Tensions in the current neutrino data and non-standard interactions

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Based on: Fukasawa, Ghosh, Yasuda, 1609.04204

Neutrino Oscillation

- Neutrino oscillation: transition from one flavor to another

  time=0; time=t;

  ν_e; $\longrightarrow$ distance=L; $\longrightarrow$ ν_e, ν_μ, ν_τ;

- Reason: the flavor eigenstates (ν_α) and mass eigenstates (ν_i having mass m_i) are not same and related by

$$|\nu_\alpha\rangle = \sum_{i=1}^{N} U_{\alpha i}^{\mathrm{PMNS}} |\nu_i\rangle$$

- The transition probability $\nu_\alpha \to \nu_\beta$:

$$P_{\alpha\beta} = |\langle \nu_\beta | \nu_\alpha(t) \rangle|^2$$

  where α, β are e, μ or τ

Neutrino oscillation in 3 generation

Full three flavour vacuum probability formula:

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{i<j} Re[U^*_{\alpha i} U^*_{\beta j} U_{\beta i} U_{\alpha j}] sin^2\frac{\Delta_{ij} L}{4E} + 2\sum_{i<j} Im[U^*_{\alpha i} U^*_{\beta j} U_{\beta i} U_{\alpha j}] sin2\frac{\Delta_{ij} L}{4E}$$

$$\Delta_{ij} = m_i^2 - m_j^2$$

Parameters of neutrino oscillation:

- Elements of U: Three mixing angles and one Dirac phase θ_{12}, θ_{23}, θ_{13}, δ_{CP}
- Two mass squared differences: Appears in $P_{\alpha\beta}$ $\Delta_{21} = m_2^2 - m_1^2$, $\Delta_{31} = m_3^2 - m_1^2$
- L and E

Comment

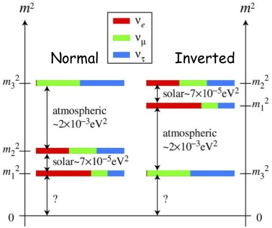
Neutrino oscillation can't probe absolute neutrino mass

Current status of oscillation parameters

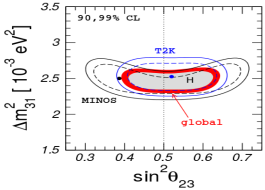
Table: νfit, November 2016, www.nu-fit.org

Parameter	Best fit	3σ
$\Delta_{21}(\times 10^{-5} eV^2)$	7.49	$7.02 - 8.08$
$\|\Delta_{31}\|(\times 10^{-3} eV^2)$	2.5	$2.4 - 2.6$
θ^o_{12}	33.72	31.52-36.18
θ^o_{23}	$50.0 \oplus 41.6$	38.8-53.3
θ^o_{13}	8.46	8.0-8.90
δ^o_{CP}	-90	-180 - +180

Unknowns



- The sign of Δm^2_{31} i.e.,
  $\Delta m^2_{31} > 0 \Rightarrow$ Normal Hierarchy (NH)
  or
  $\Delta m^2_{31} < 0 \Rightarrow$ Inverted Hierarchy (IH).



- The octant of θ_{23} i.e.,
  $\theta_{23} > 45^\circ \Rightarrow$ Higher Octant (HO) or
  $\theta_{23} < 45^\circ \Rightarrow$ Lower Octant (LO).

- δ_{CP} (violation and precision)

Experiments

Ongoing experiments to discover the unknowns

T2K in Japan

NOνA in Fermilab

What is non-standard interaction ?

Neutrino propagating in matter

- Standard NC interaction:

$$\nu_\alpha + f \to \nu_\alpha + f$$

- Non-standard NC interaction

$$\nu_\alpha + f \to \nu_\beta + f$$

can arise from the following four-fermion interaction

$$\mathcal{L} = -G_F \epsilon^f_{\alpha\beta} \bar{\nu}_\alpha \gamma^\mu \nu_\beta \bar{f} \gamma_\mu f$$

with $\epsilon_{\alpha\beta} = \sum_{f=e,u,d} \frac{N_f}{N_e} \epsilon^f_{\alpha\beta}$

NSI in neutrino oscillation

- Evolution equation with standard oscillation

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \mu_\mu\\ \nu_\tau\end{pmatrix} = \left[Udiag(E_1,E_2,E_3)U^{-1} + \begin{pmatrix}A & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \mu_\mu\\ \nu_\tau\end{pmatrix}$$

- Evolution equation with non-standard oscillation

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \mu_\mu\\ \nu_\tau\end{pmatrix} = \left[Udiag(E_1,E_2,E_3)U^{-1} + A\begin{pmatrix}1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau}\\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau}\\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau}\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \mu_\mu\\ \nu_\tau\end{pmatrix}$$

with $A = \sqrt{2}G_F N_e$

Bounds on NSI parameters

C. Biggio, M. Blennow and E. Fernandez-Martinez, JHEP **0908**, 090 (2009)

$$\begin{aligned} |\epsilon_{ee}| &< 4 \times 10^{0} \\ |\epsilon_{e\mu}| &< 3 \times 10^{-1} \\ |\epsilon_{e\tau}| &< 3 \times 10^{0} \\ |\epsilon_{\mu\mu}| &< 7 \times 10^{-2} \\ |\epsilon_{\mu\tau}| &< 3 \times 10^{-1} \\ |\epsilon_{\tau\tau}| &< 2 \times 10^{1} \end{aligned}$$

A. Friedland and C. Lunardini, Phys. Rev. D **72**, 053009 (2005)

$$\epsilon_{\tau\tau} = \frac{|\epsilon_{e\tau}|^2}{1 + \epsilon_{ee}}$$

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- Mismatch in Δm^2_{21} measurement (PRD, 88 033001)
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Objective

To explain all these 3 tensions by a single theory

Aim

Tension in Δm^2_{21} is solved in M. C. Gonzalez-Garcia and M. Maltoni, JHEP **1309**, 152 (2013)

$$H^{matt}_{eff} = A \sum_{f=e,u,d} \frac{N_f}{N_e} \begin{pmatrix} -\epsilon^f_D & \epsilon^f_N \\ \epsilon^{f*}_N & \epsilon^f_D \end{pmatrix}$$

where

$$\begin{aligned} \epsilon^f_D &= -\frac{c^2_{13}}{2}\left(\epsilon^f_{ee} - \epsilon^f_{\mu\mu}\right) + \frac{s^2_{23} - s^2_{13}c^2_{23}}{2}\left(\epsilon^f_{\tau\tau} - \epsilon^f_{\mu\mu}\right) + c_{13}s_{13}\mathrm{Re}\left[e^{i\delta_{\rm CP}}\left(s_{23}\epsilon^f_{e\mu} + c_{23}\epsilon^f_{e\tau}\right)\right] \\ &- \left(1 + s^2_{13}\right) c_{23}s_{23}\mathrm{Re}\left[\epsilon^f_{\mu\tau}\right] \\ \epsilon^f_N &= -c_{13}s_{23}\epsilon^f_{e\tau} + c_{13}c_{23}\epsilon^f_{e\mu} + s_{13}c_{23}s_{23}e^{-i\delta_{\rm CP}}\left(\epsilon^f_{\tau\tau} - \epsilon^f_{\mu\mu}\right) + s_{13}e^{-i\delta_{\rm CP}}\left(s^2_{23}\epsilon^f_{\mu\tau} - c^2_{23}\epsilon^{f*}_{\mu\tau}\right) \end{aligned}$$

with best fit points

$(\epsilon^u_D, \epsilon^u_N) = (-0.22, -0.30)$, $(\epsilon^d_D, \epsilon^d_N) = (-0.12, -0.16)$ for the solar/KamLAND data and

$(\epsilon^u_D, \epsilon^u_N) = (-0.140, -0.030)$, $(\epsilon^d_D, \epsilon^d_N) = (-0.145, -0.036)$ for global data

Aim

Our aim is to check if these 4 best-fit points also provide a solution to the other tensions

Assumption

For our analysis we assume $\theta_{23}^{fit} = 45^\circ$ and $\sin^2\theta_{13}^{fit} = 0.021$ with

$$
\begin{aligned}
\epsilon_D^f &= -\frac{c_{13}^2}{2}\left(\epsilon_{ee}^f - \epsilon_{\mu\mu}^f\right) + \frac{s_{23}^2 - s_{13}^2 c_{23}^2}{2}\left(\epsilon_{\tau\tau}^f - \epsilon_{\mu\mu}^f\right) \\
0 &= c_{13}s_{13}\mathrm{Re}\left[e^{i\delta_{\rm CP}}\left(s_{23}\epsilon_{e\mu}^f + c_{23}\epsilon_{e\tau}^f\right)\right] - \left(1+s_{13}^2\right)c_{23}s_{23}\mathrm{Re}\left[\epsilon_{\mu\tau}^f\right] \\
\epsilon_N^f &= -c_{13}s_{23}\epsilon_{e\tau}^f \\
0 &= c_{13}c_{23}\epsilon_{e\mu}^f + s_{13}c_{23}s_{23}e^{-i\delta_{\rm CP}}\left(\epsilon_{\tau\tau}^f - \epsilon_{\mu\mu}^f\right) + s_{13}e^{-i\delta_{\rm CP}}\left(s_{23}^2\epsilon_{\mu\tau}^f - c_{23}^2\epsilon_{\mu\tau}^{f*}\right) ,
\end{aligned}
$$

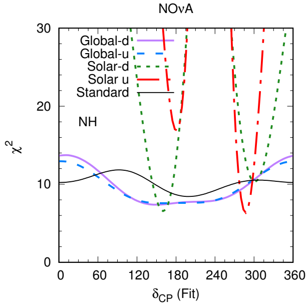
considering $\epsilon_{\mu\mu} = 0$, $\epsilon_{\mu\tau}$ real, $\epsilon_{\tau\tau} = \frac{|\epsilon_{e\tau}|^2}{1+\epsilon_{ee}}$ and calculate

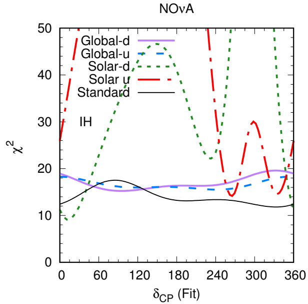
$$
\chi^2(\delta_{CP}) \equiv \sum_j \frac{1}{N_j^{\rm data}}\left[N_j^{\rm th}(\epsilon^{\rm sol}, \theta_{23}^{\rm fit}, \theta_{13}^{\rm fit}) - N_j^{\rm data}\right]^2 ,
$$

where $\epsilon^{\rm sol}$ best fit points as obtained in the solar analysis

and compared our results with the standard case i.e., solution at $(\theta_{23}^{fit}, \sin^2\theta_{13}^{fit})$ without NSI

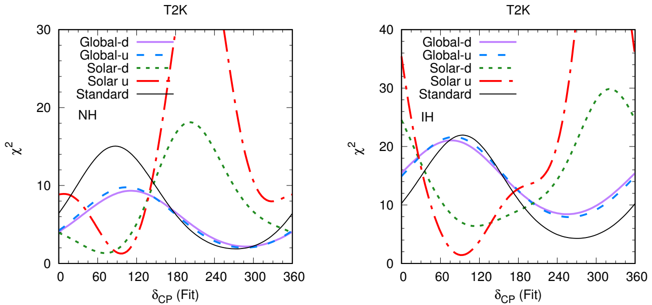
Results: NOνA





- Improvement of the NSI solution as compared to the standard solution is negligible
- Expected: since tension arise form $P_{\mu\mu}$ where NSI does not play much role

Results: T2K



- Improvement in IH is slightly better than NH

Summary

- There are three tensions in the current oscillation data
- We tried to check if all the tensions can be lifted with NSI
- At this moment NSI does not improve the tensions to great extent
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Thank you