Complementarity among Next-generation Long-baseline Experiments

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The appearance probability \( (\nu_\mu \rightarrow \nu_e) \) in matter, up to second order in the small parameters \( \alpha \equiv \Delta m^2_{21}/\Delta m^2_{31} \) and \( \sin 2\theta_{13} \),

\[
P_{\mu e} \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2[(1 - \hat{A})\Delta]}{(1 - \hat{A})^2} \theta_{13} \text{ driven}
\]

- \( \alpha \sin 2\theta_{13} \xi \sin \delta_{CP} \sin(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1 - \hat{A})\Delta]}{(1 - \hat{A})} \text{ CP-odd} \)

+ \( \alpha \sin 2\theta_{13} \xi \cos \delta_{CP} \cos(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1 - \hat{A})\Delta]}{(1 - \hat{A})} \text{ CP-even} \)

+ \( \alpha^2 \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2} \text{ Solar Term} \)

where \( \Delta \equiv \Delta m^2_{31} L/(4E) \), \( \xi \equiv \cos \theta_{13} \sin 2\theta_{21} \sin 2\theta_{23} \), and \( \hat{A} \equiv \pm(2\sqrt{2}G_F n_e E')/\Delta m^2_{31} \).

changes sign with \( \text{sgn}(\Delta m^2_{31}) \) changes sign with polarity
key to resolve hierarchy! causes fake CP asymmetry!

This channel suffers from: (Hierarchy – \( \delta_{CP} \)) & (Octant – \( \delta_{CP} \)) degeneracies. How can we break them?

Cervera et al., hep-ph/0002108
Freund et al., hep-ph/0105071

S. K. Agarwalla, Snowmass Workshop, University of Washington, Seattle, USA, 19th July 2022
Preference for Normal Mass Ordering ($\sim 2.5\sigma$), $\theta_{23} < 45$ degree and $\sin\delta < 0$ (both at 90% C.L.)
Remarkable Precision on Neutrino Oscillation Parameters

- **Esteban et al.** (NuFIT v5.1 w/ Super-K)
- **de Salas et al.** (2021)
- **Capozzi et al.** (2021)

### Parameters

- **$\sin^2 \theta_{12}$**
  - 0.02, 0.022, 0.024
- **$\sin^2 \theta_{13}$**
  - 0.02, 0.024
- **$\sin^2 \theta_{23}$**
  - 0.4, 0.45, 0.5, 0.55, 0.6
- **$\Delta m^2_{\text{sol}}$** $\times 10^{-5}$ (eV$^2$)
  - 6.8, 7.2, 7.6, 8
- **$|\Delta m^2_{\text{atm}}|$** $\times 10^{-3}$ (eV$^2$)
  - 2.4, 2.5, 2.6, 2.7, 90
- **$\delta_{\text{CP}}$ (°)**
  - 90, 180, 270, 360

### Results

- **Robust three-flavor neutrino oscillation paradigm**
- **Huge boost for the discovery of NMO, CPV, and $\theta_{23}$ Octant**

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**Figures:**

- **Figures of $\sin^2 \theta_{12}$, $\sin^2 \theta_{13}$, and $\sin^2 \theta_{23}$ distributions**
- **Figures of $\Delta m^2_{\text{sol}}$, $|\Delta m^2_{\text{atm}}|$, and $\delta_{\text{CP}}$**

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**Agarwalla, Kundu, Prakash, Singh, JHEP 03 (2022) 206**

**S. K. Agarwalla, Snowmass Workshop, University of Washington, Seattle, USA, 19th July 2022**
JUNO will improve significantly our knowledge on neutrino oscillation parameters. These developments are crucial to probe sub-leading three-flavor effects in next-generation long-baseline experiments for the discovery of NMO, leptonic CPV, and Octant of 2-3 mixing angle.
# Essential Features of DUNE, T2HK (JD), and T2HKK (JD+KD)

<table>
<thead>
<tr>
<th></th>
<th>DUNE</th>
<th>JD/KD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector Mass</td>
<td>40 kt LArTPC</td>
<td>187 kt WC (each)</td>
</tr>
<tr>
<td>Baseline</td>
<td>1300 km</td>
<td>295/1100 km</td>
</tr>
<tr>
<td>Proton Energy</td>
<td>120 GeV</td>
<td>80 GeV</td>
</tr>
<tr>
<td>Beam type</td>
<td>Wide-band, on-axis</td>
<td>Narrow-band, off-axis (2.5°)</td>
</tr>
<tr>
<td>Beam power</td>
<td>1.2 MW</td>
<td>1.3 MW</td>
</tr>
<tr>
<td>P.O.T./year</td>
<td>$1.1 \times 10^{21}$</td>
<td>$2.7 \times 10^{21}$</td>
</tr>
<tr>
<td>Oscillation Maxima</td>
<td>1st (2.6 GeV) &amp; 2nd (0.9 GeV)</td>
<td>1st (0.6 GeV) &amp; 2nd (0.6 GeV)</td>
</tr>
<tr>
<td>Run time ($\nu + \bar{\nu}$)</td>
<td>3.5 yrs + 3.5 yrs / 5 yrs + 5 yrs</td>
<td>2.5 yrs + 7.5 yrs</td>
</tr>
<tr>
<td>Sig. Norm. Err. (App.)</td>
<td>2%</td>
<td>5%</td>
</tr>
<tr>
<td>Sig. Norm. Err. (Disapp.)</td>
<td>5%</td>
<td>3.5%</td>
</tr>
</tbody>
</table>

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DUNE Collaboration: e-Print: [1606.09550](https://arxiv.org/abs/1606.09550) [physics.ins-det]


Hyper-Kamiokande Collaboration: e-Print: [1611.06118](https://arxiv.org/abs/1611.06118) [hep-ex]

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*S. K. Agarwalla, Snowmass Workshop, University of Washington, Seattle, USA, 19th July 2022*
Establishing Matter Effect and Exploring ($\rho_{\text{avg}} - \delta_{CP}$) and ($\rho_{\text{avg}} - \sin^2\theta_{23}$) Degeneracies in Next-generation Long-baseline Experiments

-- A Striking Complementarity between DUNE and T2HK (JD) / T2HKK (JD+KD)

Masoom Singh and Sanjib Kumar Agarwalla, PoS (EPS-HEP2021) 191

Masoom Singh, Soumya C., and Sanjib Kumar Agarwalla, in preparation

S. K. Agarwalla, Snowmass Workshop, University of Washington, Seattle, USA, 19th July 2022
Matter Effect in Long-Baseline Experiments

$P_{\mu e}$ (matter) - $P_{\mu e}$ (vacuum)

$\delta_{CP} = 0^\circ$
- $1^{st}$ osc. max.
- $2^{nd}$ osc. max.

DUNE
- NO

T2K/JD
- NOvA
- ESSvSB

NO

Baseline [km]

Energy [GeV]

S. K. Agarwalla, Snowmass Workshop, University of Washington, Seattle, USA, 19th July 2022
Matter Effect in Long-Baseline Experiments

\[ P_{\mu e} \text{ (matter)} - P_{\mu e} \text{ (vacuum)} \]

- \( \delta_{CP} = -90^\circ \)
- \( 1^{st} \) osc. max.
- \( 2^{nd} \) osc. max.

Energy [GeV]

Baseline [km]
Interesting complementarity between DUNE and T2HKK (JD+KD)

DUNE + T2HKK can establish matter effect > 6\sigma C.L. irrespective of the choices of NMO, $\delta_{\text{CP}}$, & $\theta_{23}$

DUNE + T2HK can establish matter effect > 5\sigma C.L. irrespective of the choices of NMO, $\delta_{\text{CP}}$, & $\theta_{23}$

S. K. Agarwalla, Snowmass Workshop, University of Washington, Seattle, USA, 19th July 2022
Rel. 1σ precision on $\rho_{\text{avg}}$ for NH: JD+KD (40%), DUNE (15%), and DUNE + JD + KD (11.2%)

Rel. 1σ precision on $\rho_{\text{avg}}$ for IH: JD+KD (35%), DUNE (12%), and DUNE + JD + KD (9.4%)
JD + KD has no sensitivity towards $\rho_{\text{avg}}$, but it can constrain the allowed range of $\delta_{CP}$.

DUNE has sensitivity towards both $\rho_{\text{avg}}$ and $\delta_{CP}$.

DUNE + JD + KD can significantly reduce the allowed region in ($\rho_{\text{avg}} - \delta_{CP}$) plane.

Masoom Singh and Sanjib Kumar Agarwalla
PoS (EPS-HEP2021) 191
Degeneracies between Average Matter Density and $\theta_{23}$

JD + KD has no sensitivity towards $\rho_{\text{avg}}$, but it can constrain the allowed range of $\theta_{23}$ quite precisely.

DUNE has sensitivity towards both $\rho_{\text{avg}}$ and $\theta_{23}$.

DUNE + JD + KD can significantly reduce the allowed region in ($\rho_{\text{avg}} - \theta_{23}$) plane.

**Masoom Singh and Sanjib Kumar Agarwalla, PoS (EPS-HEP2021) 191**
Comparison among Various Expt. for Precision Measurement of $\rho_{\text{avg}}$

Masoom Singh, Soumya C., and Sanjib Kumar Agarwalla, in preparation

S. K. Agarwalla, Snowmass Workshop, University of Washington, Seattle, USA, 19th July 2022
Is CP violated in the neutrino sector, as in the quark sector?

Mixing can cause CPV in neutrino sector, provided \( \delta_{CP} \neq 0^\circ \) and \( 180^\circ \).

Need to measure the CP-odd asymmetries:

\[
\Delta P_{\alpha\beta} \equiv P(\nu_\alpha \rightarrow \nu_\beta; L) - P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta; L) \quad (\alpha \neq \beta)
\]

\[
\Delta P_{e\mu} = \Delta P_{\mu\tau} = \Delta P_{\tau e} = 4J_{CP} \times \left[ \sin \left( \frac{\Delta m^2_{21}}{2E} L \right) + \sin \left( \frac{\Delta m^2_{32}}{2E} L \right) + \sin \left( \frac{\Delta m^2_{13}}{2E} L \right) \right]
\]

Jarlskog CP-odd Invariant \( \rightarrow \)

\[
J_{CP} = \frac{1}{8} \cos \theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \sin \delta_{CP}
\]

Three-flavor effects are key for CPV, need to observe interference.

**Conditions for observing CPV:**

1) Non-degenerate masses ✔
2) Mixing angles \( \neq 0^\circ \) & \( 90^\circ \) ✔
3) \( \delta_{CP} \neq 0^\circ \) and \( 180^\circ \) (Hints)

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*S. K. Agarwalla, Snowmass Workshop, University of Washington, Seattle, USA, 19th July 2022*
Complementarity among Next-generation Long-baseline Experiments in Searching Leptonic CP Violation

-- Combination of DUNE & T2HK is must to establish Leptonic CP Violation at 3σ for 75% values of $\delta_{CP}$

-- Impact of 2-3 mixing angle
-- Impact of neutrino and antineutrino runtime
-- Impact of exposure
-- Impact of systematic uncertainties

CP Coverage for Leptonic CP Violation at $\geq 3\sigma$ as a function of $\theta_{23}$

CP asymmetry decreases with increasing value of $\theta_{23}$ and therefore, CP coverage gets reduced for higher values of $\theta_{23}$.

Combination of DUNE and T2HK (JD) is must to achieve leptonic CP violation at 3$\sigma$ for at least 75% choices of $\delta_{CP}$.
CP Coverage for Leptonic CP Violation at $\geq 3\sigma$ as a function of $\theta_{23}$

$\theta_{23} - \delta_{CP}$ degeneracies affect the CP coverage for leptonic CP violation in DUNE for $\theta_{23}$ values close to maximal mixing.
Disappearance channel plays an important role in DUNE to enhance the CP coverage for leptonic CP violation for all $\theta_{23}$.
CP Coverage for Leptonic CPV at $\geq 3\sigma$ as a function of Exposure

$\sin^2 \theta_{23}$ (true) = 0.45

$\sin^2 \theta_{23}$ (true) = 0.5

$\sin^2 \theta_{23}$ (true) = 0.55

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CP Coverage for Leptonic CPV at $\geq 3\sigma$ as a function of Runtime

- $\sin^2 \theta_{23}^{(true)} = 0.45$
- $\sin^2 \theta_{23}^{(true)} = 0.5$
- $\sin^2 \theta_{23}^{(true)} = 0.55$

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CP Coverage for Leptonic CPV at $\geq 3\sigma$ as a function of Systematics

S. K. Agarwalla, Snowmass Workshop, University of Washington, Seattle, USA, 19th July 2022
High-Precision Measurement of Dirac CP Phase

\[ \sin^2 \theta_{23}^{\text{true}} = 0.5 \]

NO

JD/KD: App. Sys. (5%)
DUNE: App. Sys. (2%)

\[ \Delta \delta_{CP} \text{ [Deg.]} \]
\[ \delta_{CP} \text{ (true) [Deg.]} \]

JD + DUNE can measure any value of \( \delta_{CP} \) with a 1\( \sigma \) precision \( \leq 10^\circ \)


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Significant improvement in precision for CP-conserving choices of $\delta_{CP}$ w/ reduced systematics


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In $\nu_\mu$ survival probability, the dominant term is mainly sensitive to $\sin^2 2\theta_{23}$

- If $\sin^2 2\theta_{23}$ differs from 1 (recent hints), we get two solutions for $\theta_{23}$
  - One in lower octant (LO: $\theta_{23} < 45$ degree)
  - Other in higher octant (HO: $\theta_{23} > 45$ degree)

$v_\mu \rightarrow v_e$ oscillation channel can break this degeneracy. Preferred value would depend on the choice of neutrino mass ordering.

Octant ambiguity of $\theta_{23}$

Fogli and Lisi, hep-ph/9604415

S. K. Agarwalla, Snowmass Workshop, University of Washington, Seattle, USA, 19th July 2022
High-Precision Measurements of Atmospheric Oscillation Parameters

Combination of DUNE & T2HK is crucial for high-precision measurements of 2-3 oscillation parameters

Deviations from maximal $\theta_{23}$
Resolution of Octant of $\theta_{23}$
Precision on 2-3 oscillation parameters

S. K. Agarwalla, R. Kundu, S. Prakash, and M. Singh, JHEP 03 (2022) 206
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Best fit</th>
<th>3σ range</th>
<th>Relative 1σ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m_{21}^2/10^{-5}$ eV$^2$</td>
<td>7.36</td>
<td>6.93 - 7.93</td>
<td>2.3</td>
</tr>
<tr>
<td>$\sin^2 \theta_{12}/10^{-1}$</td>
<td>3.03</td>
<td>2.63 - 3.45</td>
<td>4.5</td>
</tr>
<tr>
<td>$\sin^2 \theta_{13}/10^{-2}$</td>
<td>2.23</td>
<td>2.04 - 2.44</td>
<td>3.0</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}/10^{-1}$</td>
<td>4.55</td>
<td>4.16 - 5.99</td>
<td>6.7</td>
</tr>
<tr>
<td>$</td>
<td>\Delta m_{31}^2</td>
<td>/10^{-3}$ eV$^2$</td>
<td>2.522</td>
</tr>
<tr>
<td>$\delta_{CP}/^\circ$</td>
<td>223</td>
<td>139 - 355</td>
<td>16</td>
</tr>
</tbody>
</table>

Best-fit values of the oscillation parameters, their corresponding 3σ allowed ranges, and relative 1σ precision on the oscillation parameters assuming normal mass ordering

Deviation from Maximal $\theta_{23}$

Deviation from Maximality

$\delta_{CP}^{(true)} = 223^\circ$

$\Delta \chi^2_{DM}$

$\sin^2 \theta_{23}^{(true)}$

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Precision Measurement of Atmospheric Oscillation Parameters

**Precision on \( \sin^2 \theta_{23} \)**

- **\( \Delta \chi^2_{PM} \)**
- **Parameters**:
  - **DUNE (7 yrs)**
  - **T2HK (10 yrs)**
  - **DUNE + T2HK**
  - **Capozzi et al.**

**Precision on \( \Delta m^2_{31} \)**

- 3\( \sigma \)
- **\( \Delta \chi^2_{PM} \)**
- **Parameters**:
  - **\( \Delta m^2_{31} / 10^{-3} \) (test) \[eV^2\]**

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<table>
<thead>
<tr>
<th>Parameter</th>
<th>Relative 1( \sigma ) precision (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>JD (2.5 ( \nu + 7.5 \bar{\nu} ) yrs)</td>
</tr>
<tr>
<td>( \sin^2 \theta_{23} )</td>
<td>1.18</td>
</tr>
<tr>
<td>( \Delta m^2_{31} )</td>
<td>0.25</td>
</tr>
</tbody>
</table>

*S. K. Agarwalla, Snowmass Workshop, University of Washington, Seattle, USA, 19th July 2022*
Contributions from both appearance and disappearance channels are important.
Contributions from both neutrino and antineutrino modes are crucial.
Precision Measurement of Atmospheric Oscillation Parameters

S. K. Agarwalla, Snowmass Workshop, University of Washington, Seattle, USA, 19th July 2022
Discovery of $\theta_{23}$ Octant

Octant of $\sin^2 \theta_{23}$

$\delta_{\text{CP}} \text{(true)} = 223^\circ$

S. K. Agarwalla, Snowmass Workshop, University of Washington, Seattle, USA, 19th July 2022
Exciting opportunities to address the pressing issues in three-flavour neutrino paradigm: neutrino mass ordering, leptonic CP violation, and accurate measurements of oscillation parameters

Improved precision on three-flavor oscillation parameters in the next 5 to 10 years are very crucial to set the stage for next-generation long-baseline experiments

DUNE and T2HK bring complementary information to probe the entire parameter space with high confidence level

Present is very exciting! Future is very bright!

Stay Tuned!

Thank you!

S. K. Agarwalla, Snowmass Workshop, University of Washington, Seattle, USA, 19th July 2022
Establishing Matter Effect in Long-Baseline Experiments

Masoom Singh, Sanjib Kumar Agarwalla, in preparation
Precision Measurement of Atmospheric Oscillation Parameters

\[ \Delta m^2_{31} / 10^{-3} (\text{eV}^2) \]

- **DUNE (3.5 yrs)**
- **T2HK (2.5 yrs)**
- **DUNE + T2HK**

$\sin^2 \theta_{23}$ (test)

- Solid: w/ wrong-sign
- Dashed: w/o wrong-sign

3σ; NMO

$\nu$ mode

$\bar{\nu}$ mode

$(\nu + \bar{\nu})$ modes
Precision Measurement of Atmospheric Oscillation Parameters

\[ \Delta m^2_{31}/10^{-3} \text{(eV}^2\text{)} \]

-3σ; IMO

-3σ; Mode

DUNE (3.5 yrs)
JD (2.5 yrs)
DUNE + JD

DUNE (3.5 yrs)
JD (7.5 yrs)
DUNE + JD

DUNE [3.5 yrs + 3.5 yrs]
JD [2.5 yrs + 7.5 yrs]
DUNE + JD

\( \sin^2 \theta_{23} \) (test)

\( \sin^2 \theta_{23} \) (test)

\( \sin^2 \theta_{23} \) (test)

(\( \nu + \bar{\nu} \) modes)
### Present Status of Neutrino Oscillation Parameters Circa 2021

Preference for Normal Mass Ordering (~ 2.5\(\sigma\)), \(\theta_{23} < 45\) degree and \(\sin \delta < 0\) (both at 90\% C.L.)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Ordering</th>
<th>Best fit</th>
<th>3(\sigma) range</th>
<th>“1(\sigma)” (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\delta m^2/10^{-5}) eV(^2)</td>
<td>NO, IO</td>
<td>7.36</td>
<td>6.93 – 7.93</td>
<td>2.3</td>
</tr>
<tr>
<td>(\sin^2 \theta_{12}/10^{-1})</td>
<td>NO, IO</td>
<td>3.03</td>
<td>2.63 – 3.45</td>
<td>4.5</td>
</tr>
<tr>
<td>(</td>
<td>\Delta m^2</td>
<td>/10^{-3}) eV(^2)</td>
<td>NO</td>
<td>2.485</td>
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<tr>
<td></td>
<td>IO</td>
<td>2.455</td>
<td>2.376 – 2.541</td>
<td>1.1</td>
</tr>
<tr>
<td>(\sin^2 \theta_{13}/10^{-2})</td>
<td>NO</td>
<td>2.23</td>
<td>2.04 – 2.44</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>IO</td>
<td>2.23</td>
<td>2.03 – 2.45</td>
<td>3.1</td>
</tr>
<tr>
<td>(\sin^2 \theta_{23}/10^{-1})</td>
<td>NO</td>
<td>4.55</td>
<td>4.16 – 5.99</td>
<td>6.7</td>
</tr>
<tr>
<td></td>
<td>IO</td>
<td>5.69</td>
<td>4.17 – 6.06</td>
<td>5.5</td>
</tr>
<tr>
<td>(\delta/\pi)</td>
<td>NO</td>
<td>1.24</td>
<td>0.77 – 1.97</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>IO</td>
<td>1.52</td>
<td>1.07 – 1.90</td>
<td>9</td>
</tr>
<tr>
<td>(\Delta \chi^2_{\text{IO-NO}})</td>
<td>IO-NO</td>
<td>+6.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


See also, Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou, arXiv:2007.14792v1 [hep-ph], NuFIT v5.1 w/SK

See also, de Salas, Forero, Gariazzo, Martinez-Mirave, Mena, Ternes, Tortolla, Valle, arXiv:2006.11237v2 [hep-ph]
Neutrino Mass Ordering: Important Open Question

The sign of $\Delta m_{31}^2 (m_3^2 - m_1^2)$ is not known

Neutrino mass spectrum can be normal or inverted ordered

We only have a lower bound on the mass of the heaviest neutrino

$\sqrt{2.5 \cdot 10^{-3} \text{eV}^2} \sim 0.05 \text{eV}$

We currently do not know which neutrino is the heaviest

$|U_{e1}|^2 > |U_{e2}|^2 > |U_{e3}|^2$

$\nu_e$ component of $\nu_1 > \nu_e$ component of $\nu_2 > \nu_e$ component of $\nu_3$

Mass Ordering Discrimination: A Binary yes-or-no type question