Phenomenology of Non-Standard Neutrino Interactions

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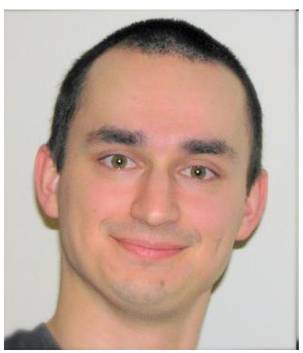

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Outline

- Introduction to neutrino oscillations
- Introduction to non-standard interactions
  - What they are
- Non-standard interactions in neutrino physics
  - Neutrino oscillations
  - Overview of the field
  - Future?
- Phenomenology of non-standard interactions
- Summary and conclusions

Lepton flavor mixing

Weak interaction eigenstates

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

Mass eigenstates

Standard parametrization

Majorana CP-violating phases

$$V_{MNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ \sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\rho} & 0 & 0 \\ 0 & e^{i\sigma} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Dirac CP-violating phase

δ

There are now strong evidences that neutrinos are massive and lepton flavors are mixed. Since in the Standard Model neutrinos are massless particles, the SM must be extended by adding neutrino masses.

Schrödinger equation

$$i\frac{d\nu}{dt}=\left[\frac{MM^{\dagger}}{2E}+V(t)\right]\nu$$

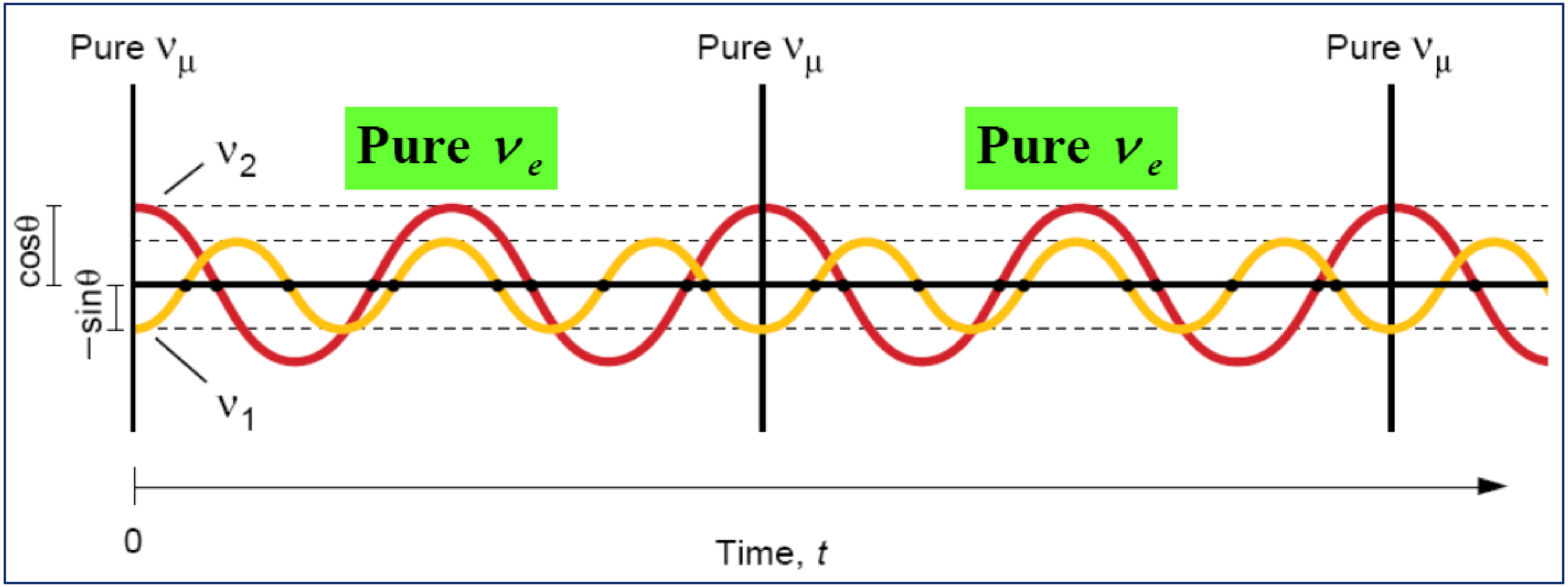
Effective matter potential

$$V(t)=\begin{pmatrix} V_e & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Neutrino oscillations

Two-flavor illustration!

Flavor changes happen during the propagation of neutrinos!



Neutrino oscillation parameters

parameter	best fit	2σ	3σ
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	$7.65^{+0.23}_{-0.20}$	7.25–8.11	7.05–8.34
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$	$2.40^{+0.12}_{-0.11}$	2.18–2.64	2.07–2.75
$\sin^2\theta_{12}$	$0.304^{+0.022}_{-0.016}$	0.27–0.35	0.25–0.37
$\sin^2\theta_{23}$	$0.50^{+0.07}_{-0.06}$	0.39–0.63	0.36–0.67
$\sin^2\theta_{13}$	$0.01^{+0.016}_{-0.011}$	≤ 0.040	≤ 0.056

Schwetz, Tórtola, Valle, NJP 2008

Unknowns:

1. $\theta_{13}=0$?
2. Sign of $\Delta m_{31}{}^2$
3. Dirac or Majorana?
4. Absolute mass scale
5. Leptonic CP violation?
6. Sterile neutrinos?
7. Non-standard interactions?
8. Non-unitary neutrino mixing?

Exp. Steps:

Improve present measurements of solar and atmospheric parameters.

Discover the last mixing angle θ_{13} (Daya Bay, Double Chooz)

CP-violating phase (δ) in the future long baseline experiments (ν-factory, β-beam).

Neutrino oscillations and …

- Neutrino oscillations:
  - The Super-Kamiokande, SNO, and KamLAND neutrino oscillation experiments have strong evidences that neutrino oscillations occur.
  - The leading description for neutrino flavor transitions.
  - Precision measurements for some of the neutrino parameters (Δm_{21}^2, $|\Delta m_{31}^2|$, θ_{12}, θ_{23}), others are still completely unknown (sign(Δm_{31}^2), θ_{13}, δ), absolute neutrino mass scale).
- However, other mechanisms could be responsible for transitions on a sub-leading level.
- Therefore, we will study phenomenologically ”new physics” effects due to non-standard neutrino interactions (NSIs).

NSIs – Phenomenological consequences

The widely studied operators responsible for NSIs:

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

(Wolfenstein, Grossman, Berezhiani-Rossi, Davidson et al., …)

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

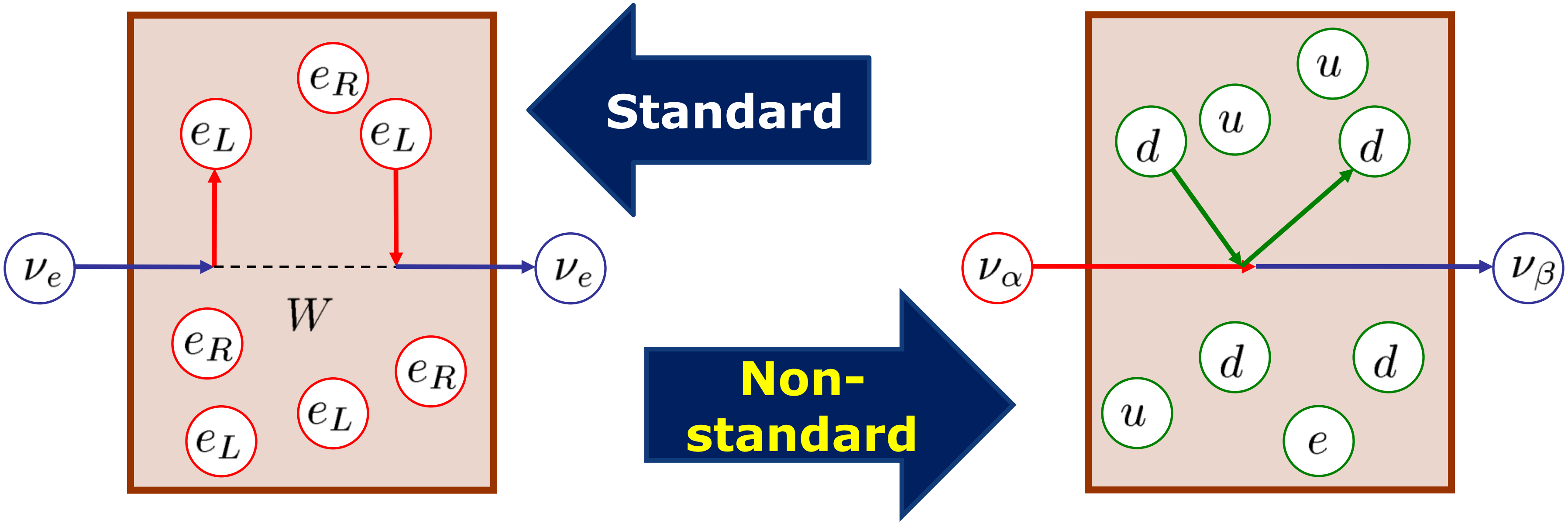
If new physics scale ~ 1(10) TeV

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

Non-renormalizable!
Not gauge invariant!

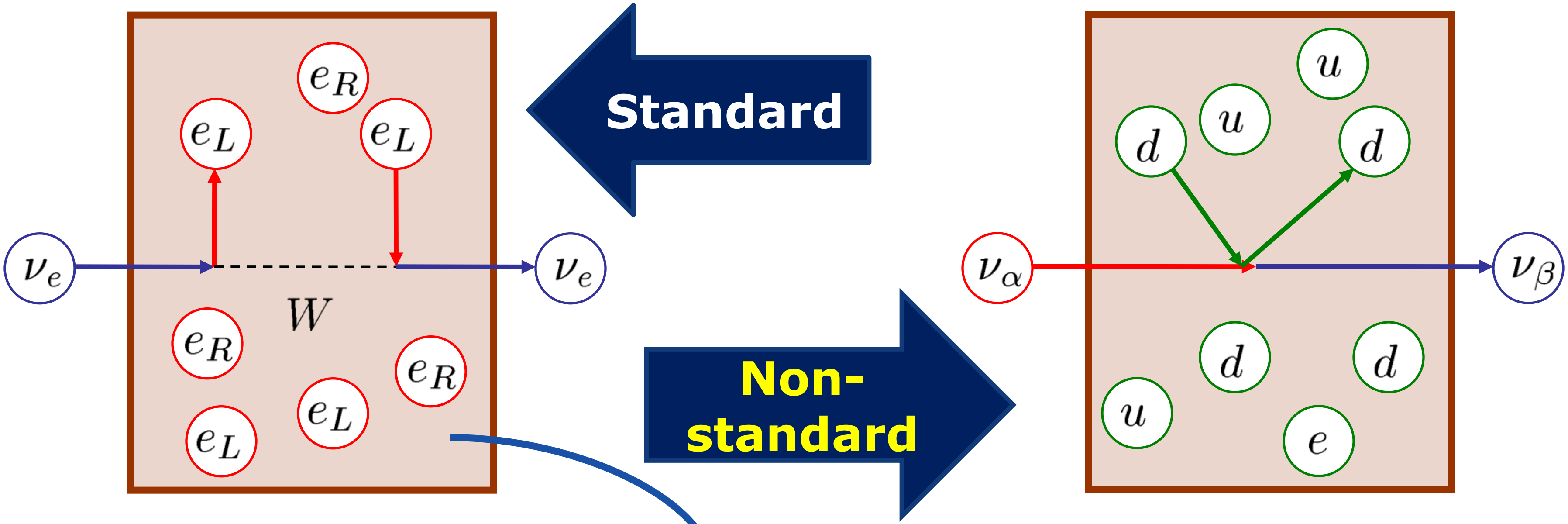
Break $SU(2)_L$ gauge symmetry explicitly

Neutrino propagation in matter with NSIs



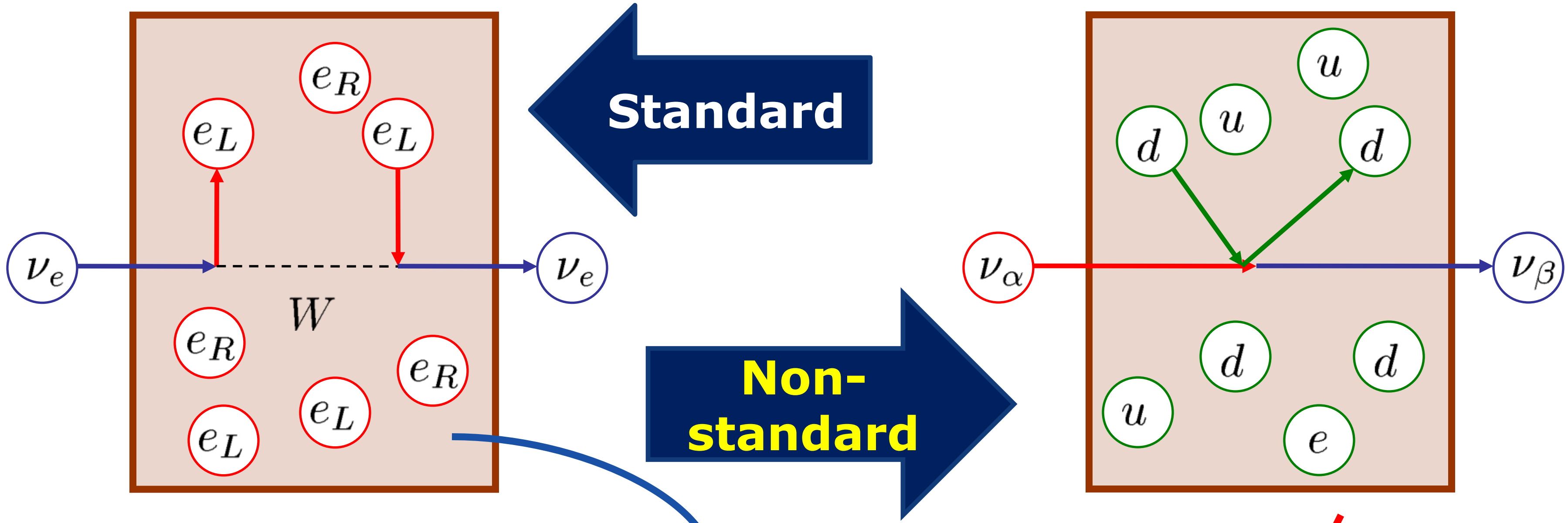
$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \frac{1}{2E}\left[U\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m^2_{21} & 0\\ 0 & 0 & \Delta m^2_{31}\end{pmatrix}U^\dagger + a\begin{pmatrix}1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau}\\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu}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

Neutrino propagation in matter with NSIs



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

Neutrino propagation in matter with NSIs



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

Neutrino oscillations with NSIs – two-flavors

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

$$\boxed{P(\nu_e \to \nu_\tau) = \sin^2 2\theta_M\ \sin^2\left(\frac{\Delta m^2_M L}{4E}\right)}$$

$$\left(\frac{\Delta m^2_M}{2EA}\right)^2 \equiv \left(\frac{\Delta m^2}{2EA}\cos 2\theta - (1+\epsilon_{ee}-\epsilon_{\tau\tau})\right)^2 + \left(\frac{\Delta m^2}{2EA}\sin 2\theta + 2\epsilon_{e\tau}\right)^2$$

$$\sin 2\theta_M \equiv \frac{\Delta m^2 \sin 2\theta + 4EA\epsilon_{e\tau}}{\Delta m^2_M}$$

Neutrino oscillations with NSIs – two-flavors

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$$\frac{1}{2E}U\begin{pmatrix}0 & 0\\ 0 & \Delta m^2\end{pmatrix}U^\dagger + A\begin{pmatrix}1 & 0\\ 0 & 0\end{pmatrix} \xrightarrow{E\to\infty} A\begin{pmatrix}1 & 0\\ 0 & 0\end{pmatrix}$$

Standard case

Non-standard case

$$\frac{1}{2E}U\begin{pmatrix}0 & 0\\ 0 & \Delta m^2\end{pmatrix}U^\dagger + A\begin{pmatrix}1+\epsilon_{ee} & \epsilon_{e\tau}\\ \epsilon_{e\tau} & \epsilon_{\tau\tau}\end{pmatrix} \xrightarrow{E\to\infty} A\begin{pmatrix}1+\epsilon_{ee} & \epsilon_{e\tau}\\ \epsilon_{e\tau} & \epsilon_{\tau\tau}\end{pmatrix}$$

NSIs at neutrino sources

$$\pi^+ \to \mu^+ + \nu_\mu , \quad \mu^+ \to e^+ + \overline{\nu}_\mu + \nu_e , \quad n \to p + e^- + \overline{\nu}_e$$

Standard

Non-standard

$$\pi^+ \to \mu^+ + \nu_e , \quad \mu^+ \to e^+ + \overline{\nu}_\mu + \nu_\mu , \quad n \to p + e^- + \overline{\nu}_\mu$$

NSIs at detectors

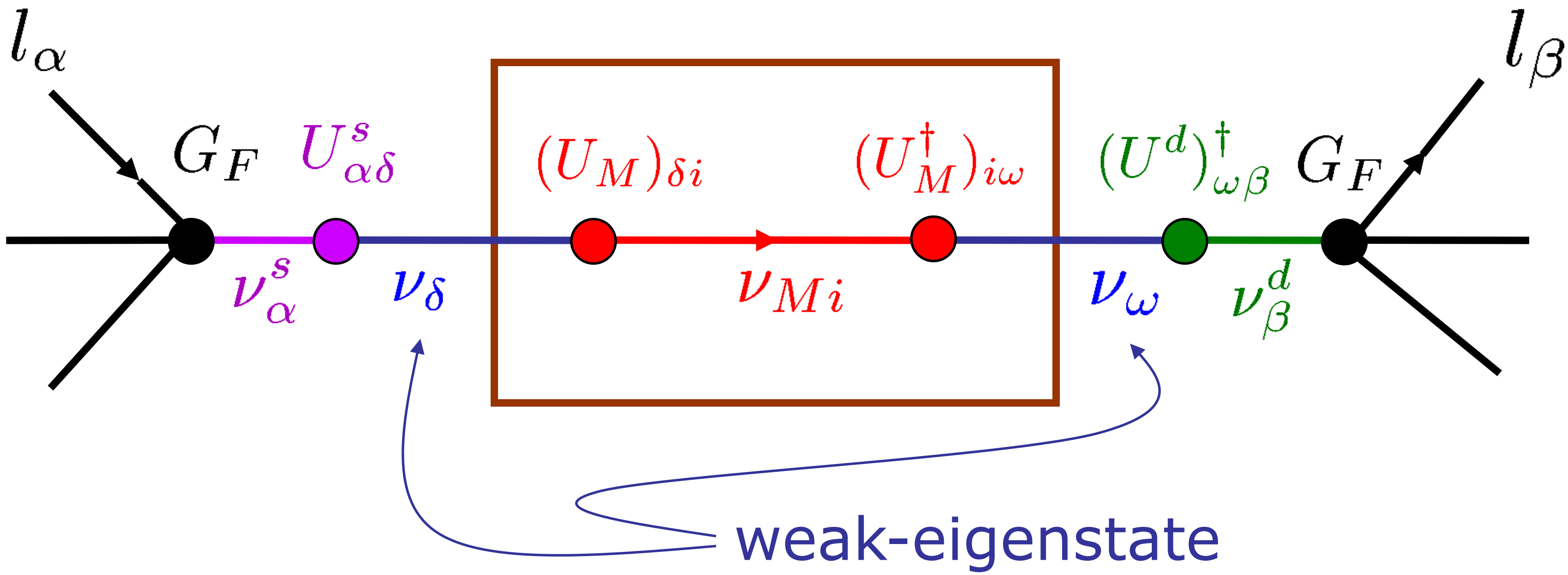
$$\nu_e + n \to p + \mu^-$$

Standard

Non-standard

$$\nu_\mu + n \to p + \mu^-$$

$$P(\nu_\alpha \to \nu_\beta) = \left| \sum_i [U^s U_M]_{\alpha i} \exp\left(i \frac{(\Delta m_M^2)_{i1} L}{4E} \right) [U^d U_M]^\dagger_{i\beta} \right|^2$$



Zero-distance effects: 2-flavor case

$$\frac{\Delta m^2 L}{4E} \to 0 \Rightarrow P(\nu_e \to \nu_\mu) \to \left(\epsilon^s_{e\mu} - \epsilon^d_{e\mu}\right)^2$$

NSIs with matter during propagation

Constraints by experiments with neutrinos and charged leptons (Davidson et al., 2003):

$$\begin{bmatrix} -0.9 < \varepsilon_{ee} < 0.75 & |\varepsilon_{e\mu}| \lesssim 3.8 \times 10^{-4} & |\varepsilon_{e\tau}| \lesssim 0.25 \\ & -0.05 < \varepsilon_{\mu\mu} < 0.08 & |\varepsilon_{\mu\tau}| \lesssim 0.25 \\ & & |\varepsilon_{\tau\tau}| \lesssim 0.4 \end{bmatrix}$$

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Constraints including loops (Biggio, Blennow, Fernández-Martínez, 2009):

Model independent bound for $\varepsilon_{e\mu}$ *increases* by a factor of 10^3!

Non-unitarity effects – Phenomenological consequences

Current experimental constraints at the 90% C.L. (Antusch *et al.*, 2008):

$$N = (1-\eta)U$$

$\eta \rightarrow$ Hermitian

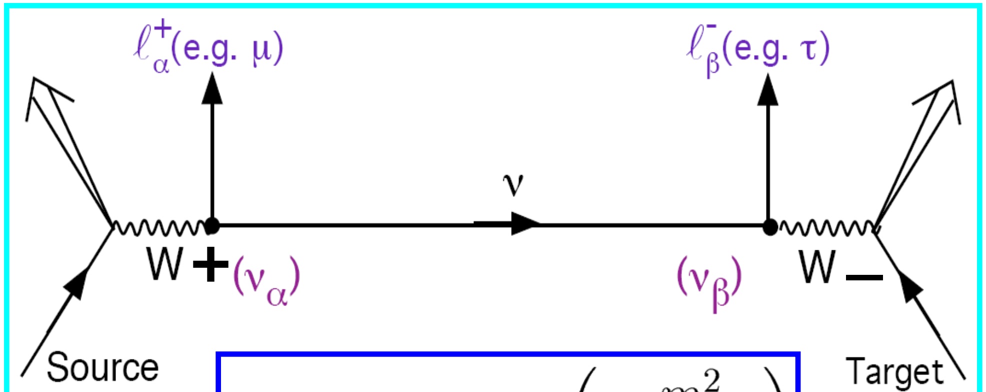
$U \rightarrow$ unitary

$$|\eta| < \begin{pmatrix} 2.0\times10^{-3} & 3.5\times10^{-5} & 8.0\times10^{-3} \\ \sim & 8.0\times10^{-4} & 5.1\times10^{-3} \\ \sim & \sim & 2.7\times10^{-3} \end{pmatrix}$$

$\mu \rightarrow e + \gamma$ etc,
W/Z decays,
universality,
ν-oscillation.

Non-unitary neutrino mixing:

$$A(W^+ \rightarrow l_\alpha^+ \nu_i) = \frac{V^*_{\alpha i}}{\sqrt{(VV^\dagger)_{\alpha\alpha}}}$$



$$A(\nu_i W^- \rightarrow l_\beta^-) = \frac{V_{\beta i}}{\sqrt{(VV^\dagger)_{\beta\beta}}}$$

$$\sum_i |A(W^+ \rightarrow l_\alpha^+ \nu_i)|^2 = 1$$

$$\mathrm{Prop}(\nu_i) = \exp\left(-i\frac{m_i^2}{2E}L\right)$$

$$\sum_i |A(\nu_i W^- \rightarrow l_\beta^-)|^2 = 1$$

Similar to the case of the NSIs in initial & final states.

Non-unitarity effects – Phenomenological consequences

Oscillation probability in vacuum (e.g., Antusch *et al.*, 2007):

$$\boxed{P_{\alpha\beta} = \sum_{i,j} \mathcal{F}^i_{\alpha\beta}\mathcal{F}^{j*}_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}(\mathcal{F}^i_{\alpha\beta}\mathcal{F}^{j*}_{\alpha\beta}) \sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right) + 2\sum_{i>j} \mathrm{Im}(\mathcal{F}^i_{\alpha\beta}\mathcal{F}^{j*}_{\alpha\beta}) \sin\left(\frac{\Delta m^2_{ij} L}{2E}\right)}$$

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"Zero-distance"
(near-detector) effect at $L = 0$

$$\mathcal{F}^i_{\alpha\beta} \equiv \sum (R^*)_{\alpha\gamma}(R^*)^{-1}_{\rho\beta}U^*_{\gamma i}U_{\rho i}$$

$$R_{\alpha\beta} \equiv \frac{(1-\eta)_{\alpha\beta}}{[(1-\eta)(1-\eta^\dagger)]_{\alpha\alpha}}$$

Non-unitarity effects – Phenomenological consequences

Oscillation probability in vacuum (e.g., Antusch *et al.*, 2007):

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Oscillation in matter (neutral currents are involved):

$$P(\nu_\mu \to \nu_\tau) \approx \sin^2\frac{\Delta_{23}}{2} - \sum_{l=4}^{6} s_{2l}s_{3l}\left[\sin(\delta_{2l}-\delta_{3l}) + A_{\rm NC}L\cos(\delta_{2l}-\delta_{3l})\right]\sin\Delta_{23}$$

$$P(\overline{\nu}_\mu \to \overline{\nu}_\tau) \approx \sin^2\frac{\Delta_{23}}{2} + \sum_{l=4}^{6} s_{2l}s_{3l}\left[\sin(\delta_{2l}-\delta_{3l}) + A_{\rm NC}L\cos(\delta_{2l}-\delta_{3l})\right]\sin\Delta_{23}$$

(Goswami, Ota 2008; Luo 2008; Xing 2009)

NSIs – What I and my collaborators have done

- NSI Hamiltonian effects on neutrino oscillations
  - ✓ Blennow, Ohlsson, Winter, JHEP **06**, 049 (2005)
  - ✓ Blennow, Ohlsson, Winter, Eur. Phys. J. C **49**, 1023 (2007)
- NSIs at MINOS and OPERA
  - ✓ Blennow, Ohlsson, Skrotzki, Phys. Lett. B **660**, 522 (2008)
  - ✓ Blennow, Meloni, Ohlsson, Terranova, Westerberg, Eur. Phys. J. C **56**, 529 (2008)
- Approximative two flavor NSIs
  - ✓ Blennow, Ohlsson, Phys. Rev. D **78**, 093002 (2008)
- NSIs for reactor neutrinos
  - ✓ Ohlsson, Zhang, Phys. Lett. B **671**, 99 (2009)
- Models and mappings for NSIs
  - ✓ Malinský, Ohlsson, Zhang, Phys. Rev. D **79**, 011301(R) (2009)
  - ✓ Meloni, Ohlsson, Zhang, JHEP **04**, 033 (2009)
  - ✓ Malinský, Ohlsson, Zhang, Phys. Rev. D **79**, 073009 (2009)
  - ✓ Malinský, Ohlsson, Xing, Zhang, Phys. Lett. B **679**, 242 (2009)

NSIs – What other physicists have done

- **Neutrino factory**
  - ✓ Huber, Kopp, Lindner, Minakata, Nunokawa, Ota, Ribeiro, Schwetz, Tang, Uchinami, Valle, Winter, Zukanovich-Funchal, …
- **Interactions and scattering**
  - ✓ Barranco, Berezhiani, Davidson, Kumericki, Mangano, Miele, Miranda, Moura, Pastor, Peña-Garay, Picek, Pinto, Pisanti, Rius, Rossi, Santamaria, Serpico, Valle, …
- **Loop bounds**
  - ✓ Biggio, Blennow, Fernández-Martínez
- **Beyond the SM**
  - ✓ Antusch, Baumann, Fernández-Martínez, …
- **CP violation**
  - ✓ Gago, Minakata, Nunokawa, Uchinami, Winter, Zukanovich-Funchal, …
- **Perturbation theory**
  - ✓ Kikuchi, Minakata, Uchinami, …
- **Gauge invariance**
  - ✓ Gavela, Hernandez. Ota, Winter, …
- **MINOS, OPERA, MiniBooNE, and future experiments**
  - ✓ DeWilde, Esteban-Pretel, Gago, Grossman, Guzzo, Huber, Johnson, Kitazawa, Kopp, Lindner, Nunokawa, Ota, Sato, Seton Williams, Spence, Sugiyama, Teves, Valle, Yasuda, Zukanovich-Funchal, …
- **Reactor, solar, and atmospheric neutrinos and superbeams**
  - ✓ Barranco, Berezhiani, Bergmann, Bolanos, de Holanda, Fornengo, Guzzo, Huber, Kopp, Krastev, Lindner, Maltoni, Miranda, Nunokawa, Ota, Palazzo, Peres, Raghavan, Rashba, Rossi, Sato, Tòmas, Tórtola, Valle, …
- **Supernovas and neutrino telescopes**
  - ✓ Esteban-Pretel, Fogli, Lisi, Miranda, Mirizzi, Montanino, Perez-Martinez, Raffelt, Tòmas, Valle, Weiss, Zepeda, …

Of the order of 500 papers on NSIs!

Models for NSIs

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

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

$$\mathcal{L}^{S}_{int} = -\lambda^{i}_{\alpha\beta}\overline{L^{c}_{\alpha}} i\sigma_2 L_{\beta} S_i$$

Integrating out the heavy scalar S generates the dimension 6 operator at tree level:

$$\mathcal{L}^{d=6,as}_{NSI} = 4\sum_{i} \frac{\lambda^{i}_{\alpha\beta}\lambda^{i*}_{\delta\gamma}}{m^2_{S_i}} (\overline{\ell^c}_{\alpha} P_L \nu_{\beta})(\bar{\nu}_{\gamma} P_R \ell^c_{\delta})$$

Antusch, Baumann, Fernández-Martínez, **2008**

Gauge invariance and NSIs

At high energy scales, where NSIs are originated, there exists SU(2)xU(1) gauge invariance.

Therefore, if there is a *six-dimensional operator*:

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

This must be a part of the gauge invariant operator

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

which involves four charged lepton operators.

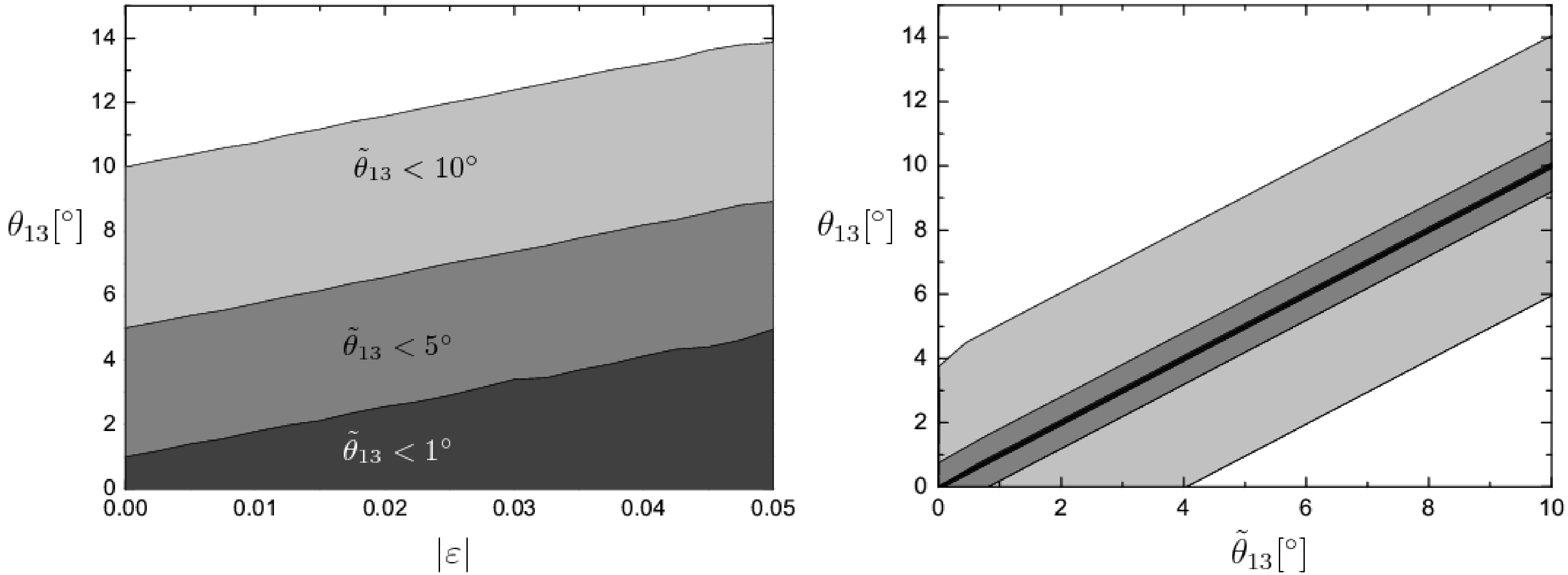
Thus, we have severe constrains from experiments:

$\mu \to 3e$: $\quad \mathrm{BR}(\mu \to 3e) < 10^{-12} \Rightarrow \varepsilon^{ee}_{e\mu} < 10^{-6}$

NSIs with SBL experiments

Ohlsson, Zhang, arXiv:0809.4835

For example Double Chooz and Daya Bay



- $\theta_{13} < 14^\circ$, which is larger than the CHOOZ bound 10°
- In despite a very small θ_{13}, a sizable effective mixing angle can be achieved due to mimicking effects.
- Even if the effective mixing angle is too small to be measured in a reactor experiment, a discovery search of a non-vanishing θ_{13} may still be carried out at a future neutrino factory.

The results are model independent!

NSIs with LBL experiments

Meloni, Ohlsson, Zhang, arXiv:0901.1784

Mappings for the effective masses with NSIs:

$$
\begin{aligned}
\tilde{m}_1^2 &\simeq \Delta_{31}\left(\hat{A}+\eta s_{12}^2+\hat{A}\varepsilon_{ee}\right) , \\
\tilde{m}_2^2 &\simeq \Delta_{31}\left[\eta c_{12}^2-\hat{A}s_{23}^2\left(\varepsilon_{\mu\mu}-\varepsilon_{\tau\tau}\right)-\hat{A}s_{23}c_{23}\left(\varepsilon_{\mu\tau}+\varepsilon_{\mu\tau}^*\right)+\hat{A}\varepsilon_{\mu\mu}\right] \\
\tilde{m}_3^2 &\simeq \Delta_{31}\left[1+\hat{A}\varepsilon_{\tau\tau}+\hat{A}s_{23}^2\left(\varepsilon_{\mu\mu}-\varepsilon_{\tau\tau}\right)+\hat{A}s_{23}c_{23}\left(\varepsilon_{\mu\tau}+\varepsilon_{\mu\tau}^*\right)\right] ,
\end{aligned}
$$

Mappings for the effective mixing matrix elements with NSIs:

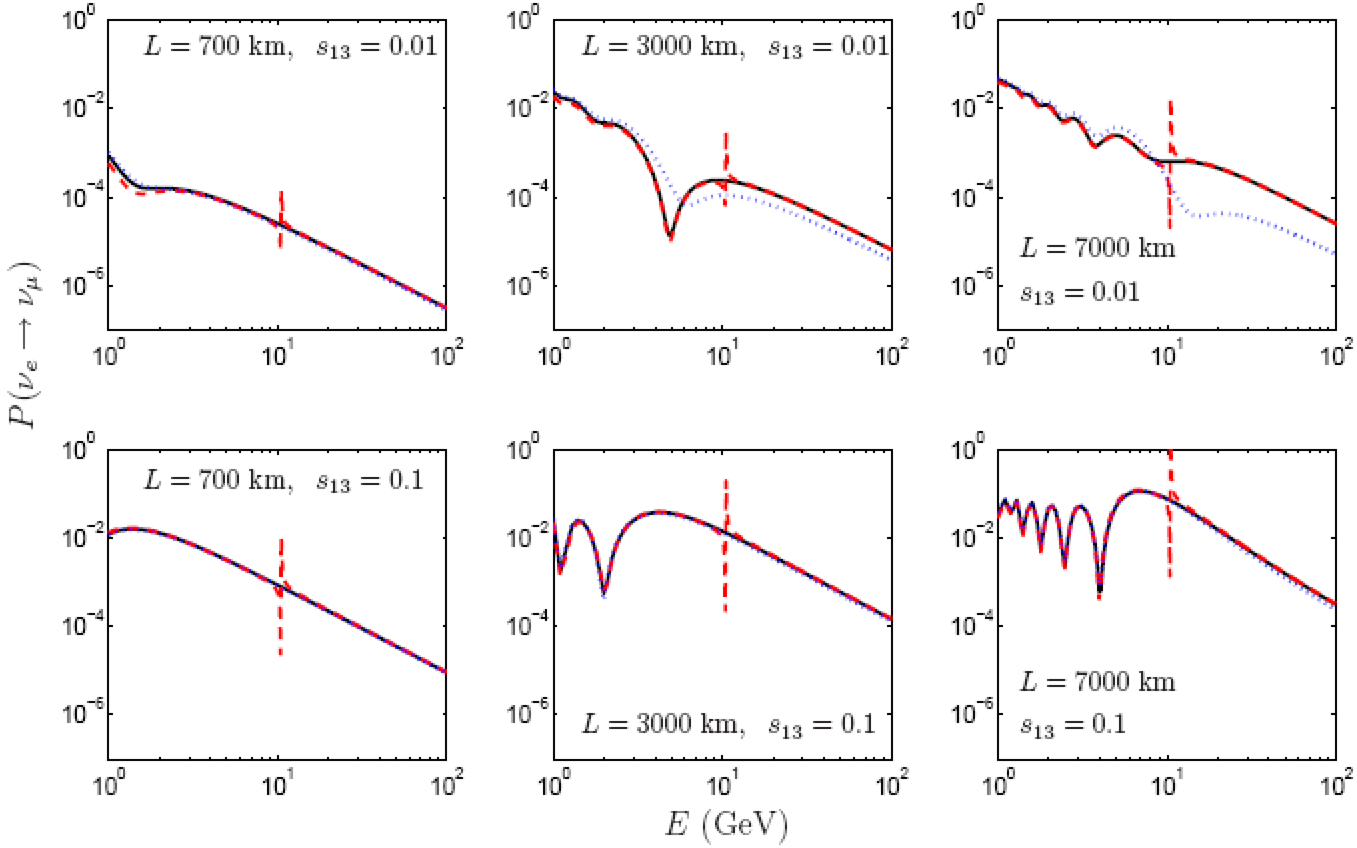
$$
\begin{aligned}
\tilde{V}_{e2} &\simeq \frac{\eta s_{12}c_{12}}{\hat{A}}+c_{23}\varepsilon_{e\mu}-s_{23}\varepsilon_{e\tau} , \\
\tilde{V}_{e3} &\simeq \frac{s_{13}e^{-\mathrm{i}\delta}}{1-\hat{A}}+\frac{\hat{A}(s_{23}\varepsilon_{e\mu}+c_{23}\varepsilon_{e\tau})}{1-\hat{A}} , \\
\tilde{V}_{\mu2} &\simeq c_{23}+s_{23}^2c_{23}\hat{A}\left(\varepsilon_{\tau\tau}-\varepsilon_{\mu\mu}\right)+s_{23}\hat{A}\left(s_{23}\varepsilon_{\mu\tau}-c_{23}^2\varepsilon_{\mu\tau}^*\right) , \\
\tilde{V}_{\mu3} &\simeq s_{23}+\hat{A}\left[s_{23}\left(\varepsilon_{\mu\mu}-\varepsilon_{\tau\tau}\right)+c_{23}\varepsilon_{\mu\tau}-s_{23}^2c_{23}\left(\varepsilon_{\mu\tau}+\varepsilon_{\mu\tau}^*\right)+s_{23}^3\left(\varepsilon_{\tau\tau}-\varepsilon_{\mu\mu}\right)\right]
\end{aligned}
$$

The results are model independent!

NSIs with LBL experiments

Meloni, Ohlsson, Zhang, arXiv:0901.1784

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



Solid curves = exact numerical results

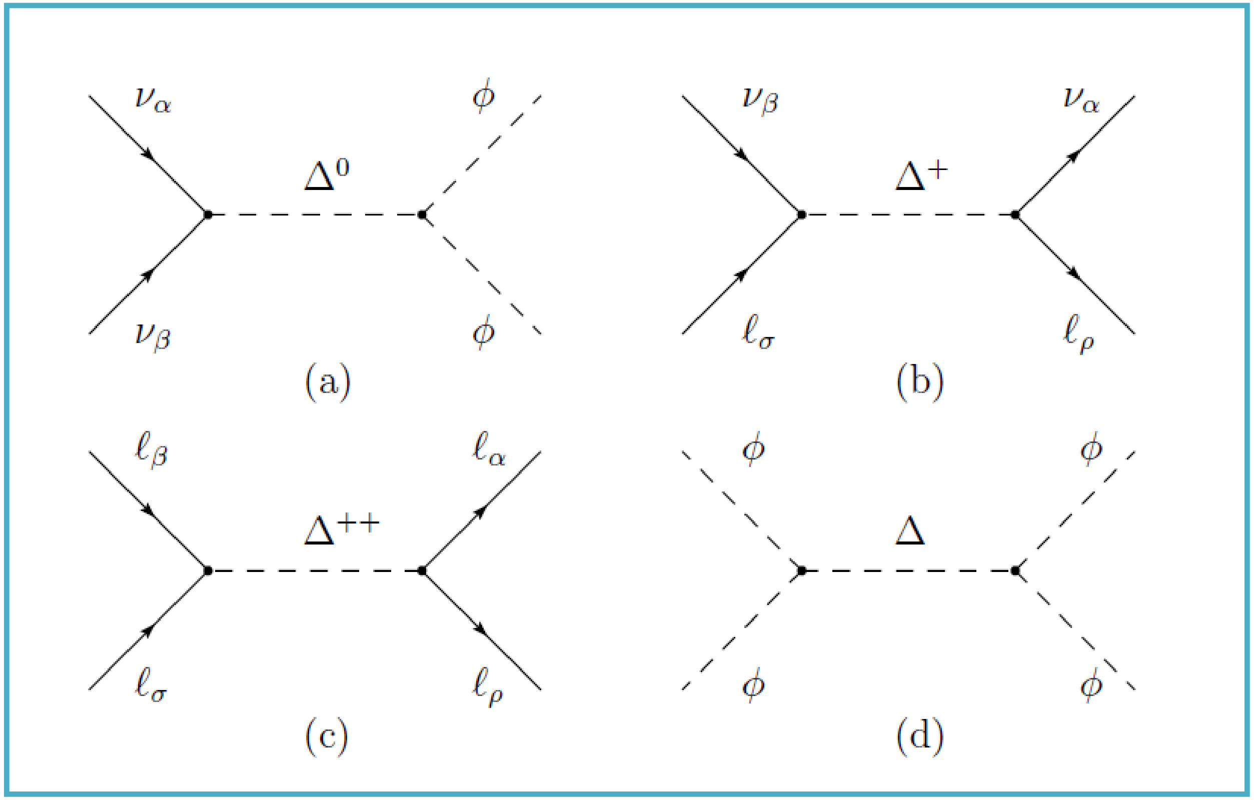
Dashed curves = our approximative results

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!

NSIs from a type-II seesaw model

Tree level diagrams with the exchange of heavy triplet Higgs:



Malinský, Ohlsson, Zhang, PRD (RC) 2009

a. Light neutrino Majorana mass term

b. Non-standard neutrino interactions

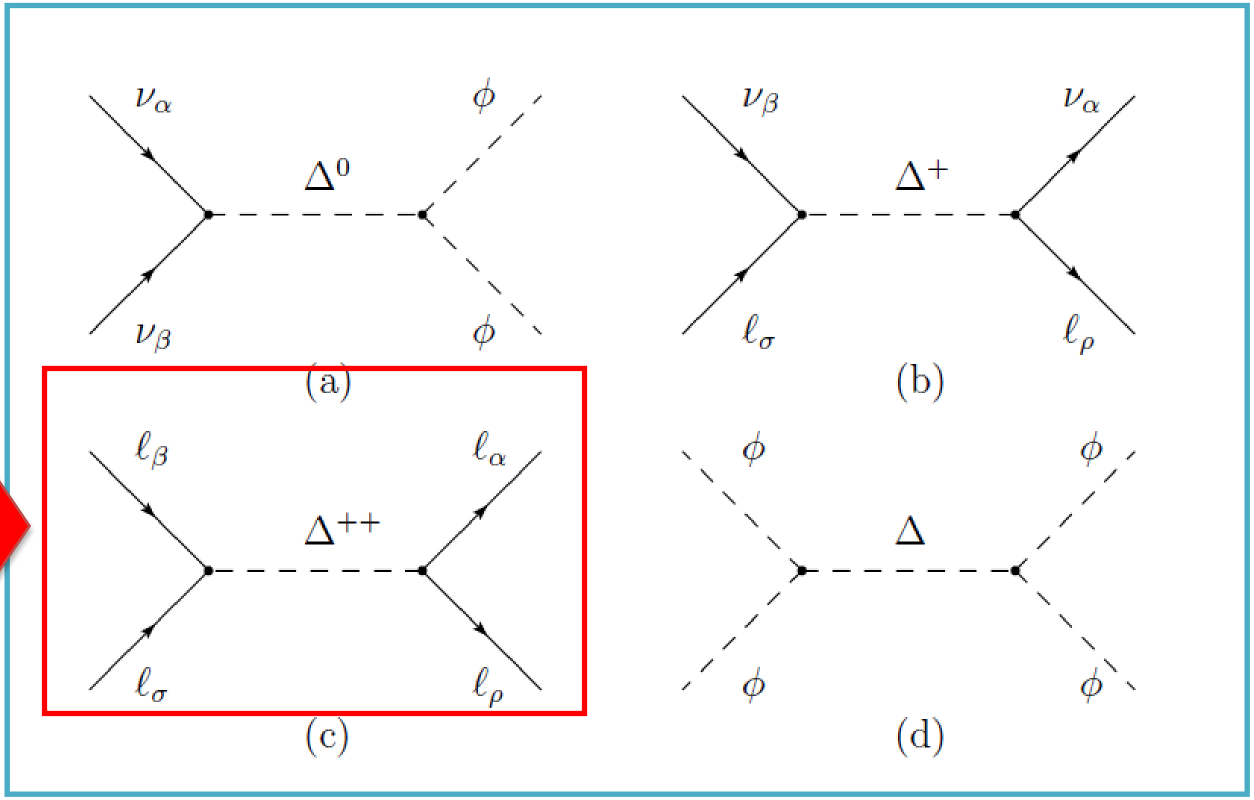
c. Interactions of four charged leptons

d. Self-coupling of the SM Higgs doublets

NSIs from a type-II seesaw model

Tree level diagrams with the exchange of heavy triplet Higgs:

To be avoided



Malinský, Ohlsson, Zhang, PRD (RC) 2009

a. Light neutrino Majorana mass term

b. Non-standard neutrino interactions

c. <u>Interactions of four charged leptons</u>

d. Self-coupling of the SM Higgs doublets

NSIs from a type-II seesaw model

Integrating out the heavy triplet field (at tree-level)!

Relations between neutrino mass matrix and NSI parameters:

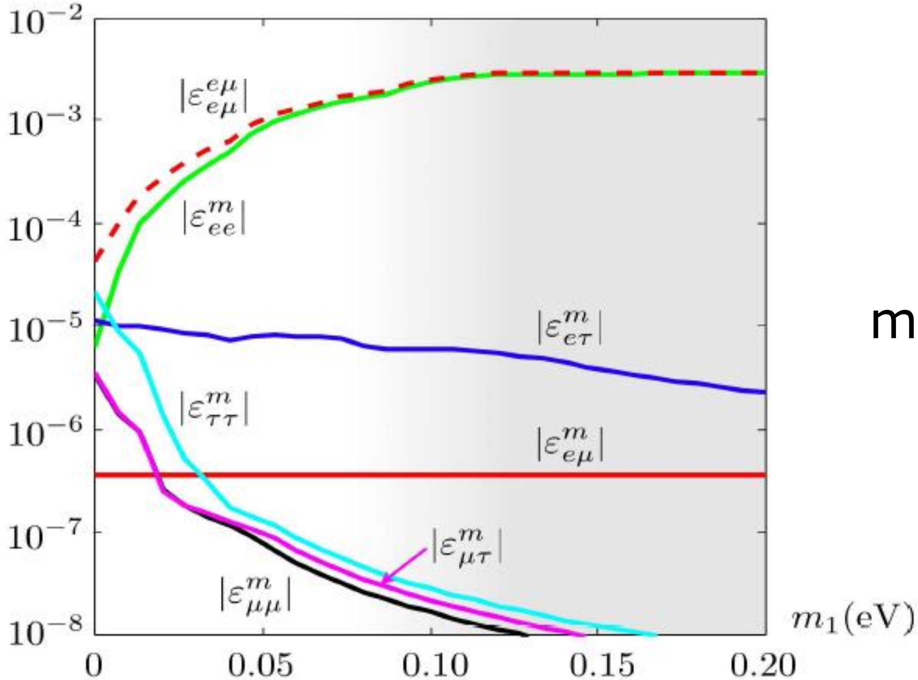
$$\boxed{\varepsilon^{\rho\sigma}_{\alpha\beta} = -\frac{m_\Delta^2}{8\sqrt{2}G_F v^4 \lambda_\phi^2}\left(m_\nu\right)_{\sigma\beta}\left(m_\nu^\dagger\right)_{\alpha\rho}}$$

Experimental constraints from LFV and rare decays, …:

Decay	Constraint on	Bound
$\mu^- \to e^- e^+ e^-$	$\lvert\varepsilon^{e\mu}_{ee}\rvert$	3.5×10^{-7}
$\tau^- \to e^- e^+ e^-$	$\lvert\varepsilon^{e\tau}_{ee}\rvert$	1.6×10^{-4}
$\tau^- \to \mu^- \mu^+ \mu^-$	$\lvert\varepsilon^{\mu\tau}_{\mu\mu}\rvert$	1.5×10^{-4}
$\tau^- \to e^- \mu^+ e^-$	$\lvert\varepsilon^{e\tau}_{e\mu}\rvert$	1.2×10^{-4}
$\tau^- \to \mu^- e^+ \mu^-$	$\lvert\varepsilon^{\mu\tau}_{\mu e}\rvert$	1.3×10^{-4}
$\tau^- \to e^- \mu^+ \mu^-$	$\lvert\varepsilon^{e\tau}_{\mu\mu}\rvert$	1.2×10^{-4}
$\tau^- \to e^- e^+ \mu^-$	$\lvert\varepsilon^{e\tau}_{\mu e}\rvert$	9.9×10^{-5}
$\mu^- \to e^- \gamma$	$\lvert\sum_\alpha \varepsilon^{e\mu}_{\alpha\alpha}\rvert$	1.4×10^{-4}
$\tau^- \to e^- \gamma$	$\lvert\sum_\alpha \varepsilon^{e\tau}_{\alpha\alpha}\rvert$	3.2×10^{-2}
$\tau^- \to \mu^- \gamma$	$\lvert\sum_\alpha \varepsilon^{\mu\tau}_{\alpha\alpha}\rvert$	2.5×10^{-2}
$\mu^+ e^- \to \mu^- e^+$	$\lvert\varepsilon^{\mu e}_{\mu e}\rvert$	3.0×10^{-3}

NSIs from a type-II seesaw model

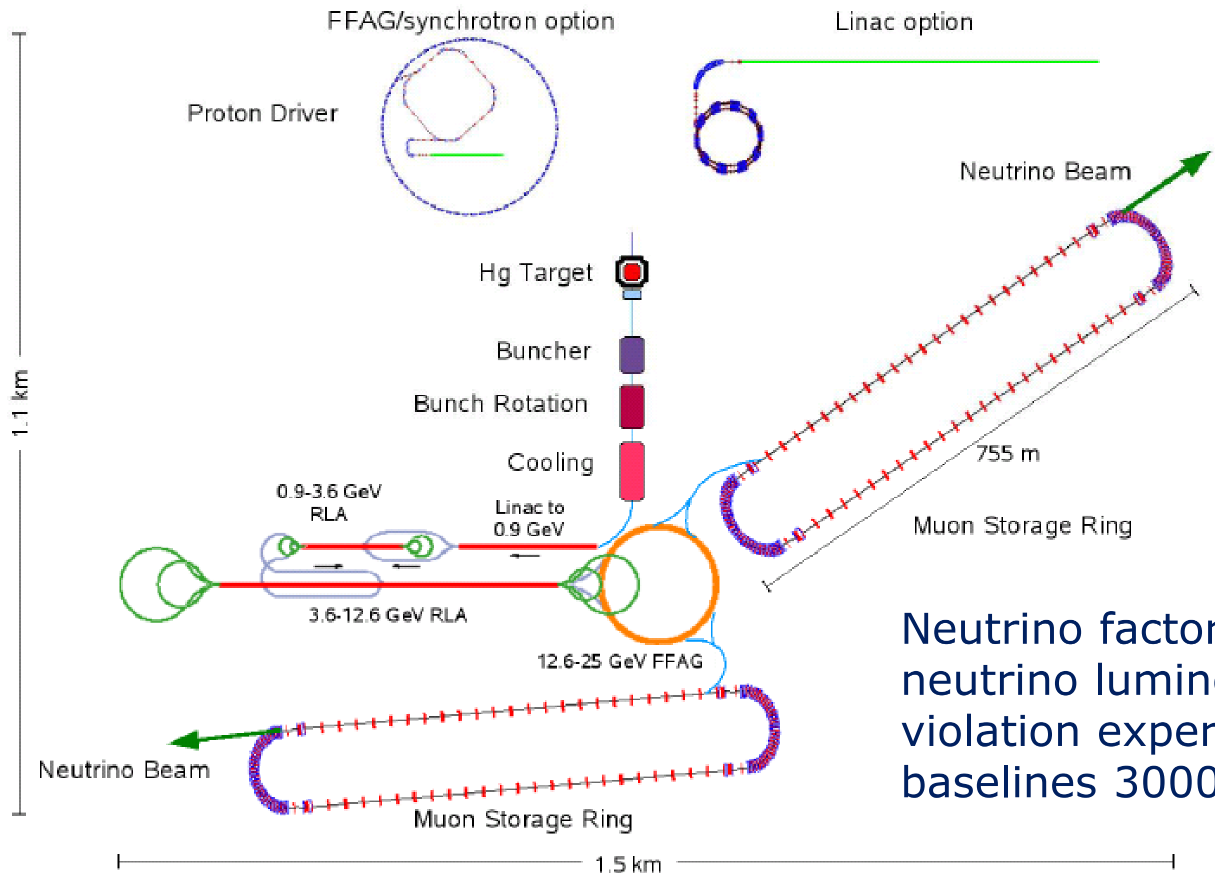
Upper bounds on NSI parameters in the triplet seesaw model:



m_Δ = 1 TeV

- For a hierarchical mass spectrum, (i.e., m_1<0.05 eV), all the NSI effects are suppressed.
- For a nearly degenerate mass spectrum, (i.e., m_1>0.1 eV), two NSI parameters can be sizable.

Phenomena at a neutrino factory



$$\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$$

$$\mu^- \to e^- + \nu_\mu + \bar{\nu}_e$$

Neutrino factory can provide sufficient neutrino luminosity to perform CP violation experiments at very long baselines 3000-7500 km.

$$\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$$

$$\mu^- \to e^- + \nu_\mu + \bar{\nu}_e$$

Power of neutrino factory:

Sensitivity reach for θ_{13} : $\sin^2 2\theta_{13} \sim 10^{-4} - 10^{-5}$

May have sensitivity for ε at the same order

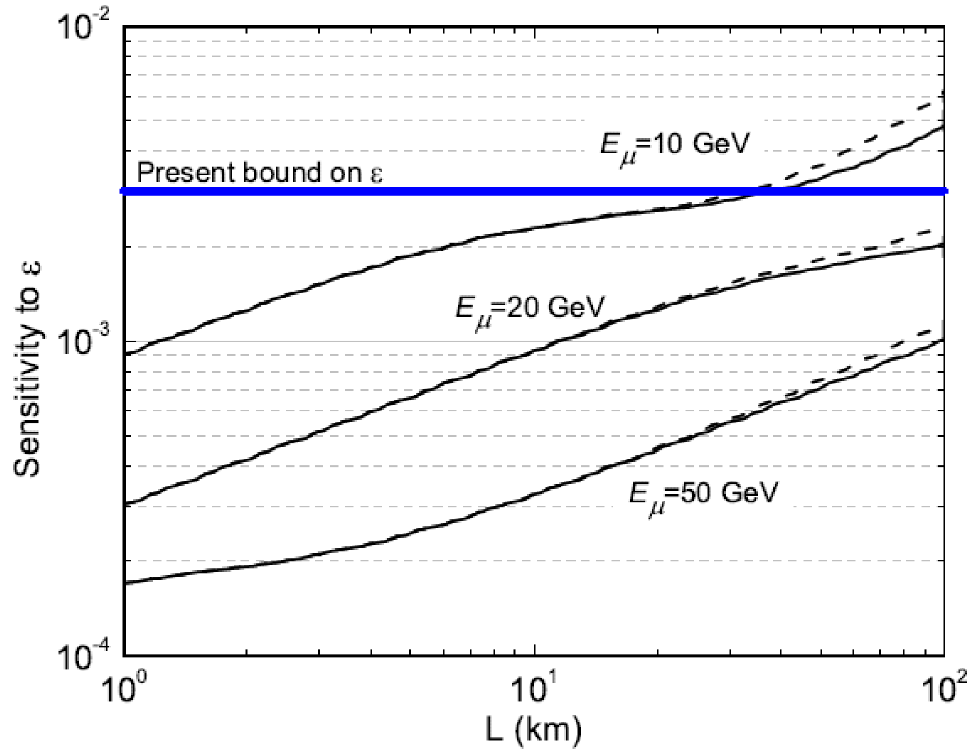
Phenomena at a neutrino factory

- Wrong sign muons at the near detector of a neutrino factory

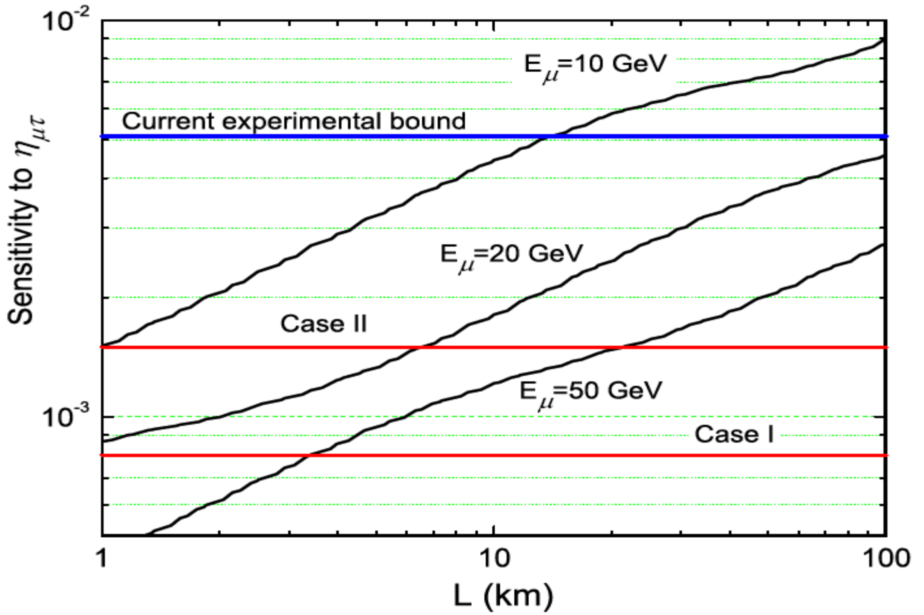
$$\mu^- \to e^- \nu_\mu \overline{\nu_e} \quad \textbf{SD vs. NSI} \quad \mu^- \to e^- \nu_e \overline{\nu_\mu}$$

Sensitivity limits at 90 % C.L.

Our setup:
10^{21} useful muon decays of each polarity, 4+4 years running of neutrinos and antineutrinos, a magnetized iron detector with fiducial mass 1 kt.



Sensitivity search at a neutrino factory



$$P_{\mu\tau} \simeq 4|\eta_{\mu\tau}|^2 + 4 s_{23}^2 c_{23}^2 \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) - 4|\eta_{\mu\tau}| \sin\delta_{\mu\tau} s_{23} c_{23} \sin\left(\frac{\Delta m_{31}^2 L}{2E}\right)$$

A near detector setup: An excellent probe for non-unitarity effects

The sensitivity is <u>decreasing</u> with the baseline length due to oscillation effects. A distance less than 100 km would be favorable for a near detector.

Malinský, Ohlsson, Zhang, arXiv:0903.1961

Inverse seesaw

SM + 3 heavy right-handed neutrinos + 3 SM gauge singlet neutrinos

Mohapatra, Valle, 1986

$$-\mathcal{L}_{\rm m} = \overline{\nu_{\rm L}} M_{\rm D} \nu_{\rm R} + \overline{S} M_{\rm R} \nu_{\rm R} + \frac{1}{2} \overline{S} \mu S^c + {\rm H.c.}$$

9x9 ν-mass matrix:

$\{\nu_L, \nu_R^c, S^c\}$

$$\boxed{M_\nu = \begin{pmatrix} 0 & M_{\rm D} & 0 \\ M_{\rm D}^T & 0 & M_{\rm R}^T \\ 0 & M_{\rm R} & \mu \end{pmatrix}}$$

Light neutrino mass matrix:

$$\boxed{m_\nu \simeq M_{\rm D} M_{\rm R}^{-1} \mu (M_{\rm R}^T)^{-1} M_{\rm D}^T = F \mu F^T}$$

Inverse seesaw

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$$-\mathcal{L}_{\rm m} = \overline{\nu_{\rm L}} M_{\rm D} \nu_{\rm R} + \overline{S} M_{\rm R} \nu_{\rm R} + \frac{1}{2} \overline{S} \mu S^c + {\rm H.c.}$$

LNV: tiny

9x9 ν-mass matrix:

$\{\nu_L, \nu_R^c, S^c\}$

$$\boxed{M_\nu = \begin{pmatrix} 0 & M_{\rm D} & 0 \\ M_{\rm D}^T & 0 & M_{\rm R}^T \\ 0 & M_{\rm R} & \mu \end{pmatrix}}$$

Light neutrino mass matrix:

$$\boxed{m_\nu \simeq M_{\rm D} M_{\rm R}^{-1} \mu (M_{\rm R}^T)^{-1} M_{\rm D}^T = F \mu F^T}$$

In the limit $\mu \to 0$: massless neutrinos & lepton number conservation

Realization in extra dimensional theories!

(Blennow, Melbéus, Ohlsson, Zhang, in progress)

Phenomenological consequences of the inverse seesaw

Non-unitarity effects

Malinský, Ohlsson, Zhang, PRD 2009

$$M_\nu = \begin{pmatrix} 0 & M_\mathrm{D} & 0 \\ M_\mathrm{D}^T & 0 & M_\mathrm{R} \\ 0 & M_\mathrm{R}^T & \mu \end{pmatrix}$$

$$\boxed{V = \begin{pmatrix} V_{3\times3} & V_{3\times6} \\ V_{6\times3} & V_{6\times6} \end{pmatrix}}$$

In the inverse seesaw model, the overall **9×9** neutrino mass matrix can be diagonalized by a unitary matrix:

$$\boxed{V^\dagger M_\nu V^* = \bar{M}_\nu = \mathrm{diag}(m_i, M_j^n, M_k^{\tilde{n}})}$$

The charged current Lagrangian in the mass basis:

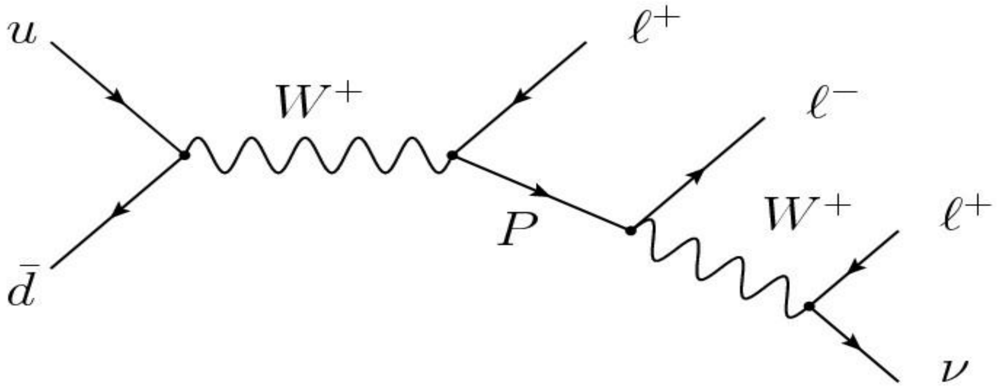
$$\boxed{-\mathcal{L}_\mathrm{CC} = \frac{g}{\sqrt{2}} W_\mu^- \overline{\ell_\mathrm{L}} \gamma^\mu \left(N \nu_{m\mathrm{L}} + F U_\mathrm{R}^* P_m^c \right) + \mathrm{H.c.}}$$

F governs the magnitude of non-unitarity effects

$$F = M_\mathrm{D} M_\mathrm{R}^{-1} \begin{cases} \sim (m_\nu/M_R)^{1/2} & \text{(Type-I seesaw)} \\ \sim (m_\nu/\mu)^{1/2} & \text{(Inverse seesaw)} \end{cases}$$

Collider signatures

- Tri-lepton production



LFV, but not LNV
Small SM background

$$pp \to \ell_\alpha^\pm \ell_\beta^\pm \ell_\gamma^\mp \nu(\bar{\nu}) + \text{jets}$$

- Lepton flavor violating decays: $\tau \to \mu\gamma$, $\tau \to e\gamma$, $\mu \to e\gamma$

$$\mathrm{BR}\left(\ell_\alpha \to \ell_\beta \gamma\right) = \frac{\alpha_W^3 s_W^2 m_{\ell_\alpha}^5}{256\pi^2 M_W^4 \Gamma_\alpha} \left| \sum_{i=1}^{3} K_{\alpha i} K_{\beta i}^* I\left(\frac{m_{P_i}}{M_W^2}\right) \right|^2$$

Different from the type-I seesaw, in the inverse seesaw model, one can have sizeable K without facing the difficulty of neutrino mass generation since they are decoupled.

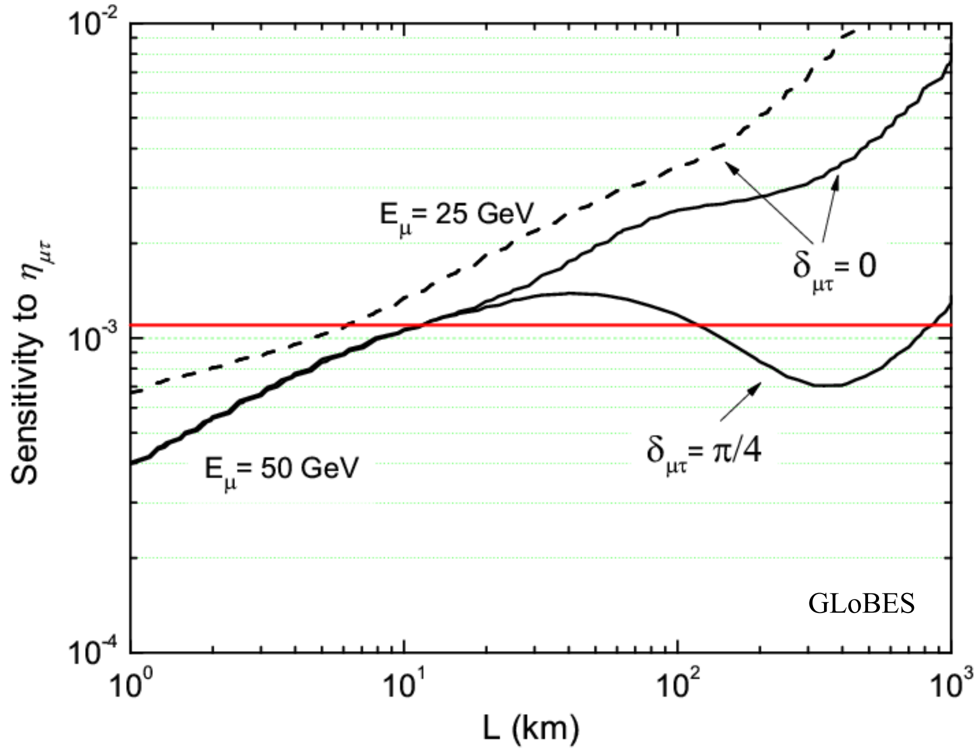
Sensitivity search at a neutrino factory

The $\nu_\mu \rightarrow \nu_\tau$ channel together with a near detector provides us with the most favorable setup to constrain the non-unitarity effects.

$$\boxed{P_{\mu\tau} \simeq 4 s_{23}^2 c_{23}^2 \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) - 4|\eta_{\mu\tau}| \sin\delta_{\mu\tau} s_{23} c_{23} \sin\left(\frac{\Delta m_{31}^2 L}{2E}\right) + 4|\eta_{\mu\tau}|^2}$$

We consider a typical neutrino factory setup with an OPERA-like near detector with fiducial mass of 5 kt. We assume a setup with approximately 10^{21} useful muon decays and five years of neutrino and another five years of anti-neutrino running.

Malinský, Ohlsson, Xing, Zhang, arXiv:0905.2889

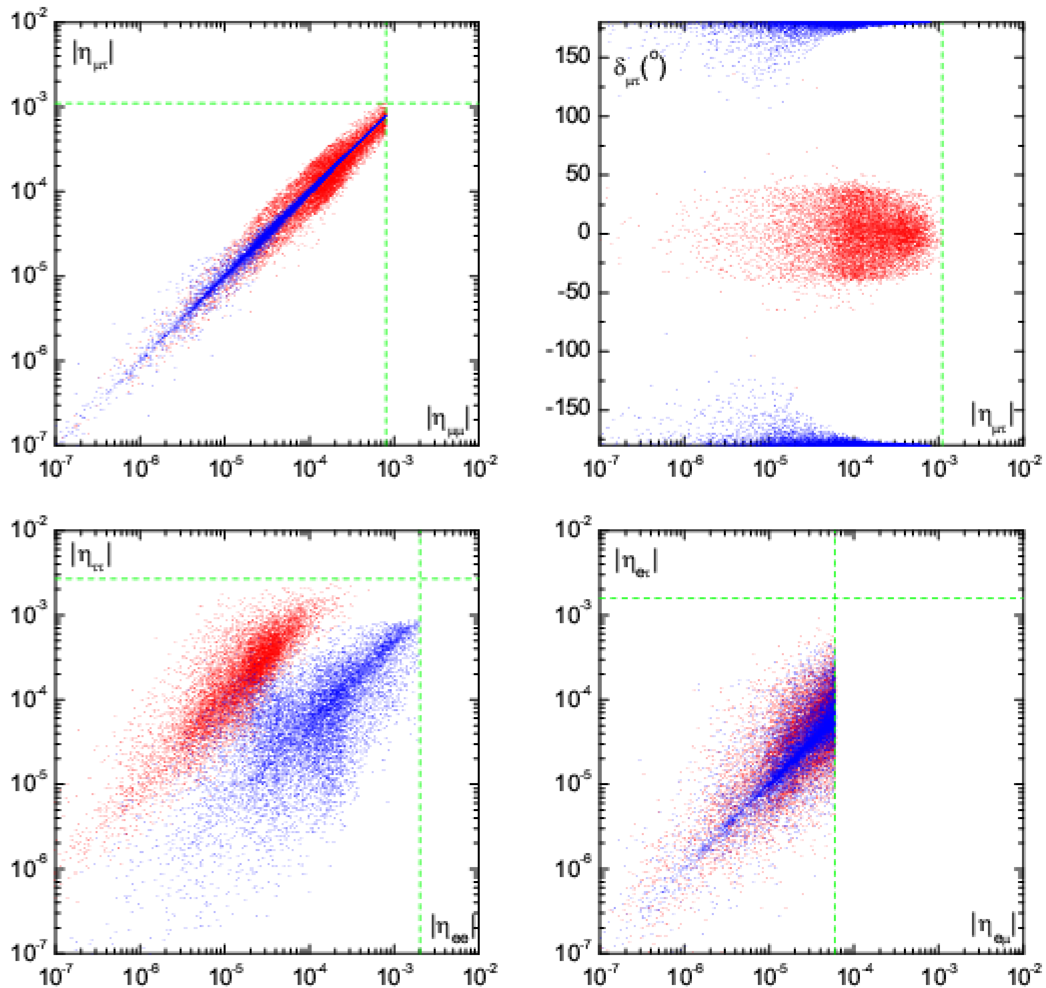


Correlation among NU parameters in the MISS

MISS = minimal inverse seesaw scenario

SM + two RH neutrinos + two LH SM gauge singlets

Red = NH
Blue = IH
Green = exp.



Each plot: 10^4 points

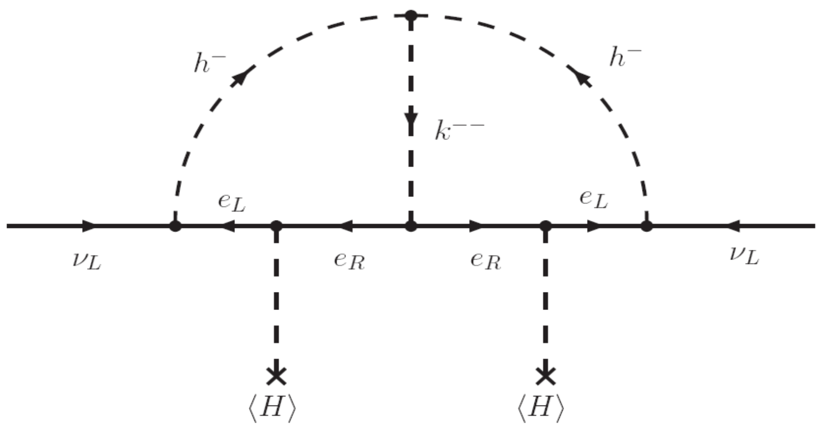
The points make up allowed regions for the MISS.

Malinský, Ohlsson, Xing, Zhang, arXiv:0905.2889

NSIs in the Zee-Babu model

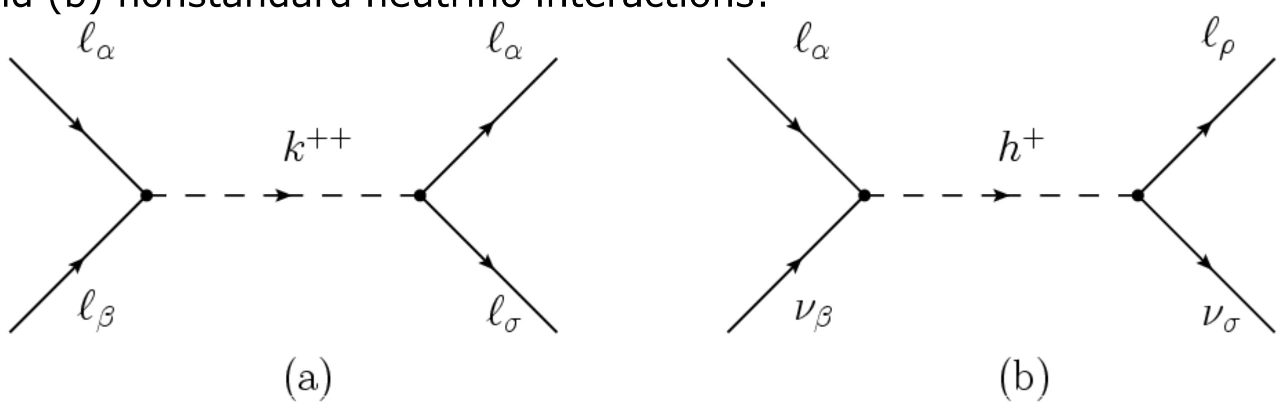
$$\mathcal{L} \;=\; \mathcal{L}_{\rm SM} + f_{\alpha\beta} L_{L\alpha}^T C i\sigma_2 L_{L\beta} h^+ + g_{\alpha\beta} \overline{e_\alpha^c} e_\beta k^{++}$$
$$-\;\; \mu h^- h^- k^{++} + {\rm h.c.} + V_H \;,$$

(Zee, 1985; 1986; Babu, 1988)



Light neutrino masses are generated by two-loop diagram!

The diagrams below are responsible for (a) non-standard interactions of four charged lepton, and (b) nonstandard neutrino interactions:

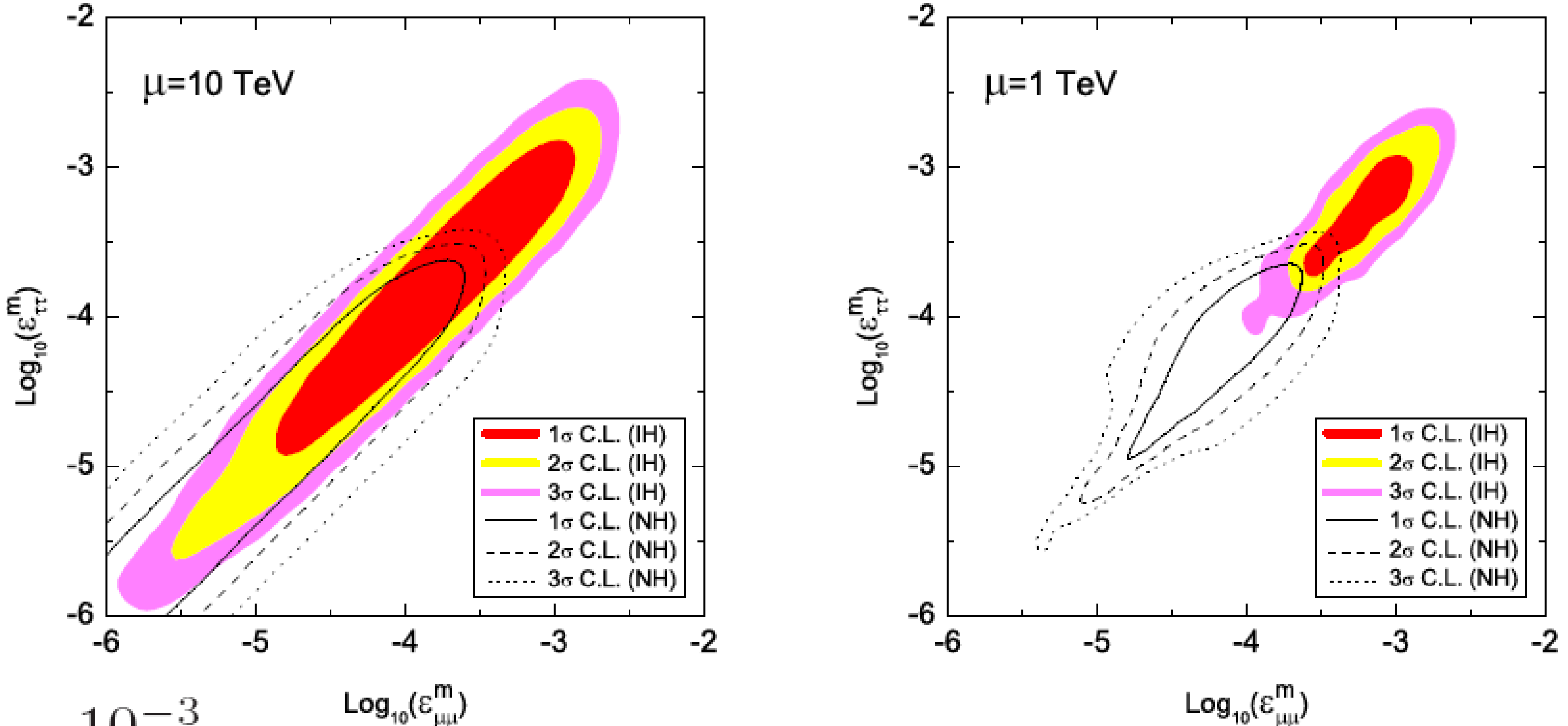


NSIs in the Zee-Babu model

Accepted by PLB today!

$$\mathcal{L} = \mathcal{L}_{\rm SM} + f_{\alpha\beta} L^T_{L\alpha} C i\sigma_2 L_{L\beta} h^+ + g_{\alpha\beta} \overline{e^c_\alpha} e_\beta k^{++} - \mu h^- h^- k^{++} + {\rm h.c.} + V_H \ ,$$

(Zee, 1985; 1986; Babu, 1988)



$\varepsilon \sim 10^{-3}$

Only for IH!

NSI parameters are correlated to neutrino masses

(Ohlsson, Schwetz, Zhang, arXiv:0909.0455)

NSIs for neutrino cross-sections

Neutrino NSIs with either electrons or 1st generation quarks can be constrained by low-energy scattering data.

Bounds are *stringent* for muon neutrino interactions, *loose* for electron neutrino, and *do not exist* for tau neutrino.

Note! In the present overview of the upper bounds on the NSI parameters, the results from Biggio, Blennow, Fernández-Martínez (0908.0607) have not been included.

Summary & conclusions

1. Non-standard neutrino interactions could be responsible for neutrino flavor transitions on a sub-leading level.
2. Mixing angles measured in reactor neutrino experiments could be dramatically modified by NSIs at sources and detectors.
3. Low-energy neutrino scattering experiments can be used to set bounds on NSI parameters.
4. The mimicking effects induced by NSIs play a very important role in short baseline experiments.
5. In the triplet seesaw model, sizable NSIs can be generated with a nearly degenerate neutrino mass spectrum.
6. Among low-scale fermionic seesaw models, the inverse seesaw model turns out to be the most plausible and realistic one, giving birth to sizable unitarity violation effects.
7. The LHC and a neutrino factory open a new window towards determining the possible NSI parameters.

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Thanks!