Measuring the neutrino CP phase and mass ordering

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Outline

- Introduction to the T2K experiment
- CP phase:
  - T2K measurement
  - Comparison to expected sensitivity
  - Feldman-Cousins critical value behaviour
- Mass ordering:
  - Frequentist properties of the mass ordering posterior probability
  - Mass ordering sensitivity
3-flavour neutrino oscillations

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} =
\begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & s_{13} e^{-i\delta} \\
0 & 1 & 0 \\
-s_{13} e^{i\delta} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

- \(c_{ij} = \cos \theta_{ij}\)
- \(s_{ij} = \sin \theta_{ij}\)

- Long baseline experiments can measure:
  - \(\theta_{23}\) and \(\Delta m^2_{32}\) via disappearance channel
  - \(\theta_{13}\) and \(\delta_{CP}\) via appearance channel
  - Mass ordering

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The T2K experiment

- Long baseline neutrino oscillation experiment in Japan
  - $\nu_\mu$ beam produced at J-PARC, Tokai
  - Near detectors at J-PARC, 280m downstream of target
  - Super-Kamiokande (SK) far detector, 295km downstream of target in Kamioka
  - Off-axis beam produces energy spectrum peaked at 0.6 GeV

- Precision measurements of $\nu_\mu$ disappearance
- Originally designed to discover $\nu_e$ appearance
- Currently searching for CP-violation
Neutrino beamline

- Stable beam running at 485kW
- Three horn magnets focus $\pi$ to produce $\nu$-mode or $\bar{\nu}$-mode beam
- Delivered $3.16 \times 10^{21}$ total protons on target (POT)

**Graph**

- Total Accumulated POT for Physics
- $\nu$-Mode Accumulated POT for Physics
- $\bar{\nu}$-Mode Accumulated POT for Physics
- $\nu$-Mode Beam Power
- $\bar{\nu}$-Mode Beam Power

**Timeline**

23 Jan. 2010 – 31 May 2018

- POT total: $3.16 \times 10^{21}$
- $\nu$-mode: $1.51 \times 10^{21}$ (47.83%)
- $\bar{\nu}$-mode: $1.65 \times 10^{21}$ (52.17%)

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Analysis approach

- **Neutrino flux model**
  - Simulation and NA61 and T2K replica target data on $\pi$ and $K$ yields

- **Neutrino cross-section model**
  - Simulation and external data on $\nu/e/h$ interactions

- **Detector model**
  - Simulation and calibration and test beam data

- **Make predictions at ND280 and SK**
  - Parametrise cross-section and flux model
  - Constrain cross-section and flux by tuning ND280 prediction to observation

- **Extract oscillation physics**
  - Perform simultaneous fits of the 5 SK samples to measure oscillation parameters
ND280 data fit

- 3 ND280 $\nu$ topologies:
  - $\nu_\mu$ CC0$\pi$, $\nu_\mu$ CC1$\pi^+$, $\nu_\mu$ CC other
- 4 ND280 $\bar{\nu}$ topologies:
  - $\bar{\nu}_\mu$ CC 1-track, $\bar{\nu}_\mu$ CC N-track
  - Wrong sign $\nu_\mu$ CC 1-track, $\nu_\mu$ CC N-track

**INGRID (on-axis)**
- Fit reduces flux and interaction model uncertainties at SK
- Also use ND280 to measure $\nu$-nucleus cross-sections
ND280 data fit

$\nu_\mu$ CC0$\pi$ data fit

<table>
<thead>
<tr>
<th>Group</th>
<th>Pre-fit Error (%)</th>
<th>Post-fit error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu$ sample</td>
<td>14.66</td>
<td>5.12</td>
</tr>
<tr>
<td>$\bar{\nu}_\mu$ sample</td>
<td>12.52</td>
<td>4.45</td>
</tr>
<tr>
<td>$\nu_e$ sample</td>
<td>16.85</td>
<td>8.81</td>
</tr>
<tr>
<td>$\bar{\nu}_e$ sample</td>
<td>14.41</td>
<td>7.13</td>
</tr>
<tr>
<td>$\nu_e$ sample with decay electron</td>
<td>21.75</td>
<td>18.38</td>
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</tbody>
</table>
Super-Kamiokande far detector

- 50kt water Cherenkov detector
- Inner detector instrumented with 11000 PMTs for 40% photo coverage
- Excellent $\nu_e/\nu_\mu$ separation and good reconstruction at T2K energy

(a) $\mu$-like ring  
(b) $e$-like ring

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Neutrino oscillation at SK

- \( \nu_\mu \to \nu_\mu = \nu_\mu \to \nu_\mu \)
- \( \Delta m^2_{23} = 2.5 \times 10^{-3} \text{ eV}^2, \sin^2 \theta_{23} = 0.5 \)
- \( 2.5^\circ \) off-axis \( \nu_\mu \) flux

- 2.5° off-axis beam flattens neutrino energy versus parent pion energy
- Results in flux peak in the region of the oscillation maximum

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SK data fits - FHC

FHC 1R\(\mu\)

FHC 1Re

Sample | Asimov A | Data
--- | --- | ---
\(\mu\)-like | 272.4 | 243
\(e\)-like | 72.8 | 75
CC1\(\pi^+\)-like | 6.9 | 15

Asimov A: \(\sin^2 \theta_{13} = 0.0212, \sin^2 \theta_{23} = 0.528,\)
\(\delta_{CP} = -1.601, \Delta m^2_{32} = 2.509 \times 10^{-3} \text{eV}^2 \text{c}^{-4}\)
SK data fits - RHC

RHC 1Rµ

<table>
<thead>
<tr>
<th>Sample</th>
<th>Asimov A</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>µ-like</td>
<td>139.5</td>
<td>140</td>
</tr>
<tr>
<td>e-like</td>
<td>16.8</td>
<td>15</td>
</tr>
</tbody>
</table>

RHC 1Re

θ (degrees)
### SK event rates

<table>
<thead>
<tr>
<th></th>
<th>$\delta_{CP} = -\pi/2$</th>
<th>$\delta_{CP} = 0$</th>
<th>$\delta_{CP} = \pi/2$</th>
<th>$\delta_{CP} = \pi$</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu$-like sample</td>
<td>272.4</td>
<td>272.1</td>
<td>272.4</td>
<td>272.8</td>
<td>243</td>
</tr>
<tr>
<td>$\nu_e$-like sample</td>
<td>72.8</td>
<td>60.8</td>
<td>49.3</td>
<td>61.3</td>
<td>75</td>
</tr>
<tr>
<td>$\bar{\nu}_\mu$-like sample</td>
<td>139.5</td>
<td>139.2</td>
<td>139.5</td>
<td>139.9</td>
<td>140</td>
</tr>
<tr>
<td>$\bar{\nu}_e$-like sample</td>
<td>16.8</td>
<td>19.2</td>
<td>21.3</td>
<td>18.9</td>
<td>15</td>
</tr>
<tr>
<td>$\nu_e$ CC1$\pi^+$-like sample</td>
<td>6.9</td>
<td>6.0</td>
<td>4.8</td>
<td>5.7</td>
<td>15</td>
</tr>
</tbody>
</table>

- $\sin^2 \theta_{12} = 0.307$
- $\Delta m_{21}^2 = 7.530 \times 10^{-5}$ eV$^2$ c$^{-4}$
- $\sin^2 \theta_{23} = 0.528$
- $\Delta m_{32}^2 = 2.509 \times 10^{-3}$ eV$^2$ c$^{-4}$
- $\sin^2 \theta_{13} = 2.12 \times 10^{-2}$
- Normal ordering
\( \delta_{CP} \)

(a) MC

(b) Data

- CP conservation is rejected at 2\(\sigma\)
Comparison of $\delta$ vs mass ordering with sensitivity

- Approximately 5% of toys are more extreme than our data
- 25% of toys exclude CP conservation at $2\sigma$ (both $\delta_{CP} = 0$ and $\delta_{CP} = \pi$)
FC critical value variation

\[ \Delta \chi^2 = \chi^2_{\text{true}} - \chi^2_{\text{min}} \]

- Normal ordering has lower critical values for \( \delta < 0 \)
- Inverted ordering has lower critical values for \( \delta > 0 \)
- Differences between FC and gaussian approx critical values
Degeneracy in $\delta$ and mass order

- Bi-event plot clearly shows $\delta$/mass order degeneracy
- $\Delta \chi^2 = \chi^2_{\text{true}} - \chi^2_{\text{min}}$ allows better fits from wrong mass ordering
- This increases $\Delta \chi^2$ values
- Disallowing fits in the wrong ordering (right plot) lowers critical values and causes convergence of critical values in the two true mass orderings

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$\nu_e$ ($\bar{\nu}_e$) event rate reaches a maximum (minimum) at $\delta = -\pi/2(+\pi/2)$

- Fluctuations to higher $\nu_e$ event rates can’t find lower $\chi^2$ beyond physical boundary
- Toys pileup at the physical boundary (right plot)
- This decreases $\Delta \chi^2$ values (left plot)
Degeneracy between $\delta = 0$ and $\delta = \pi$

Significant degeneracy between $\delta = 0$ and $\delta = \pi$

Fits around $\pm \pi$ evident at lower confidence levels $\rightarrow$ increases $\Delta \chi^2$

Lack of sensitivity to separate 0 and $\pi$ means $\Delta \chi^2 = \chi_0^2 - \chi_{\pi}^2$ is not large enough to populate the tail of the $\Delta \chi^2$ distribution

Effect disappears at higher confidence levels
Summary of critical value behaviour

- Mass ordering is discrete, acts like an additional degree of freedom, raising critical values.
- Physical boundaries lower critical values below gaussian approximation.
Frequentist properties of mass ordering posterior

- Determine the expected posterior probability distribution for the mass ordering using the Feldman-Cousins toys
- Likelihood for hypothesized hierarchy determined by averaging over the likelihoods for 101 bins of $\delta_{CP}$
- Posterior probability is then $P_{post} = \frac{L_{NO}}{L_{NO} + L_{IO}}$
Mass ordering posterior - $\delta_{CP} = -\pi/2$

For 95% threshold, rate of true hypothesis rejection $\sim 6\%$ of rate of false hypothesis rejection
Mass ordering posterior - $\delta_{CP} = 0$

- No sensitivity to determine the mass ordering

work in progress
FC summary plot

- An alternative means of presenting Feldman-Cousins information; both $\delta$ and the mass ordering in a single plot
- Use Feldman-Cousins toys to compute distributions of $\Delta \chi^2 = \chi^2_{NH} - \chi^2_{IH}$ at each true point of $\delta$ and mass ordering
Example distributions for true $\delta = 0$

- Blue and red lines represent $2\sigma$ intervals for true NO and true IO respectively.

work in progress

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FC summary plot

- 2σ intervals
- Intervals offset in $\delta_{CP}$ for readability
Conclusion

- T2K has seen a hint of CP violation, with exclusion of conservation at $2\sigma$ and a best-fit near the maximally CP violating value of $-\pi/2$
- While T2K has limited sensitivity to the mass ordering, the best-fit for $\delta$ is in the region where the ability to reject the inverted mass ordering is greatest