Results and Prospects from T2K

Kirsty Duffy, for the T2K collaboration

NuFact 2015, 11\textsuperscript{th} August 2015
• The T2K Experiment
• Oscillation Analysis on T2K
• New results from antineutrino running
  • $\bar{\nu}_e$ appearance
  • $\bar{\nu}_\mu$ disappearance
• Future prospects
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The T2K Experiment

$\nu_\mu, \nu_e, (\nu_\tau)$

Super-Kamiokande, near Kamioka, Gifu

295km

J-PARC: ND280 and INGRID, Tokai

$\nu_\mu$
T2K Near Detectors

ND280:
- Off-axis by 2.5° (same as far detector)
- Used to reduce flux and cross-section uncertainties for oscillation analysis:
  - Fine-Grained Detectors: targets. Excellent vertexing
  - Time-Projection Chambers: excellent momentum resolution and particle ID

INGRID:
- On-axis
- Used to measure beam stability, estimate flux uncertainty before ND280 fit

Both detectors also used for cross-section measurements: see talks by S. Bolognesi, A. Furmanski, M. Nirkko
T2K Far Detector: Super-K

- 50 kton water Cherenkov detector (22.5kton fiducial volume)
- Neutrino flavour identification from pattern of Cherenkov light from charged particle (<1% $\nu_\mu$ misidentified as $\nu_e$)
- No magnetic field
Beam Operations

Great East Japan Earthquake

Beam Start:
Jan 2010

7.00x10^{20} POT in ν-mode

4.04x10^{20} POT in \bar{\nu}-mode

Total:
11.04x10^{20} POT
(14% of total expected POT)
Beam Operations

Stable operation at **345kW**

Maximum beam power: **371kW**

Beam Start: Jan 2010

- 7.00x10^{20} POT in ν-mode
- 4.04x10^{20} POT in ν-mode

Great East Japan Earthquake

Stable operation at 345kW

Maximum beam power: 371kW

Total Accumulated POT for Physics

- ν-Mode Beam Power
- ν-Mode Beam Power

Run3 Run4 Run5 Run6

Run6

Accumulated # of Protons

0 0.5 1 1.5 2 2.5 3 3.5 4

Nov/06 Dec/06 Jan/05 Feb/04 Mar/04 Apr/05 May/05

Averaged Beam Power Per Hour (kW)

0 50 100 150 200 250 300 350 400
Neutrino Oscillation at T2K

\[ \nu_\mu \rightarrow \nu_\mu \]

No \( \nu \) oscillations

With \( \nu \) oscillations

Location of dip: \( \Delta m^2_{32} \)

Depth of dip: \( \sin^2 \theta_{23} \)

Magnitude of peak: \( \sin^2 \theta_{13}, \delta_{CP}, MH \)
**Previous T2K Measurements**

First measurement of $\nu_e$ appearance (7.3σ).
Independent measurement of $\theta_{13}$
(analyses performed with and without reactor constraint on $\theta_{13}$, $\sin^2 2\theta_{13} = 0.095 \pm 0.01$)

- 90% constraint on $\delta_{CP}$.

**Open questions:**
- Mass Hierarchy
- CP phase, $\delta_{CP}$
  (appearance measurements at long baseline experiments well suited to this)

World-leading measurement of $\theta_{23}$.
Significant measurement of $\Delta m^2_{32}$.

Abe, K. et al, Physical Review D 91.7 (2015): 072010
Antineutrino running at T2K

Sensitivity studies using full expected T2K POT ($7.8 \times 10^{21}$), without reactor constraint on $\theta_{13}$:

- T2K is sensitive to $\delta_{CP}$ when combining $\nu$ and $\bar{\nu}$
- Can test CPT theorem, nonstandard matter effects by comparing $\nu_\mu$ and $\bar{\nu}_\mu$ disappearance
- Comparison with reactor measurement gives a test of the PMNS framework
• The T2K Experiment

• Oscillation Analysis on T2K

• New results from antineutrino running
  • $\bar{\nu}_e$ appearance
  • $\bar{\nu}_\mu$ disappearance

• Future prospects
Flux Model

Cross-section Model

ND280 Detector Model

ND280 Data

ND data reduces flux and cross-section uncertainties

Oscillation Parameters

Super-K Data

Super-K Detector Model

ND280 Fit

Oscillation Fit

INGRID/Beam monitor Data

External Cross-section Data

NA61/SHINE Data
Near Detector Fit

- Near detector fit includes $\nu$-mode and $\bar{\nu}$-mode samples
  - $\nu$-mode: CC0$\pi$, CC1$\pi$, CC Other
  - $\bar{\nu}$-mode: $\bar{\nu}_\mu$ CC 1 track, $\bar{\nu}_\mu$ CC >1 track, $\nu_\mu$ CC 1 track, $\nu_\mu$ CC >1 track

- Fit in momentum and angle of outgoing lepton

- Used to:
  - constrain Super-K flux prediction through correlations with Near Detector flux (using beam models)
  - reduce cross-section uncertainty at Super-K by fitting parameter values in underlying models
  - estimate correlations between flux and cross-section parameters

For more information see talk “Experience from T2K near detectors” by Prof. K. Mahn (WG1+2 Parallel)
Near Detector Fit

- Predicted flux at Super-K is generally increased
- Some cross-section parameters are significantly different to prior values
- In general error on parameters is decreased
Near Detector Constraint at Super-K

The near detector significantly reduces the systematic uncertainty in the predicted event rate at Super-K

<table>
<thead>
<tr>
<th>Systematic</th>
<th>Without ND</th>
<th>With ND</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flux and Cross-section</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Common to ND280/SK</td>
<td>9.2%</td>
<td>3.4%</td>
</tr>
<tr>
<td>Super-K Only</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multi-nucleon effect on oxygen</td>
<td>9.5%</td>
<td></td>
</tr>
<tr>
<td>All Super-K Only</td>
<td>10.0%</td>
<td></td>
</tr>
<tr>
<td>All</td>
<td>13.0%</td>
<td>10.1%</td>
</tr>
<tr>
<td>Final State Interaction/Secondary Interaction at Super-K</td>
<td>2.1%</td>
<td></td>
</tr>
<tr>
<td>Super-K Detector</td>
<td>3.8%</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>14.4%</td>
<td>11.6%</td>
</tr>
</tbody>
</table>
• The T2K Experiment
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$\bar{\nu}_e$ appearance: analysis method

Introduce a discrete parameter $\beta$ to modify the $\bar{\nu}_e$ appearance probability:

$$P(\bar{\nu}_\mu \to \bar{\nu}_e) = \beta \times P_{PMNS}(\bar{\nu}_\mu \to \bar{\nu}_e)$$

Aside from this, assume CPT symmetry (oscillation parameters are the same for neutrinos and anti-neutrinos)

$\beta = 1$: $\bar{\nu}_e$ appearance in accordance with the PMNS prediction (including CP violation)

$\beta = 0$: No $\bar{\nu}_e$ appearance (new physics!)

$\beta$ switches this component on/off
$\bar{\nu}_e$ appearance: analysis method

Introduce a discrete parameter $\beta$ to modify the $\bar{\nu}_e$ appearance probability:

$$ P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = \beta \times P_{PMNS}(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) $$

We report significance for $\beta = 1$ in two ways:

• a **p-value** to characterise how anomalous our data is with respect to the $\beta = 0$ hypothesis

• a **Bayes factor ($B_{10}$)** to characterise how our data favours $\beta = 1$ over $\beta = 0$

In both cases we present two results: one using shape information in **reconstructed (anti-)neutrino energy ($E_{rec}$)** and one using shape information from **lepton kinematics ($p-\theta$)**
$\bar{\nu}_e$ appearance: analysis method

The analysis is based on the **marginal likelihood**, with all parameters other than $\beta$ integrated out:

$$\mathcal{L}(\beta) = \int \int \sum_{SK \text{ bins}} \mathcal{L}_{\text{Poisson,bin}}(\beta, \tilde{\phi}, \tilde{f}) \times \pi_{\text{Syst.}}(\tilde{f}) \times \pi_{\text{Osc.}}(\tilde{\phi}) d\tilde{\phi} d\tilde{f}$$

Prior from T2K $\nu$-mode fits ($\delta_{CP} = -1.6$)

**P-value:**

Test statistic is

$$-2(ln\mathcal{L}(\beta = 1) - ln\mathcal{L}(\beta = 0))$$

Compare to ensemble of test experiments created with $\beta=0$
\[ \bar{\nu}_e \text{ appearance: analysis method} \]

The analysis is based on the **marginal likelihood**, with all parameters other than \( \beta \) integrated out:

\[
\mathcal{L}(\beta) = \int \int \sum_{SK \text{ bins}} \mathcal{L}_{\text{Poisson,bin}}(\beta, \hat{\delta}, \hat{f}) \times \pi_{\text{Syst.}}(\hat{f}) \times \pi_{\text{Osc.}}(\hat{\delta}) d\hat{\delta} d\hat{f}
\]

**Prior from T2K \( \nu \)-mode fits** \((\delta_{CP} = -1.6)\)

**P-value:**
Test statistic is
\[-2(ln\mathcal{L}(\beta = 1) - ln\mathcal{L}(\beta = 0))\]

Compare to ensemble of test experiments created with \( \beta = 0 \)

**Bayes factor:**
Given by the posterior odds:
\[
B_{10} = \frac{\mathcal{L}(\text{Data}|\beta = 1)}{\mathcal{L}(\text{Data}|\beta = 0)}
\]
$\bar{\nu}_e$ appearance results
**$\bar{\nu}_e$ appearance: data**

- The current data set contains 3 events
- Prediction (using T2K $\nu$-mode oscillation parameters) is **3.7 events** under $\beta = 1$ and **1.3 events** under $\beta = 0$

**Event selection criteria at Super-K**
- Electron-like PID
- Fully contained in fiducial volume
- Only 1 reconstructed ring
- No decay electrons
- $p_e > 100$ MeV
- $\nu$ Erec $< 1250$ MeV
- Passes $\pi^0$ rejection
\( \bar{\nu}_e \) appearance: results

\[-2\Delta \ln \mathcal{L}_{P-\theta} = -1.16 \]
\[-2\Delta \ln \mathcal{L}_{E_{\text{rec}}} = 0.16 \]

P-values from data fit:

<table>
<thead>
<tr>
<th>Shape term</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \bar{\nu} \ E_{\text{rec}} )</td>
<td>0.16</td>
</tr>
<tr>
<td>Lepton P-( \theta )</td>
<td>0.34</td>
</tr>
</tbody>
</table>

Bayes factors from data fit:

<table>
<thead>
<tr>
<th>Shape term</th>
<th>( B_{10} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \bar{\nu} \ E_{\text{rec}} )</td>
<td>1.1</td>
</tr>
<tr>
<td>Lepton P-( \theta )</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Current data set does not provide sufficient evidence to support \( \beta = 1 \) over \( \beta = 0 \)
Future predictions for $\bar{\nu}_e$ appearance

Current data set is $4.011 \times 10^{20}$ POT and contains 3 events. Using the fitting method described here, we can expect:

- At $9.0 \times 10^{20}$ POT in $\bar{\nu}$-mode ($\approx$1 year): $p$-value $< 0.02$, Bayes factor $\approx 10$
- At $20 \times 10^{20}$ POT in $\bar{\nu}$-mode: Bayes factor $\approx 100$

(Note: predictions assume PMNS prediction is exactly correct, no statistical uncertainty)
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$\bar{\nu}_\mu$ disappearance: analysis method

Fit maximises a marginal likelihood, $\mathcal{L}$:

$$\mathcal{L} = \int \sum_{SK\, bins} \mathcal{L}_{Poisson, bin} (\hat{d}, \hat{f}) \times \pi_{Syst.}(\hat{f}) \, d\hat{f}$$

Bin data and prediction in $\bar{\nu}$ reconstructed energy.

Fix all oscillation parameters except $\sin^2 \theta_{23}$ and $\Delta m^2_{32}$ using T2K data and PDG 2014.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sin^2 \theta_{23}$</td>
<td>0.527</td>
<td>$\sin^2 \bar{\theta}_{23}$</td>
<td>0–1</td>
</tr>
<tr>
<td>$\Delta m^2_{32}$ ($\times 10^{-3} \text{eV}^2$)</td>
<td>2.51</td>
<td>$\Delta m^2_{32}$ ($\times 10^{-3} \text{eV}^2$)</td>
<td>0–20</td>
</tr>
<tr>
<td>$\sin^2 \theta_{13}$</td>
<td>0.0248</td>
<td>$\sin^2 \bar{\theta}_{13}$</td>
<td>0.0248</td>
</tr>
<tr>
<td>$\delta_{CP}$ (radians)</td>
<td>-1.55</td>
<td>$\bar{\delta}_{CP}$ (radians)</td>
<td>-1.55</td>
</tr>
<tr>
<td>$\sin^2 \theta_{12}$</td>
<td>0.304</td>
<td>$\sin^2 \bar{\theta}_{12}$</td>
<td>0.304</td>
</tr>
<tr>
<td>$\Delta m^2_{21}$ ($\times 10^{-5} \text{eV}^2$)</td>
<td>7.53</td>
<td>$\Delta m^2_{21}$ ($\times 10^{-5} \text{eV}^2$)</td>
<td>7.53</td>
</tr>
</tbody>
</table>
$\bar{\nu}_\mu$ disappearance results
$\bar{\nu}_\mu$ disappearance: data

34 events in $\bar{\nu}$-mode muon-like sample

Event selection criteria at Super-K
- Muon-like PID
- Fully contained in fiducial volume
- Only 1 reconstructed ring
- $\leq 1$ decay electron(s)
- $p_\mu > 200$ MeV

Best-fit reconstructed energy spectrum shows clear evidence of oscillation.
$\bar{\nu}_\mu$ disappearance: results

Best fit values: $sin^2 \theta_{23} = 0.46^{+0.14}_{-0.06}$

$\Delta m^2_{32} = 2.50^{+0.3}_{-0.2} \times 10^{-3} eV^2$
$\bar{\nu}_\mu$ disappearance: Comparison to T2K $\nu_\mu + \nu_e$ fit

- Results are consistent between neutrinos and antineutrinos
- Antineutrino analysis has much larger contours
$\bar{\nu}_\mu$ disappearance: Comparison to MINOS

- MINOS contour was made in $\sin^2 2\theta_{23}$ and unfolded
- Includes $\bar{\nu}$ beam and atmospheric data
- T2K contour is slightly smaller in $\sin^2 \theta_{23}$, and both see a non-maximal best-fit point
- Results are compatible

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Analysis Updates

• Analysis improvement: add **FGD 2 sample** to ND280 fit
  • FGD 2 target material includes **water** (same as Super-K)
  • Addition of FGD 2 data will allow ND to constrain more cross-section systematics
    • Current ND280 fit has little power to constrain systematics on oxygen ("Super-K only cross-section uncertainty" from table on slide 13)
    • Relative error between interactions on carbon and oxygen not well understood
    • These systematics account for the majority of the cross-section uncertainty

• **Joint fit** of $\nu$-mode and $\bar{\nu}$-mode data
  • Better constraint of $\delta_{CP}$
  • Test PMNS framework and search for nonstandard matter effects or CPT violation
Summary

• Presented first T2K results based on anti-neutrino data:
  • Analysis of $\bar{\nu}_e$ appearance
    • P-value > 15%, Bayes factor ≈ 1
  • Measurement of $\bar{\nu}_\mu$ disappearance
    • $\sin^2\theta_{23} = 0.46^{+0.14}_{-0.06}$
    • $\Delta m^2_{32} = 2.50^{+0.3}_{-0.2} \times 10^{-3} eV^2$

• Both analyses are statistics-limited

• Upcoming analysis improvements: Near-detector water sample and joint ν-mode + $\bar{\nu}$-mode fit

• $\bar{\nu}$-mode running continues: collect more data and provide improved measurement of anti-neutrino oscillation
Backup slides
Previous T2K Results

Great East Japan Earthquake

Beam Start: Jan 2010

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

Accumulated # of Protons

- $\nu_e$ app. $2.5\sigma$
- $\nu_\mu$ disapp. first result
- $\nu_e$ app. $7.3\sigma$
- $\nu_\mu$ disapp. highest $\theta_{23}$ precision

First $\delta_{CP}$ constraint

First $\bar{\nu}$ analyses

14% of total expected POT

Kirsty Duffy  •  NuFact 2015  •  37/35
ND280 Event Selection

ND280 uses different event selections for the $\nu$-mode and $\bar{\nu}$-mode samples (both necessary because Super-K can’t distinguish charge)

$\bar{\nu}$ selection
Select CC $\bar{\nu}_\mu$ candidates based on interactions with $\mu^+$:
- Highest momentum track in event has positive charge (compatible with $\mu^+$)
- This track has PID compatible with a muon

CC 1 track and CC > 1 track ($\bar{\nu}$ and $\nu$ selection in $\bar{\nu}$-mode)
Separate into two samples based on number of tracks in final state
- CC 1 track (sensitive to T2K signal mode)
- CC >1 track (sensitive to T2K background modes)

$\nu$ selection
Select CC $\nu_\mu$ candidates based on interactions with $\mu^-$:
- Highest momentum track in event has negative charge (compatible with $\mu^-$)
- This track has PID compatible with a muon

CC 0$\pi$, CC 1$\pi$, CC Other ($\nu$ selection in $\nu$-mode)
Separate into three samples based on presence of charged pion in final state
- Pions identified using track multiplicity, $dE/dX$ in TPCs, photons in ECALs
Beam Content (ν-mode and \(\bar{\nu}\)-mode)

- Much more wrong-sign contamination in \(\bar{\nu}\)-mode than ν-mode beam
- This, and smaller cross-sections for \(\bar{\nu}\) than ν, lead to the right-sign interaction rate in \(\bar{\nu}\)-mode being roughly 1/3 of the right-sign interaction rate in ν-mode
Event Vertices at Super-K ($\bar{\nu}$-mode)

$\bar{\nu}$-mode $\mu$-like selection
34 events

$\bar{\nu}$-mode $e$-like selection
3 events

Beach direction
Fiducial volume boundary
- Events during run 5
- Events during run 6
- Out of fiducial volume events
Event Vertices at Super-K (ν-mode)

**ν-mode μ-like selection**

- 120 events

**ν-mode e-like selection**

- 28 events

- Beam direction
- Fiducial volume boundary
- Events during run 1+2+3
- Events during run 4
- Out of fiducial volume events
$\bar{\nu}_e$ appearance: sensitivity

Calculate ‘expected’ p-value as the mean p-value for an ensemble of fake data experiments created with $\beta = 1$

Distribution of p-value for $\beta = 1$ fake experiments using Lepton P-\(\theta\) shape information

Mean p-value = 0.134

Distribution of p-value for $\beta = 1$ fake experiments using $\bar{\nu}$ $E_{\text{rec}}$ shape information

Mean p-value = 0.14
$\bar{\nu}_e$ appearance: Rate-only p-value

Rate-only p-value: Fraction of test experiments (created with $\beta = 0$) that have as many or more candidates as the T2K data.

<table>
<thead>
<tr>
<th>'Expected' p-value</th>
<th>Data p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.20</td>
<td>0.26</td>
</tr>
</tbody>
</table>

'Expected' p-value: Mean p-value from fitting an ensemble of fake data experiments created with $\beta = 1$.
$\bar{\nu}_e$ appearance: p-value for $\beta = 1$

$-2\Delta \ln \mathcal{L}_{P-\theta} = -1.16$

$-2\Delta \ln \mathcal{L}_{E_{\text{rec}}} = 0.16$

Distribution of test statistic for $\beta = 1$ using Lepton P-$\theta$ shape information

P-values from data fit:

<table>
<thead>
<tr>
<th>Shape term</th>
<th>P-value (cf. $\beta = 0$)</th>
<th>P-value (cf. $\beta = 1$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{\nu}$ $E_{\text{rec}}$</td>
<td>0.16</td>
<td>0.28</td>
</tr>
<tr>
<td>Lepton P-$\theta$</td>
<td>0.34</td>
<td>0.14</td>
</tr>
</tbody>
</table>

Bayes factors from data fit:

<table>
<thead>
<tr>
<th>Shape term</th>
<th>$B_{10}$ (cf. $\beta = 0$)</th>
<th>$B_{01}$ (cf. $\beta = 1$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{\nu}$ $E_{\text{rec}}$</td>
<td>1.1</td>
<td>0.9</td>
</tr>
<tr>
<td>Lepton P-$\theta$</td>
<td>0.6</td>
<td>1.7</td>
</tr>
</tbody>
</table>

Current data set does not provide sufficient evidence to support $\beta = 1$ over $\beta = 0$
\( \bar{\nu}_e \) appearance: shape terms

Why is the result so different depending on which shape term we use?

Data in lepton p-\( \theta \):

- \( \beta = 1 \)
- \( \beta = 0 \)

Data in \( \bar{\nu} E_{\text{rec}} \):

\[ \begin{align*}
\text{MC } \times 10
\end{align*} \]
Bayes factors

- The Bayes factor gives the posterior odds (given the data) of the two models $\beta = 1$ and $\beta = 0$.
- If we use equal priors on the two models it is equal to the ratio of marginal likelihoods:

$$B_{10} = \frac{\mathcal{L}(Data|\beta = 1)}{\mathcal{L}(Data|\beta = 0)}$$

By imposing the condition that the two models span the whole space of possibility, we can find the ‘level of belief’ in the $\beta = 1$ model given the data:

<table>
<thead>
<tr>
<th>$B_{10}$</th>
<th>$\log_{10}B_{10}$</th>
<th>Level of belief in $\beta = 1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&lt; 1$</td>
<td>$&lt; 0$</td>
<td>$&lt; 50%$</td>
</tr>
<tr>
<td>10</td>
<td>1</td>
<td>91%</td>
</tr>
<tr>
<td>100</td>
<td>2</td>
<td>99%</td>
</tr>
</tbody>
</table>
Comparing Bayes factors to p-values

There is no easy way to relate a Bayes factor to a p-value, because they have a fundamentally different interpretation:

- **P-value**: how likely is it that these data have arisen by chance under the null hypothesis?
  - Can only be used to reject hypotheses
  - Does not provide evidence in favour of the alternative
- **Bayes factor**: likelihood that a given hypothesis is true
  - Both hypotheses on equal footing
  - Can provide evidence *for* the null or *for* the alternative

**However**, we can relate the Bayes factor to the test statistic used to create the p-value (cross-check between analyses)
Priors for $\bar{\nu}_e$ appearance analysis

Priors for the oscillation parameters were taken from the posterior of the T2K Run 1-4 joint fit (2014):

$\delta_{CP} - \sin^2 \theta_{13}$

Normal Hierarchy

$\Delta m^2_{32} - \sin^2 \theta_{23}$

Both Hierarchies
$\bar{\nu}_\mu$ disappearance: Effect of systematics

Analysis is still very much statistics-dominated
$\bar{\nu}_\mu$ disappearance: Bayesian vs. Frequentist approach

T2K has both Bayesian and Frequentist analyses, which produce two different sets of contours:

- **Frequentist: confidence intervals** (if you repeated the experiment, there is a 90% chance of getting a best-fit point within the 90% contour)
- **Bayesian: credible intervals** (given this experiment with this data, there is a 90% chance that the true value is within the 90% contour)

These sound similar but are very different in philosophy – may produce very different results!
$\bar{\nu}_\mu$ disappearance: Bayesian vs. Frequentist approach

Expected confidence and credible intervals studied by fitting an Asimov data set

"Asimov": the content of every bin in the 'data' is set exactly equal to the PMNS prediction (no statistical errors)