Present status of three-family global fits to neutrino oscillation data

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Palazzo Grimaldi, Modica, Italy – June 17th, 2025

Instituto de Física Teórica UAM-CSIC

EXCELENCIA SEVERO OCHOA

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CSIC Consejo Superior de Investigaciones Científicas

GOBIERNO DE ESPAÑA MINISTERIO DE CIENCIA E INNOVACIÓN

AGENCIA ESTATAL DE INVESTIGACIÓN

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SM with ν masses: general three-neutrino framework

- Equation of motion: **6 parameters** (including Dirac and neglecting Majorana phases):

$$i\frac{d\vec{\nu}}{dt} = \boldsymbol{H}\,\vec{\nu}; \qquad \boldsymbol{H} = \boldsymbol{U}_{\text{vac}} \cdot \boldsymbol{D}_{\text{vac}} \cdot \boldsymbol{U}_{\text{vac}}^\dagger \pm \boldsymbol{V}_{\text{mat}};$$

$$\boldsymbol{U}_{\text{vac}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}\, e^{-i\delta_{\text{CP}}} \\ 0 & 1 & 0 \\ -s_{13}\, e^{i\delta_{\text{CP}}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \cancel{\begin{pmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}}, \quad \vec{\nu} = \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix};$$

$$\boldsymbol{D}_{\text{vac}} = \frac{1}{2E_\nu}\left[\textbf{diag}\left(0,\ \Delta m^2_{21},\ \Delta m^2_{31}\right) + \cancel{m_1^2 \boldsymbol{I}}\right]; \qquad \boldsymbol{V}_{\text{mat}} = \sqrt{2} G_F N_e\, \textbf{diag}\left(1,\ 0,\ 0\right).$$

6 parameters $\Longleftrightarrow$ 6 types of experiments

- ν_e disapp:
  - solar experiments (mainly SNO) $\rightarrow \theta_{12}$
  - rector LBL (KamLAND) $\rightarrow \Delta m^2_{21}$
  - rector MBL (Double-Chooz, Daya-Bay, Reno) $\rightarrow \theta_{13}\ [\Delta m^2_{31}]$

  } MeV sources
- ν_μ disapp:
  - atmospheric experiments (SK, IC) $\rightarrow \theta_{23}\ [\Delta m^2_{31}]$
  - accelerator long-baseline (T2K, NOvA) $\rightarrow |\Delta m^2_{31}|\ [\theta_{23}]$
- ν_e appear:
  - atmospheric (SK) & accelerator (T2K, NOvA) $\rightarrow \delta_{\text{CP}},\ \pm\Delta m^2_{31}$

  } GeV sources

Solar and reactor neutrinos

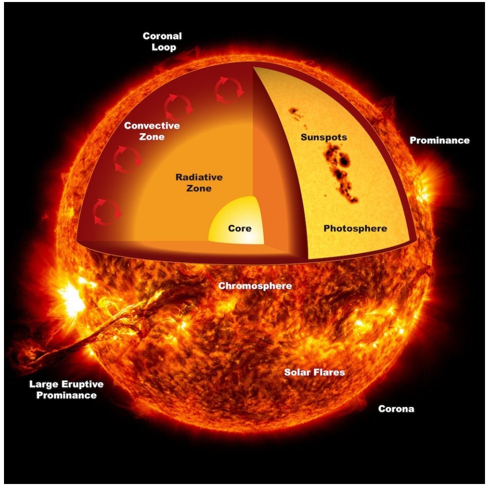
- ν_e from **nuclear** reactions $\Rightarrow$ energy in the MeV range;
- ν_μ and ν_τ indistinguishable $\Rightarrow$ no sensitivity to θ_{23} or δ_{CP}.

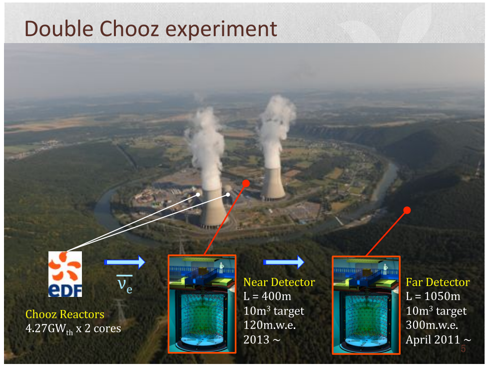
Reactor neutrinos

- $\bar{\nu}_e$ produced by nuclear **fission** in reactor's core;
- detection: inverse beta decay ($\bar{\nu}_e + p \to e^+ + n$), both e^+ and n observed in coincidence;
- negligible matter effects $\Rightarrow$ mostly vacuum params.

Solar neutrinos

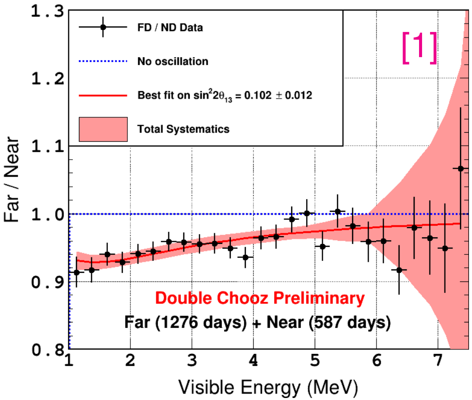
- ν_e produced by nuclear **fusion** in the core of the Sun;
- two different mechanisms at work: p-p chain and CNO cycle. Both give $4p \to {}^4\text{He} + 2e^+ + 2\nu_e + \gamma \Rightarrow$ solar light and neutrinos in well-defined mutual proportions;
- detection: various processes (CC-ν_e, NC, ES);
- matter effects very important (MSW effect).

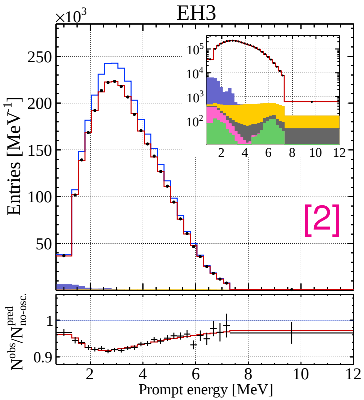


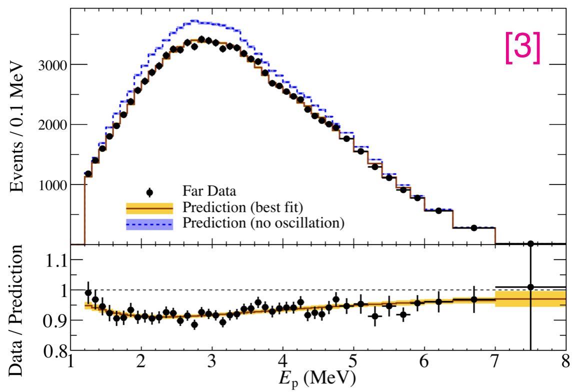


Medium-baseline reactor neutrino disappearance and θ_{13}

- Positive $\bar{\nu}_e$ disappearance ($\approx$ 1 km) in DOUBLE-CHOOZ [1], DAYA-BAY [2], RENO [3];
- experimental results are mutually consistent $\Rightarrow$ it is now a firmly established fact that $\theta_{13} \neq 0$ $\Rightarrow$ full 3ν oscillation phenomenology;
- all these experiments have spectral capabilities and detector units placed at different baselines $\Rightarrow$ uncertainties in the reactor flux predictions do **not** affect the results.







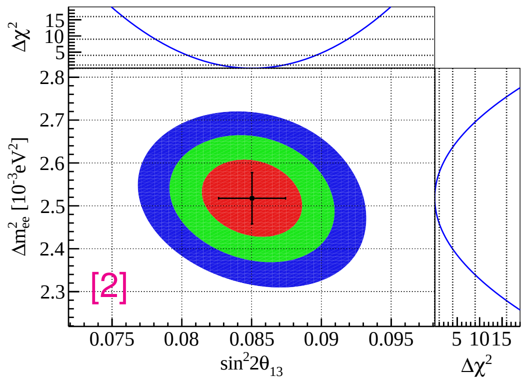
[1] T. Bezerra [DOUBLE-CHOOZ], online talk at Neutrino 2020, Fermilab, USA, June 22–July 2, 2020.

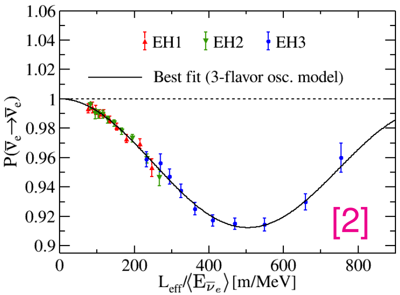
[2] F.P. An *et al.* [DAYA BAY], Phys. Rev. Lett. **130** (2023) 161802 [arXiv:2211.14988].

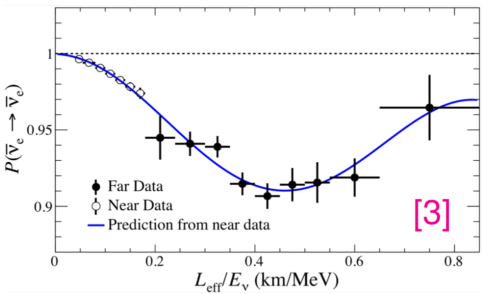
[3] J. Yoo [RENO], online talk presented at Neutrino 2020, Fermilab, USA, June 22–July 2, 2020.

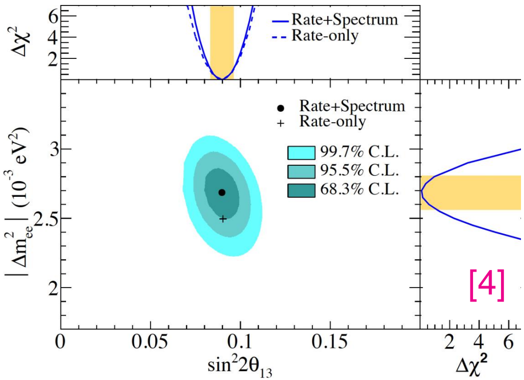
Measuring θ_{13} and Δm^2_{31} from reactor data

- FAR/NEAR spectral ratio ⇒ flux shape irrelevant;
- spectral information from Double-Chooz, Daya-Bay and Reno ⇒ oscillation pattern clearly visible ⇒ θ_{13} and Δm^2_{31} accurately determined by reactor data;
- accuracy from reactor $\nu_e \to \nu_e$ comparable with LBL $\nu_\mu \to \nu_\mu$, but oscillation channel is different ⇒ important **complementary** information available.





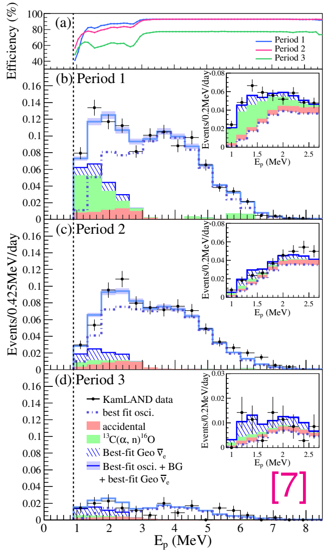




[2] F.P. An *et al.* [DAYA BAY], Phys. Rev. Lett. **130** (2023) 161802 [arXiv:2211.14988].
[3] J. Yoo [RENO], online talk at Neutrino 2020, Fermilab, USA, 22/06–2/07/2020.
[4] K.K. Joo [RENO], online talk at Neutrino 2022, Virtual Seoul, Korea, 30/05–4/06/2022.

Measuring θ_{12} and Δm^2_{21} with KamLAND data

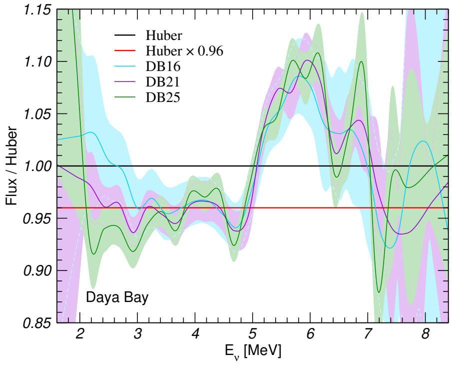
- Much longer baseline ($\approx$ 180 km) $\Rightarrow$ sensitive to θ_{12} and Δm^2_{21};
- lack of a near detector $\Rightarrow$ spectral distortions may be an issue;
- problem discussed in [5] $\Rightarrow$ impact on Δm^2_{21} found to be small;
- solution: bind KamLAND spectrum to Daya-Bay measurement [6];
- marginal matter contributions $\Rightarrow$ both θ_{12} octants allowed by data.

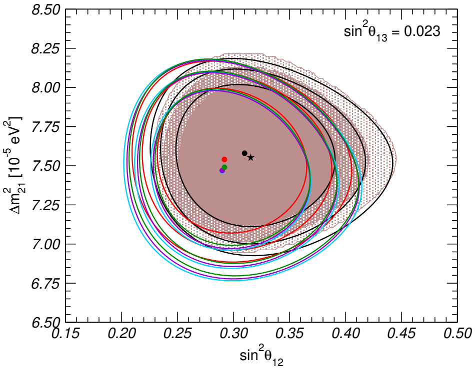


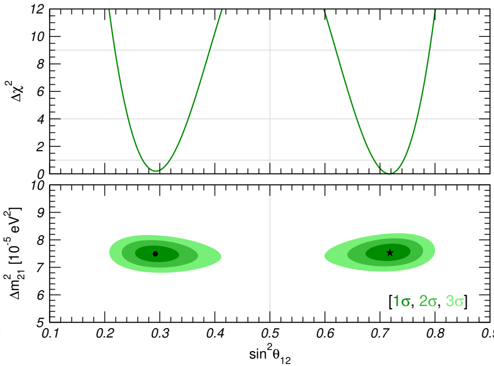
[5] F. Capozzi *et al.*, NPB **908** (2016) 218 [arXiv:1601.07777].

[6] F.P. An *et al.* [Daya Bay], PRL **134** (2025) 201802 [arXiv:2501.00746].

[7] A. Gando *et al.* [KamLAND], PRD **88** (2013) 033001 [arXiv:1303.4667].





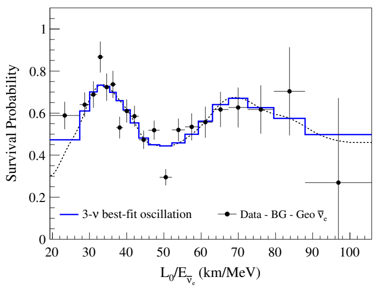


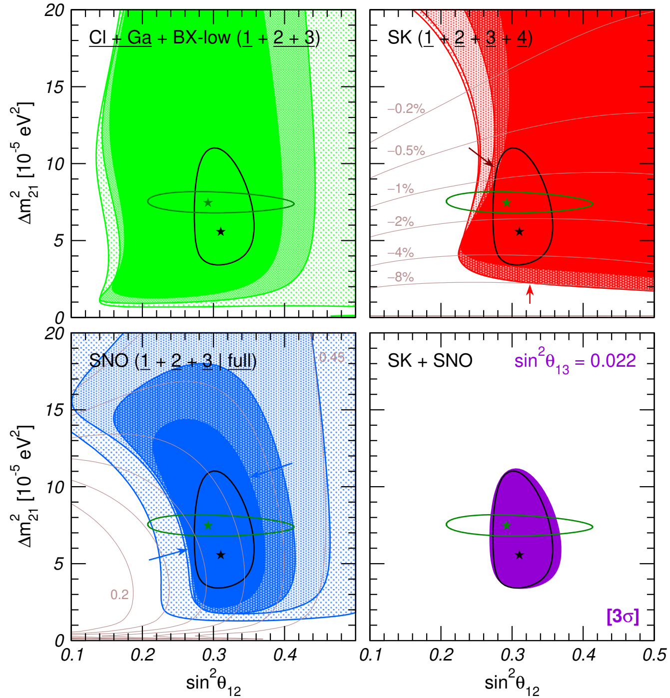
Determination of θ_{12} and Δm^2_{21} from solar neutrino data

- $P_{ee} = c_{13}^4 P_{\text{eff}} + s_{13}^4$, $\quad i\frac{d\vec{\nu}}{dt} = \left[\frac{\Delta m^2_{21}}{4E_\nu}\begin{pmatrix} -\cos 2\theta_{12} & \sin 2\theta_{12} \\ \sin 2\theta_{12} & \cos 2\theta_{12}\end{pmatrix} \pm \sqrt{2} G_F N_e \begin{pmatrix} c_{13}^2 & 0 \\ 0 & 0 \end{pmatrix}\right]\vec{\nu}, \quad \vec{\nu} = \begin{pmatrix}\nu_e \\ \nu_a\end{pmatrix}$;
- $\nu_\mu \equiv \nu_\tau \Rightarrow$ no sensitivity to θ_{23} and δ_{CP};
- $\Delta m^2_{31} \approx \infty \Rightarrow$ specific Δm^2_{31} value irrelevant;

$\Rightarrow$ data only depend on Δm^2_{21}, θ_{12} and θ_{13};

- param's: $\begin{cases} \theta_{12} \text{ dominated by SNO;} \\ \Delta m^2_{21} \text{ dominated by KamLAND;} \end{cases}$
- region given by high-E data, low-E marginal;
- strong matter effects $\Rightarrow$ fixes $\theta_{12} < 45^\circ$ octant;
- SNO-NC measurement confirms SSM;
- KamLAND precisely determines the oscillation pattern.



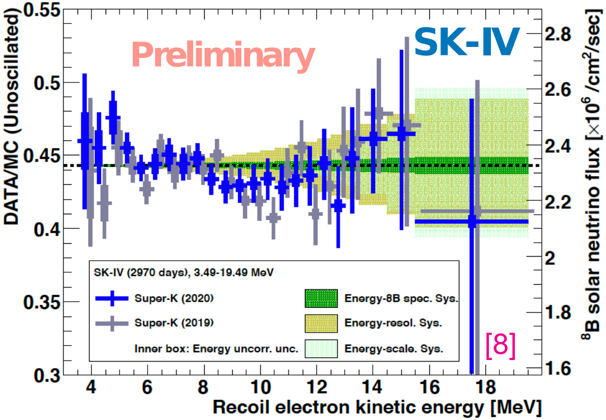


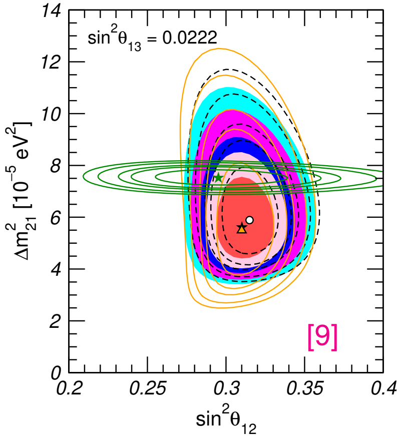
Comparison between solar and KamLAND measurements

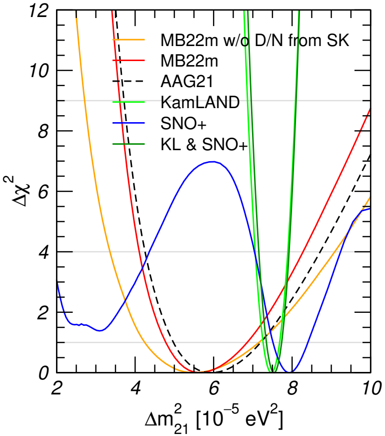
- Long-standing weak tension on preferred Δm^2_{21} from solar and KamLAND data;
- choice of the assumed solar model (GS, AGSS, MB22, …) has little impact on the issue;
- cause: { – too much D/N asymmetry in SK; – no indication of low-E turn-up
- new data [8]: { – D/N: $3.6\% \to 2.1\%$, – “hints” of turn-up.

$\Rightarrow$ tension considerably reduced after Neutrino 2020 conference.

NuFIT 6.0 (2024)







[8] Y. Nakajima [SK], online talk at Neutrino 2020, Fermilab, USA, June 22–July 2, 2020.

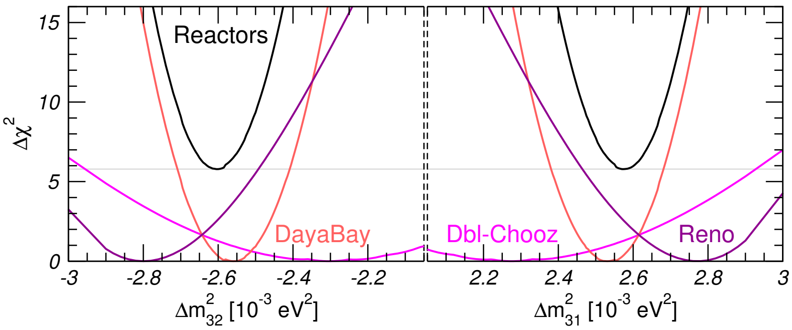
[9] I. Esteban *et al.*, JHEP **12** (2024) 216 [arXiv:2410.05380] & NuFIT 6.0 [http://www.nu-fit.org].

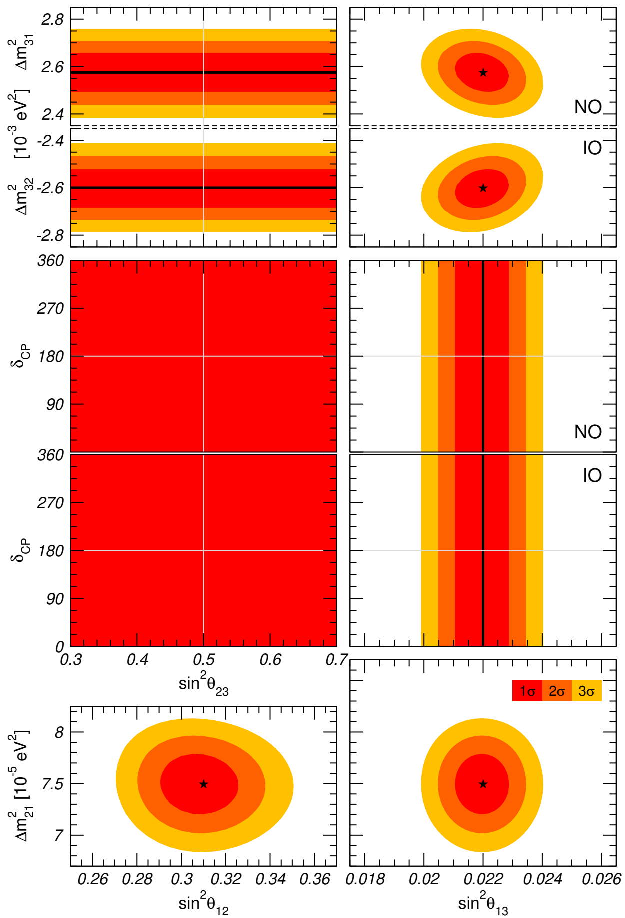
Global ν_e disappearance bounds

- Both (θ_{12}, Δm^2_{21}) and (θ_{13}, $|\Delta m^2_{31}|$) determined;
- all MBL reactors sensitive to Δm^2_{ij} only through the same effective combination $|\Delta m^2_{ee}|$, with [10]:

$$\Delta m^2_{ee} \equiv \frac{|U_{e1}|^2 \Delta m^2_{31} + |U_{e2}|^2 \Delta m^2_{32}}{|U_{e1}|^2 + |U_{e2}|^2};$$

- consequently, tensions among MBL reactors are the same for **NO** and **IO** $\Rightarrow$ no info on ordering.





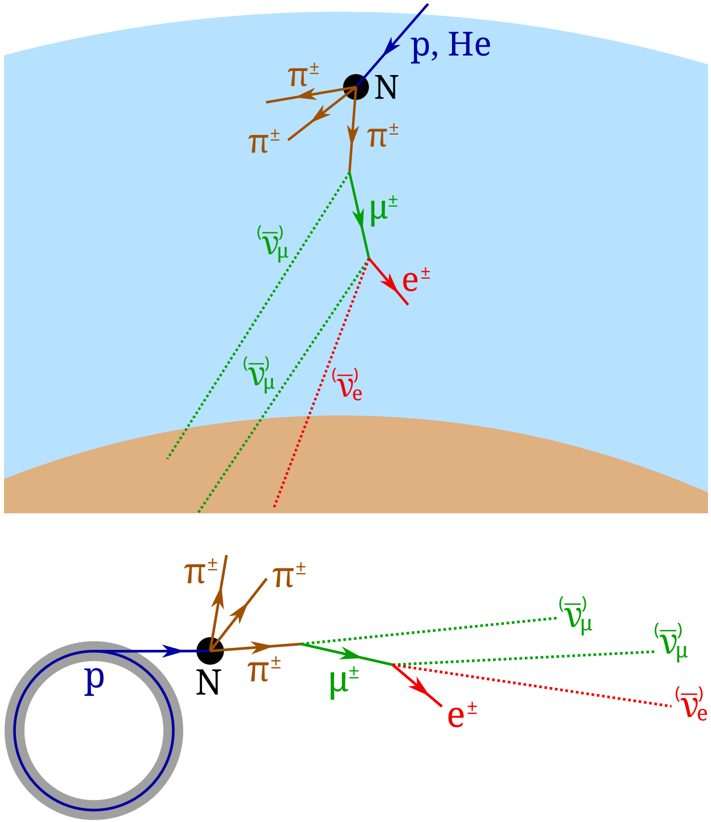
[10] Nunokawa *et al.*, Phys. Rev. D [hep-ph/0503283].

Atmospheric and accelerator neutrinos

- Atmospheric (accelerator) neutrinos are produced by the interaction of *cosmic rays* (*protons*) with the Earth's atmosphere (target):

$$\boxed{1}\quad A_{\text{in}} + A_{\text{tgt}} \to \pi^\pm, K^\pm, K^0, \ldots$$
$$\boxed{2}\quad \pi^\pm \to \mu^\pm + \nu_\mu\,,$$
$$\boxed{3}\quad \mu^\pm \to e^\pm + \nu_e + \nu_\mu\,;$$

- at the detector, some ν interacts and produces a **charged lepton**, which is observed;
- atmospheric: fluxes of ν_μ and ν_e are known with poor precision ($\approx 20\%$), but the accuracy on the ν_μ/ν_e ratio is better ($\approx 5\%$);
- accelerator: a **near detector** allow to characterize the unoscillated ν flux.



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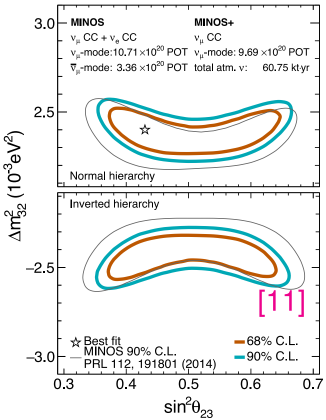
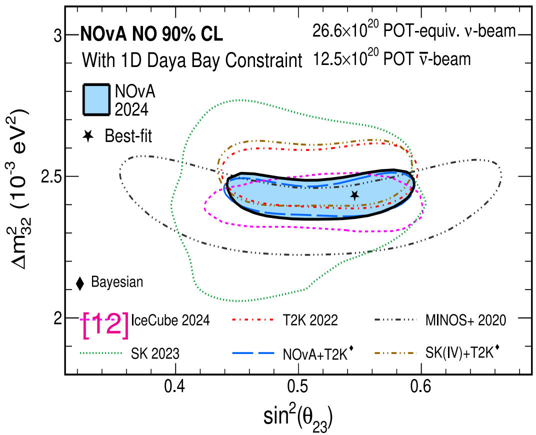
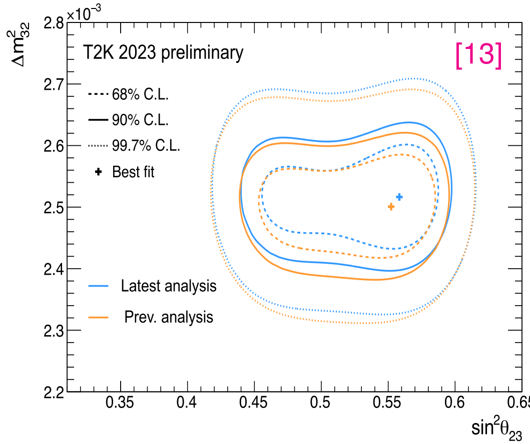
Consistency of Δm^2_{31} and θ_{23} from accelerator data

- Δm^2_{31} & θ_{23} dominated by LBL disappearance ($\nu_\mu \to \nu_\mu$) data;
- Δm^2_{21} & θ_{12} subleading contributions to LBL appearance ($\nu_\mu \to \nu_e$) $\Rightarrow$ relevant for δ_{CP};
- reasonably good agreement between all experiments in the allowed regions, although some small differences are visible.



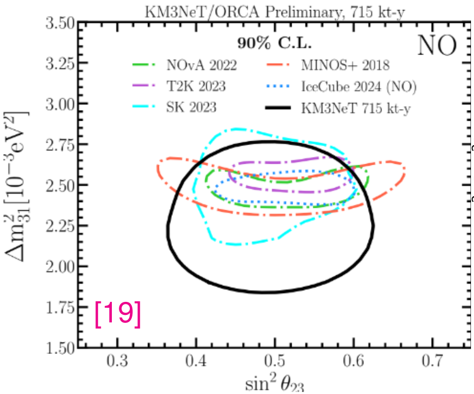


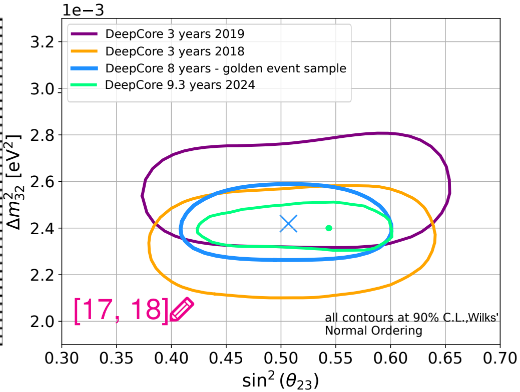


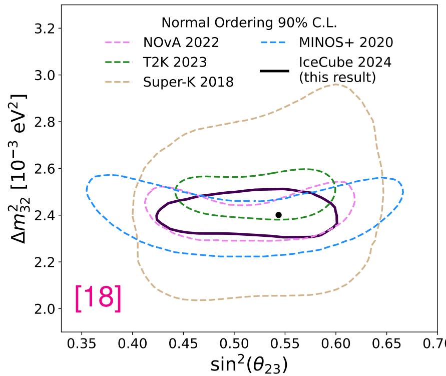
[11] T. Carroll [MINOS], online talk at Neutrino 2020, Fermilab, USA, June 22–July 2, 2020.
[12] J. Wolcott [NOvA], talk at Neutrino 2024, Milan, Italy, June 16–22, 2024.
[13] D. Carabadjac [T2K], talk at ICHEP 2024, Prague, Czech Republic, July 17–24, 2024.

The contribution of neutrino telescopes through atmospheric data

- IceCUBE/DeepCore: after many 3-year "calibration" fits [14, 15, 16], updated 8-year [17] and 9.3-year [18] results presented (but not "released") ⇒ competitive with reactors and LBL;
- Km3NET/ORCA: under deployment (23/115 strings so far [19]), fit (ORCA6+11) catching up.







[14] M.G. Aartsen *et al.* [ICECUBE], PRD **91** (2015) 072004 [arXiv:1410.7227], updated Oct. 2016. [IC16]

[15] M.G. Aartsen *et al.* [ICECUBE], PRL **120** (2018) 071801 [arXiv:1707.07081].

[16] M.G. Aartsen *et al.* [ICECUBE], PRD **99** (2019) 032007 [arXiv:1901.05366]. [IC19]

[17] R. Abbasi *et al.* [ICECUBE], PRD **108** (2023) 012014 [arXiv:2304.12236].

[18] R. Abbasi *et al.* [ICECUBE], PRL **134** (2025) 091801 [arXiv:2405.02163]. [IC24]

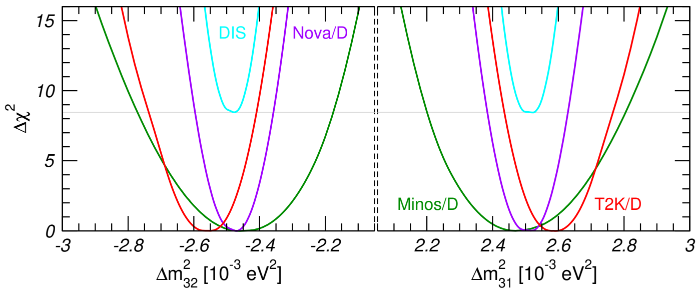
[19] J. Coelho [KM3NET], talk at Neutrino 2024, Milan, Italy, June 16–22, 2024.

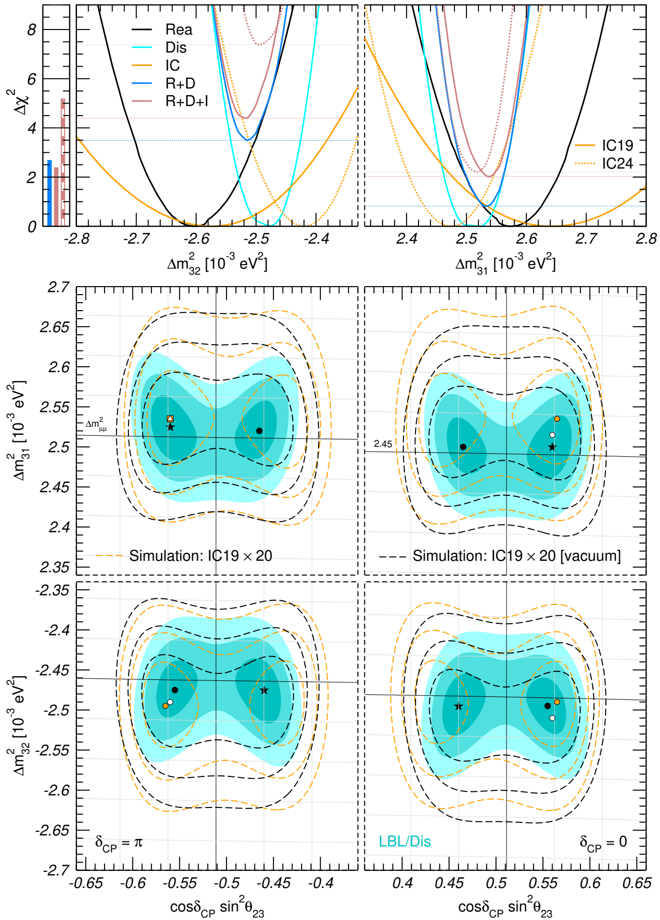
Δm^2_{31} and mass ordering

- All LBL-dis data effectively measure [10]:

$$\Delta m^2_{\mu\mu} \equiv \frac{|U_{\mu 1}|^2 \Delta m^2_{31} + |U_{\mu 2}|^2 \Delta m^2_{32}}{|U_{\mu 1}|^2 + |U_{\mu 2}|^2} \,;$$

- neither **reactor**-ν_e nor **accelerator**-ν_μ data are sensitive to the ordering, but their **combination** is: $\Delta m^2_{ee} \neq \Delta m^2_{\mu\mu} \Rightarrow$ better agreement for **NO**;
- IC: matter effects sizable $\Rightarrow \nu_\mu$ data do **not** follow $\Delta m^2_{\mu\mu} \Rightarrow$ complementary to LBL-dis.





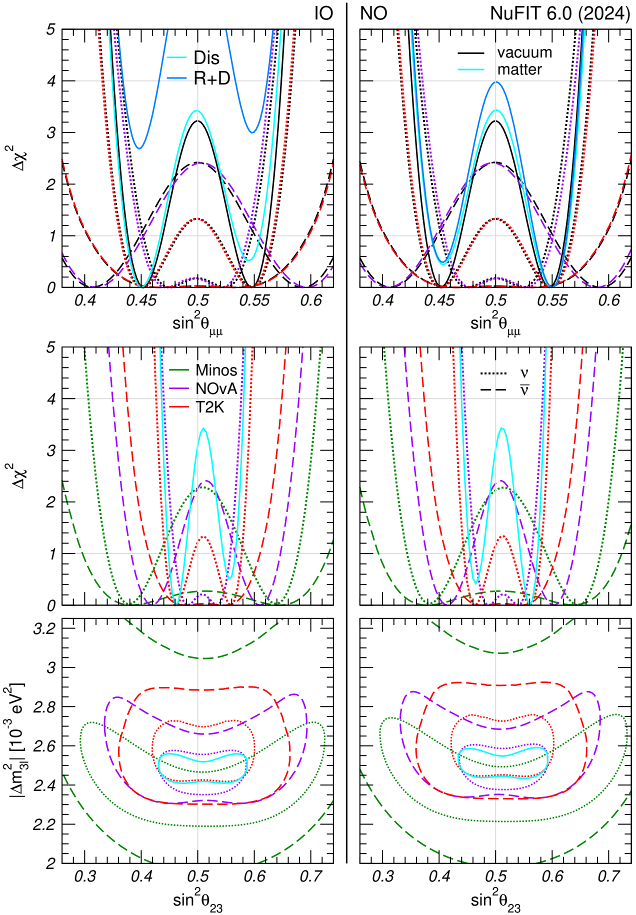
[10] Nunokawa *et al.*, PRD [hep-ph/0503283].

θ_{23} mixing and octant

- Effective LBL-disappearance mixing angle:

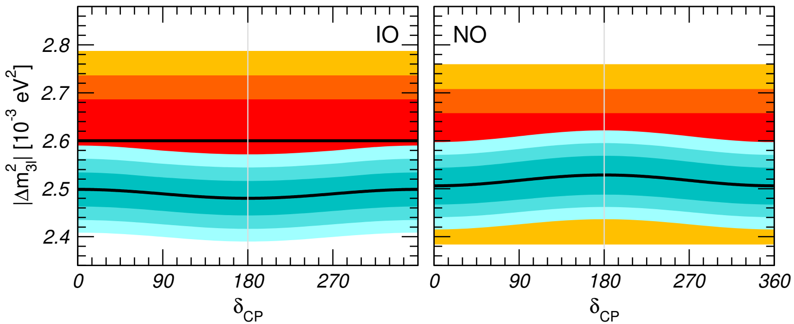
$$\sin^2\theta_{\mu\mu} \equiv |U_{\mu 3}|^2 = \sin^2\theta_{23}\cos^2\theta_{13}\,;$$

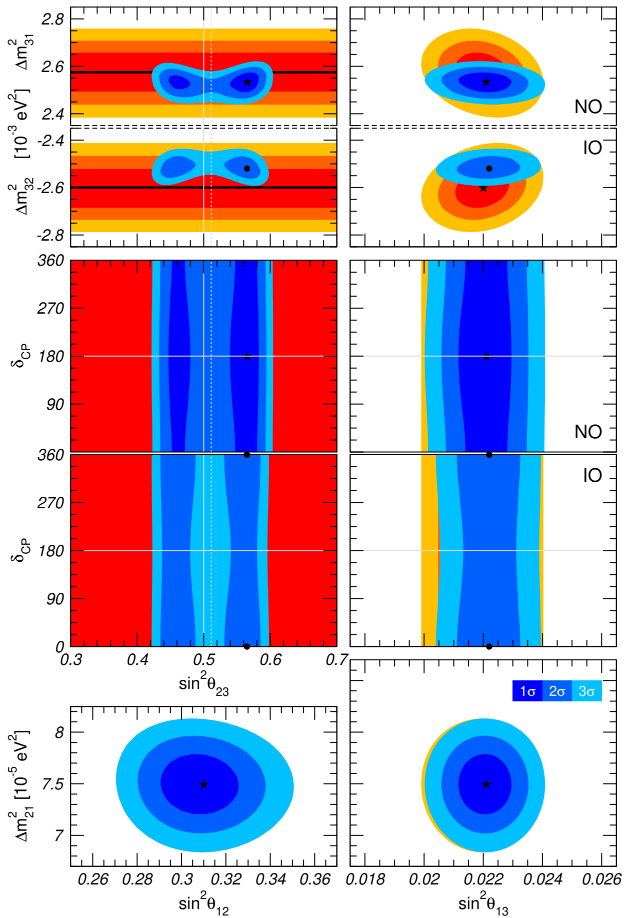
- each individual LBL-dis ν or $\bar\nu$ data slightly favor deviation from maximal $\theta_{\mu\mu}$ mixing, but without any preference for a given octant;
- matter effects (subleading) affect $\theta_{\mu\mu}$ preferred value, but not its significance. However:
  - they have opposite sign for ν and $\bar\nu$ samples;
  - they impact NOvA (& Minos) more than T2K;
- hence, overall LBL show weak octant preference (**NO** $> 45^\circ$ & **IO** $< 45^\circ$ at $\Delta\chi^2 \sim 0.4$);
- maximal $\theta_{\mu\mu}$ mixing disfavored at $\Delta\chi^2 \sim 3.4$;
- since $\Delta m^2_{\mu\mu}$ depends on θ_{23} but Δm^2_{ee} does not, combining LBL+REA impacts θ_{23} range.



Global $\nu_e + \nu_\mu$ disappearance bounds

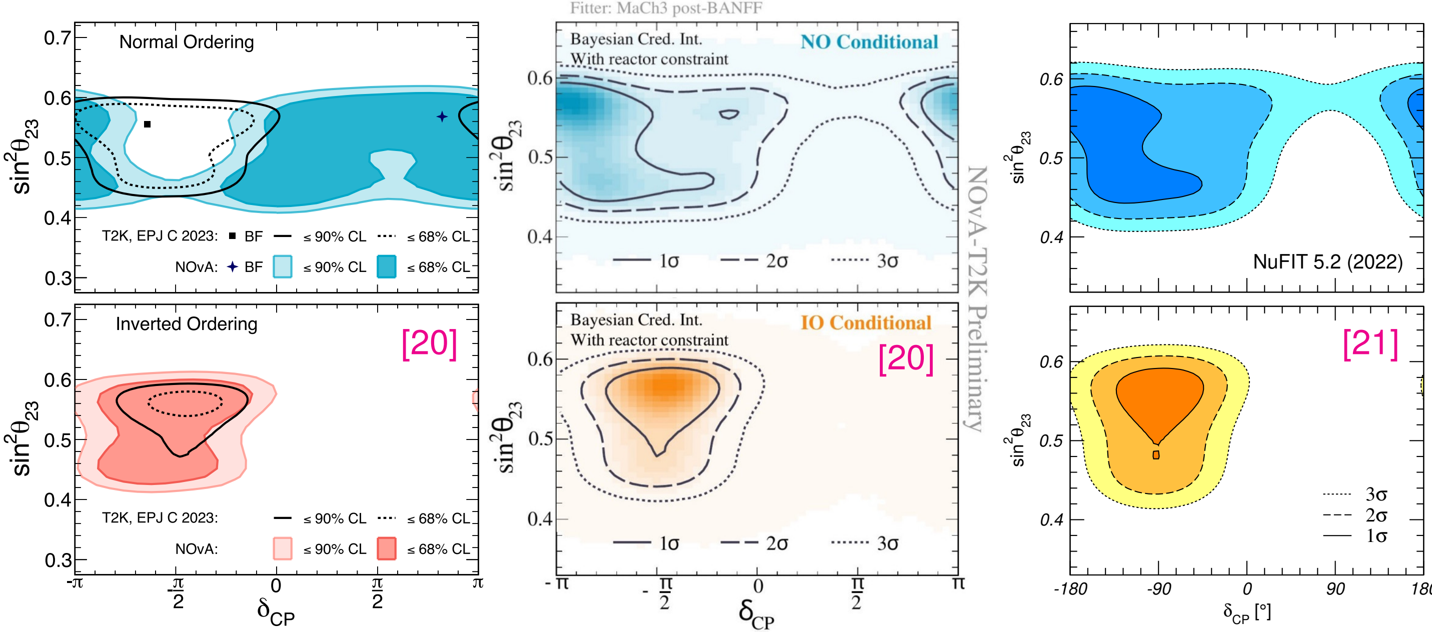
- Intrinsic contributions of ν_μ-disapp data sample:
  - uniquely determines the θ_{23} mixing angle;
  - sizably reduces the allowed range of Δm^2_{31};
- LBL-disapp alone insensitive to: $\left\{ \begin{array}{l} \Delta m^2 \text{ ordering,} \\ \text{CP violation;} \end{array} \right.$
- but combination with ν_e-disapp (& atm-dis) yields:
  - preference for **NO**: 1.5σ (IC19) $\to$ 2.3σ (IC24);
  - non-maximal θ_{23}: 2.2σ (IC19) $\to$ 1.9σ (IC24);
  - a weak dependence on the δ_{CP} phase.





Tension between NOvA and T2K data: summer 2020

- Neutrino 2020: tension on δ_{CP} between T2K and NOvA for **NO** (no problem for **IO**);
- official joint T2K/NOvA analysis finally presented [20], results very similar to estimates [21].

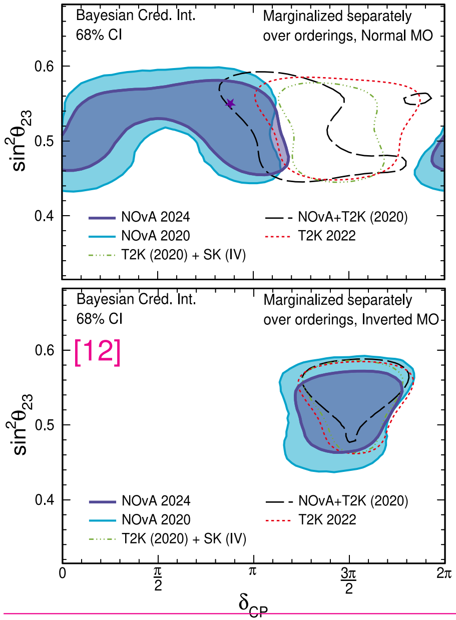


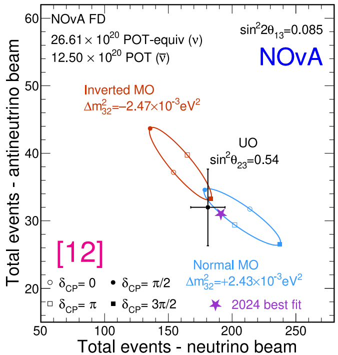
[20] M. Sanchez [NOvA], talk at Moriond-EW 2024, La Thuile, Italy, March 24–31, 2024.

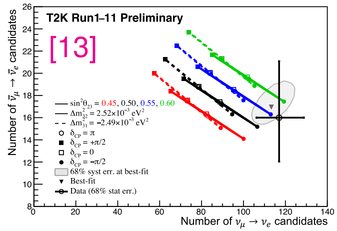
[21] I. Esteban *et al.*, JHEP **09** (2020) 178 [arXiv:2007.14792].

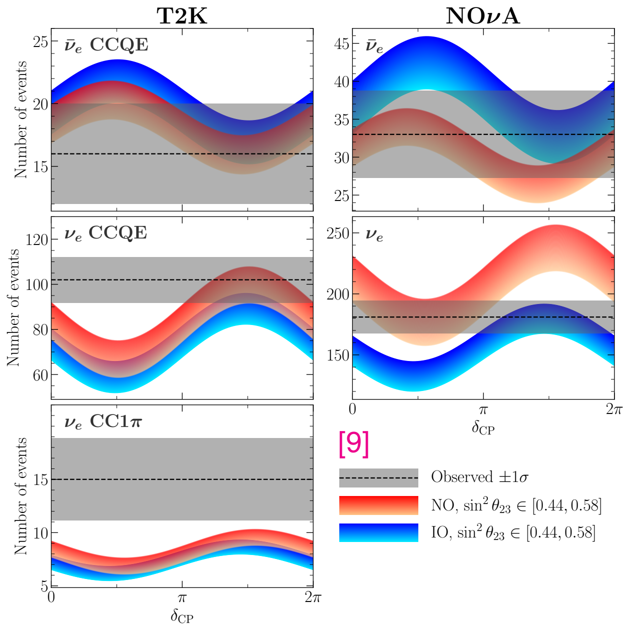
Tension between NOvA and T2K data: today

- Neutrino 2024: NOvA substantially increased ν statistics, but no qualitative change on δ_{CP}.









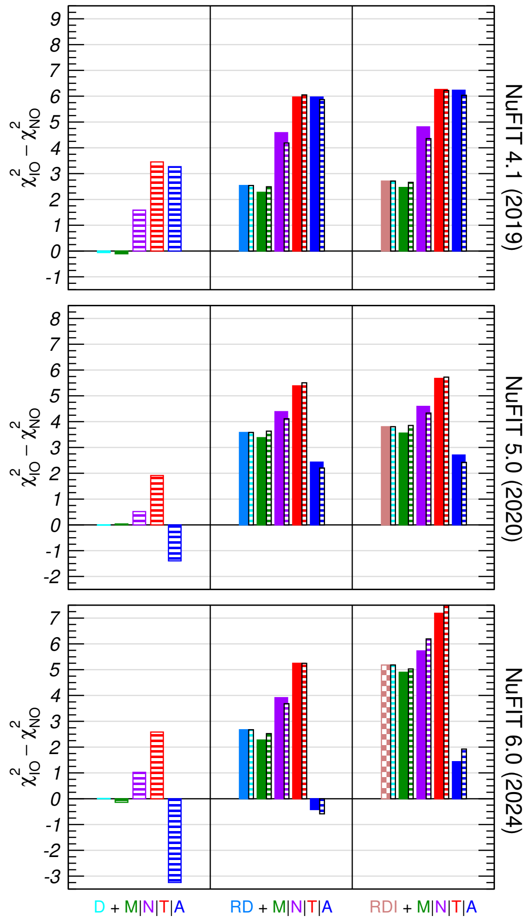
[9] I. Esteban *et al.*, JHEP **12** (2024) 216 [arXiv:2410.05380] & NuFIT 6.0 [http://www.nu-fit.org].
[12] J. Wolcott [NOvA], talk at Neutrino 2024, Milan, Italy, June 16–22, 2024.
[13] D. Carabadjac [T2K], talk at ICHEP 2024, Prague, Czech Republic, July 17–24, 2024.

Impact on the neutrino mass ordering

- when taken by themselves, both T2K and NOvA appearance data exhibit a long-standing preference for **NO**;
- but the δ_{CP} tension among them (which has become more severe over time) implies that a **joint LBL** fit prefers **IO**;
- negative $\Delta\chi^2_{\text{IO-NO}}$ contribution from ν_e appearance data is largely independent from the positive one stemming from ν_μ disappearance (both w/o and with IC atmos data):

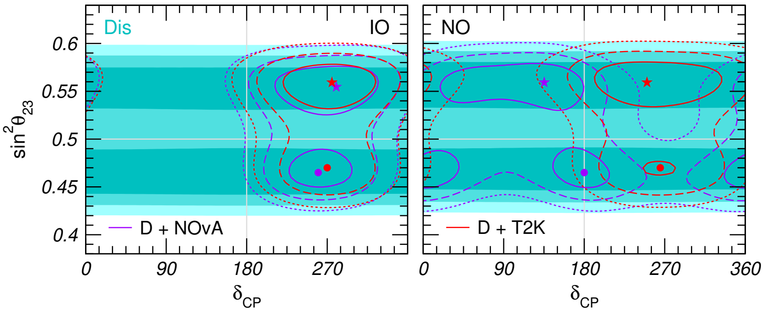
$$\text{IO} - \text{NO:} \quad \begin{cases} \Delta\chi^2_{\text{Rea+Dis+App}} \approx \Delta\chi^2_{\text{Rea+Dis}} + \Delta\chi^2_{\text{Dis+App}}\,, \\ \Delta\chi^2_{\text{Rea+Dis+IC+App}} \approx \Delta\chi^2_{\text{Rea+Dis+IC}} + \Delta\chi^2_{\text{Dis+App}} \end{cases}$$

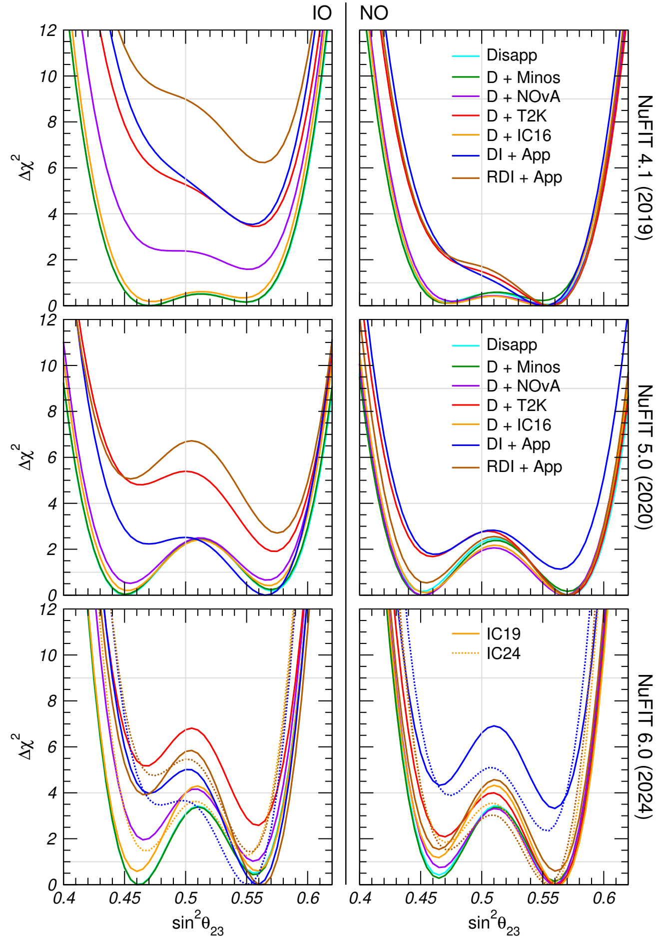
  for App $\in$ {Minos, NOvA, T2K, All-LBL};
- these *contrasting preferences* between ν_e-app and ν_μ-dis mutually cancel, leading to no indication ($\lesssim 1\sigma$);
- inclusion of Super-K atmos. data (multiple ν_e-dis, ν_μ-dis, $\nu_\mu \leftrightarrow \nu_e$ channels) yields a $\Delta\chi^2 = 5.7$ push for **NO**.



Impact of LBL-app on the θ_{23} octant

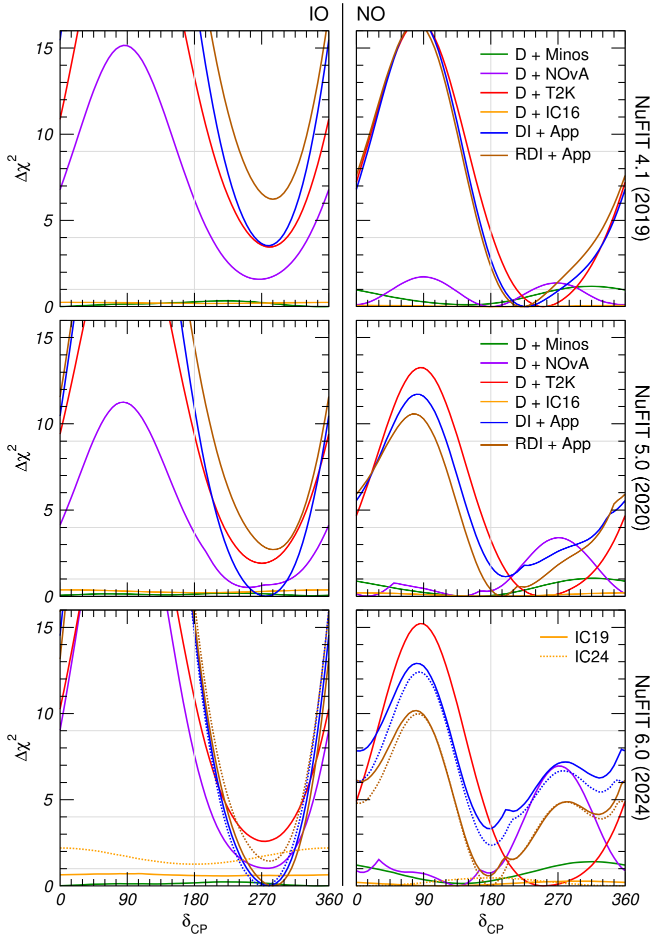
- Minos and IC16 contribution marginal; IC19/24 get some sensitivity from "cascade" (ν_e) events;
- T2K (more) and NOvA (less) both push for $\theta_{23} > 45^\circ$, irrespective of the mass ordering;
- combination of LBL-appearance data:
  - **IO**: preference for $\theta_{23} > 45^\circ$ is confirmed;
  - **NO**: the δ_{CP} tension between T2K and NOvA is less severe for $\theta_{23} < 45^\circ$, hence it cancels this hint and leads to similar minima.





Status of the CP phase

- T2K data show a clear preference for maximal CP violation ($\delta_{CP} \simeq 270^\circ$), irrespective of the assumed mass ordering;
- NOvA data also favor such value for **IO**, but for **NO** it disfavors it, preferring instead the CP conserving value $\delta_{CP} \simeq 180^\circ$;
- NOvA rejection of $\delta_{CP} \simeq 270^\circ$ has steadily increased over time: $1.2\sigma \to 1.8\sigma \to 2.6\sigma$ from the analysis of NuFIT 4.1 → 5.0 → 6.0 data;
- Minos & IceCube have practically no sensitivity to δ_{CP} and give negligible contribution;
- combined LBL+IC experiments indicate $\delta_{CP} \simeq \pi$ for **NO**, thus dominated by NOvA. Further inclusion of reactors does not change this picture.



Neutrino oscillations: where we are

- Global 6-parameter fit (including δ_{CP}):
  - **Solar**: Cl + Ga + SK(1–4) + SNO-full (I+II+III) + BX(1–3);
  - **Atmospheric**: IC19 | IC24 + SK(1–5);
  - **Reactor**: KamLAND + SNOplus + IC + DB + Reno;
  - **Accelerator**: Minos + T2K + NOvA;

- best-fit point and 1σ (3σ) ranges:

$$\theta_{12} = 33.68\,^{+0.73}_{-0.70}\,\left(^{+2.27}_{-2.05}\right), \qquad \Delta m^2_{21} = 7.49\,^{+0.19}_{-0.19}\,\left(^{+0.56}_{-0.57}\right) \times 10^{-5}\ \text{eV}^2,$$

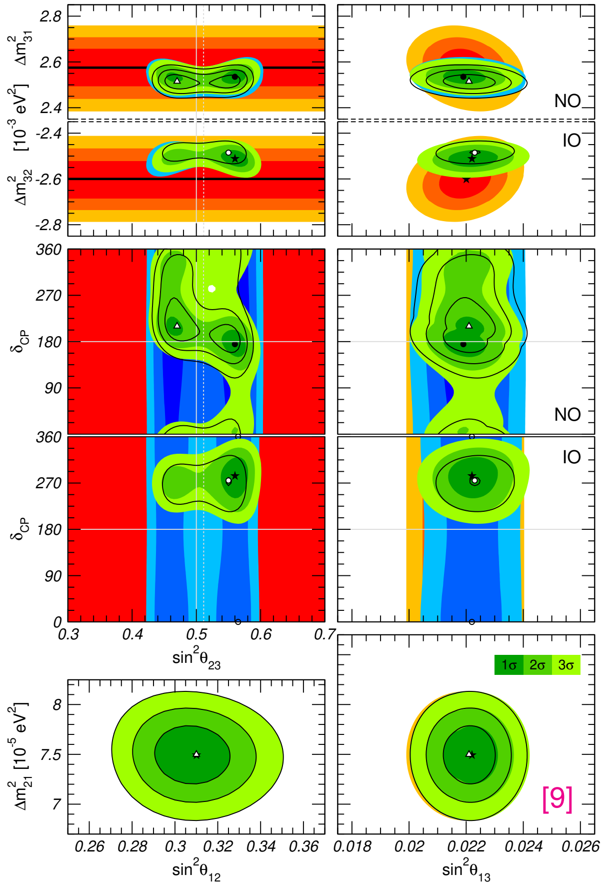
$$\theta_{23} = \begin{cases} 48.5\,^{+0.7}_{-0.9}\,\left(^{+2.0}_{-7.6}\right), \\ 48.6\,^{+0.7}_{-0.9}\,\left(^{+2.0}_{-7.2}\right), \end{cases} \qquad \Delta m^2_{31} = \begin{cases} +2.534\,^{+0.025}_{-0.023}\,\left(^{+0.072}_{-0.071}\right) \times 10^{-3}\ \text{eV}^2, \\ -2.510\,^{+0.024}_{-0.025}\,\left(^{+0.072}_{-0.073}\right) \times 10^{-3}\ \text{eV}^2, \end{cases}$$

$$\theta_{13} = 8.58\,^{+0.11}_{-0.13}\,\left(^{+0.33}_{-0.39}\right), \qquad \delta_{\text{CP}} = 285\,^{+25}_{-28}\,\left(^{+129}_{-182}\right);$$

- neutrino mixing matrix:

$$|U|_{3\sigma} = \begin{pmatrix} 0.801 \to 0.842 & 0.519 \to 0.580 & 0.142 \to 0.155 \\ 0.248 \to 0.505 & 0.473 \to 0.682 & 0.649 \to 0.764 \\ 0.270 \to 0.521 & 0.483 \to 0.690 & 0.628 \to 0.746 \end{pmatrix};$$

- ordering: $\Delta\chi^2_{\text{IO-NO}} = -0.6$ (IC19) | $+6.1$ (IC24 + SK).



[9] I. Esteban *et al.*, JHEP **12** (2024) 216 [arXiv:2410.05380] & NuFIT 6.0 [http://www.nu-fit.org].

- Most of the present data from solar, atmospheric, reactor and accelerator experiments are well explained by the 3ν oscillation hypothesis. The three-neutrino scenario is robust;
- the long-standing "hints" concerning the mass ordering, with **NO** favored over **IO** at the $2\sigma \div 3\sigma$ level, are cancelled by the T2K/NOvA tension;
- the discovery of large θ_{13} opened the road to searches for CP violation. However, results on this topic need further clarifications;
- deviation from maximal θ_{23} mixing is also still an open issue. The region $\theta_{23} > 45^\circ$ seems to be slightly preferred, especially for **IO**;
- synergies between different experiments will be crucial to increase the sensitivity.