Status and prospects of global analyses of neutrino mass-mixing parameters

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Our “pre-London” reference analysis in the standard 3ν mixing scenario:

Bari group, arXiv:1601.07777 (NPB Special Issue on ν Oscillations)

Updated in a preliminary way with some data presented here at Neutrino 2016 (thanks in particular to F. Capozzi):

• New NOvA neutrino data in appearance and disappearance channels
• New T2K anti-neutrino data in appearance channel

Other updates not (yet) included

Please focus only on “trends” of the global analysis; numbers may change when a more refined and proper analysis of the new data will be performed in due time
### Known

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta m^2$</td>
<td>2.4%</td>
</tr>
<tr>
<td>$\Delta m^2$</td>
<td>1.8%</td>
</tr>
<tr>
<td>$\sin^2 \theta_{12}$</td>
<td>5.8%</td>
</tr>
<tr>
<td>$\sin^2 \theta_{13}$</td>
<td>4.7%</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}$</td>
<td>$\sim 9%$</td>
</tr>
</tbody>
</table>

(Pre-\(\nu\)2016)

### Unknown

- CP-violating phase $\delta$
- Octant of $\theta_{23}$
- Mass Ordering $\rightarrow \text{sign}(\Delta m^2)$

[Dirac/Majorana neutrinos, Majorana phases, absolute mass scale]

In this talk

- $\Delta m^2 = (\Delta m_{13}^2 + \Delta m_{23}^2)/2$
- Mass Ordering $= \text{sign of } \Delta m^2$
Bounds on single oscillation parameters
(pre-v2016, BARI group)

Squared mass differences and mixing angles have both lower and upper bounds at more than $3\sigma$ with the exception of $\delta$ (C.L. for $\delta$ might be higher since it is cyclic, see JHEP 1509 (2015) 016)

Nearly Gaussian uncertainties for $(\Delta m^2, \sin^2 \theta_{13})$
and to a lesser extent for $(\delta m^2, \sin^2 \theta_{12})$

The best fit of $\theta_{23}$ flips from the first to the second octant by changing from NO to IO (weak indication for non maximal mixing). Maximal mixing allowed at $< 2\sigma$

Normal Ordering slightly favoured over Inverted Ordering at $\sim 1\sigma$ level

$$\Delta \chi^2_{IO-NO} = +0.98$$
Bounds on single oscillation parameters
(preliminary update)

\[ LBL \text{ Acc} + \text{ Solar} + \text{ KamLAND} + \text{ SBL Reactors} + \text{ Atmos} \]

\[ \Delta \chi^2_{\text{IO-NO}} = 3.1 \]

\text{CP phase trend:}

- \( \delta \sim 1.4 \pi \) at best fit
- CP-conserving cases (\( \delta = 0, \pi \)) disfavored at \( \sim 2\sigma \) level or more
- Significant fraction of the \([0,\pi]\) range disfavored at >3\( \sigma \)

\text{\( \theta_{23} \) trend:}

- maximal mixing disfavored at about \( \sim 2\sigma \) level
- best-fit octant flips with mass ordering

inverted ordering slightly disfavored
Single parameter bounds at 1, 2 and 3σ for Normal Ordering

The three global analyses are in good agreement with some difference about $\theta_{23}$ ranges & octant
Single parameter bounds at 1, 2 and 3\(\sigma\) for Inverted Ordering

\[ \sin^2 \theta_{12} \]

\[ \sin^2 \theta_{13} \]

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

\[ \delta m^2/10^{-5} \text{ eV}^2 \]

\[ \Delta m^2/10^{-3} \text{ eV}^2 \]

\[ \delta \]

No clear preference for normal mass ordering vs inverted ordering

\[ \Delta \chi^2(\text{IO-NO}) = +3.1 \hspace{1cm} \text{BARI (v2016) (~1.7\(\sigma\))} \]

\[ -1.03 \hspace{1cm} \text{NU-FIT v2.1 (~1\(\sigma\))} \]
In the following we shall explore these trends in more detail, by looking at parameter correlations and by considering the progressive contribution of different data sets:

(1) LBL acc + Solar + KamLAND

Solar + KL data not only provide the necessary input for \((\delta m^2, \theta_{12})\), but also independent -although weak- constraints on \(\theta_{13}\) (first “hint” ever...). The data set (1) provides, by itself, a measurement of \(\theta_{13}\).

(2) LBL acc + Solar + KamLAND + SBL Reactors

SBL reactors not only provide the most accurate determination of \(\theta_{13}\) but also an independent (and increasingly competitive) determination of \(\Delta m^2\), not limited by E-reconstruction systematics as in LBL accel.

(3) LBL acc + Solar + KamLAND + SBL Reactors + Atmospheric

Herein: Atmospheric = SK + DeepCore. Increasingly difficult to keep up with SK updates (e.g., statistical nu/nubar separation) outside the collaboration. Effects difficult to disentangle. Data added at the end.
Note:

Best fit of $\theta_{13}$ consistent with SBL reactors: synergy, not tension! Bumps due to octant degeneracy

Trend of $\delta$
already emerging from these data (i.e., without reactors)

Trend of $\theta_{23}$
Maximal mixing disfavored at $\sim 1.5\sigma$, with the two octants nearly degenerate
Adding reactors largely shrinks $\theta_{13}$ range and, to some extent, the $\Delta m^2$ range. Trend of $\delta$ strengthened, especially in IO. Best-fit octant flips with mass ordering.
Note:
adding atmosph. further shrinks the $\Delta m^2$ range
trend of $\delta$ strengthened, especially in NO
Maximal mixing more disfavored
More on best-fit octant flip (and parameter correlations)

In LBL accelerator data, $\theta_{23}$ and $\theta_{13}$ are anticorrelated via appearance data, with the $\theta_{23}$ octants largely degenerate via disappearance data.

Degeneracy slightly broken by solar + KamLAND data constraints on $\theta_{13}$
SBL reactors select the $\theta_{23}$ octant where $\theta_{13}$ is in better agreement with their constraint (first octant in NO, second octant in IO)
Atmospheric data do not spoil this trend but introduce some differences in the relative likelihood of the two octants in NO and IO. Octant degeneracy may show up in terms of “bumps” or “double bands” when marginalized away.
Unknowns: CP phase $\delta$ vs $\theta_{13}$

$\theta_{23}$ octant degeneracy effect on "wavy bands" in the $(\delta, \theta_{13})$ plane
Largely reduced by adding SBL reactor data (which select a preferred octant for given mass ordering). Note also synergy, not tension, between (LBL acc + solar + KamLAND) and (SBL Reactors) data.
Results in the \((\delta, \theta_{13})\) plane corroborated by atmospheric data
Note correlations between the parameters ($\Delta m^2$, $\theta_{23}$) important when interpreting, e.g., NOvA data that, by themselves, would prefer relatively “high” $\Delta m^2$: reduction of $\Delta m^2$ by other data (acc + reac + atm) tends to reduce also the “distance” between allowed octant ranges.

![Graphs showing correlations between $\Delta m^2$ and $\sin^2 \theta_{23}$ for LBL Acc + Solar + KL, + SBL Reactors, and + Atmos conditions.](image-url)
\((\delta, \theta_{23})\) correlations relatively weak at present
Impact on absolute mass observables

Let’s focus on $\Sigma = m_1 + m_2 + m_3$

and $m_{\beta\beta}$ (if $\nu$ are Majorana)

- Oscillation data strongly correlate $(\Sigma, m_{\beta\beta})$
- Cosmological data constrain $\Sigma$
- $0\nu\beta\beta$ data constrain $m_{\beta\beta}$

Exercise: add up $\chi^2_{osc} + \chi^2_{\Sigma} + \chi^2_{\beta\beta}$ in the $(\Sigma, m_{\beta\beta})$ plane (*)

Options:
1. minimize separately in NO and IO (two minima)
2. minimize w.r.t. the absolute minimum

In the following:  

$\begin{align*}
\text{(NO)} & \quad 2\sigma \\
\text{(IO)} & \quad 2\sigma \\
\text{3}\sigma & \quad 3\sigma \\
\end{align*}$

(*) see e.g. the discussion in Adv.High Energy Phys. 2016 (2016) 2162659
Oscillations (v2016)

Normal ordering and inverted ordering separate minima

Absolute minimum in NO, $\Delta \chi^2(\text{IO-NO}) = 3.1$
Oscillations + 0νββ (*)

Normal ordering and inverted ordering separate minima

Absolute minimum in NO, $\Delta \chi^2(\text{IO-NO}) = 3.1$

(*) $\Delta \chi^2_{\beta\beta}$ taken from KamLAND-Zen $T_{1/2}$-likelihood (K. Inoue talk at “Revealing the history of the universe with underground particle and nuclear research” ⊕ NME uncertainties from Phys. Rev. D 92, 093004 (2015)
Oscillations + $0\nu\beta\beta + \text{Cosmo "weak"} \ (*)$

Normal ordering and inverted ordering separate minima

Absolute minimum in NO,
$\Delta\chi^2(\text{IO-NO}) = 3.2$

(*) $\Delta\chi^2$ taken from "base" scenario in arXiv:1605.04320v1
Oscillations + $0\nu\beta\beta$ + Cosmo “strong” (*)

Normal ordering and inverted ordering separate minima

Inverted ordering case “under pressure” if one takes all data at face value. But too early to draw conclusions.

Absolute minimum in NO, $\Delta \chi^2 (IO-NO) = 4.6$

Future oscillation probes ——>

(*) $\Delta \chi^2$ taken from “base+BAO+H073p02” scenario in arXiv:1605.04320v1
MBL reactor exp. (JUNO, RENO-50)
Mass ordering discrimination through interference between long-wavelength oscillations driven by $(\delta m^2, \theta_{12})$ and short-wavelength ones driven by $(\Delta m^2, \theta_{13})$

Expect $O(10^5)$ events in a few years

Will also improve the accuracy on $\delta m^2$ and $\theta_{12}$ by a factor of $~10$

Experiments subject to spectral systematics

Systematic errors (e.g., energy scale, flux shape) are no longer “numbers” but “functions” [as in parton distribution function fits and precision cosmology forecasts]

Unprecedented challenges in neutrino data analyses:
must deal with “functions” which ideally should be known in size, shape, correlations and probability distributions, but in practice may also be partly unknown
After the inclusion of energy scale and flux shape uncertainties, NO (true) and IO (fit) spectra become less distinguishable → some loss of sensitivity to mass ordering.

Energy scale uncertainties $E\to E'(E)$ stretch the “x-axis”

Flux shape uncertainties $\Phi(E)\to\Phi'(E)$ stretch the “y-axis”

In the context of MBL experiments we introduce smooth deformations of the detector energy scale and the reactor antineutrino flux (up to 5th-order polynomials, i.e. +12 systematic pulls) constrained by current error bands (in blue at $\pm1\sigma$)
JUNO-like prospective sensitivity to mass ordering (our estimate*)

Abscissa scales as $T^{1/2} \rightarrow$ linear behaviour for pure statistical errors

Inclusion of energy-scale uncertainties bends the linear rise, but still allows $3\sigma$ discrimination after $\sim 6$ years of data taking. With the inclusion of flux-shape uncertainties: $3\sigma$ sensitivity in $\sim 10$ years

Also the precise determination of $(\delta m^2, \theta_{12})$ affected: accuracy decreased by a factor of $\sim 3$, and the central values biased if wrong mass ordering is assumed

(*) Phys.Rev. D92 (2015) no.9, 093011
With halved scale and flux-shape errors for both mass ordering: 3σ rejection of the wrong ordering can be achieved in ~6 years.
Mass ordering discrimination reduced by 2D spectral shape systematics due to atmospheric fluxes, cross sections, detector response, ….
Conclusions

- Ranges of well-known 3ν parameters \((\delta m^2, \theta_{12})\) & \((\Delta m^2, \theta_{13})\) confirmed by v2016 data
- CPV: \(\sin \delta < 0\) preferred also by v2016 data.
  - From very preliminary and incomplete global analysis we get
    - best fit: \(\delta / \pi \sim 1.4 \pm 0.23\) (1σ)
    - \(\sin \delta \sim 0\) disfavoured at the level of 2σ (or more)
    - \(\sin \delta \sim +1\) disfavoured at > 3σ
- Mass Ordering: IO slightly more disfavored by oscillation data
  - pre-v2016 : \(\Delta \chi^2_{IO-NO} \sim 0(1)\) (1σ)
  - post-v2016 : \(\Delta \chi^2_{IO-NO} \sim 3.1\) (1.7σ) ← focus on trend, not numbers!
  - IO also under pressure from cosmo data (in standard ΛCDM)
- Octant info: still fragile and dependent on mass ordering
- Future: Global analyses will need to tackle more refined treatments of spectral systematics