Updated three-neutrino oscillation parameters from global fits

Based on arXiv:1405.7540

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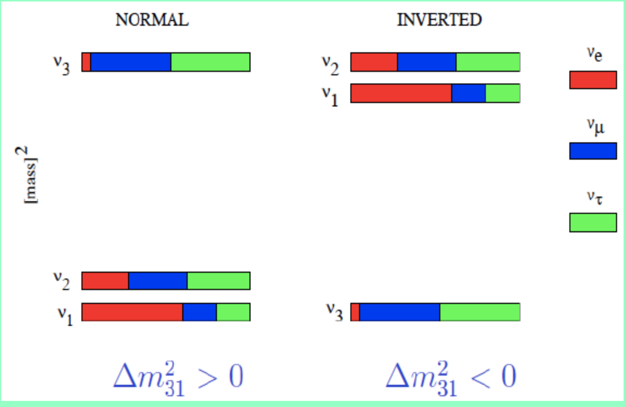
3-neutrino oscillation formalism

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

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

two possible mass orderings:



Oscillation probability:

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} Re(U^*_{\alpha i}U_{\alpha j}U_{\beta i}U^*_{\beta j})\sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right) + 2\sum_{i>j} Im(U^*_{\alpha i}U_{\alpha j}U_{\beta i}U^*_{\beta j})\sin\left(\frac{\Delta m^2_{ij}L}{2E}\right)$$

Parameter sensitivity

- $\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_e$ ← solar + KamLAND: $\theta_{12}, \Delta m^2_{21}, \theta_{13}$
- $\bar\nu_e \to \bar\nu_e$ ← SBL reactor: $\theta_{13}, \Delta m^2_{31}, \theta_{12}, \Delta m^2_{21}$
- $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu$, $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ ← atmospheric+LBL: $\theta_{23}, \Delta m^2_{31}, \theta_{13}, \Delta m^2_{21}, \delta$

Experimental Data

- **Solar** : Homestake, Gallex/GNO, SAGE, Borexino, SNO, Super-K.
- **Atmospheric** neutrino data from Super-K.
- **Reactor**: KamLAND, Double Chooz, Daya Bay, RENO.
- **Long-baseline**: K2K, MINOS, T2K.

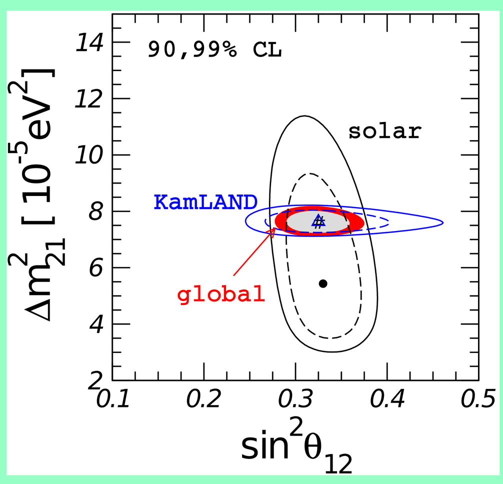
Methodology

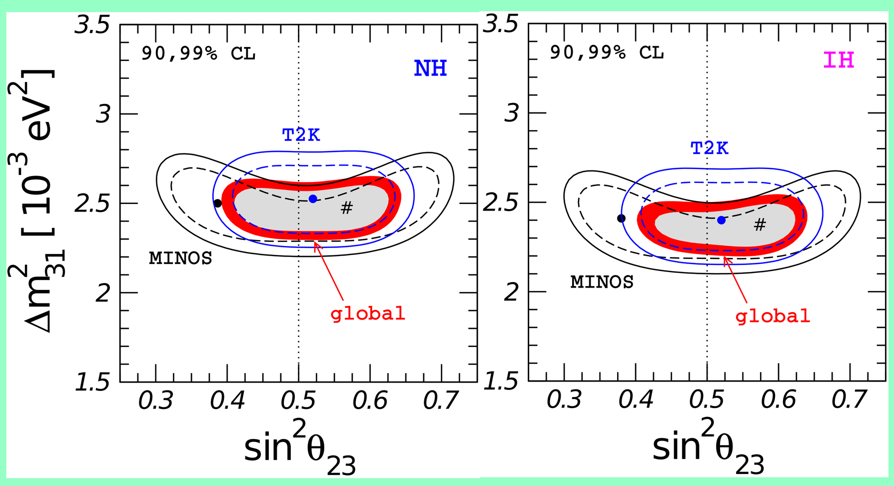
Oscillation probabilities + MC simulation of experiment → Expected data

Experiments → Observed data

Statistical analysis ➤ Allowed regions in $(\theta_{ij}, \Delta m^2_{ij}, \delta)$

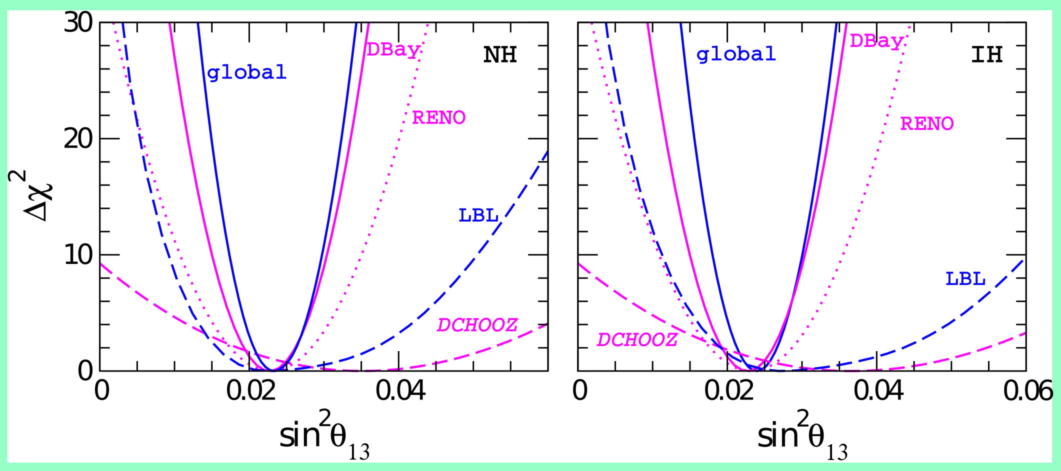
Solar and atmospheric parameters





- θ_{12} determined by solar data
- Δm^2_{21} dominated by KamLAND
- θ_{23} best constrained by T2K
- Δm^2_{31} dominated by MINOS

Reactor mixing angle



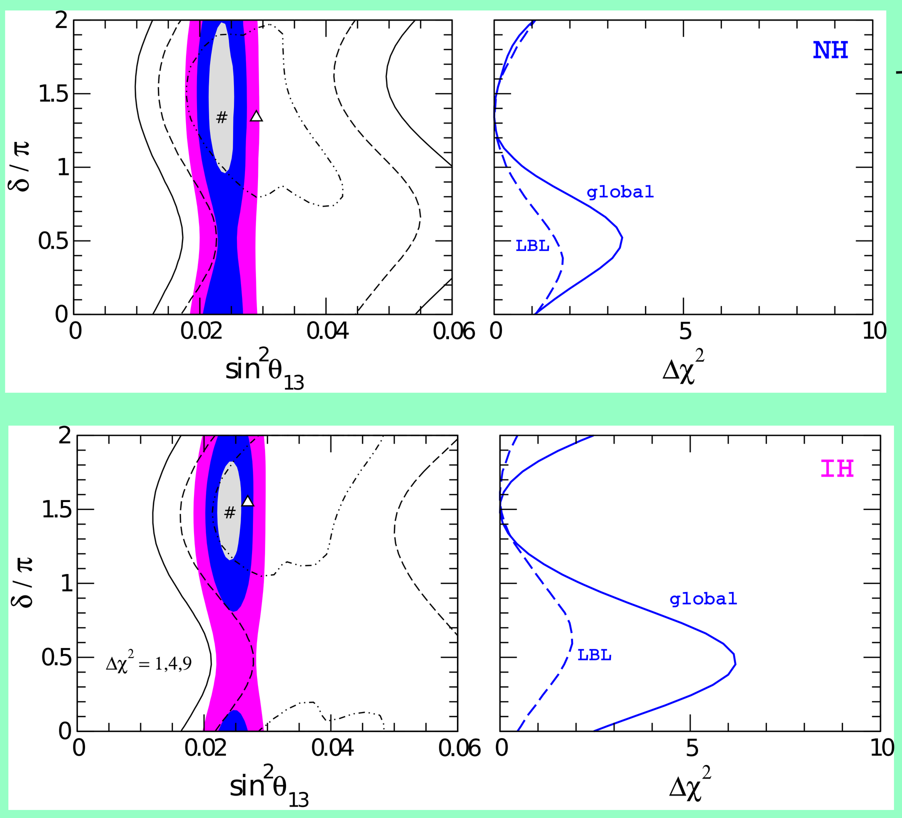
The determination of θ_{13} is totally dominated by Daya Bay

→ best fit values:

$\sin^2\theta_{13} = 0.0234 \pm 0.0020$ NH

$\sin^2\theta_{13} = 0.0240 \pm 0.0019$ IH

Sensitivity to CP phase



→ mismatch between value of θ_{13} preferred by LBL data and the one measured by Daya Bay

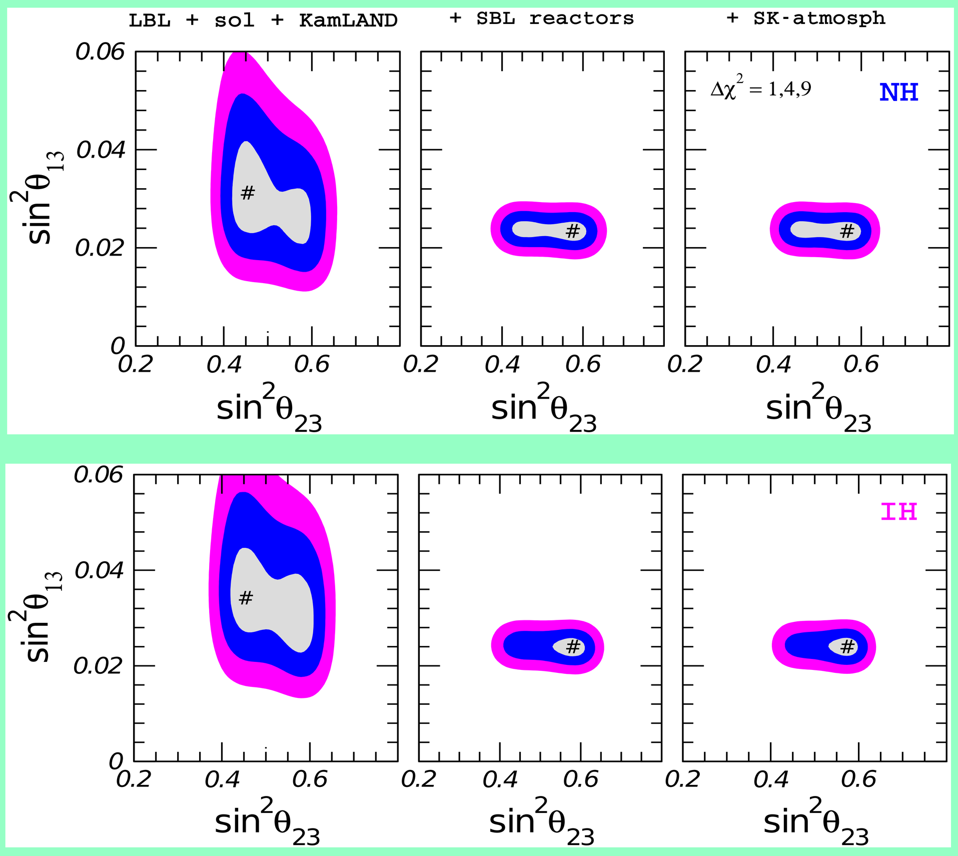
→ a significant rejection for values of $\delta \sim 0.5\pi$ emerges from the global fit: disfavoured at 1.8σ (2.5σ) for NH (IH)

→ best fit values:

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

$\delta = (1.48^{+0.34}_{-0.32})\pi$ IH

The octant of the atmospheric angle



appearance probability at LBL:

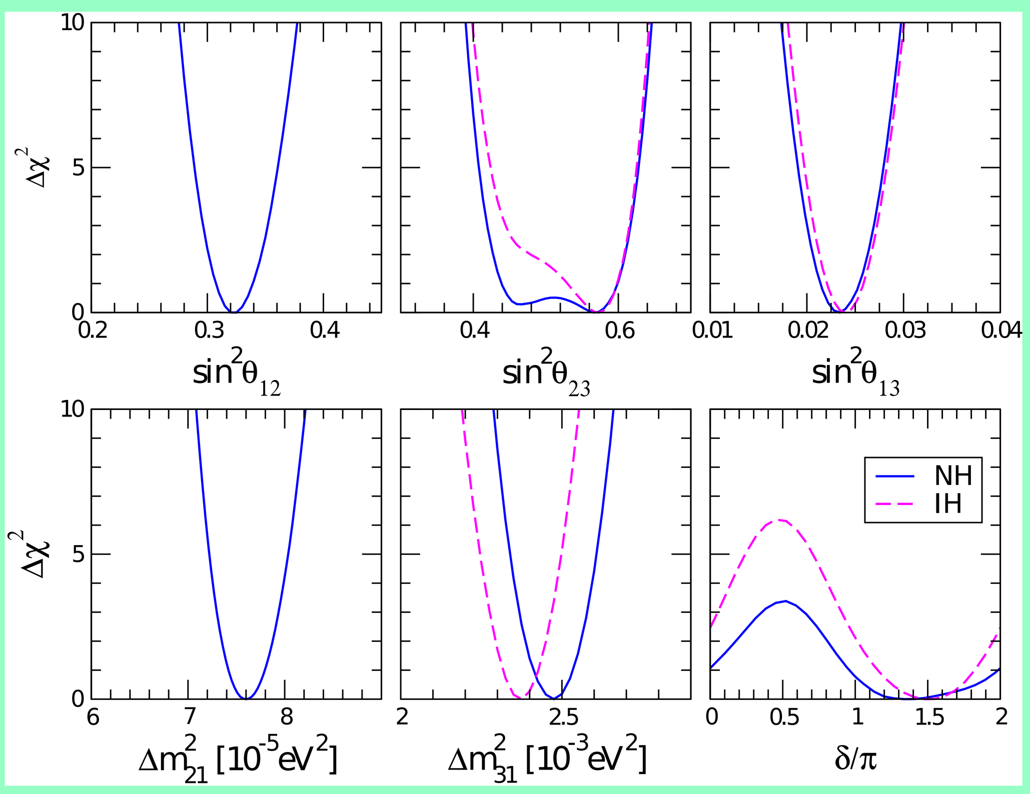
$$P_{\mu e} \propto \sin^2\theta_{23}\sin^2(2\theta_{13})$$

→ degeneracy in $\theta_{23} - \theta_{13}$ plane

→ reactor experiments fix θ_{13} and break the degeneracy moving θ_{23} to the second octant.

→ atmospheric data do not change this tendency and θ_{23} remains in the 2nd octant in the global fit

Summary of results



Solar parameters and θ_{13} determination slightly improved thanks to the latest SK-IV-sol, Daya Bay and RENO data

There is a preference for values of $\theta_{23} > \pi/4$ although for NH a local minimum appears in $\sin^2\theta_{23} = 0.467$ with $\Delta\chi^2 = 0.28$. For IH, solutions in the first octant appear only at 1.3σ

T2K provides now the most sensitive measurement of θ_{23}

An enhanced sensitivity to the CP violation phase emerges from the complementarity between accelerator and reactor data

parameter	best fit	1σ range	2σ range	3σ range
Δm^2_{21} [10^{-5}eV^2]	7.60	7.42–7.79	7.26–7.99	7.11–8.18
$\lvert\Delta m^2_{31}\rvert$ [10^{-3}eV^2] (NH)	2.48	2.41–2.53	2.35–2.59	2.30–2.65
$\lvert\Delta m^2_{31}\rvert$ [10^{-3}eV^2] (IH)	2.38	2.32–2.43	2.26–2.48	2.20-2.54
$\sin^2\theta_{12}/10^{-1}$	3.23	3.07–3.39	2.92–3.57	2.78–3.75
$\sin^2\theta_{23}/10^{-1}$ (NH)	5.67 (4.67)[a]	4.39–5.99	4.13–6.23	3.92 – 6.43
$\sin^2\theta_{23}/10^{-1}$ (IH)	5.73	5.30–5.98	4.32–6.21	4.03–6.40
$\sin^2\theta_{13}/10^{-2}$ (NH)	2.34	2.14–2.54	1.95–2.74	1.77–2.94
$\sin^2\theta_{13}/10^{-2}$ (IH)	2.40	2.21–2.59	2.02–2.78	1.83–2.97
δ/π (NH)	1.34	0.96–1.98	0.0–2.0	0.0–2.0
δ/π (IH)	1.48	1.16–1.82	0.0–0.14 & 0.81-2.0	0.0–2.0