T2K Sensitivities at $25 \times 10^{21}$ POT

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Motivation and Outline

Motivation:

- As the J-PARC beam power continues to increase, there may be the possibility to collect more T2K POT more quickly, or the possibility to request more beam time for T2K
  - This isn’t an official T2K proposal, but instead part of a discussion about what would happen if the T2K run was extended
  - At higher statistics, reduction of systematic errors becomes even more important

Outline:

- T2K sensitivities with high statistics, analysis improvements
  - $\delta_{CP}$ sensitivities at higher POT
    - With different systematic error assumptions and horn currents
  - $\sin^2 \theta_{23}$ and $\Delta m^2_{32}$ sensitivities at $25 \times 10^{21}$ POT
  - Sensitivity to MH by high-statistics T2K alone
Nominal Assumptions

The following were used in these studies unless otherwise stated:

- Joint fit of $\nu_e + \nu_\mu + \bar{\nu}_e + \bar{\nu}_\mu$
  - Fit to the Asimov (nominal) data-set – not the average of an ensemble of toy experiments
- True oscillation parameters: $\sin^2 2\theta_{13} = 0.1$, $\delta_{CP} = -90^\circ$, $\sin^2 \theta_{23} = 0.5$, $\Delta m_{32}^2 = 2.4 \times 10^{-3}$ eV$^2$, normal mass hierarchy
  - $\sim$ T2K, global best fit values
  - All four of these oscillation parameters are fit
- 5% error constraint on $\sin^2 2\theta_{13}$ from external (reactor) experiments (conservative “ultimate expected error”)
- $\sim$2% systematic errors – see next slide
  - Fully correlated between $\nu$- and $\bar{\nu}$-mode
- $\pm 250$ kA horn current
- Assuming enhanced $\pi^0$ rejection using SK fiTQun $\pi^0$ cut

Highlighted points are studied here
Systematic Error Implementation

- Systematic errors are implemented as in Prog. Theor. Exp. Phys. (2015) 043C01
  - Errors implemented as a covariance matrix binned in reconstructed neutrino energy
    - Bins for each of $\nu_e$, $\nu_\mu$, $\bar{\nu}_e$, $\bar{\nu}_\mu$
    - Fully correlated between $\nu$ and $\bar{\nu}$
    - Single nuisance parameter fit for each reconstructed energy bin
    - Matrix generated based on 2012 T2K oscillation analysis errors
  - So, errors on the reconstructed energy spectra shape are considered
- In the paper, assigned a $\sim 7\%$ “conservative” future systematic error on the number of events at SK for both $\nu_e$ and $\nu_\mu$ samples ($\sim 14\%$ for $\bar{\nu}_e$ and $\bar{\nu}_\mu$)
  - $7\% + 14\%$ reduced errors calculated by scaling 2012 error matrix
  - $2\%$ systematic errors shown here:
    - Use the same error sizes for $\nu$ and $\bar{\nu}$ ($\sim 2\%$)
      - Scaled $7\%$ errors down by a factor of $2/7$ for $2\%$ errors
  - Obviously, reaching $\sim 2\%$ systematic error level will take a lot of work by T2K analyzers
Statistics at $7.8 \times 10^{21}$ and $25 \times 10^{21}$ POT

<table>
<thead>
<tr>
<th></th>
<th>$\nu_e$ signal</th>
<th>$\nu_e$ bkg.</th>
<th>$\bar{\nu}_e$ signal</th>
<th>$\bar{\nu}_e$ bkg.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>7.8E21 POT</strong></td>
<td>$\delta = 0$</td>
<td>98.2</td>
<td>26.8</td>
<td>25.6</td>
</tr>
<tr>
<td></td>
<td>$\delta = -90^\circ$</td>
<td>121.4</td>
<td>26.4</td>
<td>19.0</td>
</tr>
<tr>
<td><strong>25E21 POT</strong></td>
<td>$\delta = 0$</td>
<td>314</td>
<td>85.9</td>
<td>82.1</td>
</tr>
<tr>
<td></td>
<td>$\delta = -90^\circ$</td>
<td>389</td>
<td>84.6</td>
<td>60.9</td>
</tr>
</tbody>
</table>

*bkg includes wrong-sign

<table>
<thead>
<tr>
<th></th>
<th>$\nu_\mu$-mode</th>
<th>$\bar{\nu}_\mu$-mode</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>7.8E21 POT</strong></td>
<td>w/o oscillation</td>
<td>2,648</td>
</tr>
<tr>
<td></td>
<td>w/ oscillation</td>
<td>741</td>
</tr>
<tr>
<td><strong>25E21 POT</strong></td>
<td>w/o oscillation</td>
<td>8,519</td>
</tr>
<tr>
<td></td>
<td>w/ oscillation</td>
<td>2,375</td>
</tr>
</tbody>
</table>

50% $\nu^-$ + 50% $\bar{\nu}$-mode
Effect of Reduction of Systematic Errors

- $\Delta\chi^2$ for resolving non-zero $\delta_{CP}$ vs. POT
- Systematic error size matters!
  $\rightarrow$ T2K measurement of $\delta_{CP}$ is systematics limited at high statistics
- Sensitivity depends on true value of $\sin^2 \theta_{23}$ (and $\delta_{CP}$, of course)
  - If errors can be reduced to 2%, T2K can make a $>3\sigma$ measurement of non-zero $\delta_{CP}$ for any value of $\sin^2 \theta_{23}$ (at $\delta_{CP} = -90^\circ$, NH)

50% $\nu^-$ + 50% $\bar{\nu}$-mode
True $\delta_{CP} = -90^\circ$, true MH = NH
Effect of Correlated vs. Uncorrelated Systematic Errors

- Errors are assumed either fully correlated or fully uncorrelated between $\nu$- and $\bar{\nu}$-mode data
- Correlations between systematic errors matter! → Should try to keep systematics as correlated as possible for $\delta_{CP}$ measurement

50% $\nu$- + 50% $\bar{\nu}$-mode
True $\delta_{CP} = -90^\circ$, true MH = NH
Importance of Taking $\nu^- + \bar{\nu}^-$-Mode Data

- T2K needs to take a combination of $\nu^- + \bar{\nu}^-$-mode to have highest sensitivity to a non-zero $\delta_{CP}$

100% $\nu$-mode

50% $\nu^- + 50\% \bar{\nu}$-mode
Different Ratios of $\nu^- + \bar{\nu}$-Mode Data

- Best choice of running ratio for maximum sensitivity to a non-zero $\delta_{CP}$ depends on the true value of $\sin^2 \theta_{23}$
- But $\sim 50\% \nu^- + 50\% \bar{\nu}$-mode gives best sensitivity for more possible values of $\sin^2 \theta_{23}$ (including $\sin^2 \theta_{23} = 0.5$)

67\% $\nu^- + 33\% \bar{\nu}$-mode

25\% $\nu^- + 75\% \bar{\nu}$-mode
\( \Delta \chi^2 \) for resolving non-zero \( \delta_{CP} \) vs. true \( \delta_{CP} \)

- 50% \( \nu^- \) + 50% \( \bar{\nu} \)-mode
- Unknown MH (true NH)
- Sensitivity is best at \(-90^\circ\) (current best fit point)

- \( 25 \times 10^{21} \) POT
- Full T2K Stats. \((7.8 \times 10^{21} \) POT\)
**\( \delta_{CP} \) Sensitivity vs. True \( \delta_{CP} \)**

- MH is known if an outside experiment measures the MH
- \( \Delta \chi^2 \) for resolving non-zero \( \delta_{CP} \) vs. true \( \delta_{CP} \)
- 50% \( \nu^- + 50\% \bar{\nu}- \)-mode, \( 25 \times 10^{21} \) POT, true NH
- Sensitivity is greatly improved at \(+90^\circ\) if MH is known
  - Known MH: \( \Delta \chi^2 \) is greater than 99% CL for 45% of \( \delta_{CP} \) values, and greater than 3\( \sigma \) for 30% of \( \delta_{CP} \) values
  - Unknown MH: \( \Delta \chi^2 \) is greater than 99% CL for 20% of \( \delta_{CP} \) values, and greater than 3\( \sigma \) for 10% of \( \delta_{CP} \) values

Known MH

Unknown MH
Improvement at ±320 kA Horn Current

Enhanced signal, reduced background at ±320 kA
→ Substantial improvement
\( \delta_{CP} \) vs. \( \sin^2 2\theta_{13} \) Sensitivity 90\% C.L.

Contour

\[
3.9 \times 10^{21} \text{ POT } \nu^- + 3.9 \times 10^{21} \text{ POT } \bar{\nu}\text{-mode}
\]

\[
12.5 \times 10^{21} \text{ POT } \nu^- + 12.5 \times 10^{21} \text{ POT } \bar{\nu}\text{-mode}
\]

No outside (reactor) constraint on \( \sin^2 2\theta_{13} \)
\( \delta_{CP} \) Precision

- NH (known), \( \delta_{CP} = -90^\circ \), \( \sin^2 \theta_{23} = 0.5 \)
- \( 25 \times 10^{21} \) POT: \( \sigma \sim 36^\circ \) (no sys. err.), \( \sim 45^\circ \) (w/ 2% sys. err.)
- \( 7.8 \times 10^{21} \) POT: \( \sigma \sim 63^\circ \)
- Further improvement if constraint on \( \sin^2 2\theta_{13} \) is used
$\delta_{CP}$ Sensitivity $\Delta \chi^2$ at $25 \times 10^{21}$ Total POT
\[ \Delta m^2_{32} \text{ vs. } \sin^2 \theta_{23} \text{ Sensitivity 90\% C.L. Contour} \]

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

\[ \sin^2 \theta_{23} = 0.53 \]

- Shown for NH only (true NH)
- Measurement at \(25 \times 10^{21}\) POT: \(\theta_{23} = 45 \pm 1.9^\circ\)
  - Current best measurement is \(46 \pm 3^\circ\) by T2K
T2K Sensitivity to Resolving MH

- $\Delta \chi^2$ for resolving MH (true NH)
- $12.5 \times 10^{21}$ POT $\nu^{-}$ + $12.5 \times 10^{21}$ POT $\bar{\nu}$-mode
- With 2% systematic errors
- Sensitivity isn’t so great.. will be more significant when combined with NO\(\nu\)A results
Conclusion

- At $25 \times 10^{21}$ POT, 2% systematic errors, T2K can achieve $>3\sigma$ measurement of non-zero $\delta_{CP}$ (at true $\delta_{CP} = -90^\circ$, NH)
  - Reducing systematic errors as much as possible ($\rightarrow$ 2% systematic errors if possible) is beneficial
  - Increasing the horn current increases the sensitivity (or increases the speed at which T2K can reach high sensitivity)
- Possible T2K constraints on other parameters ($\sin^2 \theta_{23}$, MH) are less impressive, but T2K can continue to help provide better constraints on these parameters, and can be a major contributor to global fits
Backup Slides
$\delta_{CP}$ vs. $\sin^2 2\theta_{13}$ Sensitivity $\Delta \chi^2$:
$25 \times 10^{21}$ $\nu$-Mode POT

w/out Reactor

w/ Reactor
$\delta_{CP}$ vs. $\sin^2 2\theta_{13}$ Sensitivity $\Delta \chi^2$:

$50 \times 10^{21}$ $\nu$-Mode POT

w/out Reactor

w/ Reactor
$\delta_{CP}$ vs. $\sin^2 2\theta_{13}$ Sensitivity $\Delta \chi^2$:
$12.5 \times 10^{21} \nu - + 12.5 \times 10^{21} \bar{\nu}$-Mode POT
\( \delta_{CP} \) vs. \( \sin^2 2\theta_{13} \) Sensitivity \( \Delta \chi^2 \):

\[
25 \times 10^{21} \nu^- + 25 \times 10^{21} \bar{\nu} - \text{Mode POT}
\]

w/out Reactor

w/ Reactor
$\delta_{CP}$ Sensitivity $\Delta \chi^2$ at $50 \times 10^{21}$ Total POT

w/out Reactor

w/ Reactor