How Neutrino Measurements Fit Together: Past, Present, and Future

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Introduction

• “How all neutrino experiments fit together” is a really broad topic, and we only have 20 minutes.
• This talk will focus just on some examples of fitting together neutrino oscillation experiments.
• Some other things this talk could have been about:
  – Cross-section + oscillation measurements
  – Oscillation experiments + $0\nu\beta\beta$
  – $N_\nu$ from cosmology + sterile neutrino searches
  – $m_{ve}$ vs. $m_{\beta\beta}$ vs. $\Sigma m$
    • Beta decay vs. $0\nu\beta\beta$ vs. cosmology
The Past: The Solar Neutrino Problem

- The start of neutrino oscillation physics.
• Super-Kamiokande shows that neutrinos oscillate

• SNO shows that only the $\nu_e$ flux is depleted in solar neutrinos
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• But, even the latest paper from SNO alone cannot determine the oscillation parameters unambiguously.
• Including the results from *other* solar experiments resolves the ambiguities.

• Bringing in the KamLAND reactor measurement demonstrates consistency between solar $\nu_e$ and reactor anti-$\nu_e$ and significantly increases precision.
The small tension between the two measurements in $\theta_{12}$ was, in fact, evidence of 3-flavor oscillations (e.g. $\theta_{13} > 0$).
The Present: What we know now

Oscillations among the three neutrino flavors depend on:

- The mixing matrix
  - $\theta_{23}, \theta_{13}, \delta_{CP}, \theta_{12}$
- The mass differences
  - $\Delta m_{32}^2, \Delta m_{21}^2$
- The mass hierarchy
  - The sign of $\Delta m_{32}^2$
The Present: What we know now

Let's look at a combined analysis of all available neutrino data: NuFit 3.0

Available measurements

• Neutrinos are hard to work with
  – Can only access a certain subset of flavor transitions
  – Certainly cannot see them all in the same experiment.

• Remember – oscillations depend on distance and energy.
  – Vacuum oscillations depend on $L/E$
  – Matter effects depend on $L$, too.

• Disappearance ($\nu_\alpha \rightarrow \nu_\alpha$) and appearance ($\nu_\alpha \rightarrow \nu_\beta$) probe different things.

\[
P(\nu_\mu \rightarrow \nu_\mu) = 1 - \left( \sin^2(2\theta_{13}) \sin^2(\theta_{23}) + \cos^4(\theta_{13}) \sin^2(2\theta_{23}) \right) \sin^2\left(\frac{\Delta m^2 L}{4E}\right)
\]
\[ \nu_e \rightarrow \nu_e, \nu_x \]

– Source: the Sun
– No choice of distance – all the oscillations happen in the Sun.
– Only probes \( \Delta m_{21}^2 \)
– At this energy, can only tag CC \( \nu_e \) or NC events.
• \( \text{anti-}\nu_e \rightarrow \text{anti-}\nu_e \)
  – **Nuclear reactors** produce copious anti-\( \nu_e \)'s
  – No choice of energy, but can choose baseline to match either mass splitting.
• $\nu_\mu \rightarrow \nu_\mu, \nu_e, \nu_\tau$
  – Antineutrinos, too
  – **Atmospheric neutrinos** give wide range of energies, baselines, but they are all mixed together.
  – **Accelerators** give well-controlled sources at particular energies, but we need to pay for the neutrinos.
• $\theta_{13} = 8.46^\circ \pm 0.15^\circ$
  – Went rapidly from unknown to the most precisely known mixing angle.

• $\theta_{12} = 33.56^\circ \pm 0.77^\circ$
  – Allowing non-zero $\theta_{13}$ resolves reactor-solar tension in this parameter.
\[ \Delta m_{21}^2 = (7.50 \pm 0.19) \times 10^{-5} \text{ eV}^2 \]

- This measurement is dominated by KamLAND.
- Some interesting tension with the global solar experiments which prefer \( \sim 5 \times 10^{-5} \text{ eV}^2 \)
- $\Delta m^2_{31} = (2.52 \pm 0.04) \times 10^{-3}$ eV$^2$ or $\Delta m^2_{32} = (-2.51 \pm 0.04) \times 10^{-3}$ eV$^2$
  
  - $\nu_\mu$ disappearance in accelerator, atmospheric experiments
  
  - $\nu_e$ disappearance in reactor experiments
• $\theta_{23} = 41.6^\circ \pm 0.15^\circ$ in NH 
  $\theta_{23} = 50.6^\circ \pm 0.15^\circ$ in IH
  – Primarily constrained by $\nu_\mu$ disappearance, but influences $\nu_e$ appearance.

• “Maximal mixing” allowed at about the 90% C.L.
  – $\sin^2 \theta_{23} = 0.5$
  – $\theta_{23} = 45^\circ$ or
  – $\nu_3$ is equal parts $\nu_\mu$ and $\nu_\tau$
• Some interesting tensions under the hood
  – MINOS, NOvA, Super-K favor non-maximal
  – T2K, IceCube (not shown) favor maximal

• Introducing the Daya Bay constraint on $\Delta m^2_{32}$ makes the story on maximal mixing (more) consistent.
  – This is because accelerator experiments have significant correlations between $\Delta m^2_{32}$ and $\theta_{23}$
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• What about the remaining open questions:
  – Is CP violated?
  – Mass hierarchy
  – Maximal $\mu$-$\tau$ mixing?

• Not much yet due to degeneracies
  – The normal hierarchy is favored by $\Delta\chi^2$ of 0.83.
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The Future: Mass hierarchy, three ways

- **DUNE**: matter effects in the Earth’s crust
  - Subtle effect, but with a well-understood neutrino source

M. Singh, PTEP10 (2016) 103B03.
• Resonant matter effect in the Earth’s core in atmospheric neutrinos
  – A strong effect, but with a challenging natural neutrino source.
• **IceCube**: using $\nu_\mu$ disappearance (and very high statistics)
• **Hyper-Kamiokande**: using $\nu_e$ appearance
• JUNO: Direct measurement of both $\Delta m^2_{21}$ and $\Delta m^2_{32}$ at the same time.
  – This method is completely independent of matter effects.


L. Zhan, Y. Wang, J. Cao, L. Wen
PRD 78 (2008) 111103
The Future: How do we know we are measuring $\delta_{CP}$?

• 1 or more sterile neutrinos can strongly affect a measurement of CP-violation in long-baseline experiments like DUNE and Hyper-K.

  – R. Gandhi, B. Kayser, M. Masud, S. Prakash. JHEP 1511 (2015) 039
  – S. Agarwalla, S. Chatterjee, A Palazzo. JHEP 1609 (2016) 016
  – ...

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• The answer is to either confirm or refute the existence of sterile neutrinos as soon as we can.
  – An example of complementarity between current generation and next-generation experiments.
  – Includes measurements at existing experiments built for other goals and new dedicated experiments.
Summary

\[ = R(\theta_{23}) \cdot R(\theta_{13}, \delta_{CP}) \cdot R(\theta_{12}) \]
Accelerator and Atmospheric

\[ \Delta m_{32}^2 \]

\[ \Delta m_{21}^2 \]

\[ R(\theta_{23}) \cdot R(\theta_{13}, \delta_{CP}) \cdot R(\theta_{12}) \]
Summary

\[ \Delta m^2_{32} \]

\[ \Delta m^2_{21} \]

\[ = R(\theta_{23}) \cdot R(\theta_{13}, \delta_{CP}) \cdot R(\theta_{12}) \]

Accelerator and Atmospheric

Solar
\[ = R(\theta_{23}) \cdot R(\theta_{13}, \delta_{CP}) \cdot R(\theta_{12}) \]
Backups
Open Questions in Neutrino Physics

- **Pattern of neutrino masses:**
  - What is their absolute mass?
  - Is the pattern normal, inverted, or degenerate?

- **Are neutrinos Dirac or Majorana?**

- **Pattern of neutrino mixing:**
  - Is $\nu_3$ equal parts $\nu_\mu$ and $\nu_\tau$?
    - Is the mixing maximal?
  - Do neutrino oscillations violate CP symmetry?

- **Are there sterile neutrinos?**
Create in one flavor ($\nu_\mu$), but detect in another ($\nu_e$)
Neutrino Oscillations

• Create in one flavor ($\nu_\mu$), but detect in another ($\nu_e$)

\[ \begin{align*}
   \nu_e & = \cos \theta \nu_1 + \sin \theta \nu_2 \\
   \nu_\mu & = -\sin \theta \nu_1 + \cos \theta \nu_2
\end{align*} \]

“Mixing Matrix”
Why study neutrino oscillations?

- Neutrinos are “weird”:
  - Neutrino mixing looks very different from CKM.
  - Neutrino masses are really small compared to the rest of the SM.
- Potentially CP-violating
  - Might be a window into matter-antimatter asymmetry.
- Physics beyond the standard model!
  - Oscillations are an interferometric effect – gives access to high-scale physics.

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\( \nu_\mu \) Disappearance

\[
P(\nu_\mu \rightarrow \nu_\mu) = 1 - \left( \sin^2(2\theta_{13}) \sin^2(\theta_{23}) + \right. \\
\left. \cos^4(\theta_{13}) \sin^2(2\theta_{23}) \right) \sin^2 \left( \frac{\Delta m^2 L}{4E} \right)
\]

Sub-dominant term due to small \( \theta_{13} \)

One “dip” due to the fixed baseline.

\( \nu_e \) Appearance

\[
P(\nu_\mu \to \nu_e) \approx \left| \sqrt{P_{\text{atm}}} e^{-e(\Delta_{32} + \delta_{CP})} + \sqrt{P_{\text{sol}}} \right|^2
\]

\[
\approx P_{\text{atm}} + P_{\text{sol}} + 2\sqrt{P_{\text{atm}} P_{\text{sol}}} (\cos \Delta_{32} \cos \delta_{CP} \mp \sin \Delta_{32} \sin \delta_{CP})
\]

\[
\sqrt{P_{\text{atm}}} = \sin(\theta_{23}) \sin(2\theta_{13}) \frac{\sin(\Delta_{31} - aL)}{\Delta_{31} - aL} \Delta_{31}
\]

- **NOvA Measures:**
  - \( CP \)-violating phase Phase
  - \( \theta_{23} \) octant
  - Sign of \( \Delta m^2_{32} \) – “Mass Hierarchy”

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