MASSIVE NEUTRINOS IN 2025

Concha Gonzalez-Garcia

(YITP-Stony Brook & ICREA-University of Barcelona)

Phenomenology Before and After the Standard Model

a symposium in honor of Vernon Barger

Madison, June 5, 2025

Global fit to neutrino oscillation data

AGENCIA ESTATAL DE INVESTIGACIÓN

NSF

Data to be Described

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Solar experiments

- Chlorine total rate, 1 data point.
- Gallex & GNO total rates, 2 points.
- SAGE total rate, 1 data point.
- SK1 E and zenith spect, 44 poins.
- SK2 E and D/N spect, 33 points.
- SK3 E and D/N spect, 42 points.
- SK4 2970-day E spectrum and D/N asym, 46 points.
- SNO combined analysis, 7 points.
- Borexino Ph-I 740.7-day low-E spect 33 points.
- Borexino Ph-I 246-day high-E spect ,6 points.
- Borexino Ph-II 1292-day low-E spect, 192 points.
- Borexino Ph-III 1433-day low-E spect, 120 points.

Reactor experiments

- KamLAND DS1,DS2&DS3 spectra with Daya-Bay fluxes 69 points
- DChooz FD/ND ratios with 1276-day (FD) and 587-day (ND) exposures , 26 points.
- Daya-Bay 3158-day EH1,EH2, EH3 spectra ,78 points.
- Reno 2908-day FD/ND ratios 45 points.

Atmospheric experiments

- IceCube/DeepCore 2019 3-year data.
- IceCube/DeepCore 2014 9,3-year data (χ^2 table provided
- K I-V 484 kton-years(χ^2 table provided by SK)

Accelerator experiments

- MINOS 10.71 $\times 10^{20}$ pot ν_μ-disapp data, 39 poins.
- MINOS 3.36 $\times 10^{20}$ pot $\bar{\nu}_\mu$-disapp data , 14 points.
- MINOS 10.6 $\times 10^{20}$ pot ν_e-app data , 5 points.
- MINOS 3.3 $\times 10^{20}$ pot $\bar{\nu}_e$-app data , 5 points.
- T2K 21.4 $\times 10^{20}$ pot ν_μ-disapp data, 28 points.
- T2K 21.4 $\times 10^{20}$ pot ν_e-app data, 9 points CCQE and 7 p
- T2K 16.3 $\times 10^{20}$ pot $\bar{\nu}_\mu$-disapp, 19 points.
- T2K 16.3 $\times 10^{20}$ pot $\bar{\nu}_e$-app, 9 points.
- NOνA 26.6 $\times 10^{20}$ pot ν_μ-disapp data , 21 points.
- NOνA 26.6 $\times 10^{20}$ pot ν_e-app data , 15 points.
- NOνA 12.5 $\times 10^{20}$ pot $\bar{\nu}_\mu$-disapp, 18 points.
- NOνA 12.5 $\times 10^{20}$ pot $\bar{\nu}_e$-app, 13 points.

The New Minimal Standard Model

- Minimal Extension to allow for LFV $\Rightarrow$ give Mass to the Neutrino

  $*$ With SM fields: Use ν_L^c is right-handed

$$\mathcal{L} - \mathcal{L}_{SM} = -\frac{1}{2} M_\nu \overline{\nu_L} \nu_L^C + h.c. \Rightarrow \begin{cases} L \text{ is violated} \Rightarrow \text{Majorana } \nu = \nu^c \\ SU(2)_L \text{ is violated} \Rightarrow \text{Effective LE} \end{cases}$$

  $*$ Introduce ν_R AND impose L conservation

$$\mathcal{L} - \mathcal{L}_{SM} = -M_D \overline{\nu_L} \nu_R - \frac{1}{2} M_R \overline{\nu_R} \nu_R^C + h.c. \quad \Rightarrow \text{Dirac } \nu \neq \nu^c:$$

- Either way $\Rightarrow$ Mixing in charged current interactions of massive leptons

$$\frac{g}{\sqrt{2}} W_\mu^+ \sum_{ij} \left(U_{\text{LEP}}^{ij} \, \overline{\ell^i} \, \gamma^\mu \, L \, \nu^j \; + \; U_{\text{CKM}}^{ij} \, \overline{U^i} \, \gamma^\mu \, L \, D^j \right) \; + \; h.c.$$

The New Minimal Standard Model: ν flavour oscillations

- In vacuum:

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{j\neq i}^{n} \mathrm{Re}[U^\star_{\alpha i}U_{\beta i}U_{\alpha j}U^\star_{\beta j}]\sin^2\left(\frac{\Delta_{ij}}{2}\right) + 2\sum_{j\neq i} \mathrm{Im}[U^\star_{\alpha i}U_{\beta i}U_{\alpha j}U^\star_{\beta j}]\sin\left(\Delta_{ij}\right)$$

$\Delta_{ij} = (m_i^2 - m_j^2)\frac{L}{4E}$ $\Rightarrow$ No information on ν mass scale nor Majorana/Dirac

- When osc between 2-ν dominates: $P_{\alpha\neq\beta} = \sin^2(2\theta)\,\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$

$\Rightarrow$ No information on Mass Ordering ($\equiv$ sign(Δm^2)) nor octant of θ nor CPV

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The New Minimal Standard Model: ν flavour oscillations

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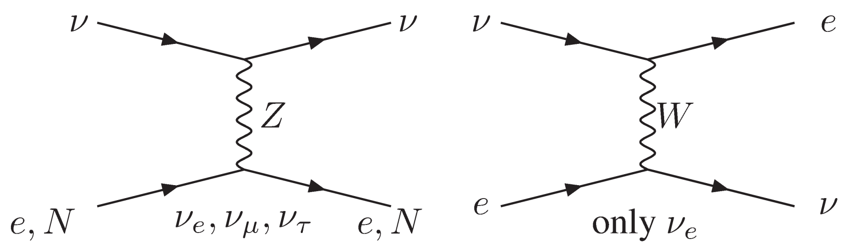
- If ν cross matter regions (Sun, Earth...)
  it interacts *coherently*
  Different flavours have different interactior



$\Rightarrow$ Effective potential in ν evolution: $V_e \neq V_{\mu,\tau} \Rightarrow \Delta V^{\nu_e} = -\Delta V^{\bar\nu_e} = \sqrt{2} G_F N_e$

$\Rightarrow$ Modification of mixing angle and oscillation wavelength (MSW)

$\Rightarrow$ For solar $\nu's$: Dependence on θ octant

$\Rightarrow$ In LBL terrestrial experiment: Dependence on sign of Δm^2 and θ octant

3ν Flavour Parameters

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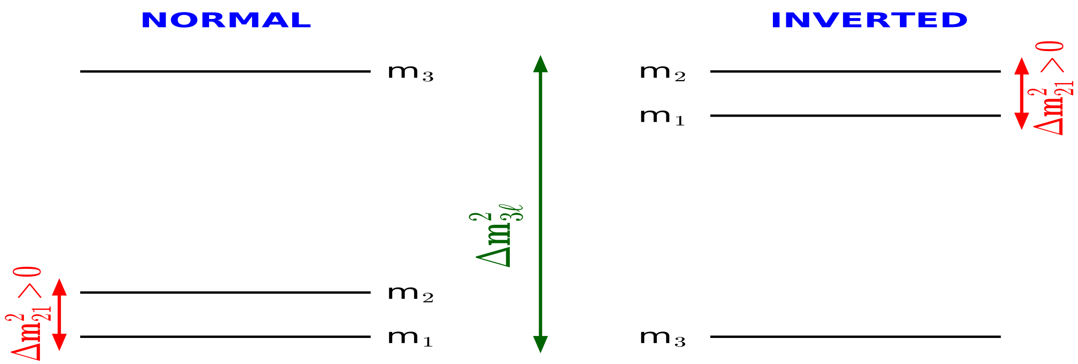
- For **for 3 ν's** : 3 Mixing angles + 1 Dirac Phase + 2 Majorana Phases

$$U_{\rm LEP} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{i\delta_{\rm cp}} \\ 0 & 1 & 0 \\ -s_{13} e^{-i\delta_{\rm cp}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- Convention: $0 \leq \theta_{ij} \leq 90^\circ$ $\quad 0 \leq \delta \leq 360^\circ$ $\quad \Rightarrow$ 2 Orderings



$\Delta m^2_{21} > 0$ by convention

$$\Delta m^2_{3\ell} = \begin{cases} \Delta m^2_{31} > 0 \text{ for NO} \\ \Delta m^2_{32} < 0 \text{ for IO} \end{cases}$$

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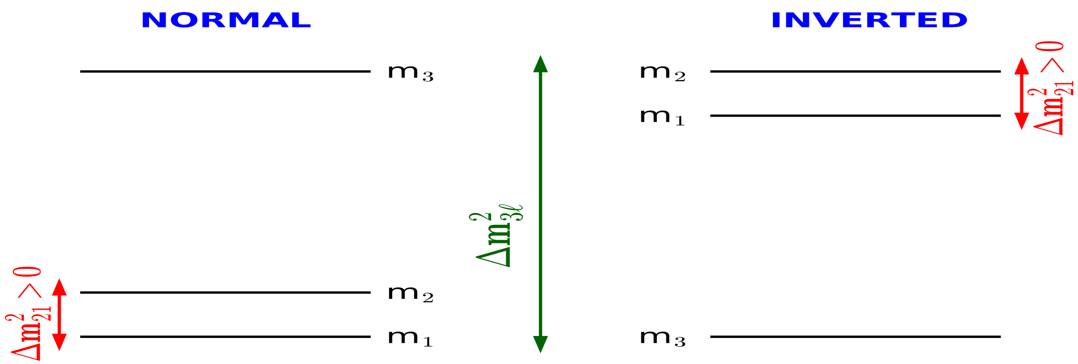

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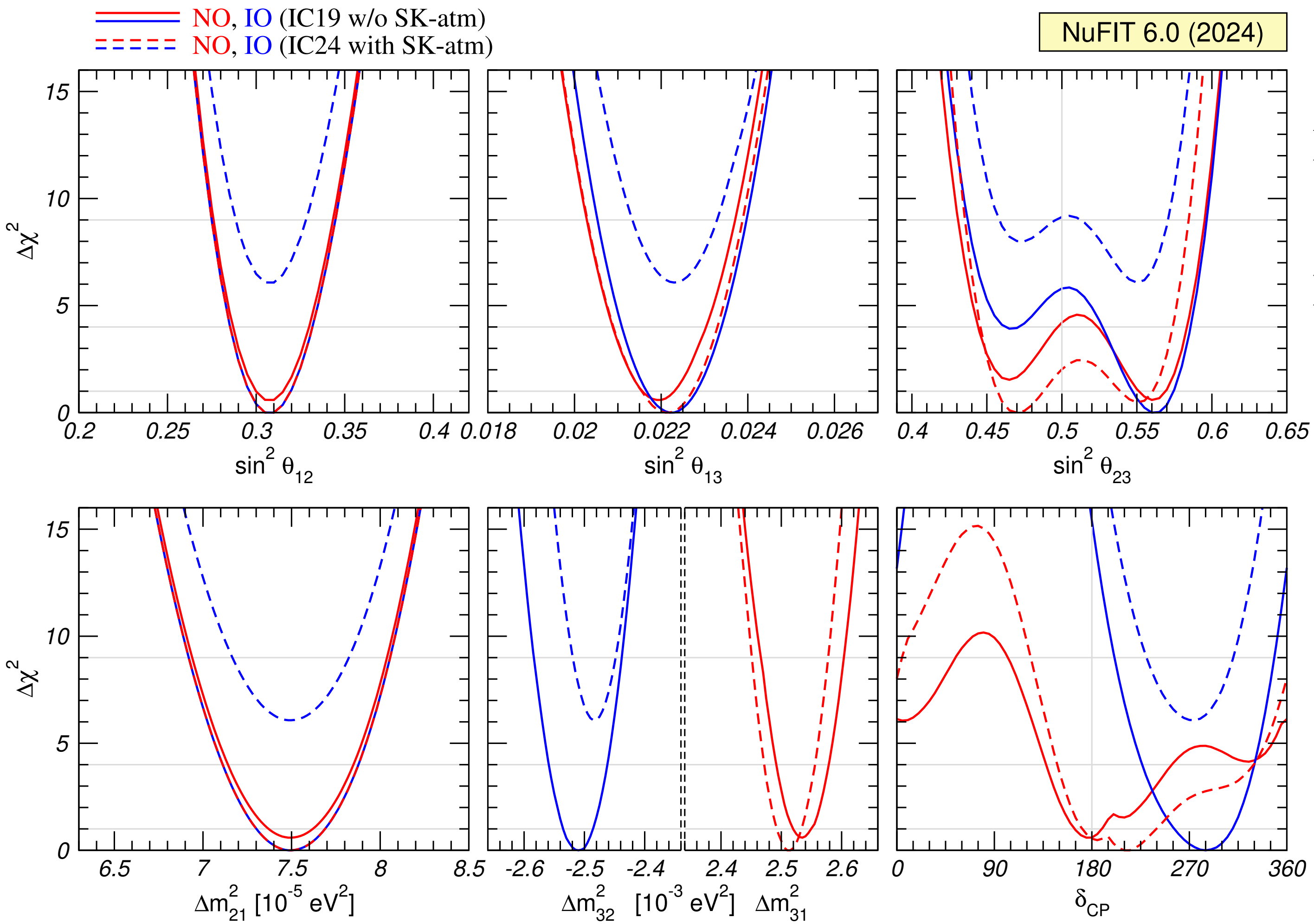
Experiment	Dominant	Important	Additional
Solar Experiments	θ_{12}	Δm^2_{21}	θ_{13}
Reactor LBL (KamLAND)	Δm^2_{21}	θ_{12}	θ_{13}
Reactor MBL (Daya Bay, Reno, D-Chooz)	θ_{13}, $\Delta m^2_{3\ell}$		
Atmospheric Experiments (SK,IC)	θ_{23}	$\Delta m^2_{3\ell}$	θ_{13} ,$\delta_{\rm cp}$
Acc LBL ν_μ Disapp (Minos,T2K,NOvA)	$\Delta m^2_{3\ell}$. θ_{23}		
Acc LBL ν_e App (Minos,T2K,NOvA)	$\delta_{\rm cp}$	θ_{13}	θ_{23}, $\Delta m^2_{3\ell}$,$\Delta m^2_{3\ell}$

Global 3 ν Flavour Parameters: Spring 2025

Global 6-parameter fit http://www.nu-fit.org

Esteban, Gonzalez-Garcia, Maltoni, Martinez, Pinheiro,Schwetz, 2410.05380

(In last years good agreement with results from Bari (2503.07752) and Valencia groups)



SK-atm $\equiv \chi^2$ table from SK1-5

IC24 $\equiv \chi^2$ table from Icecube data from 2405.02163

IC19 $\equiv$ Our analysis of Icecube data from 1902.07771

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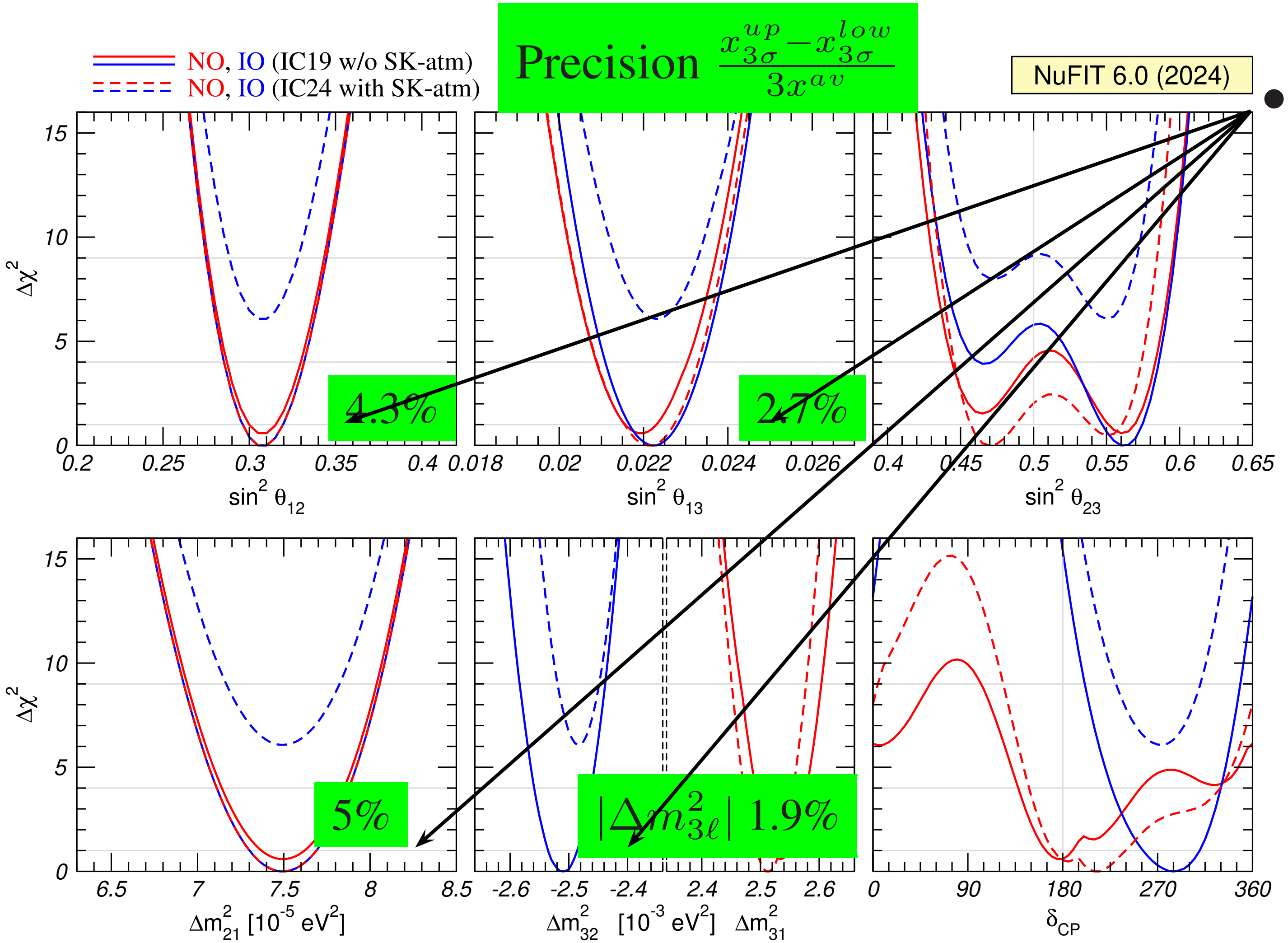

- 4 well-known parameters: $\theta_{12}, \theta_{13}, \Delta m^2_{21}, |\Delta m^2_{3\ell}|$

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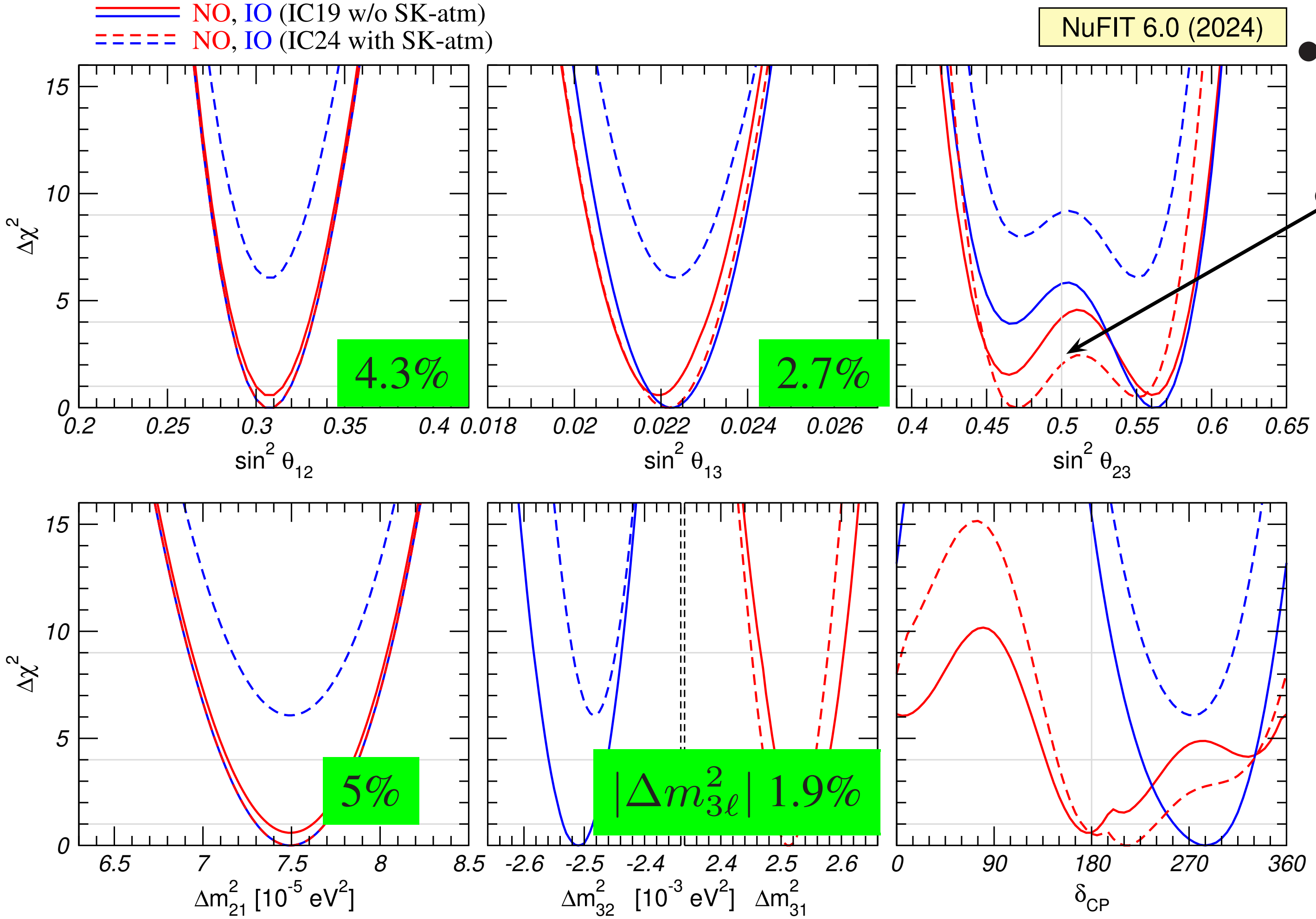

- 4 well-known parameters: $\theta_{12}, \theta_{13}, \Delta m^2_{21}, |\Delta m^2_{3\ell}|$
- θ_{23}: Least known angle Maximal? Octant? non-robust yet

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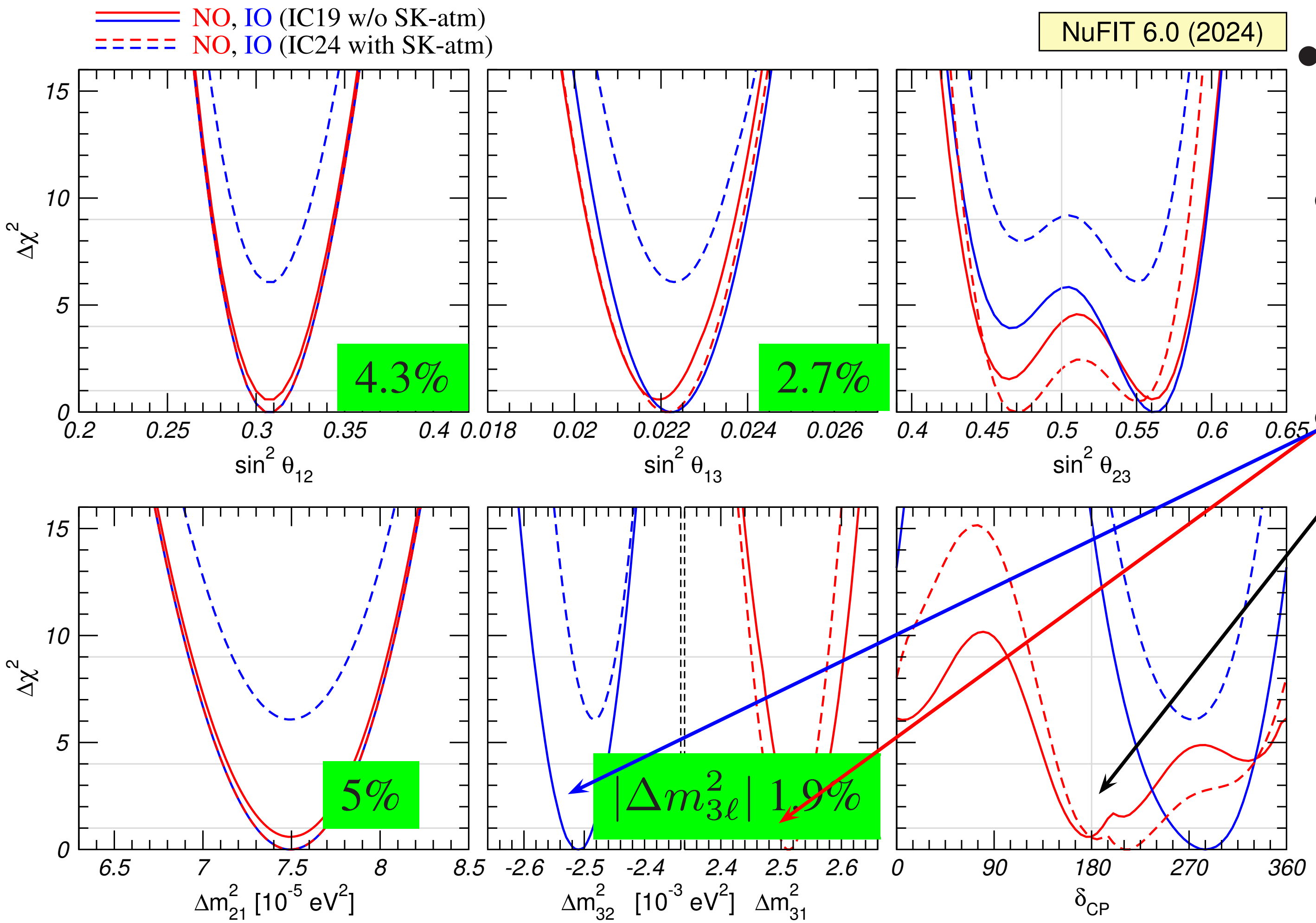

- 4 well-known parameters: θ_{12}, θ_{13}, Δm^2_{21}, $|\Delta m^2_{3\ell}|$
- θ_{23}: Least known angle
  Maximal? Octant?
  non-robust yet
- Ordering NO or IO?
  CPV?:

Mass Ordering (and CPV)

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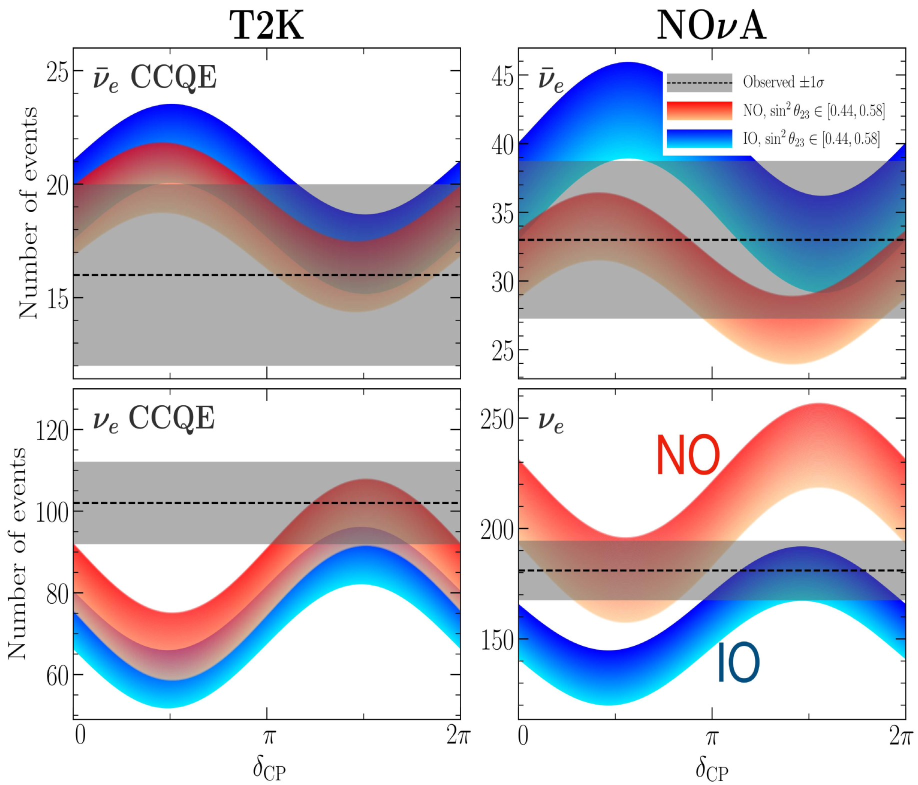
• Dominant information in ν_e vs $\overline{\nu}_e$ appearance in LBL

$$P_{\mu e} \simeq s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{31}}{B_\mp}\right)^2 \sin^2\left(\frac{B_\mp L}{2}\right) + \tilde{J}\,\frac{\Delta_{21}}{V_E}\,\frac{\Delta_{31}}{B_\mp}\,\sin\left(\frac{V_E L}{2}\right)\,\sin\left(\frac{B_\mp L}{2}\right)\,\cos\left(\frac{\Delta_{31} L}{2} \pm \delta_{CP}\right)$$

$$\Delta_{ij} = \frac{\Delta m_{ij}^2}{4E} \qquad B_\pm = \Delta_{31} \pm V_E \qquad \tilde{J} = c_{13}\,\sin^2 2\theta_{13}\,\sin^2 2\theta_{23}\,\sin^2 2\theta_{12}$$



⇒ Each T2K and NOνA favour NO

But some tension in value of δ_{CP} in NO

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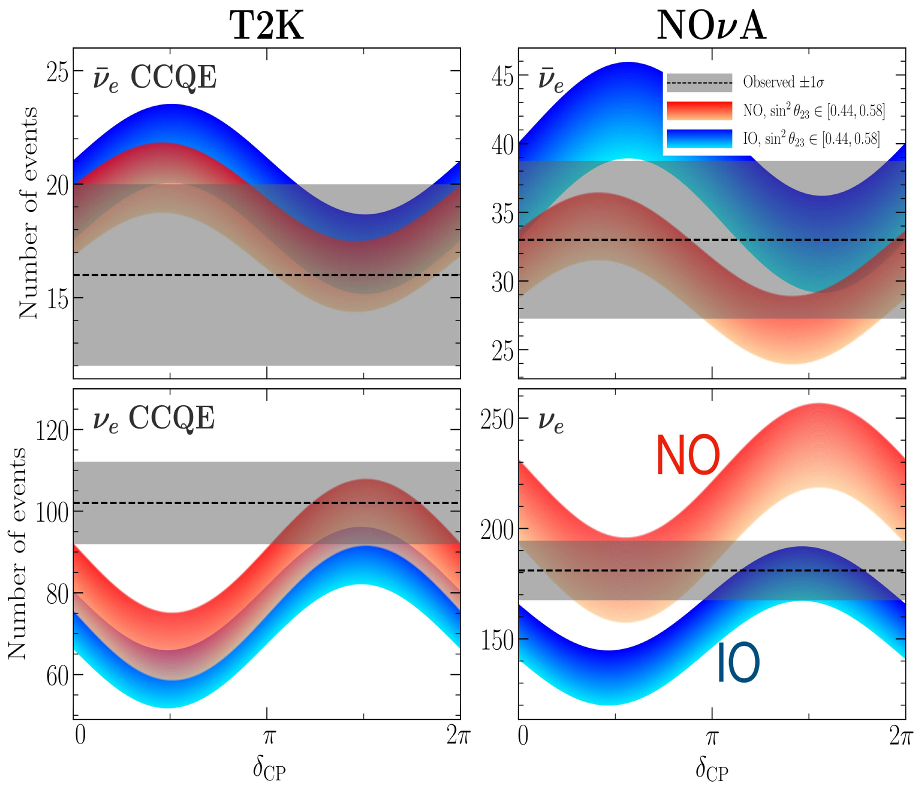

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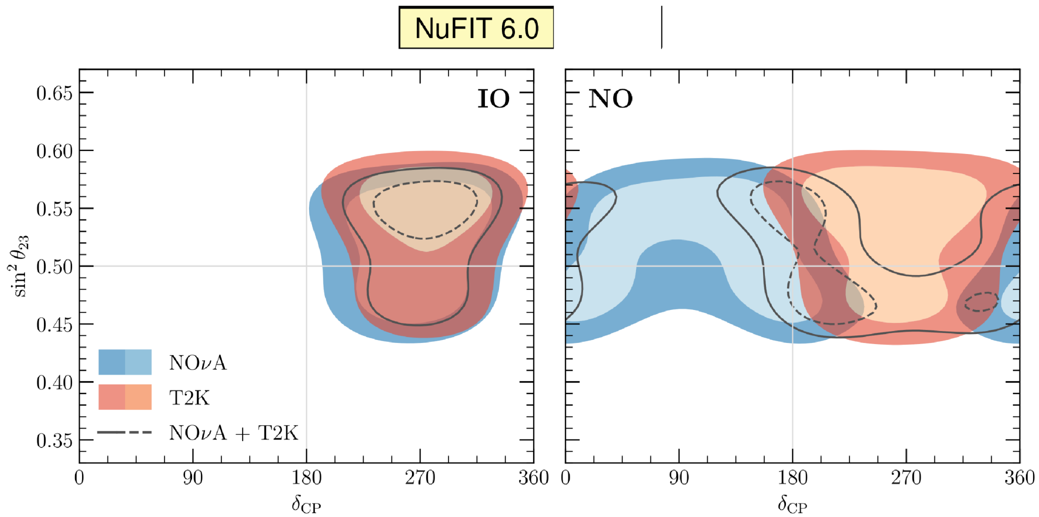
⇒ IO best fit in LBL combination



Parameter goodness-of-fit (PG) test:

	normal ordering			inverted ordering		
	χ^2_{PG}/n	p-value	$\#\sigma$	χ^2_{PG}/n	p-value	$\#\sigma$
T2K vs NOvA	7.9/3	0.047	2.0σ	1.8/3	0.61	0.5σ

No statistically significant incompatibility yet

Mass Ordering (and CPV)

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- Dominant information in ν_e vs $\overline{\nu}_e$ appearance in LBL:

  Each T2K and NOνA favour NO but tension in value of δ_{CP} in NO

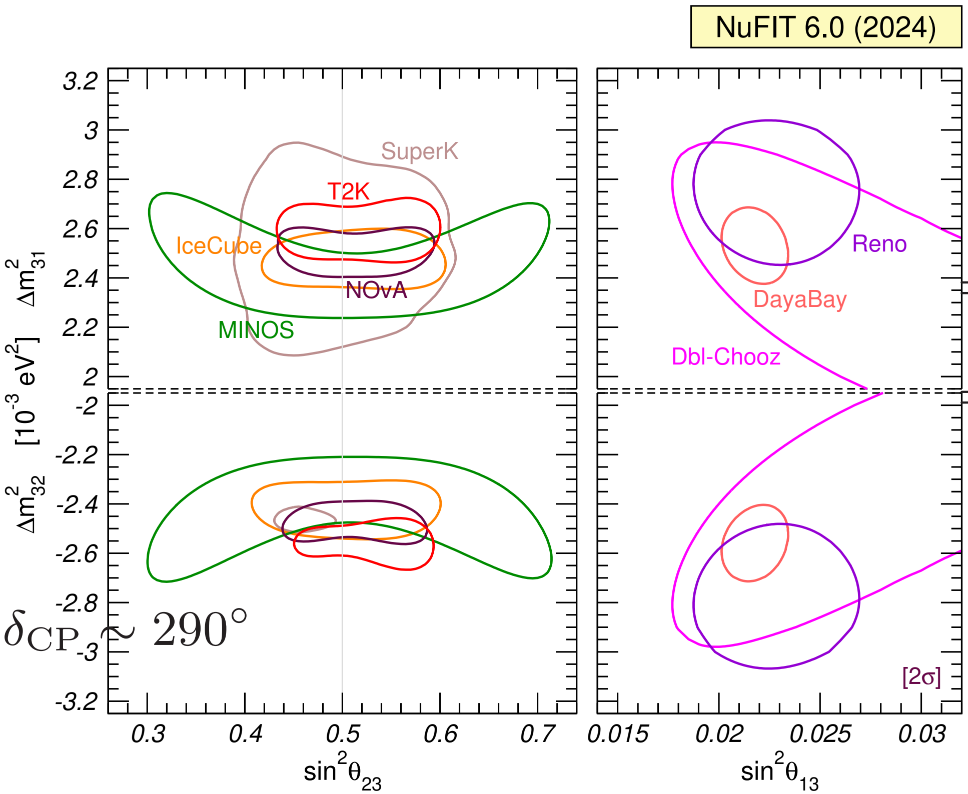
  $\Rightarrow$ IO best fit in LBL combination $\Rightarrow$ b.f. $\delta_{\rm CP} \sim 290^\circ$, CPC disfavoured at $\gtrsim 3.5\sigma$

- Additional information from ν_μ in LBL vs ν_e disapperance in MBL Reactors:

$$\Delta m^2_{\mu\mu} \simeq \Delta m^2_{3l} + \begin{matrix} c^2_{12}\Delta m^2_{21} & \text{NO} \\ s^2_{12}\Delta m^2_{21} & \text{IO} \end{matrix} + \ldots$$

$$\Delta m^2_{ee} \simeq \Delta m^2_{3l} + \begin{matrix} s^2_{12}\Delta m^2_{21} & \text{NO} \\ c^2_{12}\Delta m^2_{21} & \text{IO} \end{matrix}$$

Nunokawa,Parke,Zukanovich hep-ph/0503283



$\delta_{\rm CP} \sim 290^\circ$

$\Rightarrow$ Slightly better agreement in NO

$\Rightarrow$ LBL+Reac: NO and IO equally good

– NO: CPC $\delta_{\rm CP} \sim 180^\circ$ allowed at $\lesssim 0.6\sigma$

– IO: CPC disfavoured at $\gtrsim 3.5\sigma$ b.f.

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- Additional information from ν_μ in LBL vs ν_e disapperance in MBL Reactors:
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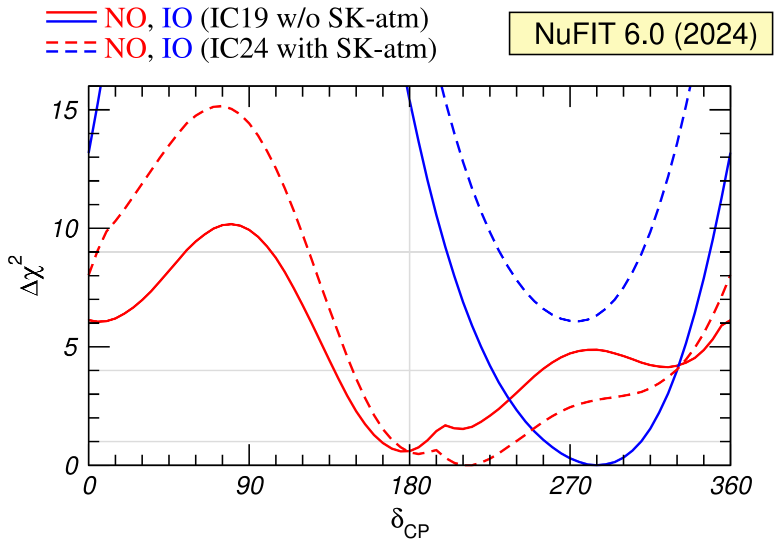
- Additional information from SK-ATM$\Rightarrow$ favouring of NO$\Rightarrow$ CPC :
  SK I-V 484 kton-years χ^2 table added $\Rightarrow \Delta\chi^2_{\rm IO-NO,with\ SK-atm} \simeq 6$



Mass Ordering (and CPV)

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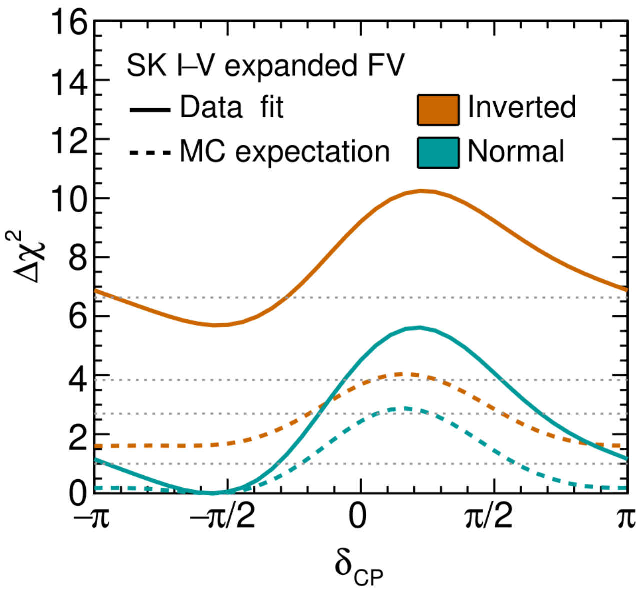
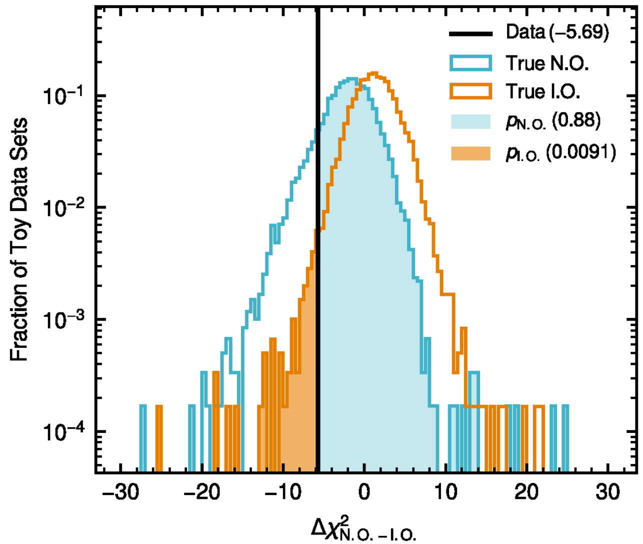
  SK I-V 484 kton-years χ^2 table added $\Rightarrow \Delta\chi^2_{\rm IO-NO, with\ SK-atm} \simeq 6$
  SK-atm result beyond expectation and not clearly compatible with any ordering





SK Coll. arXiv:2311.05105

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Flavour Parameters: leptons vs quarks

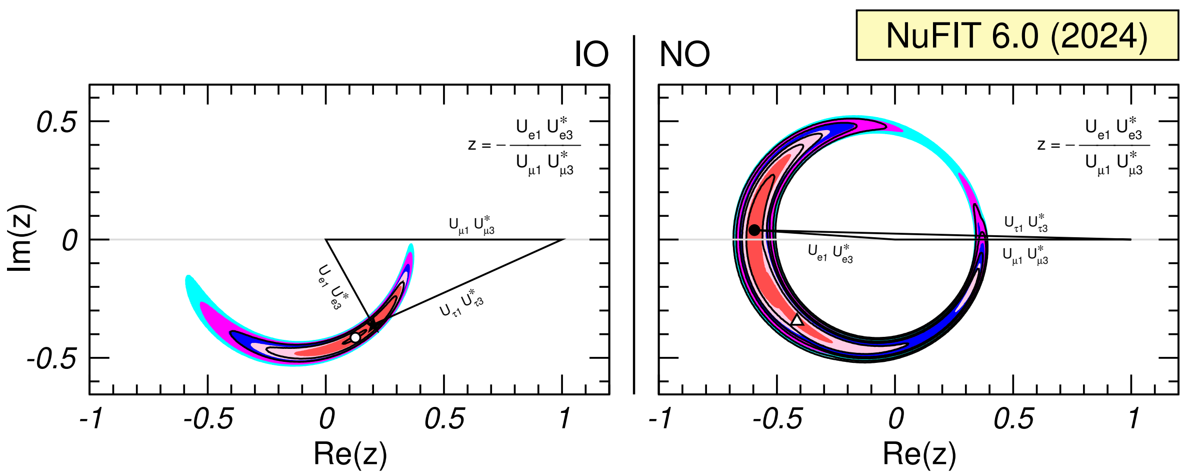
- Leptonic mixing matrix

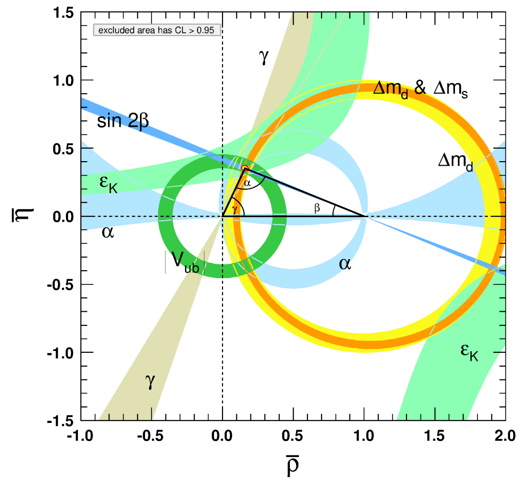
$$|U|_{3\sigma} = \begin{pmatrix} 0.80 \to 0.85 & 0.51 \to 0.56 & 0.14 \to 0.16 \\ 0.23 \to 0.51 & 0.46 \to 0.69 & 0.63 \to 0.78 \\ 0.26 \to 0.53 & 0.47 \to 0.70 & 0.61 \to 0.76 \end{pmatrix}$$

- Very different and precision very far from:

$$|V|_{\rm CKM} = \begin{pmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.0065 & (3.51 \pm 0.15) \times 10^{-3} \\ 0.2252 \pm 0.00065 & 0.97344 \pm 0.00016 & (41.2^{+1.1}_{-5}) \times 10^{-3} \\ (8.67^{+0.29}_{-0.31}) \times 10^{-3} & (40.4^{+1.1}_{-0.5}) \times 10^{-3} & 0.999146^{+0.000021}_{-0.000046} \end{pmatrix}$$

- CP violation





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Early "Global Analysis"

- Barger,Whisnant,Cline,Phillips, PLB Jun 80

Table 1
Experimental limits on neutrino oscillations and neutrino flux predictions

Observables	Source refs.	$\frac{L}{E}\frac{\text{m}}{\text{MeV}}$	Present limit	Solution A	B	C
$\langle P(\nu_e \to \nu_e)\rangle$	S [6]	10^{10}	$\gtrsim 1/4, \lesssim 1/2$	0.41	0.33	0.41
$P(\bar\nu_e \to \bar\nu_e)$	R [3,4]	1–3	>0.5	0.6–1.0	0.8–1.0	0.8 mean
	R a)	5–20		0.1–0.9	0.05–0.5	0.1–0.9
$P(\nu_e \to \nu_e)$	A	0.04	>0.85 e)	1.0	1.0	0.9
	M [12]	0.3	1.1 ± 0.4	0.95	1.0	0.8 mean
	M b)	1–3		0.6–1.0	0.8–1.0	0.8 mean
$P(\bar\nu_\mu \to \bar\nu_e)$	M [12]	0.3	<0.04	10^{-4}	10^{-3}	10^{-3}
	M b)	3		0.03	0.11	0.03
$P(\nu_\mu \to \nu_e)/P(\nu_\mu \to \nu_\mu)$	A [10,11]	0.04	$<10^{-3}$	10^{-6}	10^{-5}	10^{-4}
	A [18] c)	1–7		0–0.2	0–0.8	0–0.2
$P(\nu_e \to \nu_\tau)$	A d)	0.04	<0.2 e)	10^{-3}	10^{-5}	0.1
$P(\nu_\mu \to \nu_\tau)/P(\nu_\mu \to \nu_\mu)$	A [13]	0.04	$<2.5 \times 10^{-2}$	10^{-5}	10^{-5}	10^{-3}
$\langle P(\nu_\mu \to \nu_\mu)\rangle$	D f)	10^2–10^3	~0.5	0.51	0.51	0.51
$\langle P(\nu_c \to \nu_\mu)\rangle$	D g)	10^3–10^5		0.48	0.44	0.48
$\langle P(\nu_c \to \nu_e)\rangle$	D g)	10^3–10^5		0.42	0.33	0.42
$P(\nu_c \to \nu_\mu)$	D g)	10–10^2		0.3–0.7	0.3–0.7	0.3–0.7
$P(\nu_c \to \nu_e)$	D g)	10–10^2		0.2–0.6	0.2–0.6	0.2–0.6

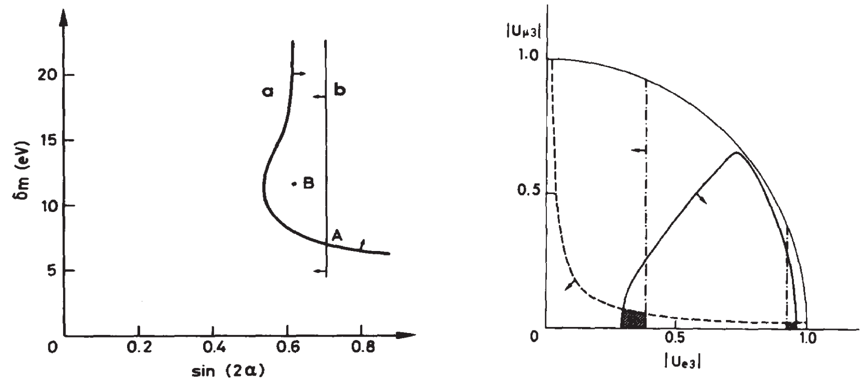
commodates all known constraints is

	δm^2_{13}	δm^2_{12}	θ_1	θ_2	θ_3	δ
Solution A:	1.0 eV^2	0.05 eV^2	45°	25°	30°	0°.
Solution B:	0.15 eV^2	0.05 eV^2	55°	0°	45°	0°
Solution C:	10 eV^2	0.05 eV^2	45°	25°	30°	0°. (6

KM-like mixing convention

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix} c_1 & s_1c_3 & s_1s_3 \\ -s_1c_2 & c_1c_2c_3 + s_2s_3e^{i\delta} & c_1c_2s_3 - s_2c_3e^{i\delta} \\ -s_1s_2 & c_1s_2c_3 - c_2s_3e^{i\delta} & c_1s_2s_3 + c_2c_3e^{i\delta}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix},$$

- De Rujula,Lusignoli,Maiani,Petcov,Petronzio, NPB May 80



$$U = \begin{pmatrix} 0.65 & 0.65 & -0.38 \\ [-0.71\,e^{i\delta} \mp |<0.021|] & [0.71\,e^{i\delta} \mp |<0.02|] & \mp|<0.06| \\ [0.27 \mp e^{i\delta}|<0.04|] & [0.27 \pm e^{i\delta}|<0.04|] & 0.92 \end{pmatrix}, \qquad (6.2)$$

with mass differences in the ranges

$$10^{-5}\ \text{eV} \lesssim \sqrt{|m_1^2 - m_2^2|} \lesssim 1\ \text{eV}\,,$$
$$\sqrt{|m_3^2 - m_1^2|} \sim 10\ \text{eV}\,.$$

Early Reactor $\mathcal{O}(eV)$ "hints"

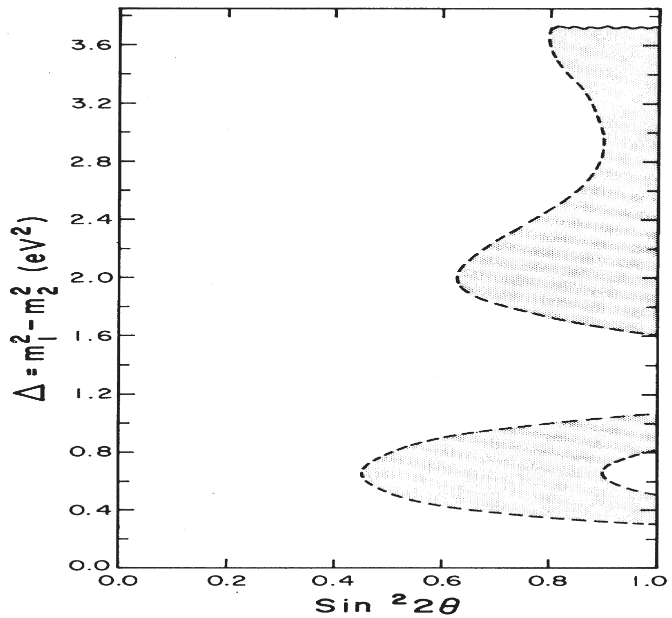
Concha Gonzalez-Garcia

- Data from Savannah River Plant

Nezrick and Reines, PR Feb 66 L=6 m

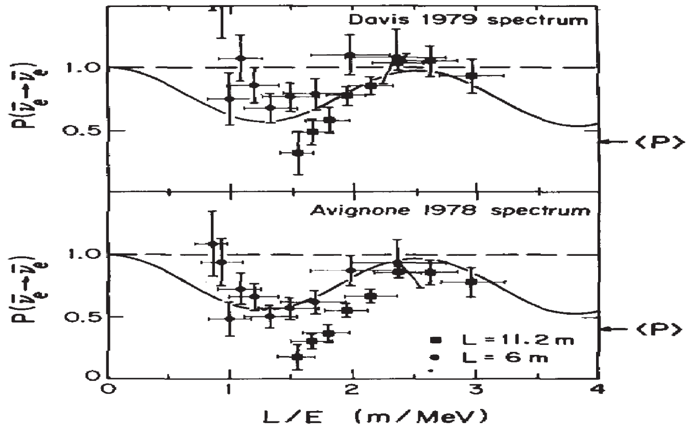
$$\frac{\bar{\sigma}_{\rm exp}}{\bar{\sigma}_{\rm th}} = 0.88 \pm 0.13$$

Reines,Sobel,Pasierb PRL Oct 80 L=11.2 m



- Early Pheno Analysis

Barger,Whisnant,Cline,Phillips, PLB Jun 80



- Even Flux Independent Analysis !!!

Silverman and Soni , PRL Feb 81