New experimental results on CPV in the lepton sector

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CP violation in the leptonic sector?

Recent results on neutrino oscillations

new window to studies of charge-parity (CP) violation in leptonic sector

Is the CP violation in neutrinos in early universe the reason for the matter-antimatter asymmetry?

The new era of precision measurements of neutrino oscillations begins!
Neutrino Oscillations

Neutrinos have non-zero mass and mixing angles
The bulk of the existing data currently is very well described by the oscillation of three active neutrinos

Many open questions:

- What is the neutrino mass hierarchy?
  - Is $\Delta m^2$ positive or negative?
    - Mass hierarchy (MH) → sign of $\Delta m^2_{32}, \Delta m^2_{31}$
    - Normal (NH): $m_3 > m_2 > m_1$
    - Inverted (IH): $m_2 > m_1 > m_3$
- Is there CP violation in the lepton sector?
  - CP symmetry is violated if $\delta_{CP} \neq 0, \pi$
- Is the $\theta_{23}$ mixing angle maximal?
  - If not, which quadrant?
- What are the precise values of the mixing angles $\theta_{ij}$?
- Majorana or Dirac?
Oscillation parameters:

mixing matrix

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

\[c_{ij} = \cos \theta_{ij}\]

\[s_{ij} = \sin \theta_{ij}\]

\[\delta_{\text{CP}}\] unknown

\[U_{\text{PMNS}} \approx \begin{pmatrix}
0.8 & 0.55 & 0.15 \\
0.4 & 0.6 & 0.7 \\
0.4 & 0.6 & 0.7
\end{pmatrix} \quad U_{\text{CKM}} \approx \begin{pmatrix}
0.97 & 0.23 & 0.004 \\
0.23 & 0.97 & 0.04 \\
0.008 & 0.04 & 1
\end{pmatrix}
\]

\[\delta_{\text{CP}} = 70^\circ\]

CP symmetry is violated in lepton sector if \(\delta_{\text{CP}} \neq 0,\pi\)
Neutrino oscillations

\[ P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - (\cos^4 \theta_{13} \sin^2 2\theta_{23}) \sin^2 \left( \frac{\Delta m^2_{31} L}{4E} \right) \]

Sensitive to \( \theta_{23} \) and \( \Delta m^2_{32} \)
Comparing neutrino and anti-neutrino disappearance: test of CPT symmetry

\( \nu_\mu \) survival probability:

\[ P(\nu_\mu \rightarrow \nu_\mu) \approx \sin^2 2\theta_{13} \times \sin^2 \theta_{23} \times \frac{\sin^2 [(1 - x)\Delta]}{(1 - x)^2} \]

\( \nu_e \) appearance probability:

\[ P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 2\theta_{13} \times \sin^2 \theta_{23} \times \frac{\sin [x\Delta] \sin [(1 - x)\Delta]}{x(1 - x)} \]

\[ x = \frac{2 \sqrt{2} G_F N_e E}{\Delta m^2_{31}} \]

For anti-neutrinos, replace \( \delta \) and \( x \) with \(-\delta\) and \(-x\)

- Leading term depends on \( \theta_{13} \) and \( \theta_{23} \),
- CP-violating phase \( \delta \Rightarrow P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \),
- Matter effect gives sensitivity to mass hierarchy: sign of \( x \).
Neutrino oscillation search

\[ P(\bar{\nu}_{\mu} \rightarrow \bar{\nu}_x): \text{deficit on the number of events (disappearance)} \]
\[ P(\nu_{\mu} \rightarrow \nu_e): \text{excess of events (appearance)} \]

CP-asymmetry searched for in long base-line experiments looking for \(\nu_{\mu} \rightarrow \nu_e\) and \(\bar{\nu}_{\mu} \leftrightarrow \bar{\nu}_e\)

Neutrinos (and anti-neutrinos) travel through matter not antimatter: electron density causes asymmetry

It is necessary to disentangle true CP-V effects due to the \(\delta\) phase from the ones induced by matter

- Keep \(L\) small (\(\sim 200\) km): so that matter effects are insignificant
- Make \(L\) large (\(>1000\) km): measure the matter effects; unfold CPV from matter effects through \(E\) dependence
Long-baseline experiments concept

Neutrino beam production $O(\text{GeV})$ → Near Detector: measure neutrino beam before oscillations → Far Detector: measure neutrino beam after oscillations

Near Detector: $N_{ND} \sim \Phi(E_{\nu})\sigma(E_{\nu})\epsilon_{ND}$

Far Detector: $N_{FD} \sim \Phi(E_{\nu})\sigma(E_{\nu})\epsilon_{FD}P_{osc}(E_{\nu})$
## Long-Baseline Experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Run</th>
<th>Peak Eₙ</th>
<th>Baseline</th>
<th>Detector</th>
</tr>
</thead>
<tbody>
<tr>
<td>K2K</td>
<td>1999 - 2004</td>
<td>1 GeV</td>
<td>250 km</td>
<td>Water Č</td>
</tr>
<tr>
<td>MINOS(+)</td>
<td>2005 - 2015</td>
<td>3 GeV</td>
<td>730 km</td>
<td>Iron/Scint</td>
</tr>
<tr>
<td>CNGS/Opera</td>
<td>2008 - 2012</td>
<td>17 GeV</td>
<td>730 km</td>
<td>Emulsion</td>
</tr>
<tr>
<td>T2K</td>
<td>2010 -</td>
<td>0.6 GeV</td>
<td>295 km</td>
<td>Water Č</td>
</tr>
<tr>
<td>DUNE*</td>
<td>2026 -</td>
<td>3 GeV</td>
<td>1300 km</td>
<td>Liq. Argon</td>
</tr>
<tr>
<td>Hyper-K**</td>
<td>2026 -</td>
<td>0.6 GeV</td>
<td>295 km</td>
<td>Water Č</td>
</tr>
</tbody>
</table>

**K2K**: confirm atmospheric neutrino oscillations  
**MINOS**: precise measurement of $|\Delta m_{32}|^2$ and $\theta_{23}$  
**Opera**: observe tau appearance in $\nu_\mu \leftrightarrow \nu_\tau$ oscillations  
**T2K**: observe $\nu_\mu \leftrightarrow \nu_e$ and $\nu_\mu \leftrightarrow \nu_\mu$ oscillations, measure $\theta_{13}$, first results in the search for CP violation  
**NOvA**: $\nu_\mu \leftrightarrow \nu_e$ at a longer baseline for mass hierarchy, CP violation, ...  

*DUNE construction approval in 2016; **Hyper-K will be seeking approval in 2017/2018
The T2K experiment

Intense Off-Axis muon (anti)neutrino beam from J-PARC to Super-Kamiokande (295 km from target production): measure oscillated neutrino flux

- Unoscillated neutrino flux is measured at the near detector (~280m)
- Two production modes: Neutrino and anti-neutrino
- Precise measurements of
  - muon (anti)neutrino disappearance
  - electron (anti)neutrino appearance
**$\nu_e$ and $\bar{\nu}_e$ appearance**

**Neutrino mode**

<table>
<thead>
<tr>
<th>Beam mode</th>
<th>Sample</th>
<th>Exp. Not Osc</th>
<th>Exp. $\delta_{CP} = 0$ (NH)</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>neutrino</td>
<td>e-like</td>
<td>6.1</td>
<td>24.2</td>
<td>32</td>
</tr>
<tr>
<td>antineutrino</td>
<td>e-like</td>
<td>2.3</td>
<td>6.9</td>
<td>4</td>
</tr>
</tbody>
</table>

Predictions:

$\nu_e$: 19.6 evts (NH, $\delta_{CP}=\pi/2$) to 28.7 evts (NH, $\delta_{CP}=-\pi/2$)

$\nu_e$: 7.7 evts (NH, $\delta_{CP}=\pi/2$) to 6.0 evts (NH, $\delta_{CP}=-\pi/2$)

Clear appearance signal for $\nu_e$

More statistics needed for $\bar{\nu}_e$
Constraints on $\theta_{13}$ and $\delta_{\text{CP}}$

Number of $\nu_e$ and $\bar{\nu}_e$ candidates compared with predictions:

- Number of observed events shows larger asymmetry than expected for $\delta_{\text{CP}} = -\pi/2$ and NH

$\theta_{13}$ in agreement with reactor experiments

- T2K begins to probe $\delta_{\text{CP}}$
- $\delta_{\text{CP}} \sim -\pi/2$ and NH preferred
- T2K disfavors region of $\delta_{\text{CP}} = +\pi/2$


Similar (but less significant) effects seen in NOvA and SuperK

Reactor experiment constraint from PDG2015 ($\sin^2 2\theta_{13} = 0.085 \pm 0.005$) shown
Constraints on $\delta_{CP}$

90% CL constraints on $\delta_{CP}$ from Feldman-Cousins method

Reactor constraint:

$\sin^2 2\theta_{13} = 0.085 \pm 0.005$ (PDG 2015)

Best fit gives $\delta_{CP} = -1.791$, Normal Hierarchy

- The allowed 90% CL intervals are:
  - $-3.13 < \delta_{CP} < -0.39$ (NH)
  - $-2.09 < \delta_{CP} < -0.74$ (IH)

- CP conserving values $\delta_{CP} = 0$ excluded at 90% C.L.

Vertical lines show the corresponding allowed 90% confidence intervals, calculated using the Feldman-Cousins method.

CP conservation hypothesis excluded at 90% CL
T2K-II

J-PARC neutrino beam upgrade

<table>
<thead>
<tr>
<th></th>
<th>Now (achieved)</th>
<th>2020</th>
<th>~2025</th>
</tr>
</thead>
<tbody>
<tr>
<td>p/spill</td>
<td>$2.4 \times 10^{14}$</td>
<td>$2.2 \times 10^{14}$</td>
<td>$3.2 \times 10^{14}$</td>
</tr>
<tr>
<td>cycle</td>
<td>2.48s</td>
<td>1.3s</td>
<td>1.16s</td>
</tr>
<tr>
<td>power</td>
<td>470kW</td>
<td>800kW</td>
<td>1.3MW</td>
</tr>
</tbody>
</table>

Intermediate Detectors
- Water Cherenkov detector at ~1-2 km
- Same technology as the far detector
- Far/Near errors cancelation

Two proposals: TITUS/nuPRISM
Off-axis angle spanning orientation.
Gd loading, magnetized $\mu$ range detector.
Will merge in unique detector

Near Detector upgrade

Construction 2020-2023 (?)
T2K-II: Near Detector Upgrade

- Goal is to reduce the cross section systematics
- Need more precise measurements at Near Detector
  - better efficiency for low momenta $\pi$ and $p$
  - $4\pi$ acceptance

Alternative configurations to the reference design under study

Workshop on “Neutrino ND based on gas TPCs”
@CERN: https://indico.cern.ch/event/568177/
https://indico.cern.ch/event/61307/
T2K-II: Near Detector Upgrade

Expression of Interest (EOI) EOI-15 @ Neutrino Platform (CERN): T2K Near Detector upgrade looking forward (HyperK/Dune)

- Signed by 190 people (including a CERN group)
- Submitted to SPSC early January
- First contact with referees and questions received

One project, two goals

- Study, optimize, design and build an upgrade of the ND280 near detector capable of improved and model-independent precision below ~4% in line with T2K-II physics needs
- Study, optimize, design a High Pressure TPC that could serve as base for a detector aimed at exploring the details of neutrino interactions. Demonstrate the concept with prototypes on a test beam.

R&D Program based at CERN (Neutrino Platform) to develop both TPC and HPTPC for neutrino experiments

Side subjects as Dark Matter searches or Double Beta Decay can be accommodated in case of common developments
T2K-II: Intermediate Detector

- Water Cherenkov detector at intermediate distance (>1 km from target) with a high-intensity neutrino beam
- Same neutrino cross section as at the far detector
- Complementary to the upgrade of Near Detector (magnetized)

- Spans off-axis 1°/4°
- Mono-chromatic neutrino beam
- Study energy dependence to neutrino interactions

- 2.5° off-axis detector with 1.27 kton FV
- Long geometry to contain high-momentum muons
- Gd loading for neutron detection
- Magnetized muon range detector

Process for merging the two proposals into a single detector design
Physics Potential of T2K-II

Unknown Mass Hierarchy

- With full T2K-II statistics able to:
  - Exclude CP conservation hypothesis at more than 3σ if $\delta_{CP} \sim -\pi/2$
  - Measure $\theta_{23}$ with resolution $\sim 1.7^\circ$

Mass Hierarchy Known

Sensitivity for $\sin^2\theta_{23} = 0.43$
The NOνA experiment

- “Conventional” beam
- Two-detector experiment:
  - Near detector
    - beam composition
    - energy spectrum
  - Far detector
    - measure oscillations and search for new physics

Significant complementarity, with different baselines and different near and far detectors
-- NOνA more sensitive to Mass Ordering
-- T2K directly sensitive to CP violation
Both experiments benefit from off-axis geometry
NOvA detectors

Extruded PVC cells filled with 11M liters of scintillator instrumented with $\lambda$-shifting fiber and APDs

Far Detector
14 kton
896 layers

Near Detector
0.3 kton
214 layers

A NOvA cell
To APD

Far detector:
14-kton, fine-grained, low-Z, highly-active tracking calorimeter → 344,000 channels

Near detector:
0.3-kton version of the same → 20,000 channels

32-pixel APD
Fiber pairs from 32 cells
NOvA results

Combined fit of the NOvA $\nu_e$ appearance and $\nu_\mu$ disappearance data

- inverted mass hierarchy disfavored

Regions of $\delta_{CP}$ vs. $\sin^2\theta_{23}$ parameter space consistent with the observed spectrum of $\nu_e$ candidates and the $\nu_\mu$ disappearance data.

Significance at which each value of $\delta_{CP}$ is disfavored for each of the four possible combinations of mass hierarchy

Future data-taking in antineutrino to resolve degeneracies
Future project: DUNE and Hyper-Kamiokande
Two complementary approaches

**Hyper-K:**
- Short baseline $\rightarrow$ no matter effects: pure CP but reduced MH
- Off axis $\rightarrow$ reduced intrinsic $\nu_e$ contamination, reduced NC backgrounds

**DUNE:**
- Long baseline $\rightarrow$ sensitive to matter effects: excellent performances in MH
- On axis: second oscillation maximum and sensitive to $\nu_\tau$ appearance (tiny effects at 1300 km)
- On axis: extended lever arm for measurement of oscillation parameters
Hyper-Kamiokande: overview

Hyper-Kamiokande is a multi-purpose Water-Cherenkov detector with a variety of scientific goals:
- Neutrino oscillations (atmospheric, accelerator and solar);
- Neutrino astrophysics;
- Proton decay;
- Non-standard physics.

Atmospheric $\nu$

Solar $\nu$

Supernova $\nu$

Accelerator $\nu$
Hyper-K CP Sensitivity

CPV sensitivity based on:
6 years with one tank + 4 years with two
Assume MH is already known

CPV coverage:
78% at 3σ
62% at 5σ

CP violation can be detected with more than 3σ (5σ) significance for 78% (62%) of values of $\delta_{CP}$
Hyper-K: 2° detector in Korea

Recently Hyper-K protocollaboration revisited the option of the second tank being in Korea
Off-axis at a baseline of ~1100 km

Longer baseline: mass hierarchy sensitivity
+ some benefit to CP sensitivity
DUNE: overview


Wide band, high purity $\nu_\mu$ beam with peak flux at 2.5 GeV operating at $\sim$1.2 MW and upgradeable.

- four identical cryostats deep underground
- staged approach to four independent 10 kt LAr detector modules
- Single-phase and double-phase readout under consideration

DUNE CP Sensitivity

CPV Discovery

$\delta_{CP}$ Measurement

Credits M.Thomson IMFP17
Towards leptonic CP asymmetry

\[ \chi^2 \]

\( \delta_{\text{CP}} \) (°)

5\( \sigma \)
3\( \sigma \)
\( \sim 2020 \)

\( \text{NH} \)

HK
DUNE
T2K-II
T2K+NOvA

Mezzetto, Neutrino 2016
Towards leptonic CP asymmetry

~3σ indication with T2K→T2K-II,
>5σ discovery and measurement with HK/DUNE

Note: “exact” comparison sometimes difficult due to different assumptions
Conclusions

Long-baseline $\nu$ oscillation experiments have played a major part in our current understanding of the neutrino.

The question of CP violation in the leptonic sector is a priority of the future neutrino program.

DUNE and Hyper-K will tackle fundamental questions:
- CP Violation
- Mass Hierarchy
- Testing the Standard Model of $\nu$
- Proton Decay
- Supernova neutrinos

The current hint for maximal leptonic CP violation can be either due to maximal leptonic CP violation or CP conservation in the presence of New Physics.
Maybe even more surprises in neutrinos!
Backup
T2K near detector complex

**INGRID**
- On-axis detector
- 7+7 (+2) identical modules
- Iron and scintillator tracking calorimeter
- Beam direction and stability monitoring

**ND280**
- Off-axis detector
- Magnet 0.2 T
- Trackers, calorimeters and muon range detectors
- Active (scintillator) and passive (water) targets
Oscillation parameters:

Mass squared difference $\Delta m^2$

Mass hierarchy (MH) $\rightarrow$ sign of $\Delta m^2_{32}$
Normal (NH): $m_3 > m_2 > m_1$
Inverted (IH): $m_2 > m_1 > m_3$

Several projects to improve sensitivity to mass ordering ……
Constraints on $\theta_{23}$ and $\Delta m^2_{32}$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Normal Hierarchy</th>
<th>Inverted Hierarchy</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sin^2 \theta_{23}$</td>
<td>0.532 (Best fit)</td>
<td>0.534 (Best fit)</td>
</tr>
<tr>
<td></td>
<td>$[0.464; 0.578]$</td>
<td>$[0.468; 0.577]$</td>
</tr>
<tr>
<td>$\Delta m^2_{32} (10^{-3} \text{eV}^2)$</td>
<td>2.545 (Best fit)</td>
<td>2.510 (Best fit)</td>
</tr>
<tr>
<td></td>
<td>$[2.461; 2.626]$</td>
<td>$[2.427; 2.591]$</td>
</tr>
</tbody>
</table>
(Anti)Neutrino interactions at T2K

The dominant neutrino interaction mode is Charge-Current Quasi-Elastic

Neutrino energy from lepton momentum and angle in CCQE hypothesis:
- 2 body kinematics
- assume target nucleon at rest

Other cross-section components
- CCQE-like multinucleon interaction (2 nucleons in the final state)
- Charged-current single-pion production (CCπ)
- Neutral-current single-pion production (NCπ)
Effect of CP violation at T2K

• Asymmetric effect on
  \( P(\nu_\mu \rightarrow \nu_e) \) and \( P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \):

  - \( \delta_{\text{CP}} = -\pi/2 \rightarrow \text{maximizes} \)
  \( P(\nu_\mu \rightarrow \nu_e) \) and \( \text{minimizes} \)
  \( P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \)

  - \( \delta_{\text{CP}} = +\pi/2 \rightarrow \text{minimizes} \)
  \( P(\nu_\mu \rightarrow \nu_e) \) and \( \text{maximizes} \)
  \( P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \)

• \( \delta_{\text{CP}} \) and Mass Hierarchy have similar effects

• Effect of \( \delta_{\text{CP}} \) on \( \nu_\mu \rightarrow \nu_e \) and \( \bar{\nu}_\mu \rightarrow \bar{\nu}_e \) is about \( \pm 20-30\% \)

• Effect of Mass Hierarchy is about \( \pm 10\% \)
T2K joint neutrino and antineutrino analysis

The oscillation parameters \( \sin^2 \theta_{23}, \Delta m^2_{32}, \sin^2 \theta_{13}, \) and \( \delta_{\text{CP}} \) are estimated by performing a joint maximum-likelihood fit of the four far-detector samples. The oscillation probabilities are calculated using the full three-flavor oscillation formulas. Matter effects are included with an Earth density of \( \rho = 2.6 \, \text{g/cm}^3 \).

The different mass orderings induce a variation of the expected events of \(~10\%\). Matter effects are negligible for the \( \nu_\mu \) and \( \bar{\nu}_\mu \) candidate samples, while they affect the number of events in the \( \nu_e \) and \( \bar{\nu}_\mu \) candidate samples by about 6\% and 4\%, respectively, for maximal CP violation.

| TABLE I. Number of \( \nu_e \) and \( \bar{\nu}_e \) events expected for various values of \( \delta_{\text{CP}} \) and both mass orderings compared to the observed numbers. |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|                 | Normal          |                 |                 | Inverted        |                 |                 |
|                 | \( \delta_{\text{CP}} = -\pi/2 \) | \( \delta_{\text{CP}} = 0 \) | \( \delta_{\text{CP}} = \pi/2 \) | \( \delta_{\text{CP}} = \pi \) | Observed |
| \( \nu_e \)    | 28.7            | 24.2            | 19.6            | 24.1            | 32           |
| \( \bar{\nu}_e \) | 6.0             | 6.9             | 7.7             | 6.8             | 4            |
| \( \nu_e \)    | 25.4            | 21.3            | 17.1            | 21.3            | 32           |
| \( \bar{\nu}_e \) | 6.5             | 7.4             | 8.4             | 7.4             | 4            |

Matter effects are negligible for the \( \nu_\mu \) and \( \bar{\nu}_\mu \) candidate samples, while they affect the number of events in the \( \nu_e \) and \( \bar{\nu}_\mu \) candidate samples by about 6\% and 4\%, respectively, for maximal CP violation.
T2K Constraints on $\delta_{CP}$

T2K with reactor constrain

Reactor experiment constraint from PDG2015
$(\sin^2 2\theta_{13} = 0.085 \pm 0.005)$ shown
\( \nu_\mu / \bar{\nu}_\mu \text{ DISAPPEARANCE} - \theta_{23} \text{ AND } \Delta m^2_{32} \)

\[
\Delta m^2_{32} = [2.16, 3.02] \times 10^{-3} \text{ eV}^2 \text{ (NH) at 90\% CL}
\]

\[
\sin^2 \theta_{23} = [0.32, 0.70] \text{ (NH) at 90\% CL}
\]

\[
\Delta m^2_{32} = [2.34, 2.75] \times 10^{-3} \text{ eV}^2 \text{ (NH) at 90\% CL}
\]

\[
\sin^2 \theta_{23} = [0.42, 0.61] \text{ (NH) at 90\% CL}
\]

No hint of CPT violation
Effect of increasing energy

T2K: $E = 0.6\,\text{GeV}$ and $L = 295\,\text{km}$

NOvA:
- For fixed $L/E = 0.4\,\text{km/MeV}$
- $\Delta m^2 = 2.4 \times 10^{-3} \,\text{eV}^2$
- $\sin^2(2\theta_{13}) = 1$
- $\sin^2(2\theta_{13}) = 0.09$

DUNE:
- $L = 1300\,\text{km}$, $<E> = 3.2\,\text{GeV}$

Increasing Energy

[$\rightarrow$ bigger matter effect and hence bigger fake CP violation]
# LBL $\nu$ experiments

<table>
<thead>
<tr>
<th>Detector</th>
<th>$E_p$ (GeV)</th>
<th>$L$ (km)</th>
<th>Runtime (yr)</th>
<th>$\varepsilon_{app}$</th>
<th>$\varepsilon_{dis}$</th>
<th>$R_\mu$</th>
<th>$R_e$</th>
<th>$E$ (GeV)</th>
<th>Bin width (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DUNE</strong></td>
<td>2.5</td>
<td>1300</td>
<td>5 $\nu + 5\bar{\nu}$</td>
<td>80%</td>
<td>85%</td>
<td>0.20/$\sqrt{E}$</td>
<td>0.15/$\sqrt{E}$</td>
<td>[0.5 – 10.0]</td>
<td>250 MeV</td>
</tr>
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<td></td>
</tr>
<tr>
<td><strong>T2K</strong></td>
<td>0.6</td>
<td>295</td>
<td>3 $\nu + 3\bar{\nu}$</td>
<td>50%</td>
<td>90%</td>
<td>0.085/$\sqrt{E}$</td>
<td>0.085/$\sqrt{E}$</td>
<td>[0.4 – 1.2]</td>
<td>40 MeV</td>
</tr>
<tr>
<td><strong>NOvA</strong></td>
<td>1.6</td>
<td>810</td>
<td>3 $\nu + 3\bar{\nu}$</td>
<td>55%</td>
<td>85%</td>
<td>0.06/$\sqrt{E}$</td>
<td>0.085/$\sqrt{E}$</td>
<td>[0.5 – 4.0]</td>
<td>125 MeV</td>
</tr>
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<td></td>
<td></td>
</tr>
<tr>
<td><strong>T2HK</strong></td>
<td>0.6</td>
<td>295</td>
<td>1 $\nu + 3\bar{\nu}$</td>
<td>50%</td>
<td>90%</td>
<td>0.085/$\sqrt{E}$</td>
<td>0.085/$\sqrt{E}$</td>
<td>[0.4 – 1.2]</td>
<td>40 MeV</td>
</tr>
</tbody>
</table>

Table 4: Detector configuration, efficiencies, resolutions and relevant energy ranges for DUNE, NOvA, T2K, T2HK.
Next questions

- $\theta_{23}$ octant? $\rightarrow$ sensitivity to $\sin^2\theta_{23}$ (same for $\nu$ and $\bar{\nu}$)

- CP violation?
  - $\delta_{CP}=0,\pi \rightarrow$ no CP violation
  - $\delta_{CP}=-\pi/2 \rightarrow$ enhance ($\nu_\mu \rightarrow \nu_e$), suppress ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$)
  - $\delta_{CP}=\pi/2 \rightarrow$ suppress ($\nu_\mu \rightarrow \nu_e$), enhance ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$) (27% effect at maximum)

- Mass hierarchy (10% effect)

...
Measuring CP-V: Majorana phases

Neutrinoless double beta experiments

Decay experiments: \((A,Z) \rightarrow (A,Z + 2) + 2e^-\).

The half-life time, \(T_{1/2}\), depends on \(m_j\), the masses of the massive neutrinos \(\nu_j\), \(\alpha_{21}\) and \(\alpha_{31}\) the CP-violating phases.

The two Majorana CPV phases \(\alpha_{21}\) and \(\alpha_{31}\) are physical only if neutrinos are Majorana particles.

CP conserved: \(\alpha_{21}, \alpha_{31} = 0\) (equal CP-parities) or \(\alpha_{21}, \alpha_{31} = \pm \pi\) (opposite CP-parities).

...CUORE, GENIUS, Majorana, SuperNEMO, EXO, GERDA, COBRA...