New Tev-scale Seesaw with Vectorlike Mediators

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The contents:

1. Landmarks calling for vectorlike TeV scale d.o.f. – Yukawa terms in focus

2. Conventional Seesaw Models:
Majorana Neutrinos with GUT-scale Majorana Mediators

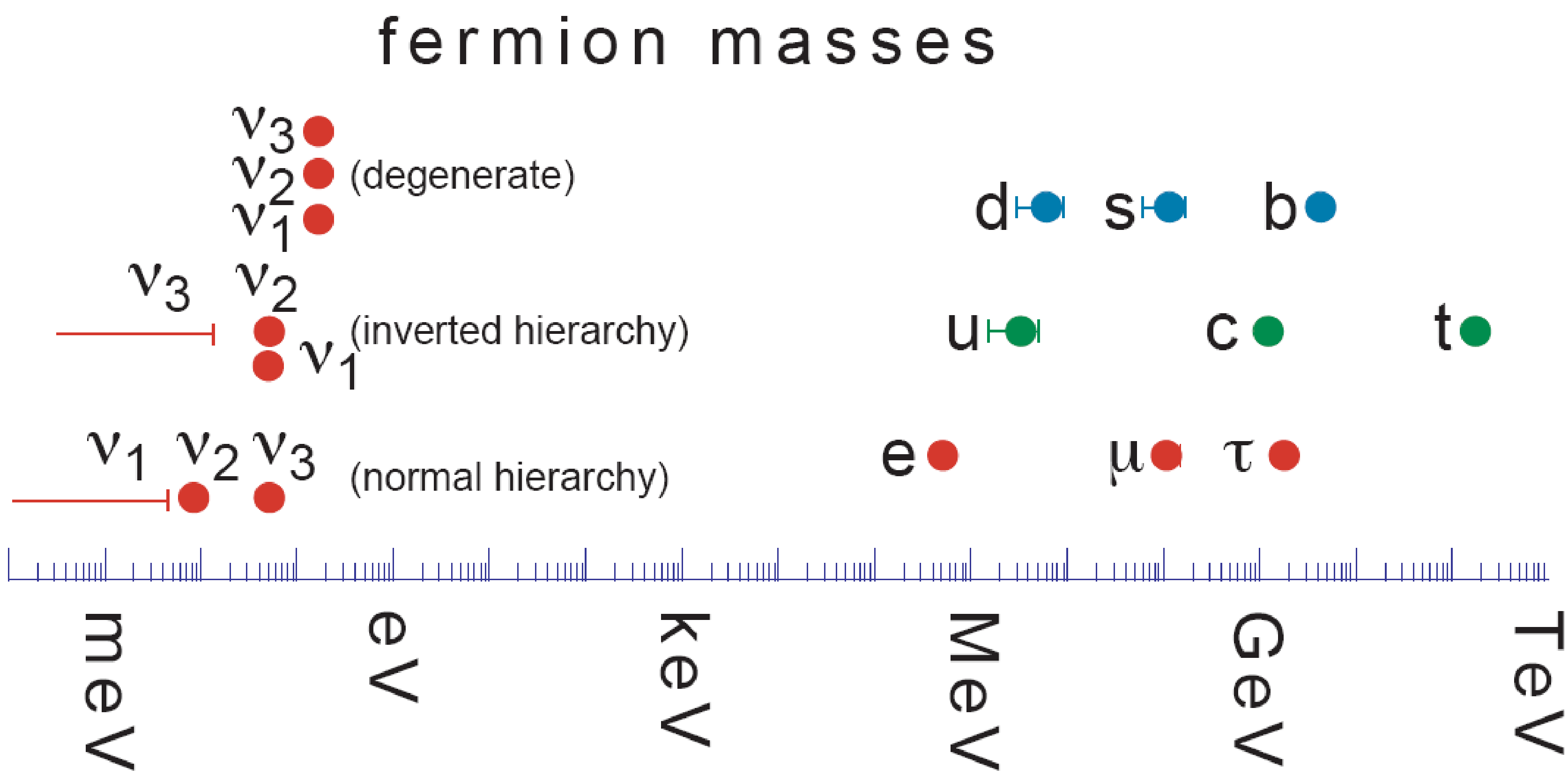
3. Novel Seesaw Model:

Majorana Neutrinos with
TeV-scale Dirac Vectorlike mediators

1. Prominent Landmarks in Addressing BSM Physics:

- Heavyness of top
- Lightness of neutrinos
- Lightness of the SM Higgs

The first two Landmarks: Lightness of ν's & Heavyness of top (Fig.Murayama'08)



The 3rd Landmark: Lightness of the SM Higgs doublets - known as the Hierarchy Problem

- Introducing the top-partner T to cancel the largest contribution to Higgs mass quadratic divergence → suggests
- Introducing such Seesaw Mediators which explain small neutrino masses without introducing extra Hierarchy Problem

Revealing new d.o.f. via QM loops:

- c quark from K-Kbar box diagram
- t quark from B-Bbar box diagram
- Followed by proposals of extra T state:

a recent revival of the latter box diagrams by Vysotsky [1], in the context of a simple extension of the standard model

[1] M. I. Vysotsky, Phys. Lett. B **644**, 352 (2007).

generalized to FC rare decays for relatively heavy T: **I.P. & B.Radovčić, PRD78, 015014 ('08)**

The SM Lagrangian extended by top-partner: weak (t',T') st's

$$\mathcal{L}_{BSM} = -M\bar{T}'_L T'_R + \left[\mu_R \bar{T}'_L t'_R + \frac{\mu_L}{v/\sqrt{2}} \left(\bar{t}', \bar{b}'\right)_L \Phi^c \, T'_R\right] + h.c.$$

- The Dirac mass term **M**
- The (t',T') mixing by two terms

μ_R and the μ_L term

The "Dirac seesaw" - by diagonalizing the mass matrix

$$M_{t-T} = (\overline{t'_L t'_R T'_L T'_R}) \begin{pmatrix} 0 & m_t & 0 & \mu_L \\ m_t & 0 & \mu_R & 0 \\ 0 & \mu_R & 0 & -M \\ \mu_L & 0 & -M & 0 \end{pmatrix} \begin{pmatrix} t'_L \\ t'_R \\ T'_L \\ T'_R \end{pmatrix}$$

- **explains the heaviness of top quark:**

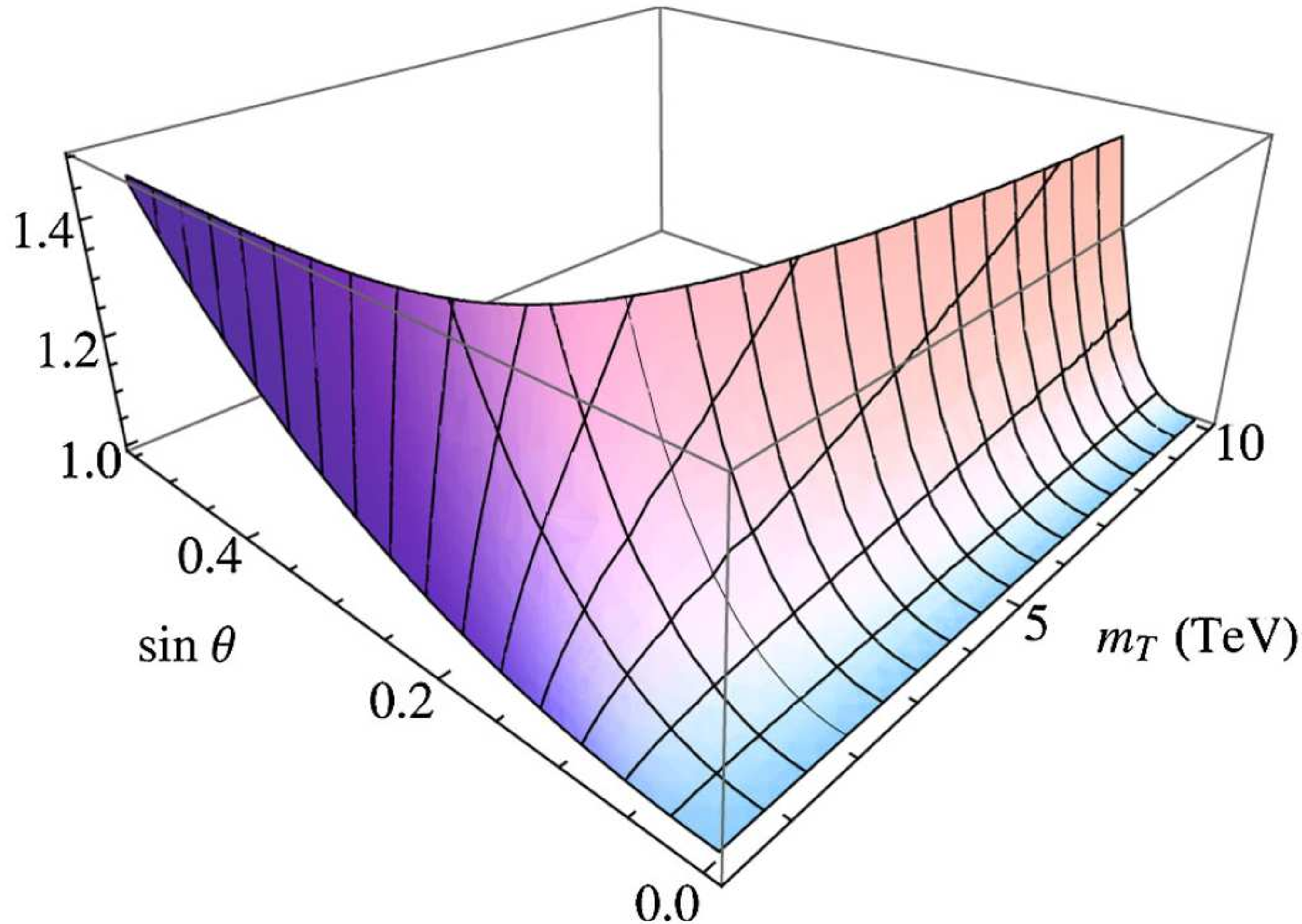
by putting $m_t = 0$, top quark gets all its mass $\sim \mu_L \mu_R / M$ from the mixing with heavy T

Assumption that T' mixes only with t'

- Generalizes the SM3 CKM to a 4x3 non-unitary matrix
- Modifies the NC couplings
- Leads to the very predictive 2-parameter model:

$T' - t'$ mixing angle θ, and the mass m_T

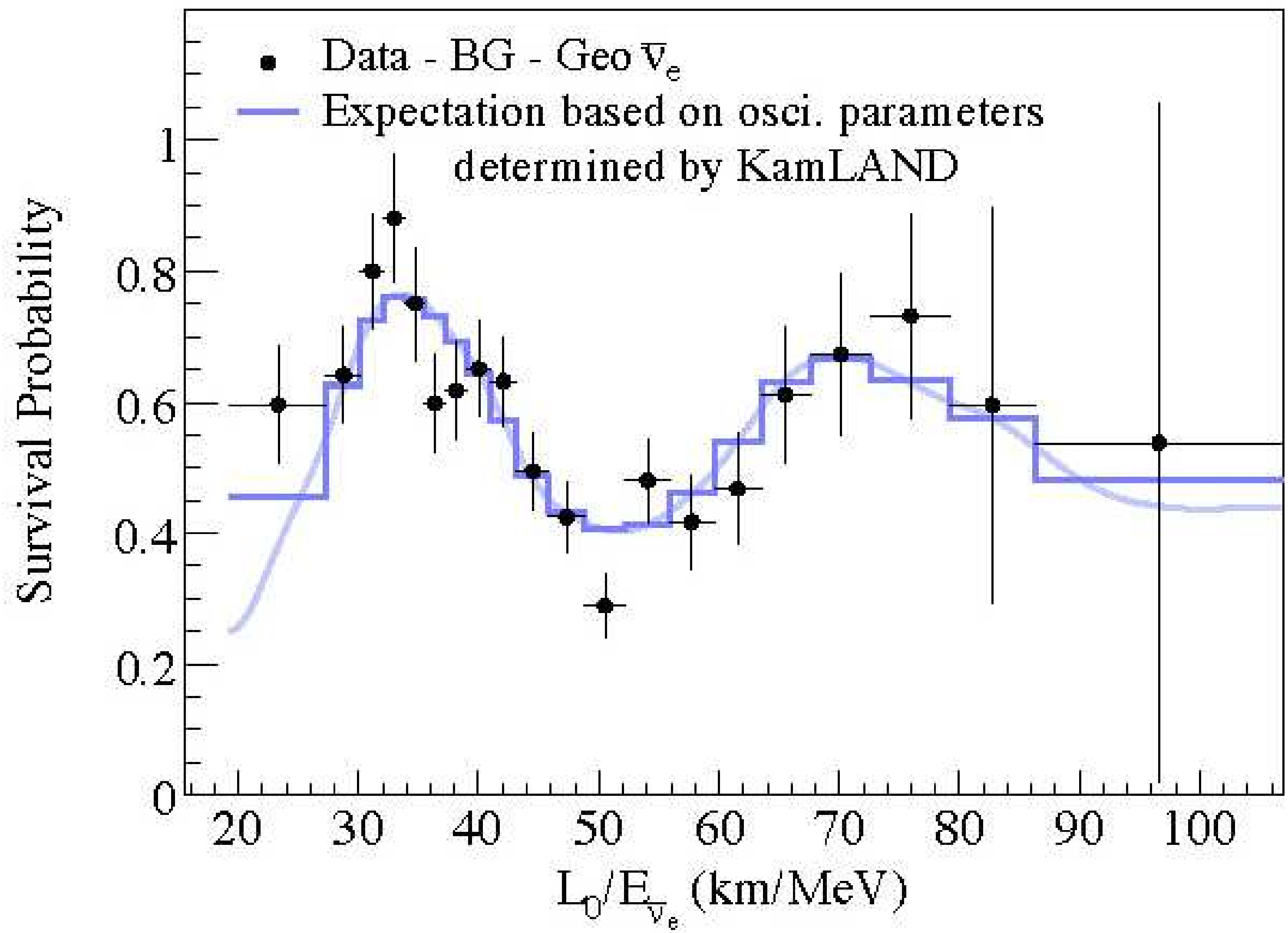
Possible ~50% enhancement of B->μμ w.r.t. the SM prediction @LHC



2. New States entering into gauge invariant Yukawa terms

Neutrino Masses beyond doubt -

KamLAND evidence of ν-masses

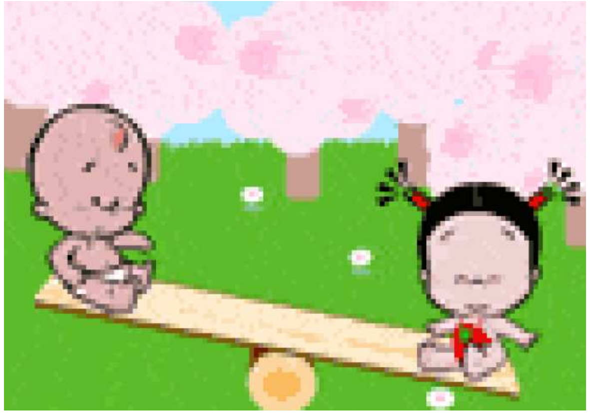


New d.o.f. and Yukawa terms explaining Neutrino Masses:

- **Light sterile neutrinos –** lacking motivation?
- **Heavy Majorana neutrinos –** conventional fermionic seesaws
- **Vectorlike Dirac fermions -** beyond Type I & III seesaw

The seesaw picture

-ascribes the lightness of ν's to the existence of some heavy-scale d.o.f.



Type-I: SM + 3 right-handed Majorana ν's (Minkowski 77; Yanagida 79; Glashow 79; Gell-Mann, Ramond, Slanski 79; Mohapatra, Senjanovic 79)

Type-II: SM + 1 Higgs triplet (Magg, Wetterich 80; Schechter, Valle 80; Lazarides et al 80; Mohapatra, Senjanovic 80; Gelmini, Roncadelli 80)

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

Other variations or combinations (e.g., type-I + type-II in SO(10) GUT)

Conventional Seesaw Mediators

Type I — three heavy right-handed neutrinos

$N_R \sim (1,1,0)$

Type II — one heavy Higgs triplet $\Delta \equiv \begin{pmatrix} \Delta^- & -\sqrt{2}\,\Delta^0 \\ \sqrt{2}\,\Delta^{--} & -\Delta^- \end{pmatrix}$

$\Delta \sim (1,3,-2)$

Type III — three heavy triplet fermions $\Sigma = \begin{pmatrix} \Sigma^0/\sqrt{2} & \Sigma^+ \\ \Sigma^- & -\Sigma^0/\sqrt{2} \end{pmatrix}$

$\Sigma \sim (1,3,0)$

Higher States are not isolated

Fermion 5-plet in conjunction with **scalar 4-plet**

$\Sigma \sim (1,5,0)$ $\Phi \sim (1,4,-1)$

Conventional "isolated" tree-level seesaw mediators

Type I — three heavy right-handed neutrinos

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

Type II — one heavy Higgs triplet $\Delta \equiv \begin{pmatrix} \Delta^- & -\sqrt{2}\,\Delta^0 \\ \sqrt{2}\,\Delta^{--} & -\Delta^- \end{pmatrix}$

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

Type III — three heavy triplet fermions $\Sigma = \begin{pmatrix} \Sigma^0/\sqrt{2} & \Sigma^+ \\ \Sigma^- & -\Sigma^0/\sqrt{2} \end{pmatrix}$

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

Integrating out heavy d.o.f. gives

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

SSB results in Majorana mass term for active neutrinos

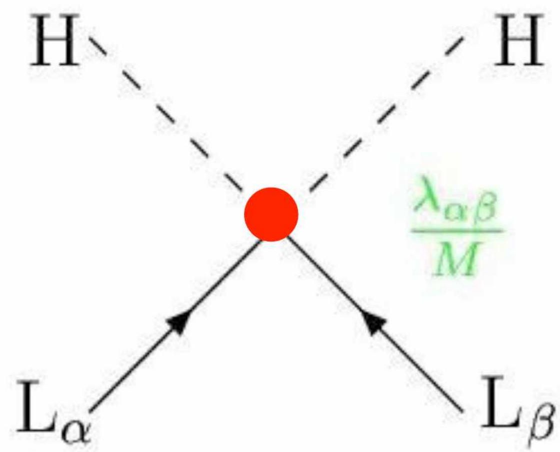
$$-\mathcal{L}_{\rm mass} = \frac{1}{2}\overline{\nu_{\rm L}} M_\nu \nu_{\rm L}^{\rm c} + {\rm h.c.}$$

$$M_\nu = \begin{cases} -\frac{1}{2} Y_\nu \frac{v^2}{M_{\rm R}} Y_\nu^T & ({\rm Type~I})\ , \\ \lambda_\Delta Y_\Delta \frac{v^2}{M_\Delta} & ({\rm Type~II})\ , \\ -\frac{1}{2} Y_\Sigma \frac{v^2}{M_\Sigma} Y_\Sigma^T & ({\rm Type~III}) \end{cases}$$

Dim 5 Weinberg's op. ~LLHH

Dimension 5 operator:

$$\lambda/M\ \underbrace{(L\ L\ H\ H)}_{O^{d=5}} \rightarrow \lambda v^2/M\ (\nu\nu)$$



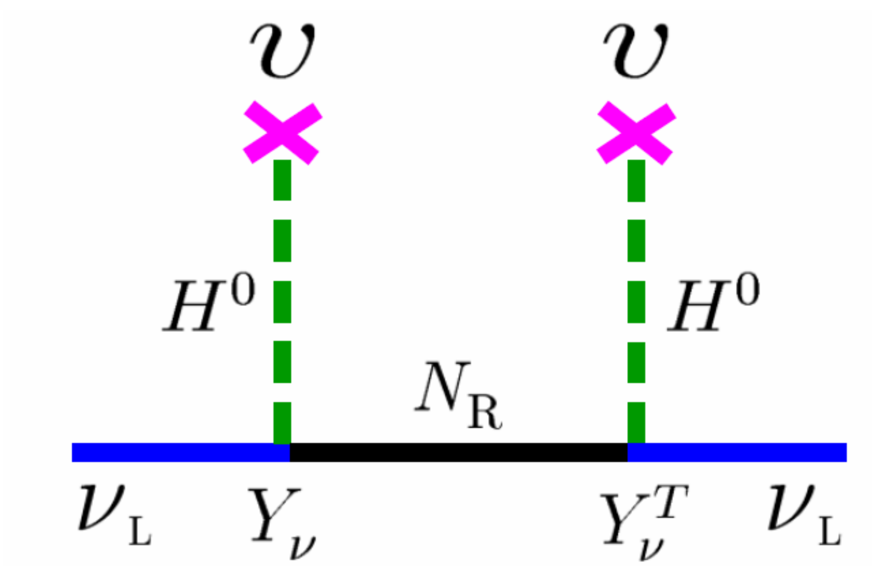
It's unique → very special role of ν masses:
lowest-order effect of higher energy physics

This mass term violates lepton number (B-L)
→ Majorana neutrinos

$O^{d=5}$ *is common to all models of Majorana* ν*s*

GUT-scale fermion mediators in Type I & III seesaw – and possible low scale mission of adjoint fermionic 24 of SU(5)

Bajc & Senjanović, JHEP 0708, 014 (2007)



$$M_\nu \approx -v^2 Y_\nu \frac{1}{M_R} Y_\nu^T$$

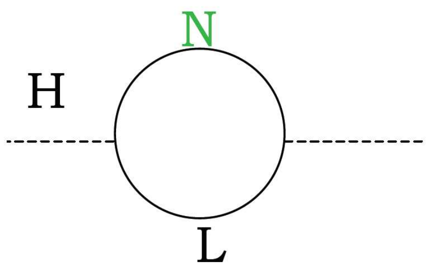
$$M_\nu \approx M_D M_R^{-1} M_D^T$$

0.01 eV

10^{15} GeV

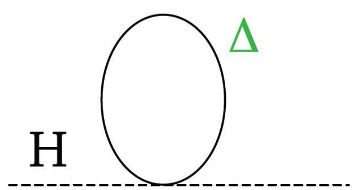
100 GeV

TeV-seesaw scale is suggested by EW hierarchy problem



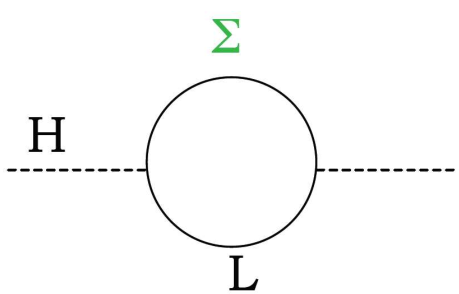
$$\delta m_H^2 = -\frac{Y_N^\dagger Y_N}{16\pi^2}\left[2\Lambda^2 + 2M_N^2 \log\frac{M_N^2}{\Lambda^2}\right]$$

(Vissani)



$$\delta m_H^2 = -3\frac{\lambda_3}{16\pi^2}\left[\Lambda^2 + M_\Delta^2\left(\log\frac{M_\Delta^2}{\Lambda^2} - 1\right)\right] - \frac{\mu_\Delta^2}{2\pi^2}\log\left(\left|\frac{M_\Delta^2 - \Lambda^2}{M_\Delta^2}\right|\right)$$

(Abada, Biggio, Bonnet, Hambye, M.B.G.)



$$\delta m_H{}^2 = -3\frac{Y_\Sigma^\dagger Y_\Sigma}{16\pi^2}\left[2\Lambda^2 + 2M_\Sigma^2 \log\frac{M_\Sigma^2}{\Lambda^2}\right]$$

Lowering seesaw scale by going to dim>5 operators:

$$\mathcal{O}^5 = \mathcal{O}_W = LLHH$$
$$\mathcal{O}^7 = (LLHH)(H^\dagger H)$$
$$\mathcal{O}^9 = (LLHH)(H^\dagger H)(H^\dagger H)$$
$$\vdots$$

$$m_\nu \sim v \left(\frac{v}{\Lambda_{\mathrm{NP}}} \right)^{d-4}$$

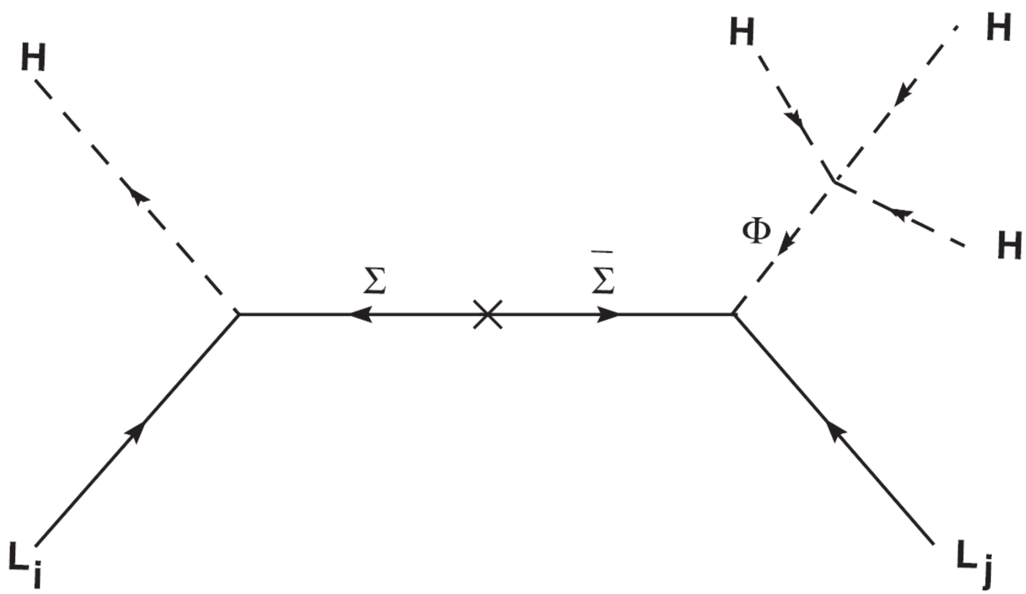
F. Bonnet, D. Hernandez, T. Ota and W. Winter, JHEP **0910**:076,2009 [0907.3143 [hep-ph]];

- NP scale 1-10 TeV with d=9 is enough for sub-eV neutrino mass
- Operators are studied for singlet, doublet and triplet mediators

3. Tree-level Seesaw diagrams giving dim > 5 Operators

- Lowering seesaw scale by multiple seesaw
  E. Ma, PRL86 ('01) 2502
  - further elaborated by
  W.Grimus,L.Lavoura,B.Radovčić,PLB 674 ('09) 117;
- Dim 7 Operator Babu et al'09, PRD 80,071702(R)
- Dim 9 Operator I.P. and B.Radovčić, PLB 687 ('10) 338

Dim-7 op.~ LLHH(H†H) Babu et al.



$$m_\nu \sim \; v^4/M^3$$

$$\mathcal{L}_{\nu\text{-mass}} = Y_i L_i H^* \Sigma + \bar{Y}_i L_i \Phi \bar{\Sigma} + M_\Sigma \Sigma \bar{\Sigma} + \text{H.c.}$$

$$\Sigma = (\Sigma^{++}, \Sigma^{+}, \Sigma^{0}) \text{ and } \bar{\Sigma} = (\bar{\Sigma}^{0}, \Sigma^{-}, \Sigma^{--})$$

- **Vectorlike fermions** transforming as $(1, 3, 2) + (1, 3, -2)$
- **Scalar 4-plet** $(\Phi^{+++}, \Phi^{++}, \Phi^{+}, \Phi^{0})$ (with $Y = 3$)

Novel Tree-level Seesaw Model

based on vectorlike Dirac fermion 5-plet Σ (I=2, Y=2) mediators

$$\Sigma_L = (\Sigma_L^{+++}, \Sigma_L^{++}, \Sigma_L^{+}, \Sigma_L^{0}, \Sigma_L^{-})$$
$$\Sigma_R = (\Sigma_R^{+++}, \Sigma_R^{++}, \Sigma_R^{+}, \Sigma_R^{0}, \Sigma_R^{-})$$

both transforming as $(1, 5, 2)$

- **In conjunction with isospin 3/2 scalar fields Φ1 and Φ2:**

$$\Phi_1 = (\Phi_1^0, \Phi_1^-, \Phi_1^{--}, \Phi_1^{---}) \qquad \Phi_2 = (\Phi_2^+, \Phi_2^0, \Phi_2^-, \Phi_2^{--})$$

transforming as $(1, 4, -3)$ and $(1, 4, -1)$, respectively.

SMG 3x2x1 symmetric terms

Dirac mass term of our seesaw mediator:

$$\mathcal{L}_{\rm M} = - M_\Sigma \overline{\Sigma}_L \Sigma_R + {\rm H.c.}$$

Yukawa term with LNC & LNV parts

$$\mathcal{L}_{\rm Y} = Y_1 \overline{l}_L \Sigma_R \Phi_1 + Y_2 \overline{\Sigma}_L (l_L)^c \Phi_2^* + {\rm H.c.}$$

Dirac seesaw by diagonalizing the mass matrix

$$\left(\bar{\nu}_L \; \overline{\Sigma_L^0} \; \overline{(\Sigma_R^0)^c}\right) \begin{pmatrix} 0 & m_2 & m_1 \\ m_2 & 0 & M_\Sigma \\ m_1 & M_\Sigma & 0 \end{pmatrix} \begin{pmatrix} (\nu_L)^c \\ (\Sigma_L^0)^c \\ \Sigma_R^0 \end{pmatrix}$$

- representing the mixing between neutral components of the SM lepton doublet and the Σ 5-plets

Mass eigenvalues:

- Two nearly degenerate Heavy states $m_{\nu_H} \sim M_\Sigma$
- Light Majorana neutrinos

$$m_\nu \sim \frac{m_1 m_2}{M_\Sigma} \sim \frac{Y_1 Y_2 v_{\Phi_1} v_{\Phi_2}}{M_\Sigma}$$

From the EW precision: $\rho = 1.0004^{+0.0008}_{-0.0004}$

$$\rho \simeq 1 - 6v_{\Phi_1}^2/v^2 + 6v_{\Phi_2}^2/v^2$$

an upper bound on v_{Φ_1} and v_{Φ_2} of a few GeV.

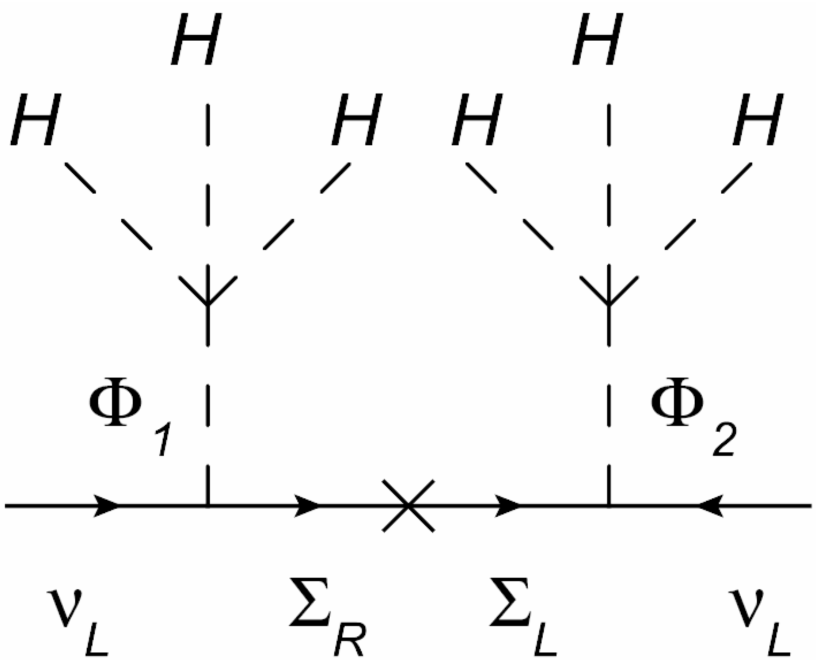
EWSB in usual way from Higgs doublet $\mu_H^2 < 0$

$$
\begin{aligned}
&V(H,\Phi_1,\Phi_2)\\
\sim\;& \mu_H^2 H^\dagger H + \mu_{\Phi_1}^2 \Phi_1^\dagger \Phi_1 + \mu_{\Phi_2}^2 \Phi_2^\dagger \Phi_2 + \lambda_H (H^\dagger H)^2\\
+\;& \{\lambda_1 \Phi_1^* H^* H^* H^* + \mathrm{H.c.}\} + \{\lambda_2 \Phi_2^* H H^* H^* + \mathrm{H.c.}\}\\
+\;& \{\lambda_3 \Phi_1^* \Phi_2 H^* H^* + \mathrm{H.c.}\}\;.
\end{aligned}
$$

- Induced vev for Φ_1 and Φ_2, scalars with $\mu_{\Phi_1}^2, \mu_{\Phi_2}^2 > 0$

$$
v_{\Phi_1} \simeq -\lambda_1 \frac{v^3}{\mu_{\Phi_1}^2}\;,\quad v_{\Phi_2} \simeq -\lambda_2 \frac{v^3}{\mu_{\Phi_2}^2}
$$

Dim-9 ~ LLHH(H†H)(H†H) tree-level op. by integrating out heavy d.o.f.



$$m_\nu \sim \frac{Y_1 Y_2 \ \lambda_1 \lambda_2 \ v^6}{M_\Sigma \ \mu^2_{\Phi_1} \ \mu^2_{\Phi_2}}$$

$$\sim v^6/M^5$$

- Light Majorana neutrino naturally in sub-eV range with TeV-scale heavy d.o.f.

Operators of dim 7 and 5 are generated at loop level from dim 9 op.

- smaller than dim 9 tree level if

$$\Lambda_{NP} < 4\pi v \simeq 2 \text{ TeV}$$

- The operator of dim 5 generated at loop level from λ_3 term is smaller than dim 9 tree level if

$$\Lambda_{NP} < \sqrt{4\pi}v \simeq 620 \text{ GeV}$$

The scale splitting Dim 5 loop & dim 9 tree-level contributions

For simplicity, $\mu_\Phi = M_\Sigma = \Lambda_{NP}$

the values $v = 174\ \text{GeV}$ and $m_\nu \sim 0.1\ \text{eV}$

& moderate $Y \sim Y' \sim \lambda_2 \sim 10^{-2}$ result in

$\Lambda_{NP} \simeq 580\ \text{GeV}$ and $v_{\Phi_1} \simeq 80\ \text{MeV}$ and $v_{\Phi_2} \simeq 60\ \text{MeV}$.

- There is a part of the parameter space where tree-level dim 9 operator dominates over loop generated dim 5 and dim 7 contributions!

Drell-Yan fusion production

- **Via CC associated production of pairs**
- **Via NC direct pair prodiction - NEW**

$$(\Sigma^{+++}, \overline{\Sigma^{++}}), (\Sigma^{++}, \overline{\Sigma^{+}})$$

$$(\Sigma^{+}, \overline{\Sigma^{0}}), (\Sigma^{0}, \overline{\Sigma^{-}})$$

$$(\Sigma^{0}, \overline{\Sigma^{0}})$$

Small mass splittings within a multiplet ...

$$M_Q - M_0 \simeq Q(Q + Y/\cos\theta_W)\Delta M$$

$$\Delta M = \alpha_2 M_W \sin^2\frac{\theta_W}{2} = (166 \pm 1) MeV.$$

- .. suppresses the cascade Σ decays

Signatures from LNC & LNV decays

$$\Sigma^{+++} \to W^+W^+l^+ \qquad \Sigma^{++} \to W^+l^+$$

$$\Sigma^+ \to W^+\nu, Zl^+, H^0l^+$$

$$\Sigma^- \to W^-\nu, Zl^-, H^0l^-$$

$$\Sigma^0 \to W^\pm l^\mp, Z\nu, H^0\nu$$

- **Two types of decays with same sign dileptons and the jets as a signature**

$$q\bar{q}' \to W^* \to \Sigma^+\overline{\Sigma^0} \to l^+Zl^+W^- \to l^+l^+jj \ ,$$

$$q\bar{q} \to Z^* \to \Sigma^0\overline{\Sigma^0} \to l^\pm W^\mp l^\pm W^\mp \to l^\pm l^\pm jj$$

Testability of New Vectorlike Matter in the reach of LHC

i) By testing the seesaw type - try to infer on new d.o.f. realized in Nature; States too heavy to be produced may be revealed through virtual loop effects

ii) New vectorlike leptonic 5-plet as a link between collider phenomenology and the origin of neutrino masses

Conclusions: FALSE

- We are introducing a falsifiable dim 9 tree-level seesaw model: corresponds to testable parameter space (acessible to the LHC)
- Drell-Yan produced 5-plet fermion Σ states decay with characteristic same sign dileptons and jet signature
- Singly charged & neutral Σ states have small mixing (~10^-6) and fast decay (~10^-13 s)
- Non-discovery of sub-TeV Σ's at the LHC leaves us with radiative (loop-induced) neutrino mass