Overview of Long-baseline Neutrino Oscillations Experiments

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# **INTERSECTIONS – CIPANP 2025**



# Neutrino Oscillation

$$\begin{pmatrix}
\nu_{e} \\
\nu_{\mu} \\
\nu_{\tau}
\end{pmatrix} = \begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\
U_{\tau 1} & U_{\tau 2} & U_{\tau 3}
\end{pmatrix}
\begin{pmatrix}
\nu_{1} \\
\nu_{2} \\
\nu_{3}
\end{pmatrix}$$

Flavor Eigenstates (interactions)

Leptonic Mixing Matrix

Mass Eigenstates (propagation)

### Quantum superposition of neutrino mass eigenstates leads to neutrino oscillation.

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Flavor Eigenstates (interactions)

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Mass Eigenstates (propagation)

Quantum superposition of neutrino mass eigenstates leads to neutrino oscillation.

$$P(\nu_{\alpha} \to \nu_{\beta}) = \left| \underbrace{\sum_{i \text{ Amplitude}}^{\text{Frequency}} e^{-i \underbrace{\frac{m_{i}^{2} L}{2E}}_{i} U_{\beta i}} \right|^{2}$$

L (baseline), E (Energy)

Experiments are designed with a typical L/E and neutrino source, to optimize sensitivity to particular  $\Delta m_{ij}^2$  scales

### Neutrino Oscillation

• Two known mass-splitting scales ( $|\Delta m_{31}^2| \sim 2 \times 10^{-3} \text{ eV}^2$ ,  $\Delta m_{21}^2 \sim 7 \times 10^{-5} \text{ eV}^2$ ) determine which oscillations the experiments can probe.

| Source          | L(m)                              | E (MeV)                          | ∆m²  (eV²)                          |
|-----------------|-----------------------------------|----------------------------------|-------------------------------------|
| Solar           | 10 <sup>10</sup>                  | 1                                | 10 <sup>-10</sup>                   |
| Atmospheric     | 10 <sup>4</sup> – 10 <sup>7</sup> | 10 <sup>2</sup> -10 <sup>5</sup> | 10 <sup>-1</sup> – 10 <sup>-4</sup> |
| Reactor SBL     | 10 <sup>2</sup> – 10 <sup>3</sup> | 1                                | 10 <sup>-2</sup> -10 <sup>-3</sup>  |
| Reactor LBL     | 10 <sup>4</sup> – 10 <sup>5</sup> | 1                                | 10 <sup>-4</sup> –10 <sup>-5</sup>  |
| Accelerator SBL | 10 <sup>2</sup>                   | 10 <sup>3</sup> –10 <sup>4</sup> | > 0.1                               |
| Accelerator LBL | 10 <sup>5</sup> -10 <sup>6</sup>  | 10 <sup>3</sup> –10 <sup>4</sup> | 10 <sup>-2</sup> –10 <sup>-3</sup>  |

Adapted from annurev-nucl-102020-101615

SBL : Short Baseline ( < 1km)

LBL : Long Baseline (10 - 1000 km)

**This Session** 

## **PMNS** Parameterization

 Widely used representation of the Leptonic Mixing Matrix, assumes unitarity and is adopted across all neutrino oscillation experiments.

$$U_{\rm PMNS} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\rm CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\rm CP}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad c_{ij} = \cos\theta_{ij}$$
Measured primarily from the following neutrino sources
$$Atmospheric \qquad Accelerator \\ \theta_{23} \sim 45^{\circ} \\ \Delta m_{32}^{2} \sim \pm 2.5 \times 10^{-3}eV^{2} \end{bmatrix} \quad Accelerator / Reactor \\ Accelerator & \theta_{23} \sim 45^{\circ} \\ \Delta m_{12}^{2} \sim 7.5 \times 10^{-5}eV^{2} \end{bmatrix}$$

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### A 25 years long odyssey 0.8 Snowmass NF01 report Denton et al arXiv:2212.00809

See <u>Peter Denton's</u> <u>talk on Thursday!</u>



"Ultimate Goal: Not Measure Parameters but Test the Formalism" - André de Gouvêa



### Is the $\theta_{23}$ mixing maximal?

Current Measured Value :  $heta_{23} \sim 45^\circ$ Precision :  $\sin^2 \theta_{23} \sim 5\%$ 

 $\begin{array}{c}
\nu_{3} \\
\bullet \nu_{e} \\
\bullet \nu_{\mu} \\
\bullet \nu_{\tau}
\end{array}$ 



Values from PDG 2020

PMNS Matrix

Values from NuFIT 5.0, arXiV:2007.14792



If  $\theta_{23} = 45^{\circ} \rightarrow |U_{\mu 3}| = |U_{\tau 3}|$ 

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Is CP violated in leptons?



credit. <u>Ar 5/ carin cann</u>

Do neutrinos and anti-neutrinos oscillate differently violating the CP symmetry? Is sin  $\delta_{CP} = 0$ ?



Values from PDG 2020



Values from NuFIT 5.0, arXiV:2007.14792



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Implications for  $\mathbf{0}_{\mathbf{V}}\beta\beta$ , cosmology

### Which neutrino is the lightest?





### Long-baseline experiments



### $v_{\mu}$ disappearance channel



### $\nu_e$ appearance channel



Complicated dependence on multiple parameters of interest.

- Opposite impact of matter effect and  $\delta_{CP}$  for  $\nu_e$  vs  $\overline{\nu}_e$  appearance probability.

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### 3 Generations of long-baseline oscillation experiments



### 3 Generations of long-baseline oscillation experiments

|         | Previous Gene<br>MINOS<br>K2K<br>OPE                   | ration<br>T                          | Current Gene | eration Next   | Generation<br>DEEP UNDERGROUND<br>NEUTRINO EXPERIMENT<br>Camiokande            |
|---------|--|--------------------------------------|--------------|--|--|
|         | 20   | 010                                  | 2020         | ) <b>2030</b>  | )<br>lapted from annurey-nucl-102020-101615                                    |
|         | Location   | Beam                                 | Baseline     | Near Detector  | Far Detector   |
| T2K     | Japan<br>(Tokai to Kamioka)                            | J-PARC 500 kW<br>(Upgrade to 1.3 MW) | 295 km       | Suite of detectors, on-and off-<br>axis  | <b>Water Cherenkov</b> , 22.5 kt fiducial, off-axis                            |
| NOvA    | United States<br>(Fermilab to Ash<br>River, Minnesota) | NuMI 850 kW                          | 810 km       | Segmented liquid scint., off-<br>axis  | <b>Segmented liquid scint</b> . 14kt active, off-axis                          |
| lyper-K | Japan<br>(Tokai to Kamioka)                            | J-PARC 1.3 MW                        | 295 km       | Suite of detectors, on-and off-<br>axis, intermediate movable<br>Water Cherenkov detector  | <b>Water Cherenkov</b> , 187 kt fiducial, off-axis                             |
| DUNE    | United States<br>(Fermilab to Lead,<br>South Dakota)   | LBNF<br>2 – 2.4 MW tunable           | 1285 km      | Liquid argon time projection<br>chamber + suite of detectors,<br>on-axis, movable off-axis | <b>Liquid argon time projection</b><br><b>chamber</b> , 40kt fiducial, on-axis |

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### Recent Results from NOvA and T2K



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T2K



# Why NOvA-T2K joint fit?

- Complementarity:
  - Power to break degeneracies.
- Full implementations:
  - Energy reconstruction and detector response
  - Detailed likelihood
  - Consistent statistical inferences across the full dimensionality
- In-depth reviews:
  - Different analysis approaches driven by contrasting detector designs
  - Models, systematic uncertainties and possible correlations

#### **Results from NOvA and T2K from 2020 datasets**



### Feb 18, 2025

# Complementarity

- Different neutrino fluxes:
  - detectors see qualitative different v-interactions.
- Different baselines:
  - NOvA sees larger matter effect due to higher neutrino energy
    - → higher sensitivity to mass ordering.

%

→Ve

P{v<sub>µ</sub>

 Therefore, associated asymmetry is higher for the longer baseline.



### Complementarity

- T2K measurements isolate impact of CP violation while NOvA has significant sensitivity to mass ordering.
- Joint analysis probes both spaces lifting degeneracies of individual experiments.



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### Detectors

- Near Detector (ND) provides valuable in-situ cancelation and constraints on:
  - neutrino flux
  - cross-section, and
  - detector uncertainties
- T2K employs different detector technologies for Near and Far detectors (FD).
- NOvA's ND and FD are functionally identical segmented liquid scintillator detectors.



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### **Systematics**

### NOvA and T2K use very different strategies to incorporate ND Data but with very similar impact on oscillation measurements.



**T2K**: Uncertainty on FD 1e-like ring  $v_e$  event rate goes from ~13% to ~5% after applying constraints from ND data fit

**NOvA**: Systematic uncertainties in the FD  $v_e$  candidate from ~15% to ~4%

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### Systematics & their correlations in the joint fit

- Flux and Detector Systematics: No significant correlations across experiments
- Cross-section Systematics: No direct mapping between the cross-section systematics parameters
  - Exception: Uncertainties in  $v_e / v_\mu$  and  $\overline{v}_e / \overline{v}_\mu$  cross-section have identical origin<sup>\*</sup> and similar treatment
    - Fully correlated in the joint fit.

### Systematics & their correlations in the joint fit

- Cross-section Systematics: No direct mapping between the cross-section systematics parameters
- Strategy: Explore a range of artificially crafted scenarios to bracket the impact
- Example: Fabricated systematics comparable to statistical uncertainty, with correlated bias in both experiments.
  - Uncorrelated and correctly correlated cases show negligible differences, while incorrectly correlating systematics shows a bias.
- Based on such studies → No additional correlations need be applied given current experimental exposures



Merits continued investigations for higher data exposures and progress towards a unified framework for cross-section modeling in future experiments!

### Robustness to alternate models

- Evaluate the robustness by fitting simulated fake data generated with various alternate models
  - Example: Suppression in single pion channel based on the tune to the MINERvA data\*
- No alternate model tests failed the preset threshold bias criteria.





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### Dataset and its compatibility

- 2020-era dataset from both experiments used for the joint-fit.
- Posterior predictive p-values (PPP)\* of 0.75 obtained for the joint fit
- The data from both experiments is described well by the joint fit.

| Channel                          | NOvA | Т2К  |
|----------------------------------|------|--|
| $\nu_e$                          | 82   | <b>94</b> (ν <sub>e</sub> )<br><b>14</b> (ν <sub>e</sub> 1π) |
| $\overline{ u}_e$                | 33   | 16   |
| $oldsymbol{ u}_{\mu}$            | 211  | 318  |
| $\overline{oldsymbol{ u}}_{\mu}$ | 105  | 137  |

\*Gelman, Meng and Stern, Stat. Sinica 6, 733 (1996)



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## $\theta_{23}$ and $\theta_{13}$

• Degeneracy in  $\sin^2 \theta_{23}$  and  $\sin^2 2\theta_{13}$  parameters for long-baseline measurements.



With reactor  $\theta_{13}$  constraint

# Mass Ordering

- NOvA-T2K joint fit has a modest preference for the Inverted Ordering, whereas individual experiments prefer Normal Ordering.
- The joint-fit enhances the precision of  $\Delta m_{32}^2$  over individual experiments.



| 2.07 4.24   | 1 36                                     |
|---|--|
| Bayes factor Advised ~33% posterior ~81% : ~19% posterior | Inverted/Normal<br>~58% : ~42% posterior |

# Mass Ordering

- Enhanced precision in  $\Delta m_{32}^2$  presents another lever on measuring neutrino mass-ordering.
  - Under wrong  $\nu$ MO, reactor and long-baseline  $\Delta m_{32}^2$  measurements will disagree\*
- Including Daya Bay's  $\Delta m_{32}^2$ , reverses the **preference back to the Normal Ordering**.
- No significant preference for either mass ordering in the joint analysis.

![](_page_27_Figure_5.jpeg)

![](_page_27_Figure_6.jpeg)

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# **CP** Violation

![](_page_28_Figure_2.jpeg)

![](_page_29_Picture_0.jpeg)

\*Note: Jarlskog plot assumes inverted ordering; left plot shows posterior marginalized over both MO simultaneously. Conclusions hold for both marginalizations.

![](_page_29_Figure_2.jpeg)

• Regardless of the mass orderings,  $\delta_{CP} = \pi/2$  lies outside 3-sigma credible interval.

- If the ordering is inverted, CP conserving values of  $\delta_{CP}$  (0,  $\pi$ ) and Jarlskog invariant J<sub>CP</sub>
  - = 0 lie outside the 3-sigma credible interval.
    - For priors that are both uniform in  $\delta_{CP}$  and uniform in sin  $\delta_{CP}$

# **Future Directions**

![](_page_31_Picture_0.jpeg)

![](_page_31_Picture_1.jpeg)

These experiments are designed to study **accelerator**, **astrophysical**, **solar and atmospheric neutrinos** and **probe SM**, **BSM**, **exotic and dark matter** physics.

![](_page_31_Figure_3.jpeg)

![](_page_31_Figure_4.jpeg)

![](_page_31_Figure_5.jpeg)

![](_page_32_Picture_0.jpeg)

![](_page_33_Picture_0.jpeg)

![](_page_33_Picture_1.jpeg)

![](_page_33_Picture_2.jpeg)

![](_page_33_Picture_3.jpeg)

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![](_page_34_Figure_0.jpeg)

- DUNE has an unrivaled sensitivity to resolve MO for any values of other oscillation parameters.
- HK has excellent sensitivity to CP violation but has a degeneracy between CP violation and MO due to its short baseline.
  - Recover CPV sensitivity with Atmospheric v's or if MO already known through DUNE/JUNO.

![](_page_35_Picture_0.jpeg)

 Both Hyper-K and DUNE offer unprecedented precision on  $\Delta m_{32}^2$ ,  $\delta_{\rm CP}$ ,  $\theta_{23}$  with multiple years of running.

![](_page_35_Figure_2.jpeg)

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See <u>Roberto Mandujano's</u>

Zoya Vallari, OSU

- JUNO is currently filling and scheduled to start taking data ~this year.
- 3σ sensitivity to Mass Ordering after ~6 years of data-taking.
- Most precise measurements of half of the neutrino oscillation parameters in 100 days.
- Ultimately, an order of magnitude improvement over current knowledge of  $\Delta m_{32}^2$ ,  $\Delta m_{21}^2$ , and  $\sin^2 2\theta_{12}$ .

![](_page_36_Figure_7.jpeg)

# Sidebar: JUNO

# Summary:

- NOvA and T2K continue to produce exciting results, together and independently.
  - Current generation experiments remain statistically limited.
- Recent slate of results deliver excellent precision on  $\Delta m_{32}^2$ .
- Small preference for upper octant when adding the  $\theta_{13}$  constraint from reactor, but all results are **consistent with the maximal mixing**.
- NOvA + T2K joint fit demonstrates compatibility of datasets.
  - Mass ordering preference remains insignificant: mild preference for inverted ordering which switches to normal ordering when including  $\Delta m_{32}^2$  from Daya Bay.
  - This fit excludes, CP conservation at  $3\sigma$ , if the mass ordering is inverted.
- Future neutrino oscillation experiments will unambiguously determine the mass ordering and probe for leptonic CV violation with highly enhanced sensitivities.

### Outlook:

- Neutrino physics is entering the precision era, putting the three-flavor neutrino paradigm to the test.
- With the next-generation experiments, we can robustly measure the neutrino sector -- or reveal anomalies!

![](_page_38_Figure_3.jpeg)

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### Thank you!

![](_page_39_Picture_1.jpeg)

Image credit: Fermilab