T2K Neutrino Oscillation Measurements

Roberto Sacco
for the T2K Collaboration

Lake Louise Winter Institute, February 22nd 2013
Introduction

Flavour mixing is a well-known phenomenon, happening when flavour eigenstates differ from mass eigenstates - described by a 3x3 mixing matrix:

- CKM matrix in the quark sector
  - measured to high precision
  - almost diagonal
- PMNS matrix in the neutrino sector
  - not as well measured as CKM
  - non-diagonal

\[ \nu_\alpha = \sum_{i=1}^{n} U_{\alpha i} \nu_i \]

\[
U = \begin{pmatrix}
1 & c_{23} & s_{23} \\
-s_{23} & c_{23} & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
c_{13} & -s_{13}e^{i\delta} & 0 \\
s_{13}e^{-i\delta} & c_{13} & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

Accelerator, atmospheric ν:

\[ \theta_{23} \sim 45^\circ \]

\[ \Delta m^2_{32} = 2.32 \times 10^{-3} \text{ eV}^2 \]
Introduction

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\[
U = \begin{pmatrix} 1 & c_{23} & s_{23} \\ -s_{23} & c_{23} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & & -s_{13}e^{i\delta} \\ & 1 & \\ -s_{13}e^{-i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} \\ -s_{12} & c_{12} \\ 0 & 0 \end{pmatrix}
\]

Solar and reactor ν: \[\theta_{12} \sim 34^\circ, \quad \Delta m_{21}^2 = 7.5 \times 10^{-5} \text{ eV}^2\]
Flavour mixing is a well-known phenomenon, happening when flavour eigenstates differ from mass eigenstates - described by a 3x3 mixing matrix:

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\begin{pmatrix}
c_{12} & s_{12} \\
-s_{12} & c_{12} \\
0 & 0
\end{pmatrix}
\]

Interference term: \( \theta_{13} \sim 9^\circ \), larger than expected!
\( \delta \) unknown
Introduction

Sensitivity to the PMNS matrix elements in long baseline experiments:

- $\nu_\mu$ disappearance

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2 \theta_{23} \sin^2 1.27 \frac{\Delta m^2_{32} L}{E_\nu}$$

sensitive to parameters $\theta_{23}$ and $\Delta m^2_{32}$

- $\nu_e$ appearance

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E_\nu} + \text{CPV term} + \text{subleading terms}$$

sensitive to parameter $\theta_{13}$

sensitive to parameter $\delta$

containing matter effect terms - change sign for $\bar{\nu}_\mu$ - mass hierarchy
The T2K Experiment

**T2K was designed to study neutrino oscillations by:**

- measuring $\nu_\mu$ disappearance
  - looking at deficit of $\nu_\mu$ rate and distortion of $\nu_\mu$ spectrum
- measuring $\nu_e$ appearance
  - looking at excess of $\nu_e$ events over background
The T2K accelerator complex

High power accelerator, providing a 30 GeV proton beam
The T2K beam

- Intense proton beam striking 90 cm graphite target
  - up to $1.1 \times 10^{14}$ p extracted every 2.5 to 3 s
- Three magnetic horns focus positively charged hadrons
  - $\nu_\mu$ from pion decay
  - (small) $\nu_e$ contamination from $\mu$ and K decay
- 2.5 degree off-axis beam
  - narrow band in energy
  - peaks at $\nu_\mu$ oscillation maximum

charged hadron production is studied on data from the CERN NA61 experiment, using a T2K replica target
The T2K dataset (June 2012)

Data runs until 2012/06/09

Protons on target (POT): $3.010 \times 10^{20}$
The T2K near detector complex

**On-axis: INGRID**

ν beam profile and direction monitor

14 iron-scintillator modules span a 10x10 m$^2$ surface beam centre:

- $0.01 \pm 0.33$ mrad (X)
- $0.11 \pm 0.37$ mrad (Y)

**Off-axis: ND280**

ν flux normalisation, cross-sections

inside UA1 magnet (0.2 T):

- 2 fine-grained detectors (FGD)
- water/carbon target
- 3 gas TPCs
- π$^0$ detector (P0D)
- electromagnetic calorimeter (ECal)

instrumented magnet yoke: SMRD

See B. Jamieson’s talk
Beam stability

**Muon Monitor**

![Muon Monitor graph showing pulse by pulse stability over different runs.](image)

**INGRID**

![INGRID graph showing number of events over different runs.](image)
The T2K far detector
The T2K far detector

Super-Kamiokande, 295 km away from J-PARC

- 22.5 kton fiducial mass Cherenkov detector (water target)
- 11129 PMTs instrument the inner region
- 1885 PMTs instrument the outer (veto) region
- select $\nu_\mu$ or $\nu_e$ events from ring shape and topology
Analysis strategy

**Maximize a global likelihood** with respect to oscillation, beam and cross-section parameters \((o, b, x)\):

\[
\mathcal{L}_{\text{tot}}(\vec{b}, \vec{x}, \vec{o}) = \mathcal{L}_{\text{pbeam}}(\vec{b}) \times \mathcal{L}_{\text{NA61}}(\vec{b}) \times \mathcal{L}_{\text{ext-}\nu}(\vec{x}) \times \mathcal{L}_{\text{ND280}}(\vec{b}, \vec{x}) \times \mathcal{L}_{\text{SK}}(\vec{b}, \vec{x}, \vec{o})
\]

...too cumbersome!

Better a **piecewise approach**: data fitted in steps, with constraints on \(b\) and \(x\) propagated between steps and proper modelling of correlations and uncertainties.

Factorize the joint likelihood into

- a part that depends on beam, cross-section, and ND280 parameters \(b, x\)
- a part that depends on SK data and \(o\)
- in a way that makes it possible to take into account correlations

and combine the two in the final oscillation fit.
Analysis strategy: beam flux prediction

Combine constraints from geometry, beam monitors, NA61 into a likelihood $\mathcal{L}_{\text{flux}}(\vec{b})$

- GEANT3 simulation of neutrino production from graphite target
- pion and kaon production tuned to experimental data (NA61)
- Normalisation in bins of $E_\nu$ and $\nu$ flavour

10-15% total error (before ND280 constraints)
Analysis strategy: cross-section parametrisation

Combine **prior knowledge on ν cross sections** into a likelihood $\mathcal{L}_{\text{xsec}}(\vec{x})$:

- Cross sections modelled with **NEUT** (and **GENIE**)
- External constraints given by **MiniBooNE**, checks on data from SciBooNE, NOMAD, etc.

Cross-section parameters model the signal and backgrounds in outgoing lepton momentum and angle:

<table>
<thead>
<tr>
<th>Cross-section Type</th>
<th>Normalization</th>
</tr>
</thead>
<tbody>
<tr>
<td>QE1 $0 &lt; E_\nu &lt; 1.5$ GeV</td>
<td>normalization</td>
</tr>
<tr>
<td>QE2 $1.5 &lt; E_\nu &lt; 3.5$ GeV</td>
<td>normalization</td>
</tr>
<tr>
<td>QE3 $E_\nu &gt; 3.5$ GeV</td>
<td>normalization</td>
</tr>
<tr>
<td>CC1π $E_\nu &lt; 2.5$ GeV</td>
<td>normalization</td>
</tr>
<tr>
<td>CC1π $E_\nu &gt; 2.5$ GeV</td>
<td>normalization</td>
</tr>
<tr>
<td>NC1π$^0$</td>
<td>normalization</td>
</tr>
</tbody>
</table>

- **QE** axial mass (QE)
- **RES** axial mass (1π)
- **pF** Fermi momentum
- **EB** binding energy
- **Spectral Function** model comparison
- **CC other** uncertainty
- **CC Coherent** uncertainty

Model uncertainty on normalization and change x-section in non-trivial way reweighting technique to ensure same cross-section changes at ND280 and SK.

Modelled as detector systematics.
Analysis strategy: ND280 input

Combine **constraints on ν flux and cross-sections** coming from **ND280** into a likelihood \( \mathcal{L}_{\text{ND280}}(\vec{b}, \vec{x}, \vec{d}) \)

- Divide ND280 data into two samples binned in \( p_\mu \) vs \( \theta_\mu \):
  - Charged current quasi-elastic (CCQE)-enhanced: \( \nu + n \rightarrow \mu + p \)
  - Charged current non quasi-elastic (CCnQE)-enhanced: producing one or more \( \pi \)

CC selection in tracker region: at least one negative track, \( \mu \) candidate originating in the near detector **tracker region**

Additional **CCQE selection**: only 1 FGD-TPC track, no Michel electron in FGD1

Flux at ND280 is highly correlated with flux at SK, since \( \nu \)'s are produced by the same decaying particles in the beam
Analysis strategy: likelihood maximisation

Maximise the resulting likelihood, extracting flux and shared ND/SK cross-section parameters with proper correlations, marginalising uncorrelated parameters

<table>
<thead>
<tr>
<th></th>
<th>Prior Value and Uncertainty</th>
<th>Fitted Value and Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_A^{QE}$ (GeV)</td>
<td>$1.21 \pm 0.45$</td>
<td>$1.19 \pm 0.19$</td>
</tr>
<tr>
<td>$m_A^{RES}$ (GeV)</td>
<td>$1.162 \pm 0.110$</td>
<td>$1.137 \pm 0.095$</td>
</tr>
<tr>
<td>CCQE Norm. 0-1.5 GeV</td>
<td>$1.000 \pm 0.110$</td>
<td>$0.941 \pm 0.087$</td>
</tr>
<tr>
<td>CC1π Norm. 0-2.5 GeV</td>
<td>$1.63 \pm 0.43$</td>
<td>$1.67 \pm 0.28$</td>
</tr>
<tr>
<td>NC1π⁰ Norm.</td>
<td>$1.19 \pm 0.43$</td>
<td>$1.22 \pm 0.40$</td>
</tr>
</tbody>
</table>

Prior value and uncertainty from fit to MiniBooNE single pion samples
Analysis at the T2K far detector

**Determination of $\theta_{23}$ and $\Delta m_{32}^2$**

Fit reconstructed energy spectra of single-ring $\mu$-like events with predicted spectra, in a 3-flavour mixing context

Ingredients:
- **MC templates** from flavour/interaction type:
  - flavour: $\nu_\mu$, $\bar{\nu}_\mu$, $\nu_e$, $\bar{\nu}_e$, oscillated $\nu_e$
  - interaction: CCQE, CC1π, CC coherent, CC other, NC1π±, NC other
- quasi-elastic reaction kinematics to reconstruct neutrino energy
- estimates of flux and cross-section parameters, with errors and correlation
- non-32 oscillation parameters:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m_{21}^2$</td>
<td>$7.5 \times 10^{-5}$ eV$^2$</td>
</tr>
<tr>
<td>$\sin^2 2\theta_{12}$</td>
<td>0.857</td>
</tr>
<tr>
<td>$\sin^2 2\theta_{13}$</td>
<td>0.098</td>
</tr>
<tr>
<td>$\delta_{CP}$</td>
<td>0</td>
</tr>
<tr>
<td>Mass hierarchy</td>
<td>Normal</td>
</tr>
<tr>
<td>Baseline</td>
<td>295 km</td>
</tr>
</tbody>
</table>

PDG 2012 best-fit values
Analysis at the T2K far detector

**Determination of \( \theta_{23} \) and \( \Delta m_{32}^2 \)**

Fit reconstructed energy spectra of single-ring \( \mu \)-like events with predicted spectra, in a 3-flavour mixing context.

Ingredients:

- **MC templates** from flavour/interaction type:
  - flavour: \( \nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e \), oscillated \( \nu_e \)
  - interaction: CCQE, CC1\( \pi \), CC coherent, CC other, NC1\( \pi^\pm \), NC other
- **quasi-elastic reaction kinematics** to reconstruct neutrino energy
- **estimates** of flux and cross-section parameters, with errors and correlation
- **non-32 oscillation parameters**: determine \( \theta_{23} \) and \( \Delta m_{32}^2 \)

Vary oscillation parameters until best fit is found.

**Binned Likelihood Ratio**

**Maximum Likelihood**
ν_μ event selection at the T2K far detector

- Event time compatible with expected arrival time
- Fully contained in the fiducial volume (>2m from the wall)

See T. Akiri’s talk
$\nu_\mu$ event selection at the T2K far detector

- only 1 ring
- PID is muon-like
- Reconstructed momentum greater than 200 MeV/c
- Number of decay electrons $\leq 1$

Good agreement data/MC
### $\nu_\mu$ event selection at the T2K far detector

Data/MC reduction, assuming 2-flavour mixing - with ND280 information

\[ \sin^2 2\theta_{23} = 1.00 \quad \Delta m_{32}^2 = 2.4 \times 10^{-3} \text{eV}^2 \]

<table>
<thead>
<tr>
<th>RUN1+2+3 3.010x10^{20}\text{POT}</th>
<th>Data</th>
<th>MC Expectations w/ oscillation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>MC total</td>
</tr>
<tr>
<td>True FV</td>
<td>-</td>
<td>296.67</td>
</tr>
<tr>
<td>FCFV</td>
<td>174</td>
<td>166.61</td>
</tr>
<tr>
<td>One-ring</td>
<td>88</td>
<td>83.56</td>
</tr>
<tr>
<td>$\mu$-like</td>
<td>66</td>
<td>67.74</td>
</tr>
<tr>
<td>$p_\mu &gt; 200\text{MeV/c}$</td>
<td>65</td>
<td>67.33</td>
</tr>
<tr>
<td>$N_{\text{dcy-e}} \leq 1$</td>
<td>58</td>
<td>57.78</td>
</tr>
<tr>
<td>Efficiency [%]</td>
<td>-</td>
<td>19.5</td>
</tr>
</tbody>
</table>
Determination of $\nu_\mu$ oscillation parameters

**Binned Likelihood Ratio**

$$\chi^2 = 2 \sum_{E_r} \left( N_{\text{SK}}^{\text{data}} \ln \frac{N_{\text{SK}}^{\text{data}}}{N_{\text{SK}}^{\text{exp}}} + (N_{\text{SK}}^{\text{exp}} - N_{\text{SK}}^{\text{data}}) \right) + (a - a_0)^T C^{-1} (a - a_0)$$

- **spectral distribution**
- **systematic parameters and correlations**
- **48 parameters**

**Systematic uncertainty**

<table>
<thead>
<tr>
<th>Source</th>
<th>before ND280 fit</th>
<th>after ND280 fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>flux and $\nu$ x-sections</td>
<td>21.8</td>
<td>4.2</td>
</tr>
<tr>
<td>uncorrelated $\nu$ x-sections</td>
<td>6.3</td>
<td></td>
</tr>
<tr>
<td>SK detector</td>
<td>10.1</td>
<td></td>
</tr>
<tr>
<td>FSI-SI</td>
<td>3.5</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>25.1</strong></td>
<td><strong>13.0</strong></td>
</tr>
</tbody>
</table>

- prediction with $\pm 1\sigma$ total error envelope
Determination of $\nu_\mu$ oscillation parameters

**Binned Likelihood Ratio**

Best fit results:  
\[ \sin^2 2\theta_{23} = 1.00 \quad \Delta m_{32}^2 = 2.44 \times 10^{-3} \text{eV}^2 \]

Goodness-of-fit test on 1000 toy MC  
\[ p\text{-value} = 0.83 \]

Feldman-Cousins confidence regions:
Determination of $\nu_\mu$ oscillation parameters

**Maximum Likelihood fit**

\[
\mathcal{L}(\tilde{\sigma}, \tilde{f}) = \mathcal{L}_{\text{norm}}(\tilde{\sigma}, \tilde{f}) \times \mathcal{L}_{\text{shape}}(\tilde{\sigma}, \tilde{f}) \times \mathcal{L}_{\text{syst}}(\tilde{f})
\]

- **expected number of events**
- **unbinned spectrum shape**
- **systematic uncertainties**

41 parameters

\[L(\tilde{o}, \tilde{f}) = L_{\text{norm}}(\tilde{o}, \tilde{f}) \times L_{\text{shape}}(\tilde{o}, \tilde{f}) \times L_{\text{syst}}(\tilde{f})\]

- $\sin^2 2\theta_{23} = 1.00$
- $\Delta m^2_{32} = 2.4 \times 10^{-3} \text{eV}^2$

<table>
<thead>
<tr>
<th>Systematic uncertainty</th>
<th>before ND280 fit</th>
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</tr>
</thead>
<tbody>
<tr>
<td>flux and $\nu$ x-sections</td>
<td>21.7</td>
<td>4.2</td>
</tr>
<tr>
<td>uncorrelated $\nu$ x-sections</td>
<td>6.2</td>
<td></td>
</tr>
<tr>
<td>SK detector + FSI-SI</td>
<td>11.0</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>25.3</strong></td>
<td><strong>13.5</strong></td>
</tr>
</tbody>
</table>

No matter effects have been considered
Determination of $\nu_\mu$ oscillation parameters

**Maximum Likelihood fit**

Best fit results: $\sin^2 2\theta_{23} = 1.00$ $\Delta m_{32}^2 = 2.45 \times 10^{-3} \text{eV}^2$

Goodness-of-fit test on 1000 toy MC
p-value = 0.85
Determination of $\nu_\mu$ oscillation parameters

All the results together in the same plot:
...let’s not forget that:

With the same dataset ($3.01 \times 10^{20}$ POT), T2K gives the only direct evidence of $\nu_e$ appearance:

11 $\nu_e$ candidates

Best fit with $1\sigma$ uncertainties

<table>
<thead>
<tr>
<th>Hierarchy</th>
<th>Best fit</th>
<th>Uncertainties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal hierarchy</td>
<td>0.094</td>
<td>$+0.053$ $-0.040$</td>
</tr>
<tr>
<td>Inverted hierarchy</td>
<td>0.116</td>
<td>$+0.063$ $-0.049$</td>
</tr>
</tbody>
</table>
Conclusions

With about 4% of the total POT that we plan to collect, T2K has:

- given the only direct evidence of $\nu_e$ appearance at 3.2 standard deviations
- measured competitively the $\nu_\mu$ disappearance parameters $\theta_{23}$ and $\Delta m_{32}$

We have shown how the integration of ND280 data can reduce dramatically the systematic uncertainties.

More to come:
data taking is ongoing, well on track to achieve the collection of $\sim 8 \times 10^{20}$ POT by 7/2013, 3× what we have shown today.
Extra slides
The T2K dataset (end of 2012)

Data taken until 2012/12/12

Protons on target (POT): $4.544 \times 10^{20}$

well on track to collect $\sim 8 \times 10^{20}$ POT by 7/2013
ND280 performance

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

TPC2

FGD1

TPC dE/dX (negative tracks)

TPC dE/dX (positive tracks)
Pulls for systematic parameters

Binned Likelihood Ratio analysis
(pages 24-25)

Maximum Likelihood fit analysis
(pages 26-27)
Goodness of fit

Binned Likelihood Ratio analysis

Maximum Likelihood fit analysis

Data: $\chi^2_{gof} = 1.771$

p-value = 0.850