Non-standard neutrino interactions from seesaw models

NuFact09, Chicago, July 2009

Contents:

- Seesaw models at the TeV scale
- Non-standard neutrino interactions and non-unitarity effects
- Discovery potential at future neutrino experiments

He Zhang

In collaboration with M. Malinský, T. Ohlsson, and Z.Z. Xing

Phys.Rev.D79,011301(R)(2009);

Phys. Rev. D79, 073009(2009); arXiv:0905.2889.

Royal Institute of Technology, Stockholm, Sweden

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

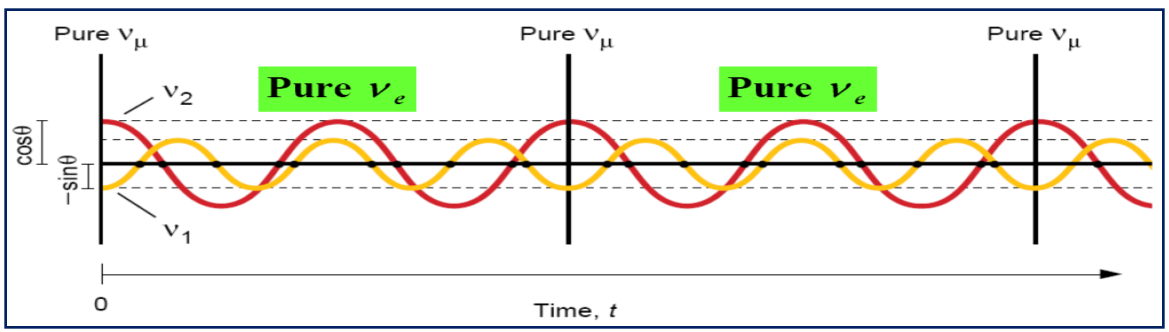
Standard Parametrization

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.

Neutrinos are massless in the SM as a result of the model's simple structure:

--- $SU(2)_L \times U(1)_Y$ gauge symmetry and Lorentz invariance;

Fundamentals of the model, mandatory for its consistency as a QFT.

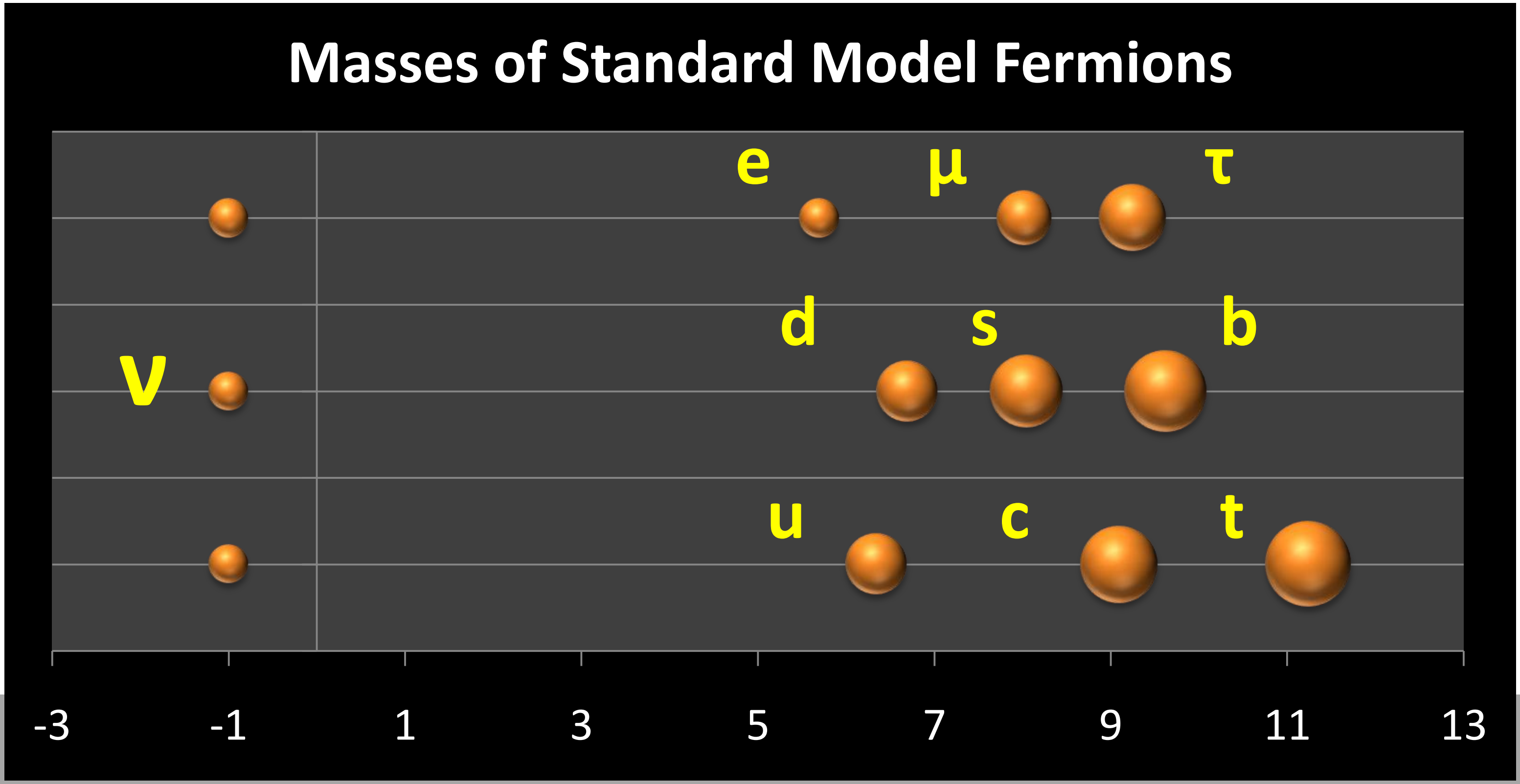
--- Economical particle content:

No right-handed neutrinos --- a Dirac mass term is not allowed.

Only one Higgs doublet --- a Majorana mass term is not allowed.

--- Renormalizability:

No dimension ≥ 5 operators --- a Majorana mass term is forbidden.

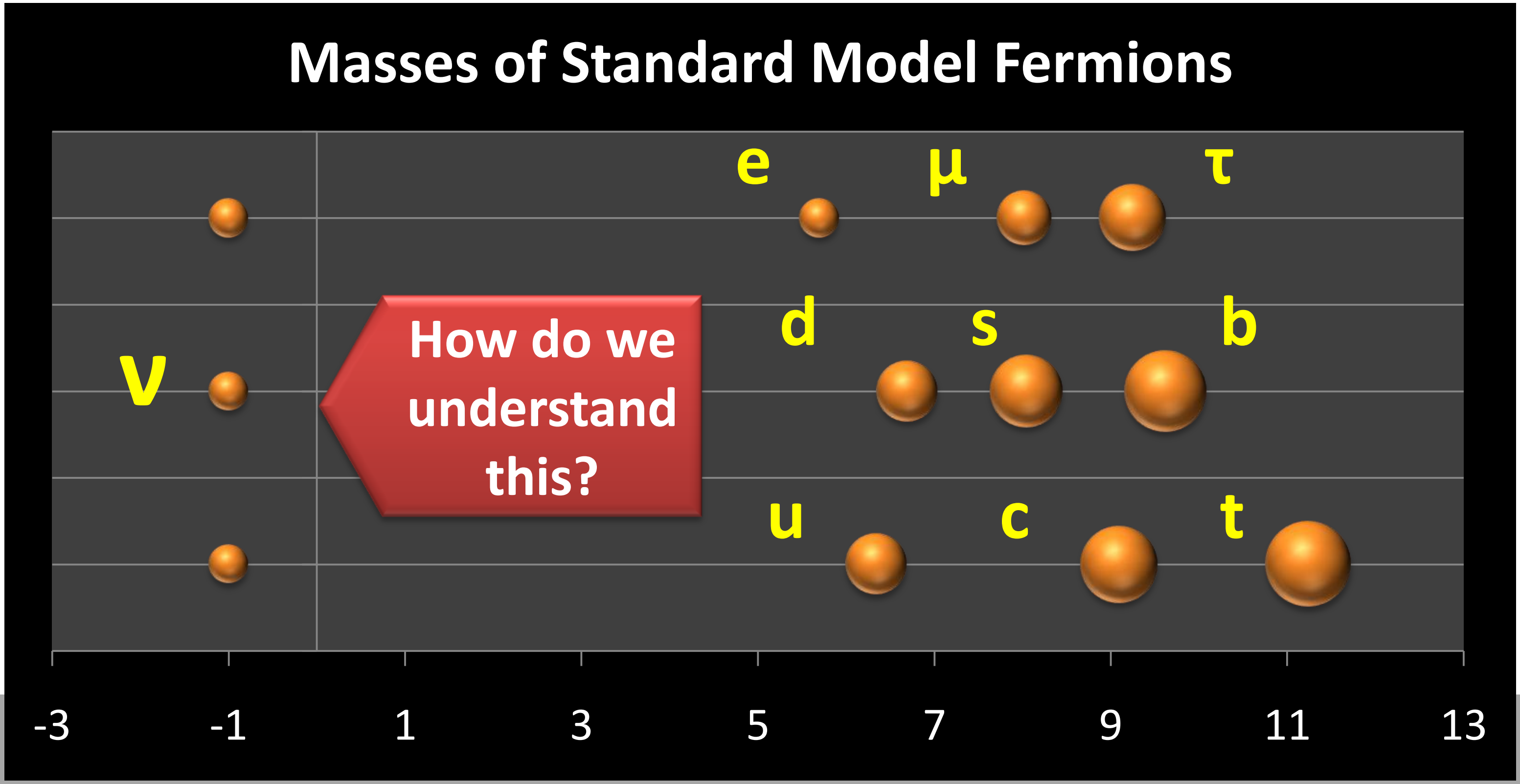


Neutrinos are massless in the SM as a result of the model's simple structure:

--- $SU(2)_L \times U(1)_Y$ gauge symmetry and Lorentz invariance;
  Fundamentals of the model, mandatory for its consistency as a QFT.

--- Economical particle content:
  No right-handed neutrinos --- a Dirac mass term is not allowed.
  Only one Higgs doublet --- a Majorana mass term is not allowed.

--- Renormalizability:
  No dimension ≥ 5 operators --- a Majorana mass term is forbidden.

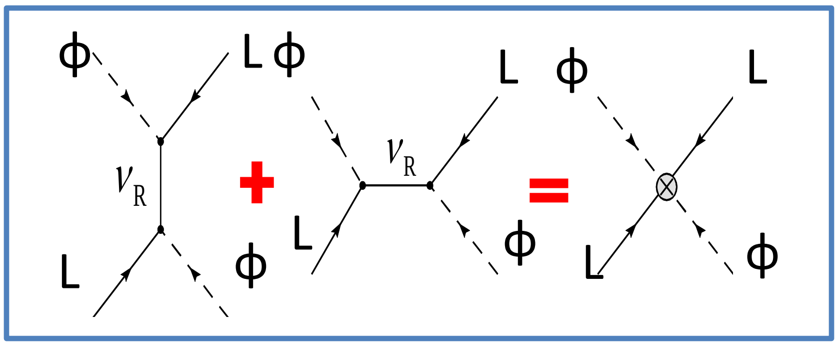


Beyond the SM: **SEESAW**

Neutrinos are Majorana particles
ν_R + Majorana & Dirac masses + seesaw
Natural description of the smallness of ν-masses

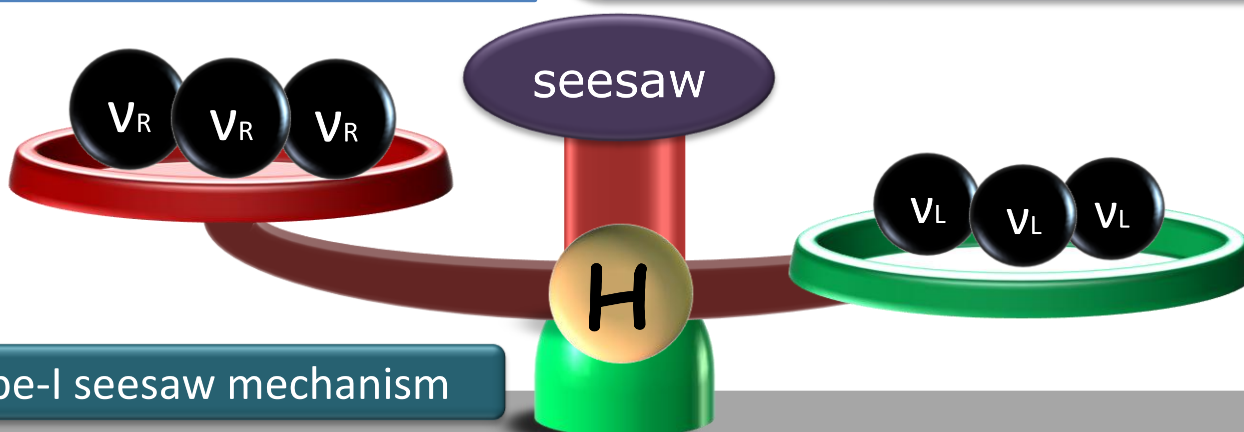
$$\mathscr{L} = \mathscr{L}_{\mathrm{SM}} + \left\{ Y \bar{l}_{\mathrm{L}} \nu_{\mathrm{R}} \tilde{\phi} + \boxed{\frac{1}{2} M_{\mathrm{R}} \bar{\nu}_{\mathrm{R}} \nu_{\mathrm{R}}^{\mathrm{C}}} + \mathrm{h.c.} \right\}$$

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

Typical seesaw models

SEESAW

SU(2)_L singlet fermions
SU(2)_L triplet scalars
SU(2)_L triplet fermions

T-1: SM + 3 right-handed (Majorana) neutrinos (Minkowski 77; Yanagida 79; Glashow 79; Gell-Mann, Ramond, Slanski 79; Mohapatra, Senjanovic 79)

$$-\mathcal{L}_{\text{lepton}} = \overline{l_{\rm L}} Y_l H E_{\rm R} + \overline{l_{\rm L}} Y_\nu \tilde{H} N_{\rm R} + \frac{1}{2}\overline{N^c_{\rm R}} M_{\rm R} N_{\rm R} + \text{h.c.}$$

T-2: SM + 1 Higgs triplet (Magg, Wetterich 80; Schechter, Valle 80; Cheng, Li 80; Lazarides et al 80; Mohapatra, Senjanovic 80; Gelmini, Roncadelli 80)

$$-\mathcal{L}_{\text{lepton}} = \overline{l_{\rm L}} Y_l H E_{\rm R} + \frac{1}{2}\overline{l_{\rm L}} Y_\Delta \Delta i\sigma_2 l^c_{\rm L} - \lambda_\Delta M_\Delta H^T i\sigma_2 \Delta H + \text{h.c.}$$

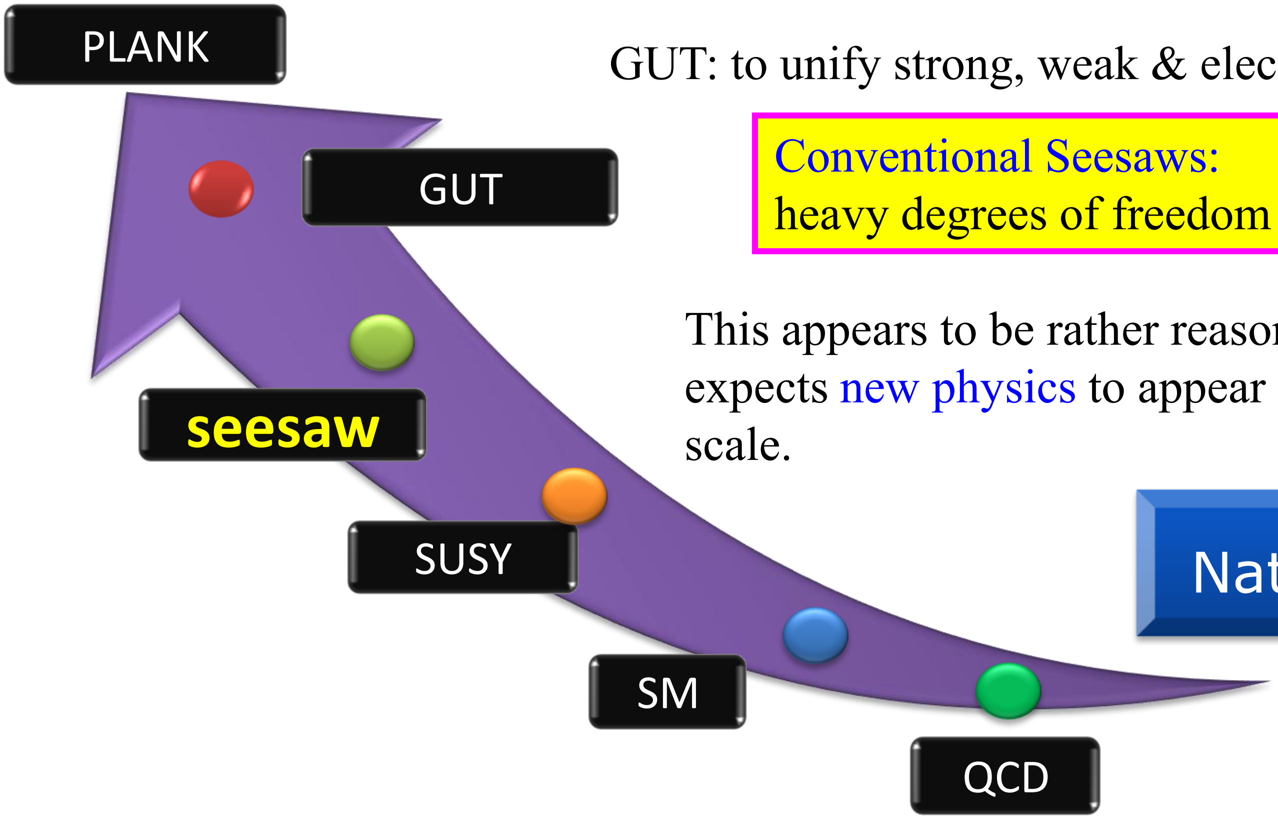
variations
combination

T-3: SM + 3 triplet fermions (Foot, Lew, He, Joshi 89)

$$-\mathcal{L}_{\text{lepton}} = \overline{l_{\rm L}} Y_l H E_{\rm R} + \overline{l_{\rm L}} \sqrt{2} Y_\Sigma \Sigma^c \tilde{H} + \frac{1}{2}\text{Tr}\left(\overline{\Sigma} M_\Sigma \Sigma^c\right) + \text{h.c.}$$

Where is the new physics?

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



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 √

Uniqueness ×

Hierarchy ×

Testability ×

TeV type-I seesaw   structural cancellation

Unnatural case: large cancellation in the leading seesaw term.

$$M_\nu \approx M_D M_R^{-1} M_D^T$$

0.01 eV   1 TeV   100 GeV

TeV-scale (right-handed) Majorana neutrinos: small masses of light Majorana neutrinos come from sub-leading perturbations.

(Buchmueller, Greub 91; Ingelman, Rathsman 93; Heusch, Minkowski 94; ……; Kersten, Smirnov 07).

$$m_D = m \begin{pmatrix} y_1 & y_2 & y_3 \\ \alpha y_1 & \alpha y_2 & \alpha y_3 \\ \beta y_1 & \beta y_2 & \beta y_3 \end{pmatrix} + \frac{y_1^2}{M_1} + \frac{y_2^2}{M_2} + \frac{y_3^2}{M_3} = 0$$

$$\boxed{M_\nu \approx M_D M_R^{-1} M_D^T = 0}$$

Underlying symmetry: discrete flavor symmetry (A_4, S_4)? Radiative corrections? Renormalization group running?

Type-III seesaw

Type-II seesaw: add one $SU(2)_L$ Higgs triplet into the SM.

$$\mathcal{L}_\Delta = Y_{\alpha\beta} L_L^{T\alpha} C\, \mathrm{i}\sigma_2 \Delta L_L^\beta + \lambda_\phi \phi^T \mathrm{i}\sigma_2 \Delta^\dagger \phi + \mathrm{H.c.}$$

$$\Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}$$

Δ is close to the TeV scale, λ_Φ is naturally tiny since $\lambda_\Phi=0$ enhances the symmetry of the model.

't Hooft's naturalness criterion (80)

At any energy scale μ, a set of parameters, $\alpha_i(\mu)$ describing a system can be small, if and only if, in the limit $\alpha_i(\mu) \rightarrow 0$ for each of these parameters, the system exhibits an enhanced symmetery.

Light neutrino mass matrix

$$\mathcal{L}_\nu^m = \frac{Y_{\alpha\beta}\lambda_\phi v^2}{m_\Delta^2}\left(\nu_{L\alpha}^c \nu_{L\beta}\right) = -\frac{1}{2}(m_\nu)_{\alpha\beta}\nu_{L\alpha}^c \nu_{L\beta}$$

Type-II seesaw: add one $SU(2)_L$ Higgs triplet into the SM.

$$\mathcal{L}_\Delta = Y_{\alpha\beta} L_L^{T\alpha} C\, i\sigma_2 \Delta L_L^\beta + \lambda_\phi \phi^T i\sigma_2 \Delta^\dagger \phi + \text{H.c.}$$

$$\Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}$$

Δ is close to the TeV scale, λ_Φ is naturally tiny since $\lambda_\Phi=0$ enhances the symmetry of the model.

't Hooft's naturalness criterion (80)

At any energy scale μ, a set of parameters, $\alpha_i(\mu)$ describing a system can be small, if and only if, in the limit $\alpha_i(\mu) \to 0$ for each of these parameters, the system exhibits an enhanced symmetery.

Light neutrino mass matrix

$$\mathcal{L}_\nu^m = \frac{Y_{\alpha\beta}\lambda_\phi v^2}{m_\Delta^2}\left(\nu_{L\alpha}^c \nu_{L\beta}\right) = -\frac{1}{2}(m_\nu)_{\alpha\beta}\nu_{L\alpha}^c \nu_{L\beta}$$

Type-(I+II) seesaw: simple combination of type-I & type-II seesaws.

The neutrino mass term:

$$-\mathcal{L}'_{\text{mass}} = \frac{1}{2}\overline{\left(\nu_\text{L}\ N_\text{R}^c\right)}\begin{pmatrix} M_\text{L} & M_\text{D} \\ M_\text{D}^T & M_\text{R} \end{pmatrix}\begin{pmatrix} \nu_\text{L}^c \\ N_\text{R} \end{pmatrix} + \text{h.c.}$$

and the seesaw relation:

$$M_\nu \approx M_\text{L} - M_\text{D} M_\text{R}^{-1} M_\text{D}^T$$

Cancellation between unrelated sources: quite unnatural

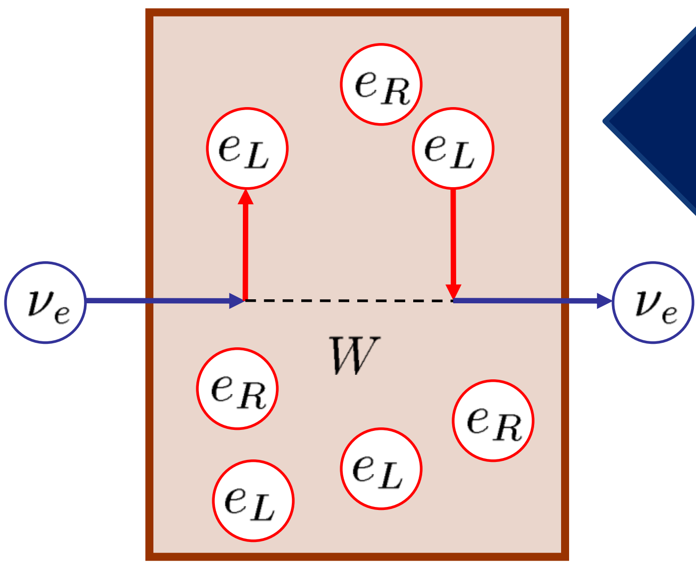
Non-standard neutrino interactions

The widely studied NSI operators

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

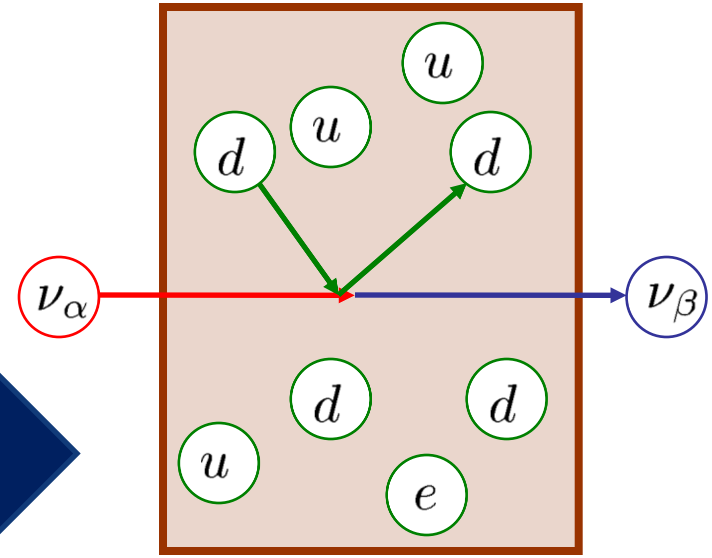
$$\varepsilon \propto \frac{m_W^2}{m_X^2}$$

$$\boxed{\text{If new physics scale} \sim 1(10)\ \text{TeV} \Rightarrow \varepsilon \sim 10^{-2}(10^{-4})}$$



Standard

Non-standard



- Non-standard interactions at neutrino sources:

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

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

- Non-standard interactions at neutrino detectors:

$\nu_e + n \to p + \mu^-$ (Standard: $\nu_\mu + n \to p + \mu^-$)

These effects can be measured even for L=0 (near detector $P_{\mu e}$ (L=0) ≠ 0)

- Non-standard interactions with matter during propagation:

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

Constraints by experiments with neutrinos and charged leptons

Davidson, Pena-Garay, Rius and Santamaria, **JHEP0303 (2003)011**
Biggio, Blennow, and Fernandez-Martinez, **arXiv:0907.0097**

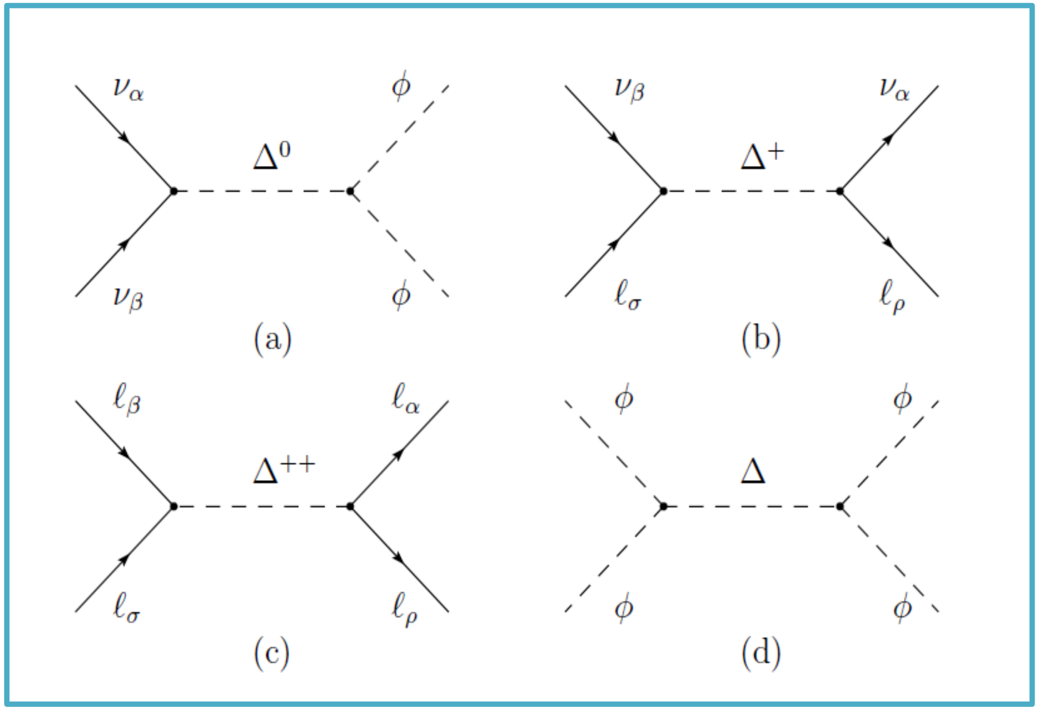
Phenomenological consequences of the type-II seesaw model

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



Malinsky, Ohlsson, Zhang, PRD(RC) 09

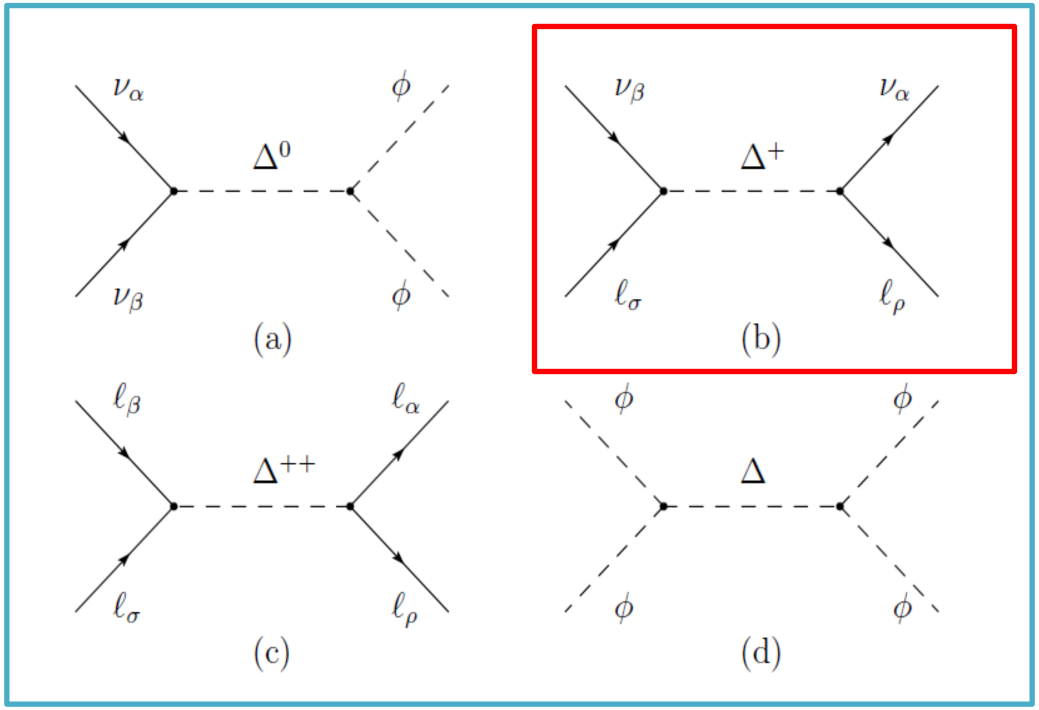
Phenomenological consequences of the type-II seesaw model

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



Malinsky, Ohlsson, Zhang, PRD(RC) 09

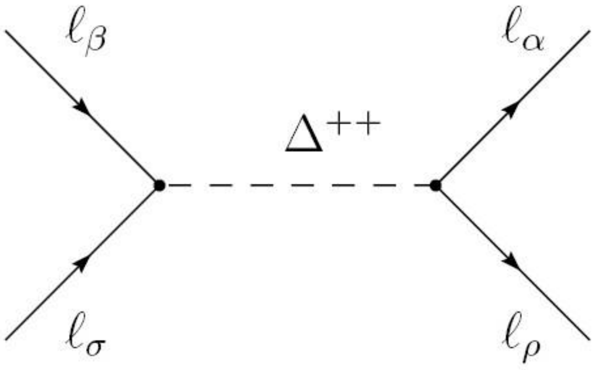
Integrating out the heavy triplet field (at tree-level)!

Relations between neutrino mass matrix and NSI parameters:

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

NSIs from type-II seesaw model

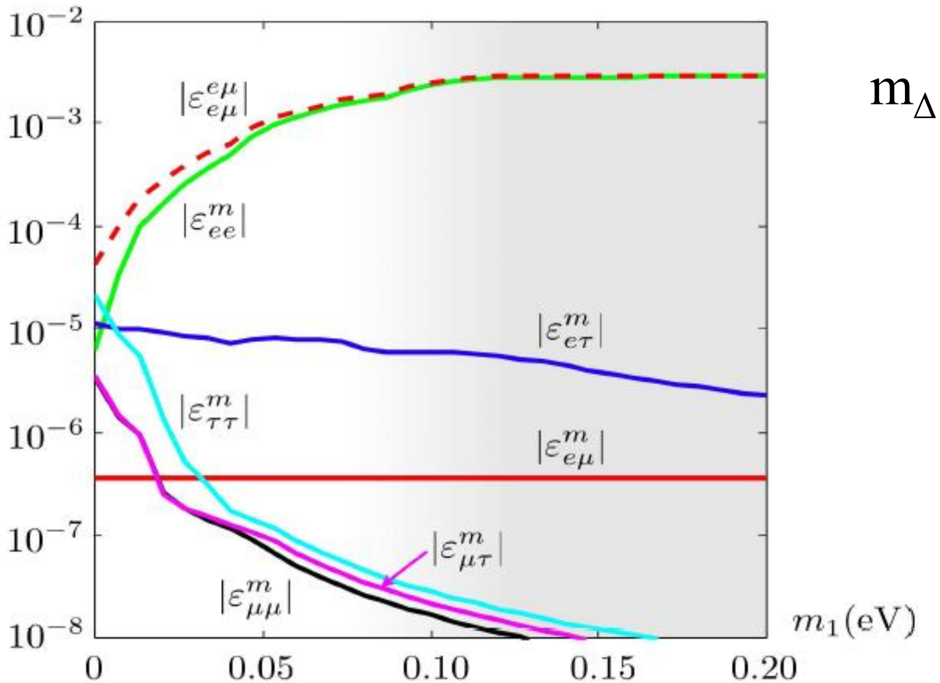
Experimental constraints from LFV and rare decays, …



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 type-II seesaw model

Upper bounds on NSI parameters in the Type-II seesaw model



$m_\Delta = 1$ 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.

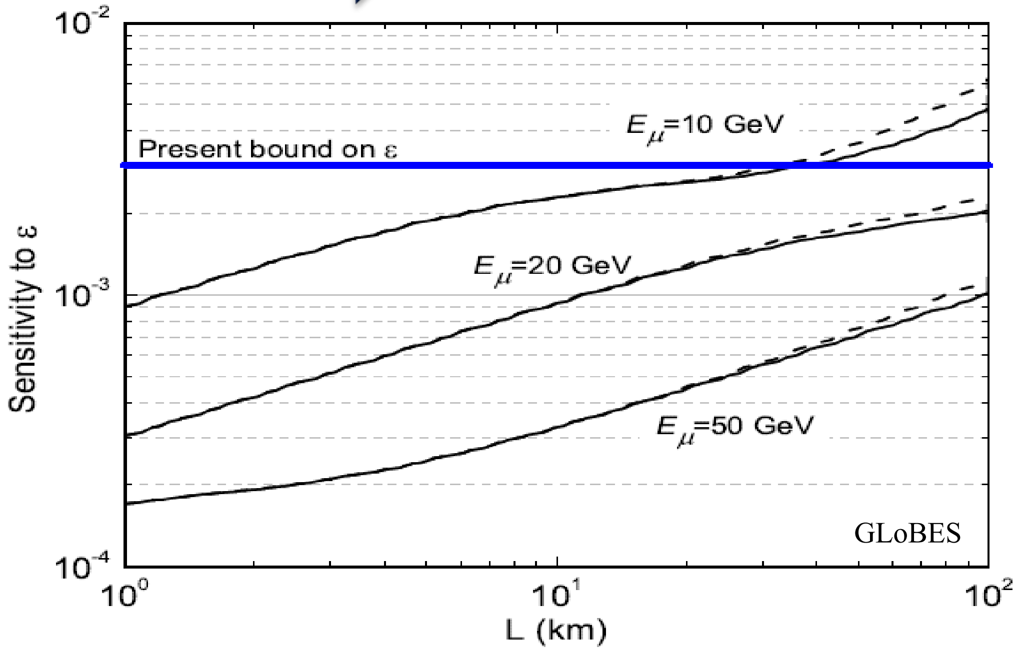
Phenomena at a neutrino factory and the LHC

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

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

Sensitivity limits at 90 % C.L.

Our settings:
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.



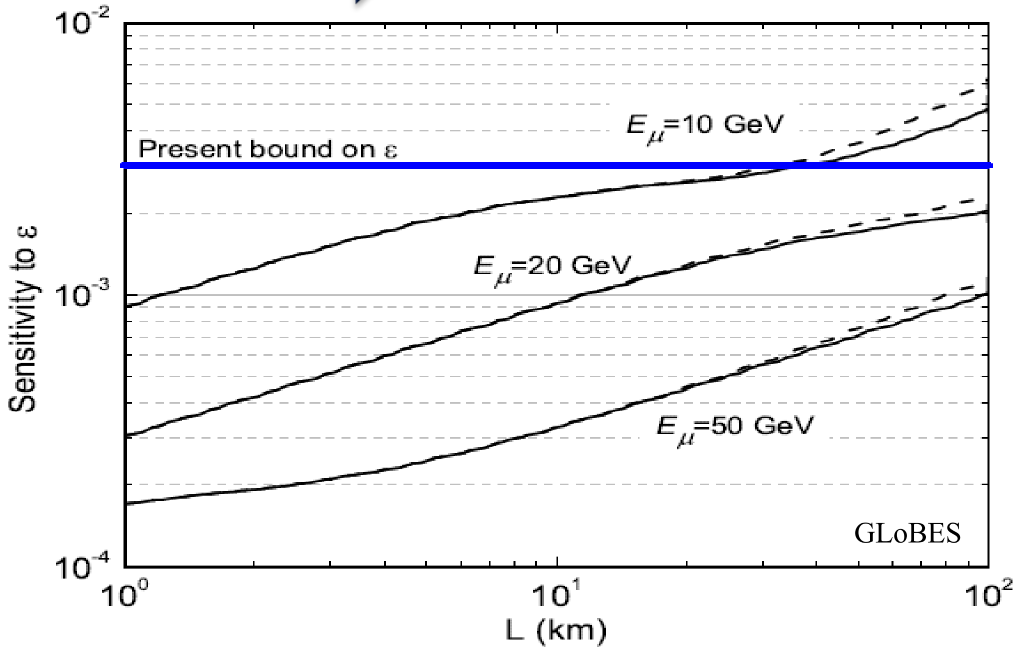
Phenomena at a neutrino factory and the LHC

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

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

Sensitivity limits at 90 % C.L.

Our settings:
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.



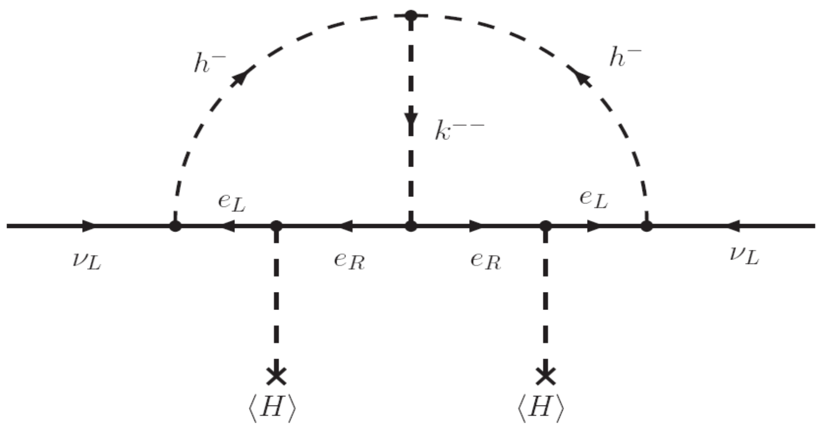
- Like-sign di-lepton production at the LHC $\Delta^{\pm\pm} \to \ell_\alpha^\pm \ell_\alpha^\pm$

The doubly charged Higgs produced at the LHC would predominantly decay into a pair of identical leptons

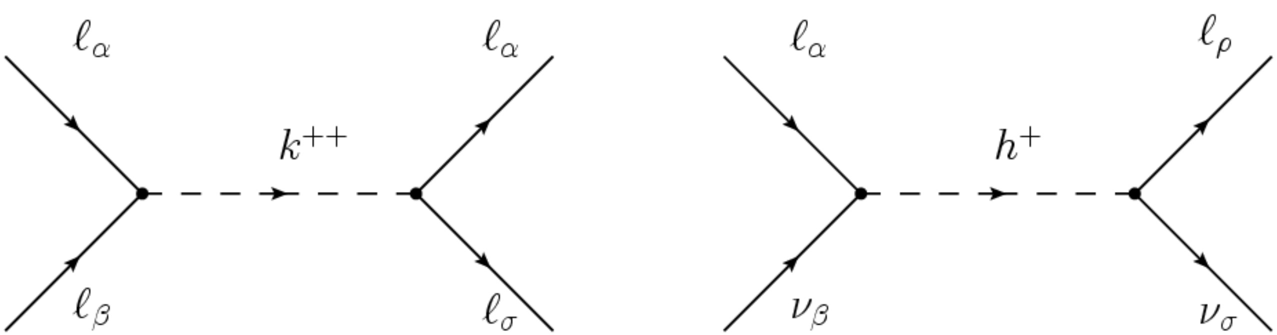
NSIs in the Zee-Babu model (Ohlsson, Schwetz and Zhang, appear soon)

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

(Zee, 85; 86; Babu, 88)



The masses of doubly and singly charged Higgs are well separated

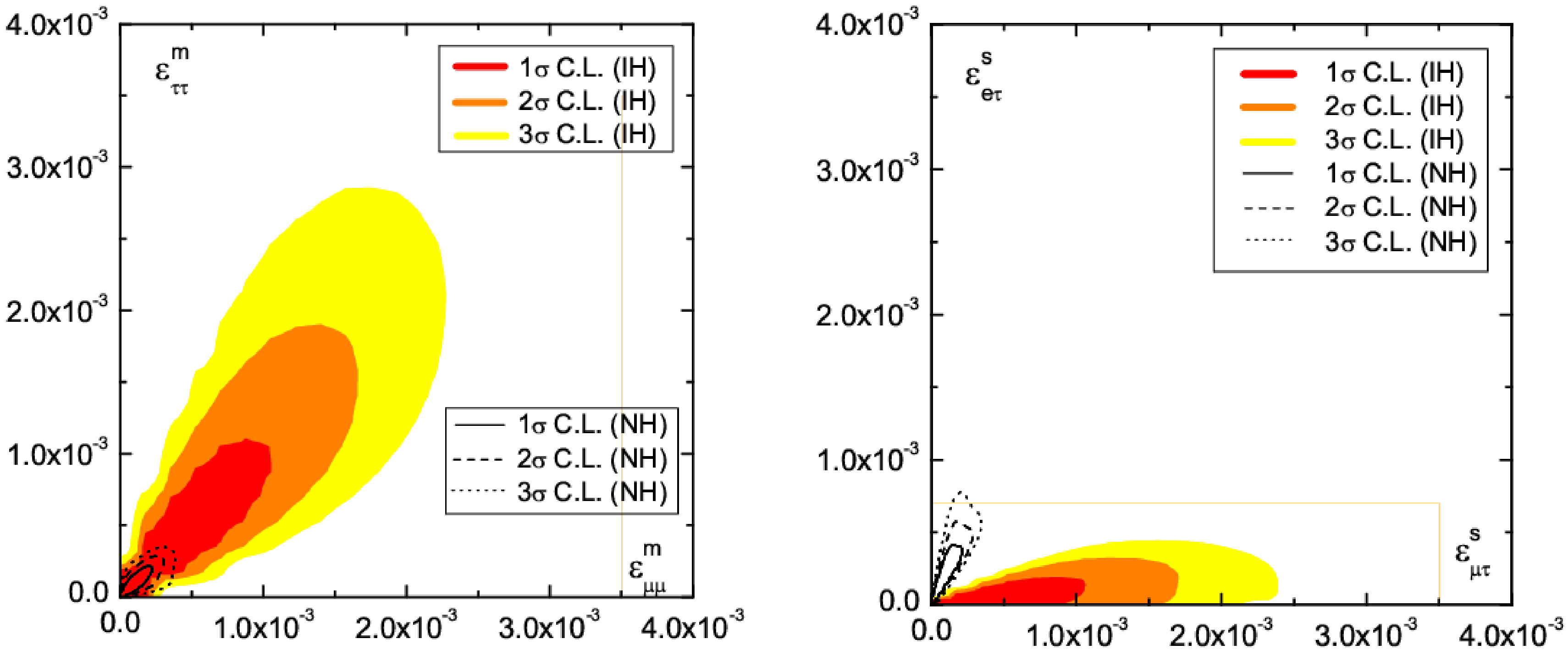


(a) (b)

NSIs in the Zee-Babu model (Ohlsson, Schwetz and Zhang, appear soon)

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

(Zee, 85; 86; Babu, 88)



NSI parameters are correlated to neutrino masses

Inverse seesaw

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

Mohapatra and Valle, 86

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

9x9 ν-mass matrix:

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

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

Light neutrino mass matrix:

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

Inverse seesaw

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

Mohapatra and Valle, 86

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

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 μ→0: massless neutrinos & lepton number conservation

Realization in extra dimension theories

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

Phenomenological consequence of the inverse seesaw model

Non-unitarity effects

Malinsky, Ohlsson, Zhang, PRD 09

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

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

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

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

The charged current Lagrangian in the mass basis:

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

F governs the magnitude of non-unitarity effects

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

Oscillation probability in vacuum (e.g., Antusch *et al* 07):

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

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

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

Oscillation probability in vacuum (e.g., Antusch *et al* 07):

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

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

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

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

Oscillation probability in vacuum (e.g., Antusch *et al* 07):

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

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

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

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

Oscillation in matter: neutral currents are involved

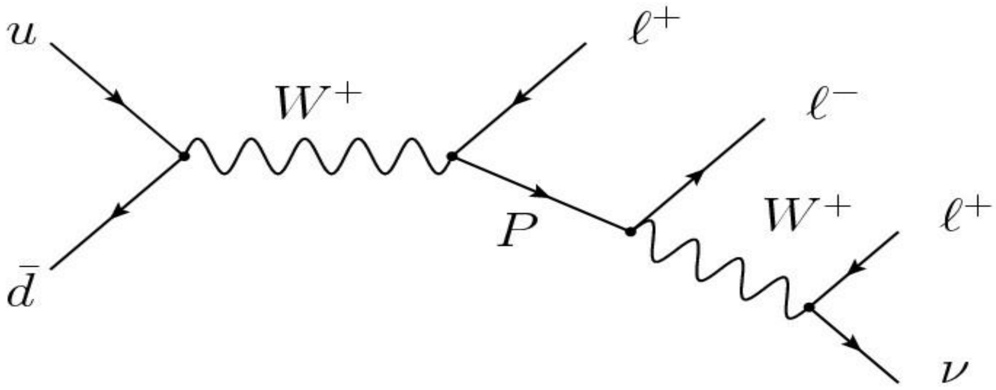
$$P(\nu_\mu \to \nu_\tau) \approx \sin^2\frac{\Delta_{23}}{2} - \sum_{l=4}^{6} s_{2l}s_{3l}\left[\sin(\delta_{2l}-\delta_{3l}) + A_{\rm NC}L\cos(\delta_{2l}-\delta_{3l})\right]\sin\Delta_{23}$$

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

(Fernandez-Martınez , Gavela, Lopez-Pavon
and Yasuda 07; Goswami and Ota 08; Xing 09)

Collider signatures:

- Tri-lepton production



LFV but not LNV
Small SM background

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

- 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.

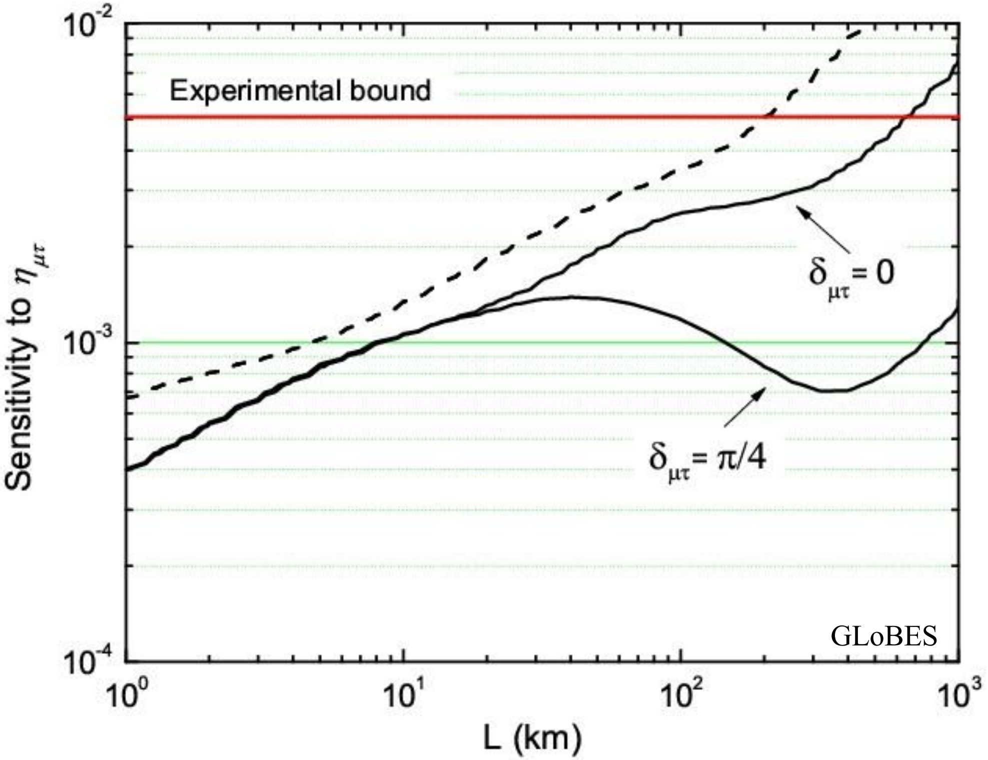
Sencivity search at a neutrino factory

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.

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

We consider a typical neutrino factory setup with an OPERA-like near detector with fiducial mass of 5 kt. We assume a setup with approximately10^{21} useful muon decays and five years of neutrino and another five years of anti-neutrino running.

Malinsky, Ohlsson, Xing & Zhang, arXiv: 0905.2889



Concluding remarks

1. Non-standard neutrino interactions could be naturally generated in low-scale seesaw models, and should be taken into account in phenomenological studies.
2. 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.
3. The LHC and neutrino factory open a new window towards understanding the origin of neutrino masses and lepton number violation around TeV scale.

Concluding remarks

1. Non-standard neutrino interactions could be naturally generated in low-scale seesaw models, and should be taken into account in phenomenological studies.
2. 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.
3. The LHC and neutrino factory open a new window towards understanding the origin of neutrino masses and lepton number violation around TeV scale.

Thanks !