Current Status of $\theta_{13}$

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We learned a lot about $\nu$-mixing from recent experiments!

\[ \theta_{\text{atmospheric}} \text{ (primarily } \theta_{23} \text{)} \]

\[ \theta_{\text{solar}} \text{ (primarily } \theta_{12} \text{)} \]

Yet our current knowledge of $\theta_{13}$ is very limited!
KamLAND and solar best fit values are not the same!
CPT-violation? Other new physics?
....or is it simply ignoring $\theta_{13}$?

Sin $2\theta_{13} = 0.1$

Sin $2\theta_{13} = 0$

Sin $2\theta_{13} = 0$

SNO's own low-energy threshold analysis

$$\theta_{13} = 7.2^{+2.0}_{-2.8} \text{ deg}$$

Note: Non-Gaussian errors
KamLAND Collaboration, 2011
The value of $\theta_{13}$ is a small. Theory has other small quantities that are not yet well-determined!

One example is the neutrino cross sections.
An approach from the first principles: Using effective field theory for low-energy neutrino-deuteron scattering

Butler, Chen

Below the pion threshold $^3S_1 \rightarrow ^1S_0$ transition dominates and one only needs the coefficient of the two-body counter term, $L_{1A}$ (isovector two-body axial current)

$L_{1A}$ can be obtained by comparing the cross section $\sigma(E) = \sigma_0(E) + L_{1A} \sigma_1(E)$ with cross-section calculated using other approaches or measured experimentally. (e.g. use solar neutrinos as a source)

Difficult to go beyond two-body systems!
Matter effects in long-baseline oscillations

Example: two flavors and normal hierarchy

\[ P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \left[ 1 + (4\sqrt{2}G_F N_e E/\delta m^2) \cos 2\theta \right] \]
\[ \quad \times \sin^2 \left[ \left( \frac{\delta m^2}{4E} + .. \right) L \right] \]

\[ P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e) = \sin^2 2\theta \left[ 1 - (4\sqrt{2}G_F N_e E/\delta m^2) \cos 2\theta \right] \]
\[ \quad \times \sin^2 \left[ \left( \frac{\delta m^2}{4E} + .. \right) L \right] \]

This can be used to distinguish normal from inverted hierarchy

Matter effects mimic CP-violation!

Matter effects increase with energy, \( E_{\text{MSW}} \sim 10 \text{ GeV} \) for Earth’s mantle
A typical disappearance experiment

\[ P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta m_{31}^2 L}{4 E_\nu} \right) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \left( \frac{\Delta m_{21}^2 L}{4 E_\nu} \right) \]
Typical Appearance Experiment

\[ P_{\nu_\mu \rightarrow \nu_e} \sim \frac{\sin^2 2\theta_{13} \sin^2 \theta_{23}}{(1 - 2\sqrt{2}G_F N_e E / \delta m^2)^2} \sin^2 \left[ \left( \frac{\delta m^2_{31}}{4E} - \frac{G_F N_e}{\sqrt{2}} \right) L \right] \]

\[ - g \frac{\sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23}}{\left( 1/2 - 2\sqrt{2}G_F N_e E / \delta m^2_{31} \right) - 1/4} \cos \left( \delta + \frac{\delta m^2_{31} L}{4E} \right) \]

\[ \times \cos \left( \frac{\delta m^2_{31} L}{4E} \right) \sin \left( \frac{G_F N_e L}{\sqrt{2}} \right) \sin \left[ \left( \frac{\delta m^2_{31}}{4E} - \frac{G_F N_e}{\sqrt{2}} \right) L \right] \]

\[ + \mathcal{O}(g^2) \]

\[ g = \frac{\delta m^2_{21}}{\delta m^2_{31}} \sim 0.03 \]
MINOS

\[ \Delta m^2 > 0 \]
- **MINOS Best Fit**
- **68% CL**
- **90% CL**
- **CHOZ 90% CL**
  - \( 2\sin^2(\theta_{13})\sin^2\theta_{23} = 1 \) for CHOZ

\[ \Delta m^2 < 0 \]
- **8.2 \times 10^{20} POT**
- **MINOS PRELIMINARY**

\( \delta_{CP} (\pi) \)

\( 2\sin^2(\theta_{13})\sin^2\theta_{23} \)
Recent T2K results

\[ \sin^2 2\theta_{23} = 1 \]

\[ \Delta m^2_{23} > 0 \]

\[ \Delta m^2_{23} < 0 \]

T2K

1.43 \times 10^{20} \text{ p.o.t.}
T2K $\nu_\mu$ disappearance

![Graph showing T2K $\nu_\mu$ disappearance data with best-fit points and method comparisons. The graph plots $\Delta m^2$ vs. $\sin^2 2\theta_{23}$ with various data points and fit curves representing different experiments and methods.]
From D. Naples at TAUP2011
CP-violation

\[ P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) - P(\nu_\mu \rightarrow \nu_e) \propto \sin \theta_{12} \sin \theta_{13} \sin \theta_{23} \]

Since we know the other mixing angles are non-zero, observation of CP-violation in neutrino oscillations hinges on a non-zero value of \( \theta_{13} \).
Knowledge of $\theta_{13}$ may help us understand

- Origin of matter-antimatter asymmetry through CP-violation.
- Origin of elements (through supernova nucleosynthesis)
- Whether the neutrino mass hierarchy is normal or inverted.
Measuring $\theta_{13}$ with Reactor Antineutrinos

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta m^2_{31} L}{4E_e} \right) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \left( \frac{\Delta m^2_{21} L}{4E_e} \right)$$

- Reactor neutrino energies are too low to produce muons. Hence this is an antineutrino disappearance experiment (also no matter effects).
- Measure ratio(s) of interaction rates in two or more detectors to cancel systematic errors.
- Those detectors will never be identical, hence one should try to control mass differences, detection efficiencies, etc.
\[
\frac{N_f}{N_n} = \left( \frac{N_{p,f}}{N_{p,n}} \right) \left( \frac{L_n}{L_f} \right)^2 \left( \frac{\epsilon_f}{\epsilon_n} \right) \left[ \frac{P_{\text{sur}}(E, L_f)}{P_{\text{sur}}(E, L_n)} \right]
\]

Ratio of detector masses

Ratio of detector efficiencies

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

SK atmospheric allowed