Status of Three-Flavor oscillations: lessons from first JUNO results

PASCOS

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With NuFIT: M.C. Gonzalez-Garcia, M. Maltoni, I. Martinez-Soler, J.P. Pinheiro & T. Schwetz

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23th June 2026

Introduction

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See arXiv:2410.05380 [JHEP 12(2025) 216] & arXiv:2601.09791

Standard Model

The Standard Model is a gauge theory based on

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

and three fermion generations

$(SU(3), SU(2))_Y$				
$(1,2)_{-\frac{1}{2}}$	$(3,2)_{\frac{1}{6}}$	$(1,1)_{-1}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{-\frac{1}{3}}$
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} u^i \\ d^i \end{pmatrix}_L$	e_R	u^i_R	d^i_R
$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	$\begin{pmatrix} c^i \\ s^i \end{pmatrix}_L$	μ_R	c^i_R	s^i_R
$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	$\begin{pmatrix} t^i \\ b^i \end{pmatrix}_L$	τ_R	t^i_R	b^i_R

with no $\nu_R \Longrightarrow$ lepton flavours are *accidentally* conserved and $\boldsymbol{m_\nu = 0}$.

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There is New Physics in the lepton sector

We have observed neutrino flavour changes:

- Atmospheric ν_μ & $\bar{\nu}_\mu$ disappear, most likely to ν_τ (SK, MINOS, ICECUBE).
- Accelerator ν_μ & $\bar{\nu}_\mu$ disappear at $L \sim 300/800$ km (K2K, T2K, MINOS, NOνA).
- Some accelerator ν_μ & $\bar{\nu}_\mu$ appear as ν_e at $L \sim 300/800$ km (T2K, MINOS, NOνA).
- Some accelerator ν_μ appear as ν_τ at $L \sim 300/800$ km (OPERA).
- Solar ν_e convert to ν_μ & ν_τ (Cl, Ga, SK, SNO, Borexino).
- Reactor $\bar{\nu}_e$ disappear at $L \sim 200$ km (KamLAND, SNO+, JUNO).
- Reactor $\bar{\nu}_e$ disappear at $L \sim 1$ km (D-Chooz, Daya Bay, Reno).

Each lepton flavour is violated: **there is physics beyond the SM**.

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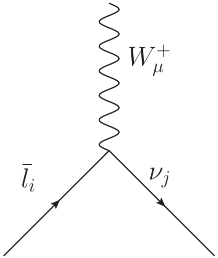
There is New Physics in the lepton sector

We have observed neutrino flavour changes (Sun, atmosphere, human-made). The minimal explanation is to give neutrinos a mass. As a consequence, leptons mix:

$$-\mathcal{L}_{CC} = \frac{g}{\sqrt{2}} W_\mu^- \sum_{ij} \left(\boldsymbol{U_{ij}^{\text{lep}}} \bar{\ell}_{iL} \gamma^\mu \nu_{jL} + U_{ij}^{\text{CKM}} \bar{u}_{iL} \gamma^\mu d_{jL} \right) + \text{h.c.}$$



Introduction

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Neutrino flavour oscillations

To **pin down the new physics**, **flavour oscillations** are a unique experimental window.

$$|\nu_\alpha(0)\rangle = \sum_i U^{\text{lep}\,*}_{\alpha i} |\nu_i\rangle \Rightarrow |\nu_\alpha(L)\rangle \simeq \sum_i U^{\text{lep}\,*}_{\alpha i} e^{-i\frac{m_i^2 L}{2E}} |\nu_i\rangle$$

$|\nu_i\rangle$ interfere:

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{i<j}^{n} \mathrm{Re}\left[U^{\text{lep}}_{\alpha i} U^{\text{lep}*}_{\beta i} U^{\text{lep}*}_{\alpha j} U^{\text{lep}}_{\beta j}\right] \sin^2 \frac{\Delta m^2_{ij} L}{4E} + 2\sum_{i<j}^{n} \mathrm{Im}\left[U^{\text{lep}}_{\alpha i} U^{\text{lep}*}_{\beta i} U^{\text{lep}*}_{\alpha j} U^{\text{lep}}_{\beta j}\right] \sin \frac{\Delta m^2_{ij} L}{2E}$$

For 2ν, $P_{\text{osc}} = \sin^2(2\theta) \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$, **insensitive to $\boldsymbol{\theta}$ octant and $\boldsymbol{\Delta m^2}$ sign**.

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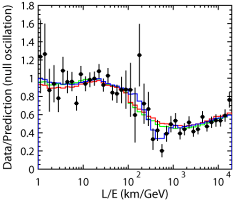
Travelling in matter, ν_e get a potential $V_{\nu_e} = \sqrt{2} G_F n_e$,

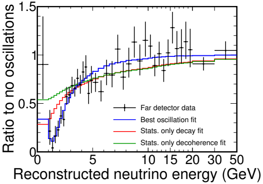
$$i\frac{d}{dx}\begin{pmatrix}|\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle\end{pmatrix} = H_{\text{eff}}\begin{pmatrix}|\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle\end{pmatrix} \; ; \; H_{\text{eff}} = \begin{pmatrix}\sqrt{2}G_F n_e & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0\end{pmatrix} + \frac{1}{2E} U^{\text{lep}} \begin{pmatrix} m_1^2 & 0 & \\ 0 & m_2^2 & \\ & & \ddots \end{pmatrix} U^{\text{lep}\dagger}$$

Experimental knowledge

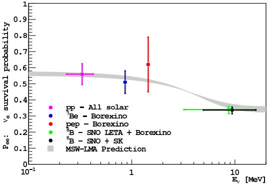
We need 3 light neutrinos



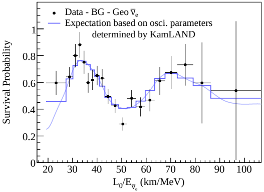
Atmospheric ν in SK



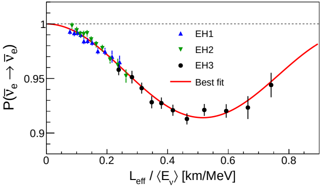
Accelerator ν in MINOS (L=735 km)



Solar ν (MSW conversion)



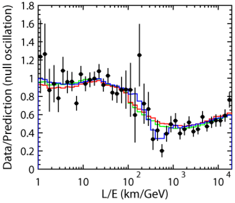
Reactor $\bar{\nu}$ in KamLAND



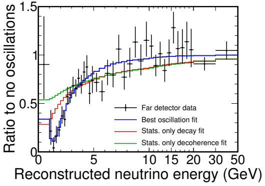
Reactor $\bar{\nu}$ in Daya Bay

Experimental knowledge

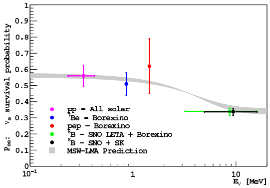
We need 3 light neutrinos



Atmospheric ν in SK



Accelerator ν in MINOS (L=735 km)



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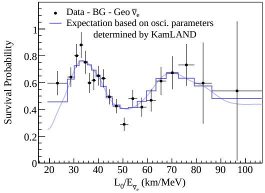
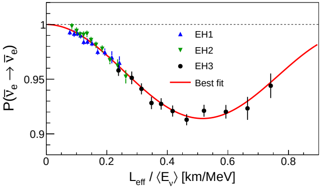


Reactor $\bar{\nu}$ in KamLAND



Reactor $\bar{\nu}$ in Daya Bay

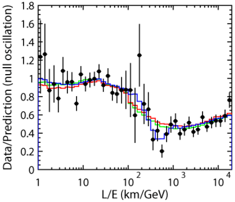
Sun $\begin{cases} \Delta m^2 \sim 10^{-5}\text{eV}^2 \\ \theta \sim 30^\circ \end{cases}$

Atm. Accel. $\begin{cases} \Delta m^2 \sim 10^{-3}\text{eV}^2 \\ \theta \sim 45^\circ \end{cases}$

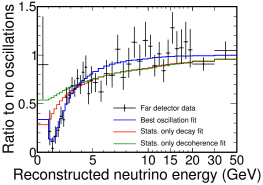
Reac. $\begin{cases} \Delta m^2 \sim 10^{-5}\text{eV}^2 \\ \theta \sim 30^\circ \\ \Delta m^2 \sim 10^{-3}\text{eV}^2 \\ \theta \sim 9^\circ \end{cases}$

Experimental knowledge

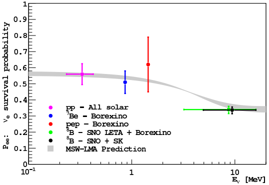
We need 3 light neutrinos



Atmospheric ν in SK



Accelerator ν in MINOS (L=735 km)



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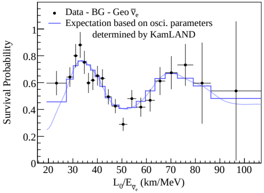
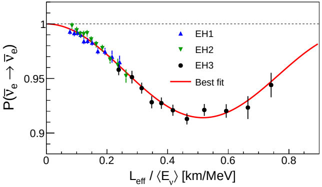


Reactor $\bar{\nu}$ in KamLAND



Reactor $\bar{\nu}$ in Daya Bay

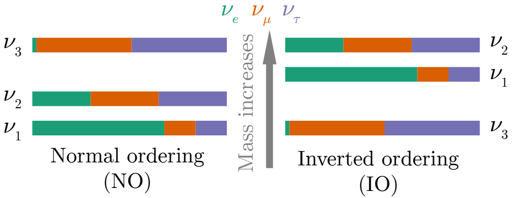
$$U^{\text{lep}}_{\alpha i} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \cdot \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \cdot \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Experimental knowledge

Status and open questions

Gonzalez-Garcia, Maltoni, Martinez-Soler, Pinheiro, Schwetz, IE *JHEP* **12**(2025) 216. NuFIT 6.0, www.nu-fit.org. See also **Capozzi et al, 2503.07752; de Salas et al, 2006.11237**.

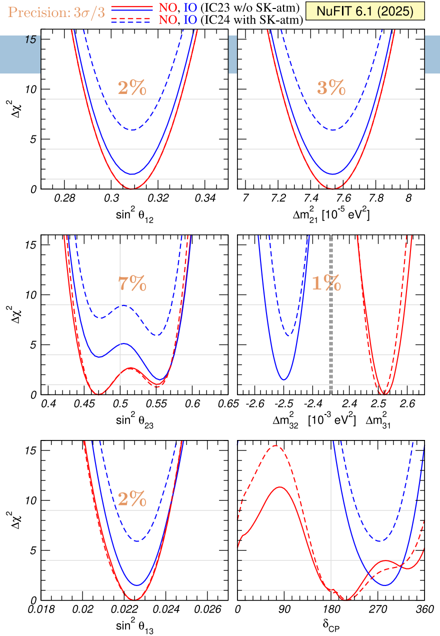
We are now measuring three-neutrino effects,



- $\theta_{23} < 45°$? $\theta_{23} > 45°$?
- CP violation?

$$P_{\nu_\alpha \to \nu_\beta} - P_{\bar{\nu}_\alpha \to \bar{\nu}_\beta} \propto J_{\text{lep}} = c_{12} c_{23} c_{13}^2 s_{12} s_{23} s_{13} \sin \delta_{\text{CP}} = (0.0333 \pm 0.0006) \sin \delta_{\text{CP}}$$

which also assess **the global consistency of the framework**.



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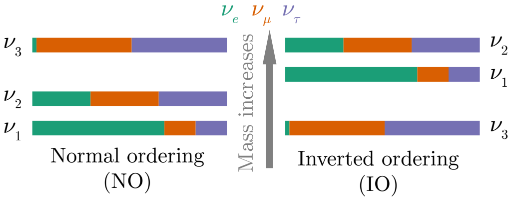

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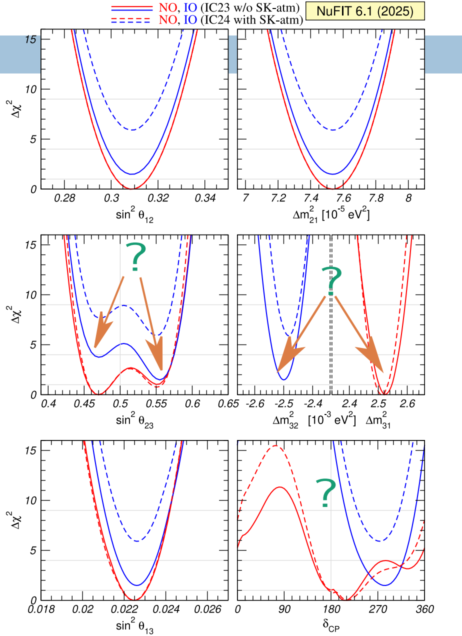

1-2 sector

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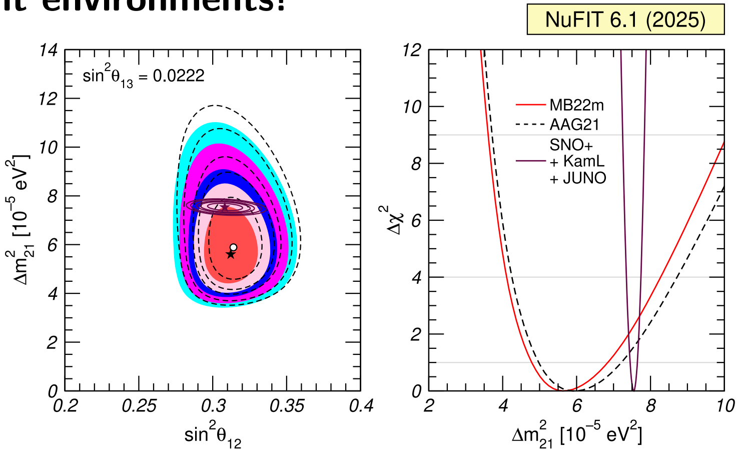
See arXiv:2410.05380 [JHEP 12(2025) 216] & arXiv:2601.09791

Dominated by solar neutrinos & long baseline reactors (**JUNO**).
Very different environments!



2-3 sector

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Mass ordering

We can determine Δm^2_{32} in

- Long Baseline (LBL) accel., $\nu_\mu \to \nu_\mu$

$$P_{\mu\mu} \simeq 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{\mu\mu} L}{4E}\right)$$

$$\boldsymbol{\Delta m^2_{\mu\mu} \simeq \Delta m^2_{32} + \sin^2\theta_{12}\Delta m^2_{21} \sim \Delta m^2_{32} + 0.3\Delta m^2_{21}}$$

- Medium Baseline reactor, $\bar{\nu}_e \to \bar{\nu}_e$

$$P_{ee} \simeq 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{ee} L}{4E}\right)$$

$$\boldsymbol{\Delta m^2_{ee} \simeq \Delta m^2_{32} + \cos^2\theta_{12}\Delta m^2_{21} \sim \Delta m^2_{32} + 0.7\Delta m^2_{21}}$$

Petcov, Piai, hep-ph/0112074 (2002)
Choubey, Petcov, Piai, hep-ph/0306017 (2003)
Nunokawa, Parke, Zukanovich-Funchal, hep-ph/0503283 (2005)

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We measure $|\Delta m^2_{\mu\mu}|$ and $|\Delta m^2_{ee}|$, we can infer $|\Delta m^2_{32}|$.

In NO, $|\Delta m^2_{32}| \sim |\Delta m^2_{\mu\mu}| - 0.3 \Delta m^2_{21}$;
$|\Delta m^2_{32}| \sim |\Delta m^2_{ee}| - 0.7 \Delta m^2_{21}$.

In IO, $|\Delta m^2_{32}| \sim |\Delta m^2_{\mu\mu}| + 0.3 \Delta m^2_{21}$;
$|\Delta m^2_{32}| \sim |\Delta m^2_{ee}| + 0.7 \Delta m^2_{21}$.

$|\Delta m^2_{\mu\mu}| - |\Delta m^2_{ee}| < 0$ in NO, > 0 in IO!
In practice, if we infer $|\Delta m^2_{32}|$ assuming the wrong ordering, we get different values from LBL and reactors!

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- Medium Baseline reactor, $\bar{\nu}_e \to \bar{\nu}_e$

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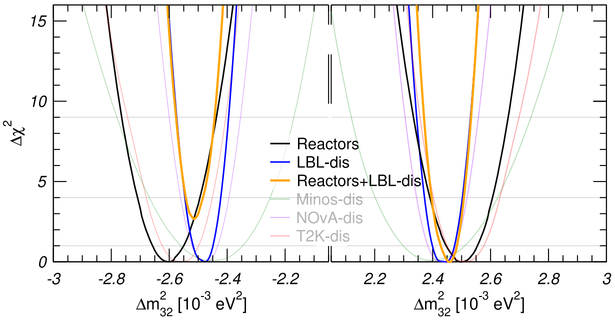

3ν effects

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See arXiv:2410.05380 [JHEP 12(2025) 216] & arXiv:2601.09791

Mass ordering, $\delta_{\rm CP}$, θ_{23} octant

$$P(\nu_\mu \to \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2\Delta_{31}(1-A)}{(1-A)^2} + \frac{\Delta_{21}}{\Delta_{31}} 8 J_{\rm lep}^{\rm max}\cos(\Delta_{31}+\delta_{\rm CP})\frac{\sin\Delta_{31}A}{A}\frac{\sin\Delta_{31}(1-A)}{(1-A)} + \mathcal{O}\left(\frac{\Delta_{21}}{\Delta_{31}}\right)^2$$

$$\Delta_{ij} = \frac{\Delta m^2_{ij} L}{4E}$$

$$(\Delta_{31}\sim 1, \Delta_{21}\sim 10^{-2})$$

$$A = 2\sqrt{2} G_F n_e \frac{E}{\Delta m^2_{31}}$$

$$J_{\rm lep}^{\rm max} = \frac{1}{8} c_{13}^2 s_{13} c_{12} s_{12} c_{23} s_{23}$$

Strongly correlated: we need as much data and independent determinations as possible!

3ν effects

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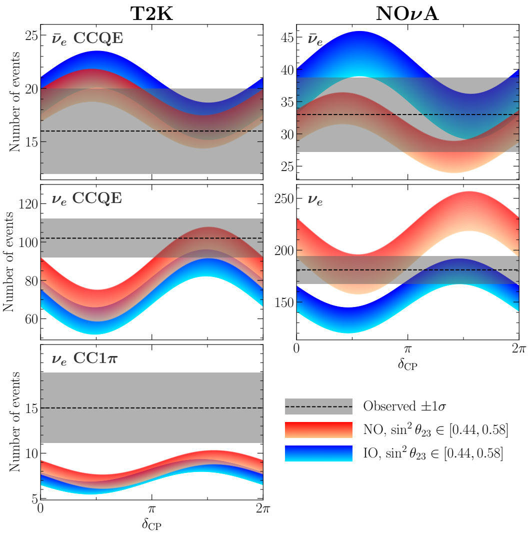
T2K vs NOνA



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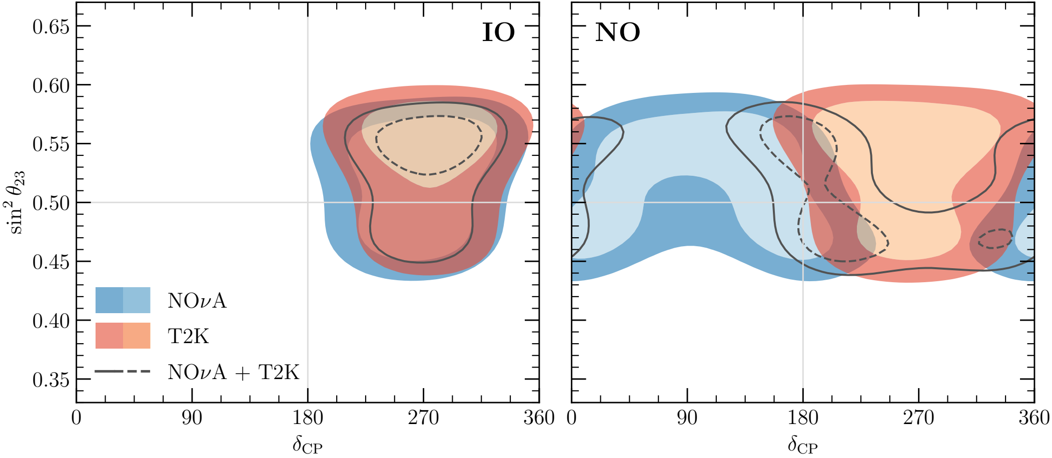

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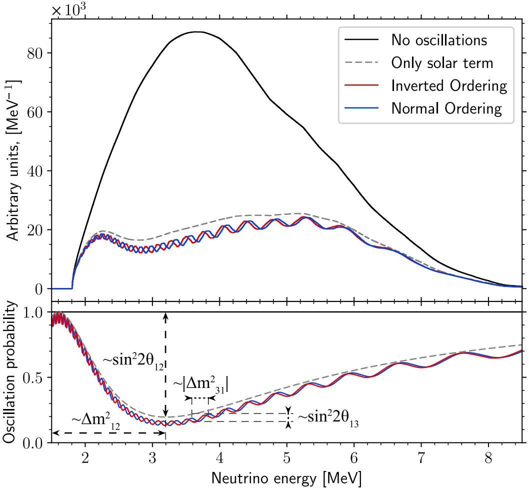
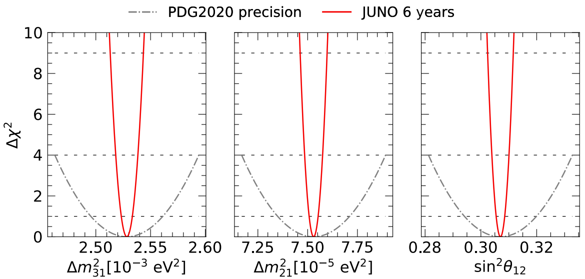
In the global picture



Sub-percent "solar" parameters

MO: **alone** ($\sim 3\sigma$) **and via** $|\Delta m^2_{ee}|$



Relevant on their own and

to overconstrain the 3ν paradigm.

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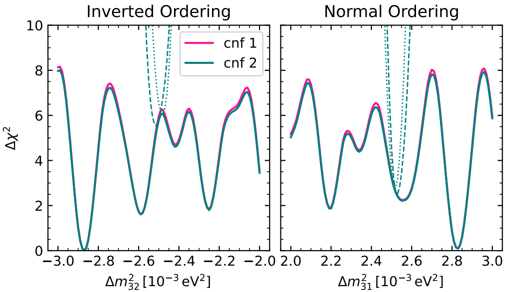
First results: mass ordering

- Present JUNO data should have some sensitivity to the mass ordering,
  - Alone?
  - $|\Delta m^2_{ee}|$ vs $|\Delta m^2_{\mu\mu}|$
- We have followed **publicly available JUNO information**: `arXiv:2601.09791`



Robust even unless nominal systematics are *significantly* inflated

Conclusions

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See arXiv:2410.05380 [JHEP 12(2025) 216] & arXiv:2601.09791

- We are currently testing and **overconstraining** the 3ν paradigm.

  Either a robust understanding of Nature or a surprise awaits!
- Most parameters are determined within $\sim 3\%$.
- A reactors + LBL tension in Δm^2_{32} *within IO* gives a $\sim 2\sigma$ preference for NO.
- A NOνA + T2K tension in $\delta_{\rm CP}$ *within NO* gives a $\sim 2\sigma$ preference for IO.
- The global analysis is at the *maximal confusion level*, with 1σ–2σ hints not pointing in the same direction,
  - Both orderings are essentially equally favored. There exist external datasets (IceCube, *Super-K*) that we cannot reproduce but prefer NO by $\sim 2.5\sigma$.
  - For NO, CP conservation is favored. For IO, maximal CP violation.
  - No clear preference for θ_{23} octant.

JUNO will have a lot to say!