Brief notes on neutrino oscillations and latest T2K results

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Oskar Klein centre

Stockholm University

Two distinct oscillation frequencies

3 neutrino oscillation probability (vacuum)

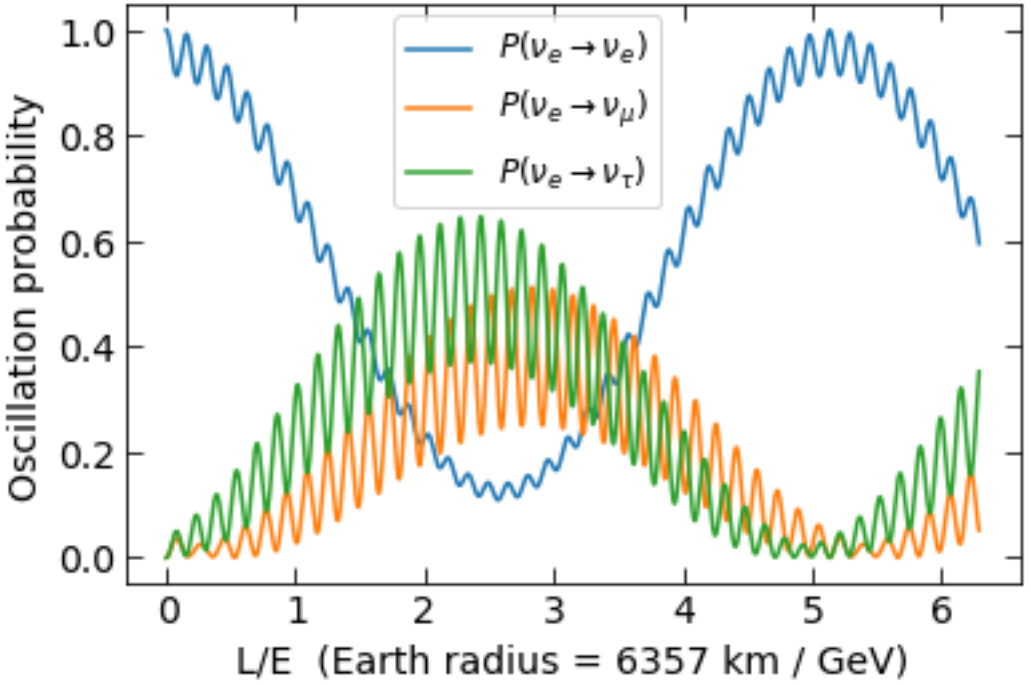
$$P_{3\nu}(\nu_\alpha \to \nu_\beta) = \sum_{k,j} U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j} \exp\left(\frac{-i\Delta m^2_{kj} L}{2E_\nu}\right)$$

$$\Delta m^2_{21} \simeq 7.5 \cdot 10^{-5}\,\mathrm{eV}^2$$

$$\Delta m^2_{31} \simeq 2.5 \cdot 10^{-3}\,\mathrm{eV}^2$$

2 neutrino approximation

$$P_{\nu_\alpha \to \nu_\beta}(L, E) = \sin^2 2\vartheta \, \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$



Oscillation parameters from best-fit values of P.F. de Salas et al, PLB 782 (2018) 633

Experiments and neutrino parameters

Different experiments are sensitive to different parameters

atmospheric angle — reactor angle — solar angle

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

CP phase

Δm^2_{31} Δm^2_{21}

Experiment	Dominant parameters	Sub-dominant parameters
Solar experiments	θ_{12}, Δm^2_{21}	θ_{13}
Short baseline Reactors	θ_{13}, Δm^2_{31}	θ_{12}, Δm^2_{21}
Telescopes (Atmospheric)	θ_{23}, Δm^2_{31}	θ_{13}, δ
LBL disappearance	θ_{23}, Δm^2_{31}	θ_{13}
LBL appearance	θ_{13}, Δm^2_{31}	θ_{23}, δ

Experiments and neutrino parameters

LBL experiments such as T2K

Disappearance probability

$$P\left(\nu_\mu \to \nu_\mu\right) \approx 1 - 4\cos^2\left(\theta_{13}\right)\sin^2\left(\theta_{23}\right)\left(1 - \cos^2\left(\theta_{13}\right)\sin^2\left(\theta_{23}\right)\right)\sin^2\left(\frac{1.27\Delta m^2_{32}\left[\mathrm{eV}^2\right]L\left[\mathrm{km}\right]}{E\left[\mathrm{GeV}\right]}\right)$$

Appearance probability

$$P\left(\nu_\mu \to \nu_e\right) \approx \left(\sin^2\left(2\theta_{13}\right)\sin^2\left(\theta_{23}\right) \mp \frac{1.27\Delta m^2_{21}\left[\mathrm{eV}^2\right]L\left[\mathrm{km}\right]}{E\left[\mathrm{GeV}\right]} 8 J_{\mathrm{CP}}\right)\sin^2\left(\frac{1.27\Delta m^2_{32}\left[\mathrm{eV}^2\right]L\left[\mathrm{km}\right]}{E\left[\mathrm{GeV}\right]}\right)$$

Jarlskog invariant

$$J_{\mathrm{CP}} = \frac{1}{8}\cos\left(\theta_{13}\right)\sin\left(2\theta_{12}\right)\sin\left(2\theta_{23}\right)\sin\left(2\theta_{13}\right)\sin\left(\delta_{\mathrm{CP}}\right)$$

T2K (Tokai to Kamioka)

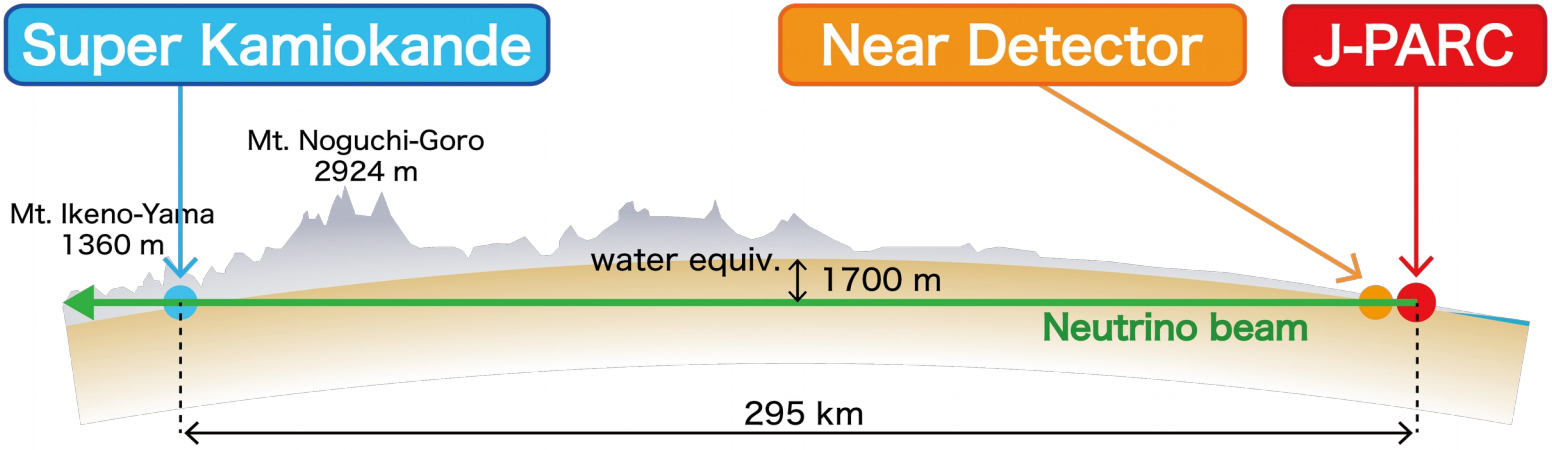
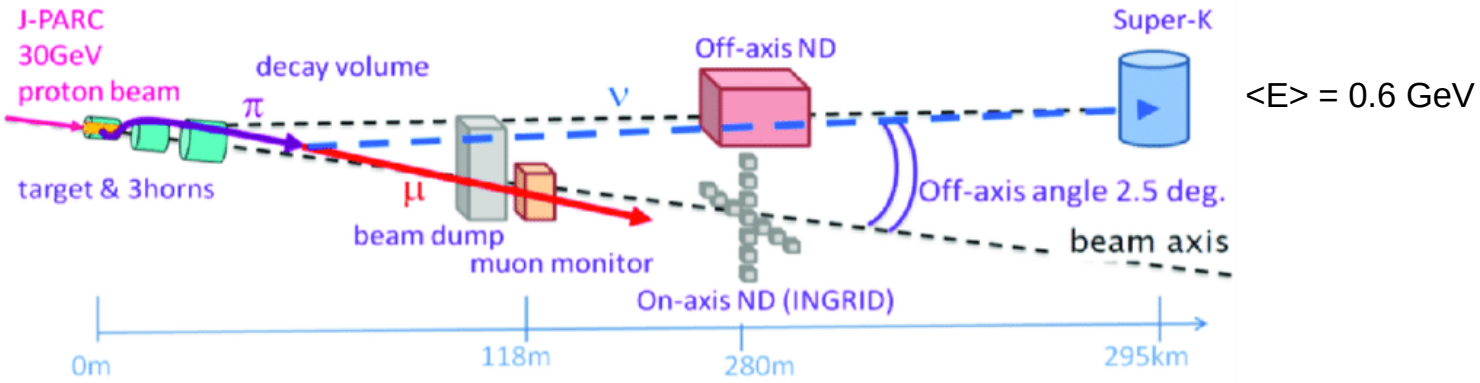


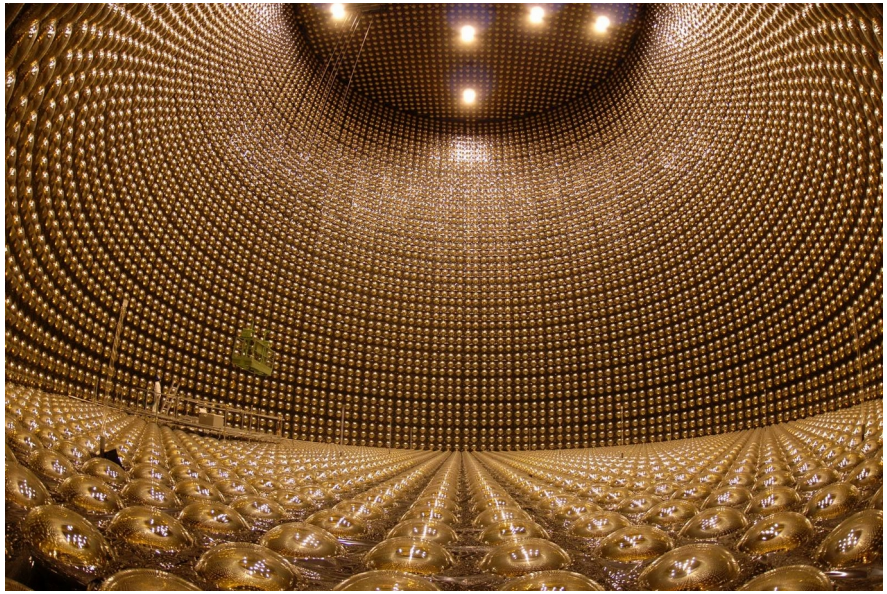
Image from: https://www.ppd.stfc.ac.uk/Pages/T2K.aspx



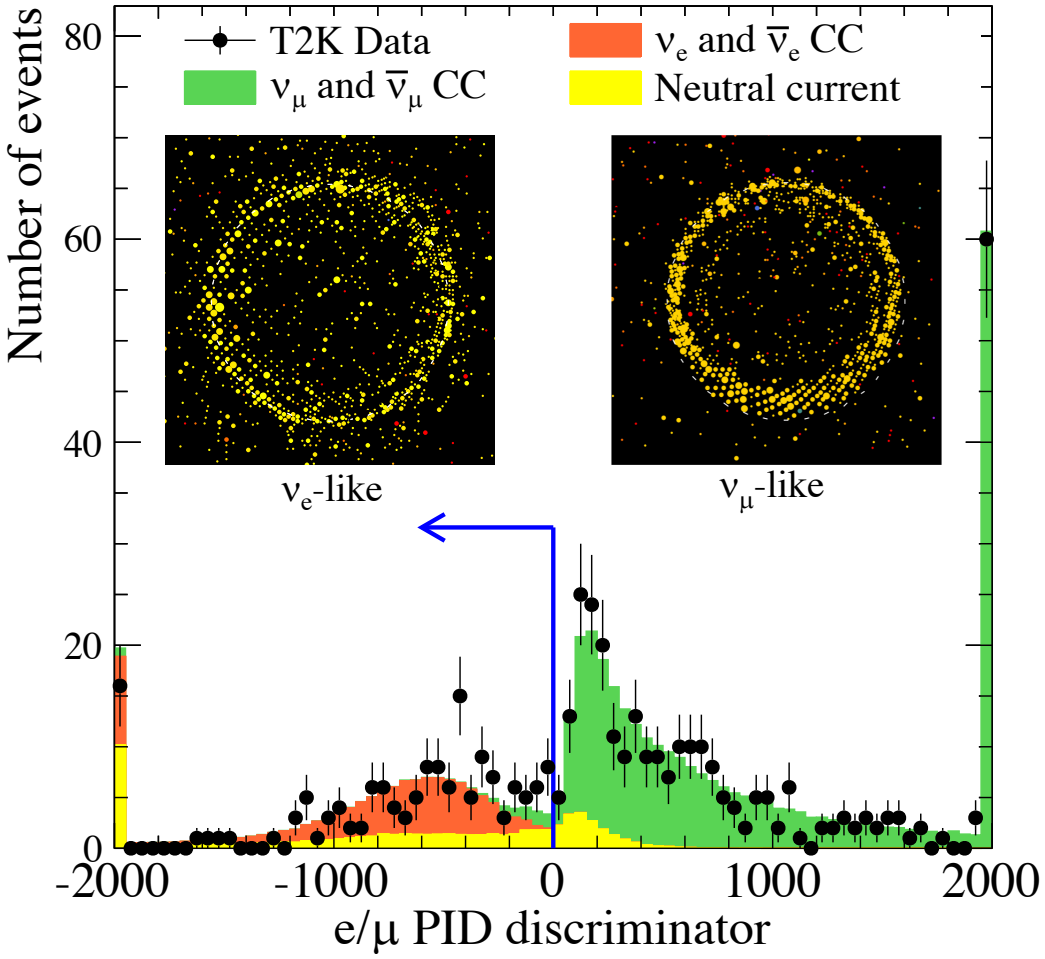
<E> = 0.6 GeV

Image from: Khabibullin, Marat. (2018). Recent results from the T2K experiment. EPJ Web of Conferences. 191. 03001

Neutrino flavour in Super-Kamiokande

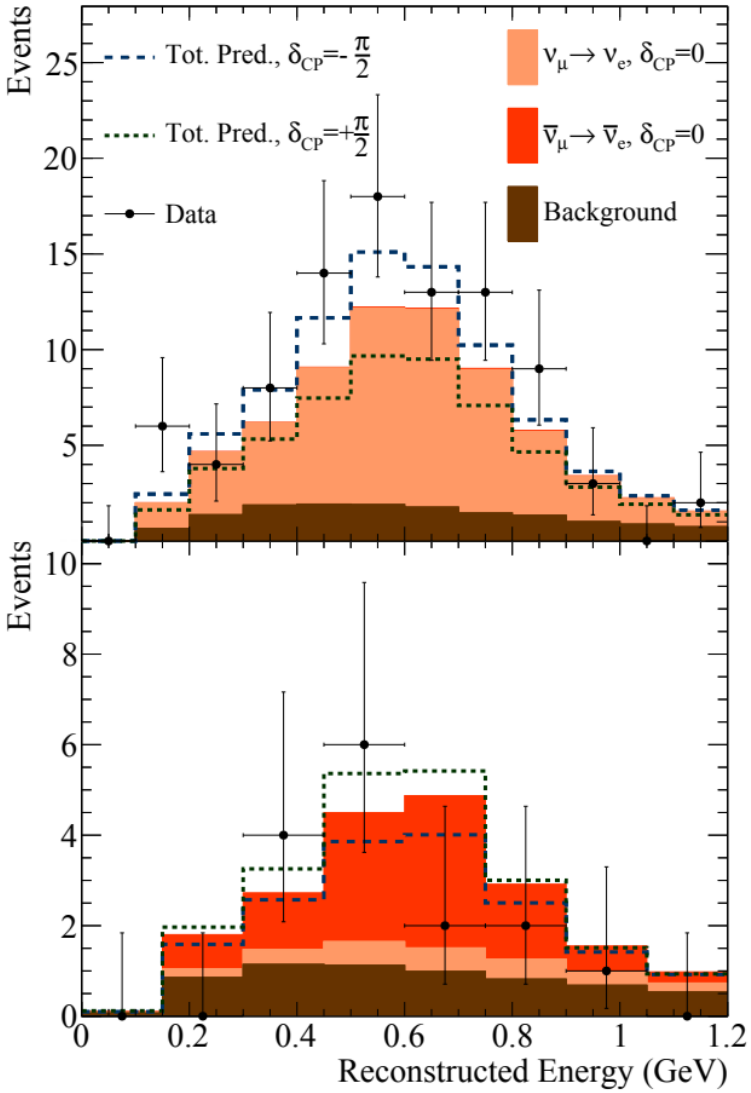


Super-Kamiokande interior



K. Abe et al, Nature (2020) 580, 339
[arXiv:1910.03887}

Effect of CP phase in event distribution



$$P\left(\nu_\mu \rightarrow \nu_e\right) \approx$$

$$\left(\sin^2\left(2\theta_{13}\right)\sin^2\left(\theta_{23}\right) \mp \frac{1.27\Delta m^2_{21}\left[\mathrm{eV}^2\right] L\left[\mathrm{km}\right]}{E\left[\mathrm{GeV}\right]} 8 J_{\mathrm{CP}}\right)$$

$$\times \sin^2\left(\frac{1.27\Delta m^2_{32}\left[\mathrm{eV}^2\right] L\left[\mathrm{km}\right]}{E\left[\mathrm{GeV}\right]}\right)$$

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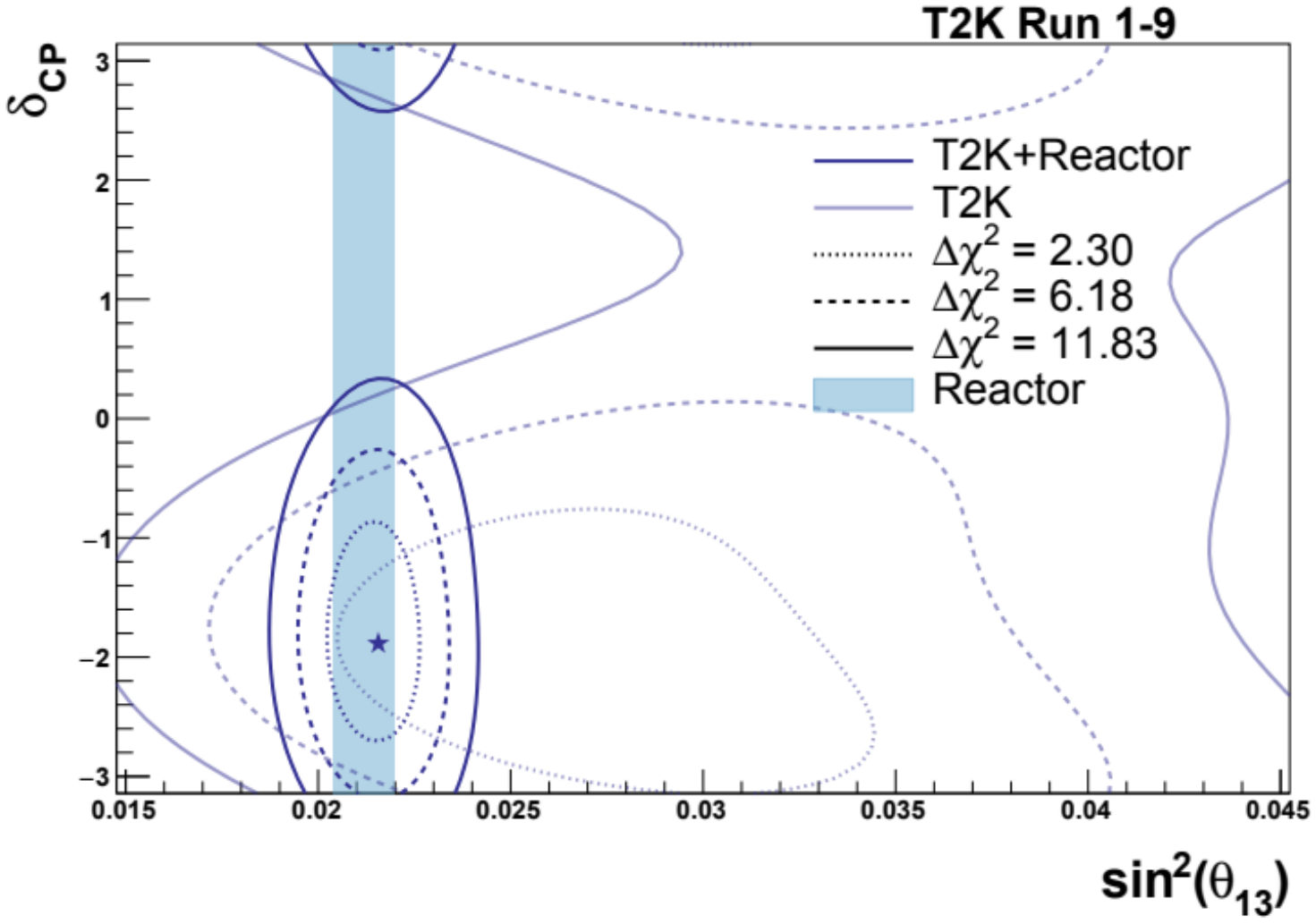
T2K (Tokai to Kamioka)



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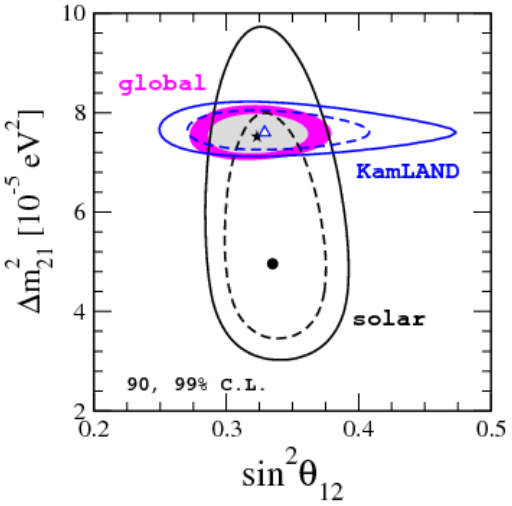
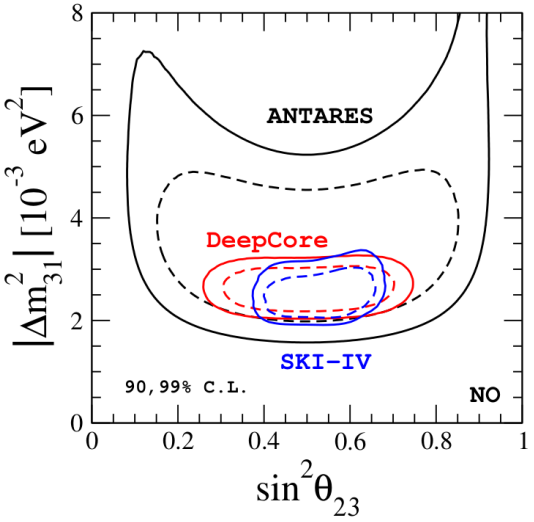
Experiments and neutrino parameters

Solar sector

Cl, Ga
SK, SNO
Borexino
KamLAND



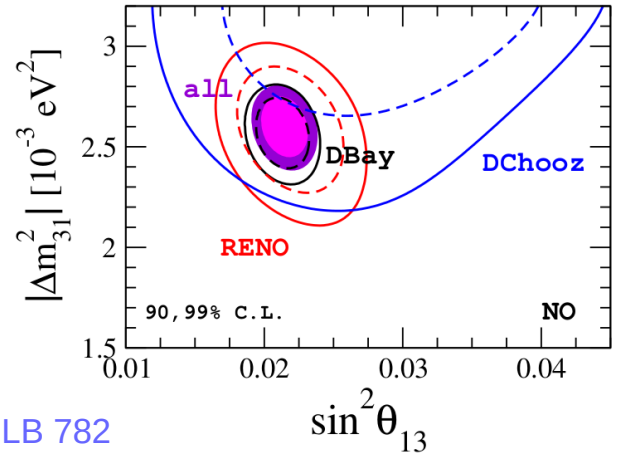


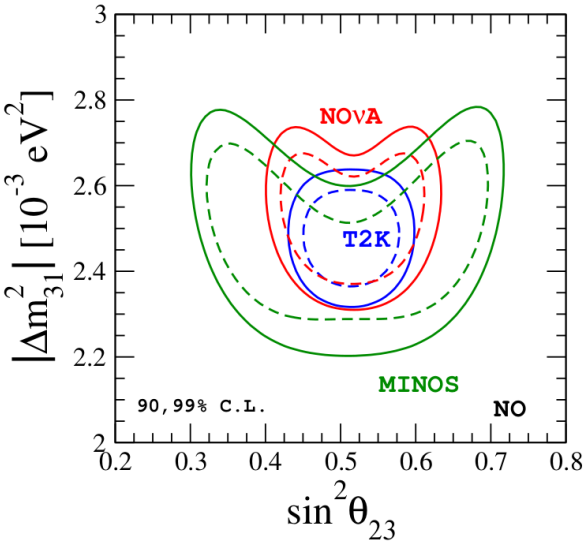
Atmospheric neutrino detectors

SK (official χ^2 maps)
IceCube-DeepCore
ANTARES

SBL reactor

Daya Bay
RENO
Double Chooz





LBL accelerator

MINOS
K2K, T2K
NOνA

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Summary global fit

parameter	best fit $\pm 1\sigma$	3σ range	
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	$7.55^{+0.20}_{-0.16}$	7.05–8.14	~2.6%
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$ (NO)	2.50 ± 0.03	2.41–2.60	~1.5%
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$ (IO)	$2.42^{+0.03}_{-0.04}$	2.31–2.51	
$\sin^2\theta_{12}/10^{-1}$	$3.20^{+0.20}_{-0.16}$	2.73–3.79	~6.3%
$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.47^{+0.20}_{-0.30}$	4.45–5.99	~5.5%
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.51^{+0.18}_{-0.30}$	4.53–5.98	
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.160^{+0.083}_{-0.069}$	1.96–2.41	~3.5%
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.220^{+0.074}_{-0.076}$	1.99–2.44	
δ/π (NO)	$1.32^{+0.21}_{-0.15}$	0.87–1.94	~13.5%
δ/π (IO)	$1.56^{+0.13}_{-0.15}$	1.12–1.94	

Relative 1 sigma uncertainties

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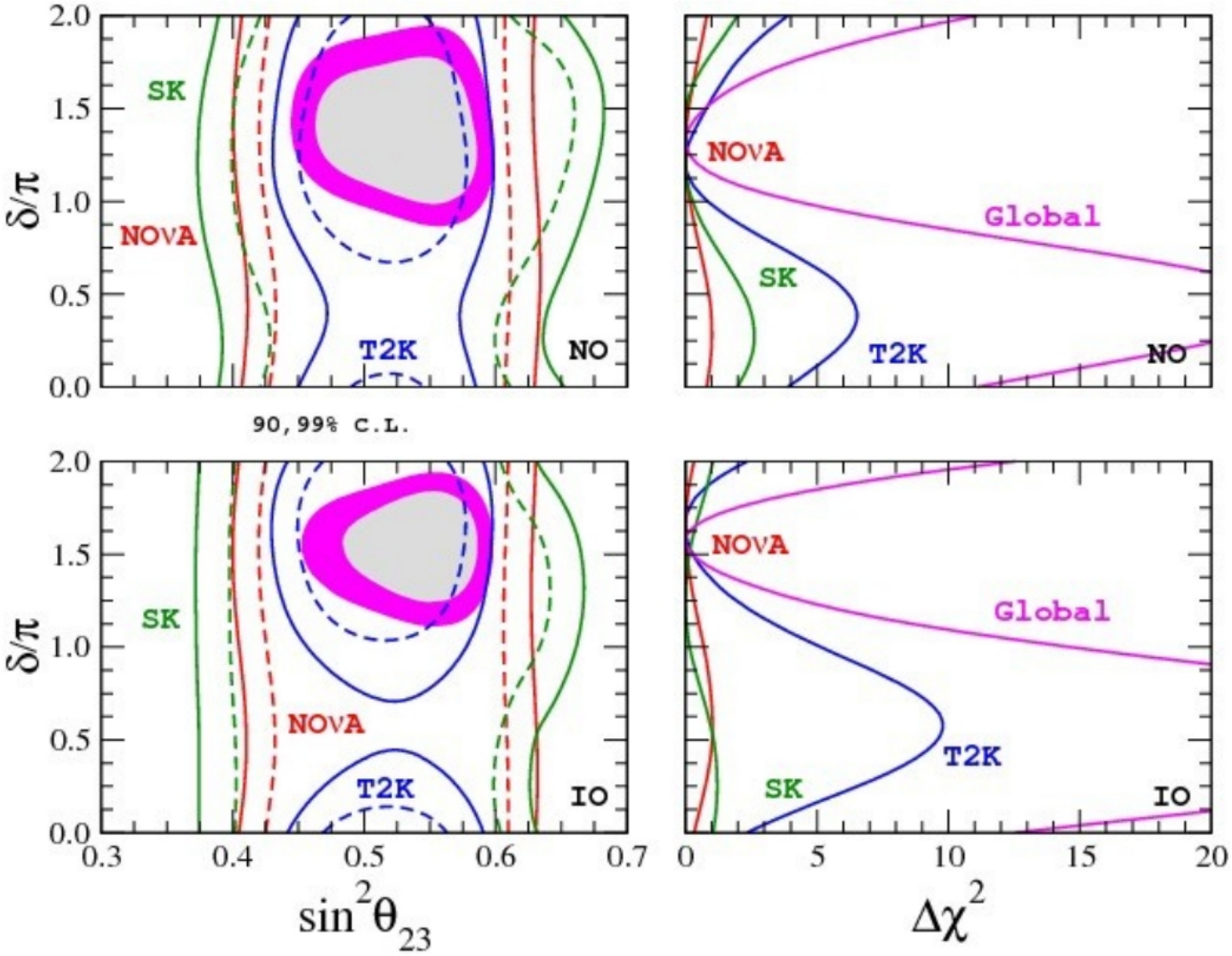
The CP phase

- Leading experiment T2K
- Global sensitivity improved thanks to reactor angle determination
- Values ~π/2 disfavoured at > 4 σ



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