Seesaw models at the TeV scale

December 06, 2010

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- Seesaw models
- Low-scale seesaw: GUT or TeV?
- Phenomenological consequences:

  Collider signatures Lepton flavor violations

  Non-standard interactions Leptogenesis

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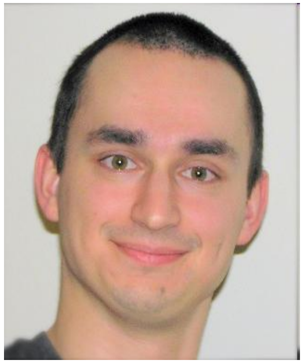

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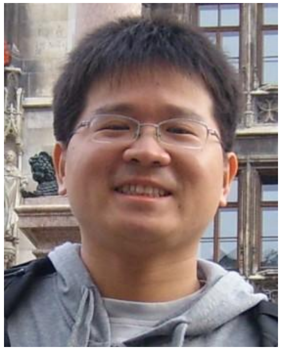

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Neutrino oscillation experiments

- Solar neutrino experiments:
  - Super-Kamiokande, SNO
  - Small mass-squared difference Δm_{21}^2 and 1-2 mixing angle
- Atmospheric neutrino experiments:
  - Super-Kamiokande
  - Large mass-squared difference Δm_{31}^2 and 2-3 mixing angle
- Accelerator neutrino experiments:
  - K2K, MINOS, CNGS-OPERA
  - Confirm atmospheric neutrino experiments
- Reactor neutrino experiments:
  - CHOOZ, KamLAND
  - 1-3 mixing angle
  - Confirm solar neutrino experiments
- Future experiments: IceCube, KATRIN, Daya Bay, Double Chooz, " neutrino factory" , ...

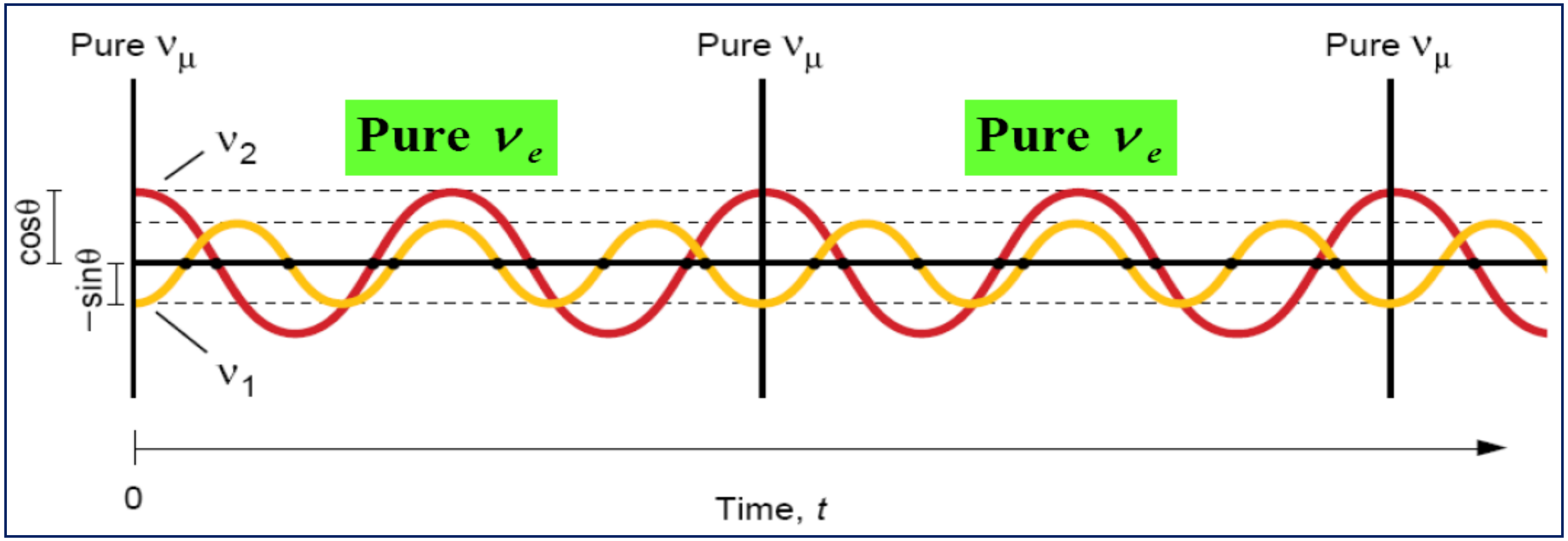
There are now strong evidences that neutrinos are massive and lepton flavors are mixed. Since in the SM neutrinos are massless particles, the SM must be extended by adding neutrino masses.

Neutrino mixing: two flavors

Neutrinos have (different) masses $\Rightarrow$ Dm^2 = m$_1^2$ – m$_2^2$

The ***Weak Eigenstates*** are a mixture of ***Mass Eigenstates***

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$



$$\boxed{P\left(\nu_\mu \to \nu_e\right) = \sin^2 2\theta \sin^2 \frac{1.27\Delta m^2 L}{E}}$$

Lepton flavor mixing: three flavors

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 phase δ

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, Tortola, Valle, 08

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Tri-maximal

$$\begin{pmatrix} \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} \\ \frac{\omega}{\sqrt{3}} & \frac{1}{\sqrt{3}} & \frac{\omega^2}{\sqrt{3}} \\ \frac{\omega^2}{\sqrt{3}} & \frac{1}{\sqrt{3}} & \frac{\omega}{\sqrt{3}} \end{pmatrix}$$

Tri-bimaximal

$$\begin{pmatrix} \frac{2}{\sqrt{6}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \end{pmatrix}$$

Bi-maximal

$$\begin{pmatrix} \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} & 0 \\ -\frac{1}{2} & \frac{1}{2} & \frac{\sqrt{2}}{2} \\ \frac{1}{2} & -\frac{1}{2} & \frac{\sqrt{2}}{2} \end{pmatrix}$$

Harrison, Perkins, Scott, 01; Xing, 01

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Unknowns:

1. θ_{13}=0?
2. Sign of $\Delta m_{31}{}^2$
3. Dirac or Majorana ?
4. Absolute mass scale
5. Leptonic CP violation?
6. Sterile neutrino?
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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).

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.

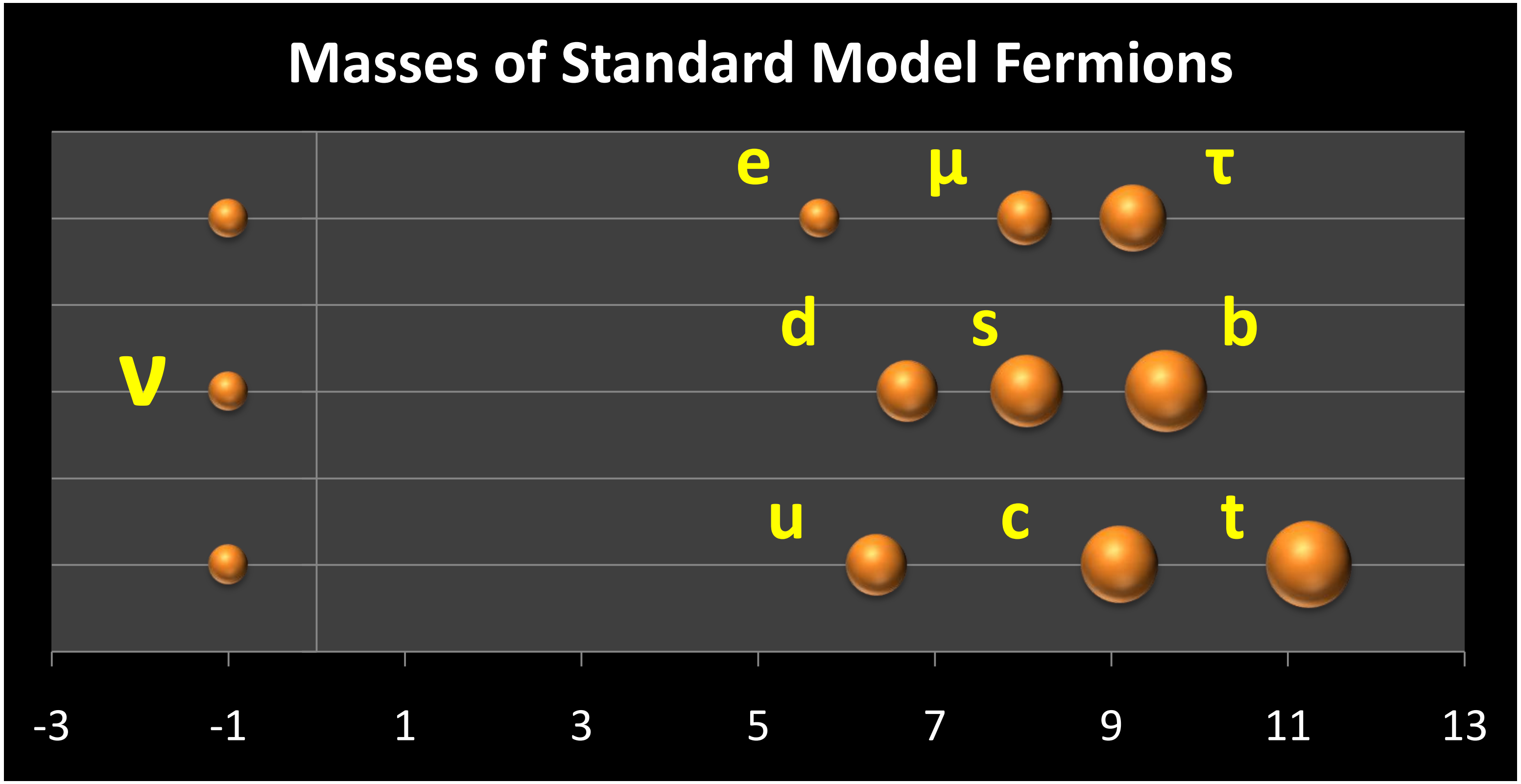
--- Economical particle content:

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.



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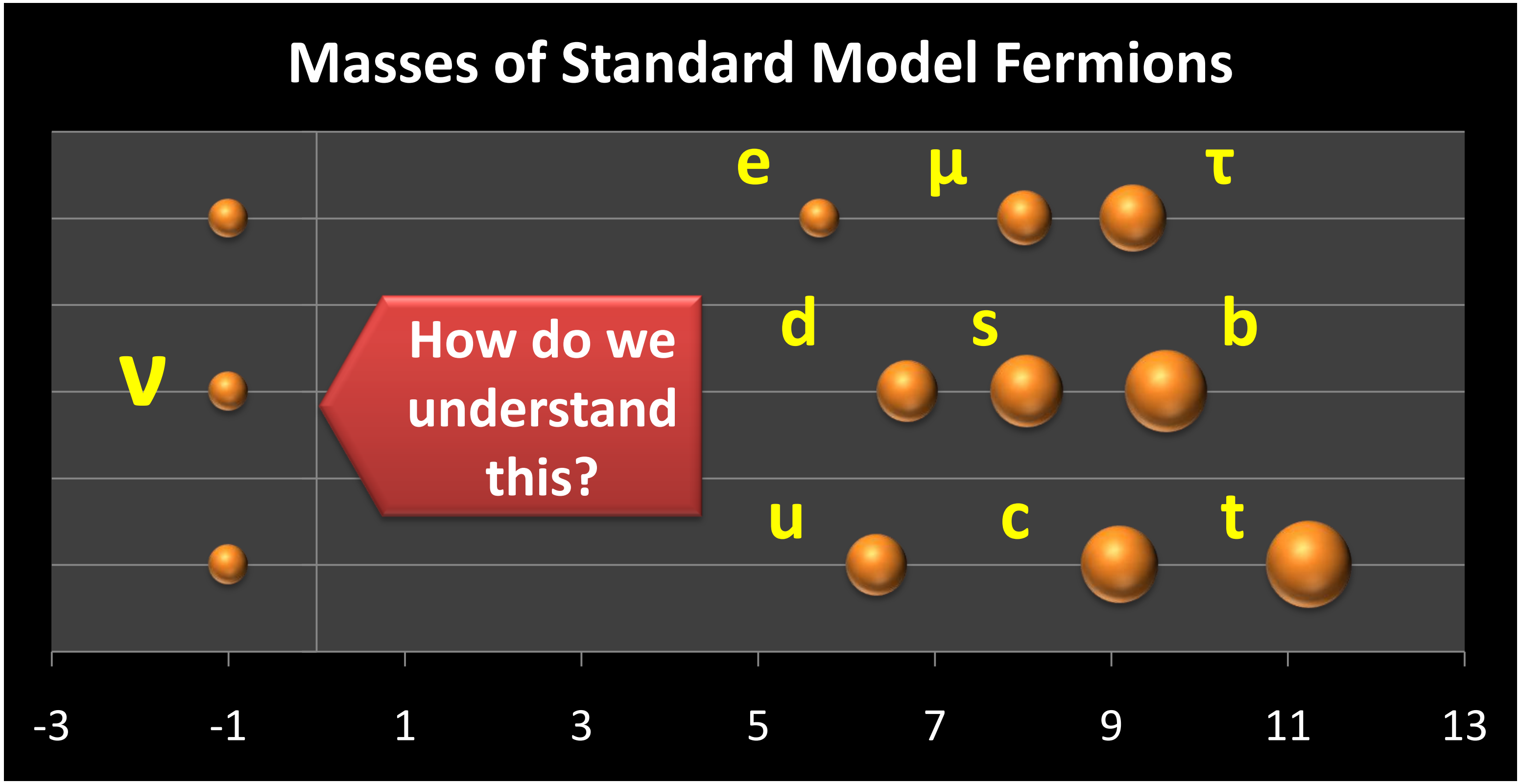


Beyond the SM

Neutrinos are Dirac particles

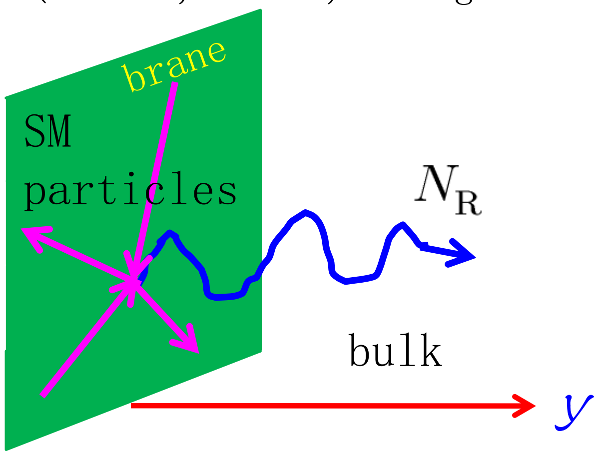
ν_R + a pure Dirac mass term

Extremely tiny Yukawa coupling ~10^{-11}, (hierarchy puzzle)

$$\mathscr{L} = \mathscr{L}_{SM} + \left\{ Y \overline{l_L} \nu_R \tilde{\phi} + \text{h.c.} \right\}$$

The smallness of Dirac masses is ascribed to the assumption that N_R have access to an extra spatial dimension

(Dienes, Dudas, Gherghetta 98; Arkani-Hamed, Dimopoulos, Dvali, March-Russell 98)



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

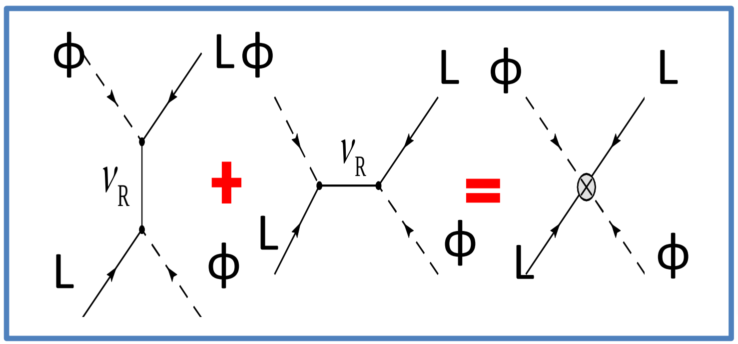
$$\boxed{\left[\overline{l_L} Y_\nu \tilde{H} N_R\right]_{y=0} \sim \frac{1}{\sqrt{L}} \left[\overline{l_L} Y_\nu \tilde{H} N_R\right]_{y=L}}$$

Neutrino masses: **Seesaw**

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

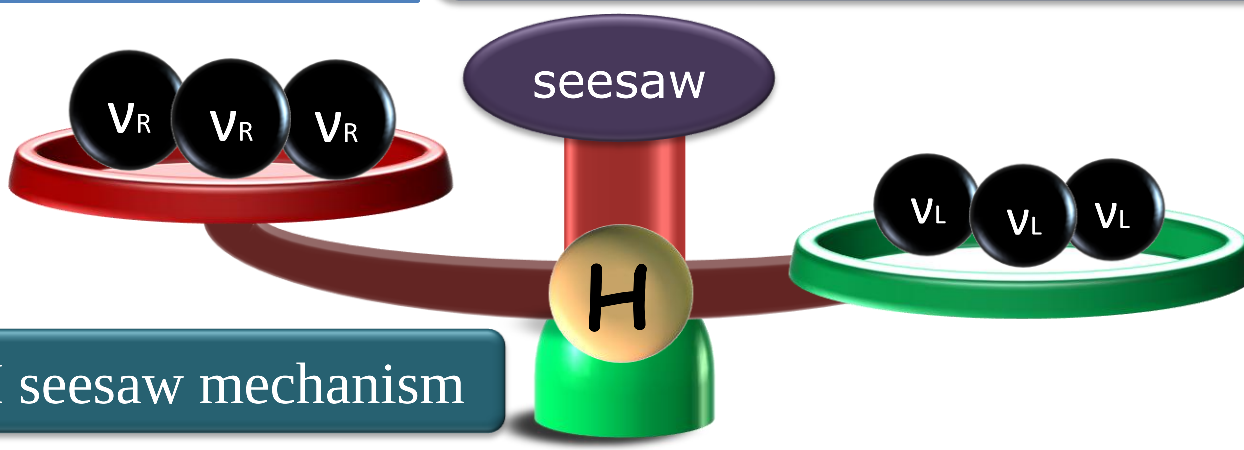
Integrate out heavy right-handed fields

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



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

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



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)

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

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)

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

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

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

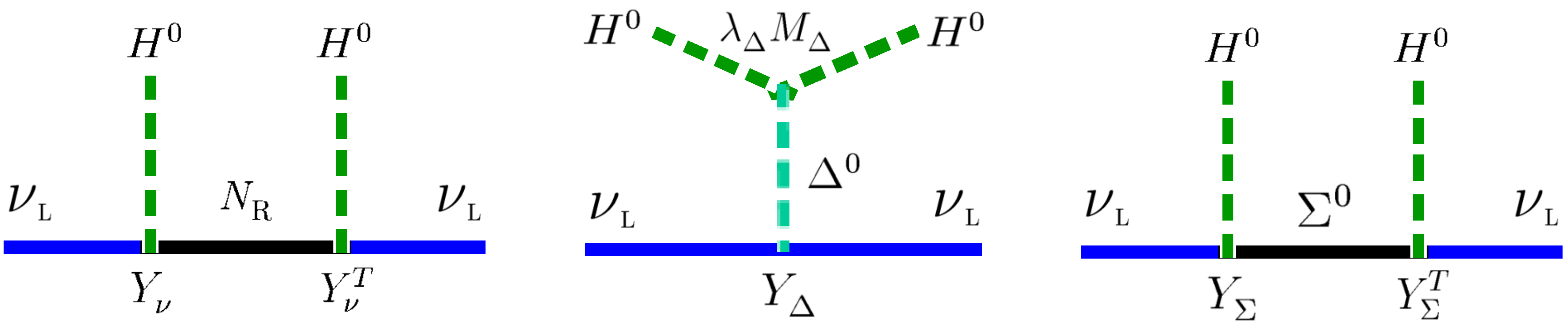
variations
&
combination

Neutrino mass from dimension-5 operators

$$\frac{\mathcal{L}_{\rm d=5}}{\Lambda} = \begin{cases} \frac{1}{2}\left(Y_\nu M_{\rm R}^{-1} Y_\nu^T\right)_{\alpha\beta} \overline{l_{\alpha \rm L}} \tilde{H} \tilde{H}^T l^c_{\beta \rm L} + {\rm h.c.} \\ -\frac{\lambda_\Delta}{M_\Delta} \left(Y_\Delta\right)_{\alpha\beta} \overline{l_{\alpha \rm L}} \tilde{H} \tilde{H}^T l^c_{\beta \rm L} + {\rm h.c.} \\ \frac{1}{2}\left(Y_\Sigma M_\Sigma^{-1} Y_\Sigma^T\right)_{\alpha\beta} \overline{l_{\alpha \rm L}} \tilde{H} \tilde{H}^T l^c_{\beta \rm L} + {\rm h.c.} \end{cases}$$

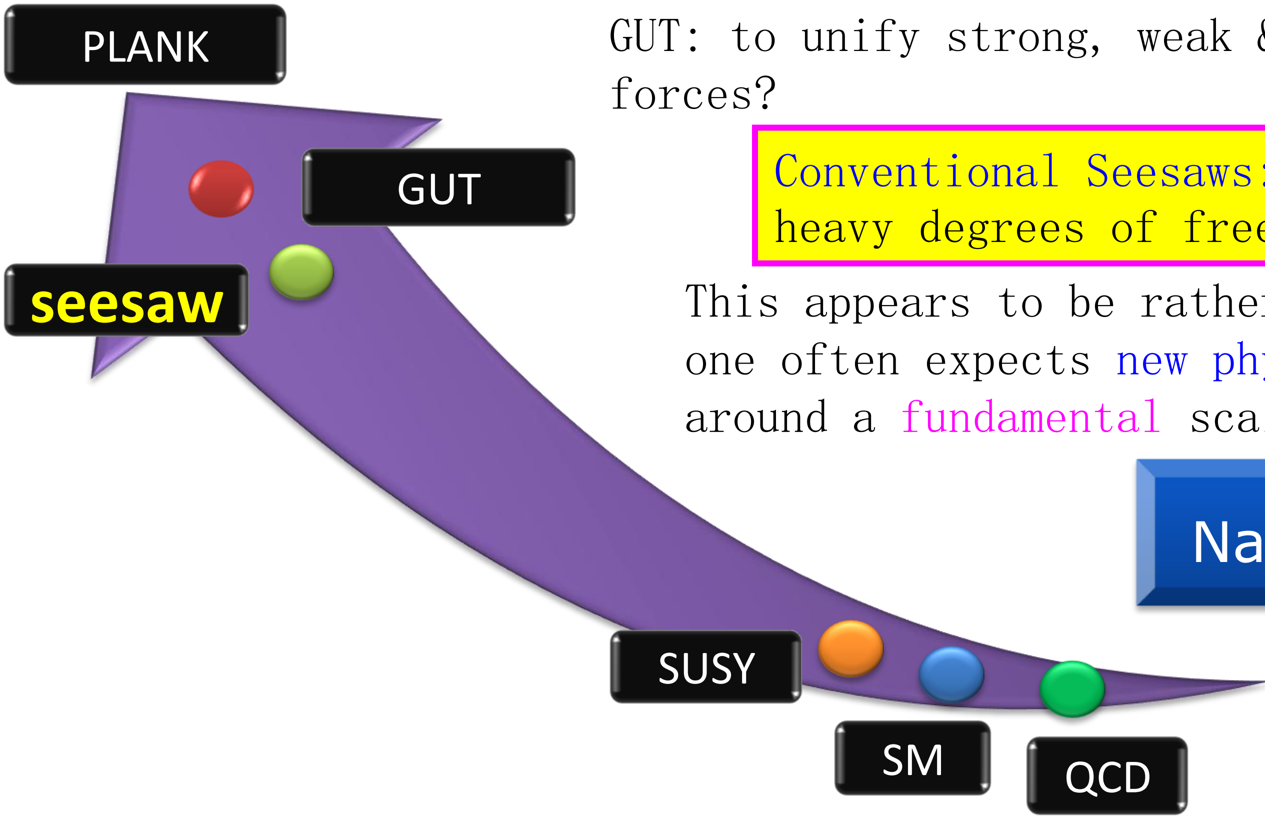
$$M_\nu = \begin{cases} -\frac{1}{2} Y_\nu \frac{v^2}{M_{\rm R}} Y_\nu^T & \text{(Type 1)} \\ \lambda_\Delta Y_\Delta \frac{v^2}{M_\Delta} & \text{(Type 2)} \\ -\frac{1}{2} Y_\Sigma \frac{v^2}{M_\Sigma} Y_\Sigma^T & \text{(Type 3)} \end{cases}$$

After SSB, a Majorana mass term is: $-\mathcal{L}_{\rm mass} = \frac{1}{2}\overline{\nu_{\rm L}} M_\nu \nu^c_{\rm L} + {\rm h.c.}$ $\quad \langle \tilde{H} \rangle = v/\sqrt{2}$



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 ×

Low-scale seesaw?

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

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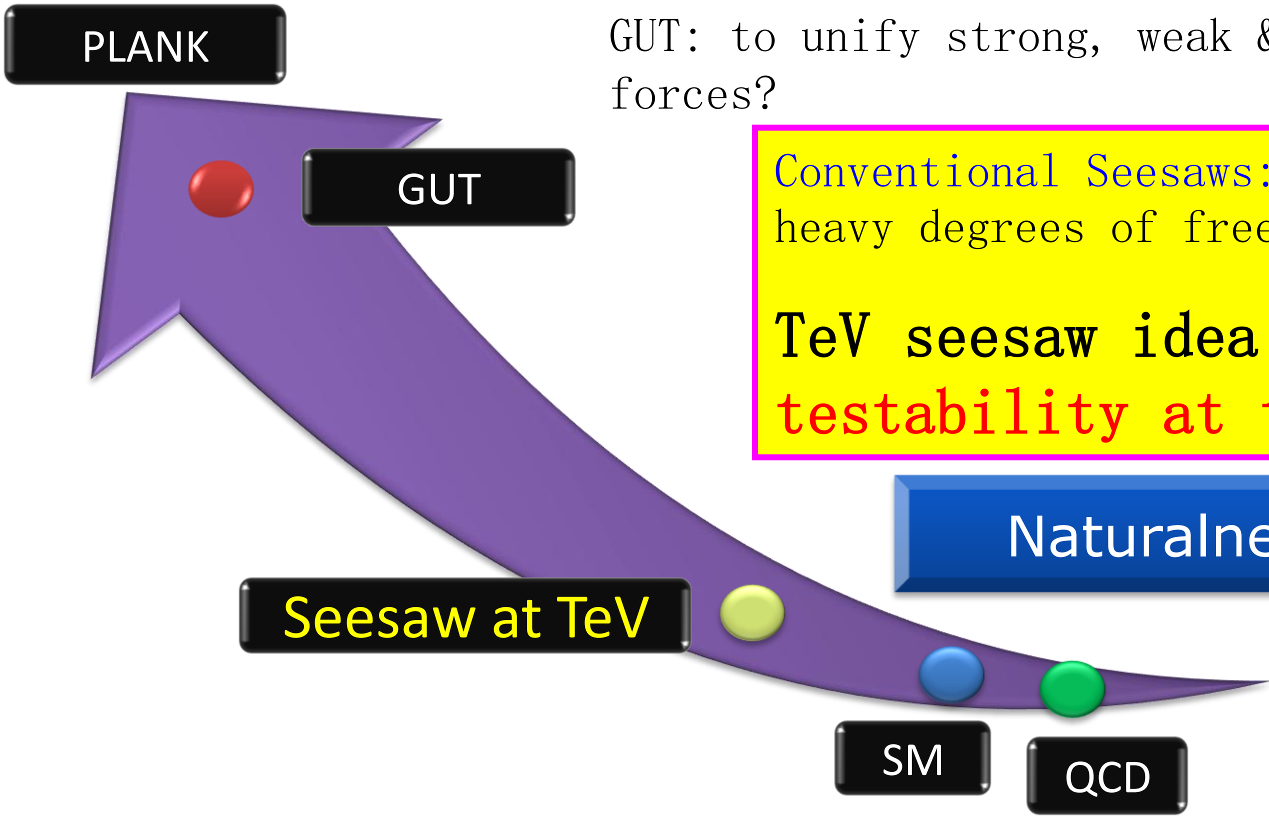
TeV seesaw idea: driven by testability at the LHC.



Naturalness & Testability

In reality, there is no direct evidence for a large or extremely large seesaw scale. So eV-, keV-, MeV- or GeV-scale seesaws are all possible, at least in principle.

Naturalness:

a low seesaw scale could be technically natural

‘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.

Potential problems of low-scale seesaws

(de Gouvea 05; 07):

- No obvious connection to a theoretically well-justified fundamental physical scale (for example, the Fermi, TeV, GUT & Planck scales);
- The neutrino Yukawa couplings turn out to be tiny, giving no actual explanation of why the masses of 3 known neutrinos are so tiny;
- In general, a very low seesaw scale does not allow the “canonical” thermal leptogenesis to work, although there could be a way out.

TeV type-I seesaw   structural cancellation

Unnatural case: large cancellation in the leading seesaw term.

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

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).

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

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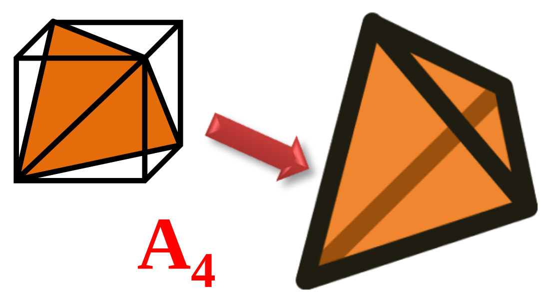
Underlying flavor symmetry: (A_4, S_4)?
Radiative corrections?
Renormalization group running?



TeV minimal type-I seesaw

Zhang, Zhou, PLB, 10

Only two right-handed neutrinos are introduced and they could be grouped together to form a Dirac particle

$$P = (P_1 + P_2)/\sqrt{2}$$

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$$M_{\rm D} = v \begin{pmatrix} y_e & y_\mu & y_\tau \\ 0 & 0 & 0 \end{pmatrix}^T , \quad M_{\rm R} = \begin{pmatrix} 0 & M \\ M & 0 \end{pmatrix}$$

One can prove that neutrinos are exactly massless to all orders

$$M_{\rm D} M_{\rm R}^{-1} M_{\rm D}^T = \mathbf{0}$$

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Neutrino masses can be generated perturbatively

$$\mathcal{M}_\nu = \begin{pmatrix} \kappa_{ee} & \kappa_{e\mu} & \kappa_{e\tau} & v y_e & \varepsilon_e \\ \kappa_{\mu e} & \kappa_{\mu\mu} & \kappa_{\mu\tau} & v y_\mu & \varepsilon_\mu \\ \kappa_{\tau e} & \kappa_{\tau\mu} & \kappa_{\tau\tau} & v y_\tau & \varepsilon_\tau \\ v y_e & v y_\mu & v y_\tau & \mu' & M \\ \varepsilon_e & \varepsilon_\mu & \varepsilon_\tau & M & \mu \end{pmatrix}$$

A very natural candidate of TeV seesaw models

Inverse seesaw

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

Mohapatra and Valle, 86

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

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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:

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

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LNV: tiny

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

Variations of type-I seesaw

SM +

two heavy neutrinos: minimal seesaw

three heavy neutrinos: type-I seesaw

four heavy neutrinos: minimal inverse seesaw

six heavy neutrinos: inverse seesaw (double seesaw)

more singlet neutrinos: multiple seesaw

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

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

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

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L violation

Δ is close to the TeV scale, while λ_Φ is naturally tiny since λ_Φ=0 enhances the symmetry of the model.

Neutrino masses

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

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

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

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

L violation

Δ is close to the TeV scale, while λ_Φ is naturally tiny since λ_Φ=0 enhances the symmetry of the model.

Neutrino masses

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

Type-I+II seesaw: both Higgs triplet and right-handed neutrinos

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

◆ Left-right symmetry?

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

Type-III seesaw: add 3 $SU(2)_L$ triplet fermions into the SM

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

$$\Sigma = \begin{pmatrix} \Sigma^0/\sqrt{2} & \Sigma^+ \\ \Sigma^- & -\Sigma^0/\sqrt{2} \end{pmatrix} \qquad M_l = Y_l v/\sqrt{2}\,, \quad M_{\rm D} = Y_\Sigma v/\sqrt{2}\,, \quad \Psi = \Sigma^- + \Sigma^{+c}$$

$$-\mathcal{L}_{\rm mass} = \overline{(e_{\rm L} \quad \Psi_{\rm L})} \begin{pmatrix} M_l & \sqrt{2} M_{\rm D} \\ \mathbf{0} & M_\Sigma \end{pmatrix} \begin{pmatrix} E_{\rm R} \\ \Psi_{\rm R} \end{pmatrix} + \frac{1}{2} \overline{(\nu_{\rm L} \quad \Sigma^0)} \begin{pmatrix} \mathbf{0} & M_{\rm D} \\ M_{\rm D}^T & M_\Sigma \end{pmatrix} \begin{pmatrix} \nu_{\rm L}^c \\ \Sigma^{0c} \end{pmatrix} + {\rm h.c.}$$

Diagonalization of the neutrino mass matrix:

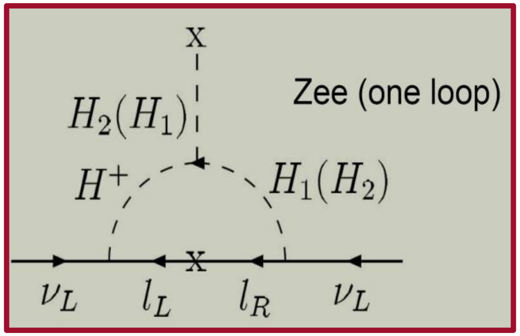
$$\begin{pmatrix} V & R \\ S & U \end{pmatrix}^\dagger \begin{pmatrix} \mathbf{0} & M_{\rm D} \\ M_{\rm D}^T & M_\Sigma \end{pmatrix} \begin{pmatrix} V & R \\ S & U \end{pmatrix}^* = \begin{pmatrix} \widehat{M}_\nu & \mathbf{0} \\ \mathbf{0} & \widehat{M}_\Sigma \end{pmatrix}$$

Seesaw formula:

$$M_\nu \equiv V \widehat{M}_\nu V^T \approx -M_{\rm D} M_\Sigma^{-1} M_{\rm D}^T$$

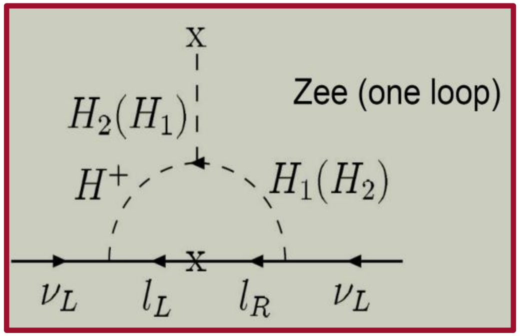
Radiative seesaw

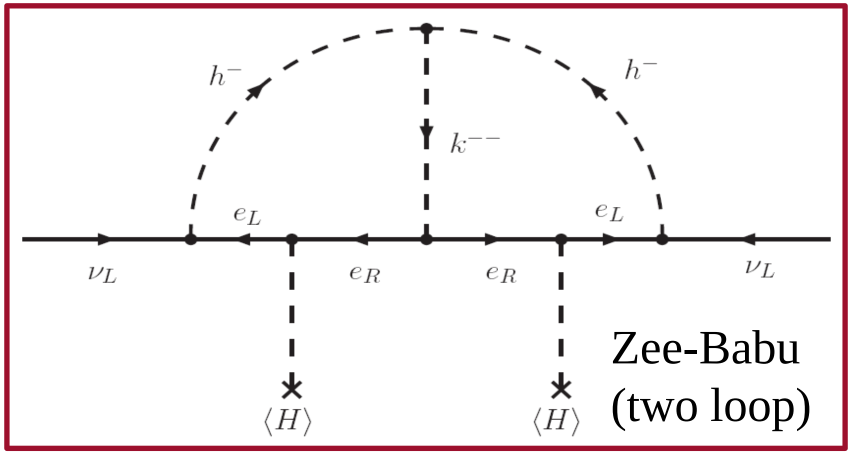
(Zee, 80, 85, 86; Babu, 88)



Radiative seesaw

(Zee, 80, 85, 86; Babu, 88)

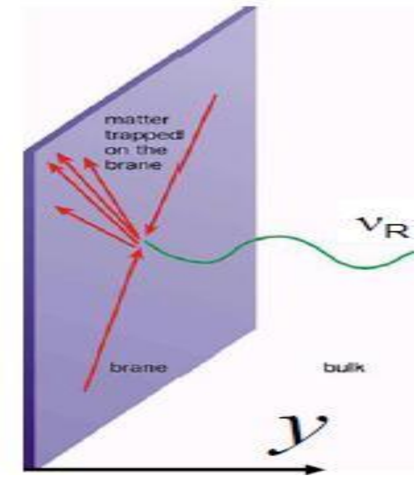




$$
\begin{aligned}
\mathcal{L} \;=\; & \mathcal{L}_{\rm SM} + f_{\alpha\beta} L^T_{L\alpha} C i\sigma_2 L_{L\beta} h^+ + g_{\alpha\beta} \overline{e^c_\alpha} e_\beta k^{++} \\
- \;& \mu h^- h^- k^{++} + \text{h.c.} + V_H \;,
\end{aligned}
$$

A speculative way out -- extra dimensional seesaw

the smallness of neutrino masses is ascribed to the assumption that right-handed neutrinos have access to an extra spatial dimension

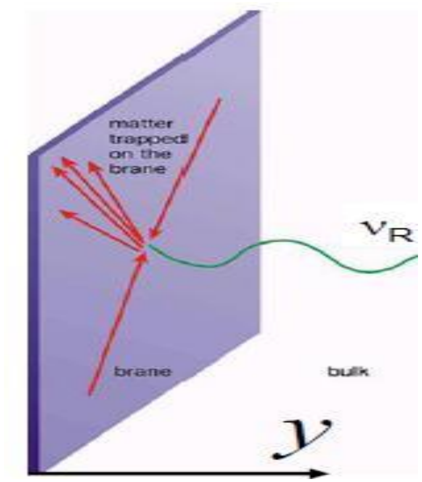


$$S = \int \mathrm{d}^4x\mathrm{d}y M_S \left[\mathrm{i}\overline{\Psi}\not{D}\Psi - \frac{1}{2}\left(\overline{\Psi^c}M_\mathrm{R}\Psi + \mathrm{h.c.}\right)\right] + \int_{y=0} \mathrm{d}^4x \left(-\frac{1}{\sqrt{M_S}}\overline{\nu_\mathrm{L}}\hat{m}\Psi - \frac{1}{\sqrt{M_S}}\overline{\nu^c_\mathrm{L}}\hat{m}^c\Psi + \mathrm{h.c.}\right)$$

Blennow, Melbéus, Ohlsson & Zhang, arXiv:1003.0669

A speculative way out -- extra dimensional seesaw

the smallness of neutrino masses is ascribed to the assumption that right-handed neutrinos have access to an extra spatial dimension



$$S = \int \mathrm{d}^4x \mathrm{d}y M_S \left[\mathrm{i}\overline{\Psi} \not{D} \Psi - \frac{1}{2} \left(\overline{\Psi^c} M_\mathrm{R} \Psi + \mathrm{h.c.} \right) \right] + \int_{y=0} \mathrm{d}^4x \left(-\frac{1}{\sqrt{M_S}} \overline{\nu_\mathrm{L}} \hat{m} \Psi - \frac{1}{\sqrt{M_S}} \overline{\nu_\mathrm{L}^c} \hat{m}^c \Psi + \mathrm{h.c.} \right)$$

If the extra dimension is compactified on the S^1/Z_2 orbifold with radius R, the full neutrino mass matrix then reads

$$\mathcal{M} = \begin{pmatrix} 0 & m_\mathrm{D} & m_\mathrm{D} & m_\mathrm{D} & \cdots & m_\mathrm{D} & m_\mathrm{D} \\ m_\mathrm{D}^T & M_\mathrm{R} & 0 & 0 & \cdots & 0 & 0 \\ m_\mathrm{D}^T & 0 & M_\mathrm{R} - \frac{1}{R} & 0 & \cdots & 0 & 0 \\ m_\mathrm{D}^T & 0 & 0 & M_\mathrm{R} + \frac{1}{R} & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & 0 & 0 \\ m_\mathrm{D}^T & 0 & 0 & 0 & 0 & M_\mathrm{R} - \frac{N}{R} & 0 \\ m_\mathrm{D}^T & 0 & 0 & 0 & 0 & 0 & M_\mathrm{R} + \frac{N}{R} \end{pmatrix}$$

Blennow, Melbéus, Ohlsson & Zhang, arXiv:1003.0669

A speculative way out -- extra dimensional seesaw

the smallness of neutrino masses is ascribed to the assumption that right-handed neutrinos have access to an extra spatial dimension

$$S = \int \mathrm{d}^4x\mathrm{d}y M_S \left[\mathrm{i}\overline{\Psi}\not{D}\Psi - \frac{1}{2}\left(\overline{\Psi^c}M_\mathrm{R}\Psi + \mathrm{h.c.}\right)\right] + \int_{y=0} \mathrm{d}^4x \left(-\frac{1}{\sqrt{M_S}}\overline{\nu_\mathrm{L}}\hat{m}\Psi - \frac{1}{\sqrt{M_S}}\overline{\nu^c_\mathrm{L}}\hat{m}^c\Psi + \mathrm{h.c.}\right)$$

Sherk--Schwarz decomposition in string theory

$$\boxed{M_i = \frac{k^{(i)}}{2}R^{-1}}$$

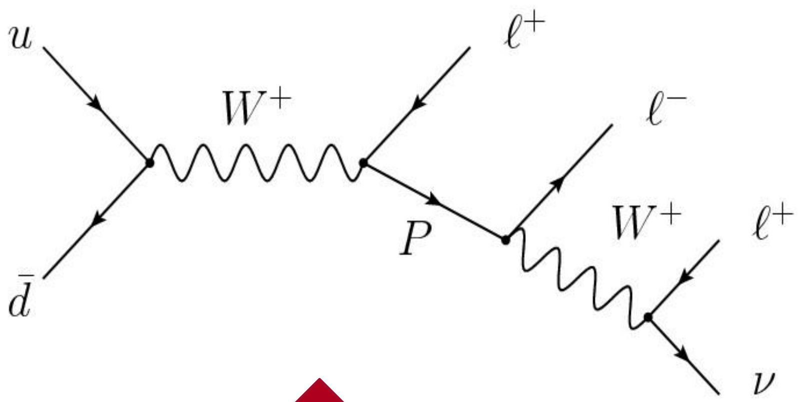
$$\boxed{m_\nu \simeq m_\mathrm{D}\left(M_\mathrm{R} + \frac{N}{R}\right)^{-1} m_\mathrm{D}^T}$$

$$\mathcal{M} = \begin{pmatrix} 0 & m_\mathrm{D} & m_\mathrm{D} & m_\mathrm{D} & \cdots & m_\mathrm{D} & m_\mathrm{D} \\ m_\mathrm{D}^T & M_\mathrm{R} & 0 & 0 & \cdots & 0 & 0 \\ m_\mathrm{D}^T & 0 & M_\mathrm{R} - \frac{1}{R} & 0 & \cdots & 0 & 0 \\ m_\mathrm{D}^T & 0 & 0 & M_\mathrm{R} + \frac{1}{R} & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & 0 & 0 \\ m_\mathrm{D}^T & 0 & 0 & 0 & 0 & M_\mathrm{R} - \frac{N}{R} & 0 \\ m_\mathrm{D}^T & 0 & 0 & 0 & 0 & 0 & M_\mathrm{R} + \frac{N}{R} \end{pmatrix}$$

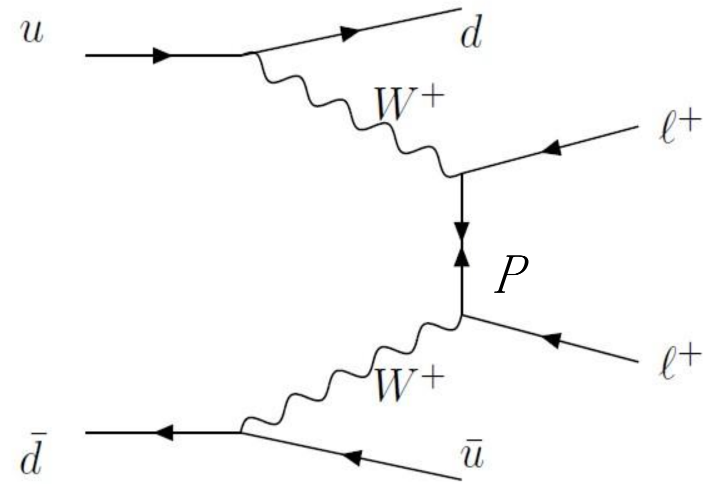
Blennow, Melbéus, Ohlsson & Zhang, arXiv:1003.0669

Phenomenological consequence: collider signatures

Fermionic seesaw: Tri-lepton signal



Resonant production



$$\sigma(pp \to \ell^{\pm}_{\alpha}\ell^{\mp}_{\beta}W^{\pm} + \text{jets}) \approx (2-\delta_{\alpha\beta})\sum_{i=1}^{2}\sigma(pp \to \ell^{\pm}_{\alpha}P^{i}_{m})$$
$$\times \mathrm{BR}(P^{i}_{m} \to \ell^{\mp}_{\beta}W^{\pm})$$

LFV but not LNV
Small SM background

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

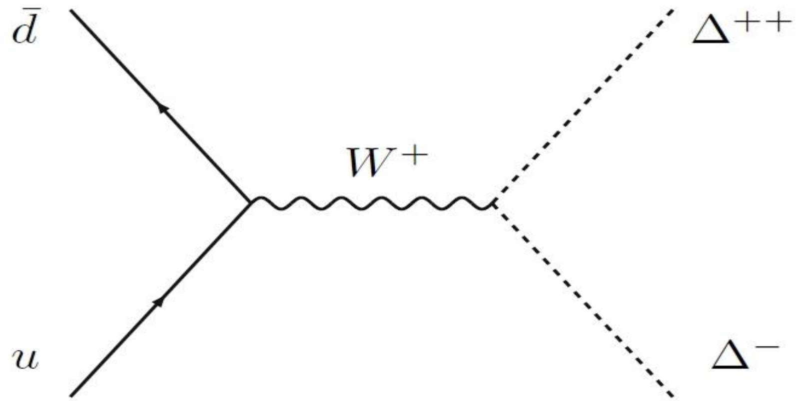
Large SM background

$$pp \to \ell^{\pm}_{\alpha}\ell^{\mp}_{\beta} + \text{jets}$$

T. Han & B. Zhang, 06

Phenomenological consequence: collider signatures

Scalar seesaw: Like-sign di-lepton production



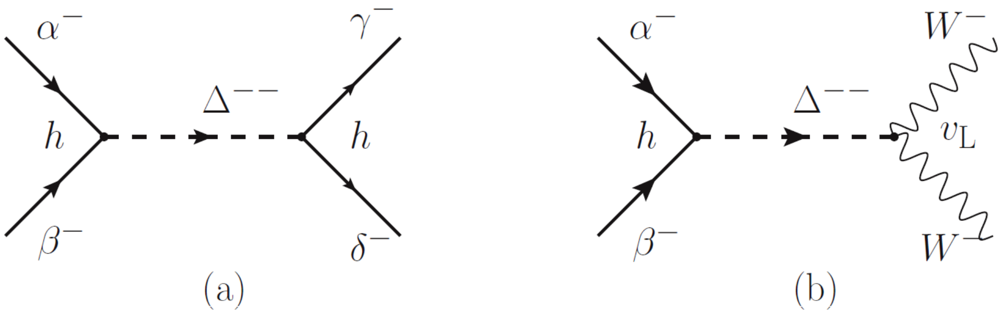
$$\boxed{\begin{aligned} q\bar{q} &\to Z^*/\gamma^* \to \Delta^{++}\Delta^{--}, \\ q\bar{q}' &\to W^* \to \Delta^{\pm\pm}\Delta^{\mp}, \\ q\bar{q} &\to Z^*/\gamma^* \to \Delta^{+}\Delta^{-}. \end{aligned}}$$

The scalar triplet can be discovered at the LHC up to 600 GeV (NH) or 800 GeV (IH) with a luminosity of 30 fb^{-1}

F. del Aguila, J.A. Aguilar-Saavedra, 09

Phenomenological consequence: collider signatures

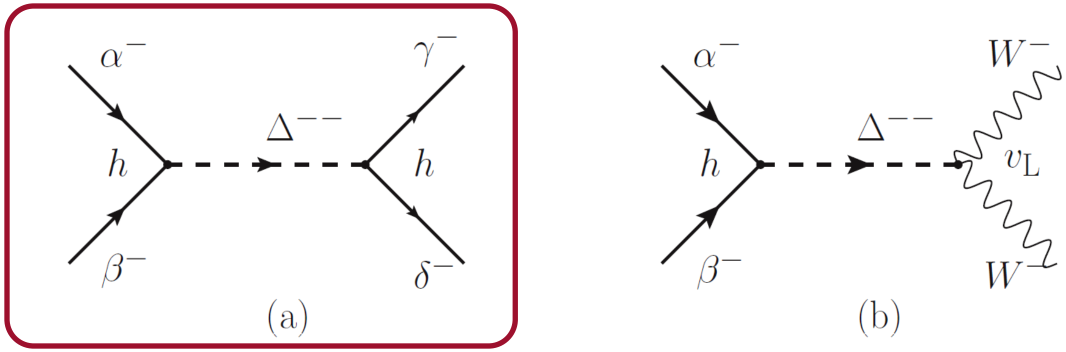
Triplet scalar at like-sign linear colliders Rodejohann, Zhang, 10

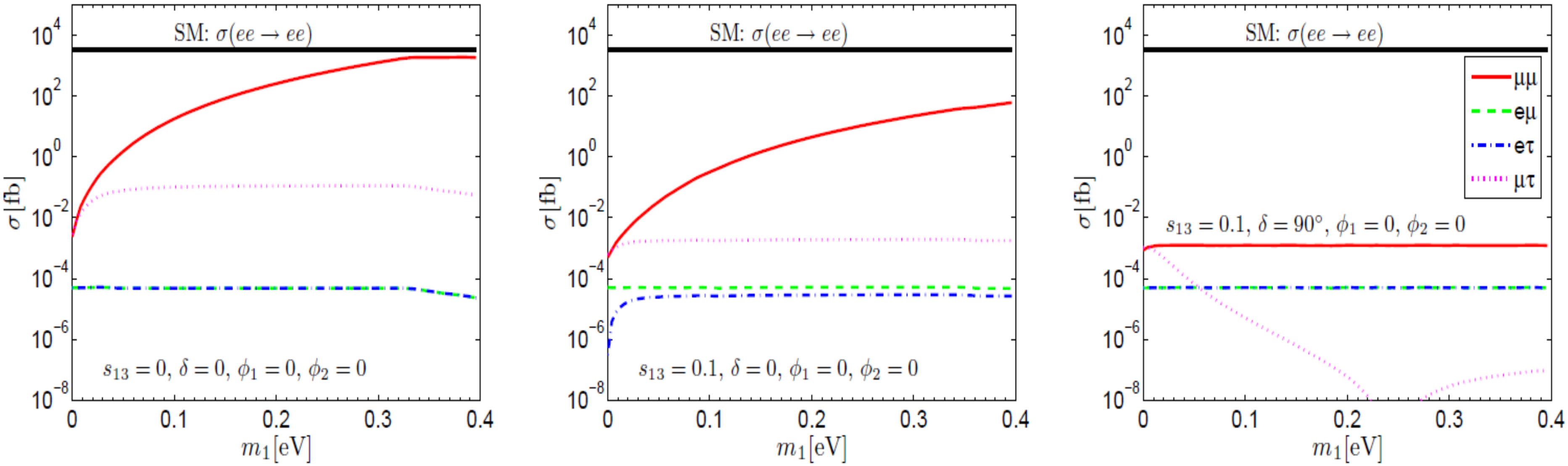


Phenomenological consequence: collider signatures

Triplet scalar at like-sign linear colliders

Rodejohann, Zhang, 10





Upper limits of cross sections $e^-e^- \to \alpha^-\beta^-$ at a linear collider with $s = 1\ \mathrm{TeV}^2$ (luminosity 80 fb^{-1}) and the triplet mass 800 GeV.

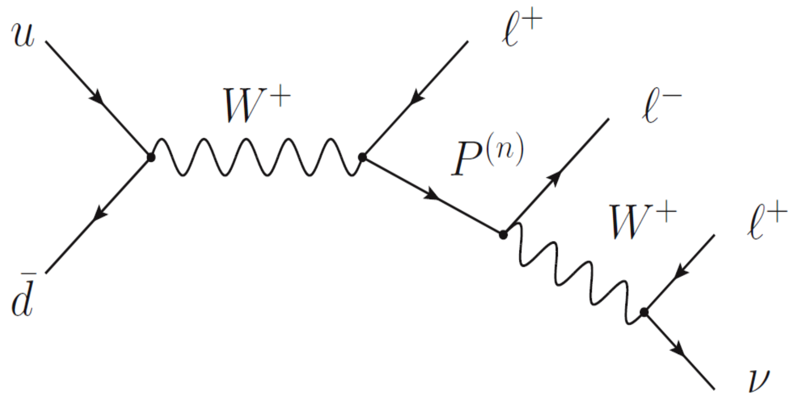
Phenomenological consequence: collider signatures

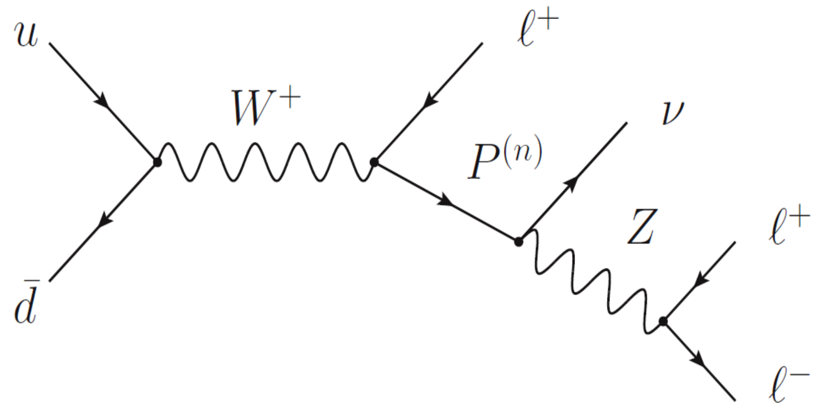
Extra dimensional seesaw at the LHC

- Heavy KK modes enter charged (neutral) current interaction

$$\mathcal{L}_{\rm CC} = -\frac{g}{\sqrt{2}}\overline{\ell_{\rm L}}\gamma^{\mu}\left[V\nu_{m\rm L} + \sqrt{2}\sum_{n=0}^{N-1}K^{(n)}P^{(n)} + K^{(N)}Y^{(N)}\right]W^{-}_{\mu} + {\rm h.c.}$$

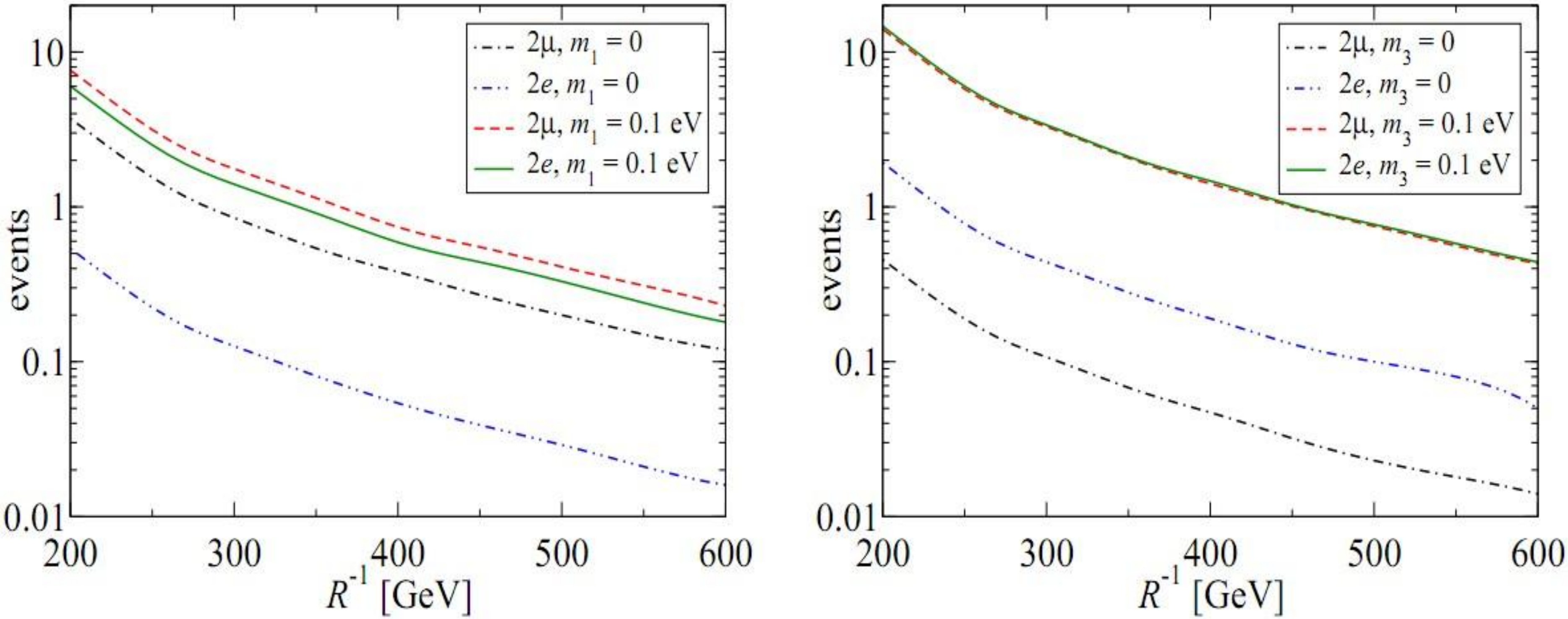
$$\mathcal{L}_{\rm NC} = \frac{g}{2\cos\theta_{\rm W}}\nu^{\dagger}_{m\rm L}\bar{\sigma}^{\mu}V^{\dagger}\left[\sqrt{2}\sum_{n=0}^{N-1}K^{(n)}P_{L}^{(n)} + K^{(N)}Y^{(N)}\right]Z_{\mu} + {\rm h.c.}$$





Phenomenological consequence: collider signatures

Extra dimensional seesaw at the LHC

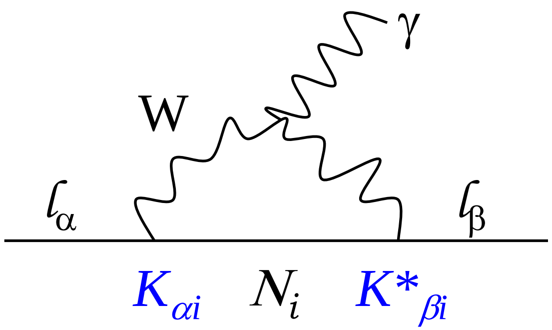


Expected number of events for the 2μ and 2e signals at the LHC as functions of the inverse radius R^{-1}, for an integrated luminosity of 30 fb^{-1}

Blennow, Melbeus, Ohlsson, Zhang, 10

Phenomenological consequence: LFV processes

Rare lepton decays: $\tau \to \mu\gamma$; $\mu \to e\gamma$



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

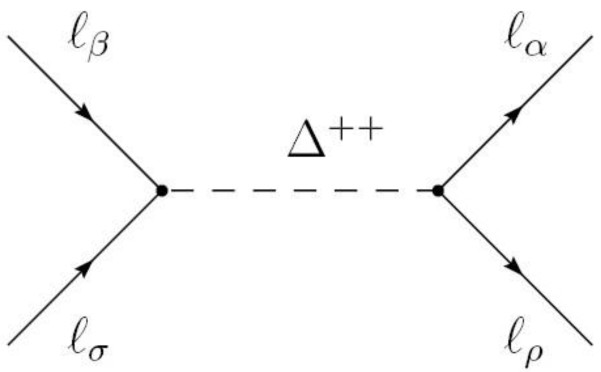
$$I(x) = -\frac{2x^3 + 5x^2 - x}{4(1-x)^3} - \frac{3x^3}{2(1-x)^4} \ln x$$

Ilakovac, Pilaftsis, 95

In the TeV seesaw models, one can have sizeable K without facing the difficulty of neutrino mass generation since they are decoupled.

Phenomenological consequence: LFV processes

LFV decays: μ→eee ; τ→μμμ …

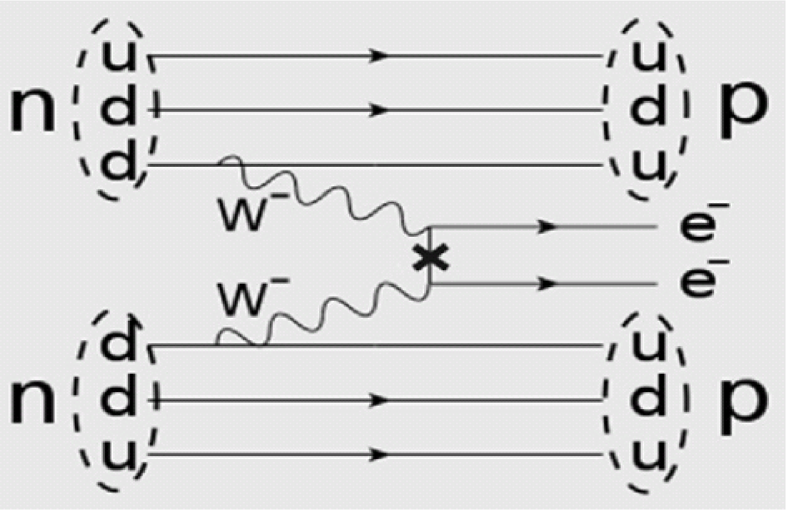


$$\Gamma(\mu^- \to e^+ e^- e^-) = \frac{m_\mu^5}{192\pi^3} \left| c^{4F}_{\mu eee} \right|^2 = \frac{m_\mu^5}{192\pi^3} \frac{1}{M_\Delta^4} |Y_{\Delta_{\mu e}}|^2 |Y_{\Delta_{ee}}|^2$$

Abada, Biggio, Bonnet, Gavela, Hambye, 07

Constraints on the Zee-Babu model are relatively weaker since the doubly and singly charged scalar are separated.

Phenomenological consequence: 0νββ decay



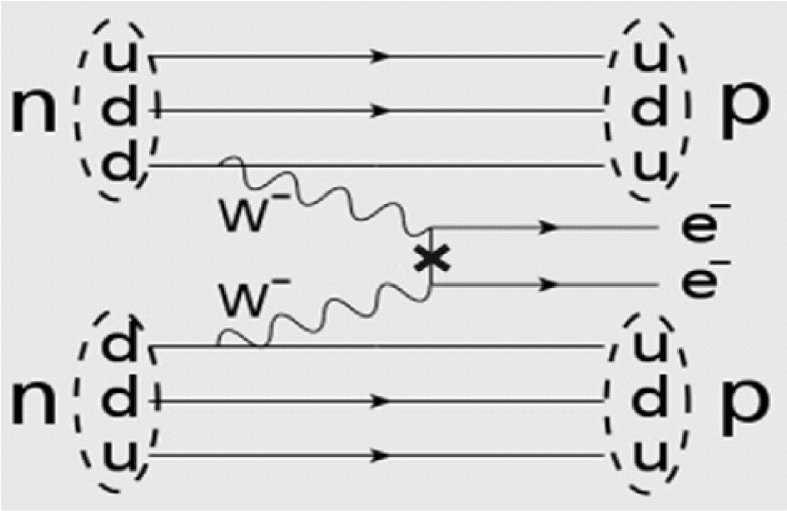
$$\Gamma_{0\nu\beta\beta} \propto \left| \sum_{i=1}^{3} V_{ei}^2 m_i - \sum_{k=1}^{n} \frac{R_{ek}^2}{M_k} M_A^2 \mathcal{F}(A, M_k) \right|^2$$

$$= \left| \sum_{k=1}^{n} R_{ek}^2 M_k \left[1 + \frac{M_A^2}{M_k^2} \mathcal{F}(A, M_k) \right] \right|,$$

Xing, 09

R: mixing between heavy and light neutrinos;
M_k: mass of heavy neutrinos; $M_A \sim 900$ GeV; F ~ 0.1

Phenomenological consequence: 0νββ decay



$$\Gamma_{0\nu\beta\beta} \propto \left| \sum_{i=1}^{3} V_{ei}^2 m_i - \boxed{\sum_{k=1}^{n} \frac{R_{ek}^2}{M_k} M_A^2 \mathcal{F}(A, M_k)} \right|^2$$

$$= \left| \sum_{k=1}^{n} R_{ek}^2 M_k \left[1 + \frac{M_A^2}{M_k^2} \mathcal{F}(A, M_k) \right] \right|,$$

Heavy neutrino contributions

Xing, 09

R: mixing between heavy and light neutrinos;
M_k: mass of heavy neutrinos; M_A ~ 900 GeV; F ~ 0.1

Phenomenological consequence: non-standard interactions

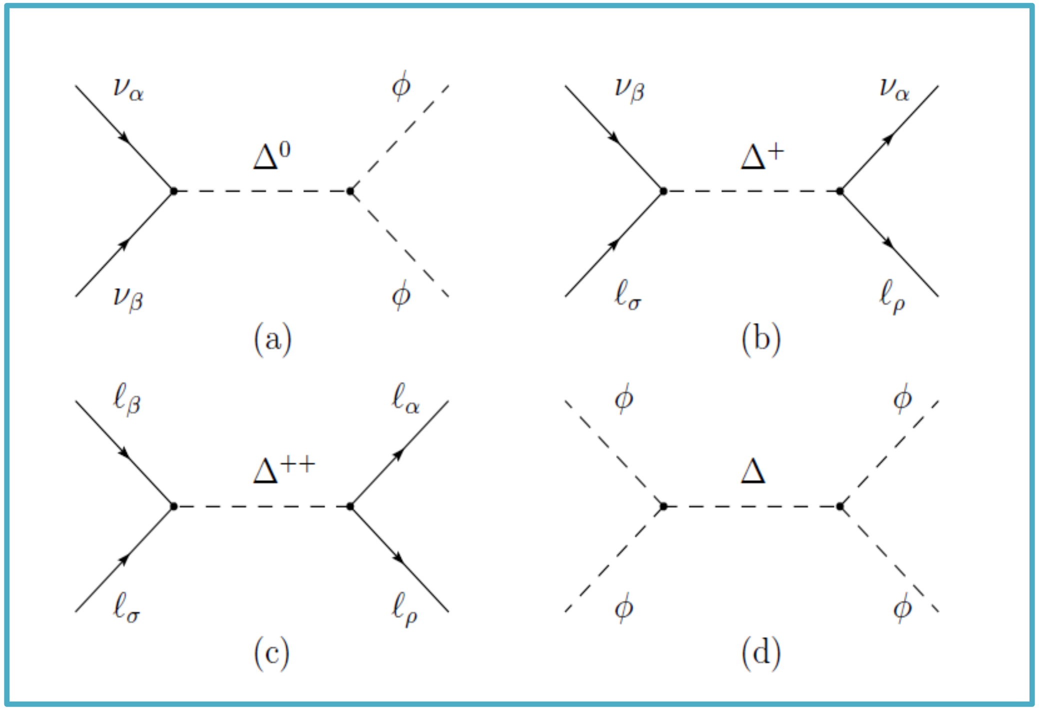
Type-II seesaw

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 consequence: non-standard interactions

Type-II seesaw

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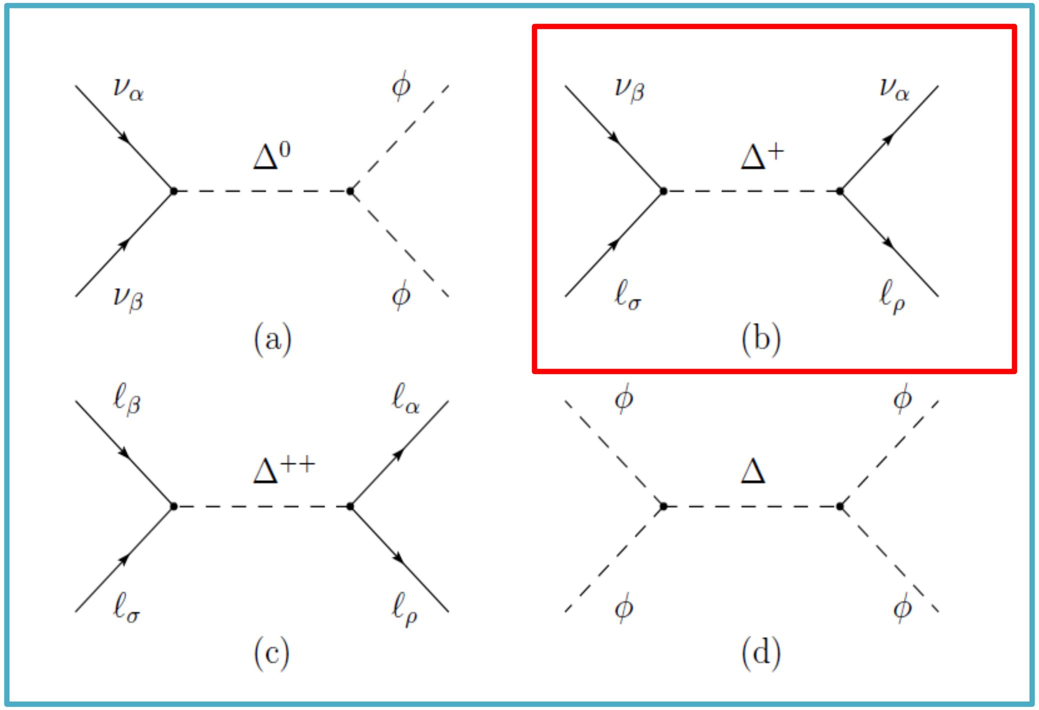


Malinsky, Ohlsson, Zhang, PRD(RC) 09

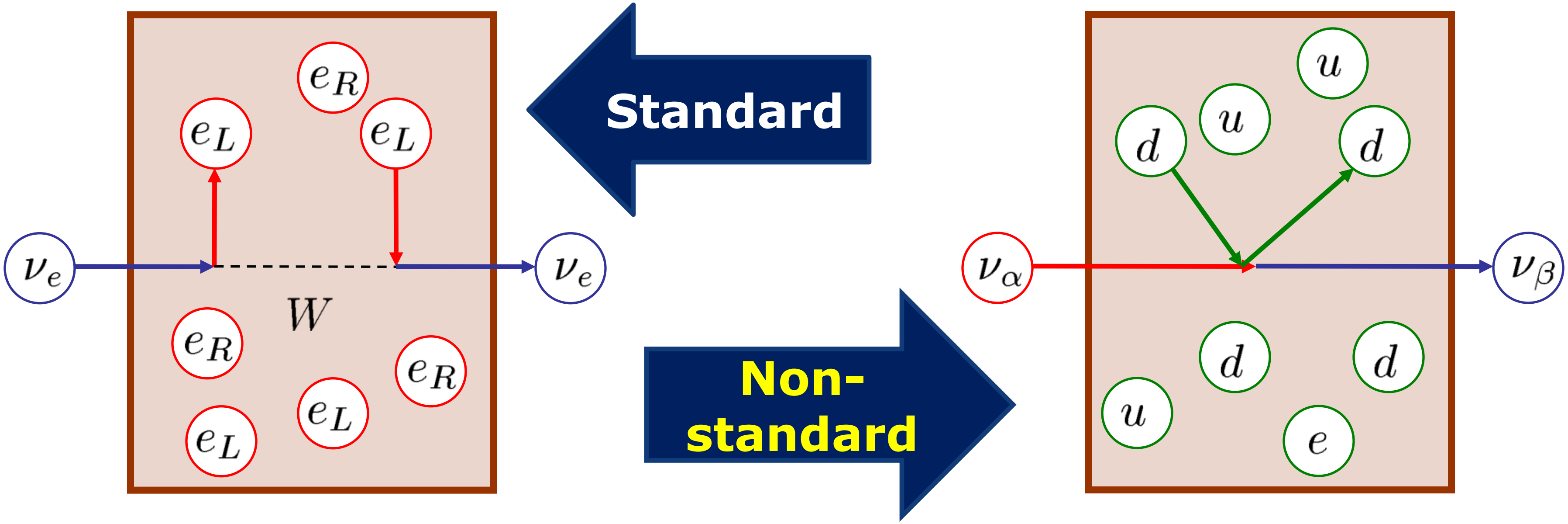
Integrating out the heavy triplet field (at tree-level)!

Relations between neutrino mass matrix and NSI parameters:

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

Phenomenological consequence: non-standard interactions

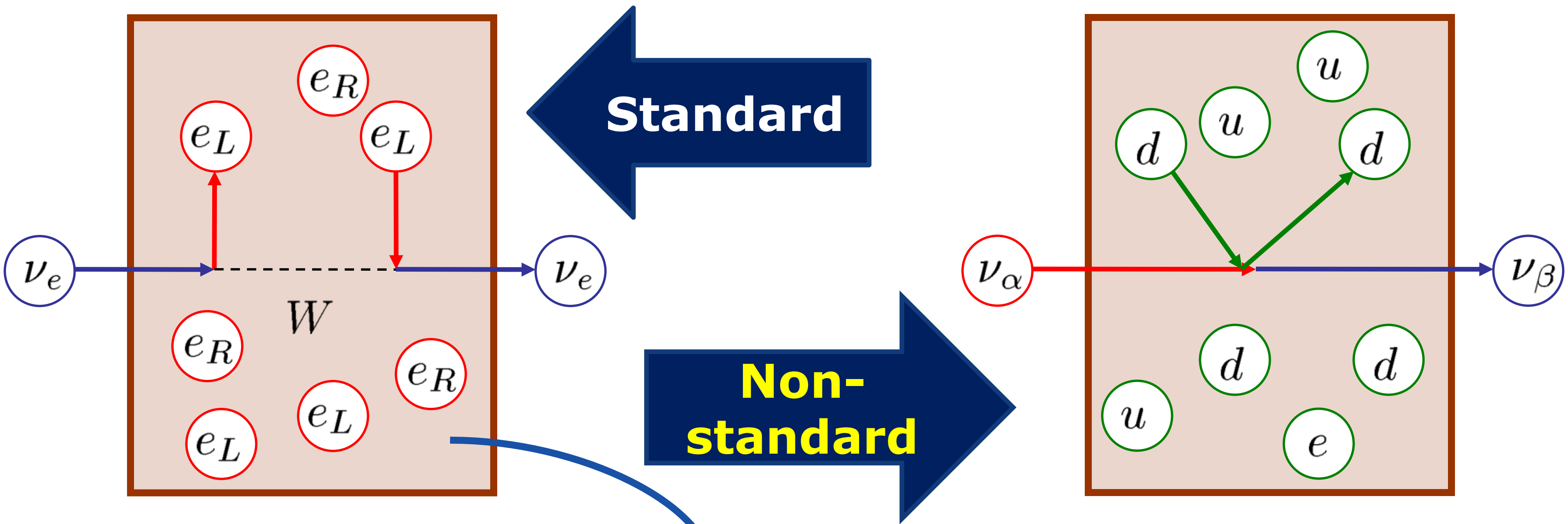
Neutrino propagation in matter with NSIs



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

Phenomenological consequence: non-standard interactions

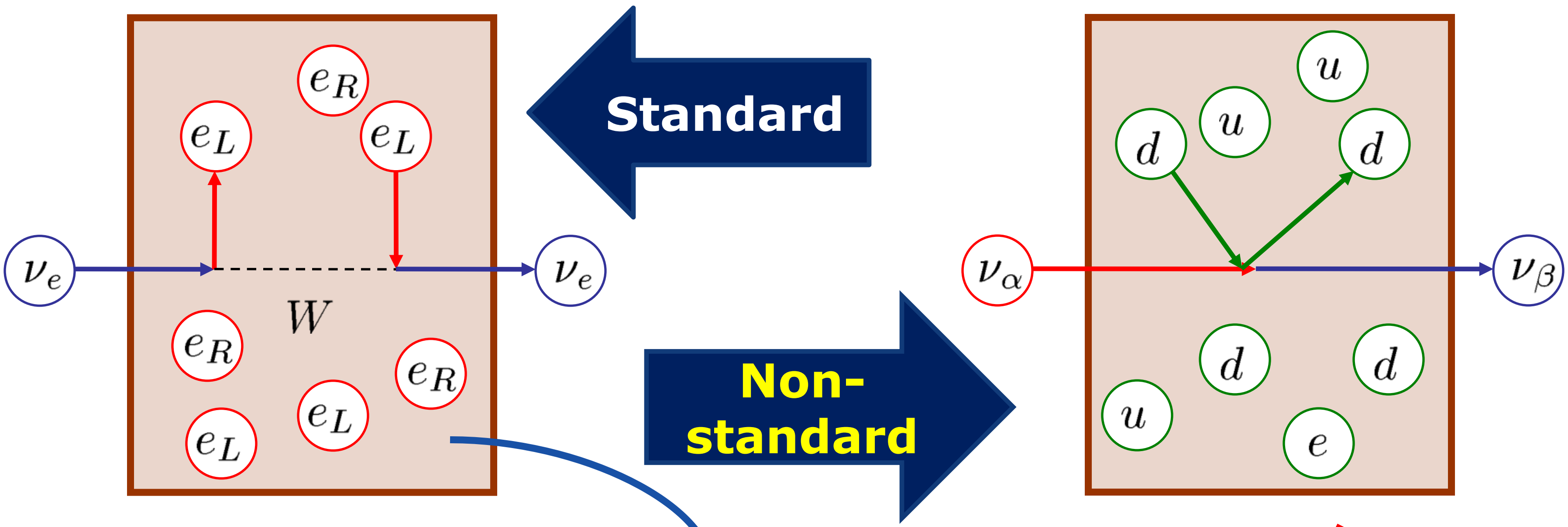
Neutrino propagation in matter with NSIs



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

Phenomenological consequence: non-standard interactions

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 oscillations with NSIs – two-flavors

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

$$\Downarrow$$

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

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

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

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

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

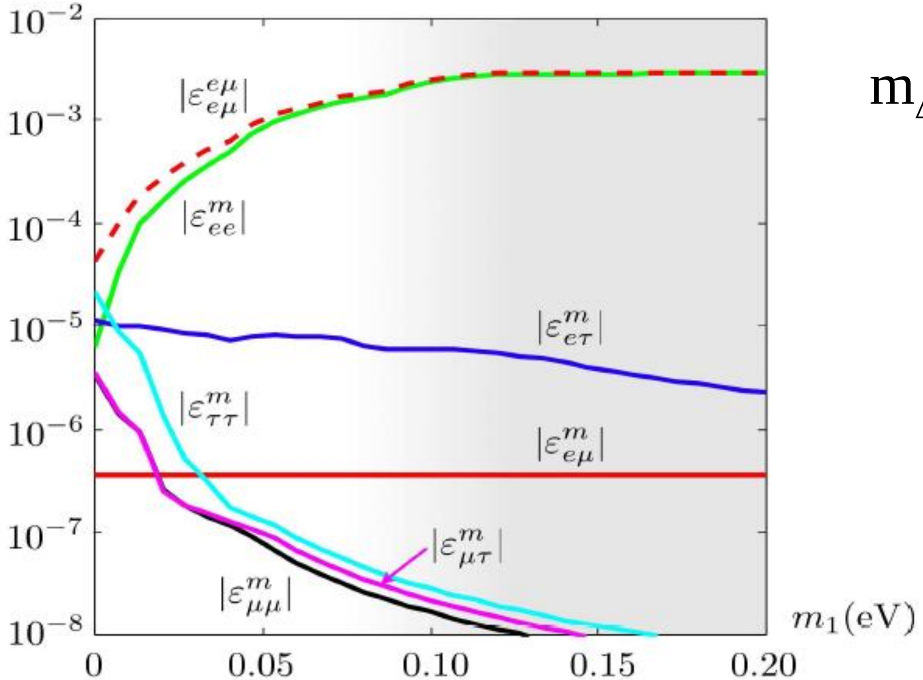
Non-Standard

Standard

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

Non-standard interactions from the type-II seesaw model

Upper bounds on NSI parameters in the type-II seesaw



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.

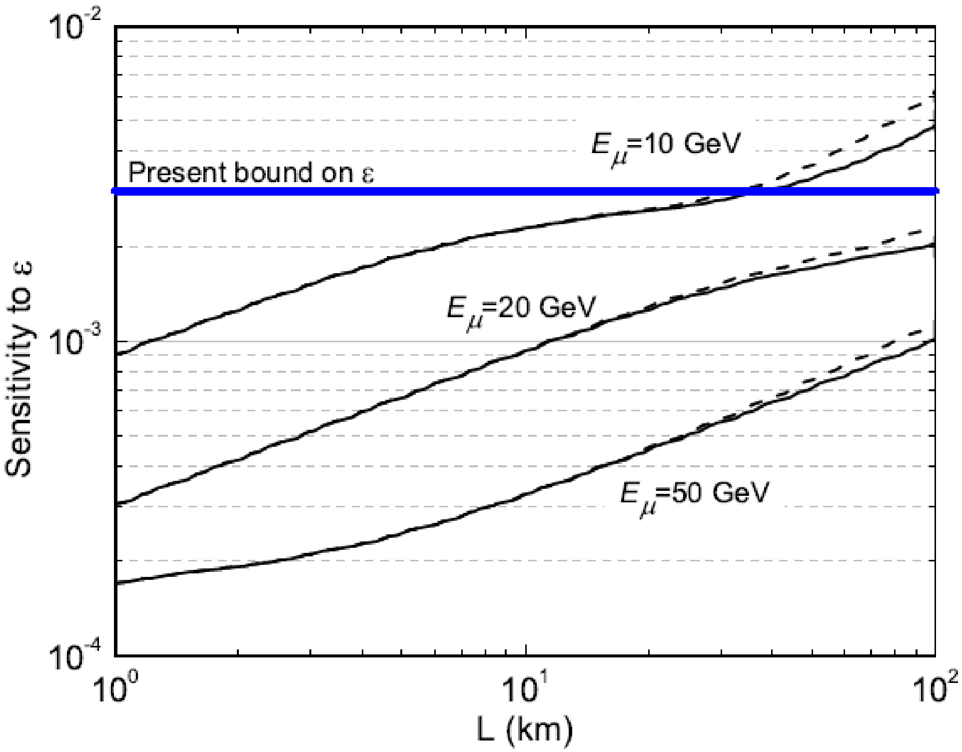
Non-standard interactions from the type-II seesaw model

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

$$\mu^- \to e^- \nu_\mu \overline{\nu_e} \quad \longleftrightarrow \quad \mu^- \to e^- \nu_e \overline{\nu_\mu}$$

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.



Malinsky, Ohlsson, Zhang, 09

Phenomenological consequence: non-unitarity effects

Inverse seesaw

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

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

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:

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

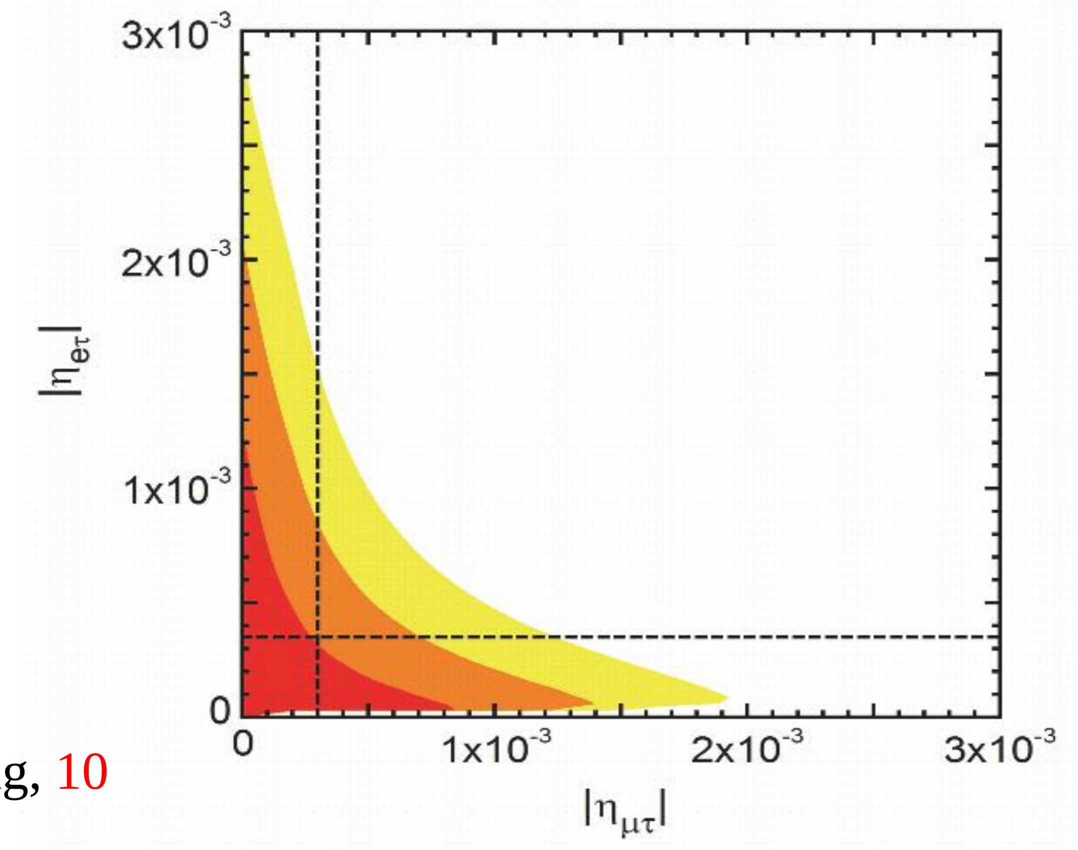
F governs the magnitude of non-unitarity effects

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

Phenomenological consequence: non-unitarity effects

$$\boxed{\eta \simeq \frac{1}{2} F F^\dagger}$$

Similar results hold for
minimal seesaw;
type-I seesaw;
minimal inverse seesaw;
inverse seesaw;
multiple seesaw;
extra dimensional seesaw



Ohlsson, Popa, Zhang, 10

- There exists a non-trivial flavor structure of the NU parameters originating from the structural cancellations of Yukawa couplings.
- The NU parameters $\eta_{e\mu}$ and $\eta_{\mu\tau}$ cannot be significant simultaneously.

Phenomenological consequence: non-unitarity effects

Current experimental constraints at 90% C.L. (Antusch *et al.*, 08)

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

$\eta \longrightarrow$ Hermitian

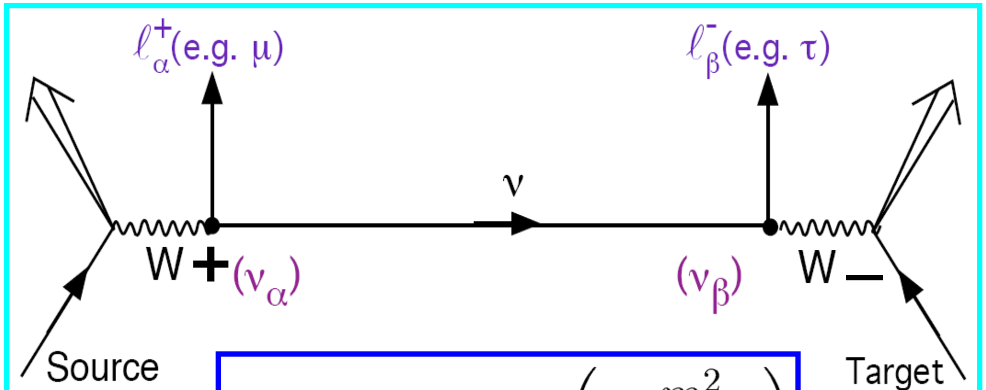
$U \longrightarrow$ unitary

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

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

Non-unitary neutrino mixing:

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



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

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

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

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

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

Non-unitarity effects in neutrino oscillations

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

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

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

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

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

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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 08; Luo 08; Xing 09)

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.

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

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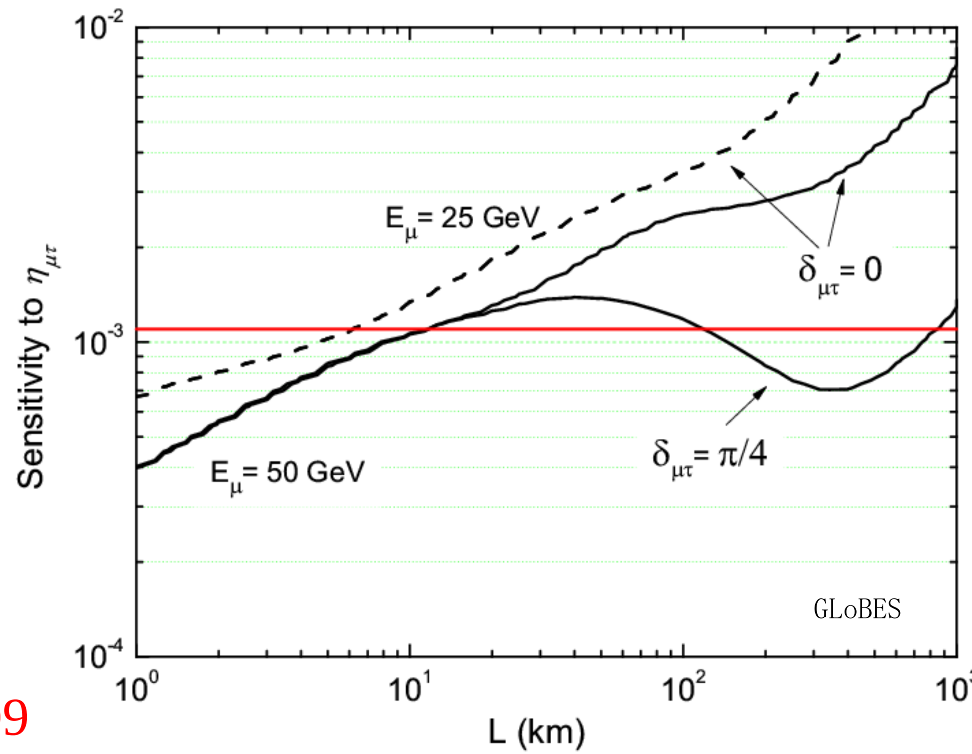
We consider a typical neutrino factory setup with an OPERA-like near detector with fiducial mass of 5 kt. We assume a setup with approximately 10^{21} useful muon decays and five years of neutrino and another five years of anti-neutrino running.



Malinský, Ohlsson, Xing, Zhang, 09

Phenomenological consequence: leptogenesis

Decays of heavy right-handed neutrinos can give rise to the baryon asymmetry of our universe measured from cosmological observations (nucleosynthesis and CMB). Fukugita, Yanagida 86

$$\eta_{\rm B} \equiv n_{\rm B}/n_\gamma = (6.1 \pm 0.2) \times 10^{-10}$$

CP violation $\Rightarrow$ L-number asymmetry $\Rightarrow$ B-number asymmetry

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CP violation → L-number asymmetry → B-number asymmetry

Typical scale $M_1 > 10^8$ GeV → TeV leptogenesis?

Main difficulties:

When heavy Majorana neutrino masses are at the TeV level, the Yukawa couplings should be reduced by more than six orders of magnitude so as to generate tiny masses for three known neutrinos via type-1 seesaw & satisfy the out-of-equilibrium condition.

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Typical scale $M_1 > 10^8$ GeV → TeV leptogenesis?

◆Resonant Leptogenesis (Pilaftsis, 04) $M_1 \approx M_2 << M_3$ $M_{N_i} \sim \text{TeV}$

◆Hierarchy of Couplings (Hambye, Ma, Sarkar, 00)

$$\left.\begin{array}{l} A \longrightarrow C+D \\ \\ B \longrightarrow C+D \end{array}\right\}$$

$m_{\mathbf{B}} >> m_{\mathbf{A}}$ and $g_{\rm B} >> g_{\rm A}$

$$A \longrightarrow B^* \longrightarrow C+D \Rightarrow \boxed{\varepsilon_{\mathbf{CP}} \propto g_{\mathbf{B}}^2}$$

Concluding remarks

1. The LHC might open a new window towards understanding the origin of neutrino masses and lepton flavor violation at the TeV scale

2. Various TeV seesaws might work (naturalness?) & their heavy degrees of freedom might show up at the LHC, neutrinoless double beta decays, neutrino oscillations, LFV decays, leptogenesis, … … (testability?);

3. A bridge between collider physics & neutrino physics is highly anticipated and, if it exists, will lead to rich phenomenology.

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Thanks !