Hints for leptonic CP violation or New Physics?

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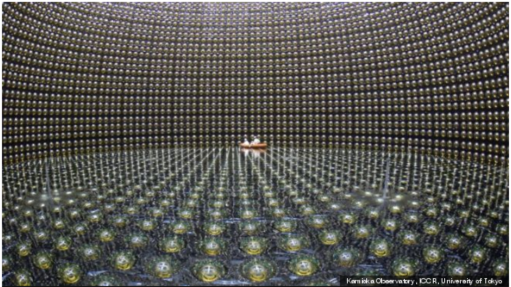
PHENO 2016
University of Pittsburgh
May 9th

In coll. with P. Huber

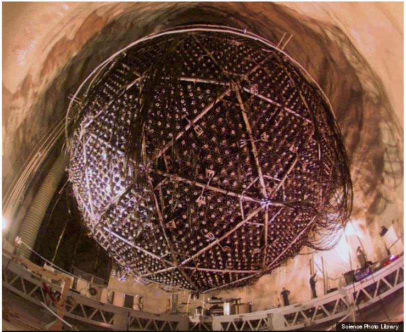
Neutrino 'flip' wins physics Nobel Prize

By Jonathan Webb
Science reporter, BBC News

6 October 2015 | Science & Environment


Kamioka Observatory, ICRR, University of Tokyo

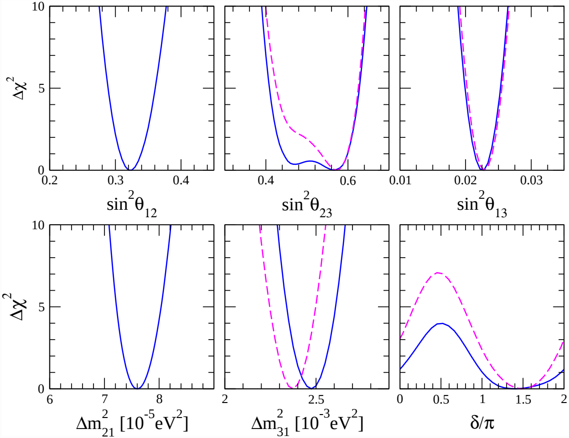
Crucial measurements were made at the Super-Kamiokande neutrino detector in Japan


Science Photo Library

The Sudbury Neutrino Observatory, like Super-K, is housed in a cavern inside a mine

Neutrino Oscillation Global Fit Results

D.V.Forero, Tórtola & Valle `(PRD` **90** `(2014))` arxiv:1405.7540



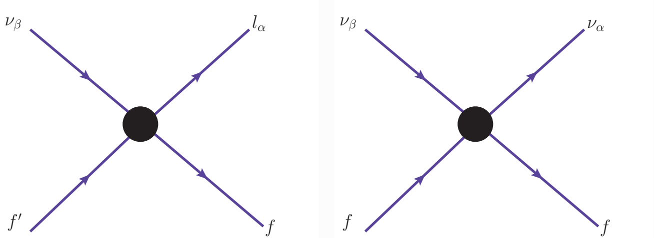
parameter	bf$\pm$ 1σ	
Δm^2_{21} [10^{-5}eV^2]	$7.60^{+0.19}_{-0.18}$	2.4%
$\lvert\Delta m^2_{31}\rvert$[$10^{-3}$eV^2]	$2.48^{+0.05}_{-0.07}$	2.4%
IH	$2.38^{+0.05}_{-0.06}$	
$\sin^2\theta_{12}/10^{-1}$	3.23 ± 0.16	5.0%
$\sin^2\theta_{13}/10^{-2}$	2.26 ± 0.12	5.3%
IH	2.29 ± 0.12	5.2%
$\sin^2\theta_{23}/10^{-1}$	$5.67^{+0.32}_{-1.24}$	7.4%
IH	$5.73^{+0.25}_{-0.39}$	6.9%
δ/π	$1.41^{+0.55}_{-0.40}$	
IH	1.48 ± 0.31	

Are the NSI interesting?

- Neutrino masses imply physics BSM.
- New neutrino interactions are expected in SM extensions accommodating $m_\nu \neq 0$.
- The exchange of new heavy particles could leave a low energy 'fingerprint' in the form of NSI.
- Neutrino oscillations at Long Baseline Neutrino (LBL) exps. are sensitive to NC-like NSI.
- Interesting SO and NSI parameter degeneracies in LBL ν-exps. could challenge the determination of the unknown ν-parameters. This talk!

The standard NSI (pheno) framework

L. Wolfenstein (PRD **17**(1978)), J.W.F Valle (PLB **199**(1987))
M.M Guzzo *et al.* (PLB **260**(1991)), E. Roulet (PRD **44**(1991))



$$\mathcal{L}_{V\pm A} = \frac{G_F}{\sqrt{2}} \sum_{f,f'} \tilde{\varepsilon}_{\alpha\beta}^{S(D),f,f',V\pm A} \left[\bar{\nu}_\beta \gamma^\rho (1-\gamma^5)\ell_\alpha\right]\left[\bar{f}'\gamma_\rho(1\pm\gamma^5)f\right]$$

$$+ \frac{G_F}{\sqrt{2}} \sum_{f} \tilde{\varepsilon}_{\alpha\beta}^{m,f,V\pm A} \left[\bar{\nu}_\alpha \gamma^\rho (1-\gamma^5)\nu_\beta\right]\left[\bar{f}\gamma_\rho(1\pm\gamma^5)f\right] + \text{h.c.}$$

From now on $\tilde{\varepsilon}_{\alpha\beta}^{S(D),f,f',V\pm A} \to 0$

NSI effects at LBL ν-experiments

Generalizing the effective matter potential

The Standard vacuum neutrino oscillation Hamiltonian is given by:

$$H_0 = \frac{1}{2E}\left[U\,\mathrm{diag}\left(0, \Delta m^2_{21}, \Delta m^2_{31}\right)\ U^\dagger\right],$$

while the general matter interaction Hamiltonian can be written as

$$H_{\mathrm{int}} = V \begin{pmatrix} 1+\varepsilon^m_{ee} & \varepsilon^m_{e\mu} & \varepsilon^m_{e\tau} \\ (\varepsilon^m_{e\mu})^* & \varepsilon^m_{\mu\mu} & \varepsilon^m_{\mu\tau} \\ (\varepsilon^m_{e\tau})^* & (\varepsilon^m_{\mu\tau})^* & \varepsilon^m_{\tau\tau} \end{pmatrix}$$

with $V = \sqrt{2}\,G_F\,N_e$ or $a_{\mathrm{CC}} \equiv 2V\,E = 7.63\times 10^{-5}\left[\frac{\rho}{\mathrm{gr/cm^3}}\right]\left[\frac{E}{\mathrm{GeV}}\right]$.

The oscillation probability is obtained as:

$$P_{\nu_\alpha\to\nu_\beta} = \left|\langle\nu_\beta|\exp\left[-i\left(H_0 + H_{\mathrm{int}}\right)\right]|\nu_\alpha\rangle\right|^2$$

Current bounds

NC-like NSI

M.C. Gonzalez-Garcia *et al.* (JHEP **152**(2013))

From a global fit of oscillation neutrino data, the 90% of C.L bounds for the LMA solution are:

$$\varepsilon_{\alpha\beta} - \varepsilon_{\mu\mu}\Big|^{f=d(u)} \in \begin{bmatrix} [0.02(0.00), 0.51] & [-0.09, 0.04] & [-0.14, 0.14] \\ \times & 0 & [-0.01, 0.01] \\ \times & \times & [-0.01, 0.03] \end{bmatrix}$$

where

$$\varepsilon^{m}_{\alpha\beta} = \sum_{f=e,u,d} \left\langle \frac{Y_f}{Y_e} \right\rangle \varepsilon^{f}_{\alpha\beta} = \varepsilon^{e}_{\alpha\beta} + Y_u \varepsilon^{u}_{\alpha\beta} + Y_d \varepsilon^{d}_{\alpha\beta}$$

In the case of ν's interacting with the Earth matter:

$$\varepsilon^{m}_{\alpha\beta} \approx \varepsilon^{e}_{\alpha\beta} + 3.051\varepsilon^{u}_{\alpha\beta} + 3.102\varepsilon^{d}_{\alpha\beta}$$

Thus, the less constrained and non-diagonal NSI coupling is $\varepsilon^{m}_{e\tau} \sim \mathcal{O}(1)$.

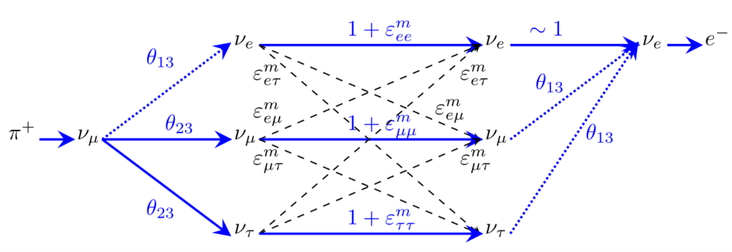
For a complete set of constrains on $\varepsilon^{f=e}_{\alpha\beta}$ see table III in Ref:

O.G Miranda *et al.* (NJP **17**(2015))

NSI effects at LBL ν-experiments

(Anti)neutrino appearance

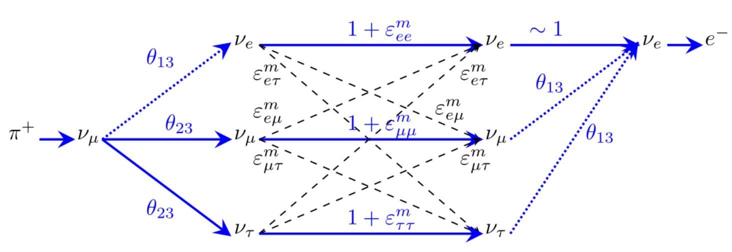
Figure taken from: J. Kopp *et al.* (PRD **77**(2008))



NSI effects at LBL ν-experiments

(Anti)neutrino appearance

Figure taken from: J. Kopp *et al.* (PRD **77**(2008))

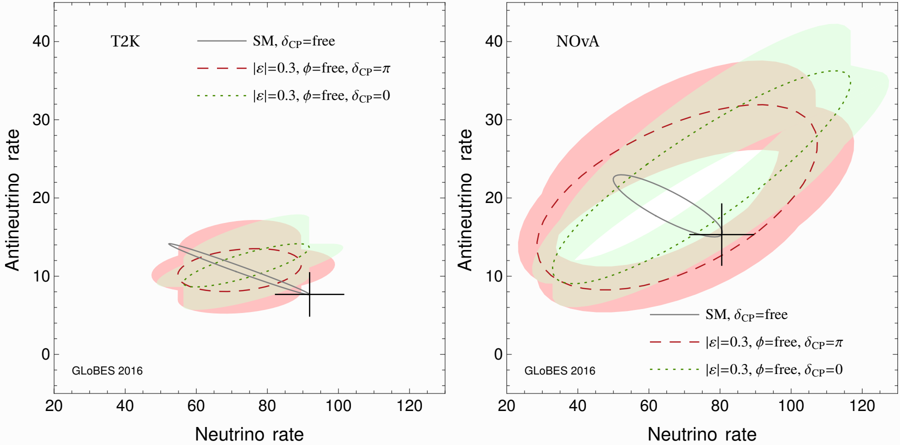


- We will consider only the (Anti)neutrino appearance channel.
- Only the off-diagonal NSI parameter $\varepsilon^m_{e\tau} \equiv |\varepsilon| \exp(i\phi) \neq 0$.
- We simulate true neutrino events including NSI and we compare them to the test SM events in both T2K (scaled 5 yrs) and NOvA (3ν+$3\bar{\nu}$).
- Our results are only for normal MH.

Results

Bi-rate plots

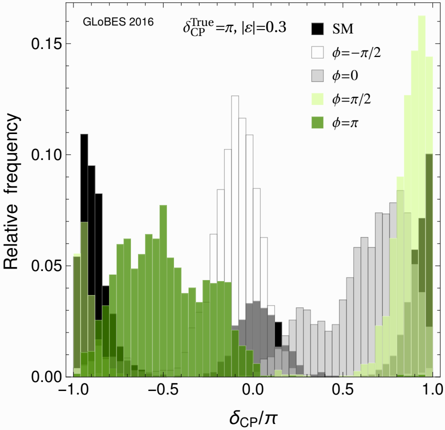
D.V.Forero and P. Huber arxiv:1601.03736

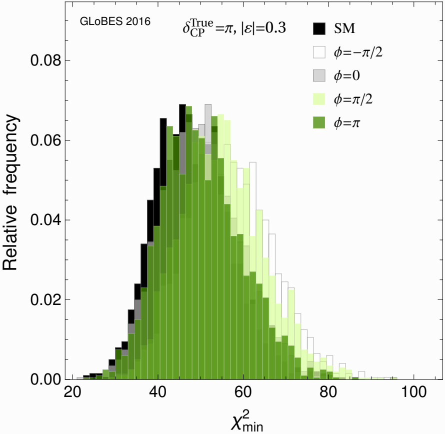


Results

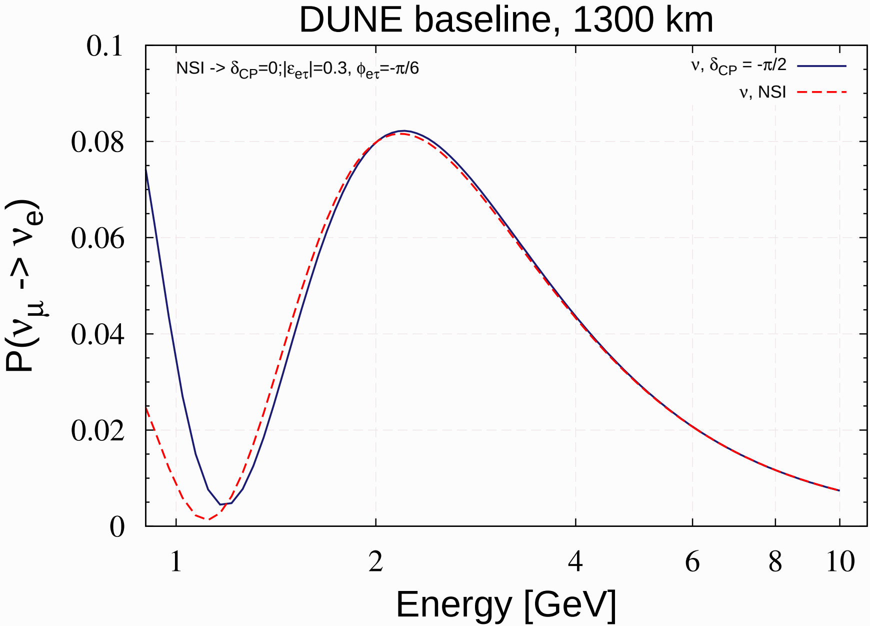
Histograms, T2K+NOvA

D.V.Forero and P. Huber arxiv:1601.03736





The future



DUNE baseline, 1300 km
NSI -> δ_{CP}=0;$|\varepsilon_{e\tau}|$=0.3, $\phi_{e\tau}$=-π/6
ν, δ_{CP} = -π/2
ν, NSI
$P(\nu_\mu \to \nu_e)$
Energy [GeV]
0.1
0.08
0.06
0.04
0.02
0
1
2
4
6
8
10

Summary

- NC-like NSI has an important impact in the ν-oscillations observed at LBL facilities.
- The NSI sensitivity in LBL ν-exps. is 'triggered' via interference with the Standard Oscillations.
- The parameter degeneracies from adding NSI could challenge the determination of the δ_{CP} phase, which is one of the main goals of the future ν-program.

THANK YOU

The beginnings

The importance of neutrino–matter interactions

L. Wolfenstein (PRD **17**(1978))

$m_\nu = 0$

- Case I: Off-diagonal NC couplings.
- Case II: Non-orthogonality among the νs in the weak basis.

Vacuum and matter ν-oscillations

- Case III: NC with diagonal couplings but including the ν_e-CC interactions with matter, Standard matter effect.

J.W.F Valle (PLB **199**(1987))

- Neutrinos remain massless due to a symmetry (total LN).
- Because of the Non-unitarity of the leptonic mixing matrix, the flavor neutrino eigenstates are not orthogonal.
- In matter 'oscillations' appear due to the interplay of CC and NC ν–interactions.

Towers of effective operators

$\Lambda > \Lambda_{EWSB}$

M.B. Gavela *et al.* (PRD **79**(2009))

$$\delta\mathcal{L}_{\text{eff}} = \frac{1}{\Lambda^2}\sum_i^{d=6} \mathcal{C}_i\, \mathcal{O}_i^{d=6} + \frac{1}{\Lambda^4}\sum_k^{d=8} \mathcal{C}_k\, \mathcal{O}_k^{d=8}\,,$$

After EWSB:

$$\epsilon^{m,L}_{\beta\alpha} = \frac{v^2}{2\Lambda^2}\left(\mathcal{C}^{\bar{L}L\bar{L}L}_{\text{NSI}}\right)^{\alpha e}_{\beta e}, \quad \epsilon^{m,R}_{\beta\alpha} = \frac{v^2}{2\Lambda^2}\left(-\frac{1}{2}\mathcal{C}_{LE} + \frac{v^2}{2\Lambda^2}(\mathcal{C}^{\mathbf{1}}_{LEH} + \mathcal{C}^{\mathbf{3}}_{LEH})\right)^{\alpha e}_{\beta e},$$

where the conditions to suppress charged LFV (4 lepton) process are:

$$\left(-\frac{1}{2}\mathcal{C}_{LE} + \frac{v^2}{2\Lambda^2}(\mathcal{C}^{\mathbf{1}}_{LEH} - \mathcal{C}^{\mathbf{3}}_{LEH})\right)^{\alpha\gamma}_{\beta\delta} = 0\,,$$

$$\left(\mathcal{C}^{\mathbf{1}}_{LL} + \mathcal{C}^{\mathbf{3}}_{LL} + \frac{v^2}{2\Lambda^2}\left(\mathcal{C}^{\mathbf{111}}_{LLH} + \mathcal{C}^{\mathbf{331}}_{LLH} - \mathcal{C}^{\mathbf{133}}_{LLH} - \mathcal{C}^{\mathbf{313}}_{LLH}\right)\right)^{\alpha\gamma}_{\beta\delta} = 0\,,$$

Towers of effective operators

$\Lambda > \Lambda_{EWSB}$

M.B. Gavela *et al.* (PRD **79**(2009))

Assumptions, limitations and consequences of the analysis:

- The analysis is limited to operators induced at *tree level*.
- With $d = 6$ operators (obeying the cancellation rules) it is not possible to obtain all the NSI couplings, for instance, $\varepsilon^{m}_{e\tau}$.
- The $d = 8$ operators (obeying the cancellation rules) are the potential candidates to generate 'large' NSI.
- For $d = 8$, and the mediators (2 to do the cancellation job) coupling to only SM bilinears, $d = 6$ contributions are also produced. Thus, some fine-tuning or extra symmetries are need.
- In a $d = 8$ case fulfilling all the requirements one should be careful with one-loop corrections since they can spoil the $d = 6$ cancellation conditions.

Many requirements (and some fine-tuning) have to be fulfilled to generate 'large NSI' when Λ is above the EWSB scale. Are there another possibilities?

NSI via light mediators, $m_X \ll m_Z$

Y. Farzan *et al.* arxiv:1512.09147

New light gauge boson from U(1)’ gauge models with a non-trivial two component representation for the left-handed leptons:

- From the low energy relation: $\varepsilon G_F \sim (g_X/m_X)^2$, to generate $\varepsilon \sim 1$, the condition $g_X/m_X = G_F^{1/2}$ should be fulfilled.

The non-detection of the new particle implies:

- Instead of the usual requirement $m_X \gg m_Z$ (which produces $\varepsilon \ll 1$), a second option considers $g_X \ll 1$. Specifically, $g_X \sim 5 \times 10^{-5}$ and $m_X \sim 10\,\text{MeV}$.