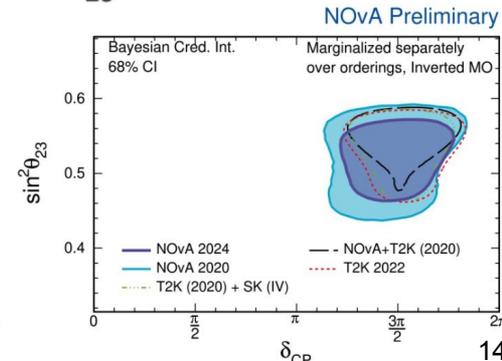
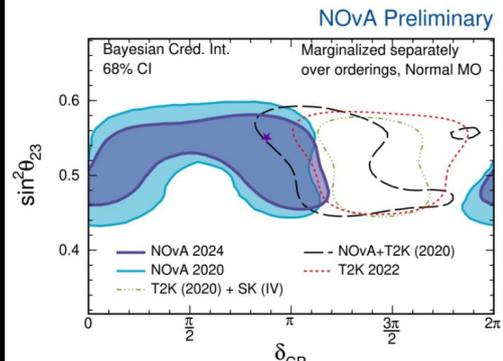
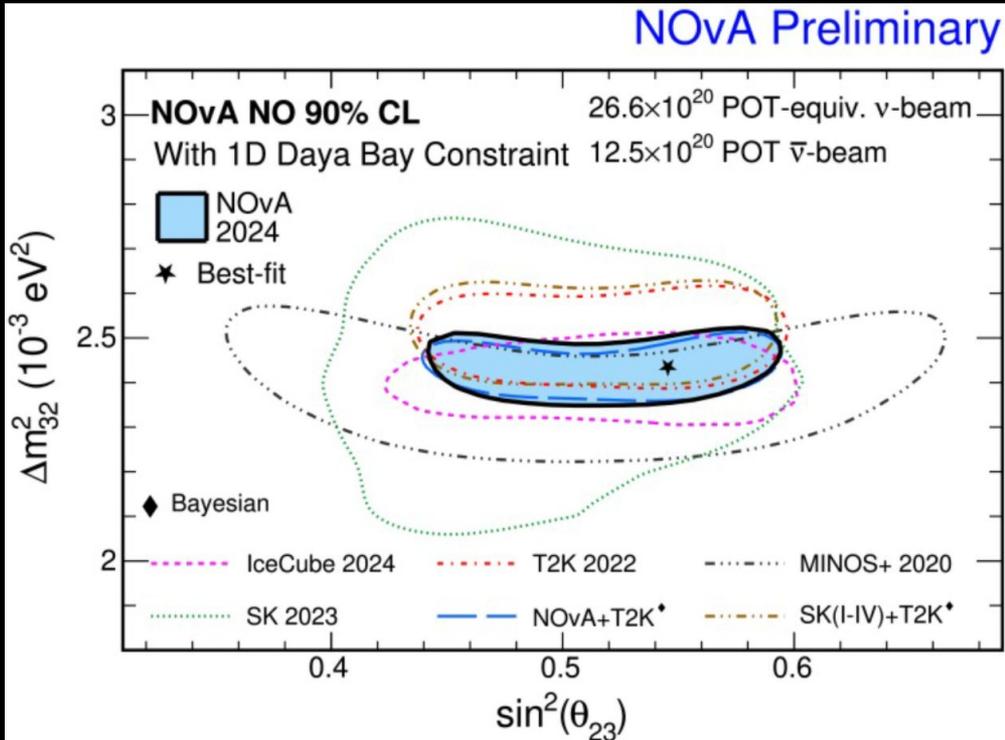
- Small joint preference for IO, with individual preference for NO (coin toss in each case).
- Including 2D prior from Daya Bay reverses preference back to NO.



	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

Current Global 3 Flavour Picture

- Global agreement between acc. & atm.experiments in Δm_{32}^2 .
- Consistent with maximal mixing.
- The global data points towards Normal Ordering, with insignificant preference.
- δ_{CP} picture confusing in NO, CP violation preferred in IO



Summary

- **The first full joint analysis between two long-accelerator neutrino oscillation experiments.**
 - Different baselines, detector technologies, target materials, and analysis techniques.
- **World-best constraint on $|\Delta m_{32}^2|$**
- **No significant preference for the mass ordering.**
 - Highest posterior in Inverted Ordering, significance of a coin toss.
 - Switches back to Normal Ordering with addition of reactors.
- **$\delta_{CP} = \pi/2$ heavily disfavoured, and outside of the 3-sigma regardless of MO.**
 - CPV heavily preferred in Jarlskog-Invariant
- **More data collected by NOvA & T2K since the joint analysis.**
 - **Stay tuned for more results in the future!**



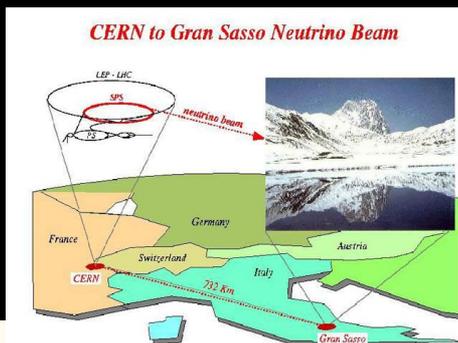
量子ビーム研究センター

AVRDC LABORATORY QUANTUM BEAM RESEARCH CENTER



BACKUPS

Long Baseline Oscillations



CNGS/OPERA

CERN to LNGS
730 km, 400 kW

NOvA

Fermilab to Ash River
810 km, 400-900+ kW

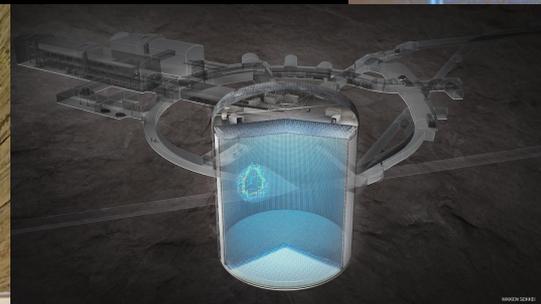
DUNE

Fermilab to SURF
1300 km, 2-2.4 MW



KEK

KEK to Kamioka
250 km, 5 kW



ESSνSB+
v factories

MINOS(+)

Fermilab to Soudan
734 km, 400+ kW

T2K

J-PARC to Kamioka
295 km, 380-1000+ kW

Hyper-Kamiokande

J-PARC to Kamioka
295 km, 750 kW - 1.3 MW

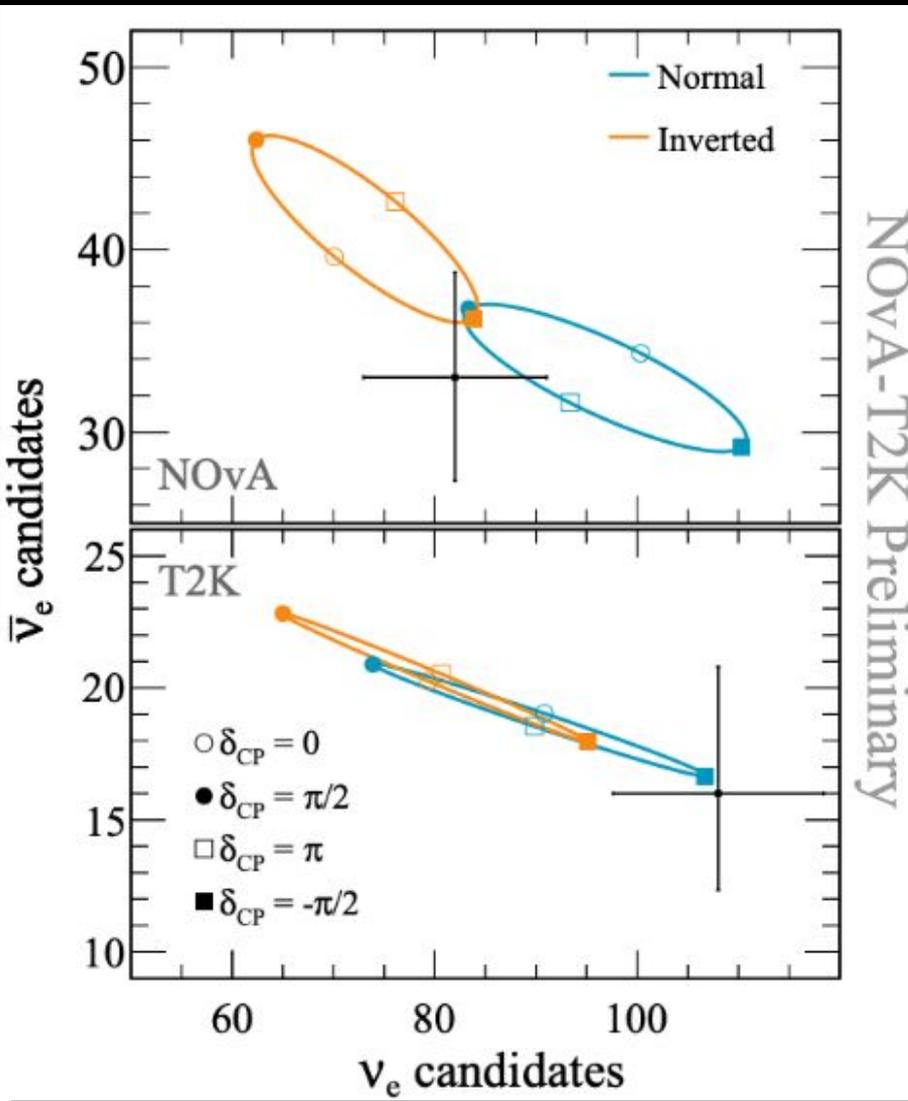
PAST

CURRENT

FUTURE

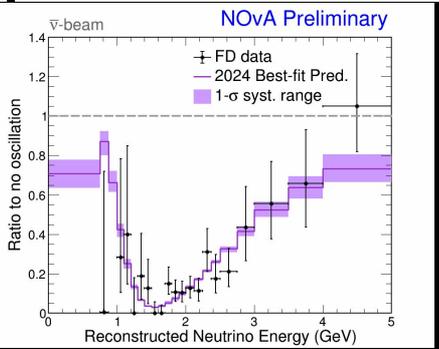
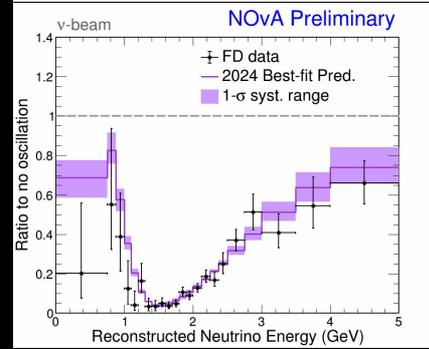
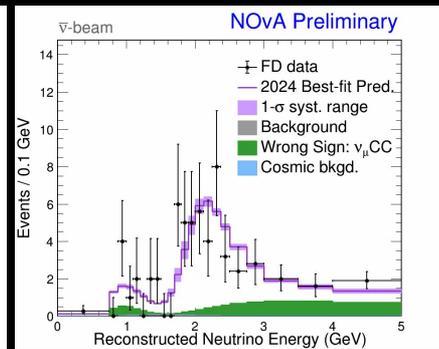
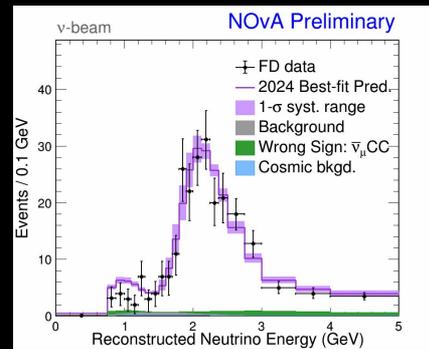
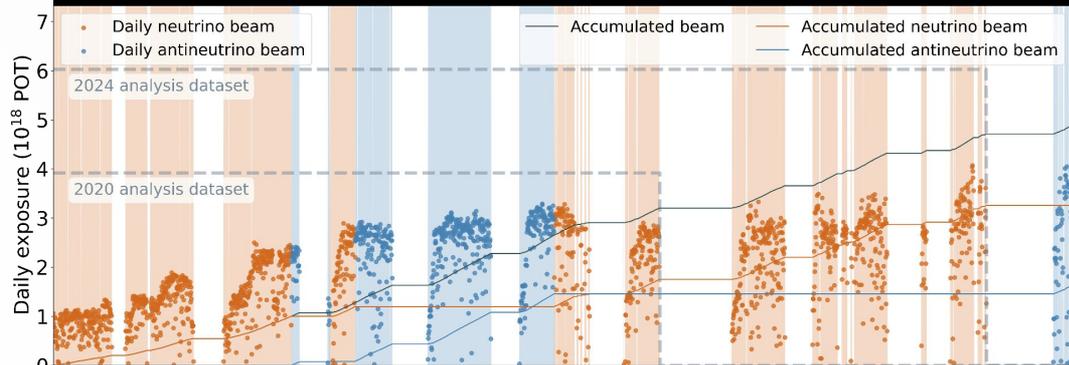
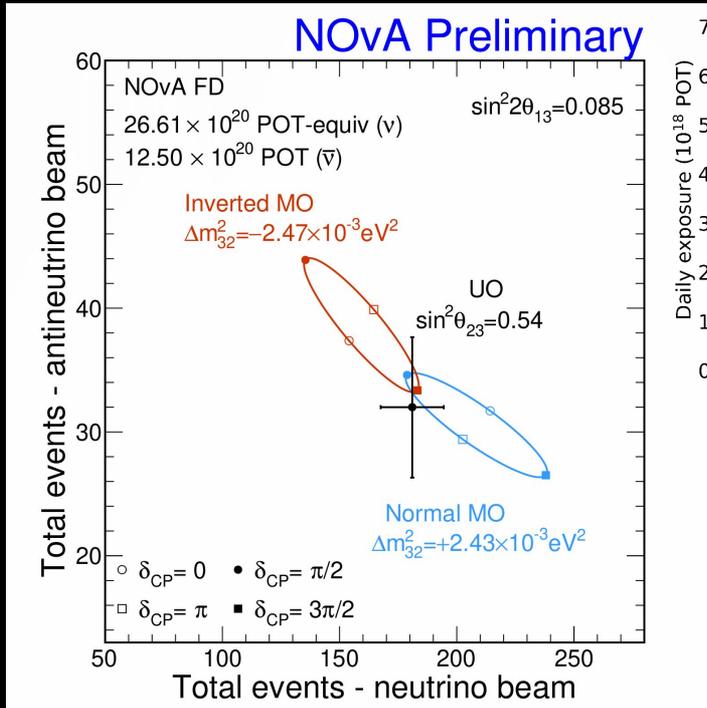
NOvA-T2K Joint Analysis

- Different baselines & energies help with disentangling degeneracies.
- NOvA has better sensitivity to mass ordering, thanks to longer baseline.
- T2K has better sensitivity to CP violation.
- Used 2020-era datasets & models from both experiments.



NOvA-T2K Preliminary

NOvA Data



- Analysed data up to 2024, 39.11×10^{20}

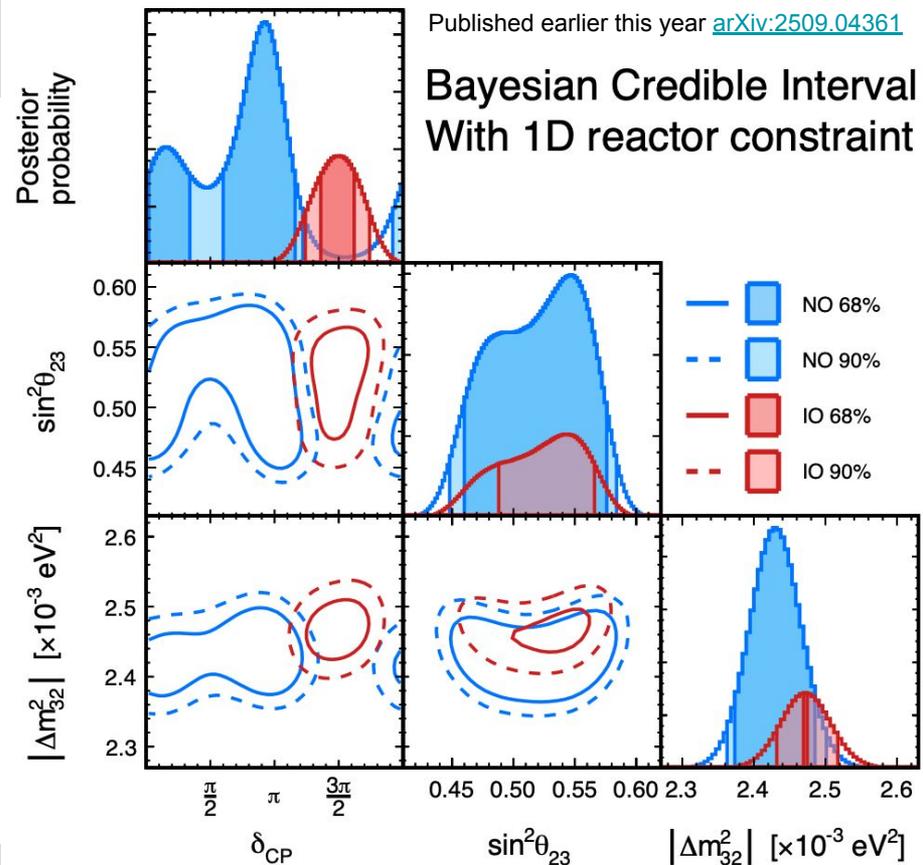
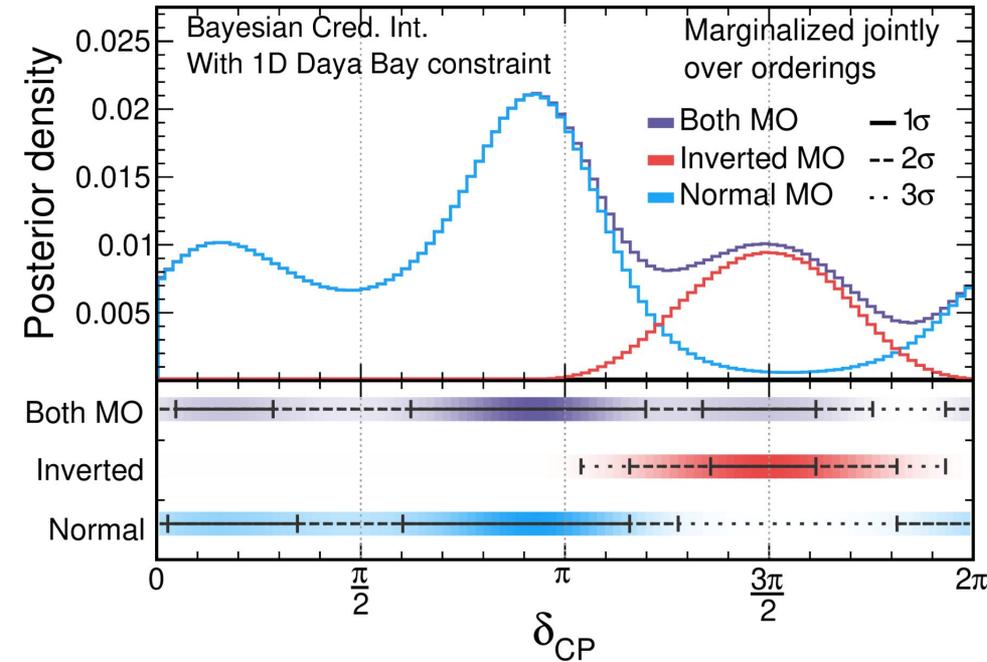
POT

- 26.61×10^{20} POT $\bar{\nu}$ -mode
- 12.50×10^{20} POT ν -mode

- $181 \nu_e, 384 \nu_\mu, 181 \bar{\nu}_\mu, 32 \nu_e$

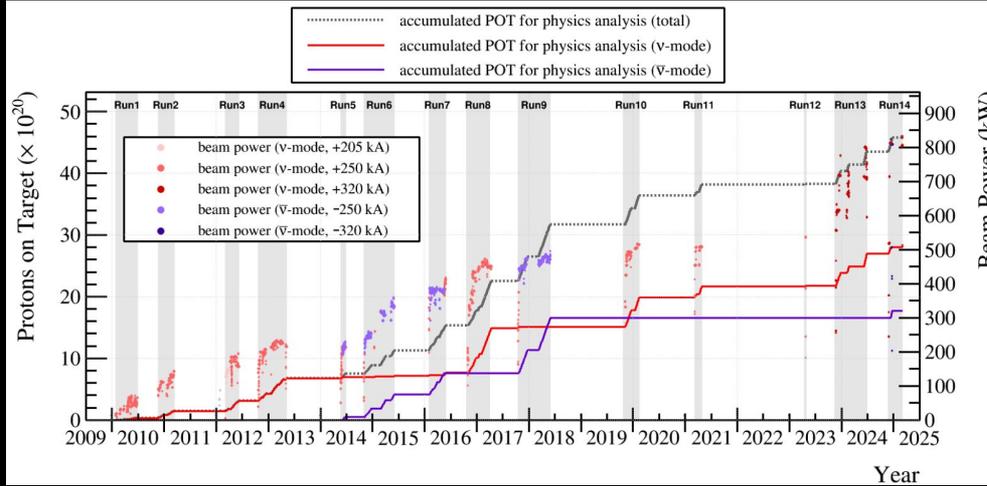
NOvA Results

NOvA Preliminary

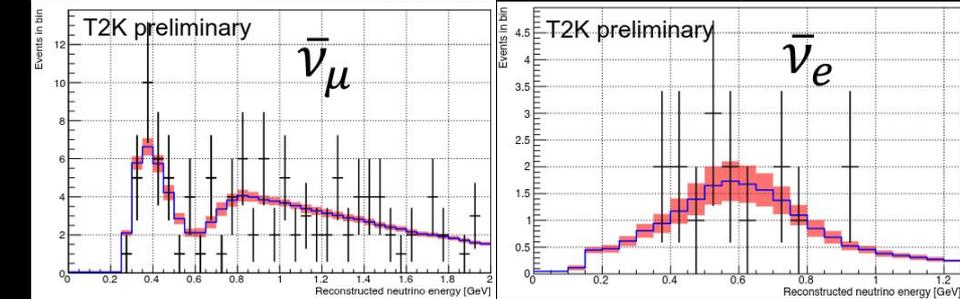
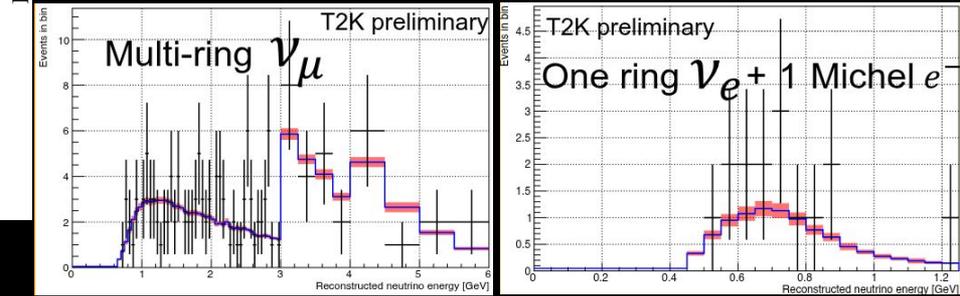
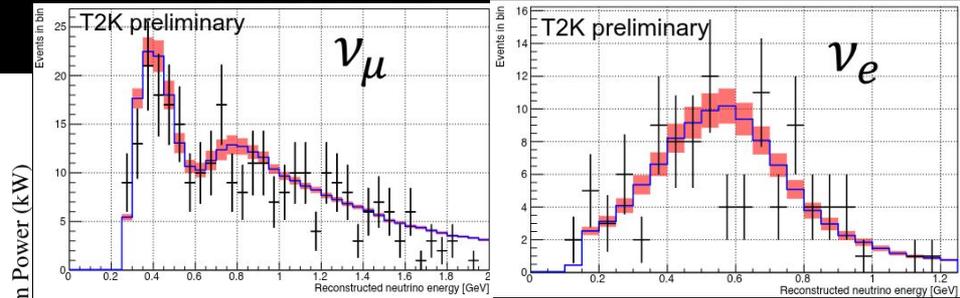


- World best single-experiment Δm_{32}^2 measurement.
- Slight preference for NO, with Bayes Factor of 2.4 (70%), changes with reactors:
 - 1D Daya Bay BF: 3.3 (77%)
 - 2D Daya Bay BF: 6.6 (87%)
- No strong preference for CP violation or conservation in NO.

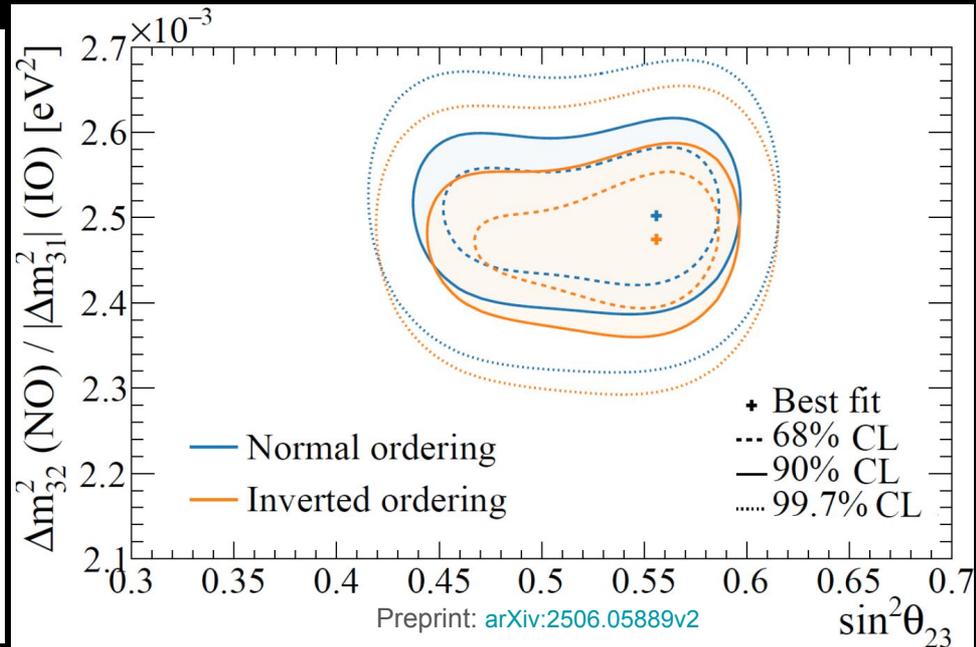
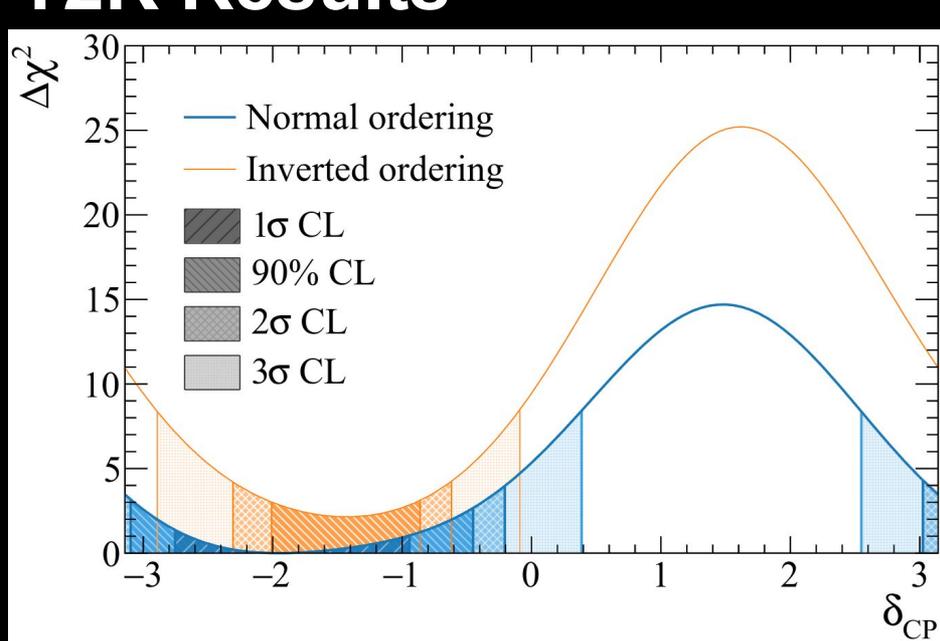
T2K Data



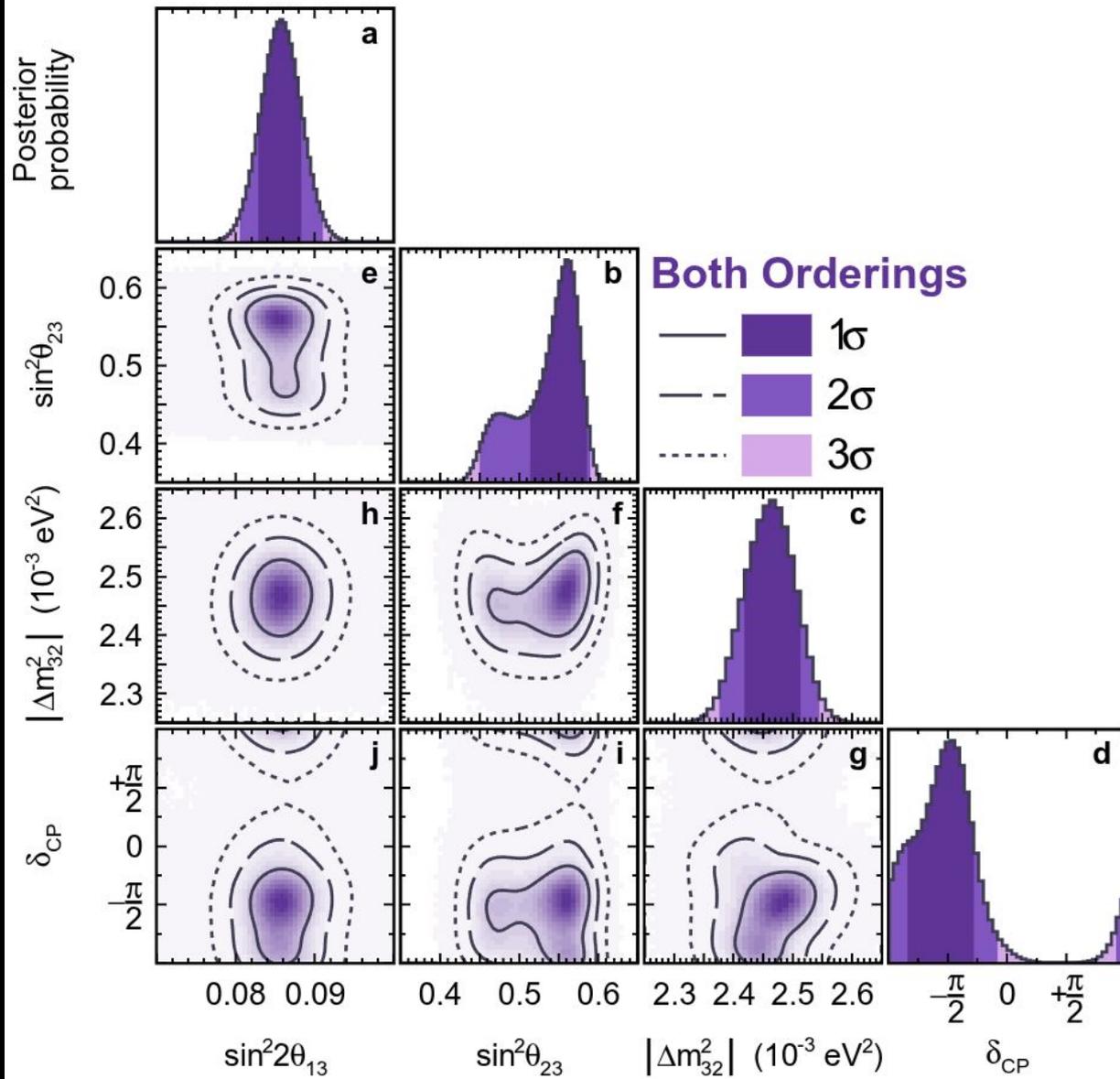
- Analysed 36×10^{20} POT
 - 19.7×10^{20} POT ν -mode
 - 16.3×10^{20} POT $\bar{\nu}$ -mode
- 117 ν_e , 497 ν_μ , 137 $\bar{\nu}_\mu$, 16 $\bar{\nu}_e$
- Data up to 2020 analysed.

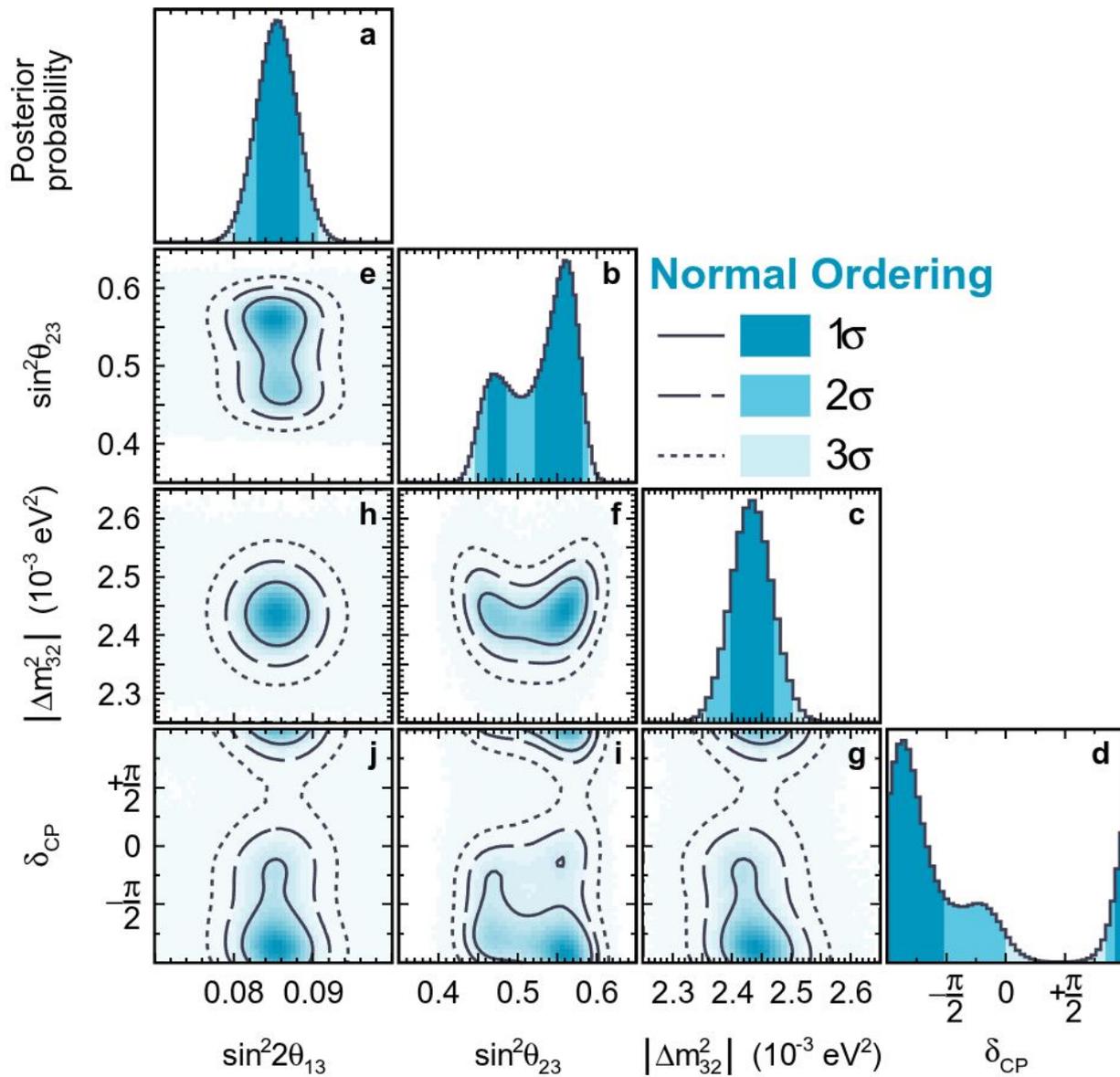


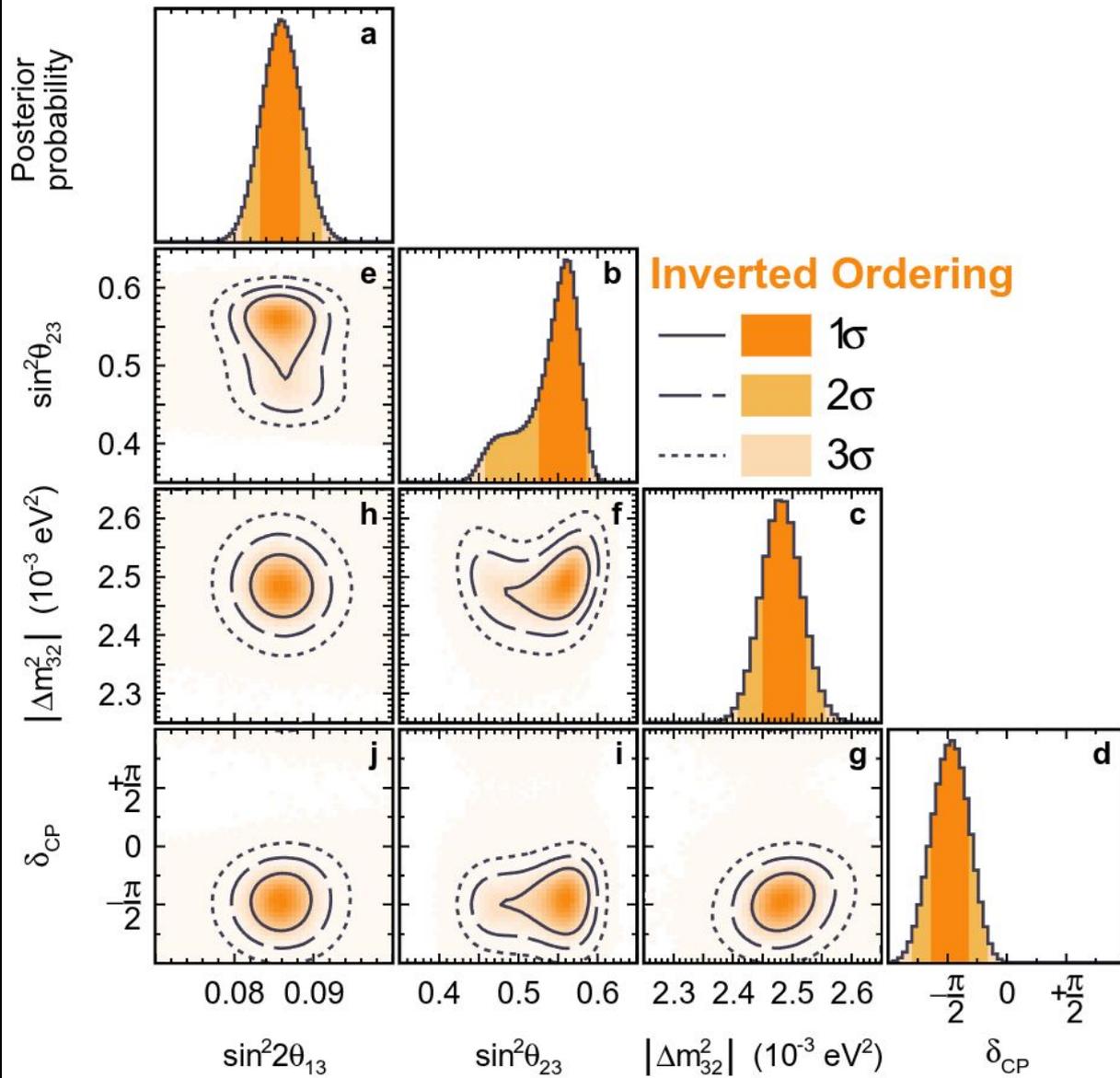
T2K Results



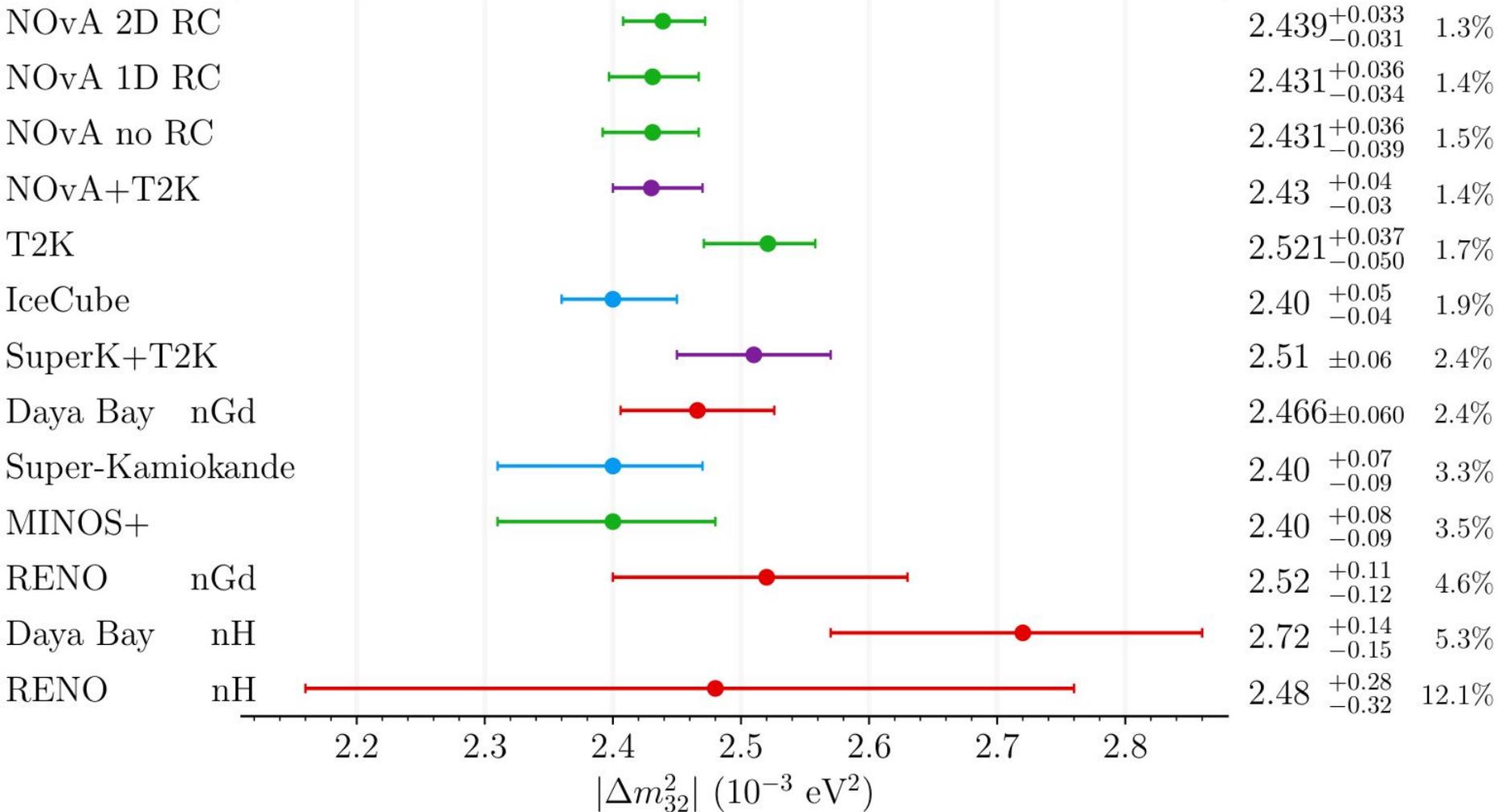
- T2K data disfavors $\delta_{CP} = \pi/2$ in both orderings.
- Preference towards CPV, with best fit values close to $-\pi/2$.
- Marginal preference for the normal mass ordering (1.7-sigma).





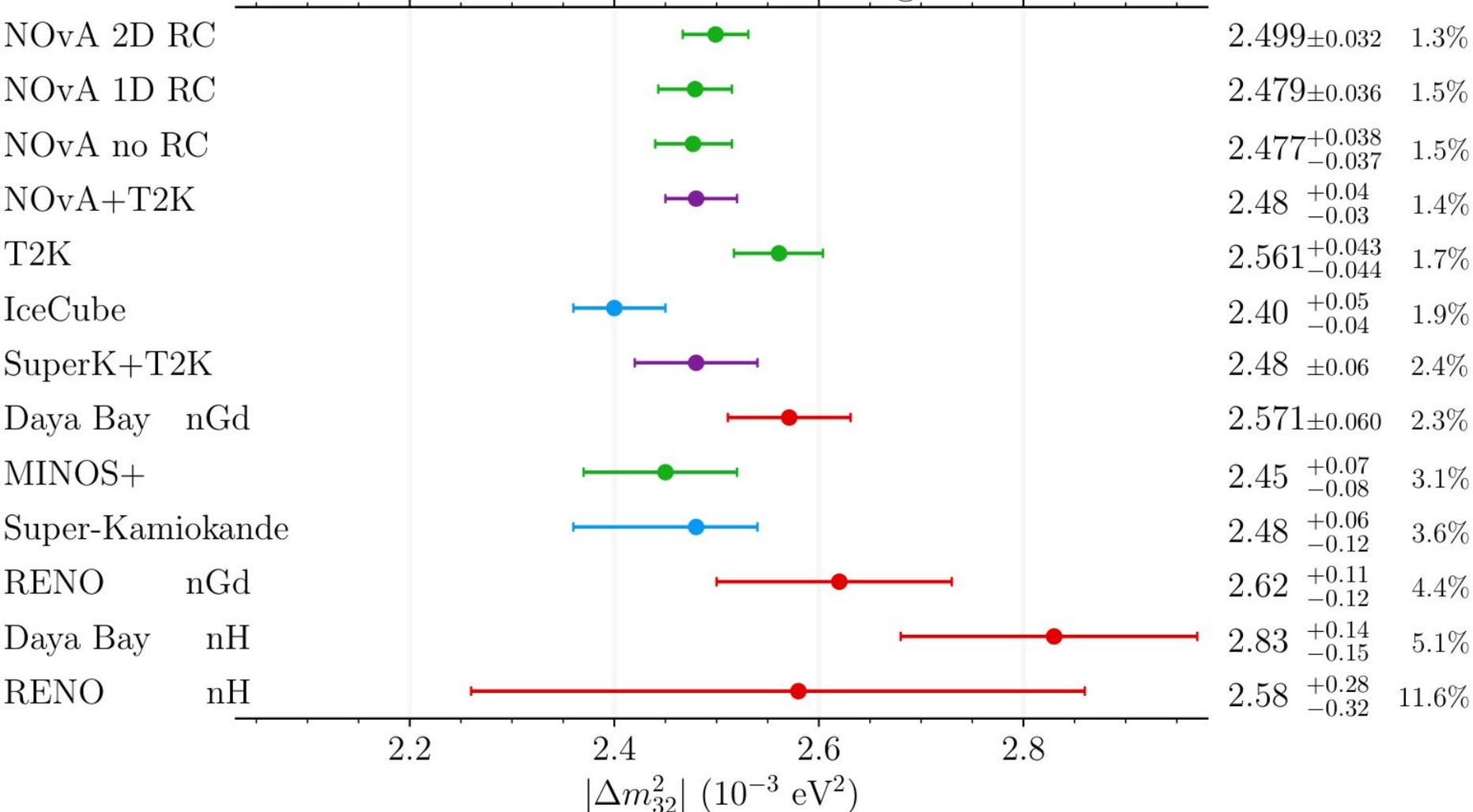


Normal mass ordering



v14.1 2025.02: git.jimr.ru/mu/osc

Inverted mass ordering



v14.1 2025.02: git.jinr.ru/mu/osc