The T2K and NOvA Experiments

DISCRETE 2026

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Outline

I Neutrino oscillation and long-baseline experiments
II The T2K and NOvA experiments
III Beamlines and detectors
IV Neutrino oscillation strategies
V Latest results
- T2K+NOvA 3ν-oscillation
- T2K-only, NOvA-only 3ν-oscillation
- With reactor and atmospheric friends
- Beyond 3ν-paradigm

VI Near-future prospects

Neutrino Oscillation and (All Sorts of) Motivations

Neutrino (lepton) mixing in 3ν-paradigm

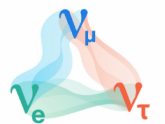


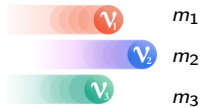
Image by Symmetry Magazine

Flavor Eigenstates

Mass Eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\text{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mixing Matrix



Squared-mass splittings
$\Delta m^2_{ij} \equiv m^2_i - m^2_j$

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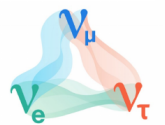


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$$U_{\text{PMNS}} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\text{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\text{CP}}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

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

Measured from the following neutrino sources


Atmospheric

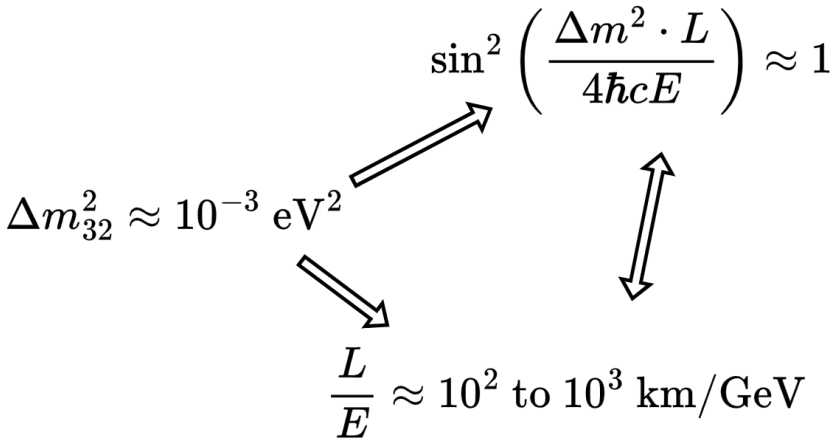

Accelerator


Reactor


Solar

Image by Symmetry Magazine

Where is the first oscillation maximum for Δm^2_{32}?



Hundreds of kilometers away and $\approx$ GeV is one solution

But why use hundreds km and GeVs?

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With E from 10^{-1} to 10^{1} GeV, we can study both electron (ν_e) and muon (anti)neutrinos (ν_μ), potentially even tau (anti)neutrinos (ν_τ), being above the CC production thresholds for both e and μ (or even τ).

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Studying different flavor transitions provide **complementary information** for inferring the neutrino oscillation model within a single experimental configuration.

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Image by Symmetry Magazine

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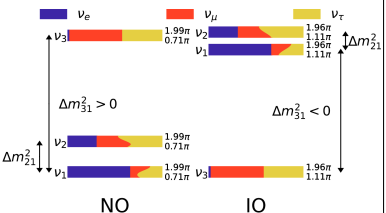
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LBL experiments with $L/E \sim 10^{2-3}$ km/GeV are sensitive to

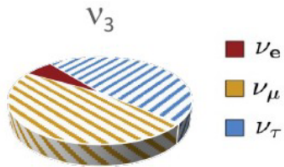
Δm^2_{32}, NO/IO

What is the ordering of the ν masses?

Normal (NO) or inverted (IO)?



θ_{23}



Is 23 mixing maximal? $\mu\tau$ symmetry?

Is $\theta_{23} \lessgtr 45°$?

δ_{CP}, J_{CP}

Is there significant CP violation in the lepton sector?

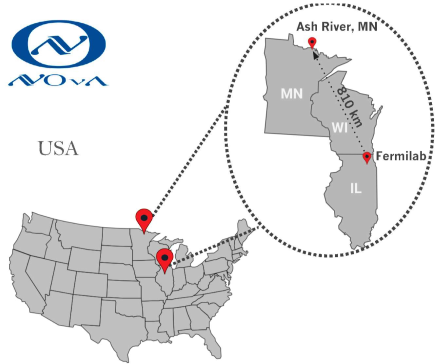


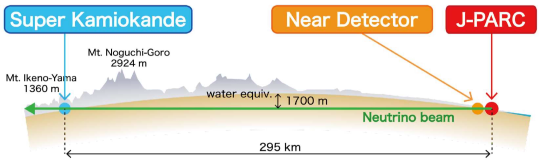
$$J_{CP} = s_{13}c_{13}^2 s_{12}c_{12}s_{23}c_{23}\sin\delta_{CP}$$

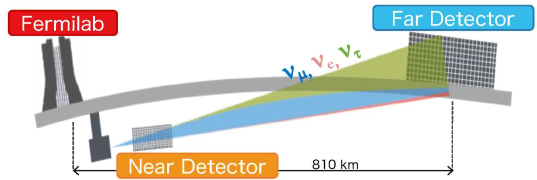
... also θ_{13}

The T2K and NOvA Experiments


T2K
Japan
Kamioka
295 km
Tokai


NOvA
USA
Ash River, MN
MN
810 km
WI
Fermilab
IL


Super Kamiokande
Near Detector
J-PARC
Mt. Noguchi-Goro
2924 m
Mt. Ikeno-Yama
1360 m
water equiv.
1700 m
Neutrino beam
295 km


Fermilab
Far Detector
ν_μ, ν_e, ν_τ
Near Detector
810 km

Neutrino energies

- Both experiments have detectors located slightly off-axis (2.5° T2K, 0.84° NOvA) to get narrow and highly pure $\nu_\mu/\bar{\nu}_\mu$ spectra

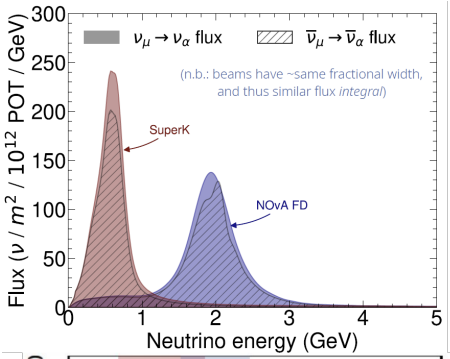
  NOvA peak at $\sim$ 2 GeV

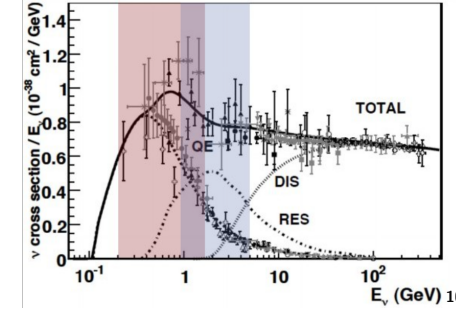
  T2K peak at $\sim$ 0.6 GeV

- Different ν energy corresponds to different phenomenological **types of interactions**

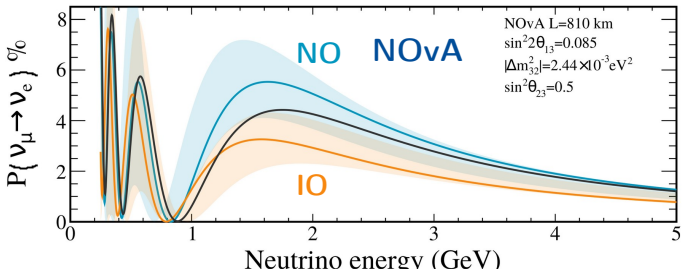
  NOvA: transition region, mixture of QE, 2p2h, RES π production and DIS

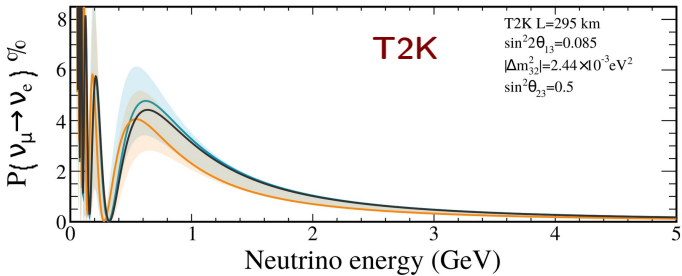
  T2K: mostly QE with 2p2h and RES, DIS in tail





Baselines





NOvA: 810 km

T2K: 295 km

MATTER EFFECTS

- Higher energy and longer baseline enhances the **mass ordering dependent matter effects**, which are degenerate with CP violation effects
- Lower energy and shorter baseline reduces the matter effects to get **less degenerate CPV values of δ_{CP}**

The impact on $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ differs for each experiment



Lifting degeneracies

- Different **energies** and **baselines** give different oscillation probabilities and parameter sensitivity

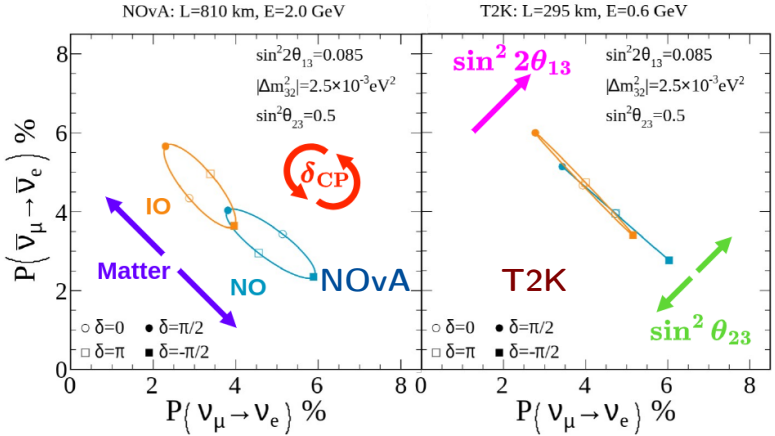
NOvA:

- Better mass ordering sensitivity
- Degenerate for around $\delta_{CP} = \pi/2$ and $-\pi/2$ (CPV)

T2K:

- Better δ_{CP} sensitivity
- Degenerate for around $\delta_{CP} = 0$ and π (no-CPV)

- Joint analysis probes both spaces **lifting degeneracies of individual experiments**



NO: $P(\nu_\mu \to \nu_e) \uparrow \quad P(\bar{\nu}_\mu \to \bar{\nu}_e) \downarrow$

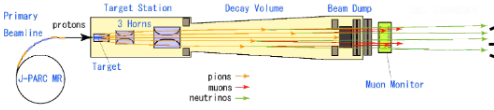
IO: $P(\nu_\mu \to \nu_e) \downarrow \quad P(\bar{\nu}_\mu \to \bar{\nu}_e) \uparrow$

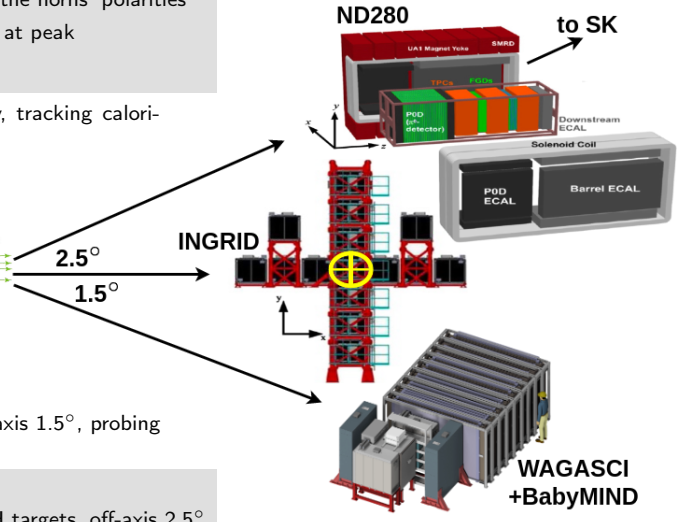
Beamlines and Detectors

beamline and near detectors

- Switching between ν and $\bar{\nu}$ beam by inverting the horns' polarities
- Almost pure $\nu_\mu/\bar{\nu}_\mu$ beam with $< 1\%$ of $\nu_e/\bar{\nu}_e$ at peak
- Reached operating power ≈900 kW

- **INGRID** monitors beam direction and stability, tracking calorimeter, on-axis, Fe + plastic scintillator





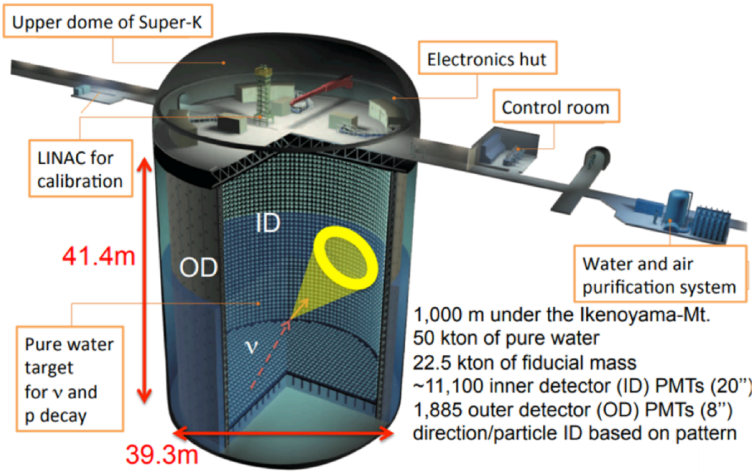
- **WAGASCI+BM** H_2O target, magnetized, off-axis 1.5°, probing spectrum variations with the off-axis angle

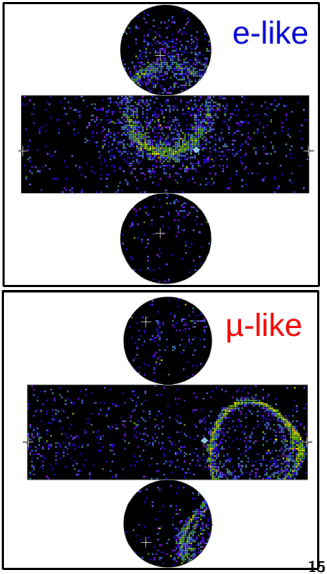
ND280

- 0.2 T magnet, trackers+calorimeters, H_2O/CH targets, off-axis 2.5°
- Directly used in the analysis to constrain XSecs, beam $\nu_e/\bar{\nu}_e$, etc.

– T2K far detector

Excellent μ/e-like rings separation (ν_μ/ν_e CC int.)

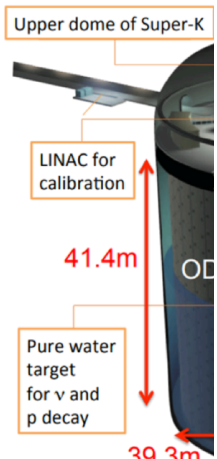


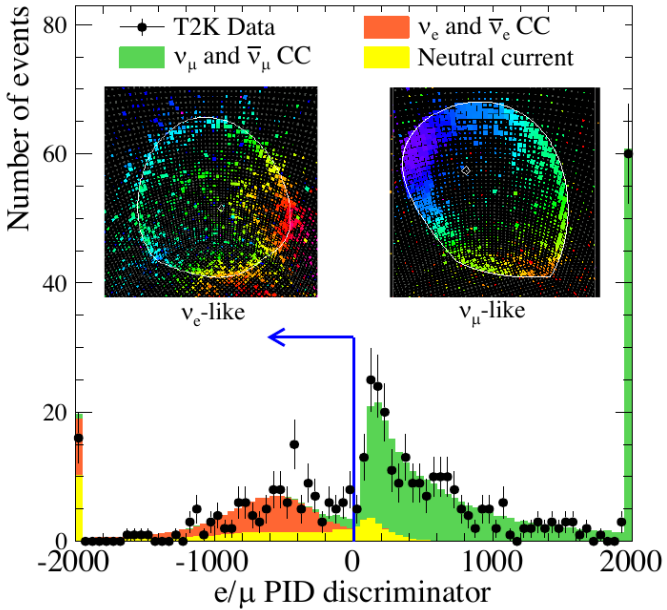


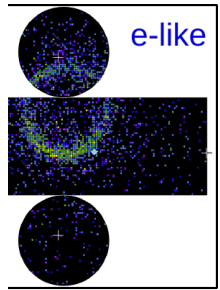
– T2K

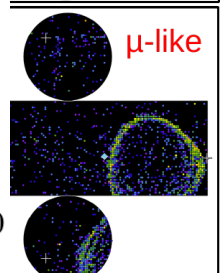
Excellent μ/e-like rings

Adapted from arXiv:1910.03887v2

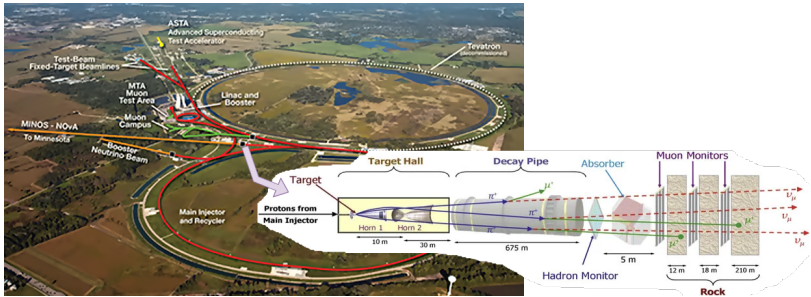


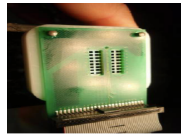


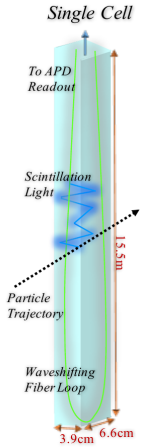




detectors and NuMI beamline

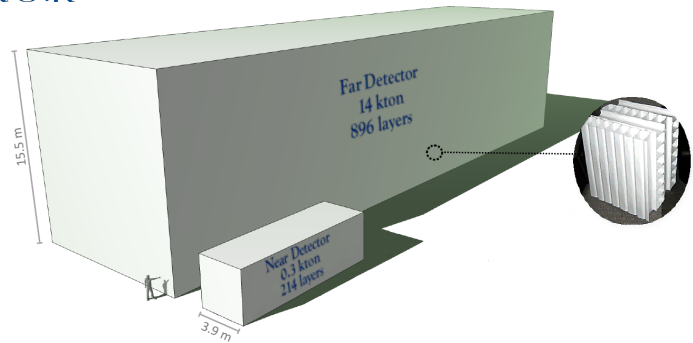


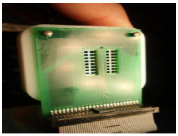


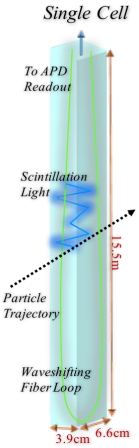


- NuMI: 120 GeV protons, power up to > 1 MW, down since Jun 2024
- Two functionally similar detectors 810 km apart – **Near (ND)** and **Far (FD)**
- FD on the surface, ND about 100 m underground
- Consist of extruded plastic cells with alternating vertical and horizontal orientation for 3D reconstruction of neutrino interactions
- Liquid scintillator, tracking calorimeter, 65% active mass (FD 14 kt, ND 0.3 kt)
- Energy estimation from μ range, EM and hadronic shower calorimetry

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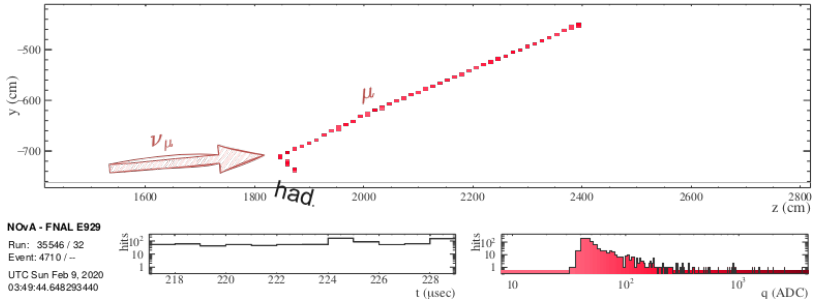


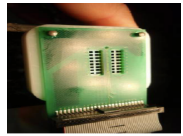


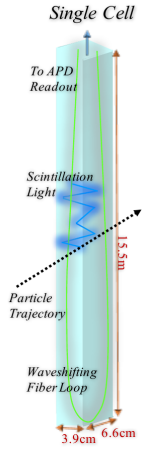


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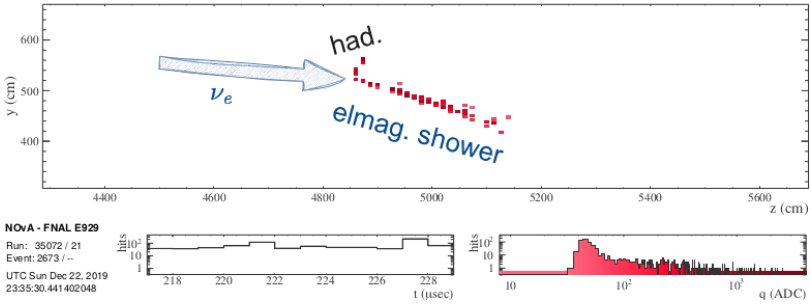


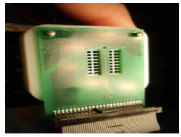


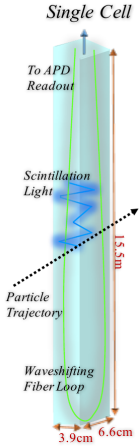


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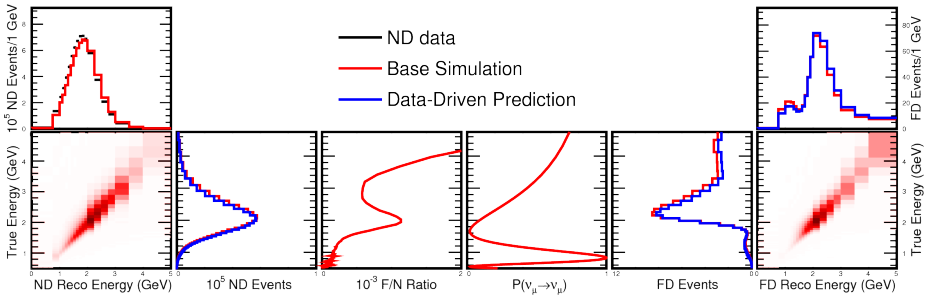


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Neutrino Oscillation Analysis Strategies

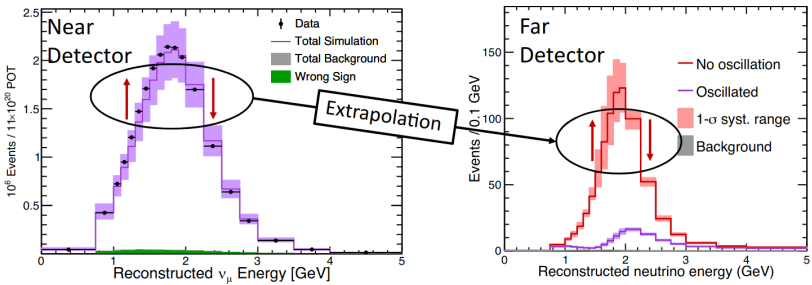
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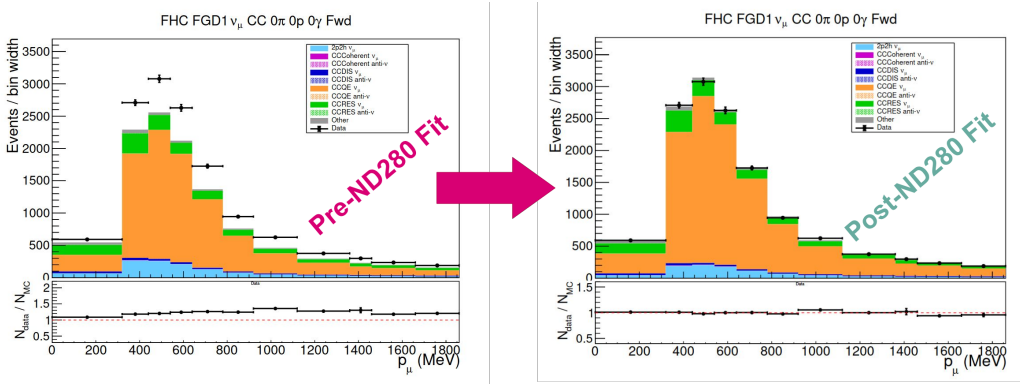
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- The ND measured spectra are used to correct FD MC oscillated predictions using the **Far/Near (F/N)** transformation
- Due to functional similarity of both detectors, this procedure largely cancels detector correlated uncertainties (ν flux and cross sections)

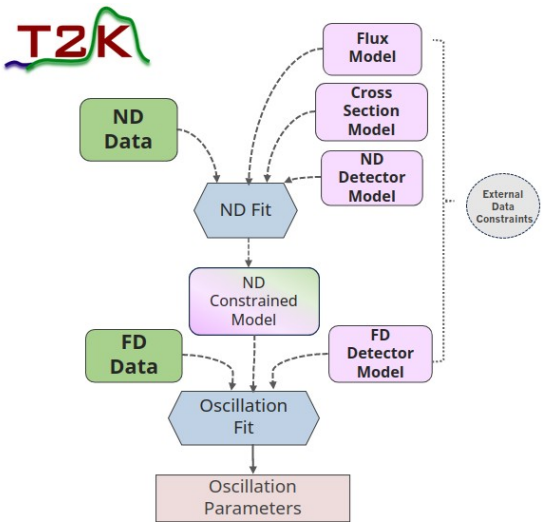


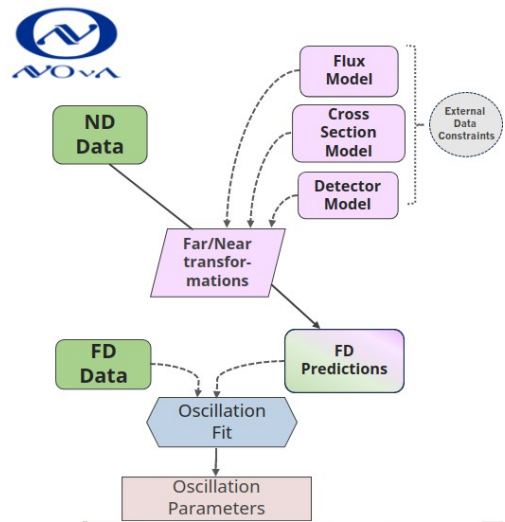
T2K analysis strategy

- **Fit to ND280 data moves the model parameters** from their pre-fit values and **constrains them**
- This data fit might be **sequential** (ND fit → constrained model → FD fit) or **simultaneous** (ND+FD data simultaneous fit)
- Model dependence is checked with **out-of-model tests for analysis robustness**



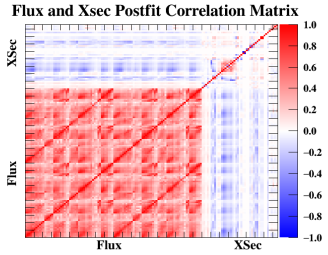
Analysis strategies compared

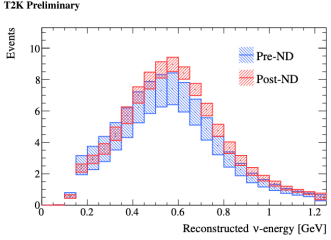


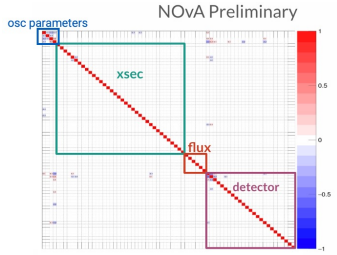


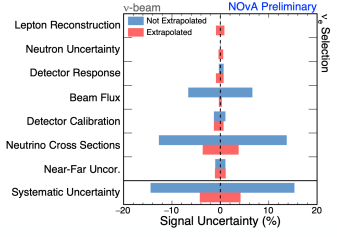
Analysis strategies compared

Different approaches have a similar impact on the resulting systematic uncerts



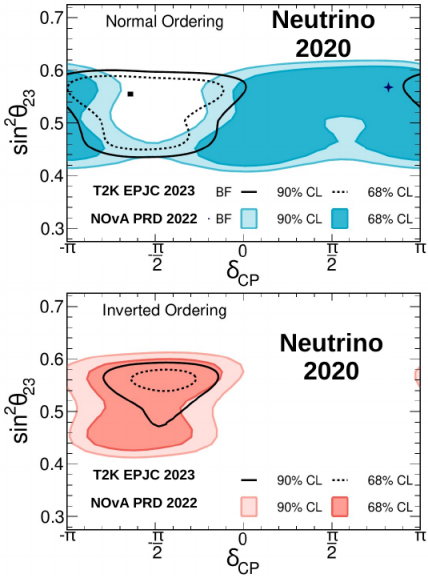






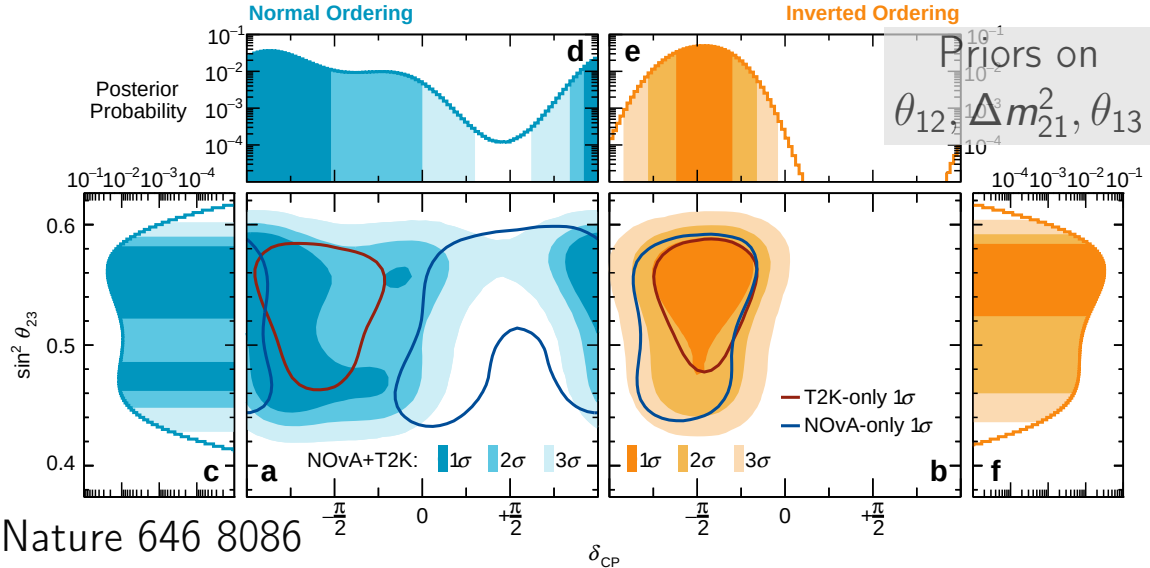
Motivation to combine

- Different experimental setups of oscillation baseline and energies lead to **different physics sensitivity**
  - NOvA mass ordering sensitivity
  - T2K CP-violation sensitivity
- **Full implementation of**
  - **Consistent statistical inference** across the full dimensionality
  - Each experiments' **detailed likelihood**
  - **Energy reconstruction and detector response**
- **In-depth review of**
  - Models, systematic uncertainties and their possible correlations
  - Different analysis strategies driven by different detector designs
- **Roughly doubled statistical power of individual experiments**



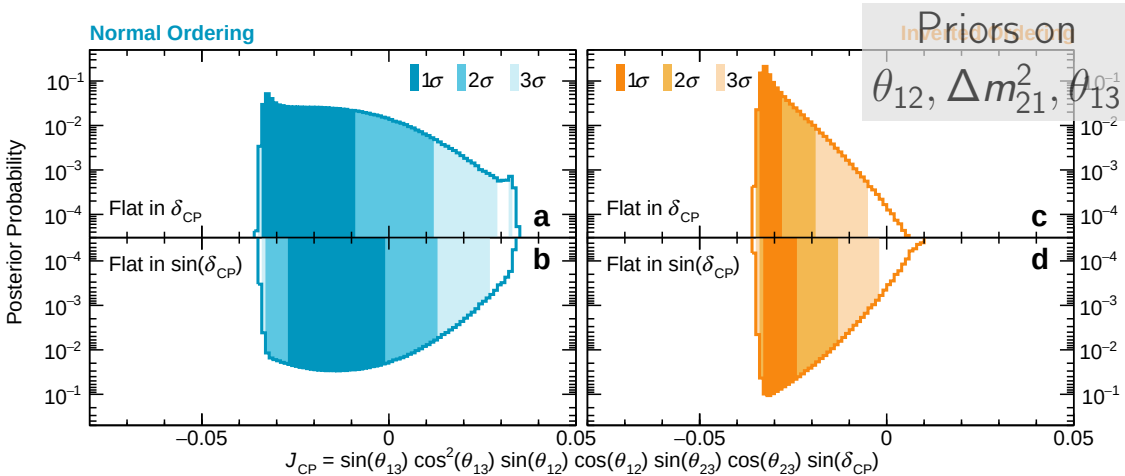
T2K and NOvA 3ν Oscillation Latest

T2K results 2024, based on 2020 analyses



Nature 646 8086

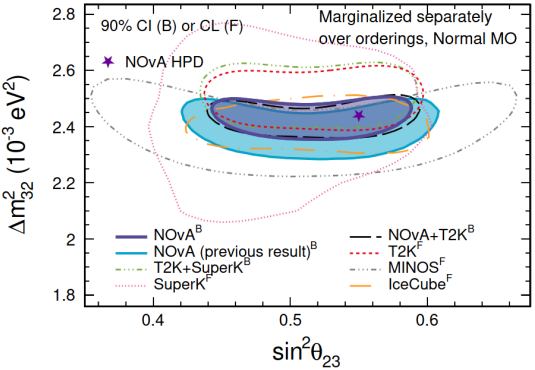
T2K ν OVA results 2024, based on 2020 analyses

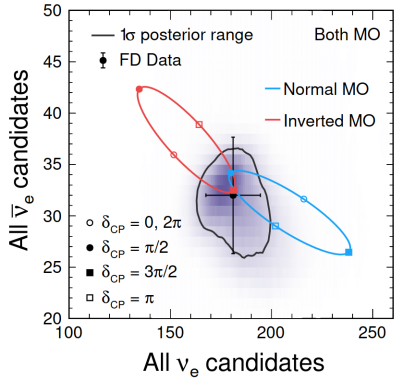


Nature 646 8086

10yr of data, 2024

PRL 136 011802





- Doubled ν exposure since 2020:
  26.61e20 POT ν-beam
  12.50e20 POT $\bar{\nu}$-beam
- One of the most precise Δm^2_{32} measurements
- With $\sin^2\theta_{13}$ prior, NOvA shows a 77% preference for NO

- Degeneracy between mass-ordering hypothesis and δ_{CP} measurement
- Disfavoring combinations of IO, $\delta_{CP} = +\pi/2$ (4σ) and NO, $\delta_{CP} = +3\pi/2$ (2.5σ)
- No strong preference for CP violation or conservation

ν_μ vs ν_e, 2026

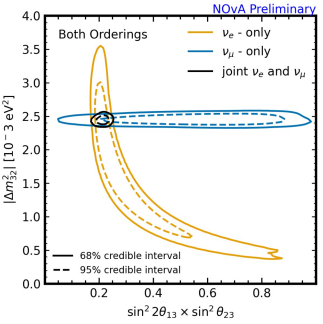
- Stress-testing the 3ν-paradigm with flavor-specific analysis, isolating the complementary information from $\nu_\mu \to \nu_\mu$ and $\nu_\mu \to \nu_e$ transitions:

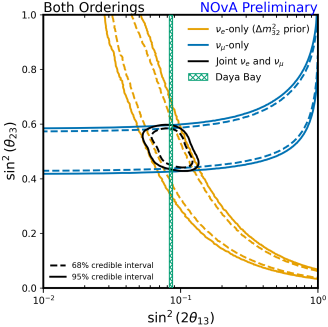
  $\nu_\mu \to \nu_\mu$: $\sin^2 2\theta_{23}, |\Delta m^2_{32}|$
  $\nu_\mu \to \nu_e$: $\sin^2 2\theta_{13}, \sin^2 \theta_{23}, \Delta m^2_{32}$

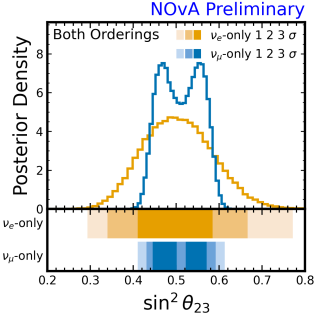
- All analyses (including $\nu_\mu + \nu_e$) are consistent with maximal 23-mixing

- Consistency across analyses and reactor measurements supports the robustness of 3ν-paradigm

- Last T2K ν_μ and $\bar{\nu}_\mu$ disappearance analyses in PRD 108 072011

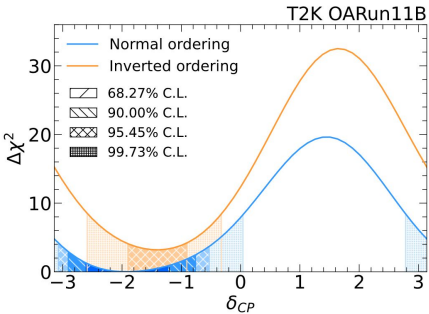


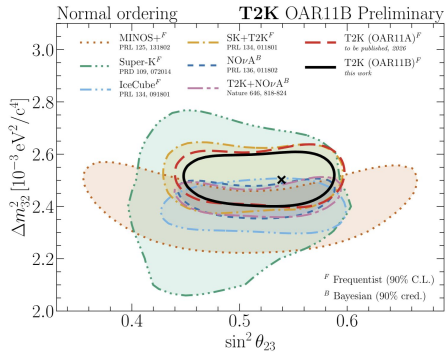




OAR11B, 2026

- 2^{nd} analysis update since PRL 135 261801
- +10% of ν-beam data with Gd-loaded SK (Run 11)
- Extended SK multi-ring ν_e selections
- ND280 backward and high-angle ν_μ CC samples
- Improved reconstruction



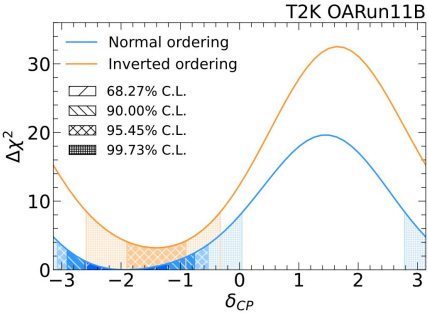


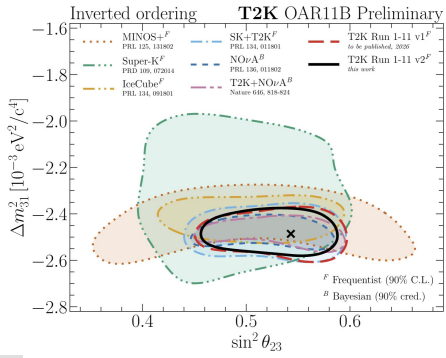
- Preference for maximally CP-violating values of δ_{CP}, **CP-conservation excluded at 95% CL**
- Using $\sin^2\theta_{13}$ reactor constraints
- Inflating Δm^2_{32} unc. from alternative interaction model studies
- Weak preference for NO (78%) and $\sin^2\theta_{23} > 0.5$ (67%)

Nominal analysis compared to 5 alternative int. models

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Nominal analysis compared to 5 alternative int. models

With a Little Help from Friends

Reactor constraints

Recall the oscillation probabilities:



Some LBL
θ_{23} vs. θ_{13} ambiguity

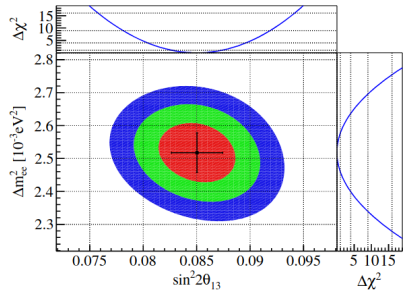
$$P(\nu_\mu \to \nu_e) \propto \sin^2\theta_{23}\sin^2 2\theta_{13}$$

$$1 - P(\bar{\nu}_e \to \bar{\nu}_e) \propto \sin^2\theta_{13}$$

Simple θ_{13} dependence

Recent 2D constraints from Daya Bay PRL 130 161802
also from RENO PRD 111 112006

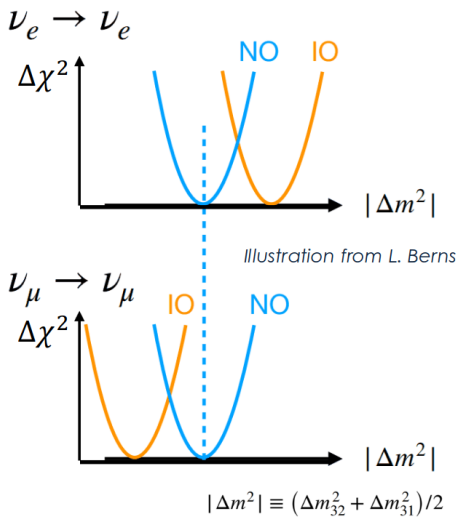
$$\Delta m^2_{ee} \simeq \cos^2\theta_{12}|\Delta m^2_{31}| + \sin^2\theta_{12}|\Delta m^2_{32}|$$



LBL with reactor friends

- JUNO reports %-level constraints on Δm^2_{32} from $\bar{\nu}_e \to \bar{\nu}_e$
- T2K, NOvA report %-level constraints on Δm^2_{32} from $\nu_\mu \to \nu_\mu$ and $\bar{\nu}_\mu \to \bar{\nu}_\mu$
- The best fit values shift depending on the assumed mass ordering (by a factor of Δm^2_{21})
- The shift is in the opposite direction for electron and muon neutrino disappearance
- The right mass ordering is the one in which reactor experiments agree with long-baseline and atm. measurements

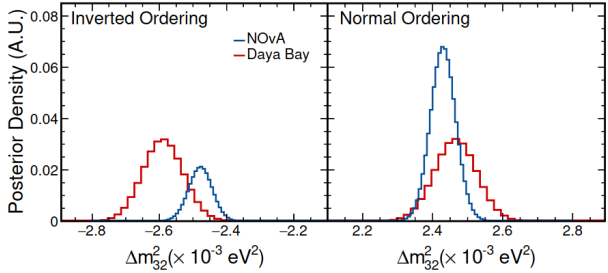
Combinations of high-statistics $\nu_\mu \to \nu_\mu$ LBL channels with reactor and JUNO enable higher sensitivity to neutrino mass ordering. Expect about 3σ for combined measurements.



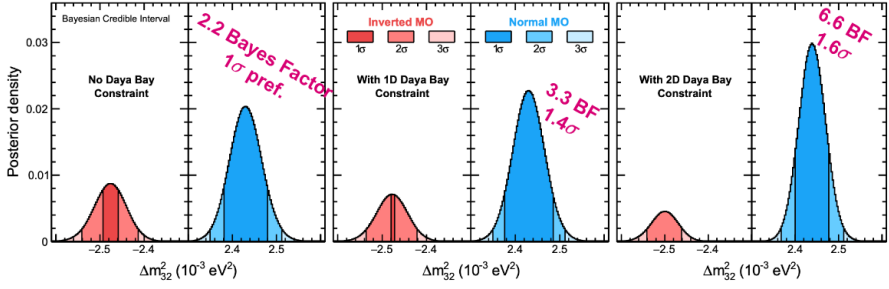
2D reactor constraint

- Reactor Δm^2_{ee} maps differently on Δm^2_{32} for NO/IO
- NOvA and Daya Bay measurements "disagree" in IO, but agree in NO

NOvA's notable preference for NO (1σ) is more pronounced when including the 2D Daya Bay constraint (up to 1.6σ)



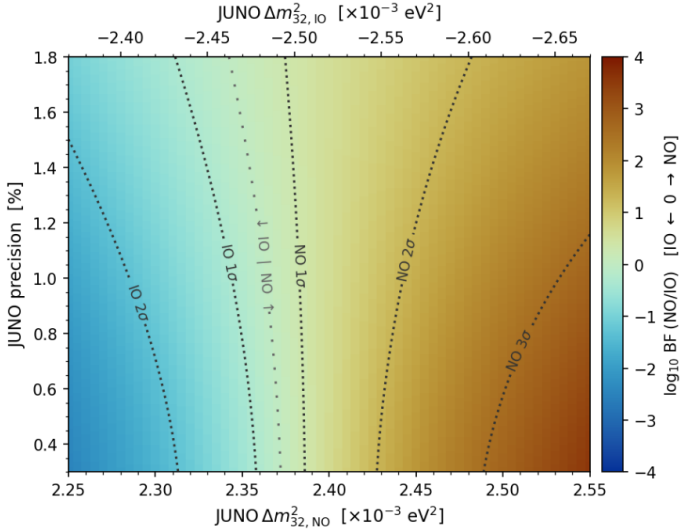
arXiv:2606.14121



PRL 136 011802

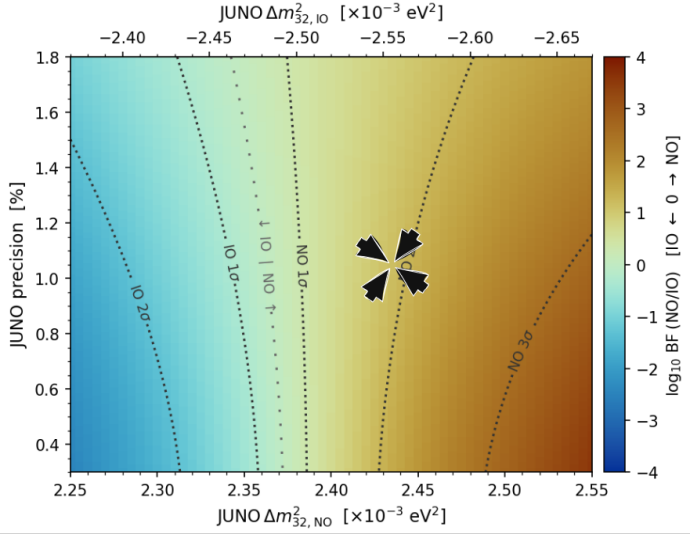
sensitivity

- arXiv:2606.14121
- Notably promising sensitivity prospects come from combining NOvA measurements with Daya Bay and JUNO
- NO/IO Δm^2_{32} disagreement between reactor exps and NOvA enables up to 3σ sensitivity for MO determination depending on the precision of the JUNO measurements
- See NOvA's interactive tool: link
- For current JUNO results (arXiv:2609.37895), there is $\sim 1.9\sigma$ **preference for NO when combining with NOvA**
- Requires proper joint analysis though



sensitivity

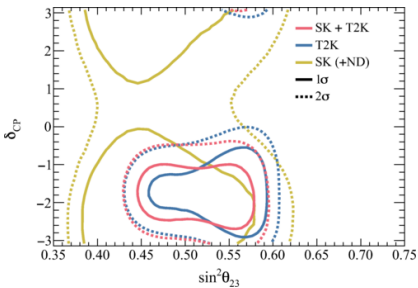
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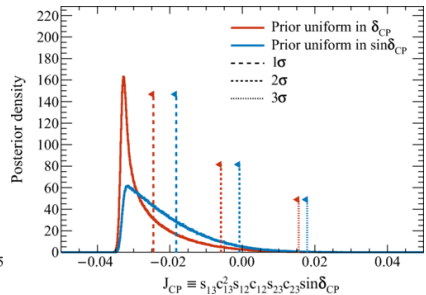


T2K SUPER-K results 2024, based on 2020

- Combining the accelerator $\nu_\mu \rightarrow \nu_{\mu/e}$ (below 5 GeV) with atmospheric $\nu_\mu \rightarrow \nu_{\mu/e}$ (sub-/multi-GeV samples) enhances the T2K sensitivity to $\sin\delta_{\mathrm{CP}}$
- More stringent constraints with SK ordering sensitivity can be reported **NO/IO conditionally**

PRL 134 011801





- If IO, CPC values of δ_{CP} outside 2σ CI
- $J_{\mathrm{CP}} \geq 0$ outside 2σ CIs, $\delta_{\mathrm{CP}} = \pi/2$ outside 3σ CIs

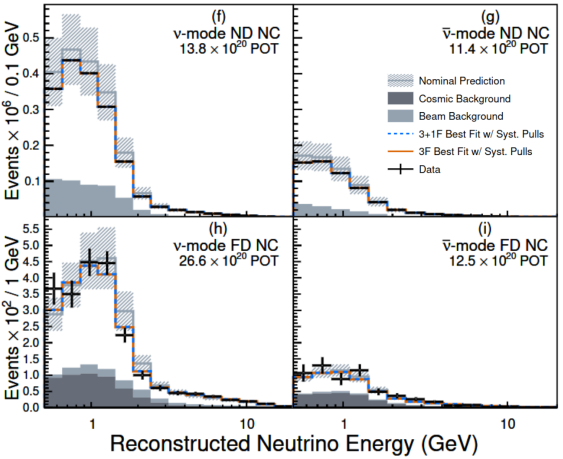
Beyond 3ν-paradigm

3+1, sterile neutrinos

- Testing minimal 3+1 sterile model:

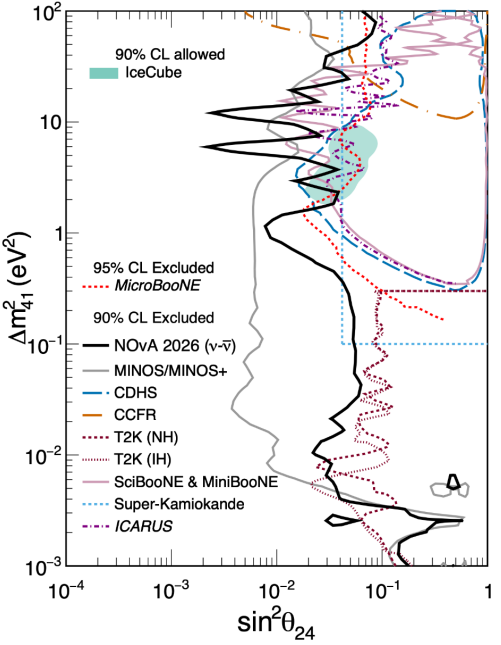
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_s\end{pmatrix} = \begin{pmatrix}U_{e1} & U_{e2} & U_{e3} & U_{e4}\\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4}\\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4}\\ U_{s1} & U_{s2} & U_{s3} & U_{s4}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\\ \nu_4\end{pmatrix}$$

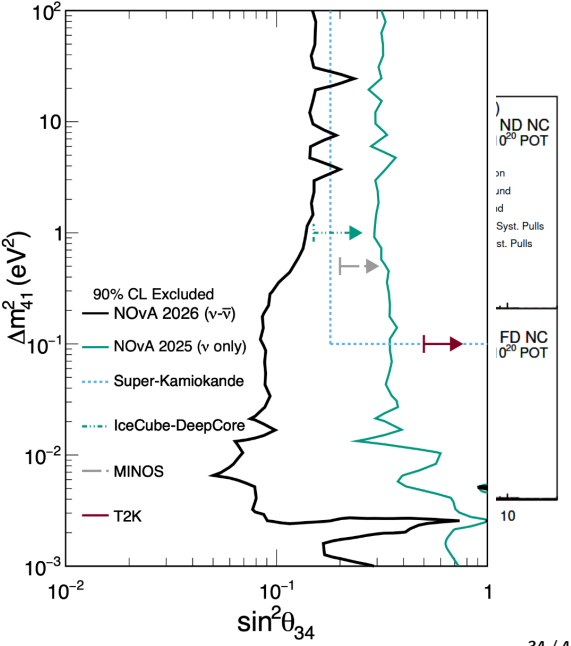
- The analysis combines $\nu_\mu \to \nu_\mu$ CC disappearance samples with $\nu_\mu \to \nu_X$ NC disappearance samples (no NC disappearance in 3ν-paradigm)
- Very good agreement between 3 and 3+1 model fit across all samples in both ν- and $\bar{\nu}$-enriched beams
- Beam systs constrained through a dedicated ν-on-e sample
- Sensitive to both higher and lower Δm^2_{41}:
  High Δm^2_{41}: fast oscillations in ND
  Low Δm^2_{41}: slow oscillations in FD



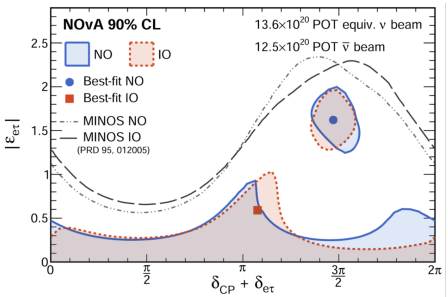
arXiv:2609.08900

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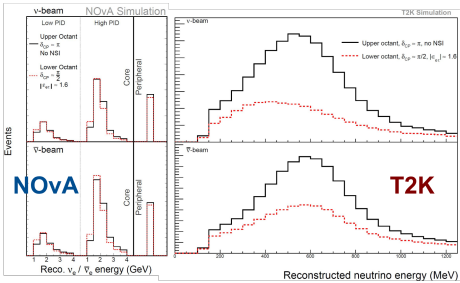


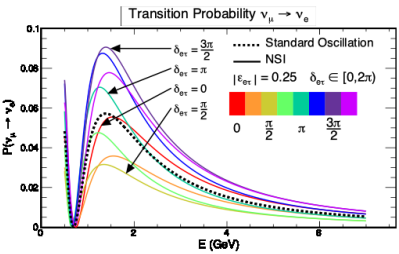
non-standard interactions



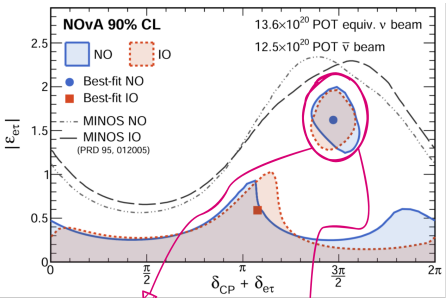
$$H_f = \frac{1}{2E} U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} U^\dagger + V_{\mathrm{CC}} \begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix}$$

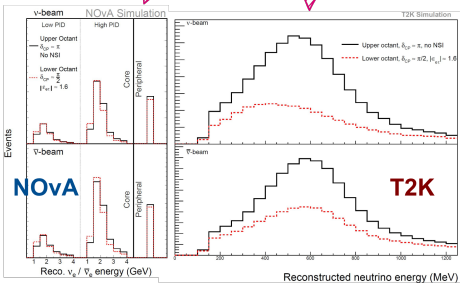
- NOvA NSI analysis in PRL 133 201802
- Extra complex NSI parameters alter matter effects and introduce new sources of CP violation
- Though NOvA by itself can place strong NSI constraints, some level of degeneracy is still present in neutrino spectra
- Adding T2K breaks the degeneracy for NOvA's allowed NSI parameters points
- **Joint analysis in progress**





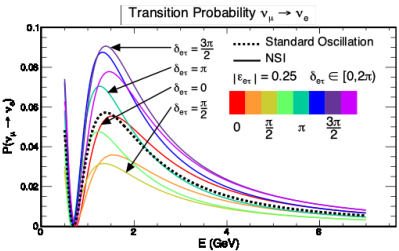
non-standard interactions





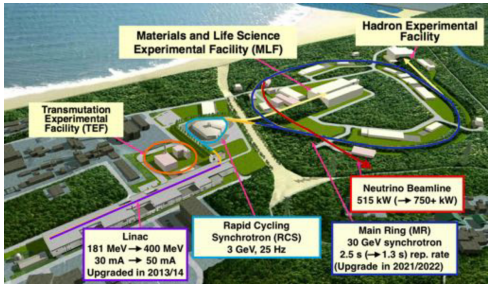
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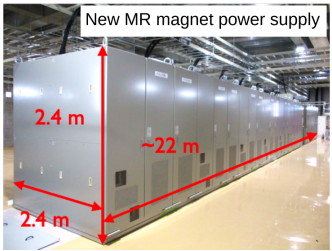
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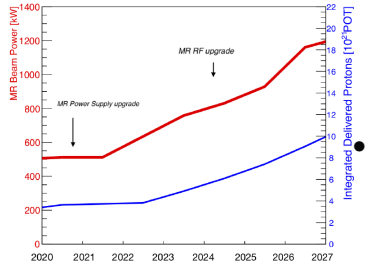
Near-future Prospects

T2K beam upgrade



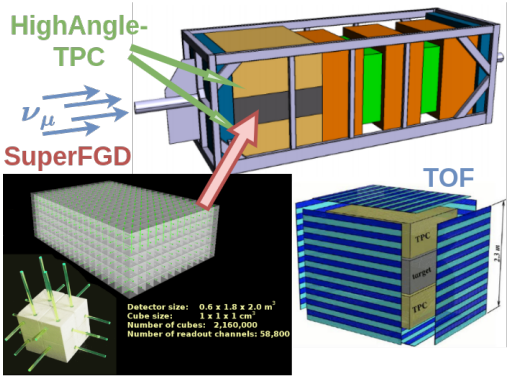


T2K Projected POT (Protons-On-Target)



- Main Ring (MR) **reached** $\approx$ **900 kW** stable operation during 2026
- Upgrades during the 2-year shutdown:
  - New MR fast extraction magnets and power supply (**rep. rate** 2.48 s $\rightarrow$ **1.25 s**)
  - New proton focusing magnet
  - New beam monitors and μ monitor
  - New target and target cooling system
  - New focusing horns and power supplies (**250 kA** $\rightarrow$ **320 kA**)
- **Targeting for over 1.3 MW** with MR RF systems upgrade (**down to 1.16 s** rep. rate)

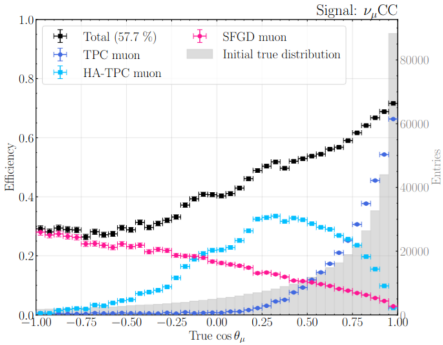
ND280 upgrade

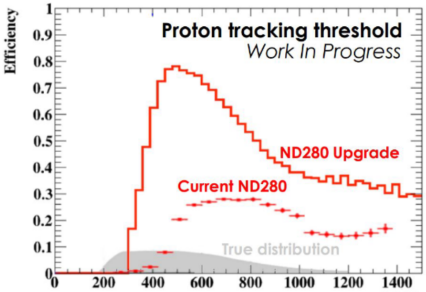


Replacing P0D with a set of new high performance detectors

Upgrade finished in May 2024

New scint. target 2 million cubes, ≈60000 fibers.





ND280 upgrade essentially enhances the detector acceptance to access new regions of phase space when constraining ν and $\bar{\nu}$ interactions for ν oscillation analysis and XSecs

IMPLEMENTING INTO THE OSCILLATION ANALYSIS

The need of future joint analyses

- Success of recent collaboration among neutrino experiments on T2K+NOvA or T2K+SK encouraging greater efforts for full-scale joint analyses
- Important to include full systematics modelling in the high-statistics era (JUNO, DUNE, Hyper-K), accounting for full likelihood maps
- Correlate related uncertainties (detector response, interaction modelling)
- Cross-check neutrino interaction generators and models
- There is still quite a lot of data expected from both T2K and NOvA experiments before the new generation of neutrino observatories arrives!

	NOvA	T2K	Super-K
Analyzed Exp.	39e20 POT	37e20 POT	3244.4 days (water)
Expected Exp.	**72e20 POT**	**100e20 POT**	**+4 years** (water+Gd)

Conclusions

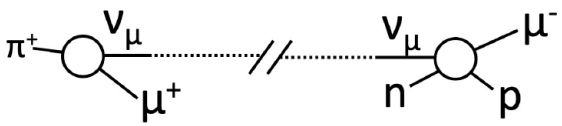
Conclusions

- **T2K** excludes CP-conservation at $\sim 2\sigma$, consistent with max CP-violation in lepton sector
- **NOvA** disfavors MO-dependent combinations IO, $\delta_{CP} = +\pi/2$ (4σ) and NO, $-\pi/2$ (2.5σ)
- **NOvA** tests the 3ν-paradigm with sterile ν analysis (NC disappearance) and NSI
- **T2K+NOvA** exclude CP-conservation at 3σ for IO
- **T2K+SK** exclude Jarlskog $J_{CP} = 0$ at 1.9σ or higher
- **NOvA+2D Reactors+JUNO** have about 1.9σ preference for NO

- Expecting significantly more data for NOvA and T2K by the end of their lifetime, T2K upgrades to improve the analyses in coming years
- Successful inter-collaborative efforts help establish a cooperative environment benefiting the next generation of neutrino observatories (JUNO, Hyper-K, DUNE)

BACKUP

Disappearance oscillation probabilities



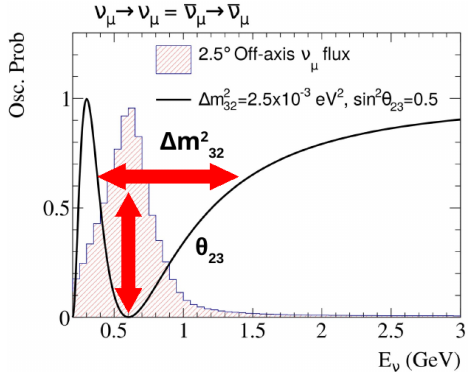
Leading order $\sin^2 2\theta_{23}$ and Δm^2_{32}

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

$\sin^2 2\theta_{23}$:
mixing angles rule the oscillation amplitude

Δm^2_{32} :
squared mass-splittings rule the oscillation frequency

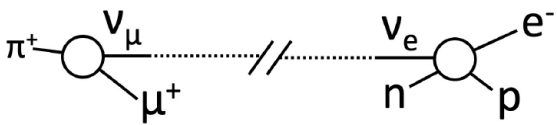
Max $\sin^2\theta_{23} = 1$ corresponds to maximal mixing of $\theta_{23} = 45°$



$\Delta m^2_{ij} \equiv m^2_i - m^2_j$

Squared mass-splittings of neutrino masses

Appearance oscillation probabilities



Leading order $\sin^2\theta_{23}, \sin^2 2\theta_{13}$ and Δm^2_{32} in vacuum

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23} \cdot \sin^2 2\theta_{13} \cdot \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$

+ δ_{CP} dependent terms CP violating

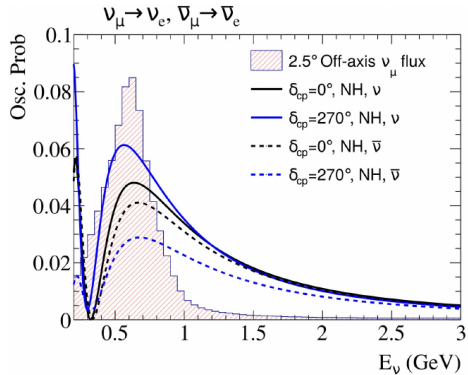
+ δ_{CP} dependent terms CP conserving

+ other terms

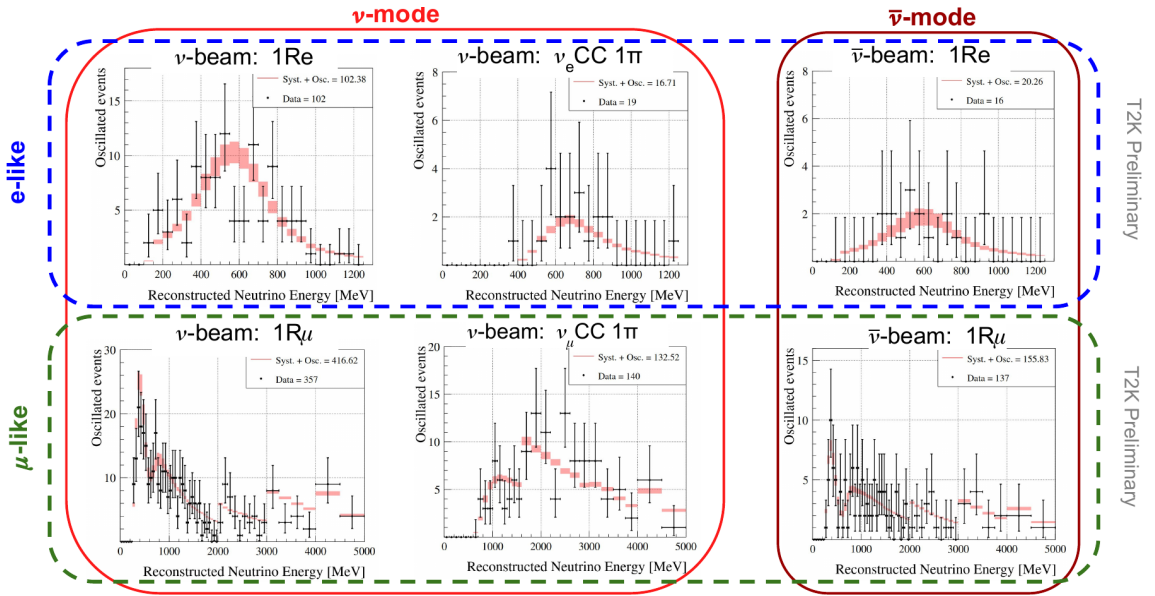
$\delta_{CP} = \pi/2$: less $\nu_\mu \to \nu_e$, more $\bar{\nu}_\mu \to \bar{\nu}_e$
$\delta_{CP} = -\pi/2$: more $\nu_\mu \to \nu_e$, less $\bar{\nu}_\mu \to \bar{\nu}_e$

Matter effects

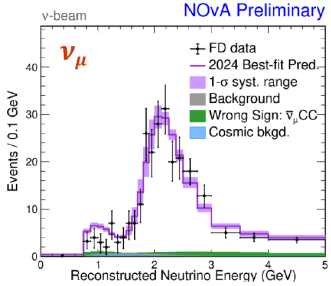
ν_e coherent forward scattering on pseudo-free electrons of matter modify $\nu_\mu \to \nu_e$, depends on the **sign of Δm^2_{32}** (mass ordering)

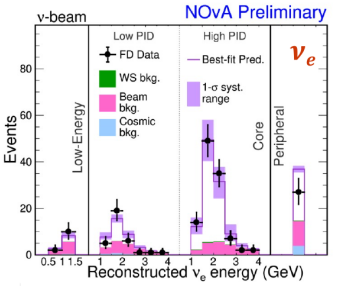


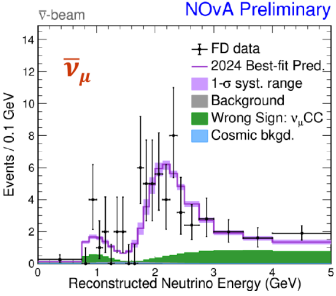
T2K OAR11B data

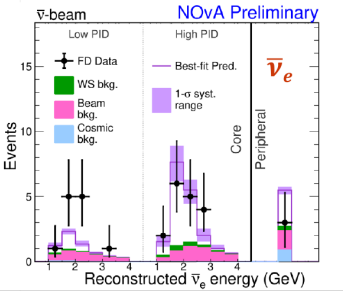


NOvA 2024 data



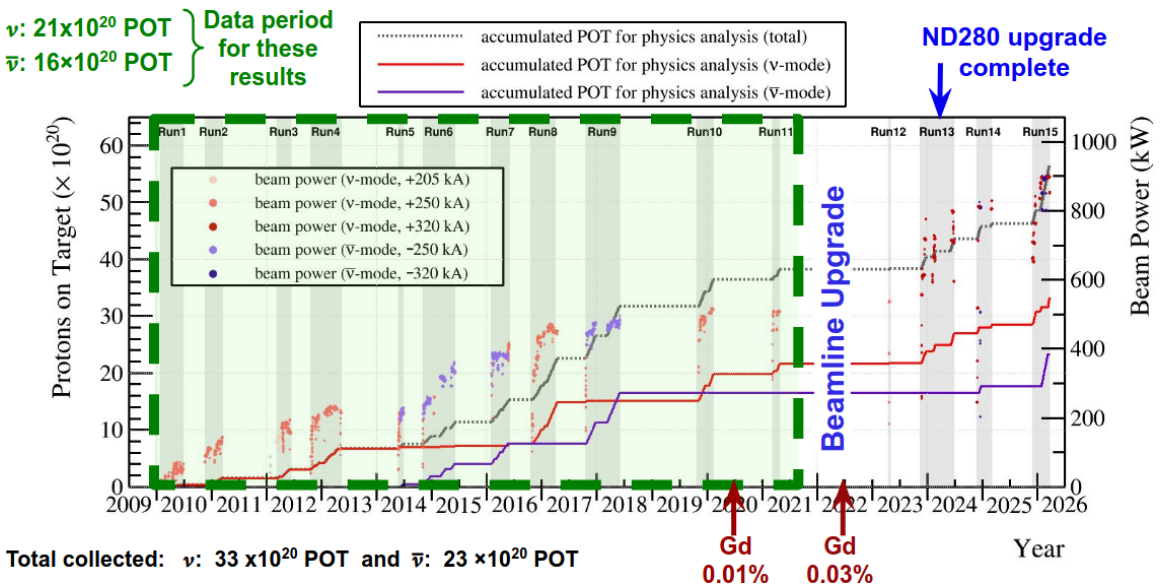




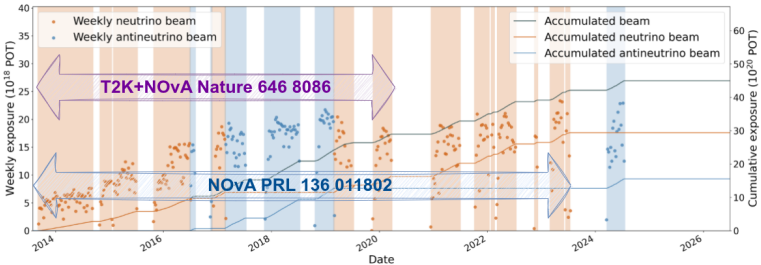


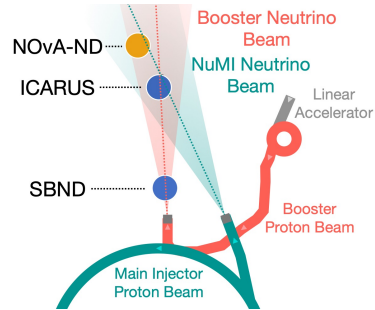
Channel	2024 Dataset	PPP value = 0.48
ν_e	169 (ν_e) 12 ($Low\ E$)	0.58 (ν_e) 0.72 ($Low\ E$)
$\bar{\nu}_e$	32	0.19
ν_μ	384	0.59
$\bar{\nu}_\mu$	106	0.39

T2K collected data



NOvA collected data





- NuMI reached 1 MW in Jun 2024, down since Aug 2024
- Came back last month
- $\bar{\nu}$ data still in the box

- Collecting BNB triggers since 2025

	NuMI	BNB
Protons Per Pulse	5e13	5e12
Rep Rate (Hz)	<1	5
Proton Energy (GeV)	120	8
Off-axis angle (°)	0.8	9.24
Baseline (km)	~1	~0.768

NOvA vs T2K comparison

Experiment	**NOvA**	**T2K**
Country Laboratory Started	USA Fermilab 2014	Japan KEK, J-PARC 2010
Baseline ν energy peak Off angle	810 km 2 GeV 0.84° / 14.6 mrad	295 km 0.6 GeV 2.5° / 43.6 mrad
ν Source $\nu + \bar{\nu}$ POT 2020	120 GeV protons, max 760 kW $(1.36 + 1.25) \times 10^{21}$	30 GeV protons, max 515 kW $(1.97 + 1.63) \times 10^{21}$
Near Detector	**NOvA ND** liquid scintillator tracking calorimeter NO MAGNET	**ND280** TPC trackers targets of pl. scintillator or water magnetized to distinguish $\nu_\mu/\bar{\nu}_\mu$
Far Detector	**NOvA FD** 14 kt liquid scintillator tracking calorimeter	**SuperK** 50 (22.5) kt water Cherenkov 13k (11k) PMTs
ν interactions	QE, 2p2h, RES, DIS mix	Mostly QE, 2p2h and RES bkg
Near-to-far	Direct correction of FD MC based on the ND data (F/N trans.)	Fit to ND data which constrains the interaction and flux parameters
Energy estimator	Lepton and hadronic calorimetry	Lepton kinematics (elastic)

Joint analysis strategy

Nature 646 8086 **based on Bayesian versions of 2020 analyses:** T2K: *EPJC 83 782* NOvA: *PRD 110 012005*

Full statistical treatment of experiments integrated via containerized environment:

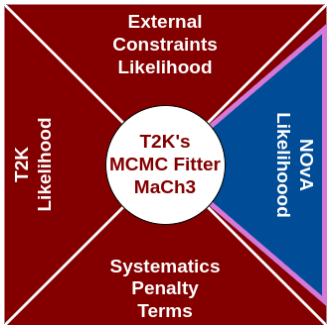
- **Each experiment can run the other's analysis** through an analysis software container
- **Full access to Monte-Carlo and data** while preserving each experiments' unique analysis approach

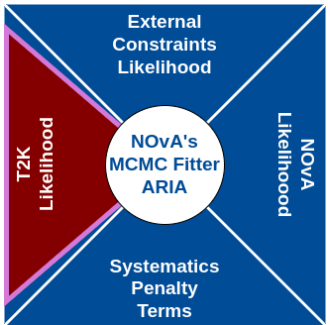
Two Bayesian Markov Chain Monte Carlo (MCMC) fitters: MaCh3 (T2K) and ARIA (NOvA)

Both give the same output format:

- Results are presented as **posterior densities** and **credible intervals** (regions) for parameters of interest
- Discrete model preferences (neutrino mass ordering, θ_{23} octant) presented with **Bayes factors**

Multiple analysis streams and independent implementation of the framework provides rigorous validation





Models and systematics

Common model deemed not practical, instead we studied the effect of systematics on the measurement
What? When? How much? . . . to correlate common physics parameters between the two experiments?

FLUX MODEL

- Different energies
- Different external data tuning
- Different treatment in the analysis

$\Rightarrow$ No significant correlations between the experiments

---

DETECTOR MODEL

- Different detector designs and technologies
- Different selections
  - Inclusive vs exclusive outgoing π
- Different reconstruction techniques
  - Calorimetry vs lepton kinematics

$\Rightarrow$ No significant correlations between the experiments

---

CROSS-SECTION MODEL

- Expecting correlations from common physics
- Different interaction models and generators
  - Optimized for different energies
- Systematics designed for individual models and analysis approaches

$\Rightarrow$ Investigate the impact of correlations in the joint analysis

Checks on impact of correlations in interaction models

Strategy

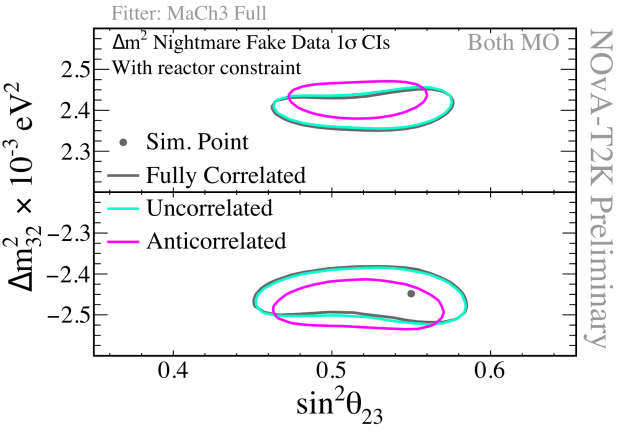
- Study parameters and their inter-experimental correlations with a significant impact on the parameters of interest δ_{CP}, $\sin^2\theta_{23}$, Δm^2_{32}

Fully correlating ν_μ/ν_e and $\bar{\nu}_\mu/\bar{\nu}_e$ cross-section uncertainties, treatment is identical (large δ_{CP} impact)

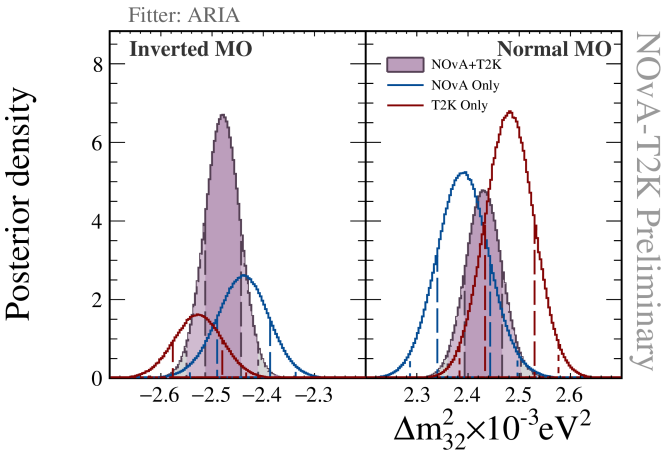
Otherwise, no direct mapping of the systematic parameters between the experiments

- Fabricated, simulated and studied a fully correlated bias for Δm^2_{32} or $\sin^2\theta_{23}$
- **Impact of correlations merits further investigation for future analyses with increased statistics**
- Given current (2020) statistics, the overall sensitivity gains from correctly correlating systematics would be small, while incorrectly correlating leads to bias

One example of a study to assess the importance of inter-experimental correlations



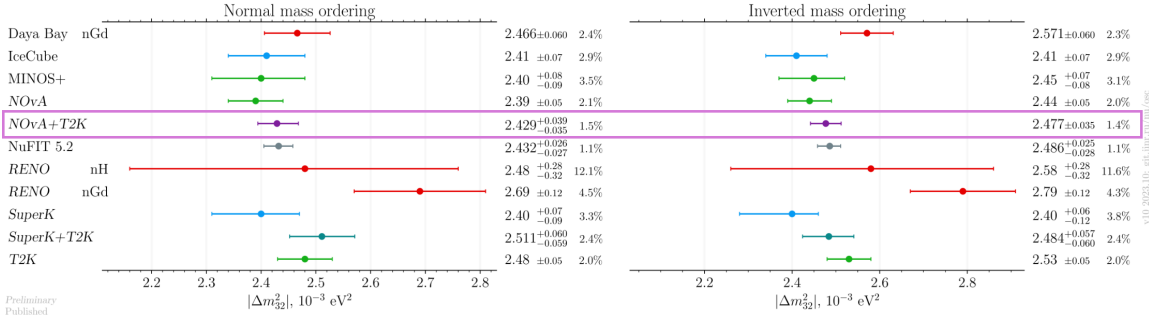
Comparison to NOvA-only and T2K-only results



- Joint analysis flips the preference for the IO
- T2K and NOvA individually prefer NO
- **Joint analysis enhances Δm^2_{32} precision**

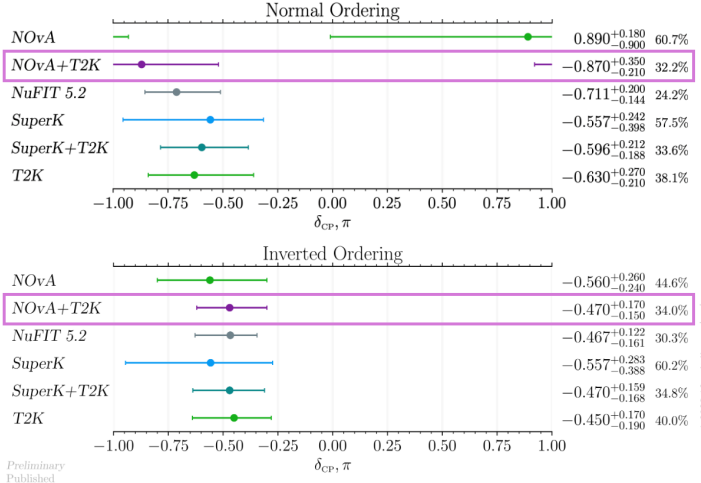
Δm^2_{32} global comparisons

- Δm^2_{32} measurements are largely consistent across different experiments
- This analysis **has smallest uncertainty in Δm^2_{32}** (newest NOvA 2024 results competitive)
- Showing 1σ CIs for Δm^2_{32} for both orderings conditionally

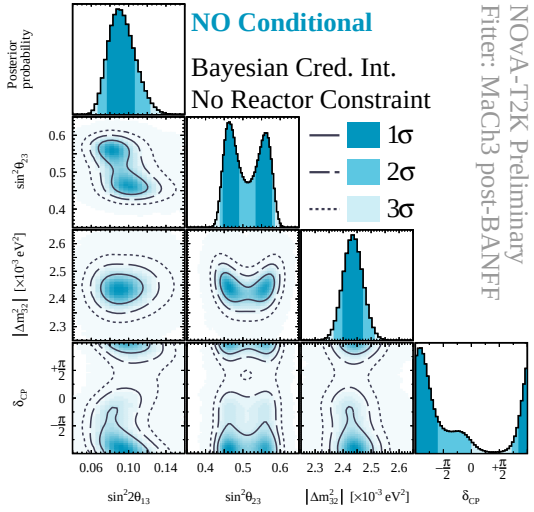


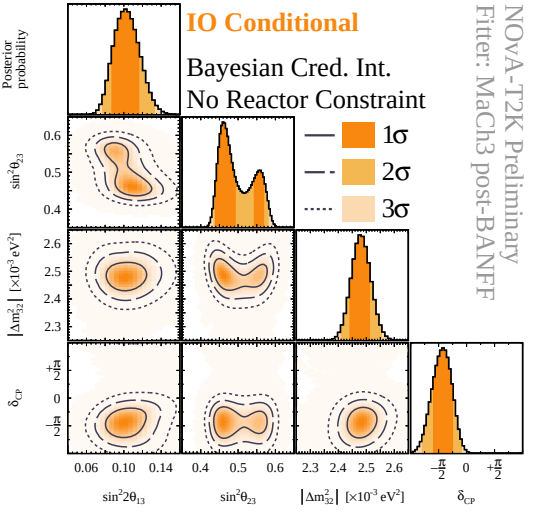
δ_{CP} global comparisons

- δ_{CP} measurements are consistent across many experiments and joint analyses
- Precision is still limited by the low statistics

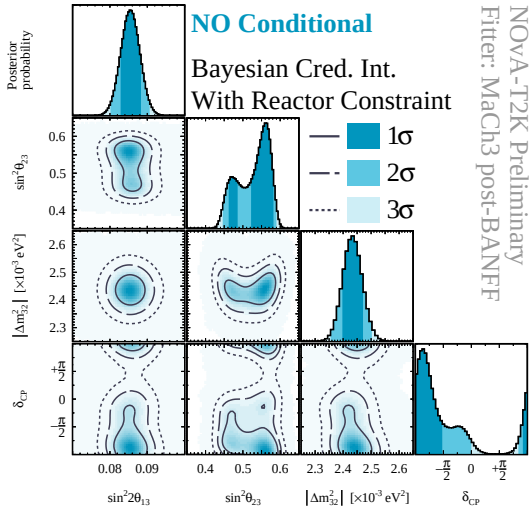


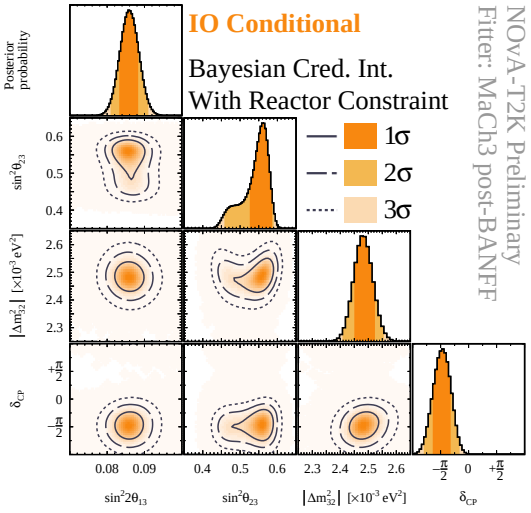
Results w/o reactor constraint, triangle plots





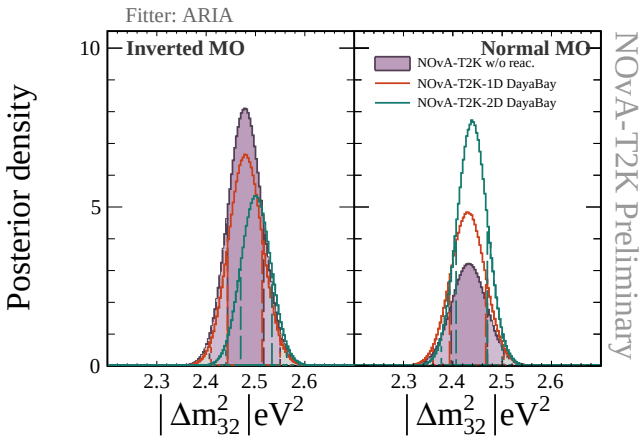
Results with reactor constraint, triangle plots



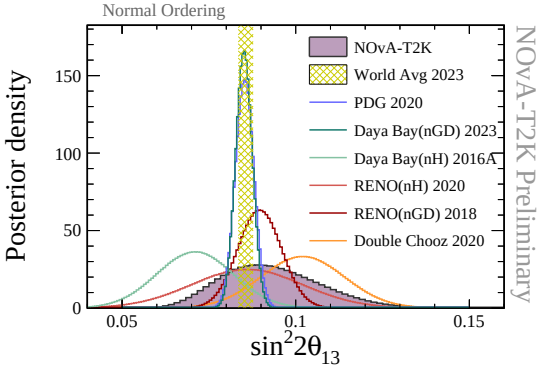


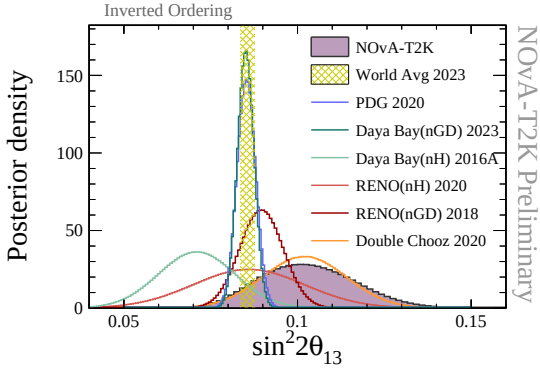
Daya Bay 2D constraints $\sin^2 2\theta_{13}$ and Δm^2_{32}

	NO RC	**1D** RC	**2D** RC
Mass ordering	2.4 71%:29% IO:NO	1.3 57%:43% IO:NO	1.4 59%:41% NO:IO
θ_{23} octant	1.2 54%:46% LO:UO	3.6 78%:22% UO:LO	3.2 76%:24% UO:LO

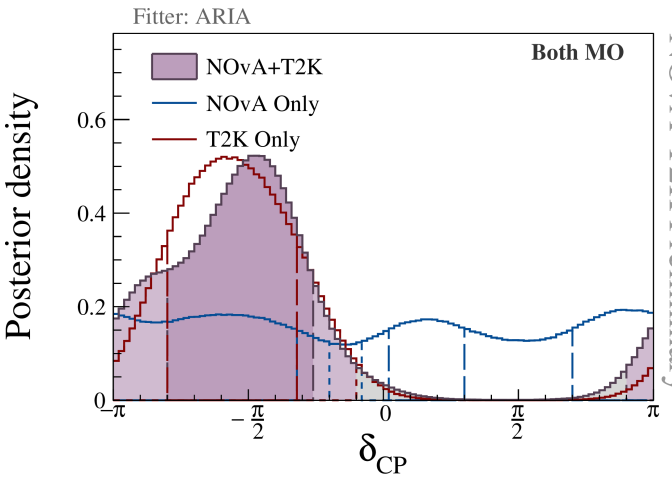


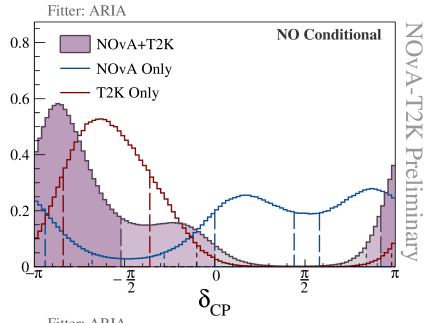
$\sin^2 2\theta_{13}$ comparisons

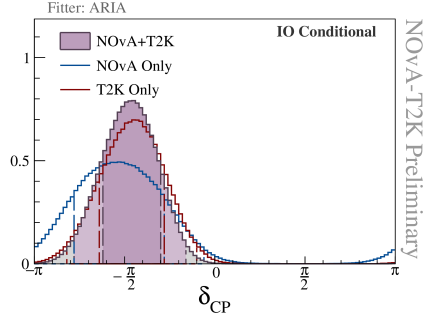




NOvA- and T2K-only comparisons

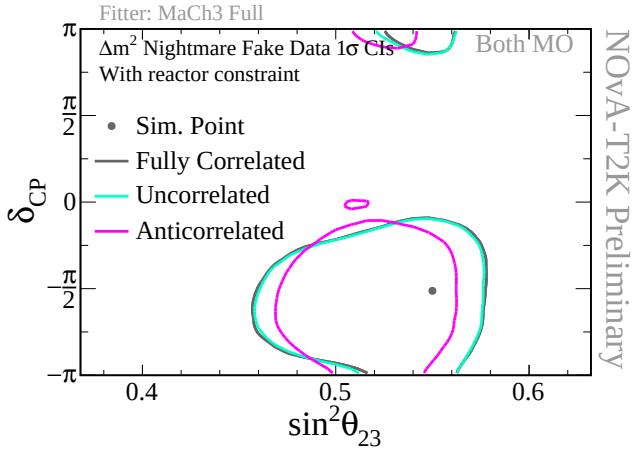


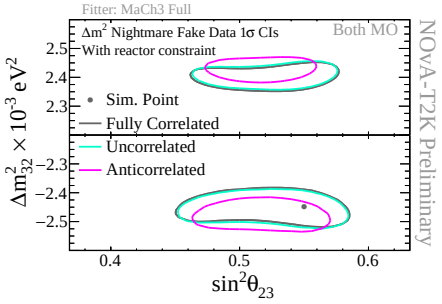


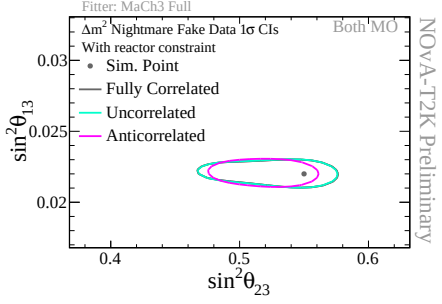


Correlation studies, Δm^2_{32} nightmare

Derived as a 10% energy scale systematic for T2K
and as an inflated neutron tagging systematic for NOvA







Checks on alternative models

- Evaluate the robustness of the analysis against alternative models
- Generate mock data for both experiments by changing MC simulation with several sets of oscillation parameters
- Fit the mock data and check the impact on the results

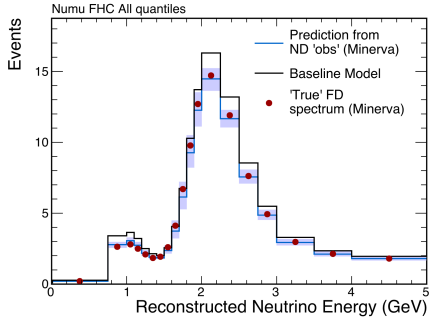
Pre-decided criteria to assess the impact

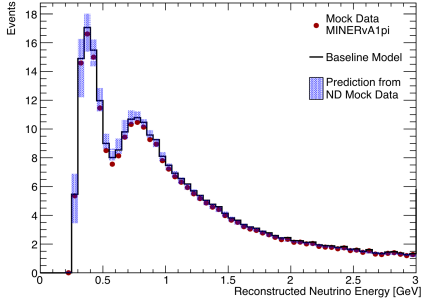
- Change in the width of 1D credible intervals $< 10\%$
- Change in central value is not larger than 50% of estimated systematic uncertainty

Example is for the suppression in single π channel seen in the MINERvA results *PRD 100 072005*

Additional tests: cross-experiment models after ND constraint, alternative nuclear response model HF-CRPA, . . .

No alternate model tests failed the preset threshold bias criteria





Checks on alternative models

- Evaluate the robustness of the analysis against alternative models
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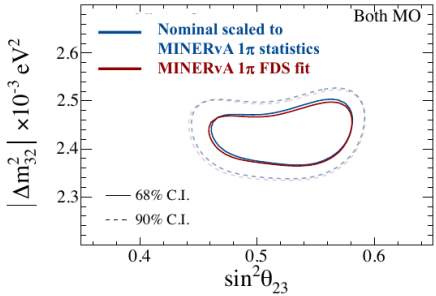
Pre-decided criteria to assess the impact

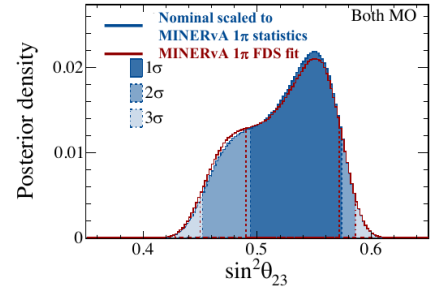
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Additional tests: cross-experiment models after ND constraint, alternative nuclear response model HF-CRPA, ...

No alternate model tests failed the preset threshold bias criteria





Alternative models studies

Studied 3 alternate models which gave largest biases for the T2K 2020 analysis:

"Non-QE" ND280 CC0π data are under-predicted by the T2K pre-fit prediction. This difference can be taken accounted for by the large freedom in the CCQE model. To check this large freedom does not cause bias, an alternate model where this underprediction is attribution to only non-QE processes is produced. See *Eur.Phys.J.C 83 782* for details.

"MINERvA-1π" Suppression of CC and NC resonant pion production at low-Q2 to describe for GENIE v2 implementation of Rein-Seghal model to describe the data, *PRD 100 072005*.

"π SI" GEANT4 model (10.1016/S0168-9002(03)01368-8) was replaced with NEUT's Salcedo–Oset (10.1016/0375-9474(88)90310-7).

Alternative models studies, HF-CRP

Hartree Fock (HF) – Continuum Random Phase Approximation (CRPA), 10.1103/PhysRevC.92.024606

- Applies modifications to the nuclear models (Spectral Function for T2K, Local Fermi Gas for NOvA)
- Recent T2K analyses have included an additional smearing on Δm^2_{32} due to bias seen when studying this alternate model
  - T2K and NOvA independently studied the impact of this on their 2020-era analyses
  - When taken together in the context of the joint analysis, the bias is not larger than the thresholds set for any of the other alternate models

