Phenomenology of three-neutrino oscillations

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I. Conventional oscillations in the new SM

General three-neutrino oscillation framework

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

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

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

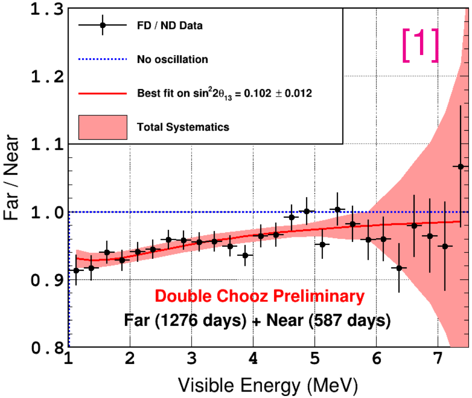
$$\mathbf{D}_{\text{vac}} = \frac{1}{2E_\nu}\left[\operatorname{diag}\left(0,\, \Delta m^2_{21},\, \Delta m^2_{31}\right) + \xcancel{m_1^2 \mathbf{I}}\right]; \qquad \mathbf{V}_{\text{mat}} = \sqrt{2} G_F N_e \operatorname{diag}(1,\, 0,\, 0)\,.$$

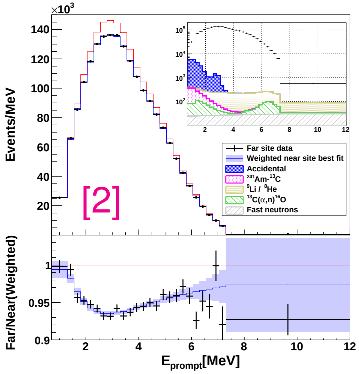
6 parameters $\Longleftrightarrow$ 6 types of experiments

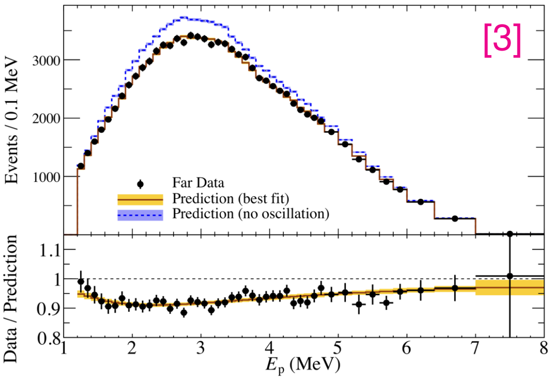
- **SOLAR** sector:
  - – solar experiments (mainly SNO) ⟶ θ_{12}
  - – rector LBL (KamLAND) ⟶ Δm^2_{21}
- **REACT** sector:
  - – rector MBL (Double-Chooz, Daya-Bay, Reno) ⟶ θ_{13} $[\Delta m^2_{31}]$
- **ATMOS** sector:
  - – atmospheric experiments (SK, DC) ⟶ θ_{23}
  - – accelerator LBL-DIS $\nu_\mu \to \nu_\mu$ (T2K, NOvA) ⟶ Δm^2_{31} $[\theta_{23}]$
  - – accelerator LBL-APP $\nu_\mu \to \nu_e$ (T2K, NOvA) ⟶ δ_{CP}

Reactor neutrino disappearance and θ_{13}

- Positive $\bar{\nu}_e$ disappearance signal 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.







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

[2] D. Adey *et al.* [DAYA BAY], Phys. Rev. Lett. **121** (2018) 241805 [`arXiv:1809.02261`].

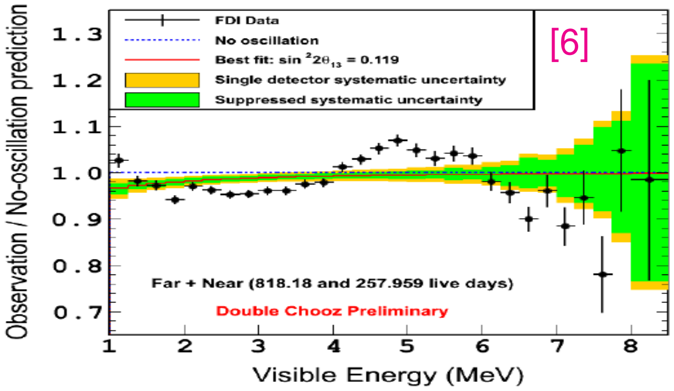
[3] J. Yoo [RENO], online talk presented at Neutrino 2020, Fermilab, USA, June 22–July 2, 2020.

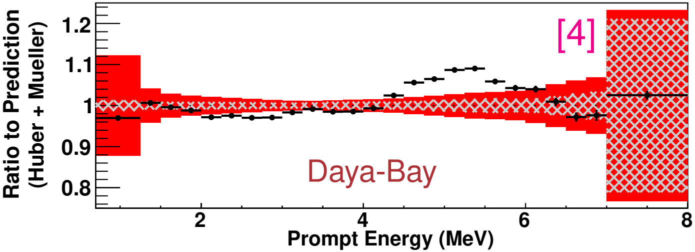
I. Conventional oscillations in the new SM

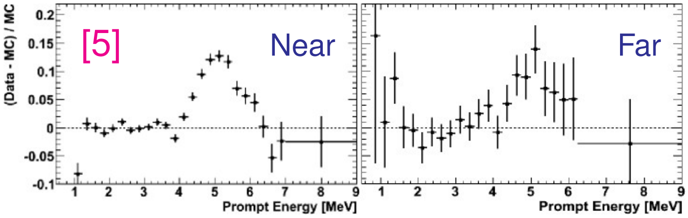
Trouble with reactor fluxes

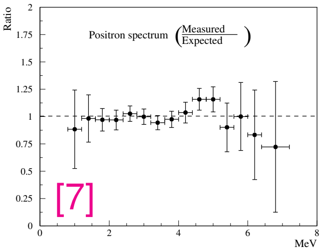
- Neutrino 2014: RENO [5] reported an excess of events around 5 MeV;
- excess (not deficit) & independent of L ⇒ **flux feature**, not ~~neutrino oscillations~~;
- seen by Daya-Bay [4], Dbl-Chooz [6], and many others (also old Chooz [7]);

⇒ reactor flux under experimental scrutiny.









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[4] F. P. An *et al.* [Daya-Bay], CPC **41** (2017) [`arXiv:1607.05378`].

[5] S.H Seo [RENO], talk at Neutrino 2014, Boston, USA, June 2-7, 2014.

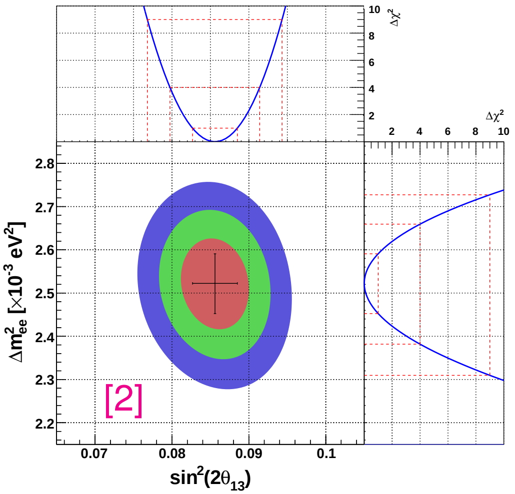
[6] I.G. Botella [Double-Chooz], talk at EPS 2017, Venice, Italy.

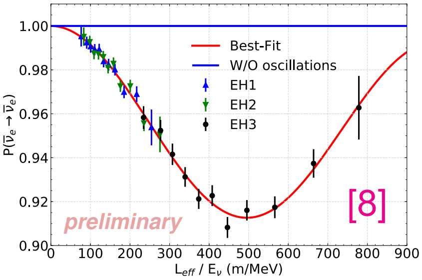
[7] M. Apollonio *et al.* [Chooz], PLB **466** (1999) 415 [`hep-ex/9907037`].

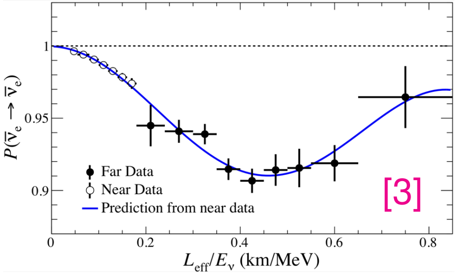
I. Conventional oscillations in the new SM

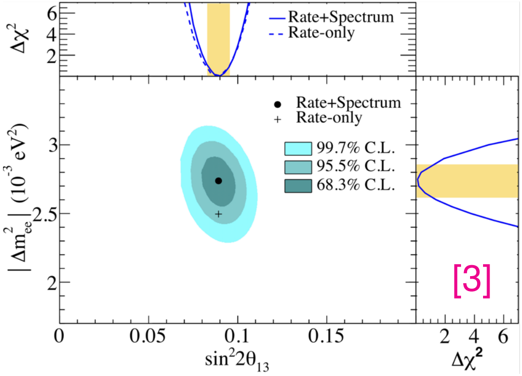
Measuring θ_{13} and Δm^2_{31} from reactor data

- Spectral information from Double-Chooz, Daya-Bay and Reno ⇒ oscillation pattern clearly visible ⇒ θ_{13} and Δm^2_{31} accurately determined by reactor data;
- FAR/NEAR spectral ratio ⇒ flux shape irrelevant;
- 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.









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[2] D. Adey *et al.* [DAYA-BAY], `arXiv:1809.02261`.

[3] J. Yoo [RENO], online talk at Neutrino 2020.

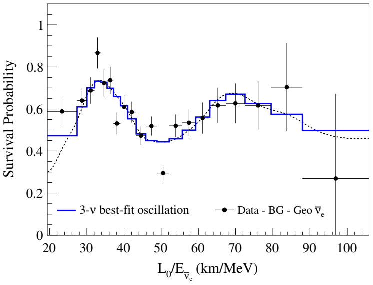
[8] J.P. Ochoa-Ricoux [DAYA-BAY], talk at Neutrino 2018.

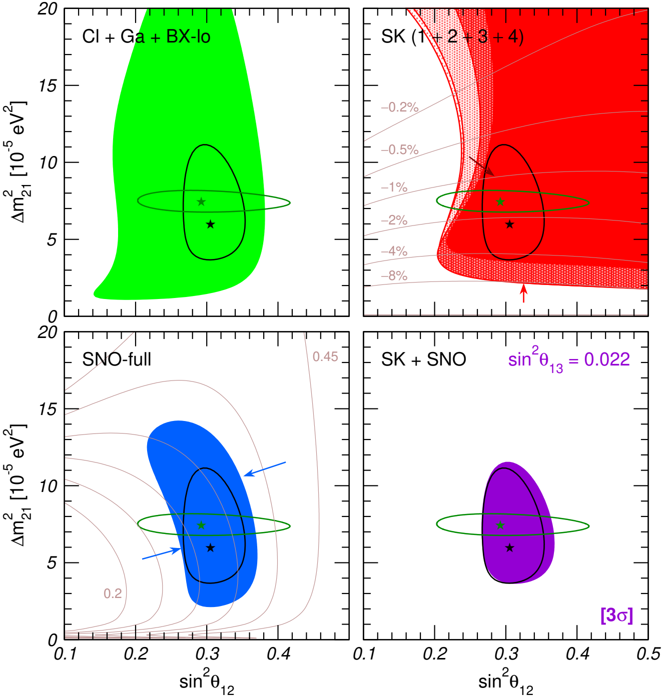
Relevance of solar data in the determination of Δm^2_{21} and θ_{12}

- $P_{ee} = c_{13}^4 P_{\text{eff}} + s_{13}^4$, $\quad i\frac{d\vec{\nu}}{dt} = \left[\frac{\Delta m^2_{21}}{4E_\nu}\begin{pmatrix}-\cos 2\theta_{12} & \sin 2\theta_{12} \\ \sin 2\theta_{12} & \cos 2\theta_{12}\end{pmatrix} \pm \sqrt{2} G_F N_e \begin{pmatrix} c_{13}^2 & 0 \\ 0 & 0 \end{pmatrix}\right]\vec{\nu}, \quad \vec{\nu} = \begin{pmatrix}\nu_e \\ \nu_a\end{pmatrix}$;
- $\nu_\mu \equiv \nu_\tau \Rightarrow$ 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: $\begin{cases} \theta_{12} \text{ dominated by SNO;} \\ \Delta m^2_{21} \text{ dominated by KamLAND;} \end{cases}$
- solar region determined by high-E data, low-E contribution marginal;
- SNO-NC measurement confirms SSM;
- KamLAND precisely determines the oscillation pattern.



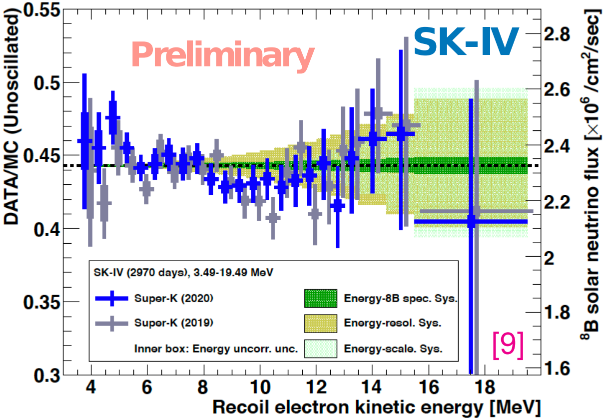


I. Conventional oscillations in the new SM

Tension between solar and KamLAND data

- Long-standing weak tension on preferred Δm^2_{21} from solar and KamLAND data;
- choice of the assumed solar model (GS or AGSS) had little impact on the issue;
- cause:
  - – too much D/N asymmetry in SK
  - – no indication of low-E turn-up
- new data [9]:
  - – D/N: $3.6\% \rightarrow 2.1\%$,
  - – “hints” of turn-up.

⇒ tension considerably reduced after Neutrino 2020 conference.



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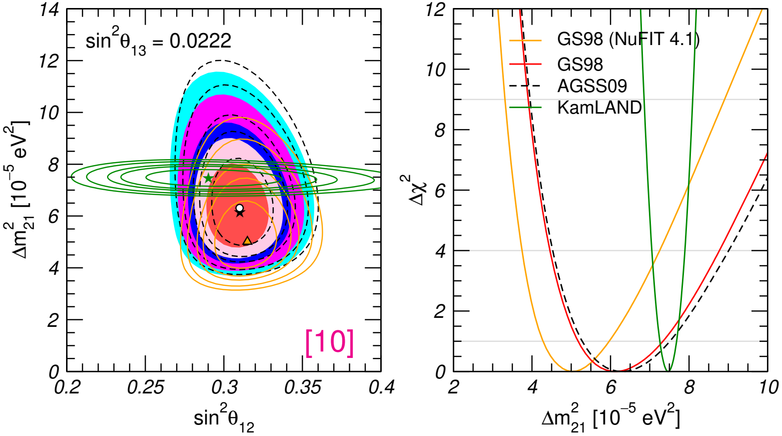

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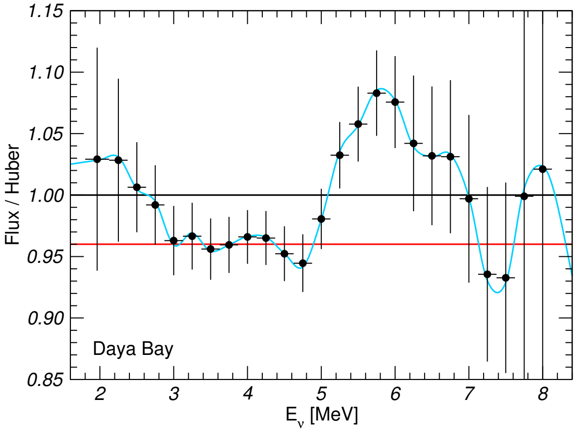
[9] Y. Nakajima [SK], online talk at Neutrino 2020, Fermilab, USA, June 22–July 2, 2020.

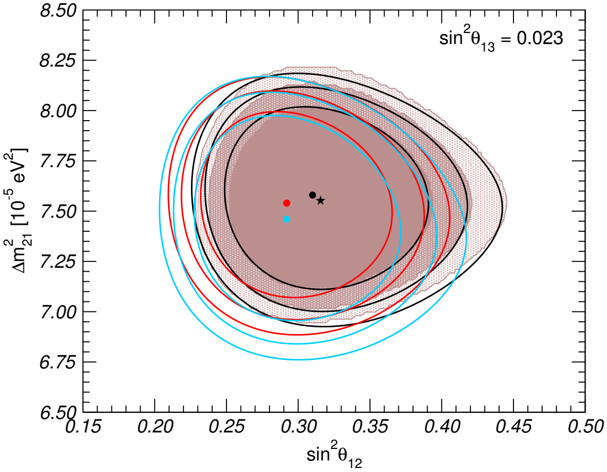
[10] I. Esteban *et al.*, JHEP **09** (2020) 178 [`arXiv:2007.14792`] & NuFIT 5.1 [`http://www.nu-fit.org`].

KamLAND and reactor ν spectrum

- KamLAND detects neutrinos from various reactors, and has **no** near detector. Hence, spectral distortions may be potentially relevant;
- the effects of such distortions in KamLAND were discussed briefly in [11], and more in detail in [12]. In both cases the impact on Δm^2_{21} was found to be small;
- since 2017 we fix KamLAND reactor spectrum to the measured Daya-Bay ν flux [4];

⇒ the determination of Δm^2_{21} is robust against reactor flux uncertainties, and does not help in reconciling solar and KamLAND data.





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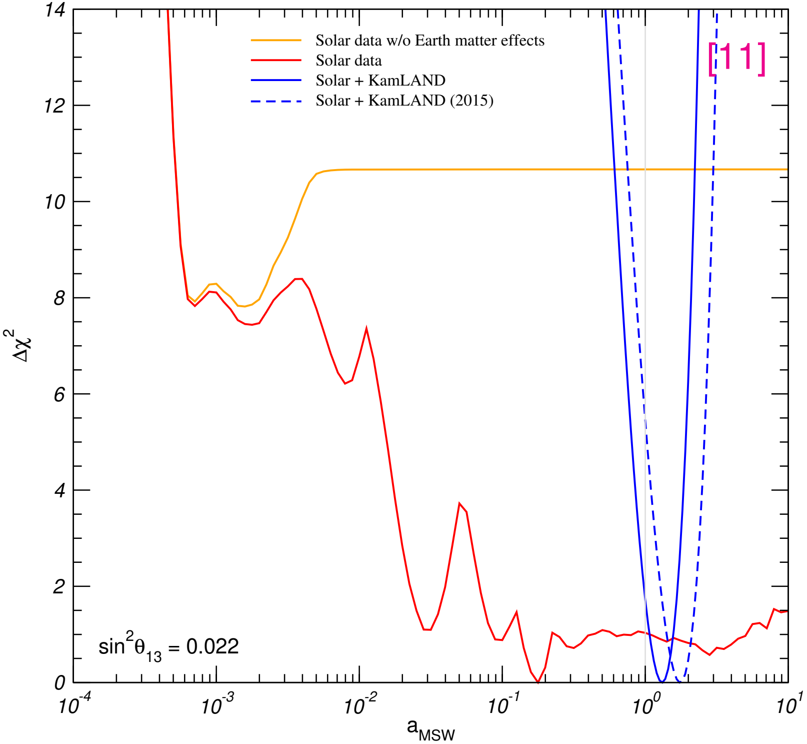
[4] F.P. An *et al.* [DAYA-BAY], `arXiv:1607.05378`.
[11] M. Maltoni, A.Yu. Smirnov, `arXiv:1507.05287`.
[12] F. Capozzi *et al.*, `arXiv:1601.07777`.

Relevance of MSW effects in solar data

- Parametrization: $V_e \to a_{\text{MSW}} V_e$;
- first proposed in [13];
- combination of solar and KamLAND data results in a strong bound on a_{MSW};
- 3σ range: $0.66 < a_{\text{MSW}} < 2.14$;
- ease of solar and KamLAND tension improves compatibility with $a_{\text{MSW}} = 1$ as expected in the SM;
- neglecting Earth matter effects in solar data leads to a $\sim 3.3\sigma$ worsening of solar χ^2.



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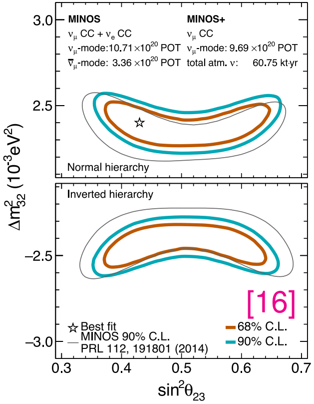
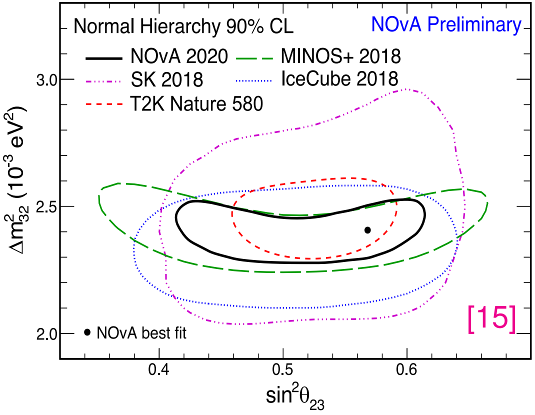
[13] G. L. Fogli, E. Lisi, A. Marrone, A. Palazzo, Phys. Lett. B **583** (2004) 149 [`hep-ph/0309100`].

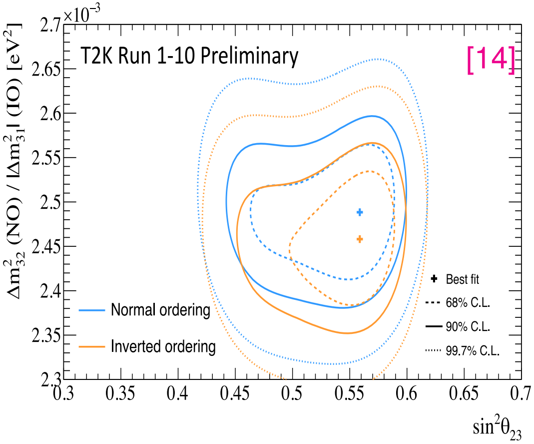
[11] M. Maltoni, A. Yu. Smirnov, Eur. Phys. J. A **52** (2016) 87 [`arXiv:1507.05287`]

Atmospheric oscillations: Δm^2_{31} and θ_{23}

- Δm^2_{31} & θ_{23} dominated by LBL disappearance ($\nu_\mu \to \nu_\mu$) data;
- Δm^2_{21} effects contribute only at subleading level;
- reasonably good agreement between all experiments in the allowed regions, although some small differences are visible.







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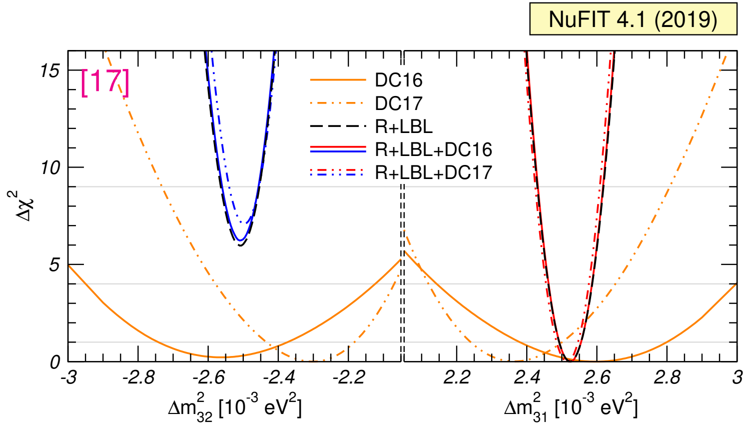
[14] P. Dunne [T2K], online talk at Neutrino 2020, Fermilab, USA, June 22–July 2, 2020.

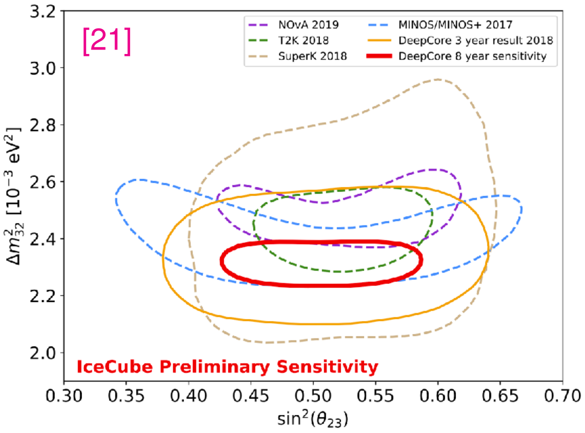
[15] A. Himmel [NOvA], online talk at Neutrino 2020, Fermilab, USA, June 22–July 2, 2020.

[16] T. Carroll [MINOS], online talk at Neutrino 2020, Fermilab, USA, June 22–July 2, 2020.

The contribution of IceCUBE/DeepCore

- Various analysis (DC16 [18], DC17 [19], DC19 [20]) of IceCUBE/DeepCore data have been presented, all based on three years of data (but **not** the same years);
- contribution to global fit still limited, but analysis with eight years is in progress [21].





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[17] I. Esteban *et al.*, JHEP **01** (2019) 106 [`arXiv:1811.05487`] & NuFIT 4.1 [`http://www.nu-fit.org`].

[18] M.G. Aartsen *et al.* [DEEPCORE], PRD **91** (2015) 072004 [`arXiv:1410.7227`], updated Oct. 2016.

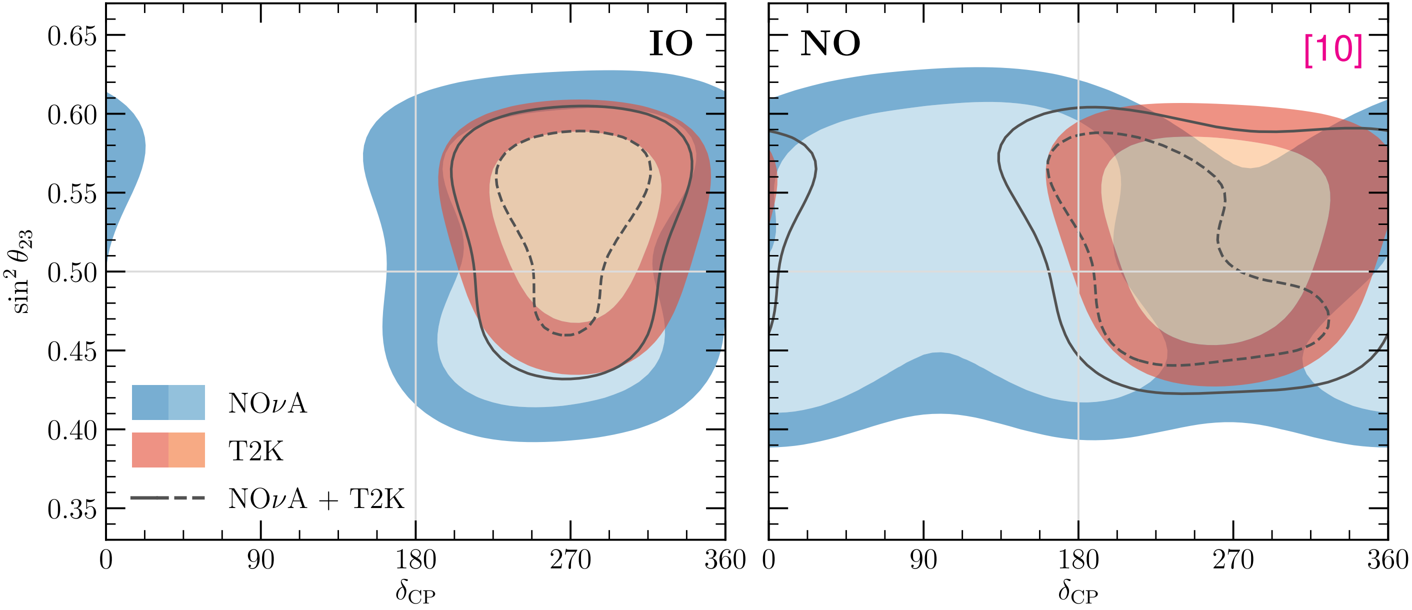
[19] M.G. Aartsen *et al.* [DEEPCORE], PRL **120** (2018) 071801 [`arXiv:1707.07081`].

[20] M.G. Aartsen *et al.* [DEEPCORE], PRD **99** (2019) 032007 [`arXiv:1901.05366`].

[21] S. Blot [DEEPCORE], online talk at Neutrino 2020, Fermilab, USA, June 22–July 2, 2020.

Tension between NOvA and T2K data

- The new data presented at the Neutrino 2020 conference [15] show some tension on the determination of δ_{CP} between T2K and NOvA for the case of normal ordering (NO).



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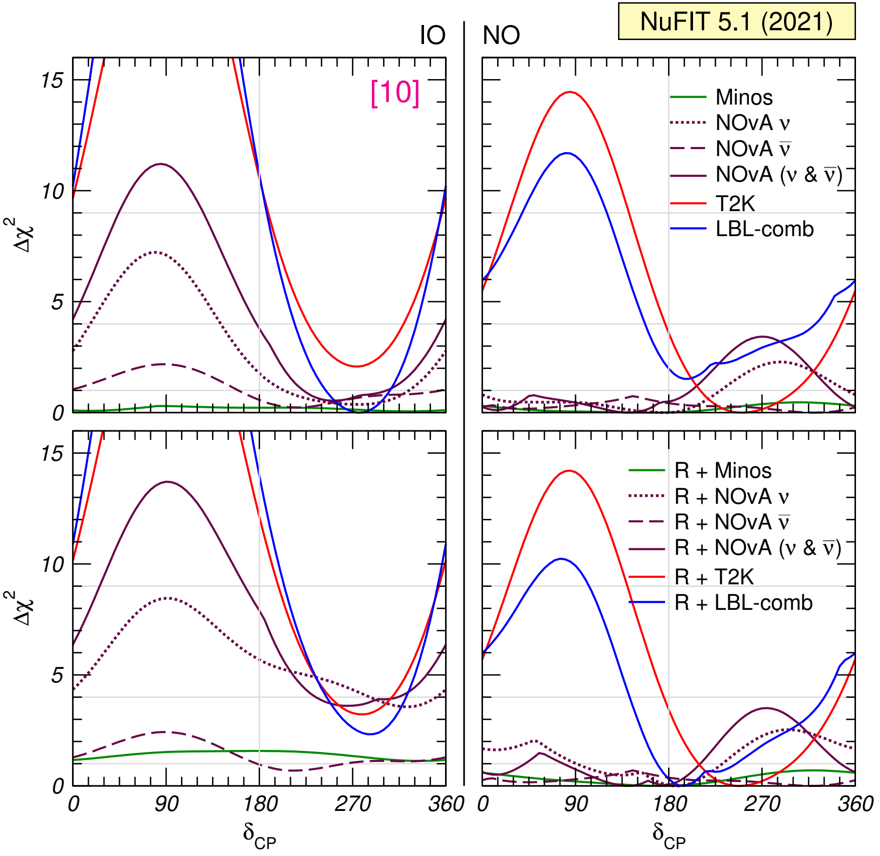
[15] A. Himmel [NOvA], online talk at Neutrino 2020, Fermilab, USA, June 22–July 2, 2020.

[10] I. Esteban *et al.*, JHEP **09** (2020) 178 [`arXiv:2007.14792`] & NuFIT 5.1 [`http://www.nu-fit.org`].

I. Conventional oscillations in the new SM

Status of the CP phase

- T2K data show a clear preference for maximal CP violation ($\delta_{\text{CP}} \simeq -\pi/2$), irrespective of the mass ordering;
- NOvA data also favor such value for **IO**, but for **NO** it disfavors it at 1.9σ, preferring instead $\delta_{\text{CP}} \simeq \pm\pi$ (CP-cons);
- Minos has practically no sensitivity to δ_{CP};
- combined LBL experiments indicate $\delta_{\text{CP}} \simeq \pi$ for NO, thus dominated by NOvA.



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[10] I. Esteban *et al.*, JHEP **09** (2020) 178 [`arXiv:2007.14792`] & NuFIT 5.1 [`http://www.nu-fit.org`].

Δm^2_{31} and mass ordering

- When taken by **themselves**, all LBL experiments exhibit a small preference for **NO** over **IO**;
- however, the δ_{CP} tension between T2K and NOvA imply than **combined** LBL data prefer **IO**;
- further combination with **reactors** restores the preference for **NO**, due to better agreement in the allowed Δm^2_{31} range;
- inclusion of Super-K atmospheric data raises the significance to 2.6σ ($\Delta\chi^2 = 7.0$).

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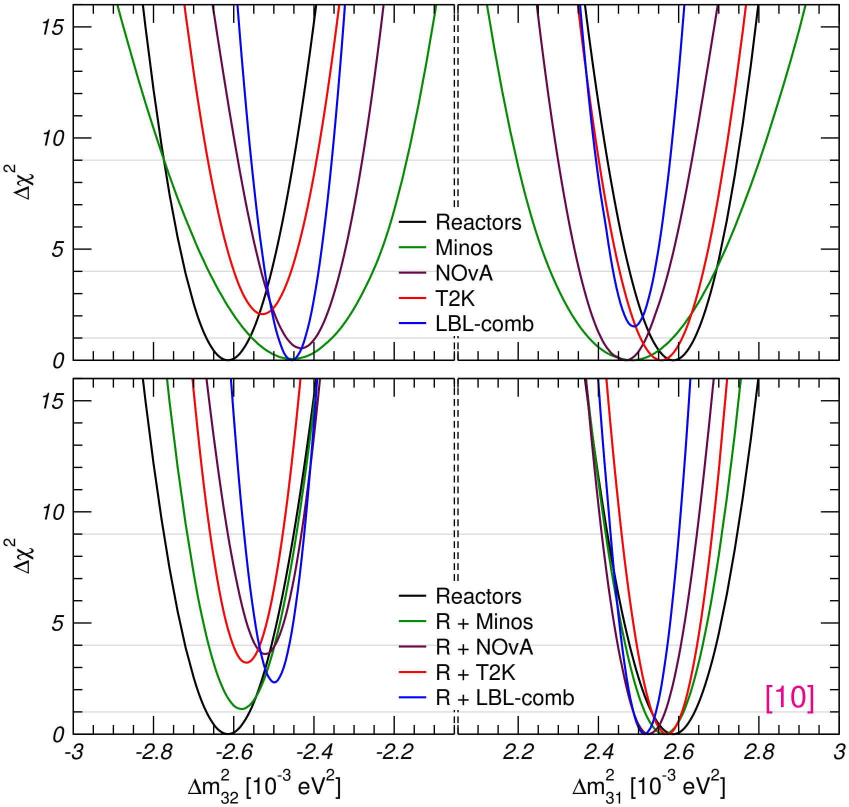

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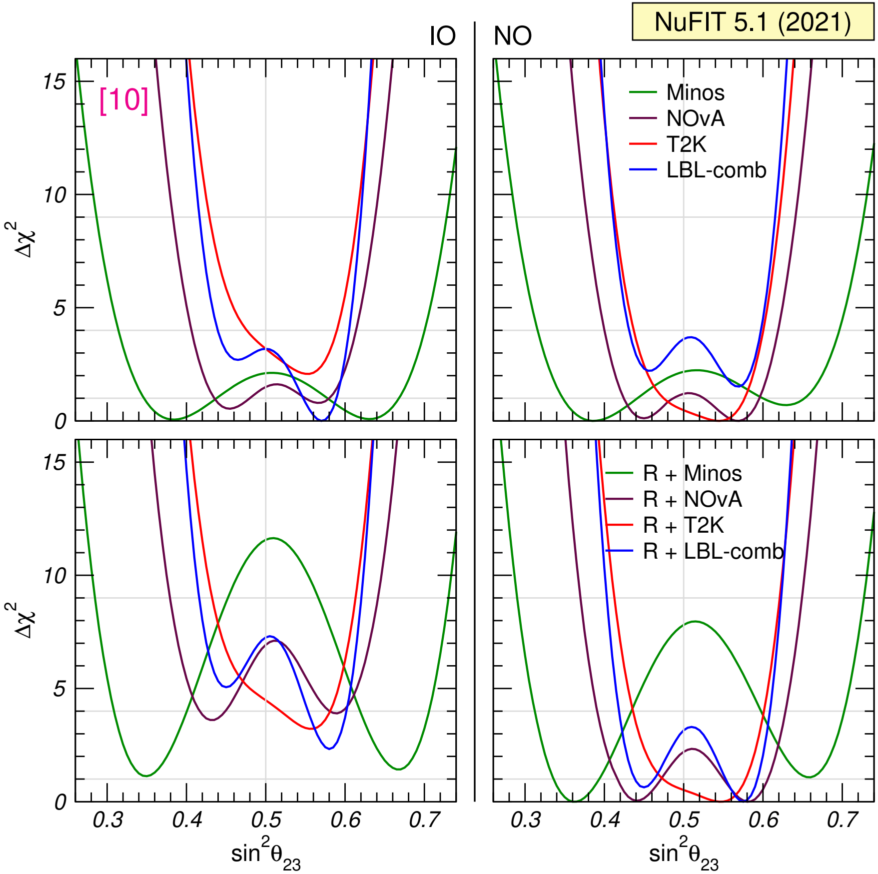
[10] I. Esteban *et al.*, JHEP **09** (2020) 178 [`arXiv:2007.14792`] & NuFIT 5.1 [`http://www.nu-fit.org`].

I. Conventional oscillations in the new SM

θ_{23} mixing and octant

- Disappearance data:
  - T2K data clearly favor maximal mixing;
  - NOvA data slightly favor non-maximal mixing, but significance is reduced with respect to the 2018 release;
  - Minos shows strongest deviation but lowest statistics;
- appearance data:
  - all experiments (except Minos) slightly favor $\underline{\theta_{23} > 45^\circ}$;
- similar results for **NO** and **IO**.



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[10] I. Esteban *et al.*, JHEP **09** (2020) 178 [`arXiv:2007.14792`] & NuFIT 5.1 [`http://www.nu-fit.org`].

I. Conventional oscillations in the new SM

Neutrino oscillations: where we are

- Global 6-parameter fit (including δ_{CP}):
  - **Solar**: Cl + Ga + SK(1–4) + SNO-full (I+II+III) + Bx;
  - **Atmospheric**: DeepCore;
  - **Reactor**: KamLAND + Dbl-Chooz + Daya-Bay + Reno;
  - **Accelerator**: Minos + T2K + NOvA;
- best-fit point and 1σ (3σ) ranges:

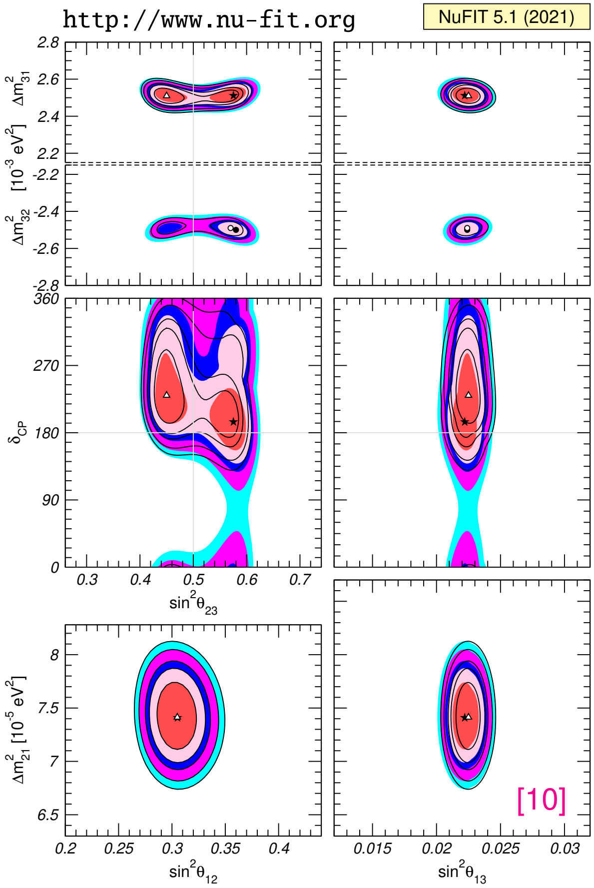
$$\theta_{12} = 33.44\,^{+0.77}_{-0.74}\,\left({}^{+2.42}_{-2.17}\right), \qquad \Delta m^2_{21} = 7.42\,^{+0.21}_{-0.20}\,\left({}^{+0.62}_{-0.60}\right) \times 10^{-5}\ \text{eV}^2,$$

$$\theta_{23} = \begin{cases} 49.2\,^{+1.0}_{-1.3}\,\left({}^{+2.8}_{-9.7}\right), \\ 49.5\,^{+1.0}_{-1.2}\,\left({}^{+2.6}_{-9.7}\right), \end{cases} \qquad \Delta m^2_{31} = \begin{cases} +2.515\,^{+0.028}_{-0.028}\,\left({}^{+0.084}_{-0.084}\right) \times 10^{-3}\ \text{eV}^2, \\ -2.498\,^{+0.028}_{-0.029}\,\left({}^{+0.085}_{-0.086}\right) \times 10^{-3}\ \text{eV}^2, \end{cases}$$

$$\theta_{13} = 8.57\,^{+0.13}_{-0.12}\,\left({}^{+0.40}_{-0.37}\right), \qquad \delta_{\text{CP}} = 194\,^{+52}_{-25}\,\left({}^{+211}_{-89}\right);$$

- neutrino mixing matrix:

$$|\mathbf{U}|_{3\sigma} = \begin{pmatrix} 0.801 \to 0.845 & 0.513 \to 0.579 & 0.143 \to 0.156 \\ 0.232 \to 0.507 & 0.459 \to 0.694 & 0.629 \to 0.779 \\ 0.260 \to 0.526 & 0.470 \to 0.702 & 0.609 \to 0.763 \end{pmatrix}.$$



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[10] I. Esteban *et al.*, JHEP **09** (2020) 178 [`arXiv:2007.14792`] & NuFIT 5.1 [`http://www.nu-fit.org`].

Non-standard neutrino interactions: formalism

- Effective low-energy Lagrangian for **standard** neutrino interactions with matter:

$$\mathcal{L}_{\text{SM}}^{\text{eff}} = -2\sqrt{2}G_F \sum_{f,\beta} \Big([\bar\nu_\beta \gamma_\mu L \ell_\beta][\bar f \gamma^\mu L f'] + \text{h.c.} \Big) - 2\sqrt{2}G_F \sum_{f,P,\beta} g_P^f [\bar\nu_\beta \gamma_\mu L \nu_\beta][\bar f \gamma^\mu P f]$$

  where $P \in \{P_L, P_R\}$, (f, f') form an SU(2) doublet, and g_P^f is the Z coupling to fermion f:

$$\begin{array}{llll} g_L^\nu = \dfrac{1}{2}\,, & g_L^\ell = \sin^2\theta_W - \dfrac{1}{2}\,, & g_L^u = -\dfrac{2}{3}\sin^2\theta_W + \dfrac{1}{2}\,, & g_L^d = \dfrac{1}{3}\sin^2\theta_W - \dfrac{1}{2}\,, \\ g_R^\nu = 0\,, & g_R^\ell = \sin^2\theta_W\,, & g_R^u = -\dfrac{2}{3}\sin^2\theta_W\,, & g_R^d = \dfrac{1}{3}\sin^2\theta_W\,; \end{array}$$

- here we consider NC-like **non-standard** neutrino-matter described by:

$$\mathcal{L}_{\text{NSI}}^{\text{eff}} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \varepsilon_{\alpha\beta}^{fP} [\bar\nu_\alpha \gamma_\mu L \nu_\beta][\bar f \gamma^\mu P f]\,;$$

- ordinary matter composed by $\{e, u, d\}$ ⇒ ν propagation sensitive to NSI with them;

- some experiments sensitive to $\nu - e$ elastic scattering ⇒ NC-like NSI with e affect both propagation and interactions ⇒ require dedicated treatment ⇒ not considered here;

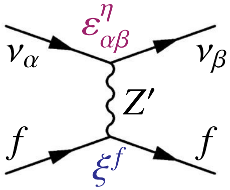
- conversely, NC-like NSI's with quarks do **not** affect processes such as lepton appearance, which involve quarks through CC interactions ⇒ only ν propagation affected.

Non-standard neutrino interactions: formalism

- Conventionally, only NSI with either u or d quarks have been considered;
- still, both cases can appear simultaneously, and produce consequences (*e.g.*, cancellations) which invalidate the u-only or d-only bounds;
- however, most general parameter space too large to handle ⇒ simplifications needed;
- here we assume that the ν flavor structure is **independent** of the charged fermion type:

$$\varepsilon_{\alpha\beta}^{fP} \equiv \varepsilon_{\alpha\beta}^{\eta}\, \xi^{fP} \quad \Rightarrow \quad \mathcal{L}_{\text{NSI}}^{\text{eff}} = -2\sqrt{2}G_F \Big[\sum_{\alpha,\beta} \varepsilon_{\alpha\beta}^{\eta} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)\Big]\Big[\sum_{fP} \xi^{fP} (\bar{f}\gamma_\mu P f)\Big];$$

- since neutrino **propagation** is only sensitive to the vector couplings:



$$\varepsilon_{\alpha\beta}^{f} \equiv \varepsilon_{\alpha\beta}^{fL} + \varepsilon_{\alpha\beta}^{fR} = \varepsilon_{\alpha\beta}^{\eta}\, \xi^{f} \quad \text{with} \quad \xi^{f} = \xi^{fL} + \xi^{fR};$$

- only the direction in the (ξ^u, ξ^d) plane is non-trivial for ν oscillations ⇒ define an angle η:

$$\xi^u = \frac{\sqrt{5}}{3}(2\cos\eta - \sin\eta), \qquad \xi^d = \frac{\sqrt{5}}{3}(2\sin\eta - \cos\eta);$$

- special cases: $\eta = \pm 90^\circ$ (n), $\eta = 0$ (p), $\eta \approx 26.6^\circ$ (u), $\eta \approx 63.4^\circ$ (d).

Non-standard interactions and 3ν oscillations

- Equation of motion: **6** (vac) + **8** (NSI-ν) + **1** (NSI-q) = **15** parameters [22]:

$$i\frac{d\vec{\nu}}{dt} = \mathbf{H}\,\vec{\nu}; \qquad \mathbf{H} = \mathbf{U}_\text{vac}\cdot\mathbf{D}_\text{vac}\cdot\mathbf{U}_\text{vac}^\dagger \pm \mathbf{V}_\text{mat}; \qquad \mathbf{D}_\text{vac} = \frac{1}{2E_\nu}\,\text{diag}\left(0,\ \Delta m^2_{21},\ \Delta m^2_{31}\right);$$

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

$$\mathcal{E}_{\alpha\beta}(x) \equiv \sum_f \frac{N_f(x)}{N_e(x)}\,\varepsilon^f_{\alpha\beta} = \sqrt{5}\,\varepsilon^\eta_{\alpha\beta}\,[\cos\eta + Y_n(x)\sin\eta]\,, \qquad Y_n(x) \equiv \frac{N_n(x)}{N_e(x)}\,,$$

$$\mathbf{V}_\text{mat} \equiv \mathbf{V}_\text{SM} + \mathbf{V}_\text{NSI} = \sqrt{2}G_F N_e(x) \begin{pmatrix} 1+\mathcal{E}_{ee}(x) & \mathcal{E}_{e\mu}(x) & \mathcal{E}_{e\tau}(x) \\ \mathcal{E}^\star_{e\mu}(x) & \mathcal{E}_{\mu\mu}(x) & \mathcal{E}_{\mu\tau}(x) \\ \mathcal{E}^\star_{e\tau}(x) & \mathcal{E}^\star_{\mu\tau}(x) & \mathcal{E}_{\tau\tau}(x) \end{pmatrix};$$

- notice that our definition of $\mathbf{U}_\text{vac}$ differ by the “usual” one by an overall rephasing, $\mathbf{U}_\text{vac} = \mathbf{\Phi}\cdot\mathbf{U}\cdot\mathbf{\Phi}^*$ with $\mathbf{\Phi} \equiv \text{diag}(e^{i\delta_\text{CP}}, 1, 1)$, which is irrelevant in the standard case of no-NSI.

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[22] I. Esteban *et al.*, JHEP **08** (2018) 180 [`arXiv:1805.04530`].

The generalized mass ordering degeneracy

- General symmetry: $\mathbf{H} \to -\mathbf{H}^*$ does not affect the neutrino probabilities;
- we have $\mathbf{H} = \mathbf{H}_\text{vac} \pm \mathbf{V}_\text{mat}$. For vacuum, $\mathbf{H}_\text{vac} \to -\mathbf{H}_\text{vac}^*$ occurs if: $\begin{cases} \Delta m^2_{31} \to -\Delta m^2_{32}\,, \\ \theta_{12} \to \pi/2 - \theta_{12}\,, \\ \delta_\text{CP} \to \pi - \delta_\text{CP}\,, \end{cases}$
- notice how this transformation links together mass ordering and solar octant [23, 24, 25];
- for matter, $\mathbf{V}_\text{mat} \to -\mathbf{V}_\text{mat}^*$ requires: $\begin{cases} [\mathcal{E}_{ee}(x) - \mathcal{E}_{\mu\mu}(x)] \to -[\mathcal{E}_{ee}(x) - \mathcal{E}_{\mu\mu}(x)] - 2\,, \\ [\mathcal{E}_{\tau\tau}(x) - \mathcal{E}_{\mu\mu}(x)] \to -[\mathcal{E}_{\tau\tau}(x) - \mathcal{E}_{\mu\mu}(x)]\,, \\ \mathcal{E}_{\alpha\beta}(x) \to -\mathcal{E}_{\alpha\beta}^*(x) \qquad (\alpha \neq \beta)\,, \end{cases}$
- since $\mathbf{V}_\text{mat} = \mathbf{V}_\text{SM} + \mathbf{V}_\text{NSI}$ and $\mathbf{V}_\text{SM}$ is fixed, this symmetry requires NSI;
- in general, $\mathcal{E}_{\alpha\beta}(x)$ varies along trajectory ⇒ symmetry only approximate, **unless**:
  - NSI proportional to electric charge ($\eta = 0$), so same matter profile for SM and NSI;
  - neutron/proton ratio $Y_n(x)$ is constant, and same for all the neutrino trajectories.

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[23] M.C. Gonzalez-Garcia, M. Maltoni, JHEP **09** (2013) 152 [`arXiv:1307.3092`]

[24] P. Bakhti, Y. Farzan, JHEP **07** (2014) 064 [`arXiv:1403.0744`].

[25] P. Coloma, T. Schwetz, Phys. Rev. D **94** (2016) 055005 [`arXiv:1604.05772`].

Matter potential for solar and KamLAND neutrinos

- One mass dominance ($\Delta m^2_{31} \to \infty$) $\Rightarrow$ $P_{ee} = c^4_{13} P_{\text{eff}} + s^4_{13}$ with the probability P_{eff} determined by an effective 2ν model (as in the SM):

$$i\frac{d\vec{\nu}}{dt} = \left[\mathbf{H}^{\text{eff}}_{\text{vac}} + \mathbf{H}^{\text{eff}}_{\text{mat}}\right]\vec{\nu}, \qquad \vec{\nu} = \begin{pmatrix}\nu_e \\ \nu_a\end{pmatrix}, \qquad \mathbf{H}^{\text{eff}}_{\text{vac}} \equiv \frac{\Delta m^2_{21}}{4E_\nu}\begin{pmatrix}-\cos 2\theta_{12} & \sin 2\theta_{12}\, e^{i\delta_{\text{CP}}} \\ \sin 2\theta_{12}\, e^{-i\delta_{\text{CP}}} & \cos 2\theta_{12}\end{pmatrix},$$

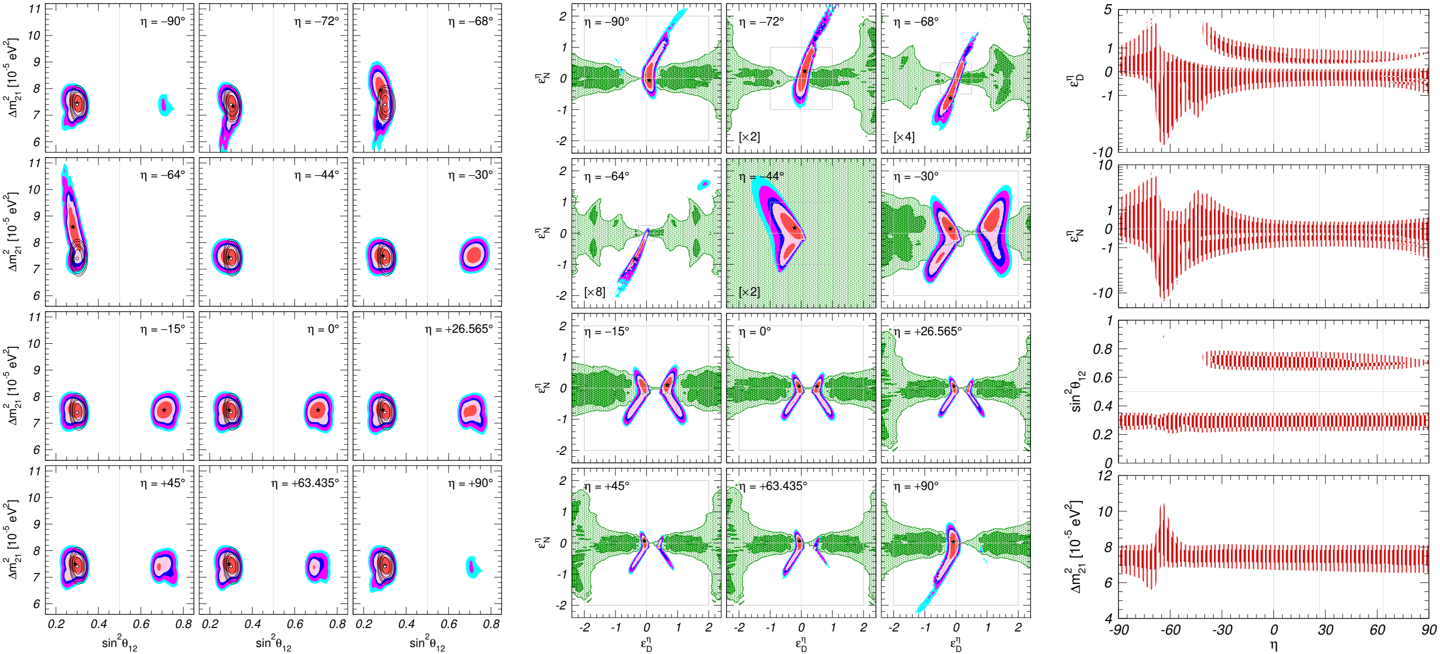
$$\mathbf{H}^{\text{eff}}_{\text{mat}} \equiv \sqrt{2}\, G_F N_e(r) \left[\begin{pmatrix}c^2_{13} & 0 \\ 0 & 0\end{pmatrix} + \sqrt{5}\left[\cos\eta + Y_n(x)\sin\eta\right]\begin{pmatrix}-\varepsilon^\eta_D & \varepsilon^\eta_N \\ \varepsilon^{\eta\star}_N & \varepsilon^\eta_D\end{pmatrix}\right],$$

$$\begin{cases} \varepsilon^\eta_D = c_{13}s_{13}\,\text{Re}\left(s_{23}\,\varepsilon^\eta_{e\mu} + c_{23}\,\varepsilon^\eta_{e\tau}\right) - (1 + s^2_{13})c_{23}s_{23}\,\text{Re}(\varepsilon^\eta_{\mu\tau}) \\ \qquad\quad - c^2_{13}(\varepsilon^\eta_{ee} - \varepsilon^\eta_{\mu\mu})/2 + (s^2_{23} - s^2_{13}c^2_{23})\,(\varepsilon^\eta_{\tau\tau} - \varepsilon^\eta_{\mu\mu})/2\,, \\ \varepsilon^\eta_N = c_{13}(c_{23}\,\varepsilon^\eta_{e\mu} - s_{23}\,\varepsilon^\eta_{e\tau}) + s_{13}\left[s^2_{23}\,\varepsilon^\eta_{\mu\tau} - c^2_{23}\,\varepsilon^{\eta\star}_{\mu\tau} + c_{23}s_{23}(\varepsilon^\eta_{\tau\tau} - \varepsilon^\eta_{\mu\mu})\right]; \end{cases}$$

- solar data can be perfectly fitted by NSI only $\Rightarrow$ solar LMA solution **is unstable** with respect to the introduction of NSI;
- KamLAND **requires** Δm^2_{21} but only weakly sensitive to NSI $\Rightarrow$ it **determines** Δm^2_{21};
- in the solar core $Y_n(x) \in [1/6, 1/2]$ $\Rightarrow$ approximate cancellation of NSI for $\eta \in [-80^\circ, -63^\circ]$.

Oscillation results for solar and KamLAND neutrinos

- Generalized mass-ordering degeneracy ⇒ new LMA-D solution with $\theta_{12} > 45°$ [26];
- $\eta = 0$ ⇒ NSI terms proportional to $N_p(x) \equiv N_e(x)$ ⇒ the degeneracy becomes exact.



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[26] O.G. Miranda, M.A. Tortola, J.W.F. Valle, JHEP **10** (2006) 008 [`hep-ph/0406280`].

Matter potential for atmospheric and long-baseline neutrinos

- In Earth matter: $Y_n(x) \to Y_n^\oplus \approx 1.051 \Rightarrow \mathcal{E}_{\alpha\beta}(x) \to \varepsilon_{\alpha\beta}^\oplus$ becomes an effective parameter:

$$\varepsilon_{\alpha\beta}^\oplus \equiv \sqrt{5}\,[\cos\eta + Y_n^\oplus \sin\eta]\,\varepsilon_{\alpha\beta}^\eta\,,$$

- the bounds on $\varepsilon_{\alpha\beta}^\oplus$ are independent of the quark couplings (*i.e.*, of η);
- for $\eta = \arctan(-1/Y_n^\oplus) \approx -43.6^\circ$ ATM+LBL data imply **no** bound on $\varepsilon_{\alpha\beta}^\eta$;
- the NSI parameter space is too big to be properly studied ⇒ simplification needed;
- bounds on $\varepsilon_{\alpha\beta}^\oplus$ are weakest when $\mathbf{V}_\text{mat} \propto \delta_{e\alpha}\delta_{e\beta} + \varepsilon_{\alpha\beta}^\oplus$ has two degenerate eigenvalues [27] ⇒ focus on such case ⇒ introduce parameters ($\varepsilon_\oplus$, φ_{12}, φ_{13}, α_1, α_2) and define:

$$\begin{aligned}
\varepsilon_{ee}^\oplus - \varepsilon_{\mu\mu}^\oplus &= \varepsilon_\oplus\,(\cos^2\varphi_{12} - \sin^2\varphi_{12})\cos^2\varphi_{13} - 1\,,\\
\varepsilon_{\tau\tau}^\oplus - \varepsilon_{\mu\mu}^\oplus &= \varepsilon_\oplus\,(\sin^2\varphi_{13} - \sin^2\varphi_{12}\cos^2\varphi_{13})\,,\\
\varepsilon_{e\mu}^\oplus &= -\varepsilon_\oplus \cos\varphi_{12}\sin\varphi_{12}\cos^2\varphi_{13}\, e^{i(\alpha_1-\alpha_2)}\,,\\
\varepsilon_{e\tau}^\oplus &= -\varepsilon_\oplus \cos\varphi_{12}\cos\varphi_{13}\sin\varphi_{13}\, e^{i(2\alpha_1+\alpha_2)}\,,\\
\varepsilon_{\mu\tau}^\oplus &= \varepsilon_\oplus \sin\varphi_{12}\cos\varphi_{13}\sin\varphi_{13}\, e^{i(\alpha_1+2\alpha_2)}\,.
\end{aligned}$$

- for definiteness we also assume on CP conservation and set $\delta_\text{CP} = \alpha_1 = \alpha_2 = 0$.

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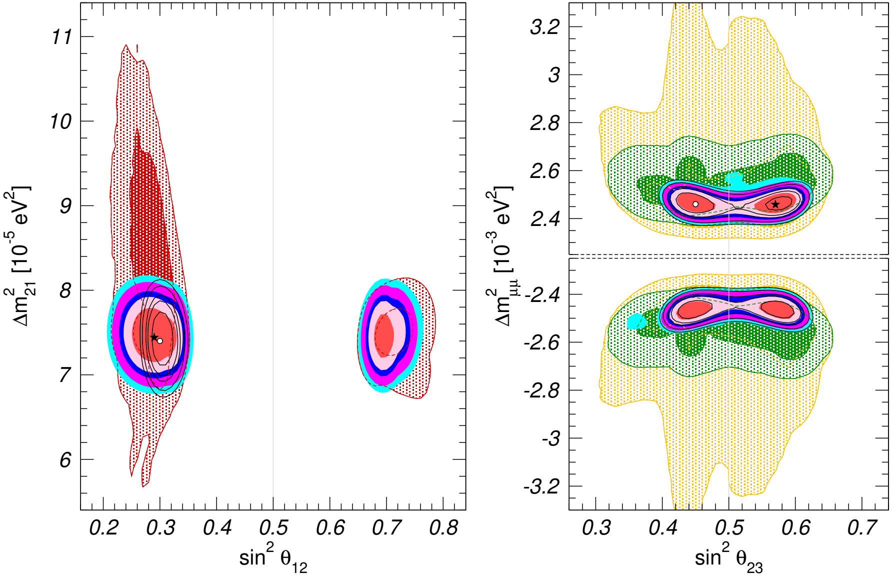
[27] A. Friedland, C. Lunardini, M. Maltoni, Phys. Rev. D **70** (2004) 111301 [`hep-ph/0408264`].

Impact of NSI on the oscillation parameters

- Once marginalized over η, analysis of solar + KamLAND data shows strong deterioration of the precision on Δm^2_{21} and θ_{12}, as well as the appearance of the LMA-D solution [26];
- a similar worsening appears in ATM + LBL-dis + LBL-app + IceCUBE + MBL-rea analysis;
- synergies between solar and atmospheric sectors allow to recover the SM accuracy on most parameters (except θ_{12});
- notice that the LMA-D solution persists also in the global fit;
- high-energy atmos. IceCUBE data have no sensitivity to oscillations ($P_{\mu\mu} \propto 1/E^2$), hence they contribute little.



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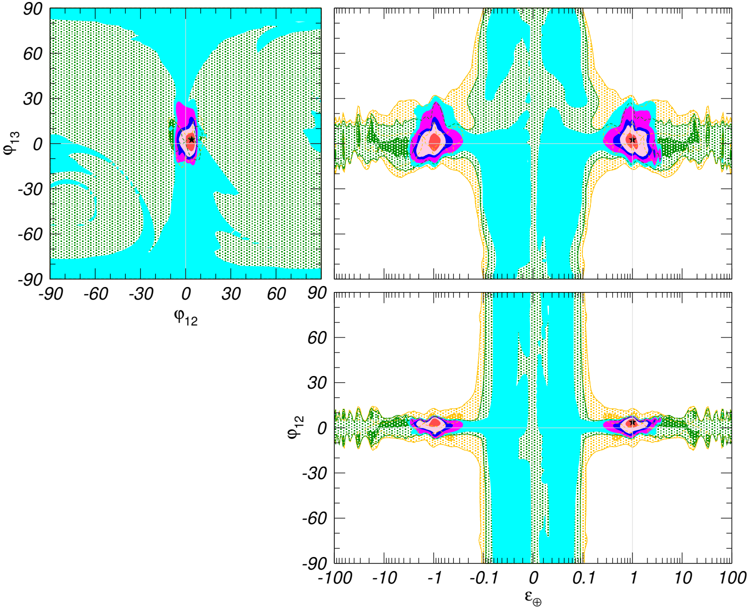
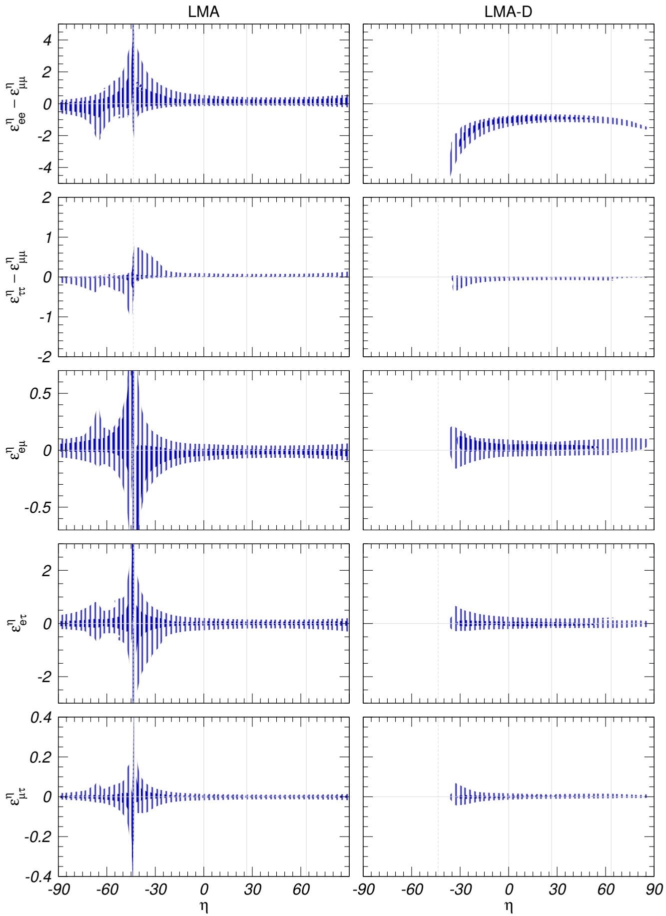
[26] O.G. Miranda, M.A. Tortola, J.W.F. Valle, JHEP **10** (2006) 008 [`hep-ph/0406280`].

Determination of NSI parameters

- Reduced ($\varepsilon_\oplus$, φ_{12}, φ_{13}) parameter space can be constrained by joint solar+KamLAND and ATM+LBL analysis;
- bounds can then be recast in term of $\varepsilon^\eta_{\alpha\beta}$.





The COHERENT experiment

- Observation of coherent neutrino-nucleus scattering [28] allows to put bounds on NSI through the effective charges ($Y_n^{\text{coh}} \approx 1.407$):

$$Q_\alpha^2 \propto \left[(g_p^V + Y_n^{\text{coh}} g_n^V) + \varepsilon_{\alpha\alpha}^{\text{coh}}\right]^2 + \sum_{\beta\neq\alpha} (\varepsilon_{\alpha\beta}^{\text{coh}})^2$$

$$\text{with} \quad \varepsilon_{\alpha\beta}^{\text{coh}} = \sqrt{5}\,[\cos\eta + Y_n^{\text{coh}} \sin\eta]\,\varepsilon_{\alpha\beta}^\eta\,;$$

- for $\eta = \arctan(-1/Y_n^{\text{coh}}) \approx -35.4^\circ$ no bound on $\varepsilon_{\alpha\beta}^\eta$ is implied;
- separate bounds on diagonal $\varepsilon_{\alpha\alpha}^\eta$ couplings can be placed.

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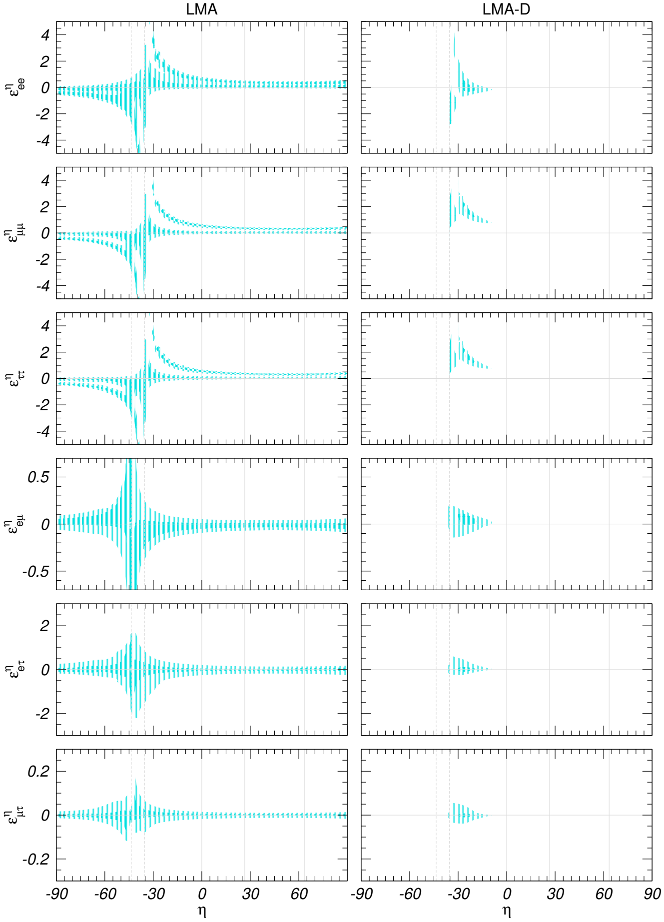
[28] D. Akimov *et al.* [COHERENT], Science **357** (2017) 1123 [`arXiv:1708.01294`].

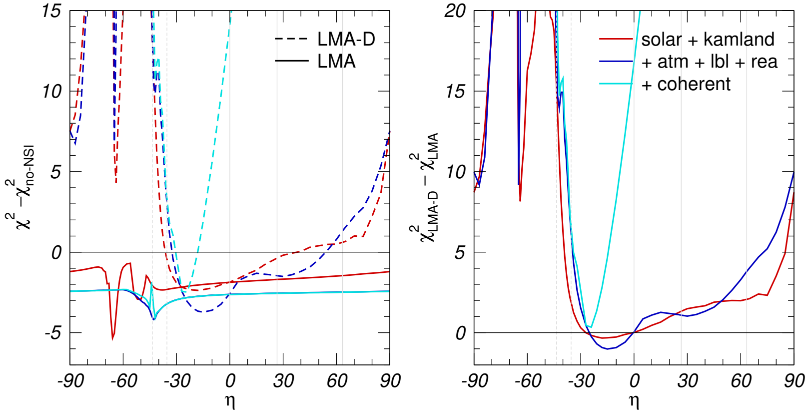
[29] P. Coloma, I. Esteban *et al.*, JHEP **02** (2020) 023 [`arXiv:1911.09109`].

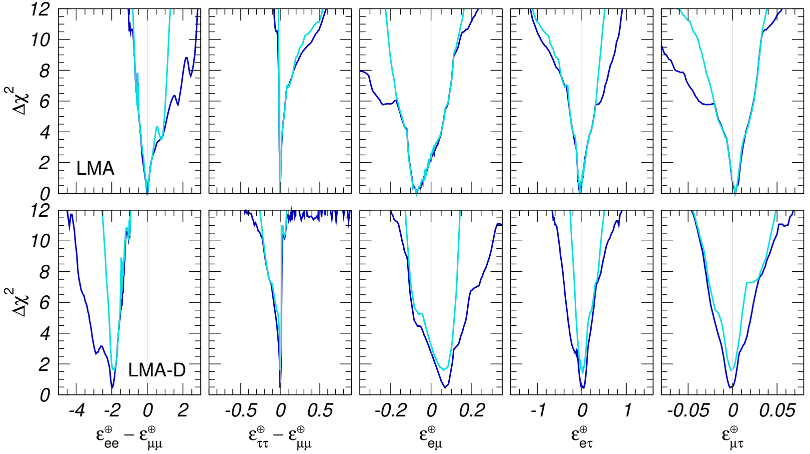


General NSI bounds

- Inclusion of COHERENT data rules out LMA-D for NSI with u, d, or p, but **not** in the general case;
- unlike oscillation data, COHERENT is sensitive to $\varepsilon^\eta_{ee} + \varepsilon^\eta_{\mu\mu} + \varepsilon^\eta_{\tau\tau}$;
- general 2σ bounds [29]:

OSCILLATIONS			+ COHERENT (t+E Duke)	
	LMA	LMA $\oplus$ LMA-D		LMA = LMA $\oplus$ LMA-D
$\varepsilon^u_{ee} - \varepsilon^u_{\mu\mu}$	$[-0.072, +0.321]$	$\oplus[-1.042, -0.743]$	ε^u_{ee}	$[-0.031, +0.476]$
$\varepsilon^u_{\tau\tau} - \varepsilon^u_{\mu\mu}$	$[-0.001, +0.018]$	$[-0.016, +0.018]$	$\varepsilon^u_{\mu\mu}$	$[-0.029, +0.068] \oplus [+0.309, +0.415]$
			$\varepsilon^u_{\tau\tau}$	$[-0.029, +0.068] \oplus [+0.309, +0.414]$
$\varepsilon^u_{e\mu}$	$[-0.050, +0.020]$	$[-0.050, +0.059]$	$\varepsilon^u_{e\mu}$	$[-0.048, +0.020]$
$\varepsilon^u_{e\tau}$	$[-0.077, +0.098]$	$[-0.111, +0.098]$	$\varepsilon^u_{e\tau}$	$[-0.077, +0.095]$
$\varepsilon^u_{\mu\tau}$	$[-0.006, +0.007]$	$[-0.006, +0.007]$	$\varepsilon^u_{\mu\tau}$	$[-0.006, +0.007]$
$\varepsilon^d_{ee} - \varepsilon^d_{\mu\mu}$	$[-0.084, +0.326]$	$\oplus[-1.081, -1.026]$	ε^d_{ee}	$[-0.034, +0.426]$
$\varepsilon^d_{\tau\tau} - \varepsilon^d_{\mu\mu}$	$[-0.001, +0.018]$	$[-0.001, +0.018]$	$\varepsilon^d_{\mu\mu}$	$[-0.027, +0.063] \oplus [+0.275, +0.371]$
			$\varepsilon^d_{\tau\tau}$	$[-0.027, +0.067] \oplus [+0.274, +0.372]$
$\varepsilon^d_{e\mu}$	$[-0.051, +0.020]$	$[-0.051, +0.038]$	$\varepsilon^d_{e\mu}$	$[-0.050, +0.020]$
$\varepsilon^d_{e\tau}$	$[-0.077, +0.098]$	$[-0.077, -0.098]$	$\varepsilon^d_{e\tau}$	$[-0.076, +0.097]$
$\varepsilon^d_{\mu\tau}$	$[-0.006, +0.007]$	$[-0.006, +0.007]$	$\varepsilon^d_{\mu\tau}$	$[-0.006, +0.007]$
$\varepsilon^p_{ee} - \varepsilon^p_{\mu\mu}$	$[-0.190, +0.927]$	$\oplus[-2.927, -1.814]$	ε^p_{ee}	$[-0.086, +0.884] \oplus [+1.083, +1.605]$
$\varepsilon^p_{\tau\tau} - \varepsilon^p_{\mu\mu}$	$[-0.001, +0.053]$	$[-0.052, +0.053]$	$\varepsilon^p_{\mu\mu}$	$[-0.097, +0.220] \oplus [+1.063, +1.410]$
			$\varepsilon^p_{\tau\tau}$	$[-0.098, +0.221] \oplus [+1.063, +1.408]$
$\varepsilon^p_{e\mu}$	$[-0.145, +0.058]$	$[-0.145, +0.145]$	$\varepsilon^p_{e\mu}$	$[-0.124, +0.058]$
$\varepsilon^p_{e\tau}$	$[-0.238, +0.292]$	$[-0.292, +0.292]$	$\varepsilon^p_{e\tau}$	$[-0.239, +0.244]$
$\varepsilon^p_{\mu\tau}$	$[-0.019, +0.021]$	$[-0.021, +0.021]$	$\varepsilon^p_{\mu\tau}$	$[-0.013, +0.021]$





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[29] P. Coloma, I. Esteban, M.C. Gonzalez-Garcia, M. Maltoni, JHEP **02** (2020) 023 [`arXiv:1911.09109`].

Summary

- 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, seem to be fading away;
- 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 still an open issue. $\theta_{23} > 45^\circ$ slightly preferred;
- sinergies between different experiments will be crucial to increase the sensitivity;
- the possibility of physics beyond the 3ν paradigm remains open.