

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 Eligio Lisi) for inviting me to present this review on NSIs!

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)*.

Neutrino oscillations: Leptonic flavor mixing

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:

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

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

Neutrino oscillations: Schrödinger-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:

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

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

Seminal work: **Wolfenstein (1978)**



Erwin Schrödinger

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

$$\begin{aligned}\Delta m_{21}^2 &= m_2^2 - m_1^2 &= (7.50 \pm 0.185) \cdot 10^{-5} \text{ eV}^2 \\ |\Delta m_{31}^2| &= |m_3^2 - m_1^2| &= \left(2.45^{+0.067}_{-0.071}\right) \cdot 10^{-3} \text{ eV}^2 \\ \sin^2 \theta_{12} &= &0.30^{+0.013}_{-0.012} \\ \sin^2 \theta_{13} &= &0.023 \pm 0.0023 \\ \sin^2 \theta_{23} &= &0.42^{+0.037}_{-0.031}\end{aligned}$$

T. Schwetz, "Review on global fits", What's ν ?, Florence, Italy, June 25, 2012

(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. $\text{sign}(\Delta m_{31}^2)$
 - The Dirac CP-violating phase δ
 - The Majorana CP-violating phases ρ and σ

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-Riu, 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](https://arxiv.org/abs/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](https://arxiv.org/abs/hep-ph/0502147)

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

NSI operators:

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

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:

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

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 $\varepsilon^s = (\varepsilon^d)^\dagger$.

Neutrino transition probability:

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

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

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

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

with

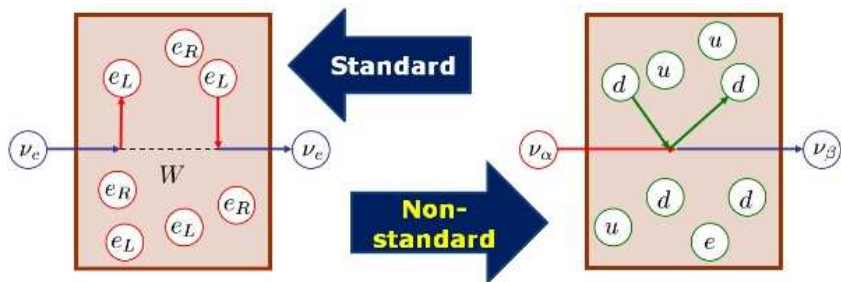
$$\mathcal{J}_{\alpha\beta}^i = U_{\alpha i}^* U_{\beta i} + \sum_{\gamma} \varepsilon_{\alpha\gamma}^s U_{\gamma i}^* U_{\beta i} + \sum_{\gamma} \varepsilon_{\gamma\beta}^d U_{\alpha i}^* U_{\gamma i} + \sum_{\gamma,\delta} \varepsilon_{\alpha\gamma}^s \varepsilon_{\delta\beta}^d U_{\gamma i}^* U_{\delta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

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

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



Three-flavor neutrino evolution equation with matter NSIs:

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

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: $\hat{A} \equiv A/\Delta m_{31}^2$ $\alpha \equiv \Delta m_{21}^2/\Delta m_{31}^2$

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

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

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

Mappings for the effective mixing matrix elements with NSIs:

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

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

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

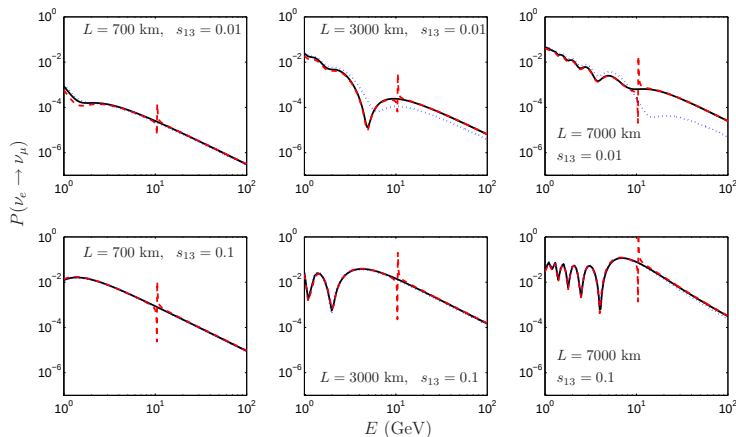
Meloni, Ohlsson, Zhang, [arXiv:0901.1784](#)

The results are model independent!

Important for NSIs with long-baseline experiments

Mappings between effective and fundamental parameters II

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



Meloni, Ohlsson, Zhang, [arXiv:0901.1784](https://arxiv.org/abs/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:

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

See e.g. [Kitazawa, Sugiyama, Yasuda, hep-ph/0606013](#)

Two-flavor neutrino oscillation probability:

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

with effective parameters

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

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

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

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

$$\mathcal{L}_{\text{int}}^S = -\lambda_{\alpha\beta} \bar{L}_\alpha^c i\sigma_2 L_\beta S$$

Bilenky, Santamaria, [hep-ph/9310302](#)

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

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

Antusch, Baumann, Fernández-Martínez, [arXiv:0807.1003](#)

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

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:

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

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

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

which involves four charged-lepton operators.

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

$$\text{BR}(\mu \rightarrow 3e) < 10^{-12}$$

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

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

The two-flavor hybrid model: [Gonzalez-Garcia, Maltoni, hep-ph/0404085](#)

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

The two-flavor ν_μ survival probability:

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

where

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

with

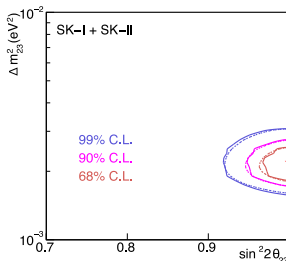
$$\begin{aligned} R_0 &= \sqrt{2} G_F N_f \frac{4E}{\Delta m^2} \sqrt{|\varepsilon|^2 + \frac{\varepsilon'^2}{4}} \\ \xi &= \frac{1}{2} \arctan \left(\frac{2\varepsilon}{\varepsilon'} \right) \end{aligned}$$

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](https://arxiv.org/abs/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 $\theta_{23} = 45^\circ$)

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

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 $\Delta m_{21}^2 = 0$)

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

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](#)

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.

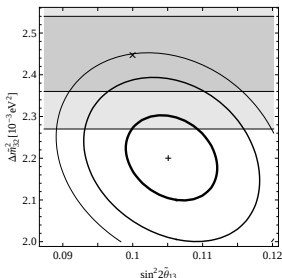
$$-0.200 < \varepsilon_{\mu\tau} < 0.070 ,$$

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

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_{32}^2 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 $\nu_e \rightarrow \nu_\mu$. [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](#)

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](#)

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](#)

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

$$\left(\begin{array}{ccc} |\varepsilon_{ee}^{\mu e}| < 0.025 & |\varepsilon_{e\mu}^{\mu e}| < 0.030 & |\varepsilon_{e\tau}^{\mu e}| < 0.030 \\ |\varepsilon_{\mu e}^{\mu e}| < 0.025 & |\varepsilon_{\mu\mu}^{\mu e}| < 0.030 & |\varepsilon_{\mu\tau}^{\mu e}| < 0.030 \\ |\varepsilon_{\tau e}^{\mu e}| < 0.025 & |\varepsilon_{\tau\mu}^{\mu e}| < 0.030 & |\varepsilon_{\tau\tau}^{\mu e}| < 0.030 \end{array} \right)$$

$$\left(\begin{array}{ccc} |\varepsilon_{ee}^{ud}| < 0.041 & |\varepsilon_{e\mu}^{ud}| < 0.025 & |\varepsilon_{e\tau}^{ud}| < 0.041 \\ |\varepsilon_{\mu e}^{ud}| < \begin{cases} 1.8 \cdot 10^{-6} \\ 0.026 \end{cases} & |\varepsilon_{\mu\mu}^{ud}| < 0.078 & |\varepsilon_{\mu\tau}^{ud}| < 0.013 \\ |\varepsilon_{\tau e}^{ud}| < \begin{cases} 0.087 \\ 0.12 \end{cases} & |\varepsilon_{\tau\mu}^{ud}| < \begin{cases} 0.013 \\ 0.018 \end{cases} & |\varepsilon_{\tau\tau}^{ud}| < 0.13 \end{array} \right)$$

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

Biggio, Blennow, Fernández-Martínez, [arXiv:0907.0097](https://arxiv.org/abs/0907.0097)

Experiments that could find signatures of NSIs:

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

- 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](https://arxiv.org/abs/1209.2710).

Questions?



The EPS HEP 2013 conference

International Europhysics Conference on High Energy Physics

Stockholm, Sweden

July 18-24, 2013

“Neutrino Physics” will be included in the program!