Global Analysis of 3 Flavour Neutrino Oscillations

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March 18, 2019

This project has received funding/support from the European Unions Horizon 2020 research and innovation programme under the Marie Sklodowska -Curie grant agreement No 674896
Global analysis of the three-flavour neutrino oscillations
synergies and tensions in the determination of $\theta_{23}$, $\delta_{CP}$ and the mass ordering

I. Esteban, M.C. Gonzalez-Garcia, Alvaro Hernandez-Cabezudo, Michele Maltoni, Thomas Schwetz

Introduction

PMNS matrix parametrization

\[ U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1} & 0 & 0 \\ 0 & e^{i\alpha_2} & 0 \\ 0 & 0 & 1 \end{pmatrix} \]

NO: \( m_1 < m_2 < m_3 \)

IO: \( m_3 < m_1 < m_2 \)

\[ \Delta m^2_{3\ell} = \begin{cases} \Delta m^2_{31} > 0 \text{ for NO,} \\ \Delta m^2_{32} < 0 \text{ for IO} \end{cases} \]

\( \Delta m^2_{21} \ll |\Delta m^2_{31}| \simeq |\Delta m^2_{32}| \) where \( \Delta m^2_{ij} = m_i^2 - m_j^2 \)

Data is updated up to Fall 2018

- Reactors experiments determine \( \theta_{13} \), all included KamLAND are independent of flux predictions
- Minos, T2K and NOvA data and their interplay with reactor experiments: \( \theta_{23}, \delta_{CP} \) and mass ordering
- Atmospheric neutrinos: Deep-Core 3-years data set and an independent analysis including Super-K atmospheric tabulated information


### General results

With current data (up to Fall 2018)

- $\theta_{12} : 14\%$
- $\theta_{13} : 8.9\%$
- $\theta_{23} : 27\% [24\%]$
- $\delta_{CP} : 100\% [92\%]$
- $\Delta m_{21}^2 : 16\%$
- $|\Delta m_{3\ell}^2| : 7.8\% [7.6\%]$

\[
\theta_{12}, \theta_{23}, \theta_{13} \text{ & } \delta_{CP}, \\
\Delta m_{sol}^2 \ll \Delta m_{atm}^2 \text{ (Mass ordering)}
\]

- NO is favour over IO, $\Delta \chi^2 = 4.7(9.3)$
- $\sin^2 \theta_{23}$ 2° octant $\Delta \chi^2 = 4.4(6.0)$
- CP violation, $\Delta \chi^2 = 1.5(1.8)$
$\sin^2 \theta_{13} = 0.0224$

$\sin^2 \theta_{12} = 0.31$

$\Delta m^2_{21} = (4.7, 7.5) \times 10^{-5} \text{ eV}^2$

2σ tension

- Robustness wrt Solar models
- Solar spectrum
- Day-night effect

KamLAND flux is independent of reactor $\bar{\nu}_e$ flux predictions
**LBL accelerator and MBL reactor experiments**

Disappearance $\nu_\mu \rightarrow \nu_\mu$ results and non-maximal $\theta_{23}$

$$P_{\mu\mu} \approx 1 - \sin^2 2\theta_{\mu\mu} \sin^2 \frac{\Delta m^2_{\mu\mu} L}{4E_\nu};$$

$$\sin^2 \theta_{\mu\mu} = \cos^2 \theta_{13} \sin^2 \theta_{23}$$

$$\Delta m^2_{\mu\mu} = \sin^2 \theta_{12} \Delta m^2_{31} + \cos^2 \theta_{12} \Delta m^2_{32} + \cos \delta_{CP} \sin \theta_{13} \sin 2\theta_{12} \tan \theta_{23} \Delta m^2_{21}$$

**NuFit 4.0 (2018)**

NOvA $\bar{\nu}$ and Minos $\nu$ favour non-maximal mixing with $\Delta \chi^2 \approx 7, 9$

Reactor data push $\Delta m^2_{3\ell}$ to larger values $\Rightarrow$ preference for non-maximal mixing

Qualitatively similar behaviour for IO
LBL accelerator and MBL reactor experiments

Appearance $\bar{\nu}_\mu \rightarrow \nu_e$ results $\theta_{23}$ octant and $\delta_{CP}$

\[ N_{\nu_e} \approx N_{\nu} \left[ 2s_{23}^2(1+2oA) - C' \sin \delta_{CP}(1+oA) \right] \]

\[ N_{\bar{\nu}_e} \approx N_{\bar{\nu}} \left[ 2s_{23}^2(1-2oA) + C' \sin \delta_{CP}(1-oA) \right] \]

\[ C' \approx 0.28 \text{ (at} \theta_{13}, \theta_{12}, \Delta m_{21}^2, |\Delta m_{3}\ell|^2) \]

\[ o \equiv \text{sgn}(\Delta m_{3}\ell)^2, \quad A \equiv \left| \frac{2E_\nu V}{\Delta m_{3}\ell} \right| \]

<table>
<thead>
<tr>
<th></th>
<th>T2K CCQE ((\nu))</th>
<th>T2K CC1(\pi) ((\nu))</th>
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<tr>
<td>(N^\nu)</td>
<td>40</td>
<td>3.8</td>
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</tr>
<tr>
<td>(N_{\nu_{\text{obs}}})</td>
<td>75</td>
<td>15</td>
<td>9</td>
<td>58</td>
<td>18</td>
</tr>
<tr>
<td>(N_{\nu_{\text{obs}}}-N_{\nu_{\text{bck}}})</td>
<td>61.4</td>
<td>13.6</td>
<td>6.1</td>
<td>43.6</td>
<td>13.8</td>
</tr>
</tbody>
</table>

Both $\nu$ and $\bar{\nu}$ events are enhanced by increasing $s_{23}^2$:

- T2K: $\nu$ data dominate, $s_{23}^2 > 0.5$, constraint by maximal mixing preferred by appearance
- NOvA: prefers also $s_{23}^2 > 0.5$

\[ \sin \delta_{CP} \simeq +1 (-1) \text{ suppress (increase) } \nu \text{ events and the opposite for } \bar{\nu} \]

- T2K: $\sin \delta_{CP} = -1$ minimizes $\nu$ data and maximizes $\bar{\nu}$ data
- NOvA, for NO $\sin \delta_{CP} = 1$ and $s_{23}^2 > 0.5$,
- Small tension between NOvA and T2K
Mass Ordering

\[ N_{\nu_e} \approx \mathcal{N}_\nu \left[ 2s_{23}^2(1 + 2oA) - C' \sin \delta_{CP}(1 + oA) \right] \]

\[ N_{\bar{\nu}_e} \approx \mathcal{N}_{\bar{\nu}} \left[ 2s_{23}^2(1 - 2oA) + C' \sin \delta_{CP}(1 - oA) \right] \]

\[ C' \approx 0.28 \text{ (at } \theta_{13}, \theta_{12}, \Delta m^2_{21}, |\Delta m^2_{3\nu}|) \]

\[ o \equiv \text{sgn}(\Delta m^2_{3\nu}), \quad A \equiv \frac{2E_\nu V}{|\Delta m^2_{3\nu}|} \]

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<tr>
<th>( N' )</th>
<th>T2K CCQE (( \nu ))</th>
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Sensitivity to mass ordering:
- matter effects
- \( \nu_\mu \) and \( \nu_e \) disappearance combination

* For NO(IO) \( \nu \) events are enhanced(suppressed) due to matter effects. The contrary for \( \bar{\nu} \).
* For NO(IO) the matter effect increases(decreases) the impact of \( \delta_{CP} \) for neutrinos while the opposite happens for anti-neutrinos.

T2K favours NO
Adding NOvA lowers NO significance

A combination of \( \nu_e \) and \( \nu_\mu \) disappearance data increase the significance for NO
Atmospheric Neutrinos

Deep-Core 3 years-data set

Super-Kamiokande

SK data goes into the same direction as our global analysis without SK

- Preference for NO, $\Delta \chi^2 = 4.3$
- Preference for $\delta_{CP} \sim 270^\circ$ over $\delta_{CP} \sim 90^\circ$ at $\Delta \chi^2 = 3$
- Slight preference for the second octant of $\theta_{23}$

Super-Kamiokande tabulated $\chi^2(\Delta m^2_{3\ell}, \theta_{23}, \theta_{13}, \delta_{CP})$ is also included in our analysis.

K. Abe et al. [arXiv:1710.09126]
Two analysis with and without the Super-Kamiokande atmospheric neutrino data

- $2\sigma$ tension in KamLAND vs solar data $\Delta m_{21}^2$

- Preference for the second octant $\theta_{23}$
  - Disappearance Minos $\nu$ and NOvA $\bar{\nu}$ disfavours maximal mixing, specially when combining with reactors
  - Appearance T2K and NOvA prefer the second octant of $\theta_{23}$

- NOvA $\bar{\nu}$ is in tension with T2K determining $\delta_{CP}$ in NO, so that CP conservation is disfavoured only at $\Delta \chi^2 \leq 2$

- T2K and NOvA prefer NO individually, but their combination decreases significance $\Delta \chi^2 \sim 2$

- LBL + reactors gives a preference for NO $\Delta \chi^2 \sim 4.5$

- Adding SK, NO is favoured at the level of $3\sigma$
Backup slides
### NuFIT 4.0 (2018)

#### without SK atmospheric data

<table>
<thead>
<tr>
<th></th>
<th>Normal Ordering (best fit)</th>
<th>Inverted Ordering ($\Delta \chi^2 = 4.7$)</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>bfp ±1σ</td>
<td>3σ range</td>
</tr>
<tr>
<td>$\sin^2 \theta_{12}$</td>
<td>$0.310^{+0.013}_{-0.012}$</td>
<td>0.275 → 0.350</td>
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<td>$\theta_{12}/^\circ$</td>
<td>$33.82^{+0.78}_{-0.76}$</td>
<td>31.61 → 36.27</td>
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<tr>
<td>$\sin^2 \theta_{23}$</td>
<td>$0.580^{+0.017}_{-0.021}$</td>
<td>0.418 → 0.627</td>
</tr>
<tr>
<td>$\theta_{23}/^\circ$</td>
<td>$49.6^{+1.0}_{-1.2}$</td>
<td>40.3 → 52.4</td>
</tr>
<tr>
<td>$\sin^2 \theta_{13}$</td>
<td>$0.02241^{+0.00065}_{-0.00065}$</td>
<td>0.02045 → 0.02439</td>
</tr>
<tr>
<td>$\theta_{13}/^\circ$</td>
<td>$8.61^{+0.13}_{-0.13}$</td>
<td>8.22 → 8.99</td>
</tr>
<tr>
<td>$\delta_{CP}/^\circ$</td>
<td>$215^{+40}_{-29}$</td>
<td>125 → 392</td>
</tr>
<tr>
<td>$\Delta m^2_{21}$</td>
<td>$7.39^{+0.21}_{-0.20}$</td>
<td>6.79 → 8.01</td>
</tr>
<tr>
<td>$\Delta m^2_{32}$</td>
<td>$+2.525^{+0.033}_{-0.032}$</td>
<td>$+2.427 → +2.625$</td>
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#### with SK atmospheric data

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<tr>
<td>$\sin^2 \theta_{23}$</td>
<td>$0.582^{+0.015}_{-0.019}$</td>
<td>0.428 → 0.624</td>
</tr>
<tr>
<td>$\theta_{23}/^\circ$</td>
<td>$49.7^{+0.9}_{-1.1}$</td>
<td>40.9 → 52.2</td>
</tr>
<tr>
<td>$\sin^2 \theta_{13}$</td>
<td>$0.02240^{+0.00065}_{-0.00066}$</td>
<td>0.02044 → 0.02437</td>
</tr>
<tr>
<td>$\theta_{13}/^\circ$</td>
<td>$8.61^{+0.12}_{-0.13}$</td>
<td>8.22 → 8.98</td>
</tr>
<tr>
<td>$\delta_{CP}/^\circ$</td>
<td>$217^{+40}_{-28}$</td>
<td>135 → 366</td>
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<td>$\Delta m^2_{21}$</td>
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DC16 data set is included in our global analysis
DC17 data set, we can not reproduce and is not included in our analysis
Projections on neutrino mass scale observables

Neutrino Oscillations give no information on the absolute mass scale for neutrinos

- Lower bound on the heavier mass: \( |m_i| \geq \sqrt{\Delta m_{ij}^2} \)
- Lower bound on the sum of neutrino masses

Information on the mass

**\( \beta \) decay experiments** \( ^3 H \to ^3 He + e^- + \bar{\nu}_e \) \( (m_{\nu e} \leq 2.2\text{eV}) \)

\[
m_{\nu e}^2 = \frac{\sum_i m_i^2 |U_{ei}|^2}{\sum_i |U_{ei}|^2} = \sum_i m_i^2 |U_{ei}|^2 = c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2
\]

**0\(\nu\)\(\beta \beta\) decay** \( (A, Z) \to (A, Z + 2) + e^- + e^- \) \( m_{ee} \lesssim 0.06 - 0.200\text{ eV} \) at 90\% CL.

\[
m_{ee} = \left| \sum_i m_i U_{ei}^2 \right| = \left| m_1 c_{13}^2 c_{12}^2 e^{i2\alpha_1} + m_2 c_{13}^2 s_{12} e^{i2\alpha_2} + m_3 s_{13}^2 e^{-i2\delta_{CP}} \right|
\]