Non-Standard Neutrino Interactions

Tommy Ohlsson

Department of Theoretical Physics,
Royal Institute of Technology (KTH),
Stockholm, Sweden

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My collaborators

He Zhang

Walter Winter

Francesco Terranova

Michal Malinský

Davide Meloni

Mattias Blennow

Zhi-zhong Xing

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?
- Non-standard interactions for neutrino cross-sections
- 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

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

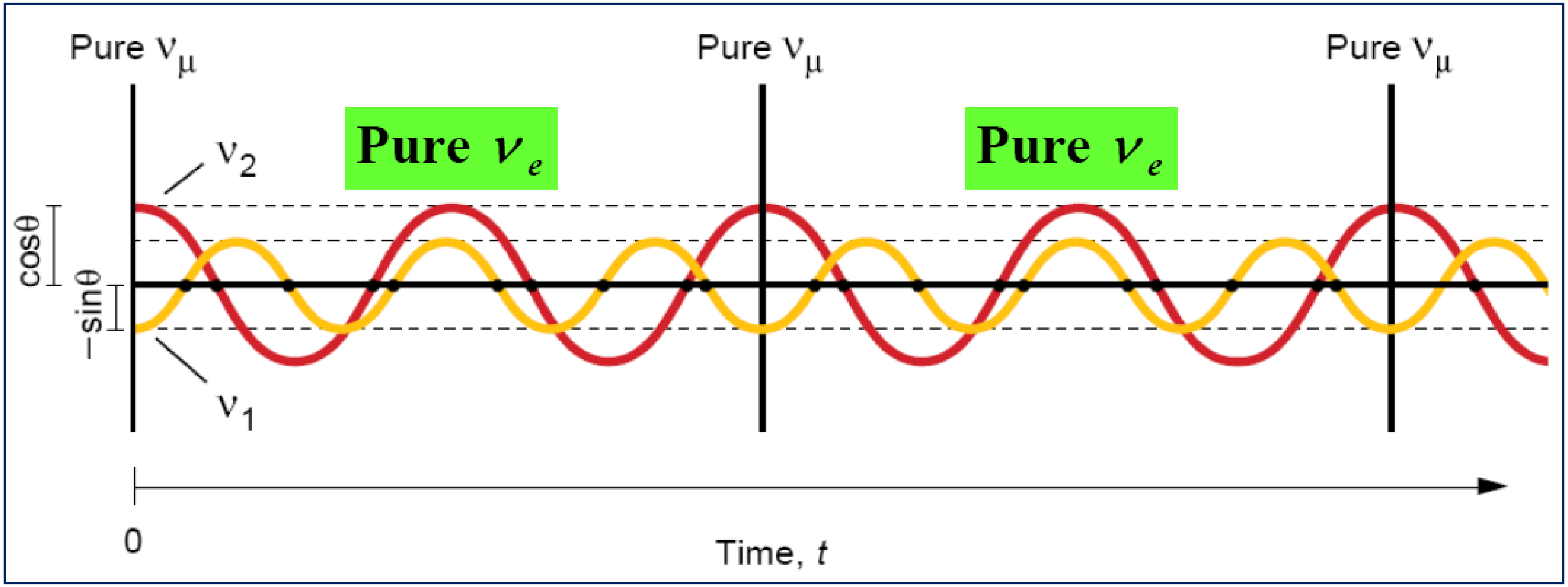
Effective matter potential

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

Neutrino oscillations

Two-flavor illustration!

Flavor changes happen during the propagation of neutrinos!



Neutrino oscillation parameters

parameter	best fit	2σ	3σ
Δm^2_{21} $[10^{-5}\text{eV}^2]$	$7.65^{+0.23}_{-0.20}$	7.25–8.11	7.05–8.34
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\text{eV}^2]$	$2.40^{+0.12}_{-0.11}$	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).

NSIs – Phenomenological consequences

The widely studied operators responsible for NSIs:

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

(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

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

Non-renormalizable!
Not gauge invariant!

Break $SU(2)_L$ gauge symmetry explicitly

Neutrino oscillations and …

- Neutrino oscillations:

  The Super-Kamiokande, SNO, and KamLAND neutrino oscillation experiments have <u>strong</u> evidences that neutrino oscillations occur.

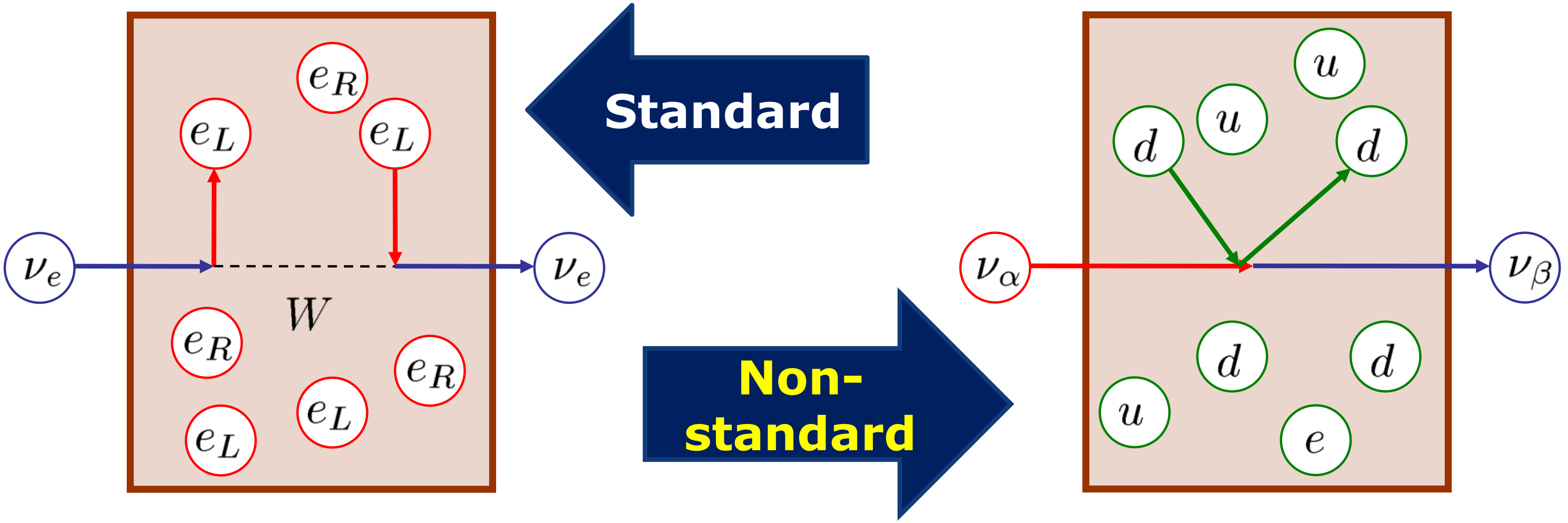
  The leading description for neutrino flavor transitions.

  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.

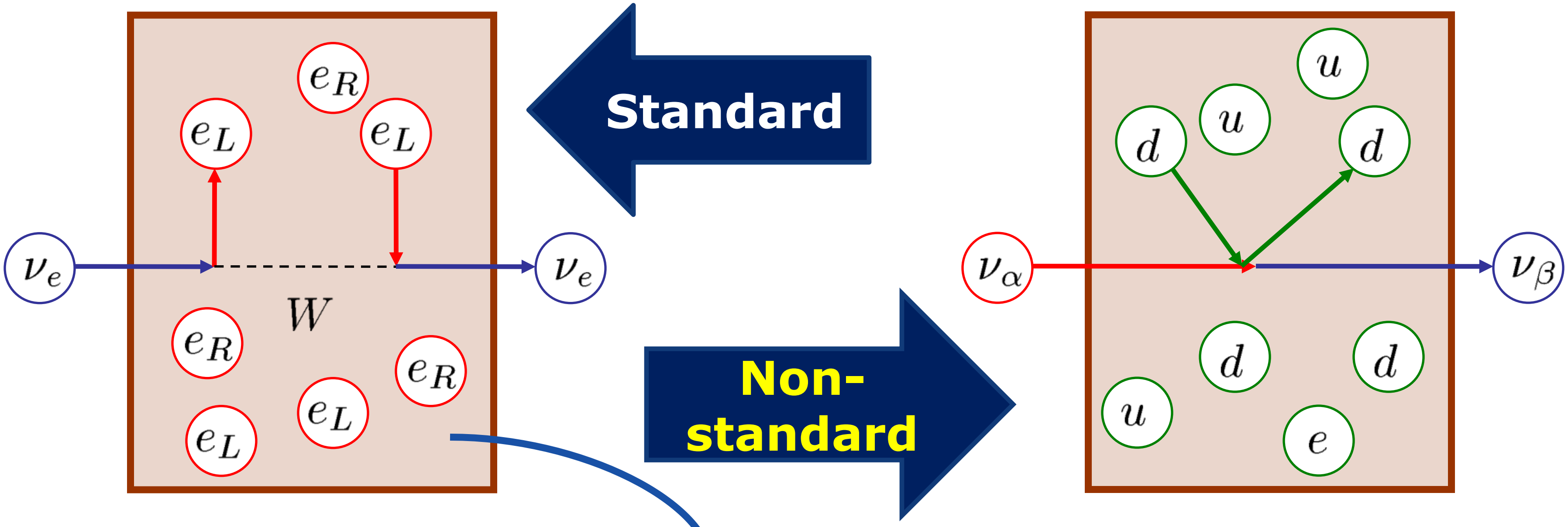
- Therefore, we will study phenomenologically ”new physics” effects due to non-standard neutrino interactions (NSIs).

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



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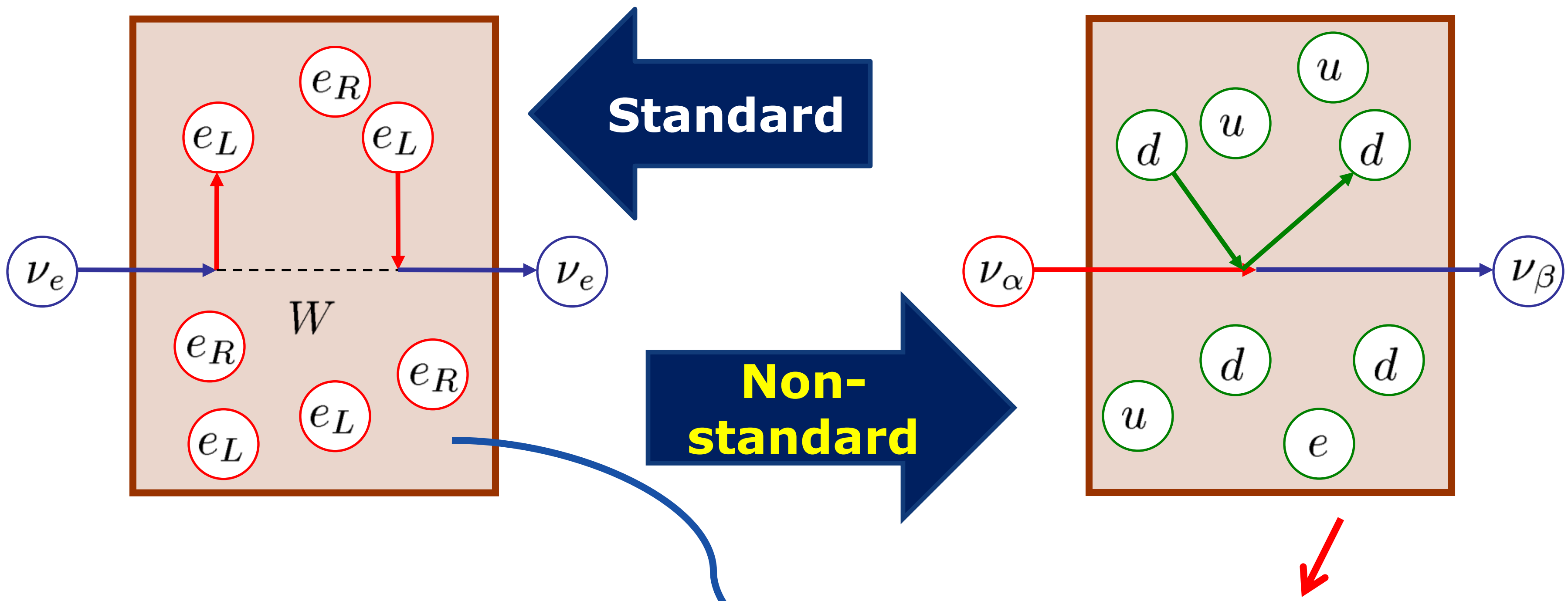
Neutrino propagation in matter with NSIs



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Neutrino oscillations with NSIs – two-flavors

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

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

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

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

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

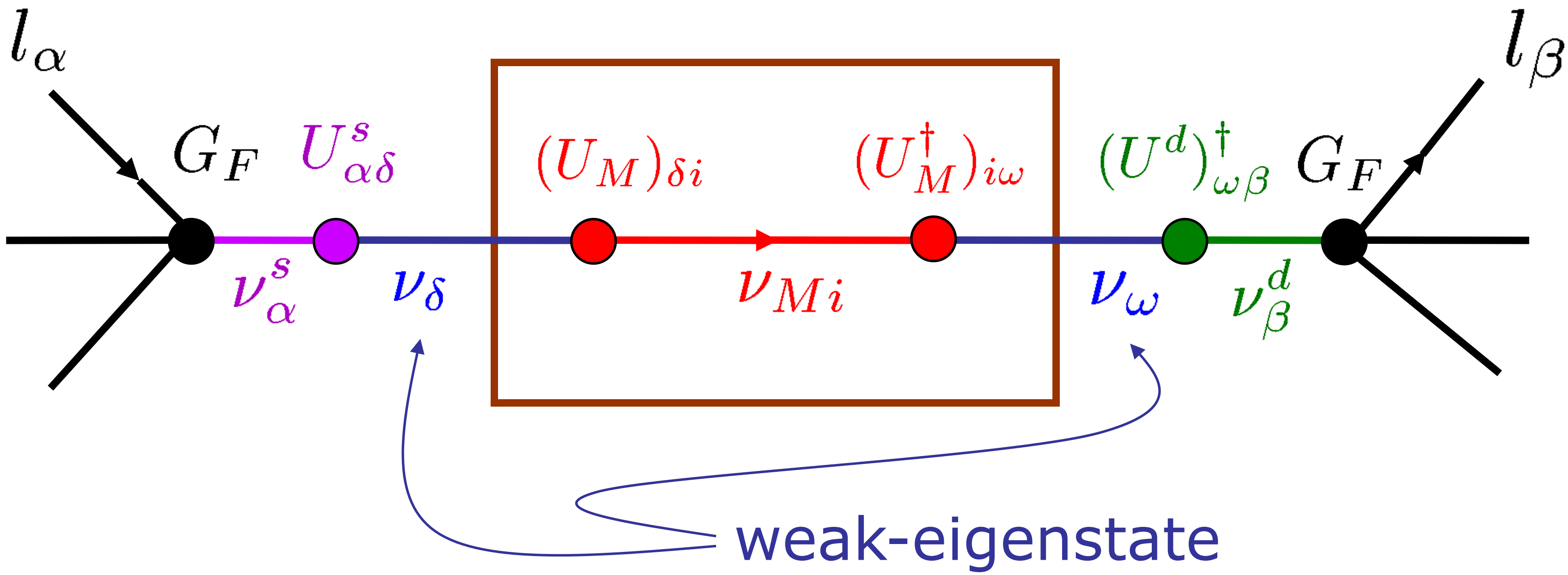
$$\nu_e + n \to p + \mu^-$$

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

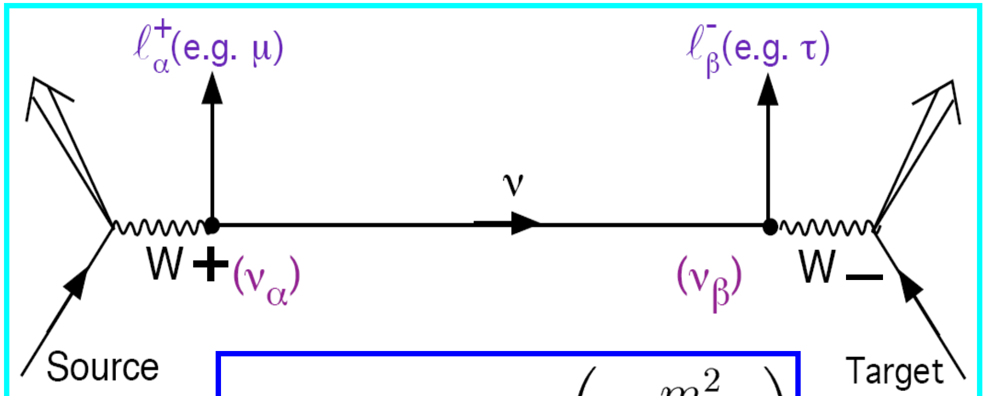
$U \rightarrow$ unitary

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

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

Non-unitary neutrino mixing:

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



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

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

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

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

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):

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

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

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

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)

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):

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

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

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

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*:

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

This must be a part of the gauge invariant operator

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

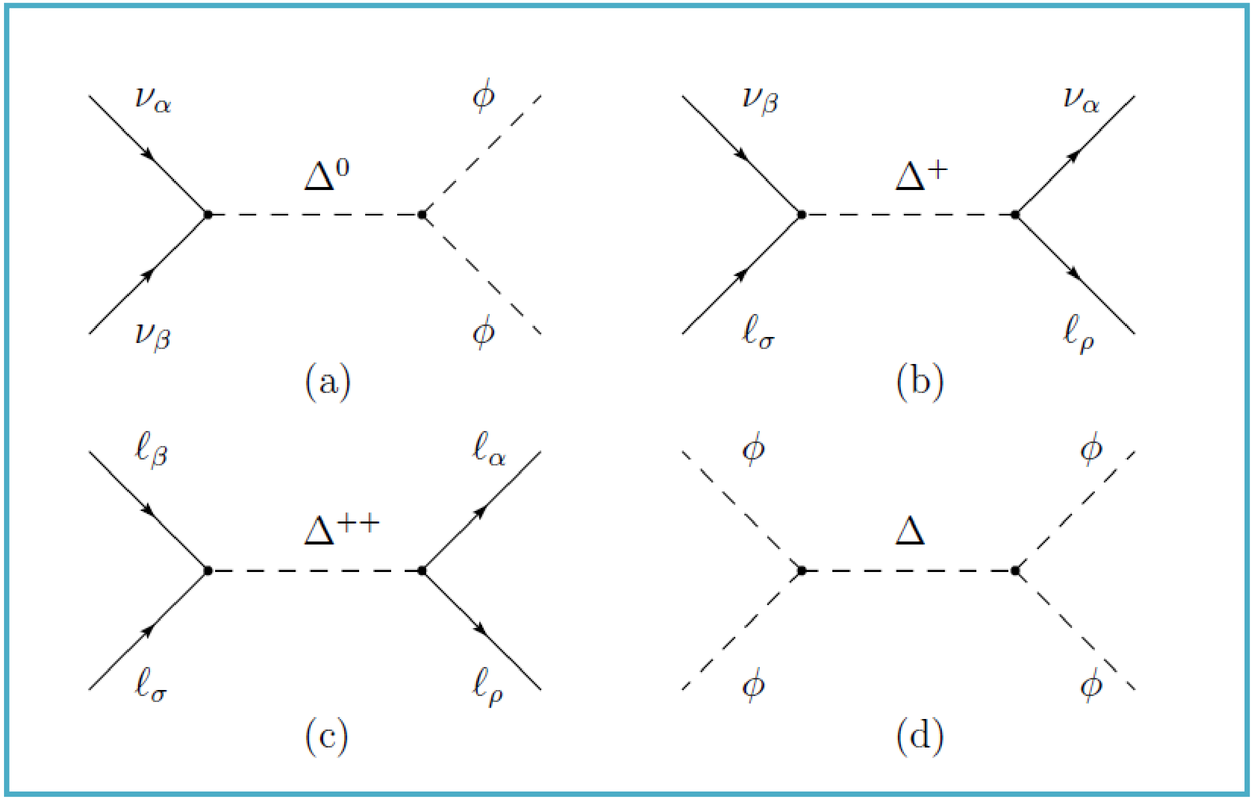
which involves four charged lepton operators.

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 from a type-II seesaw model

Tree level diagrams with the exchange of heavy triplet Higgs:



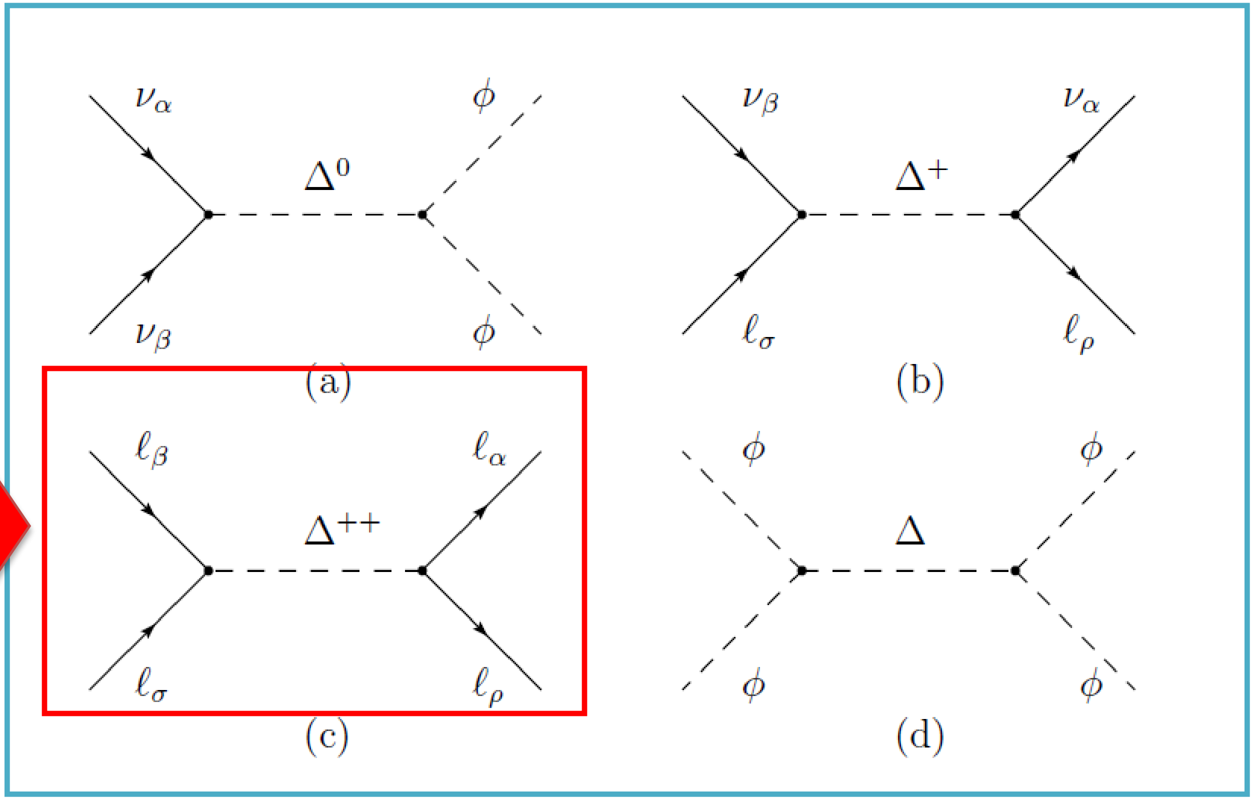
Malinský, Ohlsson, Zhang, PRD(RC) 2009

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



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NSIs from a type-II seesaw model

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

Relations between neutrino mass matrix and NSI parameters:

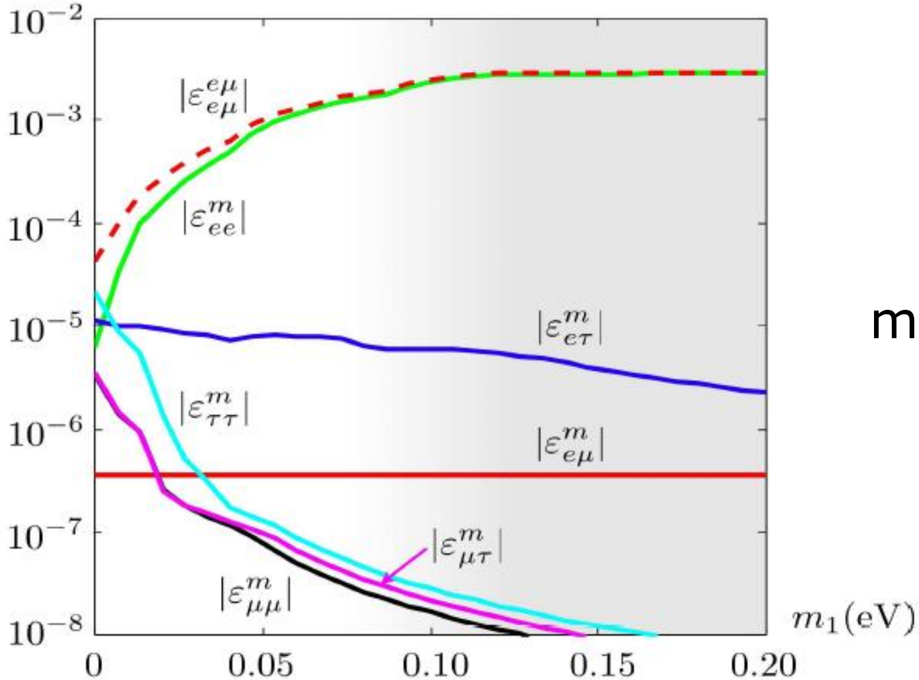
$$\varepsilon_{\alpha\beta}^{\rho\sigma} = -\frac{m_\Delta^2}{8\sqrt{2}G_F v^4 \lambda_\phi^2} (m_\nu)_{\sigma\beta} \left(m_\nu^\dagger\right)_{\alpha\rho}$$

Experimental constraints from LFV and rare decays, …:

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

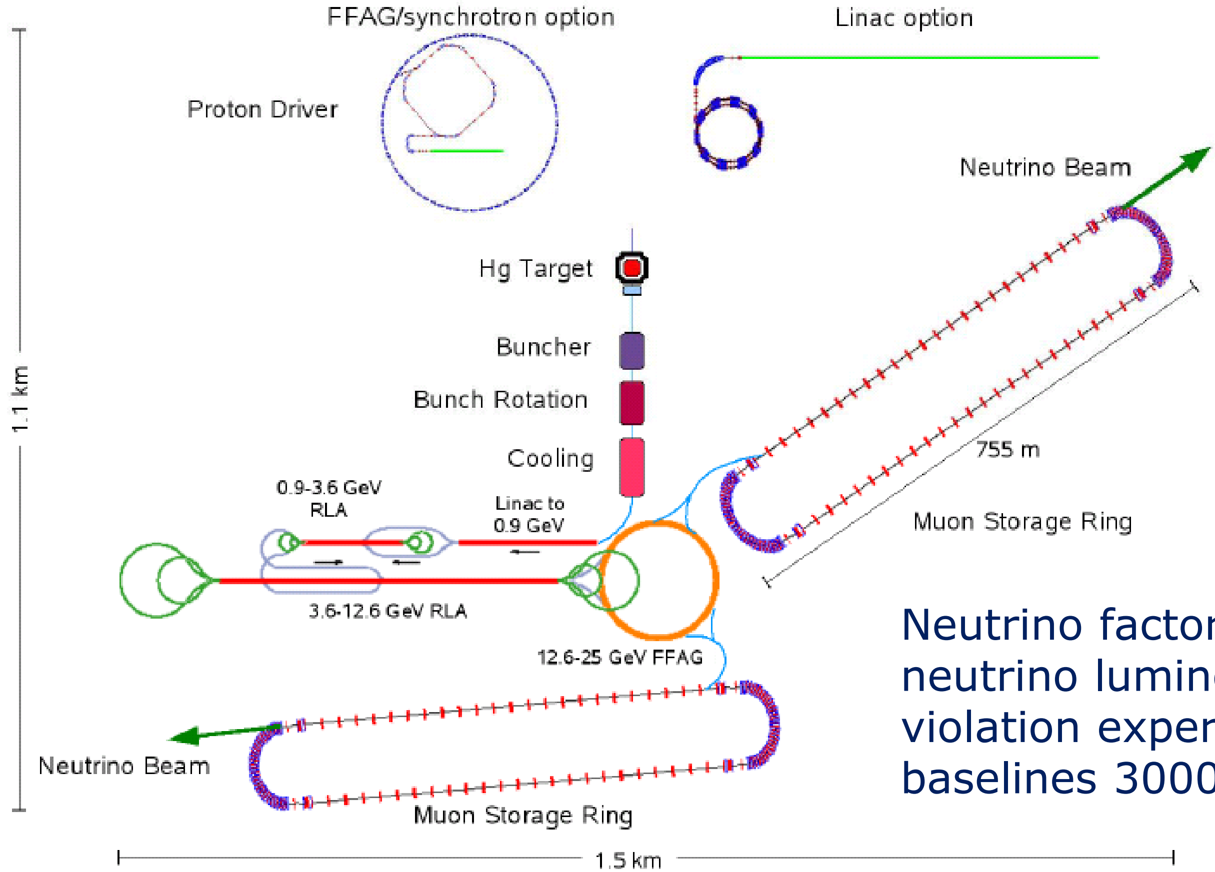
Upper bounds on NSI parameters in the triplet seesaw model:



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

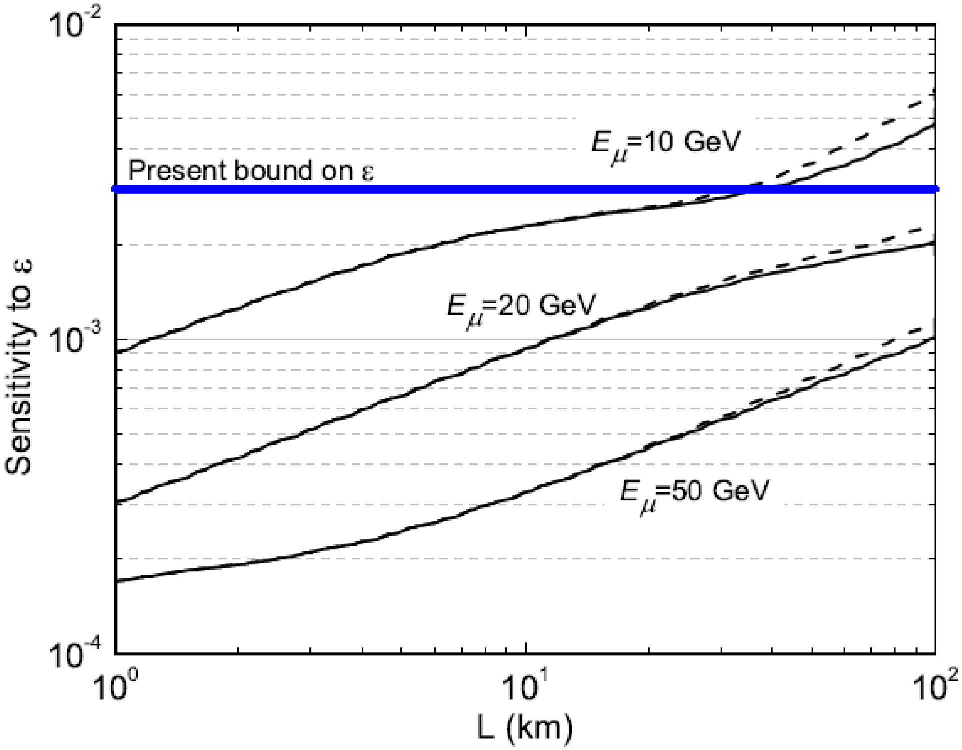
Phenomena at a neutrino factory

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

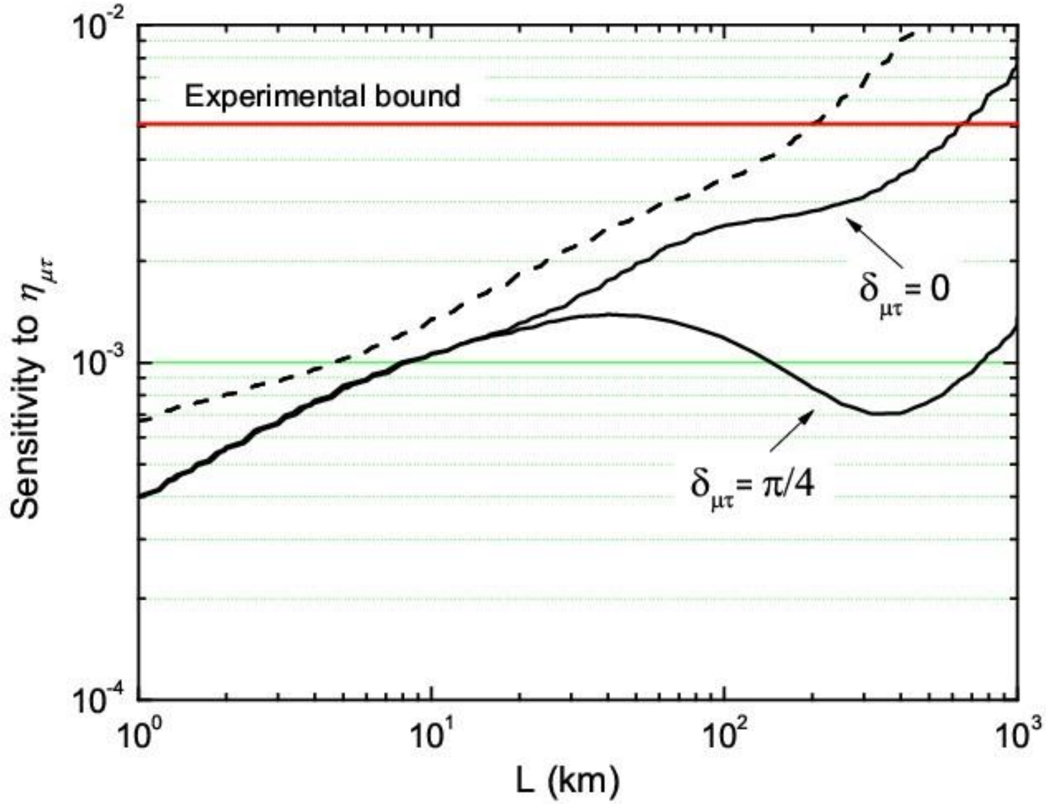
$\mu^- \rightarrow e^- \nu_\mu \overline{\nu_e}$ **SD vs. NSI** $\mu^- \rightarrow e^- \nu_e \overline{\nu_\mu}$

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



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

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.

NSIs for neutrino cross-sections

Electron neutrino-electron scattering:

$$\sigma(\nu_e e \to \nu e) = (1.17 \pm 0.17)\frac{G_F^2 m_e E_\nu}{\pi}$$

(LSND result, best measurement)

Including NSIs:

$$\sigma(\nu_e e \to \nu e) = \frac{2G_F^2 m_e E_\nu}{\pi}\left[(1 + g_L^e + \varepsilon_{ee}^{eL})^2 + \sum_{\alpha \neq e} |\varepsilon_{\alpha e}^{eL}|^2 + \frac{1}{3}(g_R^e + \varepsilon_{ee}^{eR})^2 + \frac{1}{3}\sum_{\alpha \neq e} |\varepsilon_{\alpha e}^{eR}|^2\right]$$

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90 % CL bounds on NSIs (only one NSI at a time):

$$-0.07 < \varepsilon_{ee}^{eL} < 0.11$$

$$-1. < \varepsilon_{ee}^{eR} < 0.5$$

$$|\varepsilon_{\tau e}^{eL}| < 0.4 \qquad |\varepsilon_{\tau e}^{eR}| < 0.7$$

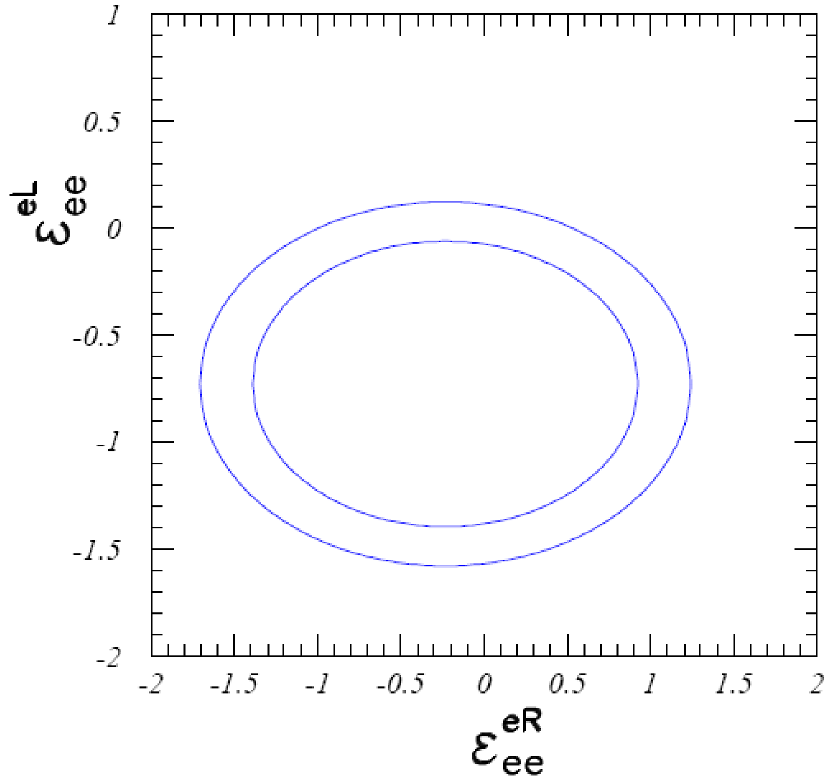
(flavor changing)

Davidson et al., 2003

NSIs for neutrino cross-sections

Electron neutrino-electron scattering:

90 % CL region (between the two ellipses) of two NSIs simultaneously:



Davidson et al., 2003

NSIs for neutrino cross-sections

Electron neutrino-quark scattering:

$$R^e = \frac{\sigma(\nu_e N \to \nu X) + \sigma(\bar{\nu}_e N \to \bar{\nu} X)}{\sigma(\nu_e N \to e X) + \sigma(\bar{\nu}_e N \to \bar{e} X)} = (\tilde{g}_{Le})^2 + (\tilde{g}_{Re})^2 = 0.406 \pm 0.140$$

(CHARM collaboration)

Including NSIs:

$$\begin{aligned}
(\tilde{g}_{Le})^2 &= (g_L^u + \varepsilon_{ee}^{uL})^2 + \sum_{\alpha \neq e} |\varepsilon_{\alpha e}^{uL}|^2 + (g_L^d + \varepsilon_{ee}^{dL})^2 + \sum_{\alpha \neq e} |\varepsilon_{\alpha e}^{dL}|^2 \\
(\tilde{g}_{Re})^2 &= (g_R^u + \varepsilon_{ee}^{uR})^2 + \sum_{\alpha \neq e} |\varepsilon_{\alpha e}^{uR}|^2 + (g_L^d + \varepsilon_{ee}^{dR})^2 + \sum_{\alpha \neq e} |\varepsilon_{\alpha e}^{dR}|^2
\end{aligned}$$

NSIs for neutrino cross-sections

Electron neutrino-quark scattering:

90 % CL bounds on NSIs (only one NSI at a time):

$$-1. < \varepsilon_{ee}^{uL} < 0.3$$
$$-0.3 < \varepsilon_{ee}^{dL} < 0.3$$
$$-0.4 < \varepsilon_{ee}^{uR} < 0.7$$
$$-0.6 < \varepsilon_{ee}^{dR} < 0.5$$

(flavor diagonal)

$$|\varepsilon_{\tau e}^{qP}| < 0.5 \qquad q = u, d \qquad P = L, R$$

(flavor changing)

90 % CL region of several NSIs simultaneously:

$$0.176 < (0.3493 + \varepsilon_{ee}^{uL})^2 + (-0.4269 + \varepsilon_{ee}^{dL})^2 + (-0.1551 + \varepsilon_{ee}^{uR})^2 + (0.0775 + \varepsilon_{ee}^{dR})^2 < 0.636$$

Davidson et al., 2003

NSIs for neutrino cross-sections

Muon neutrino-electron scattering:

$$g_V^e = -0.035 \pm 0.017 \quad \text{and} \quad g_A^e = -0.503 \pm 0.017$$

$$g_L^e = -0.269 \pm 0.017 \quad \text{and} \quad g_R^e = 0.234 \pm 0.017$$

(CHARM II collaboration)

→

90 % CL bounds on NSIs (only one NSI at a time):

$$-0.025 < \varepsilon_{\mu\mu}^{eL} < 0.03$$

$$-0.027 < \varepsilon_{\mu\mu}^{eR} < 0.03$$

(flavor diagonal)

$$|\varepsilon_{\tau\mu}^{eP}| < 0.1 \qquad P = L, R$$

(flavor changing)

Davidson et al., 2003

NSIs for neutrino cross-sections

Muon neutrino-quark scattering:

$$(\tilde{g}_{L\mu})^2 = 0.3005 \pm 0.0014 \qquad \text{and} \qquad (\tilde{g}_{R\mu})^2 = 0.0310 \pm 0.0011$$

(NuTeV collaboration)

90 % CL bounds on NSIs (only one NSI at a time):

$$-0.009 < \varepsilon_{\mu\mu}^{uL} < -0.003 \qquad \text{or} \qquad 0.002 < \varepsilon_{\mu\mu}^{dL} < 0.008$$

$$-0.008 < \varepsilon_{\mu\mu}^{uR} < 0.003$$

$$-0.008 < \varepsilon_{\mu\mu}^{dR} < 0.015 \; ,$$

(flavor diagonal)

$$\left|\varepsilon_{\tau\mu}^{qR}\right| < 0.05 \; . \qquad q = u, d$$

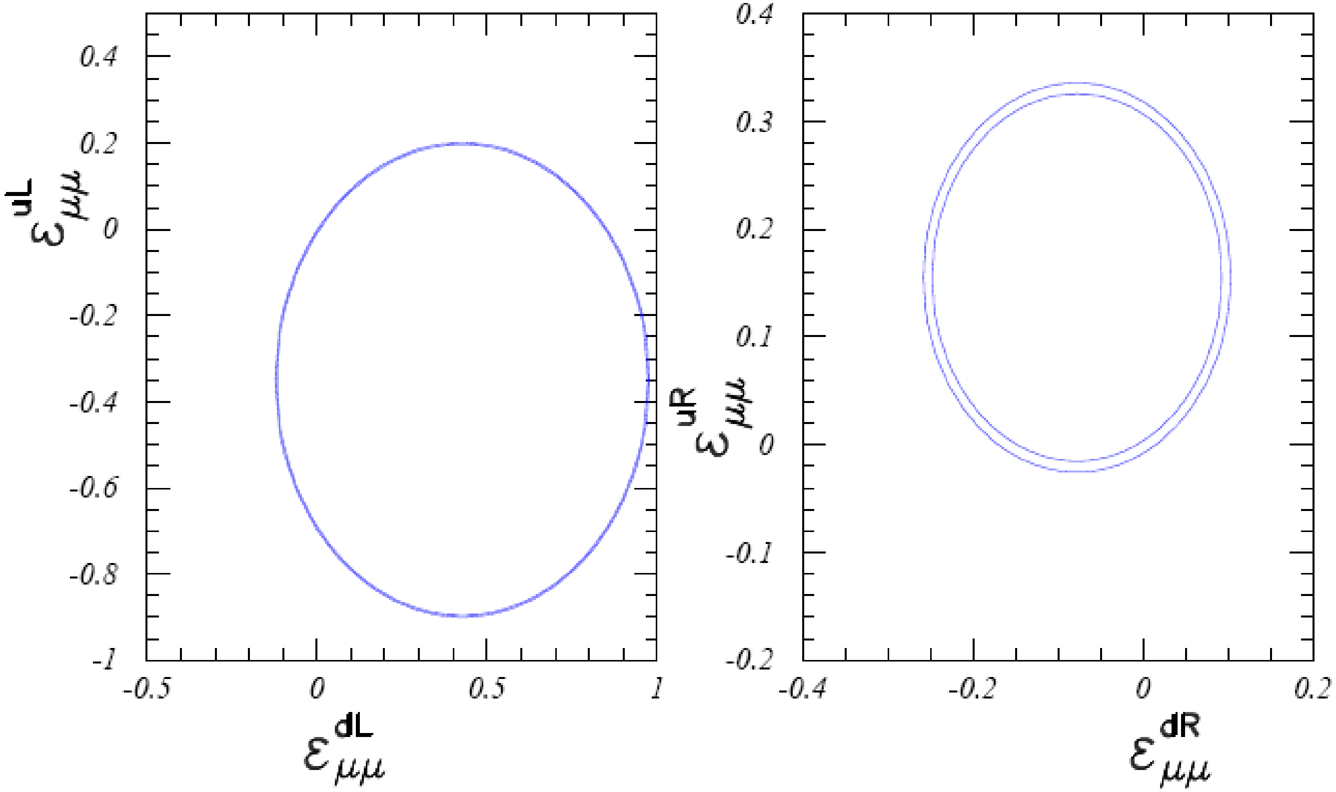
(flavor changing)

Davidson et al., 2003

NSIs for neutrino cross-sections

Muon neutrino-quark scattering:

90 % CL regions of two NSIs simultaneously:



Davidson et al., 2003

NSIs for neutrino cross-sections

$e^+e^- \to \nu\bar{\nu}\gamma$ cross section at LEP II:

90 % CL on flavor diagonal NSIs:

$$-0.6 < \varepsilon_{\tau\tau}^{eL} < 0.4$$
$$-0.4 < \varepsilon_{\tau\tau}^{eR} < 0.6$$

90 % CL on flavor changing NSIs:

$$|\varepsilon_{\alpha\beta}^{eP}| < 0.4 \qquad P = L, R,\ \alpha = \tau,\ \beta = e, \mu$$

Davidson et al., 2003

Summary & conclusions

1. Non-standard neutrino interactions could be responsible for neutrino flavor transitions on a sub-leading level.
2. Low-energy neutrino scattering experiments can be used to set bounds on NSI parameters.
3. The LHC and a neutrino factory open a new window towards determining the possible NSI parameters.

Thanks!

The seesaw mechanism

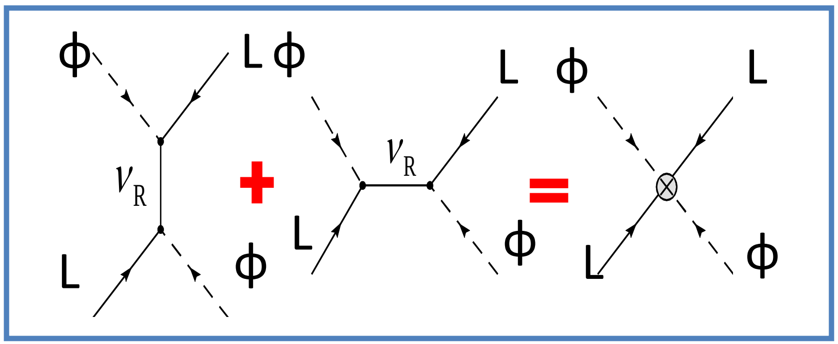
1. Neutrinos are Majorana particles

ν_R + Majorana & Dirac masses + seesaw

Natural description of the smallness of ν masses

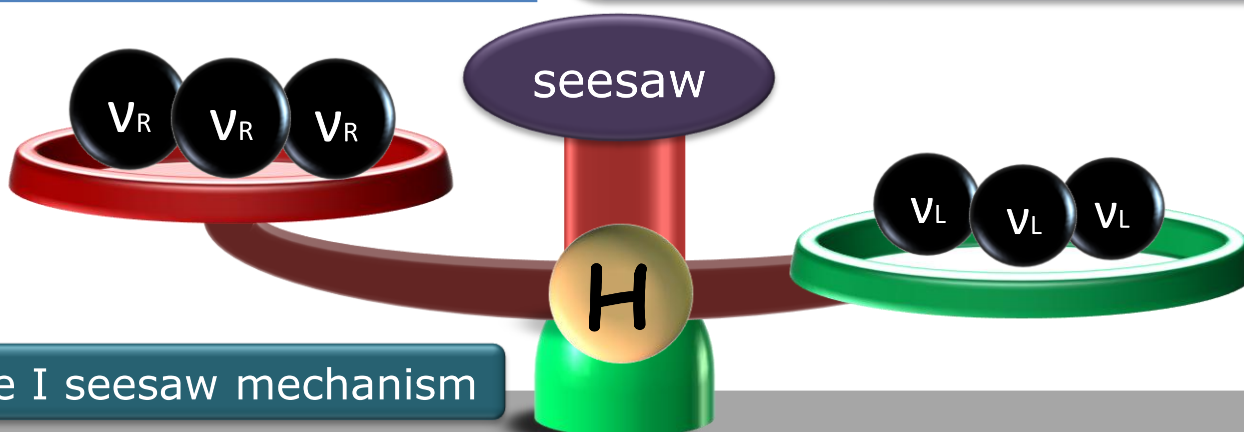
$$\mathscr{L} = \mathscr{L}_{\mathrm{SM}} + \left\{ Y \bar{l}_{\mathrm{L}} \nu_{\mathrm{R}} \tilde{\phi} + \boxed{\frac{1}{2} M_{\mathrm{R}} \bar{\nu}_{\mathrm{R}} \nu_{\mathrm{R}}^{\mathrm{C}}} + \mathrm{h.c.} \right\}$$

Integrate out heavy right-handed fields



$$-iY^T \frac{\not p + M_R}{p^2 - M_R^2} Y \left(\varepsilon_{cd}\varepsilon_{ba} + \varepsilon_{ca}\varepsilon_{bd} \right) P_L = i\kappa \left(\varepsilon_{cd}\varepsilon_{ba} + \varepsilon_{ca}\varepsilon_{bd} \right) P_L$$

$$p^2 \ll M_R^2 \Rightarrow \boxed{Y^{\mathrm{T}} M_{\mathrm{R}}^{-1} Y = \kappa} \Rightarrow \boxed{m_\nu = -m_{\mathrm{D}}^{\mathrm{T}} M_{\mathrm{R}}^{-1} m_{\mathrm{D}}}$$



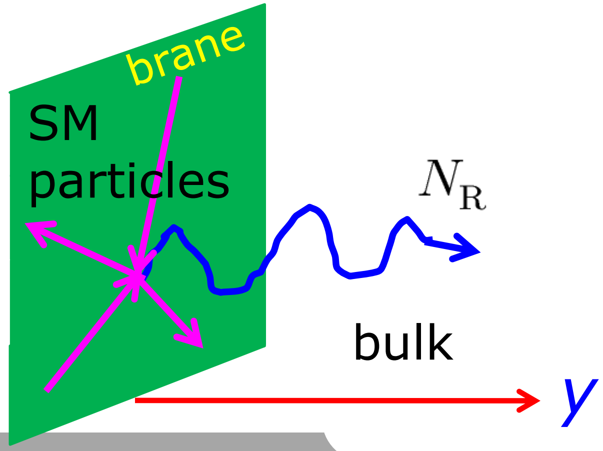
Type I seesaw mechanism

The seesaw mechanism

2. Neutrinos are Dirac particles
ν_R + a pure Dirac mass term
Extremely tiny Yukawa coupling ~10^{-11}, hierarchy puzzle

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \left\{ Y \overline{l_{\rm L}} \nu_{\rm R} \tilde{\phi} + {\rm h.c.} \right\}$$

A speculative way out: the smallness of Dirac masses is ascribed to the assumption that N_R have access to an extra spatial dimension (Dienes, Dudas, Gherghetta 1998; Arkani-Hamed, Dimopoulos, Dvali, March-Russell 1998):

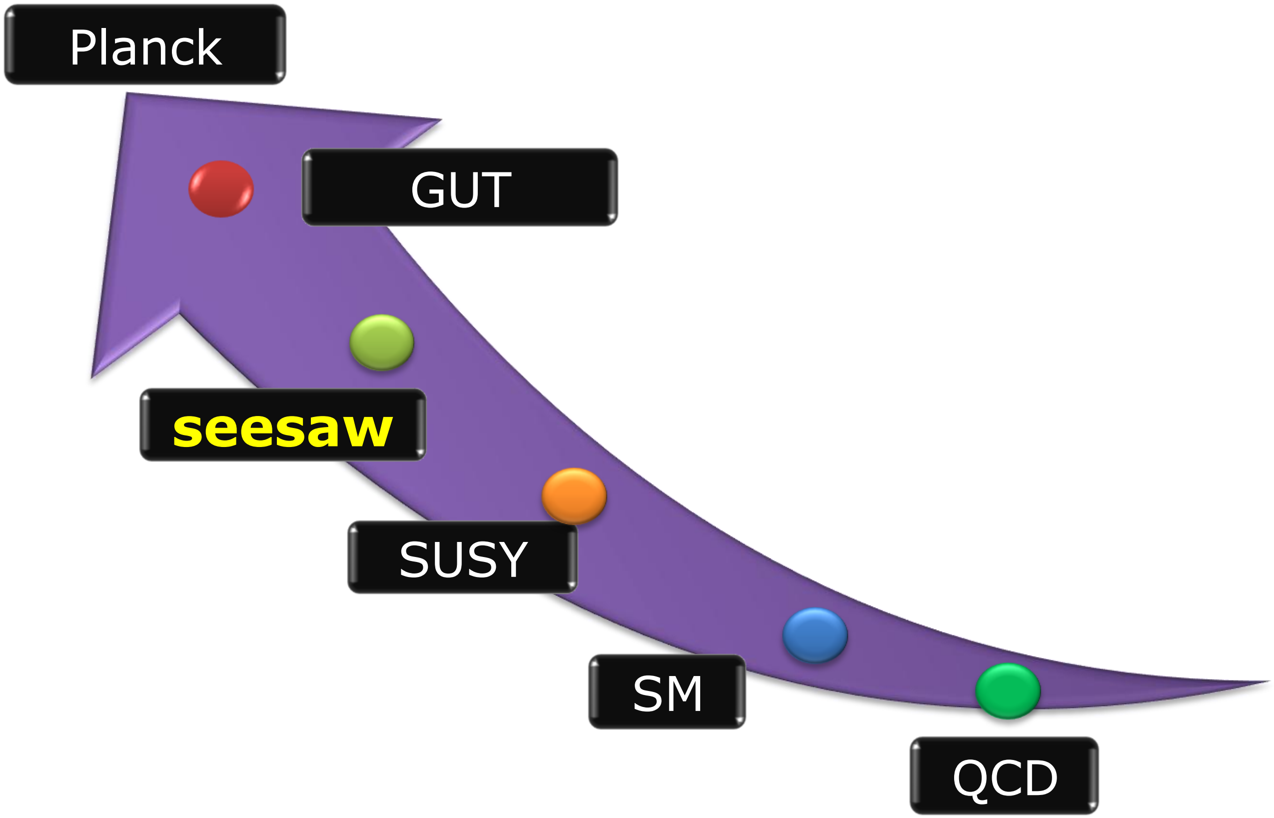


The wavefunction of N_R spreads out over the extra dimension y, giving rise to a suppressed Yukawa interaction at $y = 0$.

$$\left[\overline{l_{\rm L}} Y_\nu \tilde{H} N_{\rm R}\right]_{y=0} \sim \frac{1}{\sqrt{L}} \left[\overline{l_{\rm L}} Y_\nu \tilde{H} N_{\rm R}\right]_{y=L}$$

Where is the “new physics”?

What is the energy scale at which the seesaw mechanism works?



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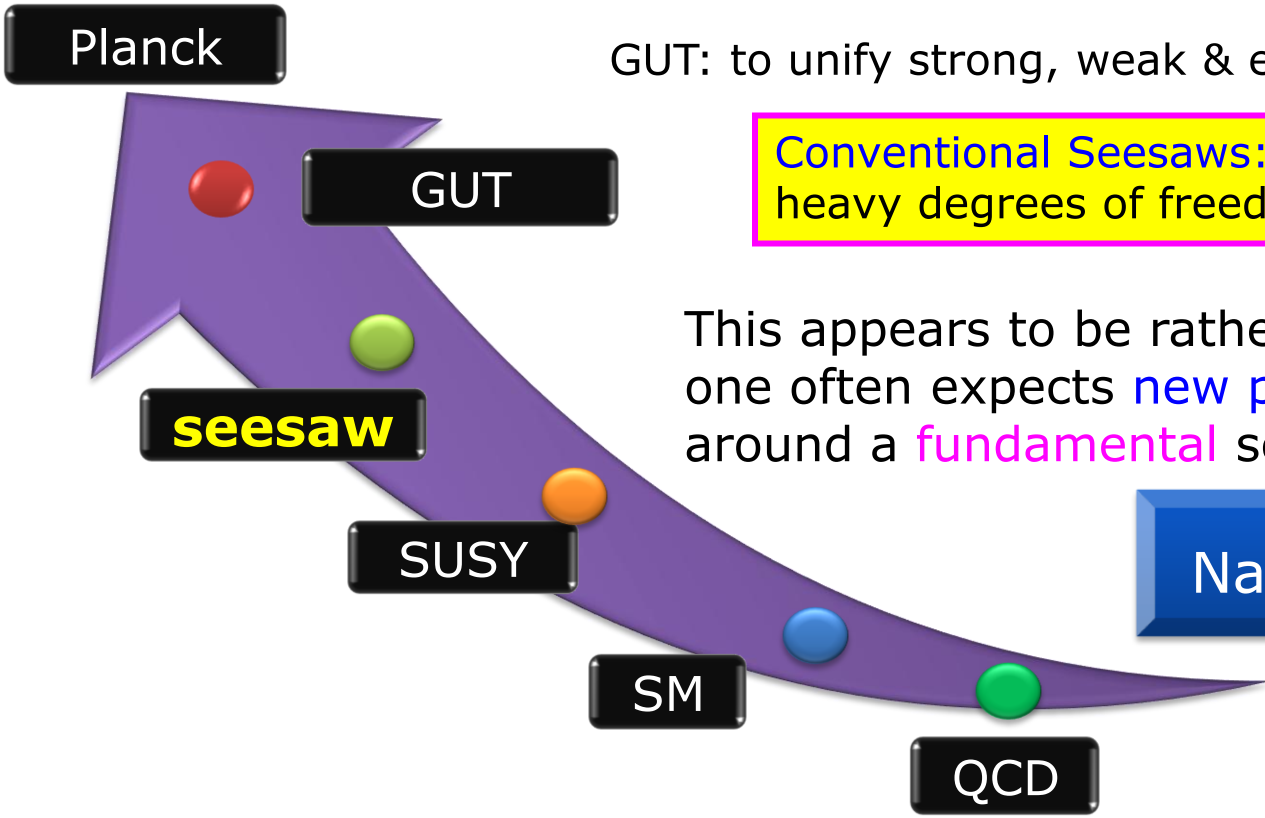

GUT: to unify strong, weak & electromagnetic forces?

Conventional Seesaws:
heavy degrees of freedom near Λ_{GUT}.

This appears to be rather reasonable, since one often expects new physics to appear around a fundamental scale.

Naturalness √

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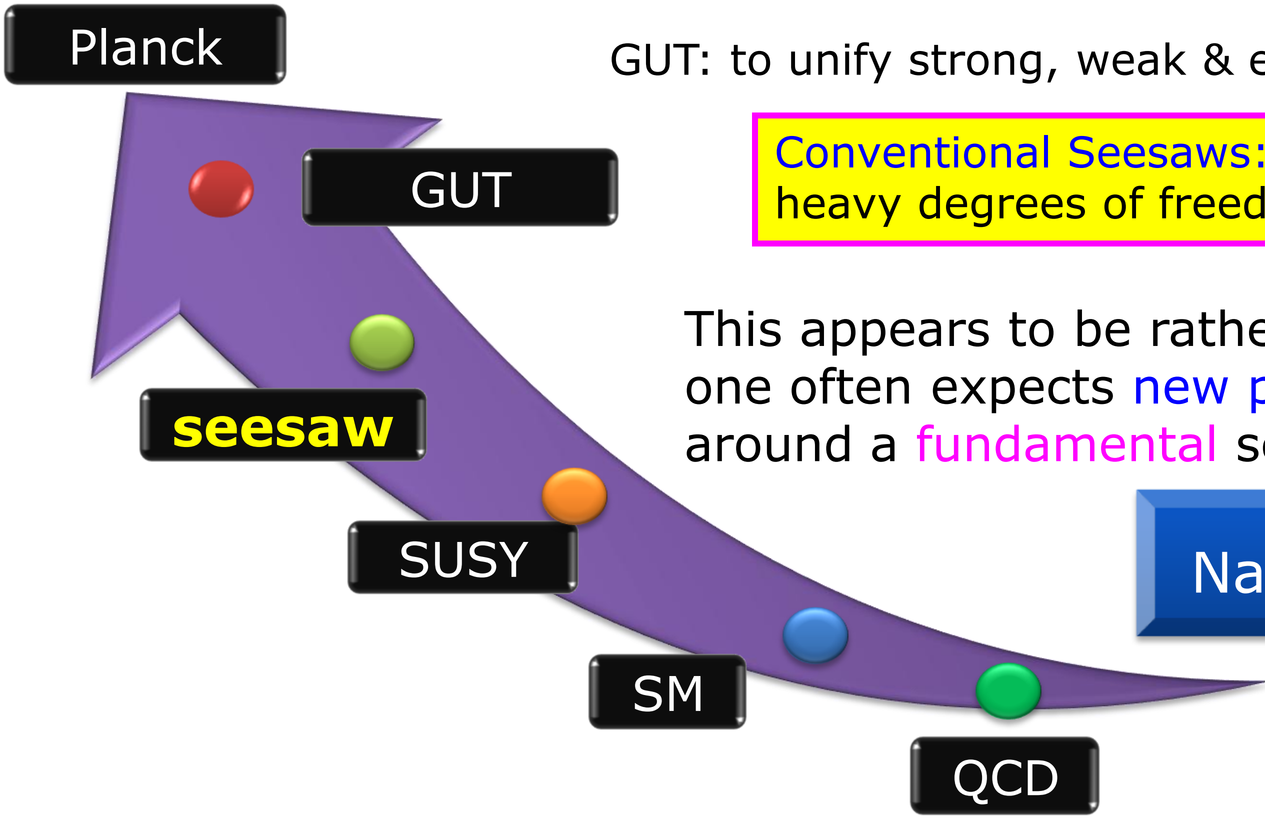
What is the energy scale at which the seesaw mechanism works?



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Conventional Seesaws:
heavy degrees of freedom near Λ_{GUT}.

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Naturalness √

Uniqueness ×

Hierarchy ×

Testability ×