Status of Non-Standard Neutrino Interactions

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This talk is based on the following review:

T. Ohlsson, arXiv:1209.2710

Thanks to my collaborators on NSIs: Mattias Blennow, Michal Malinský, Davide Meloni, Thomas Schwetz, Francesco Terranova, Walter Winter, Zhi-zhong Xing, and He Zhang

Thanks also to the organizers (and especially Yasaman Farzan) for inviting me to present this review on NSIs!

Outline

This talk is organized as follows:

- Neutrino flavor transitions with NSIs
  - neutrino oscillations
  - alternative scenarios for neutrino flavor transitions (decoherence, decay, NSIs)
- NSIs with three neutrino flavors
  - production and detection NSIs, the zero-distance effect
  - matter NSIs
  - mappings, approximate formulas
- Theoretical models for NSIs
- Phenomenology of NSIs
  - atmospheric, accelerator, and reactor neutrinos
  - accelerators, neutrino factory
  - astrophysical neutrinos (solar, supernova, other sources)
- Phenomenological bounds on NSIs
  - direct bounds on matter NSIs
  - direct bounds on production and detection NSIs
- Sensitivities and discovery reach of NSIs

- Neutrino oscillations: The *leading* description for neutrino flavor transitions
- However, other mechanisms could be responsible for transitions on a *sub-leading* level.
- Therefore, we will phenomenologically study "new physics" effects due to *non-standard neutrino interactions (NSIs)*.

Weak interaction eigenstates vs. mass eigenstates:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Neutrino mixing in terms of "jelly beans", Symmetry Magazine

Standard parametrization:

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}\mathrm{e}^{-\mathrm{i}\delta} \\ 0 & 1 & 0 \\ -s_{13}\mathrm{e}^{\mathrm{i}\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \mathrm{e}^{\mathrm{i}\rho} & 0 & 0 \\ 0 & \mathrm{e}^{\mathrm{i}\sigma} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Pontecorvo (1957, 1967); Maki, Nakagawa, Sakata (1962)

Neutrino oscillations: Schödinger-like equation

The neutrino vector of state:

$$\nu = \begin{pmatrix} \nu_e & \nu_\mu & \nu_\tau \end{pmatrix}^T$$

Schrödinger-like equation for neutrino oscillations in matter:

$$\mathrm{i}\frac{\mathrm{d}\nu}{\mathrm{d}t} = \frac{1}{2E}\left[MM^\dagger + \mathrm{diag}(A,0,0)\right]\nu \equiv H\nu\,,$$

where E is the neutrino energy, $M = U\,\mathrm{diag}(m_1, m_2, m_3)\,U^T$ is the neutrino mass matrix, and $A = 2\sqrt{2}EG_F N_e$ is the effective (ordinary) matter potential.

Seminal work: Wolfenstein (1978)

Erwin Schrödinger

Present values of neutrino parameters

- Global fits of experimental neutrino data give (assuming normal mass ordering):

$$\begin{aligned}
\Delta m_{21}^2 = m_2^2 - m_1^2 &= (7.50 \pm 0.185) \cdot 10^{-5}\,\mathrm{eV}^2 \\
|\Delta m_{31}^2| = |m_3^2 - m_1^3| &= \left(2.47^{+0.069}_{-0.067}\right) \cdot 10^{-3}\,\mathrm{eV}^2 \\
\sin^2\theta_{12} &= 0.30 \pm 0.013 \\
\sin^2\theta_{13} &= 0.023 \pm 0.0023 \\
\sin^2\theta_{23} &= 0.41^{+0.037}_{-0.025}
\end{aligned}$$

M.C. Gonzalez–Garcia *et al.*, `arXiv:1209.3023`

(see also D. Forero *et al.*, `arXiv:1205.4018` and G. Fogli *et al.*, `arXiv:1205.5254`)

- Currently unknown quantities:
  - The absolute neutrino mass scale m_1
  - The sign of Δm_{31}^2, i.e. $\mathrm{sign}(\Delta m_{31}^2)$
  - The Dirac CP-violating phase δ
  - The Majorana CP-violating phases ρ and σ

Neutrino decoherence and neutrino decay

Other descriptions for transitions of neutrinos:

- neutrino decoherence

  Grossman, Worah (1998); Lisi, Marrone, Montanino (2000); Adler (2000); Gago *et al.* (2001, 2002); Ohlsson (2001); Fogli *et al.* (2003); Barenboim, Mavromatos (2005); Morgan *et al.* (2006); Anchordoqui *et al.* (2005); Barenboim *et al.* (2006); Fogli *et al.* (2007); Alexandre *et al.* (2008); Ribeiro *et al.* (2008); Mavromatos *et al.* (2008); Farzan, Schwetz, Smirnov (2008)

- neutrino decay

  Bahcall, Cabibbo, Yahil (1972); Barger, Keung, Pakvasa (1982); Valle (1983); Barger *et al.* (1999); Choubey, Goswami (2000); Barger *et al.* (1999); Fogli *et al.* (1999); Pakvasa (2000); Choubey, Goswami, Majumdar (2000); Bandyopadhyay, Choubey, Goswami (2001); Lindner, Ohlsson, Winter (2001, 2002); Josipura, Masso, Mohanty (2002); Beacom *et al.* (2003); Indumathi (2002); Ando (2003); Fogli *et al.* (2004); Ando (2004); Palomares-Riuz, Pascoli, Schwetz (2005); Meloni, Ohlsson (2007); Gonzalez-Garcia, Maltoni (2008); Maltoni, Winter (2008); Mehta, Winter (2011); Baerwald, Bustamante, Winter (2012)

However, such descriptions are now ruled out as the leading-order mechanism behind neutrino flavor transitions. Super-Kamiokande (2004), KamLAND (2005), Fogli *et al.*, `arXiv:0704.2568`, MINOS (2008, 2011)

But such descriptions could be sub-leading mechanisms and the origin of the NSIs.

See e.g. Blennow, Ohlsson, Winter, `hep-ph/0502147`

The phenomenological consequences of NSIs have been investigated in great detail in the literature.

NSI operators:

$$\mathcal{L}_{\rm NSI} = -2\sqrt{2} G_F \varepsilon_{\alpha\beta}^{ff'C} \left(\overline{\nu_\alpha}\gamma^\mu P_L \nu_\beta\right) \left(\overline{f}\gamma_\mu P_C f'\right)$$

where $\varepsilon_{\alpha\beta}^{ff'C}$ are NSI parameters.

Wolfenstein (1978); Grossman (1995); Berezhiani, Rossi (2002); Davidson *et al.* (2003)

Using the NSI operators, we find the effective NSI parameters:

$$\varepsilon_{\alpha\beta} \propto \frac{m_W^2}{m_X^2}$$

If the new physics scale, i.e., the NSI scale, is of the order 1(10) TeV, then one obtains

$$\varepsilon_{\alpha\beta} \sim 10^{-2} (10^{-4})$$

Neutrino states at sources and detectors:

$$
\begin{aligned}
|\nu_\alpha^s\rangle &= |\nu_\alpha\rangle + \sum_{\beta=e,\mu,\tau} \varepsilon^s_{\alpha\beta}|\nu_\beta\rangle = (1+\varepsilon^s)U|\nu_m\rangle \\
\langle\nu_\beta^d| &= \langle\nu_\beta| + \sum_{\alpha=e,\mu,\tau} \varepsilon^d_{\alpha\beta}\langle\nu_\alpha| = \langle\nu_m|U^\dagger[1+(\varepsilon^d)^\dagger]
\end{aligned}
$$

Superpositions of pure orthonormal flavor eigenstates

Grossman (1995); Gonzalez-Garcia *et al.* (2001); Bilenky, Giunti (1993); Meloni *et al.* (2010)

If production and detection processes are the same, then $\varepsilon^s = \left(\varepsilon^d\right)^\dagger$.
Neutrino transition probability:

$$
\begin{aligned}
P(\nu_\alpha^s \to \nu_\beta^d; L) &= \left|\sum_{\gamma,\delta,i}\left(1+\varepsilon^d\right)_{\gamma\beta}\left(1+\varepsilon^s\right)_{\alpha\delta} U_{\delta i}U^*_{\gamma i}\, \mathrm{e}^{-\mathrm{i}\frac{m_i^2 L}{2E}}\right|^2 \\
&= \sum_{i,j}\mathcal{J}^i_{\alpha\beta}\mathcal{J}^{j*}_{\alpha\beta} - 4\sum_{i>j}\mathrm{Re}(\mathcal{J}^i_{\alpha\beta}\mathcal{J}^{j*}_{\alpha\beta})\sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right) \\
&+ 2\sum_{i>j}\mathrm{Im}(\mathcal{J}^i_{\alpha\beta}\mathcal{J}^{j*}_{\alpha\beta})\sin\left(\frac{\Delta m^2_{ij}L}{2E}\right)
\end{aligned}
$$

with $\mathcal{J}^i_{\alpha\beta}$ being some quantity.

What happens with the formula for the neutrino transition probability at $L = 0$?

$$P(\nu_\alpha^s \to \nu_\beta^d; L = 0) = \sum_{i,j} \mathcal{J}_{\alpha\beta}^i \mathcal{J}_{\alpha\beta}^{j*}$$

with

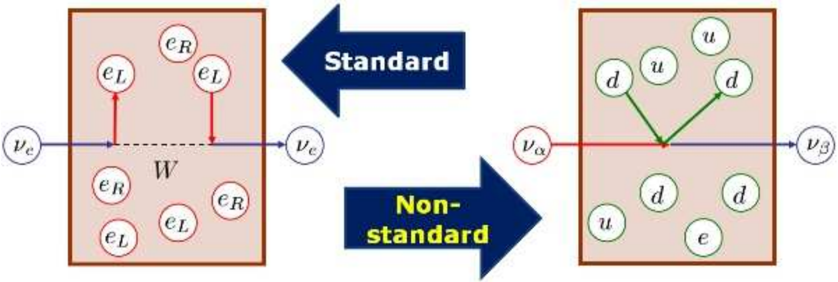
$$\mathcal{J}_{\alpha\beta}^i = U_{\alpha i}^* U_{\beta i} + \sum_\gamma \varepsilon_{\alpha\gamma}^s U_{\gamma i}^* U_{\beta i} + \sum_\gamma \varepsilon_{\gamma\beta}^d U_{\alpha i}^* U_{\gamma i} + \sum_{\gamma,\delta} \varepsilon_{\alpha\gamma}^s \varepsilon_{\delta\beta}^d U_{\gamma i}^* U_{\delta i}$$

Thus, in general, the $\sum_{i,j} \mathcal{J}_{\alpha\beta}^i \mathcal{J}_{\alpha\beta}^{j*}$ is different from zero or one. This is known as the *zero-distance effect*. (It could be measured with a near detector close to a source.) Langacker, London (1988)

In the case that $\varepsilon^s = \varepsilon^d = 0$ (i.e., without NSIs), then

$$\sum_{i,j} \mathcal{J}_{\alpha\beta}^i \mathcal{J}_{\alpha\beta}^{j*} = \sum_{i,j} U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^* = \delta_{\alpha\beta}$$

Matter NSIs



Three-flavor neutrino evolution equation with matter NSIs:

$$\mathrm{i}\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \frac{1}{2E}\left[U\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m_{21}^2 & 0\\ 0 & 0 & \Delta m_{31}^2\end{pmatrix}U^\dagger + A\begin{pmatrix}1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau}\\ \varepsilon_{e\mu}^* & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau}\\ \varepsilon_{e\tau}^* & \varepsilon_{\mu\tau}^* & \varepsilon_{\tau\tau}\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

Wolfenstein (1978); Valle (1987); Guzzo, Masiero, Petcov (1991); Roulet (1991)

In general, this gives rise to rather cumbersome neutrino transition probabilities.

Mappings between effective and fundamental parameters

Mappings for the effective masses with NSIs: $\hat{A} \equiv A/\Delta m_{31}^2 \quad \alpha \equiv \Delta m_{21}^2/\Delta m_{31}^2$

$$\tilde{m}_1^2 \simeq \Delta m_{31}^2 \left(\hat{A} + \alpha s_{12}^2 + \hat{A}\varepsilon_{ee}\right)$$

$$\tilde{m}_2^2 \simeq \Delta m_{31}^2 \left[\alpha c_{12}^2 - \hat{A} s_{23}^2 \left(\varepsilon_{\mu\mu} - \varepsilon_{\tau\tau}\right) - \hat{A} s_{23} c_{23} \left(\varepsilon_{\mu\tau} + \varepsilon_{\mu\tau}^*\right) + \hat{A}\varepsilon_{\mu\mu}\right]$$

$$\tilde{m}_3^2 \simeq \Delta m_{31}^2 \left[1 + \hat{A}\varepsilon_{\tau\tau} + \hat{A} s_{23}^2 \left(\varepsilon_{\mu\mu} - \varepsilon_{\tau\tau}\right) + \hat{A} s_{23} c_{23} \left(\varepsilon_{\mu\tau} + \varepsilon_{\mu\tau}^*\right)\right]$$

Mappings for the effective mixing matrix elements with NSIs:

$$\tilde{U}_{e3} \simeq \frac{s_{13} \mathrm{e}^{-\mathrm{i}\delta}}{1 - \hat{A}} + \frac{\hat{A}(s_{23}\varepsilon_{e\mu} + c_{23}\varepsilon_{e\tau})}{1 - \hat{A}}$$

$$\tilde{U}_{e2} \simeq \frac{\alpha s_{12} c_{12}}{\hat{A}} + c_{23}\varepsilon_{e\mu} - s_{23}\varepsilon_{e\tau}$$

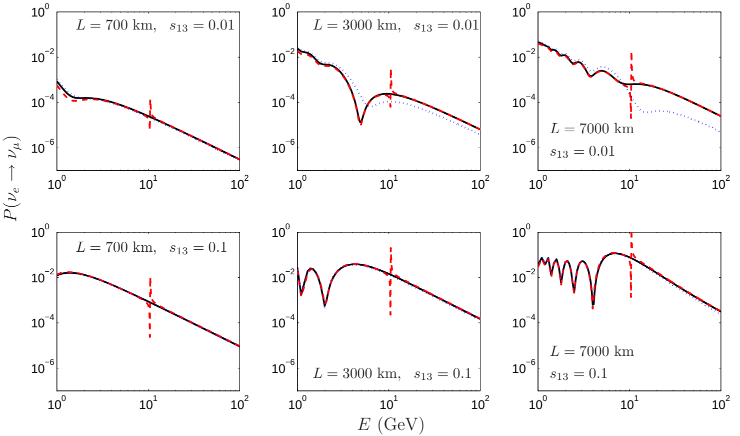
$$\tilde{U}_{\mu 3} \simeq s_{23} + \hat{A}\left[c_{23}\varepsilon_{\mu\tau} + s_{23} c_{23}^2 \left(\varepsilon_{\mu\mu} - \varepsilon_{\tau\tau}\right) - s_{23}^2 c_{23} \left(\varepsilon_{\mu\tau} + \varepsilon_{\mu\tau}^*\right)\right]$$

Meloni, Ohlsson, Zhang, arXiv:0901.1784

The results are model independent!

Important for NSIs with long-baseline experiments

Neutrino oscillations probabilities for the electron neutrino-muon neutrino channel:



Meloni, Ohlsson, Zhang, arXiv:0901.1784

solid curves = exact numerical results; dashed curves = approximate results; dotted curves = results without NSIs

Agreement to an extremely good precision! A singularity exists around 10 GeV due to the limitation of non-degenerate perturbation theory.

Approximate formulas for two neutrino flavors

Two-flavor neutrino evolution equation with matter NSIs:

$$\mathrm{i}\frac{\mathrm{d}}{\mathrm{d}L}\begin{pmatrix}\nu_e\\ \nu_\tau\end{pmatrix} = \frac{1}{2E}\left[U\begin{pmatrix}0 & 0\\ 0 & \Delta m^2\end{pmatrix}U^\dagger + A\begin{pmatrix}1+\varepsilon_{ee} & \varepsilon_{e\tau}\\ \varepsilon_{e\tau} & \varepsilon_{\tau\tau}\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\tau\end{pmatrix}$$

See e.g. Kitazawa, Sugiyama, Yasuda, hep-ph/0606013

Two-flavor neutrino oscillation probability:

$$P(\nu_e \to \nu_\tau; L) = \sin^2(2\theta_M)\sin^2\left(\frac{\Delta m_M^2 L}{2E}\right)$$

with effective parameters

$$\left(\Delta m_M^2\right)^2 = \left[\Delta m^2\cos(2\theta) - A\left(1+\varepsilon_{ee}-\varepsilon_{\tau\tau}\right)\right]^2 + \left[\Delta m^2\sin(2\theta) + 2A\varepsilon_{e\tau}\right]^2$$

$$\sin(2\theta_M) = \frac{\Delta m^2\sin(2\theta) + 2A\varepsilon_{e\tau}}{\Delta m_M^2}$$

See also Blennow, Ohlsson, arXiv:0805.2301 for a detailed discussion on approximate formulas for two neutrino flavors with NSIs.

Theoretical models for NSIs

How to realize NSIs in a more fundamental framework with some underlying high-energy physics theory, which would respect the SM gauge group $\mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1)$?

A toy model (SM + one heavy scalar field S):

$$\mathcal{L}^S_{\mathrm{int}} = -\lambda_{\alpha\beta} \overline{L^c_\alpha} \mathrm{i}\sigma_2 L_\beta S$$

Bilenky, Santamaria, hep-ph/9310302

Integrating out S generates a dimension-six operator at tree level:

$$\mathcal{L}^{\mathrm{d=6,as}}_{\mathrm{NSI}} = 4 \frac{\lambda_{\alpha\beta}\lambda^*_{\delta\gamma}}{m_S^2} \left(\overline{\ell^c}_\alpha P_L \nu_\beta\right) \left(\bar{\nu}_\gamma P_R \ell^c_\delta\right)$$

Antusch, Baumann, Fernández-Martínez, arXiv:0807.1003

Other examples of theoretical models for NSIs: different seesaw models, the Zee–Babu model, . . .

Theoretical models for NSIs II

In general, theories beyond the SM must respect gauge symmetry invariance, which implies strict constraints on possible models for NSIs.

See e.g. Gavela, Hernandez, Ota, Winter, arXiv:0809.3451

Therefore, if there is a dimension-6 operator:

$$\frac{1}{\Lambda^2}\left(\bar{\nu}_\alpha \gamma^\rho P_L \nu_\beta\right)\left(\bar{\ell}_\gamma \gamma_\rho P_L \ell_\delta\right) \quad \Rightarrow \quad \varepsilon^{ee}_{e\mu}$$

However, the dimension-6 operator must be a part of the more general form

$$\frac{1}{\Lambda^2}\left(\bar{L}_\alpha \gamma^\rho L_\beta\right)\left(\bar{L}_\gamma \gamma_\rho L_\delta\right)$$

which involves four charged-lepton operators.

Thus, we have severe constraints from experiments on processes like $\mu \to 3e$, i.e.,

$$\mathrm{BR}(\mu \to 3e) < 10^{-12}$$

which leads to the following upper bound on the above chosen NSI parameter

$$\varepsilon^{ee}_{e\mu} < 10^{-6}$$

The two-flavor hybrid model: Gonzalez-Garcia, Maltoni, hep-ph/0404085

$$\mathrm{i}\frac{\mathrm{d}}{\mathrm{d}L}\begin{pmatrix}\nu_\mu \\ \nu_\tau\end{pmatrix} = \frac{1}{2E}\left[U\begin{pmatrix}0 & 0 \\ 0 & \Delta m^2\end{pmatrix}U^\dagger + A\begin{pmatrix}1+\varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{\mu\tau} & \varepsilon_{\tau\tau}\end{pmatrix}\right]\begin{pmatrix}\nu_\mu \\ \nu_\tau\end{pmatrix}$$

The two-flavor ν_μ survival probability:

$$P(\nu_\mu \to \nu_\mu; L) = 1 - P(\nu_\mu \to \nu_\tau; L) = 1 - \sin^2(2\Theta)\sin^2\left(\frac{\Delta m_{31}^2 L}{4E}R\right)$$

where

$$\begin{aligned}\sin^2(2\Theta) &= \frac{1}{R^2}\left[\sin^2(2\theta) + R_0^2\sin^2(2\xi) + 2R_0\sin(2\theta)\sin(2\xi)\right] \\ R &= \sqrt{1 + R_0^2 + 2R_0\left[\cos(2\theta)\cos(2\xi) + \sin(2\theta)\sin(2\xi)\right]}\end{aligned}$$

with

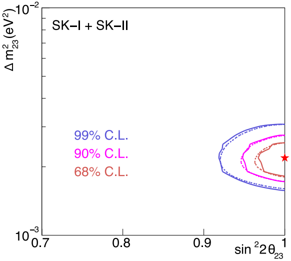
$$\begin{aligned}R_0 &= \sqrt{2}G_F N_f \frac{4E}{\Delta m^2}\sqrt{|\varepsilon|^2 + \frac{\varepsilon'^2}{4}} \\ \xi &= \frac{1}{2}\arctan\left(\frac{2\varepsilon}{\varepsilon'}\right)\end{aligned}$$

Results from Super-Kamiokande

Using the two-flavor hybrid model together with atmospheric neutrino data from the Super-Kamiokande I (1996-2001) and II (2003-2005) experiments, the Super-Kamiokande collaboration has obtained the following results at 90 % C.L.

$$|\varepsilon_{\mu\tau}| < 1.1 \cdot 10^{-2} \quad \text{and} \quad |\varepsilon_{\tau\tau} - \varepsilon_{\mu\mu}| < 4.9 \cdot 10^{-2}$$

Thus, the Super-Kamiokande collaboration has found no evidence for matter NSIs in its atmospheric neutrino data.



Mitsuka *et al.* (Super-Kamiokande Collaboration), arXiv:1109.1889

Studies include searches for matter NSIs with the K2K, MINOS, OPERA, T2K, and T2KK.

In the case of the MINOS experiment, the important NSI parameters are $\varepsilon_{e\tau}$, $\varepsilon_{\mu\tau}$, and $\varepsilon_{\tau\tau}$ and one of the interesting transition probabilities is (assuming $\theta_{23} = 45^\circ$)

$$P(\nu_\mu \to \nu_\mu; L) \simeq 1 - \sin^2\left(\left|\frac{\Delta m_{31}^2}{4E} - \varepsilon_{\mu\tau}\frac{A}{2E}\right| L\right)$$

Mann, Cherdack, Musial, Kafka, arXiv:1006.5720

In the case of the OPERA experiment, the important NSI parameter is $\varepsilon_{\mu\tau}$ and the interesting transition probability is (assuming $\Delta m_{21}^2 = 0$)

$$P(\nu_\mu \to \nu_\tau; L) = \left|c_{13}^2 \sin(2\theta_{23})\frac{\Delta m_{31}^2}{4E} + \varepsilon_{\mu\tau}^*\frac{A}{2E}\right|^2 L^2 + \mathcal{O}(L^3)$$

Blennow, Meloni, Ohlsson, Terranova, Westerberg, arXiv:0804.2744

Thus, there exists a degeneracy between the fundamental neutrino oscillation parameters and the NSI parameter $\varepsilon_{\mu\tau}$. Note that it has been shown that the OPERA experiment is not very sensitive to the NSI parameters $\varepsilon_{e\tau}$ and $\varepsilon_{\tau\tau}$.

Esteban-Pretel, Valle, Huber, arXiv:0803.1790

Results from MINOS

Using a model based on the ν_μ survival probability together with data from the MINOS experiment, the MINOS collaboration has obtained the following result for the matter NSI parameter $\varepsilon_{\mu\tau}$ at 90 % C.L.

$$-0.200 < \varepsilon_{\mu\tau} < 0.070$$

which means that MINOS has found no evidence for matter NSIs in its neutrino data, at least not a non-zero value for the matter NSI parameter $\varepsilon_{\mu\tau}$.

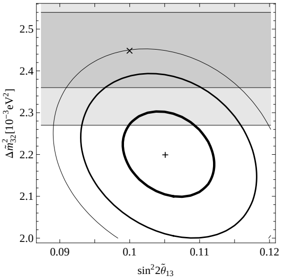
Coelho (for the MINOS Collaboration), poster presented at Neutrino 2012

NSIs with reactor neutrinos

To my knowledge, there exist only three studies with reactor neutrinos and NSIs.

- A combined study of the performance of reactor and superbeam neutrino experiments in the presence of NSIs Kopp, Lindner, Ota, Sato, arXiv:0708.0152
- A study of only reactor neutrino experiments and NSIs Ohlsson, Zhang, arXiv:0809.4835

  → The measured value for θ_{13} could be a combination of the fundamental value for θ_{13} and effects of NSI parameters.
- NSIs at the Daya Bay experiment Leitner, Malinský, Roskovec, Zhang, arXiv:1105.5580



The effects of the non-standard interactions in the determination of the standard oscillation parameters θ_{13} and Δm^2_{32} at Daya Bay after 3 years of running.

NSIs with accelerators and a future neutrino factory

Accelerators:

- LEP provides bounds on NSIs of the order of $\varepsilon \lesssim (10^{-2} \div 10^{-3})$ at $\sqrt{s} \sim 200$ GeV. Davidson, Sanz, arXiv:1108.5320
- If NSIs are contact interactions at LHC energies, LHC should have a sensitivity reach of NSIs of the order of $\varepsilon \gtrsim 3 \cdot 10^{-3}$ at 14 TeV and with 100 fb^{-1} of data. Davidson, Sanz, arXiv:1108.5320

A future neutrino factory:

- A 100 GeV neutrino factory could probe flavor-changing neutrino interactions of the order of $|\varepsilon| \lesssim 10^{-4}$ at 99 % C.L. Huber, Valle, hep-ph/0108193
- There is an entanglement between the mixing angle θ_{13} and NSI parameters, which would be solved in the best way by using the appearance channel $\nu_e \to \nu_\mu$. Huber, Schwetz, Valle, hep-ph/0111224, hep-ph/0202048
- There are degeneracies between CP violation and NSI parameters.
- A neutrino factory has excellent prospects in detecting NSIs originating from "new physics" at the TeV scale. Kopp, Lindner, Ota, hep-ph/0702269
- Off-diagonal NSI parameters could be tested down to the order of 10^{-3}, whereas diagonal NSI parameter combinations such as $\varepsilon_{ee} - \varepsilon_{\tau\tau}$ and $\varepsilon_{\mu\mu} - \varepsilon_{\tau\tau}$ could only be tested down to 10^{-1} and 10^{-2}, respectively. Coloma, Donini, López-Pavón, Minakata, arXiv:1105.5936

NSIs with astrophysical neutrinos

Solar neutrinos and NSIs:

- Sensitivity analysis of NSIs, using data from the Super-Kamiokande and SNO experiments
  Berezhiani, Raghavan, Rossi, hep-ph/0111138
- Signature and bounds for NSIs at the Borexino experiment
- The LENA proposal – a probe for NSIs
  Garcés, Miranda, Tórtola, Valle, arXiv:1112.3633

Supernova neutrinos and NSIs:

- Three-flavor analysis for the possibility of probing NSIs
  Esteban-Pretel, Tomàs, Valle, arXiv:0704.0032
- Interplay between collective effects and NSIs
  Esteban-Pretel, Tomàs, Valle, arXiv:0909.2196; Dasgupta, Raffelt, Tamborra, arXiv:1001.5396

Astrophysical sources of neutrinos and NSIs:

- Production and detection NSIs of high-energy neutrinos at neutrino telescopes, using neutrino flux ratios Blennow, Meloni, arXiv:0901.2110

Direct bounds on matter NSIs

The model-independent bounds on the matter NSI parameters (for the Earth):

$$\begin{pmatrix} |\varepsilon_{ee}| < 2.5 & |\varepsilon_{e\mu}| < 0.21 & |\varepsilon_{e\tau}| < 1.7 \\ & |\varepsilon_{\mu\mu}| < 0.046 & |\varepsilon_{\mu\tau}| < 0.21 \\ & & |\varepsilon_{\tau\tau}| < 9.0 \end{pmatrix}$$

$\therefore$ Bounds on matter NSIs $\sim 10^{-2} \div 10$

Biggio, Blennow, Fernández-Martínez, `arXiv:0907.0097`

Direct bounds on production and detection NSIs

The most stringent bounds for charged-current-like NSIs for terrestrial experiments:

$$\begin{pmatrix} |\varepsilon^{\mu e}_{ee}| < 0.025 & |\varepsilon^{\mu e}_{e\mu}| < 0.030 & |\varepsilon^{\mu e}_{e\tau}| < 0.030 \\ |\varepsilon^{\mu e}_{\mu e}| < 0.025 & |\varepsilon^{\mu e}_{\mu\mu}| < 0.030 & |\varepsilon^{\mu e}_{\mu\tau}| < 0.030 \\ |\varepsilon^{\mu e}_{\tau e}| < 0.025 & |\varepsilon^{\mu e}_{\tau\mu}| < 0.030 & |\varepsilon^{\mu e}_{\tau\tau}| < 0.030 \end{pmatrix}$$

$$\begin{pmatrix} |\varepsilon^{ud}_{ee}| < 0.041 & |\varepsilon^{ud}_{e\mu}| < 0.025 & |\varepsilon^{ud}_{e\tau}| < 0.041 \\ |\varepsilon^{ud}_{\mu e}| < \begin{cases} 1.8 \cdot 10^{-6} \\ 0.026 \end{cases} & |\varepsilon^{ud}_{\mu\mu}| < 0.078 & |\varepsilon^{ud}_{\mu\tau}| < 0.013 \\ |\varepsilon^{ud}_{\tau e}| < \begin{cases} 0.087 \\ 0.12 \end{cases} & |\varepsilon^{ud}_{\tau\mu}| < \begin{cases} 0.013 \\ 0.018 \end{cases} & |\varepsilon^{ud}_{\tau\tau}| < 0.13 \end{pmatrix}$$

$\therefore$ Bounds on production and detection NSIs $\sim 10^{-2}$

Biggio, Blennow, Fernández-Martínez, `arXiv:0907.0097`

Sensitivity and discovery reach of NSIs

Experiments that could find signatures of NSIs:

- Reactor neutrino experiments (?)
- LHC
- A future neutrino factory

Summary & Conclusions

- Discussion of NSIs as sub-leading effects to the standard paradigm for neutrino flavor transitions (i.e. neutrino oscillations)
- Production and detection NSIs including the zero-distance effect
- Matter NSIs
- Approximate analytical model-independent mappings
- Approximate two-flavor formulas for neutrino flavor transitions
- Experimental results of upper bounds on NSIs from the Super-Kamiokande and MINOS collaborations $\Rightarrow$ No evidence for matter NSIs
- Sensitivity reaches of NSIs for accelerators, a future neutrino factory, and the reactor neutrino experiment Daya Bay
- Mimicking effects play an important role in reactor neutrino experiments, especially for θ_{13} $\Rightarrow$ Is the fundamental value for θ_{13} smaller than the measured value?
- Phenomenological upper bounds on NSIs (matter NSIs, production and detection NSIs, and neutrino cross-sections)
- Sensitivity and discovery reach of NSIs (LHC and a future neutrino factory)

Thank you for your attention!

Please check arXiv:1209:2710.

Questions?