Updated three-neutrino oscillation parameters from global fits

(Based on arXiv:1405.7540)

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3-neutrino oscillation formalism

- Neutrino mixing is described by 3 mixing angles and 1 Dirac (+2 Majorana) CP phase:

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

- two possible mass orderings:

- neutrino oscillation probability

\[
P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4 \sum_{i \neq j} Re(U^*_{\alpha i} U_{\alpha j} U_{\beta i}^* U_{\beta j}^*) \sin^2 \left( \frac{\Delta m_{ij}^2 L}{4E} \right) + 2 \sum_{i \neq j} Im(U^*_{\alpha i} U_{\alpha j} U_{\beta i}^* U_{\beta j}^*) \sin \left( \frac{\Delta m_{ij}^2 L}{2E} \right)
\]
Experimental data and methodology

Data included

- **solar**: Homestake, Gallex/GNO, SAGE, Borexino, SNO, Super-K
- **reactor**: KamLAND, Double Chooz, RENO, Daya Bay
- **atmospheric**: Super-K
- **LBL**: K2K, MINOS, T2K

Methodology

Oscillation probabilities + MC simulation of experiment

- Experiments
- Expected data
- Statistical analysis
- Allowed regions in \((\theta_{ij}, \Delta m^2_{ij}, \delta)\)
Solar and atmospheric parameters

- $\theta_{12}$ determined by solar data
- $\Delta m^2_{21}$ dominated by KamLAND.
- mismatch between $\Delta m^2_{21}$ from solar and KamLAND

- $\theta_{23}$ best constrained by T2K
- $\Delta m^2_{31}$ dominated by MINOS
- SK-atm data in agreement with LBL
  * T2K prefers maximal $\theta_{23}$
  * MINOS prefers non-maximal $\theta_{23}$
The determination of $\theta_{13}$ is totally dominated by Daya Bay.

$$\sin^2 \theta_{13} = 0.0234 \pm 0.0020 \quad \text{NH}$$
$$\sin^2 \theta_{13} = 0.0240 \pm 0.0019 \quad \text{IH}$$
The octant of the atmospheric angle

- Appearance probability at LBL:
  
  \[ P_{\mu e} \propto \sin^2 \theta_{23} \sin^2(2\theta_{13}) \]

  \[ \rightarrow \text{degeneracy in } \theta_{13}-\theta_{23} \text{ plane} \]

- Reactor data fix \( \theta_{13} \) and break the degeneracy moving \( \theta_{23} \) to the 2nd octant.

- SK-atm data do not change this tendency and \( \theta_{23} \) remains in the 2nd octant in global fit
Sensitivity to the CP phase

→ mismatch between $\theta_{13}$ value measured by reactors and preferred LBL-value for certain values of $\delta$.

→ significant rejection for values of $\delta \sim 0.5\pi$ emerges from the global fit: disfavoured at 1.8$\sigma$ (2.5$\sigma$) for NH (IH).

→ best fit values:

$\delta = (1.34^{+0.64}_{-0.38})\pi$ (NH)

$\delta = (1.48^{+0.34}_{-0.32})\pi$ (IH)
Update after Neutrino-2014 Conference

- **Double Chooz**: 467.9 days [arXiv:1406.7763]
  
  rate + shape analysis: \( \sin^2 2\theta_{13} = 0.090^{+0.032}_{-0.029} \) \( 33\% \) precision \( (36\%) \)

- **RENO**: 800 days [talk by Seon-Hee Seo]
  
  rate-only analysis: \( \sin^2 2\theta_{13} = 0.101 \pm 0.008 \text{ (stat)} \pm 0.010 \text{ (syst)} \) \( 13\% \) uncert. \( (18\%) \)

- **Daya Bay**: 621 days of data \( (6\text{AD} + 8\text{AD}) \) [Talk by Chao Zhang]
  
  rate + shape analysis: \( \sin^2 2\theta_{13} = 0.084 \pm 0.005 \) \( 6\% \) precision \( (9\%) \)

  \( \rightarrow \) lower best fit value

- **new reactor component at \( \sim 5 \text{ MeV} \)** observed in RENO \( (3.6\sigma) \) and Double Chooz \( (3.0\sigma) \), correlated with reactor thermal power.

  \( \rightarrow \) origin of the excess?

  \( \rightarrow \) not very relevant for \( \theta_{13} \) measurement, based on Far/Near comparison
Impact of new data over the global fit

Before ν-2014
(arXiv:1405.7540)

<table>
<thead>
<tr>
<th>Model</th>
<th>$\theta_{13}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NH</td>
<td>$0.023 \pm 0.002$</td>
</tr>
<tr>
<td>IH</td>
<td>$0.024 \pm 0.002$</td>
</tr>
</tbody>
</table>

After ν-2014
(this update)

<table>
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<tbody>
<tr>
<td>NH</td>
<td>$0.0200 \pm 0.0014$</td>
</tr>
<tr>
<td>IH</td>
<td>$0.0216 \pm 0.0010 - 0.0012$</td>
</tr>
</tbody>
</table>

$\sim 8\%$ $\sim 5\%$

→ new Daya Bay data favour lower value of $\theta_{13}$ and increase precision
Impact of new data over the global fit

Before $\nu$-2014
(arXiv:1405.7540)

$\theta_{23}$ octant

After $\nu$-2014
(this update)

- NH: local minimum at 1st octant with $\Delta \chi^2 = 0.28$
- IH: 1st octant values allowed with $\Delta \chi^2 > 1.5$

$\rightarrow$ lower $\theta_{13}$ value favours slightly larger values of $\theta_{23}$ (2nd octant)
Impact of new data over the global fit

Before \(v\)-2014
\(\text{(arXiv:1405.7540)}\)

- Best fit: \(\delta \sim 1.5\pi\) for NH and IH
- NH: \(\delta \sim 0.5\pi\) disfavoured at 1.8\(\sigma\)
- IH: \(\delta \sim 0.5\pi\) disfavoured at 2.5\(\sigma\)

After \(v\)-2014
\(\text{(this update)}\)

- Best fit: \(\delta \sim 1.5\pi\) for NH and IH
- NH: \(\delta \sim 0.5\pi\) disfavoured at 2.2\(\sigma\)
- IH: \(\delta \sim 0.5\pi\) disfavoured at 2.8\(\sigma\)

→ lower \(\theta_{13}\) value increases the tension with LBL data, enhancing the rejection against \(\delta \sim 0.5\pi\)
Updated global fit summary

- No indication for correct mass ordering: \( \Delta \chi^2 (\text{IH} - \text{NH}) = -0.6 \)
Summary

* Recent T2K data provide the most sensitive measurement of $\theta_{23}$

* Our global fit shows a preference for $\theta_{23} > \pi/4$, although for NH a local minimum appears in $\sin^2\theta_{23} = 0.47$ with $\Delta \chi^2 = 0.71$. For IH, solutions in the first octant appear only at 1.4$\sigma$.

* $\theta_{13}$ determination improved thanks to last results from reactor experiments, mainly Daya Bay.

* An enhanced sensitivity to the CP violation phase emerges from the complementarity between accelerator and reactor data (increased after Neutrino-2014).

* No sensitivity to neutrino mass hierarchy.