Results from Long-baseline Neutrino Oscillation Experiments

Workshop on Water Cherenkov Experiments for Precision Physics
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I Motivation for long-baseline (LBL) neutrino oscillation experiments

II Neutrino beams

III LBL concept

IV Recent LBL experiments

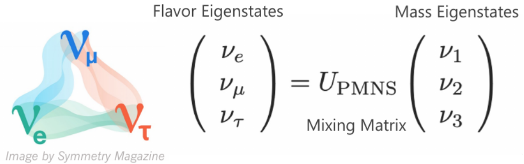
  a NOvA results (2024)

  b T2K results (2023)

  c T2K+NOvA results (2024 based on 2020)

Motivation for LBL Experiments

Neutrino (lepton) mixing in 3ν-paradigm



m_1

m_2

m_3

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

Neutrino (lepton) mixing in 3ν-paradigm

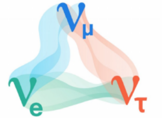


Image by Symmetry Magazine

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

m_1

m_2

m_3

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

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

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

Measured from the following neutrino sources

Atmospheric

Accelerator

Reactor

Solar

Image by Symmetry Magazine

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

$$\sin^2\left(\frac{\Delta m^2 \cdot L}{4\hbar c E}\right) \approx 1$$

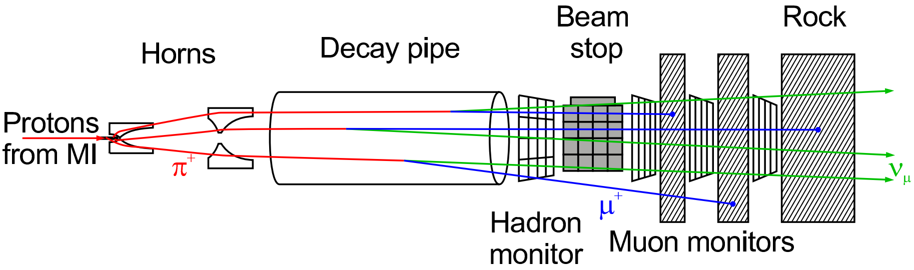
$$\Delta m^2_{32} \approx 10^{-3}\ \mathrm{eV}^2$$

$$\frac{L}{E} \approx 10^2 \text{ to } 10^3\ \mathrm{km/GeV}$$

Hundreds of kilometers away with $\sim$GeV energies

Neutrino Beams

Neutrino beam

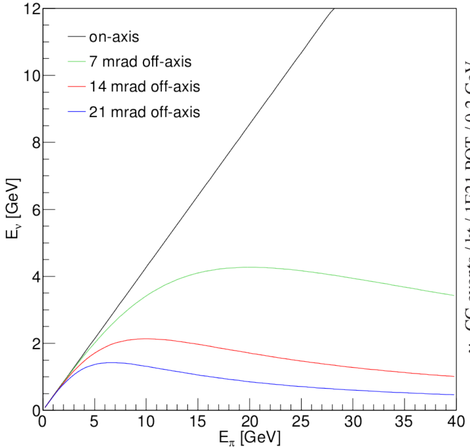


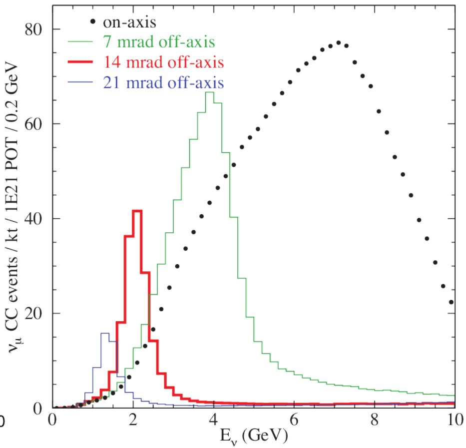
- Neutrinos come from decays of secondary π and K produced in collisions of high-energy protons with a target (graphite)

$$\pi^{\pm}, K^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}/\bar{\nu}_{\mu}$$

- Switching polarity of the focusing horns to select oppositely charged particles means effectively **switching between ν and $\bar{\nu}$ dominated beams**

Neutrino beam energy spectrum





- The ν source is not point-like, at least from the perspective of the near detectors.
- There is also extra contamination from K and secondary μ decays.

Why use neutrino beams?

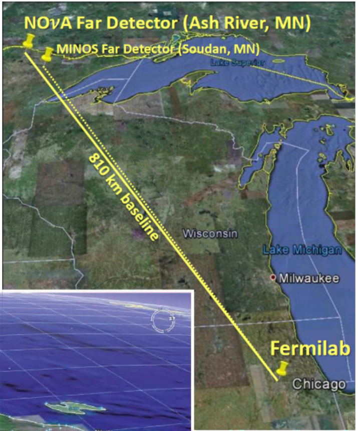
- Dominant direction, not isotropic like natural neutrino sources
- Precise timing helps with backgrounds
- Multi-level monitoring via beam monitors and near detectors
- Can be tuned to the desired neutrino energy
- Beam intensity is a matter of technological advancement, not natural occurrence

CONS: It is sort of expensive

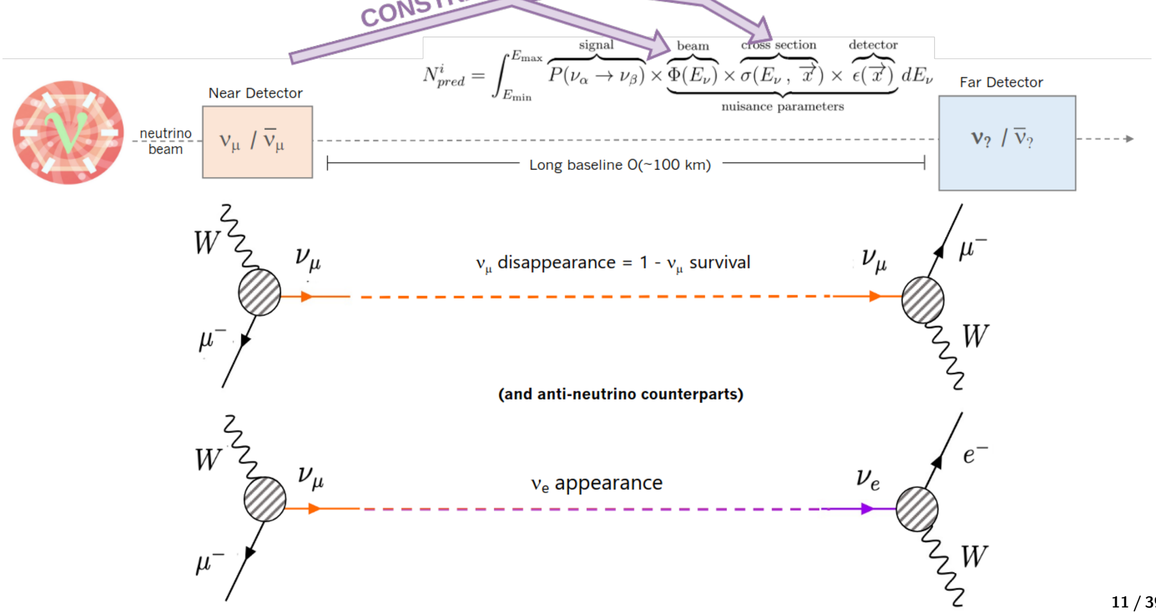
LBL Concept

Overview

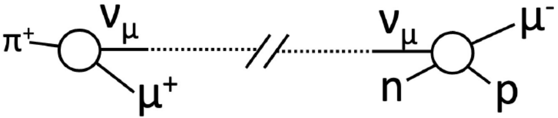
- Find a lab to provide neutrino beam
- Build a huge detector about hundreds of kilometers away, while a smaller one nearby
- Shoot neutrinos, see what happens



Measurement concept



Disappearance oscillation probabilities

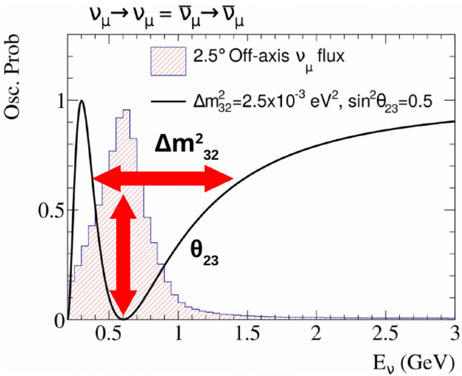


Leading order $\sin^2 2\theta_{23}$ and Δm^2_{32}

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

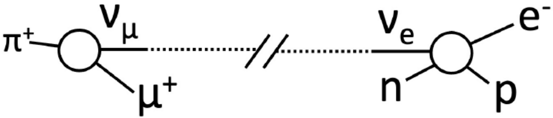
$\sin^2 2\theta_{23}$:
mixing angles rule the oscillation amplitude

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



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

Appearance oscillation probabilities



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

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

$+\ \delta_{CP}$ dependent terms violating CP

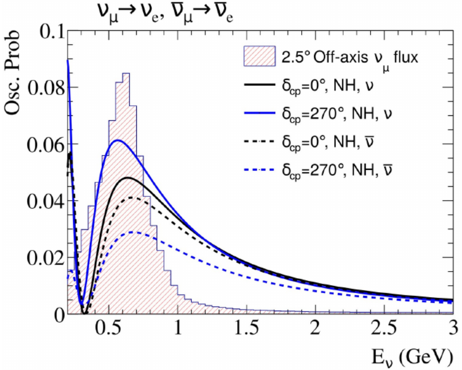
$+\ \delta_{CP}$ dependent terms conserving CP

$+$ 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)

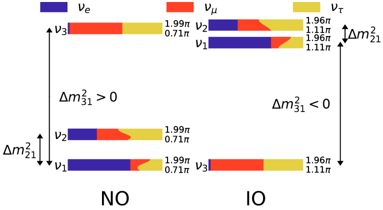


LBL experiments with $L/E \sim 10^{2-3}$ km/GeV are sensitive to

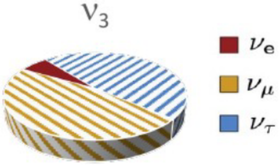
Δm^2_{32}, NO/IO

What is the ordering of the ν masses?

Normal (NO) or inverted (IO)?



θ_{23}



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

Is $\theta_{23} \lesseqgtr 45°$?

δ_{CP}, J_{CP}

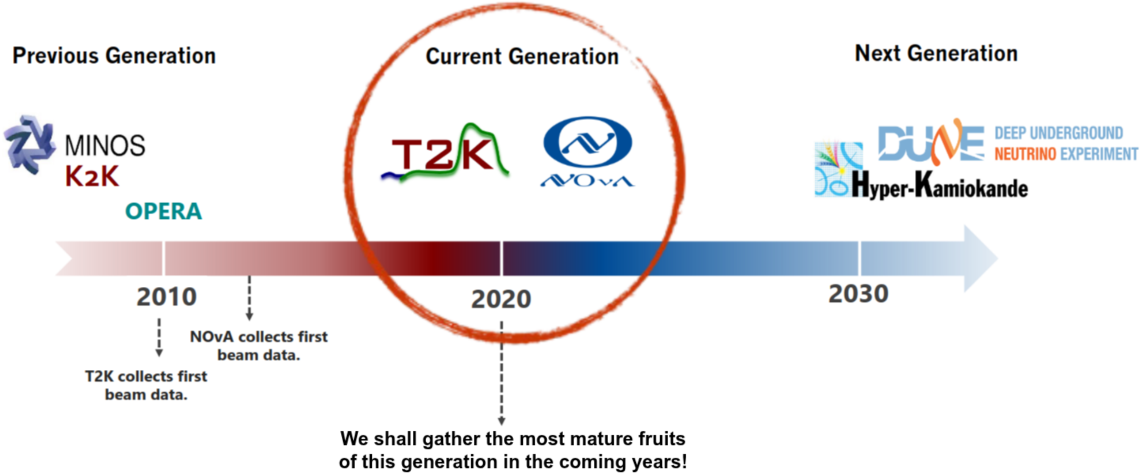
Is there significant CP violation in the lepton sector?

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

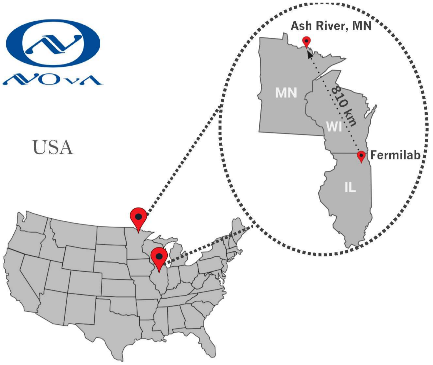
... also θ_{13}

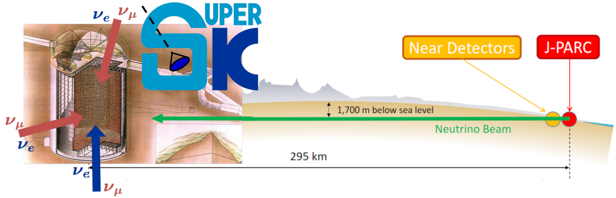
Recent LBL experiments

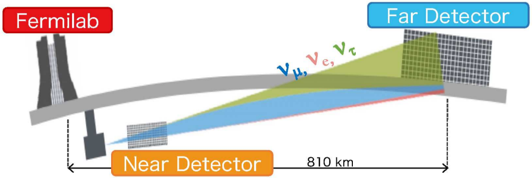
LBL generations

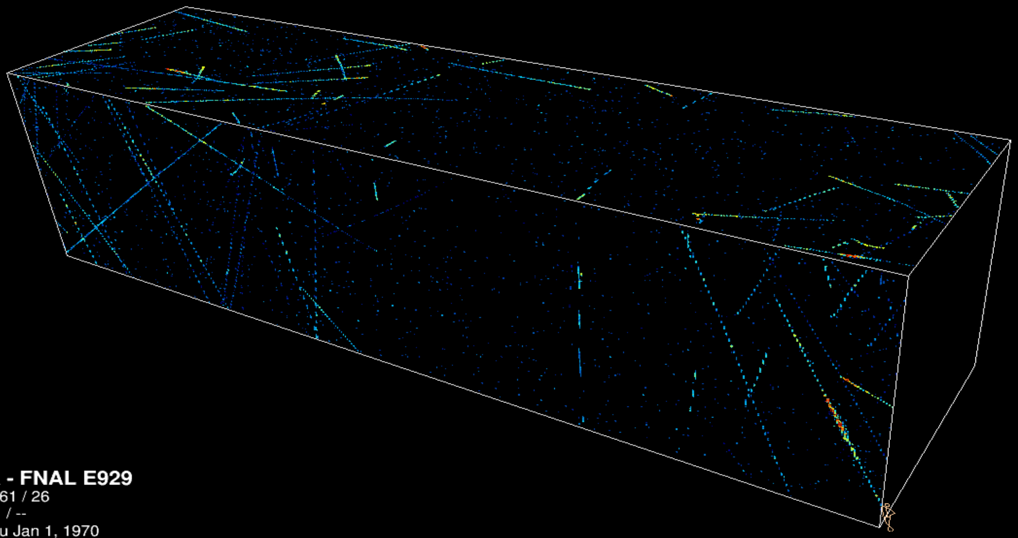


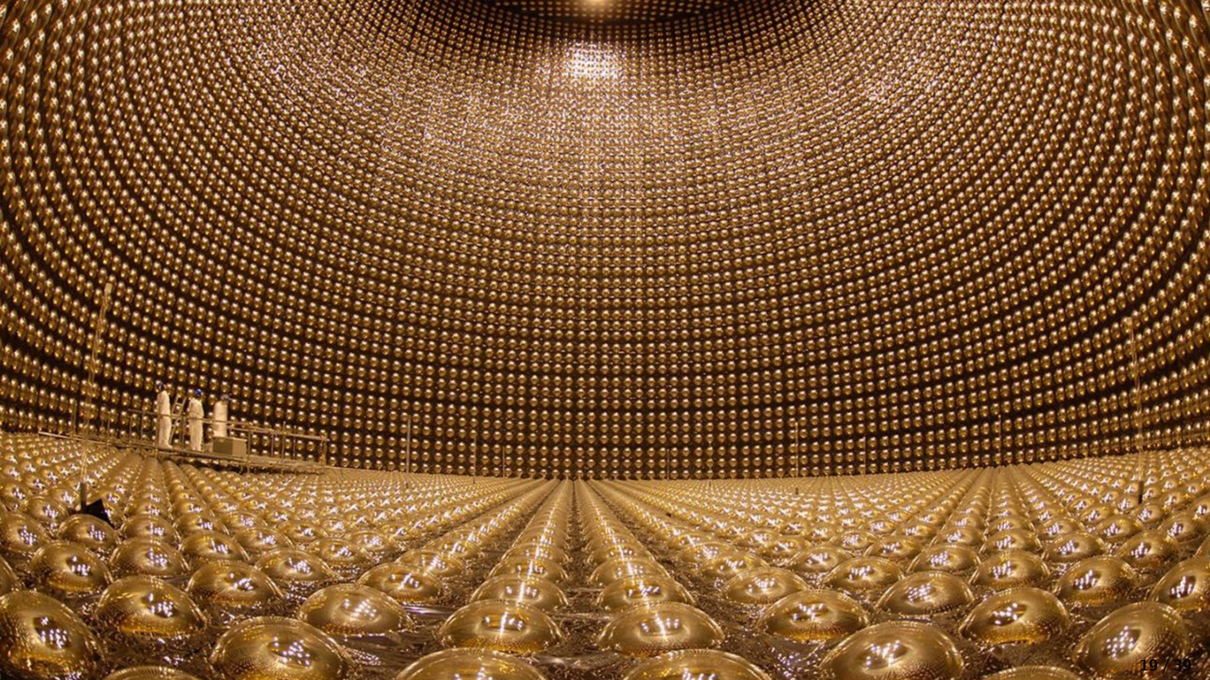

Japan
Tokai
Kamioka
295 km


USA
Ash River, MN
MN
WI
810 km
Fermilab
IL


Near Detectors
J-PARC
1,700 m below sea level
Neutrino Beam
295 km


Fermilab
Far Detector
Near Detector
810 km


NOvA - FNAL E929
Run: 161 / 26
Event: 1 / --
UTC Thu Jan 1, 1970
00:00:0.005000000



Neutrino energies

- Both experiments have their 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

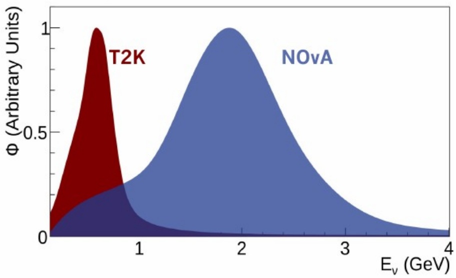
  T2K peak at $\sim$ 0.6 GeV

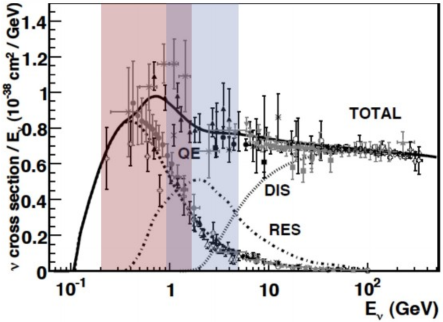
- Different ν energy corresponds to different phenomenological **types of interactions**

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

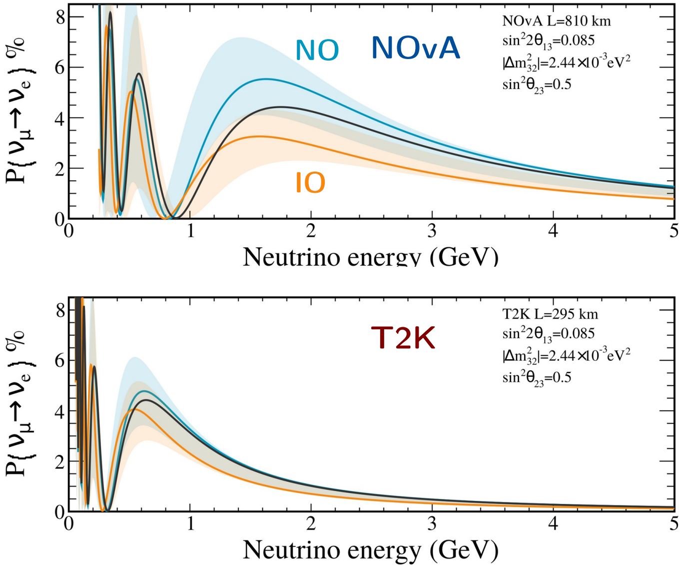
  T2K:
  mostly QE with 2p2h and RES, DIS in tail

Neutrino flux





Baselines



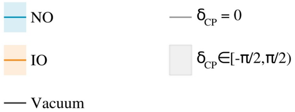
NOvA: 810 km

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 $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ differs for each experiment



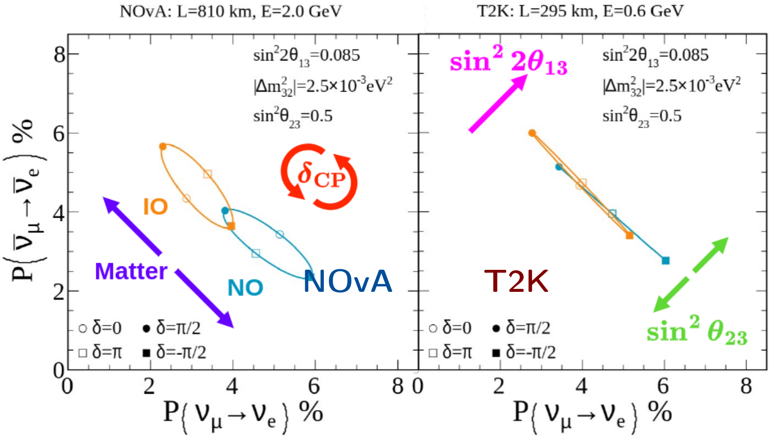
Lifting degeneracies

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

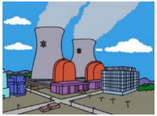
IO: $P(\nu_\mu \to \nu_e)\downarrow \quad P(\bar{\nu}_\mu \to \bar{\nu}_e)\uparrow$

Reactor constraints

Recall the oscillation probabilities:

Some LBL
θ_{23} vs. θ_{13} ambiguity

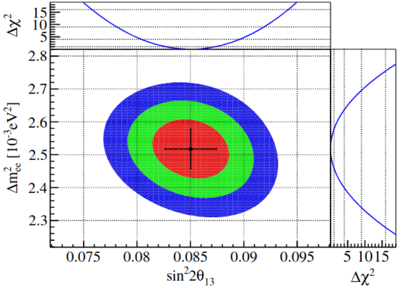
$$P(\nu_\mu \to \nu_e) \propto \sin^2\theta_{23}\sin^2 2\theta_{13}$$



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

Simple θ_{13} dependence

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

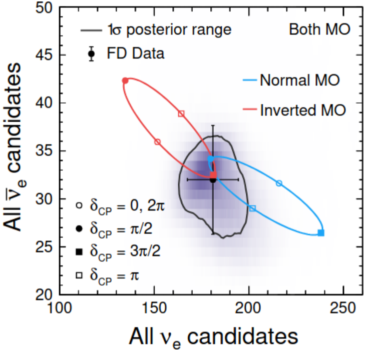


$$\Delta m^2_{ee} \simeq \cos^2\theta_{12}|\Delta m^2_{31}| + \sin^2\theta_{12}|\Delta m^2_{32}|$$

(2024)

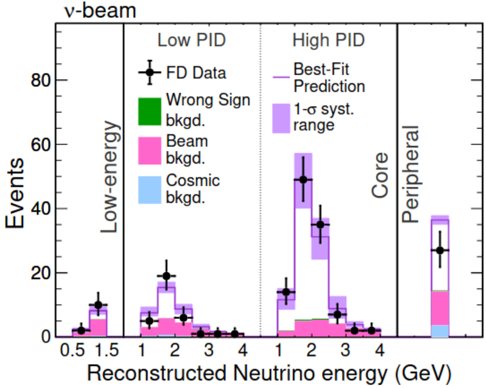
Notables for 2024 (since 2020)

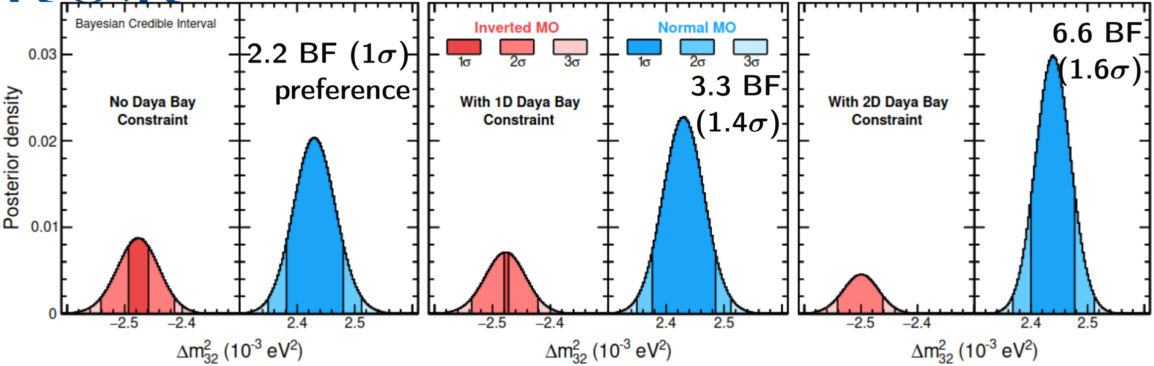
- Recently out arXiv:2509.04361
- 26.6e20 POT ν (+96%), 12.5e20 POT $\bar{\nu}$
- New low energy ν_e-like sample
- CNN-based cosmic rejection



Basic analysis strategy

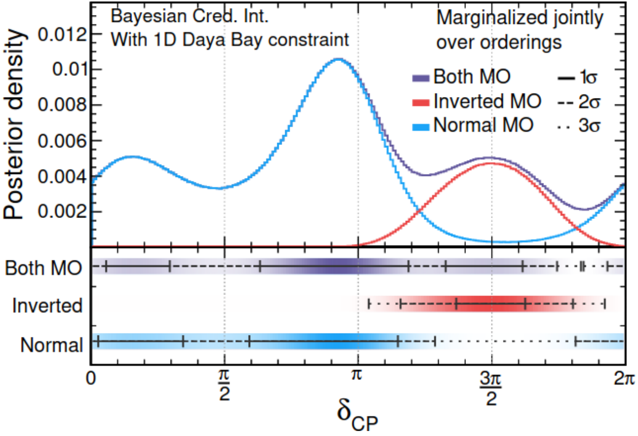
- Exploit similarity of the Far and Near detectors through F/N technique to cancel out interactions and flux systematic uncertainties
- Near detector data-driven prediction of signal and ν_e beam bkg.
- Energy reconstructed from μ path, otherwise calorimetrically, ν_μ samples of different E_{had} fractions
- CNN (Neural Network) for identification, ν_e samples of low and high PID
- Peripheral ν_e sample of not-fully-contained ν_e-like events



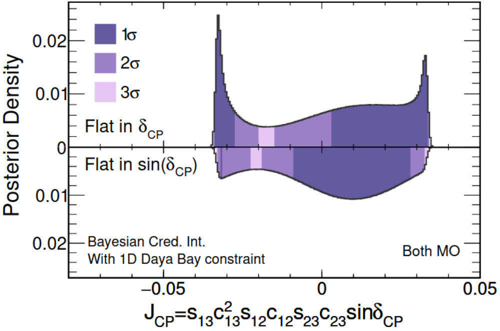


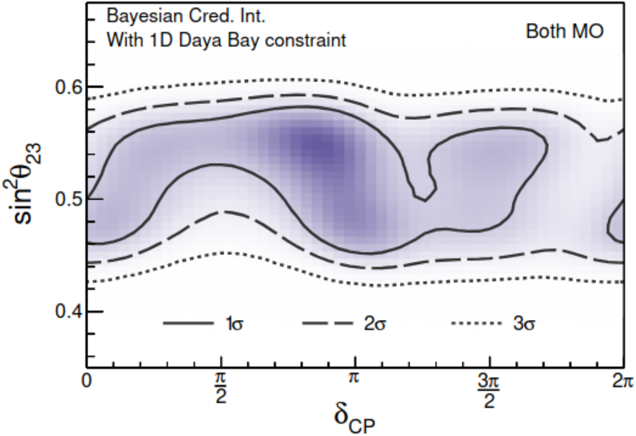
Notable preference for NO, more pronounced with Daya Bay (reactor) constraints on $\sin^2 2\theta_{13}$ (1D constraint) and $\sin^2 2\theta_{13} + \Delta m^2_{ee}$ (2D constraint) from PRL 130 161802

BF = Bayes Factor



- The sensitivity to J_{CP} ($\sin\delta_{\mathrm{CP}}$) is highly correlated with other oscillation parameters (namely θ_{23})
- Degenerate effects of matter and CPV $\sin\delta_{\mathrm{CP}}$
- Weak constraints on δ_{CP}





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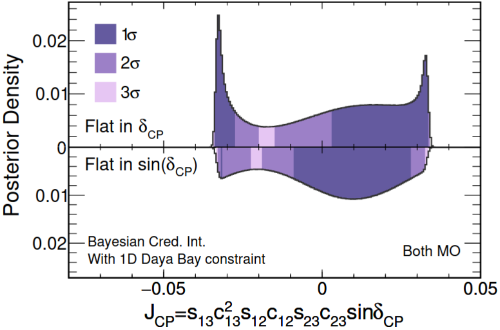
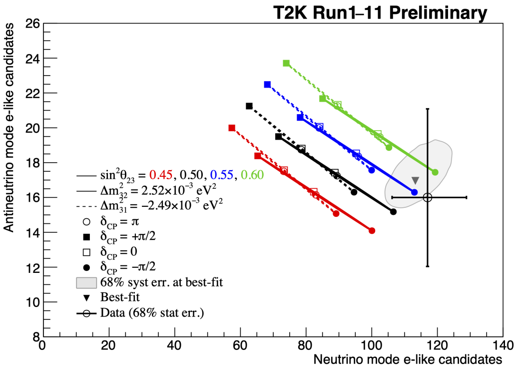


T2K (2023)

Basic analysis strategy

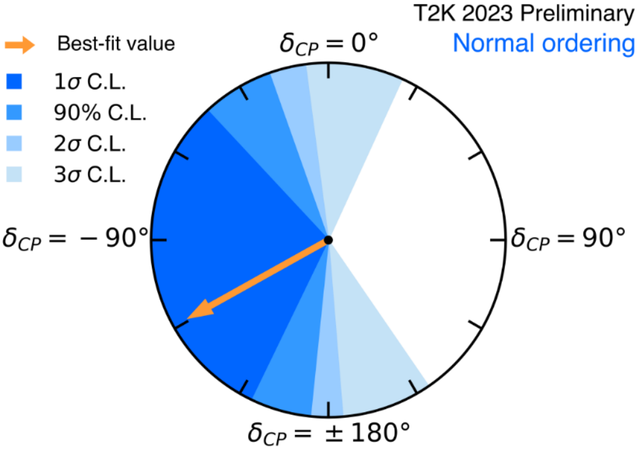
- CCQE and CC1π^+ ν-like SK samples, energy from kinematics
- Identification based on Cherenkov rings shape e-like vs. μ-like
- Numerous ND280 ν_μ and $\bar{\nu}_\mu$ CC0π and bkg. samples by FS particle multiplicity to constrain interaction models (NEUT generator)
- Consequential (ND280→SK) or simultaneous (ND280+SK) fitting



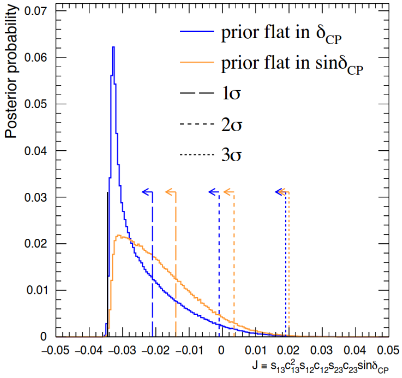
beam	e-like	μ-like
ν	1Ring-e+0Me	1Ring-μ+0-1Me
	1Ring-e+1Me	Multi-Ring-μ+1-2Me
$\bar{\nu}$	1Ring-e+0Me	1Ring-μ+0-1Me

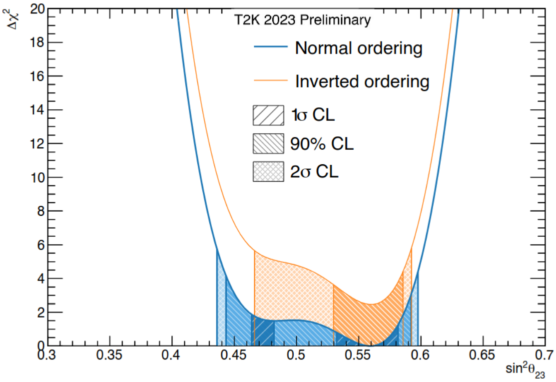
Notable updates for 2023

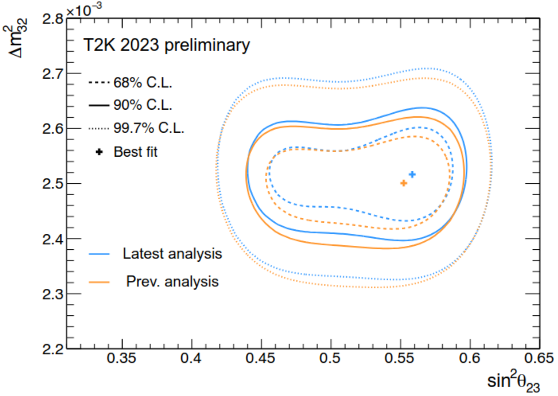
- Minor update on 2022 analysis version with extra SK μ-like sample recently on arXiv:2506.05889
- 21.4e20 POT ν (+9% on EPJC 83 782), 16.3e20 POT $\bar{\nu}$
- Improved selection of Michel es (needed after Gd loading, applied to all data)
- Improved SK detector systematics model further reducing the uncertainties



- The only (single-)experiment capable of constructing the 3σ CIs on $\delta_{\rm CP}$
- **CP-conserving values excluded at >90% CL** (not confirmed in 2 of 18 studies of fake data sets)
- Best-fit $\delta_{\rm CP}$ very close to CPV maximal $-\pi/2$







Small preference for upper octant of θ_{23}, minor improvements in precision of Δm^2_{32}, insignificant NO preference, overall consistent with previous analysi(e)s (for 10 years already)

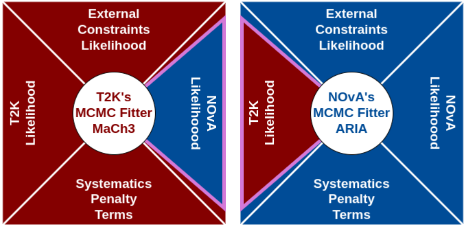
T2K + NOvA (2024 based on 2020)

- Full detailed likelihood functions for both experiments
- Full detailed energy reconstruction, detector effects, etc.
- Consistent statistical inference methods
- In-depth review of exp. analysis methods
- CON: Correlations in “non-transferable” interaction models

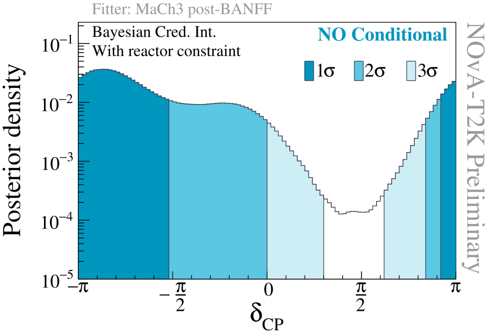
Notables from the joint analysis

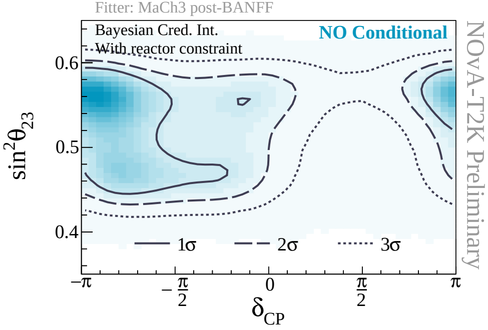
- Based on 2020 analyses *EPJC 83 782* (T2K) and *PRD 106 032004* (NOvA)
- Combined at the level of likelihoods
- Still dominated by statistics
- Minimal correct analysis as correlations do not matter
- **The data from both experiments is described well**

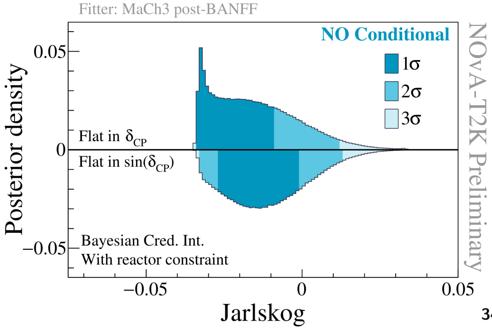
FLUX MODEL	$\Rightarrow$	No significant correlations between the experiments
DETECTOR MODEL	$\Rightarrow$	No significant correlations between the experiments
CROSS-SECTION MODEL	$\Rightarrow$	Investigate the impact of correlations in the joint analysis



- **Neither ordering** has a preference for δ_{CP} values around $+\pi/2$ (outside 3σ CI)
- **Normal ordering** allows for a **broad range** of δ_{CP}
- **If inverted ordering, CPC δ_{CP} values outside 3σ CIs**
- Robust under change of δ_{CP} prior







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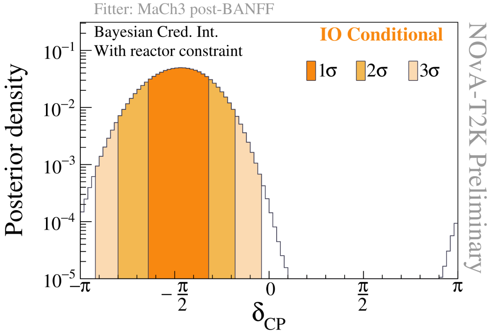
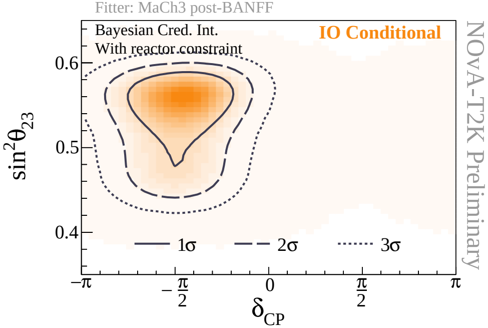
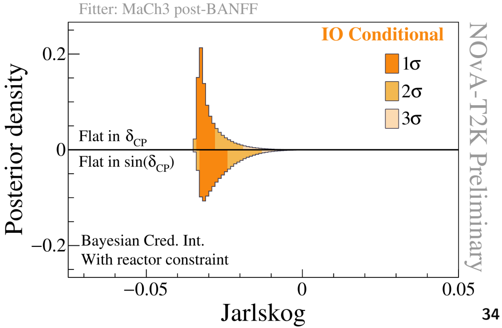






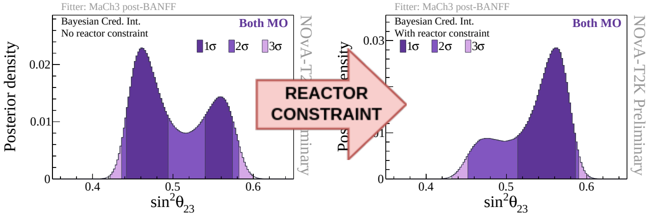
- **Modest preference for $\sin^2\theta_{23} > 0.5$, Bayes factor 3.6**
- **Very weak preference for IO, Bayes factor 1.3**
- **Posterior probability 57% for $\Delta m^2_{32} < 0$**
- **Posterior probability 43% for $\Delta m^2_{32} > 0$**

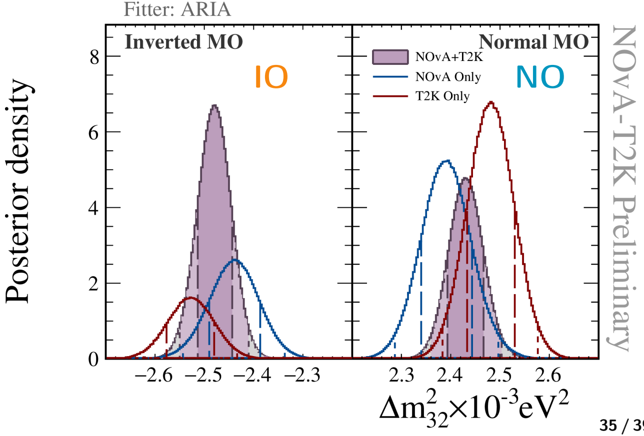
- Consistent with other measurements
- **Smallest uncertainty in $\Delta m^2_{32} < 2$ %** (newest NOvA 2024 results competitive)

Marginalizing over $\Delta m^2_{32} \lessgtr 0$ separately leads to **NO/IO "conditional" credible regions**

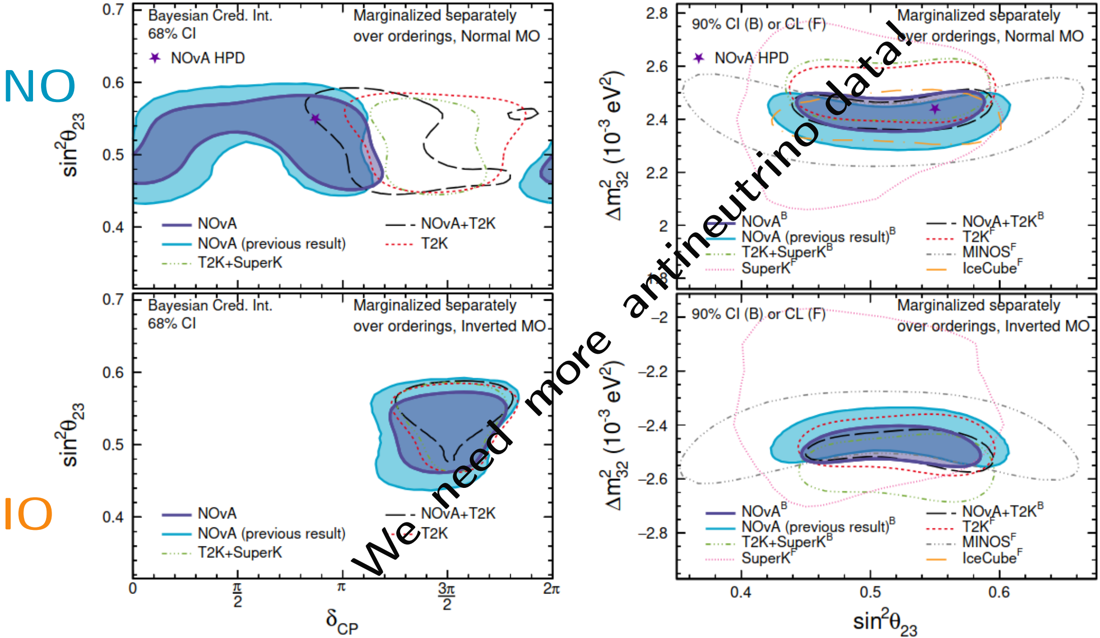
$$\Delta m^2_{32}\big|_{\mathrm{IO}} = -2.48^{+0.03}_{-0.04} \times 10^{-3}\ \mathrm{eV}^2$$

$$\Delta m^2_{32}\big|_{\mathrm{NO}} = 2.43^{+0.04}_{-0.03} \times 10^{-3}\ \mathrm{eV}^2$$





Pre-Conclusion


NO
IO
Bayesian Cred. Int.
68% CI
Marginalized separately over orderings, Normal MO
NOvA HPD
NOvA
NOvA (previous result)
T2K+SuperK
NOvA+T2K
T2K
Marginalized separately over orderings, Inverted MO
δ_{CP}
$\sin^2\theta_{23}$
90% CI (B) or CL (F)
Δm^2_{32} (10^{-3} eV^2)
NOvA[B]
NOvA (previous result)[B]
T2K+SuperK[B]
SuperK[F]
NOvA+T2K[B]
T2K[F]
MINOS[F]
IceCube[F]
We need more antineutrino data!

Conclusions

Conclusions

- LBL neutrino oscillation experiments are sensitive to CP violation, mass ordering and other important aspects of neutrino physics
  - CP-conserving values of δ_{CP} outside 90% CL (T2K)
  - Notable synergy with reactor exps. on MO (NOvA)
  - If IO, CP-conserving δ_{CP} values outside 3σ CL (T2K+NOvA)
- Current LBL measurements of NOvA, T2K, and NOvA+T2K provide leading constraints on several neutrino oscillation parameters
- T2K and NOvA precision era has just begun
- Future next-generation "discovery machines" of Hyper-Kamiokande and DUNE will rely on T2K and NOvA experience in LBL programs to provide high-precision neutrino measurements and answer critical questions of neutrino physics

BACKUP

The "*my-precious*" channel $\nu_\mu \to \nu_e$

$$
\begin{aligned}
P(\nu_\mu \to \nu_e; L, E, A) \approx\ & 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\Delta_{31} \\
& + 8c_{13}^2 s_{12} s_{13} s_{23} (c_{12}c_{23}\cos\delta_{\rm CP} - s_{12}s_{13}s_{23}) \cos\Delta_{32} \sin\Delta_{31} \sin\Delta_{21} \\
& - 8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin\delta_{\rm CP} \sin\Delta_{32} \sin\Delta_{31} \sin\Delta_{21} \\
& + 4s_{12}^2 c_{13}^2 (c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta_{\rm CP}) \sin^2\Delta_{21} \\
& - 8c_{13}^2 s_{13}^2 s_{23}^2 \frac{AL}{4E_\nu}(1 - 2s_{13}^2)\cos\Delta_{32}\sin\Delta_{31} + 8c_{13}^2 s_{13}^2 s_{23}^2 \frac{A}{\Delta m_{31}^2}(1-2s_{13}^2)\sin^2\Delta_{31}
\end{aligned}
$$

dominant term

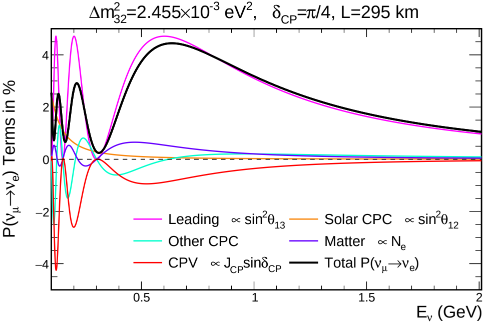
other CPC

CPV

solar CPC

matter

$s_{ij} \equiv \sin\theta_{ij}, c_{ij} \equiv \cos\theta_{ij} \qquad \Delta_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E_\nu} \qquad A(E_\nu) \equiv 2\sqrt{2} G_{\rm F} N_e E_\nu, \qquad \bar{\nu}: A \to -A, \delta_{\rm CP} \to -\delta_{\rm CP}$

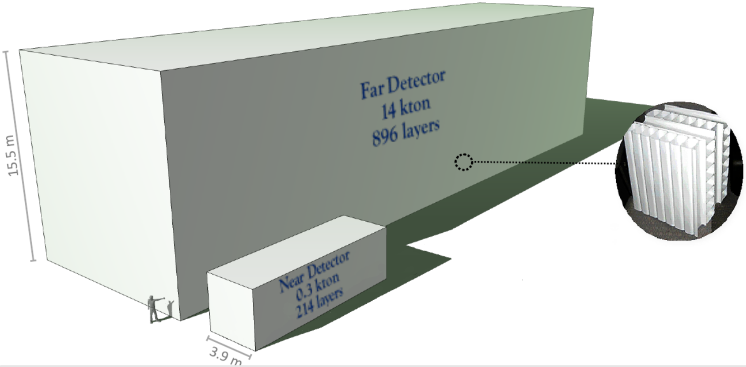


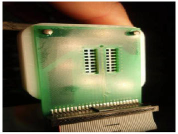
Long-baseline acc.

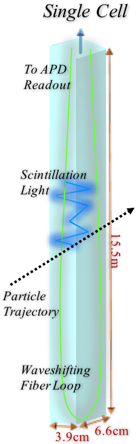
Atmospheric

Crucial $\sin^2\theta_{13}$ from reactor $\bar{\nu}_e \to \bar{\nu}_e$ experiments

NOvA detectors

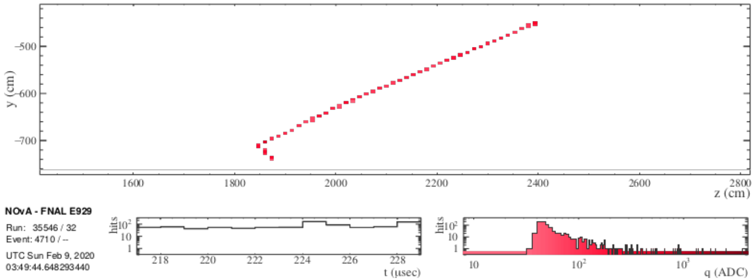


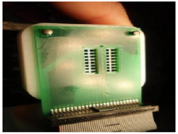


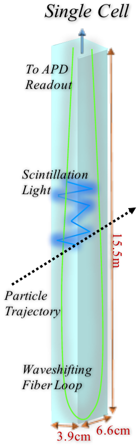


- Two functionally similar detectors 810 km apart – **Near (ND)** and **Far (FD)**
- FD on the surface, ND about 100 m underground
- Consist of extruded plastic cells with alternating vertical and horizontal orientation for 3D reconstruction of neutrino interactions
- Filled with liquid scintillator, tracking calorimeter with 65% active mass (FD 14 kton, ND 0.3 kton)
- Energy estimation from μ range, EM and hadronic shower calorimetry

NOvA detectors







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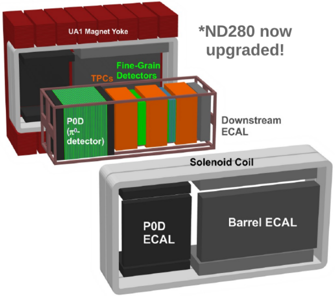
T2K detectors

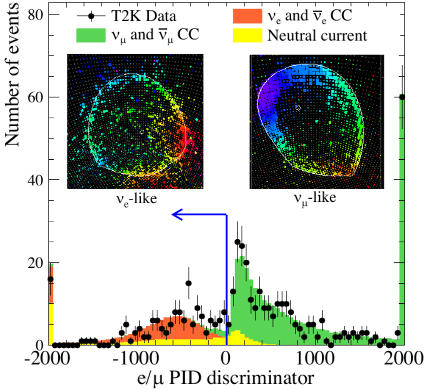
ND280

- TPC tracker with excellent PID
- Plastic scintillator target (C) + water layers (O)
- **MAGNETIZED** to distinguish ν_μ and $\bar{\nu}_\mu$
- Selected neutrino events with reconstructed μ track and number of π: CC1μ0π, CC1μ1π, CC1π



*ND280 now upgraded!

Adapted from arXiv:1910.03887v2

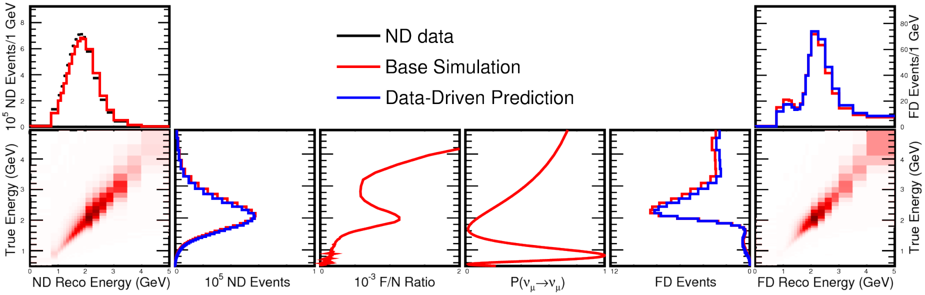


Super-Kamiokande

- 50kt water Cherenkov detector
- Excellent μ/e-like Cherenkov rings separation (ν_μ vs ν_e CC interactions)
- Reconstruction from lepton kinematics

NOvA analysis strategy

- ND sees the neutrino spectrum as a combination of **neutrino *flux*** from NuMI, **CC *cross sections***, ***detector acceptance*** and ***selection efficiency***
- 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)



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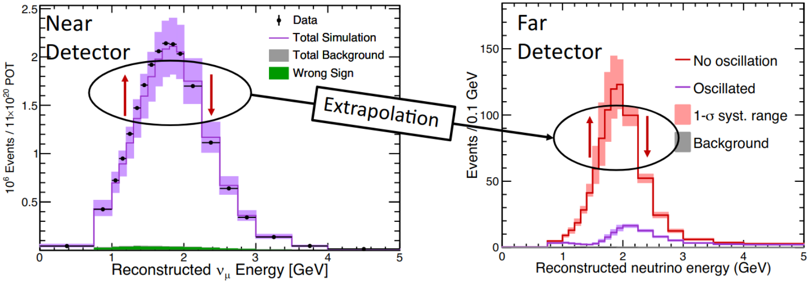
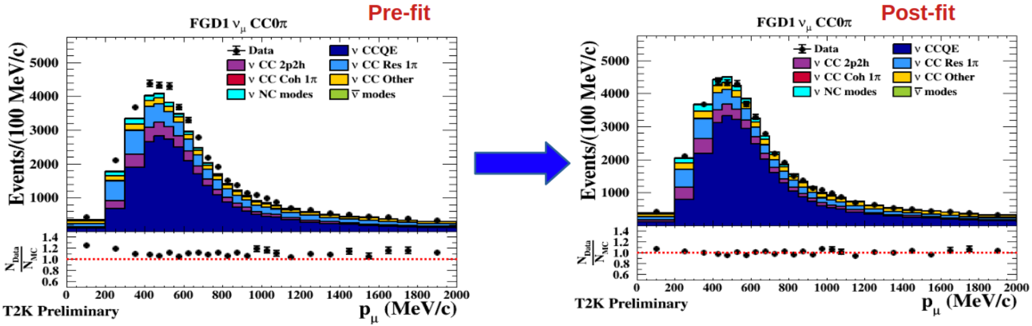


T2K analysis strategy

- **Fit to ND280 data move the model parameters** from their -pre-fit values and also **constrain them**
- This data fit might be **sequential** (ND fit $\rightarrow$ constrained model $\rightarrow$ FD fit) or **simultaneous** (ND+FD data simultaneous fit)



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)

T2K+NOvA models and systematics

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

T2K+NOvA checks on impact of correlations

Strategy

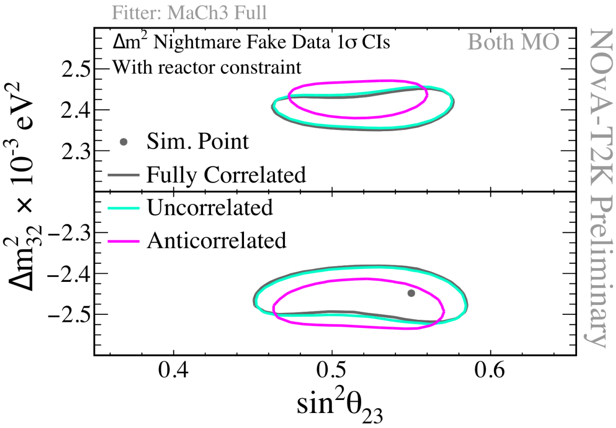
- Study parameters and their inter-experimental correlations with a significant impact on the parameters of interest δ_{CP}, $\sin^2\theta_{23}$, Δm^2_{32}

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

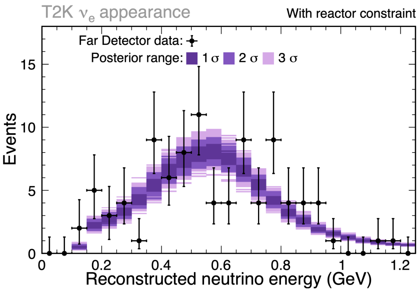


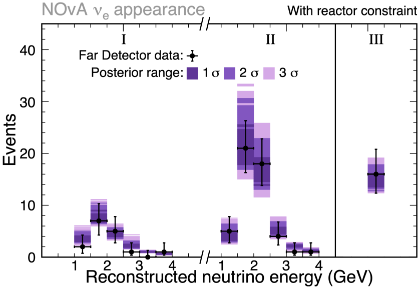
Goodness of fit, compatibility of datasets

- Joint analysis uses data collected by each experiment until 2020

  NOvA: 1.36 (ν) + 1.25 ($\bar{\nu}$) $\times 10^{21}$ POT
  T2K: 1.97 (ν) + 1.63 ($\bar{\nu}$) $\times 10^{21}$ POT
- Using posterior predictive p-values (PPP) to assess the goodness of fit (good PPP is around 0.5)
- **The data from both experiments is described well by the joint fit**

Channel	NOvA	T2K	Total
ν_e	82	$94_{(\nu_e)}$ $14_{(\nu_e 1\pi)}$	**190**
$\bar{\nu}_e$	33	16	**49**
ν_μ	211	318	**529**
$\bar{\nu}_\mu$	105	137	**242**





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Channel	P-value NOvA	P-value T2K	P-value Combined
ν_e	0.90	$0.19_{(\nu_e)}$ $0.79_{(\nu_e 1\pi)}$	**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**
All	0.64	0.72	**0.75**