Carla Biggio
MPI, München

Can we disentangle among different models for neutrino mass in the near future?

Based on:

- Abada, CB, Bonnet, Gavela, Hambye
  accepted for publication on JHEP [0707.4058[hep-ph]]
- Antusch, CB, Fernández-Martínez, Gavela, López-Pavón
  JHEP 0610:084,2006 [hep-ph/0607020]

Project Review 2007, MPI, 17-18 December 2007

ν masses beyond the SM

- ν masses $\rightarrow$ (first) signal of new physics (NP) beyond the SM

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  advocate NP @ higher energy scale M

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To take into account effects of generic NP at low energy

→ effective field theories: NP effects encoded in
higher dimensional operators

$$L^{eff} = L^{SM} + \frac{c^{d=5}}{M} O^{d=5} + \frac{c^{d=6}}{M^2} O^{d=6} + \ldots$$

Many $O^{d>4}$ operators can be built with SM fields but
$O^{d=5}$ is UNIQUE!

d=5 operator

Weinberg 79

$$\frac{\lambda_{\alpha\beta}}{M}\left(\overline{\ell^c_{L\alpha}}\tilde{\phi}^*\right)\left(\tilde{\phi}^\dagger \ell_{L\beta}\right) + \text{h.c} \quad \rightarrow \quad m_\nu = \frac{\lambda_{\alpha\beta}}{M}\frac{v^2}{2}$$

$\lambda_{\alpha\beta}$ depends on the model

$\lambda_{\alpha\beta} \sim O(1)$, $M \sim M_{GUT}$, $v = v_{EW}$
$\rightarrow$ $m_\nu \sim 10^{-2}$ eV

d=5 operator

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$\lambda_{\alpha\beta}$ depends on the model

$\lambda_{\alpha\beta} \sim O(1)$, $M \sim M_{GUT}$, $v = v_{EW}$
$\rightarrow\ m_\nu \sim 10^{-3}$

D=5 operator violates lepton number $\rightarrow$ ν must be Majorana

d=5 operator

Weinberg 79

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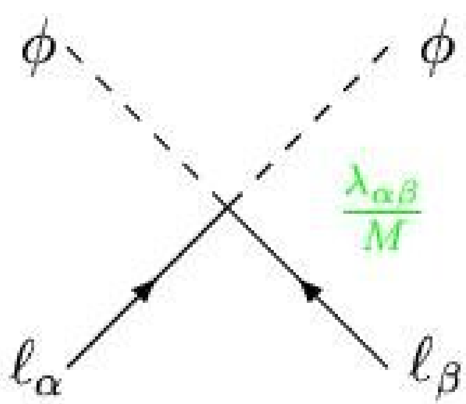
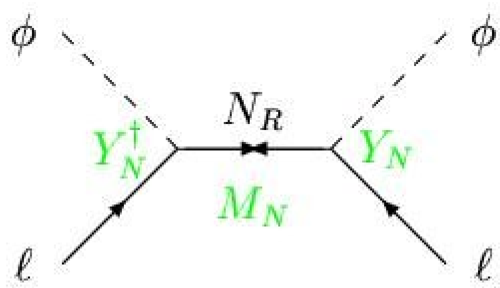


In how many ways
can I obtain this $O^{d=5}$?

Tree-level realizations of see-saw mechanism

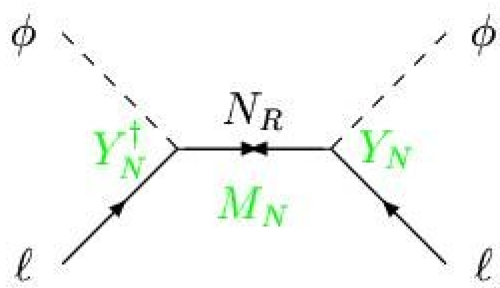


Type I See-Saw

Minkowski, Gell-Mann, Ramond, Slansky, Yanagida, Glashow, Mohapatra, Senjanovic, …

N_R fermionic singlet

Tree-level realizations of see-saw mechanism



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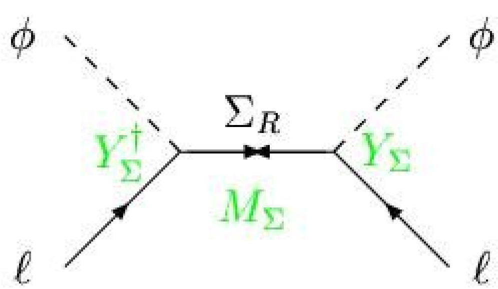
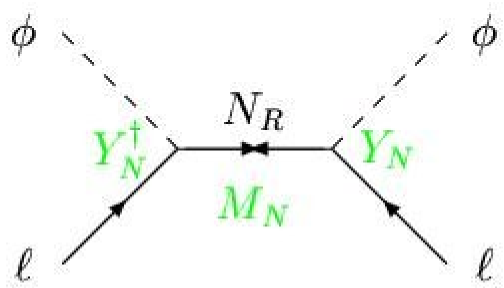


Type III See-Saw

Ma, Hambye et al., Bajc & Senjanovic…

t_R fermionic triplet

Tree-level realizations of see-saw mechanism



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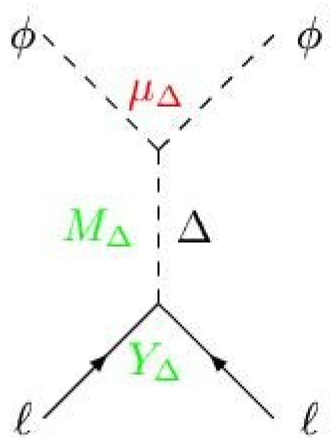
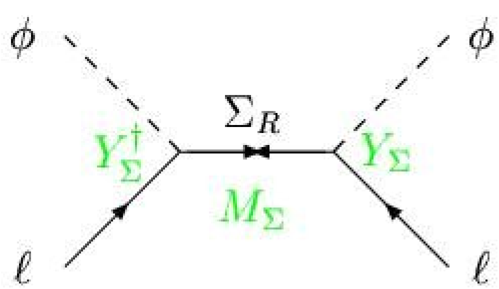


Type II See-Saw

Magg, Wetterich, Lazarides, Shafi, Mohapatra, Senjanovic, Schecter, Valle, …

Δ scalar triplet



Type III See-Saw

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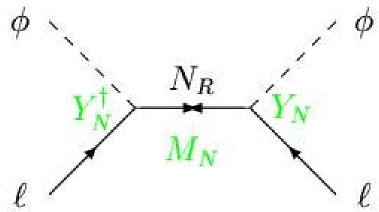
t_R fermionic triplet

C.Biggio, MPI, München

Low-energy effects of see-saw: type I



$$\mathcal{L}^{SM} + i\,\overline{N_R}\,\partial\!\!\!/\,N_R - \overline{\ell_L}\,\widetilde{\phi}\,Y_N^\dagger\,N_R - \frac{1}{2}\,\overline{N_R}\,M_N\,N_R{}^c + \text{h.c.}$$

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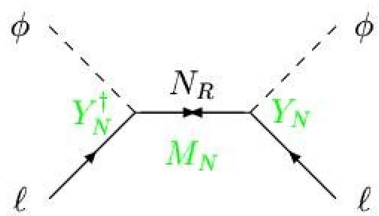

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Integrate out N_R

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \delta\mathcal{L}^{d=5} + \delta\mathcal{L}^{d=6} + \cdots$$

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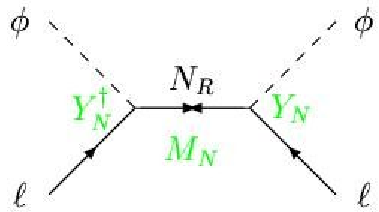

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$$\frac{1}{2}\,c^{d=5}_{\alpha\beta}\,\left(\overline{\ell^c_{L\alpha}}\,\tilde{\phi}^*\right)\left(\tilde{\phi}^\dagger\,\ell_{L\beta}\right) + \text{h.c.}$$

$$c^{d=5} = Y_N^T\,\frac{1}{M_N}\,Y_N$$

It generates ν mass:

$$-\frac{1}{2}\,Y_N^T\,\frac{v^2}{M_N}\,Y_N$$

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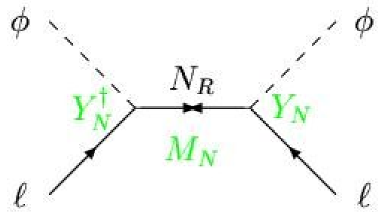

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It generates ν mass:

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It renormalises kinetic energy

Broncano, Gavela, Jenkins 02

Low-energy effects of see-saw: type I

$$\mathcal{L}^{d\leq 6}_{\text{neutrino}} = i\,\overline{\nu}_{L\alpha}\,\partial\!\!\!/\,\left(\delta_{\alpha\beta}+\epsilon^N_{\alpha\beta}\right)\,\nu_{L\beta} - \frac{1}{2}\overline{\nu_L{}^c}_\alpha\, m_{\alpha\beta}\,\nu_{L\beta} - \frac{1}{2}\overline{\nu_L}_\alpha\, m^*_{\alpha\beta}\,\nu_{L\beta}{}^c$$

$$\epsilon^N \equiv \frac{v^2}{2}\,c^{d=6}$$

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Kinetic terms → diag. & norm. → unitary transf. + rescaling

$m_{\alpha\beta}$ → diagonalized → unitary transformation $\boldsymbol{U^\nu}$

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N is not unitary

$$J^{-\,CC}_\mu \equiv \overline{e_L}_\alpha\,\gamma_\mu\,N_{\alpha i}\,\nu_i,$$

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Antusch, CB, Fernández-Martínez, Gavela, López-Pavón 2006

Low-energy effects of see-saw: type I

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- neutrino oscillations
- unsuppressed $l_\alpha \to l_\beta \gamma$

Antusch, CB, Fernández-Martínez, Gavela, López-Pavón 2006

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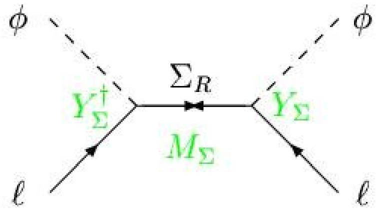
- neutrino oscillations
- unsuppressed $l_\alpha \to l_\beta \gamma$

- neutrino oscillation in matter
- invisible Z decay

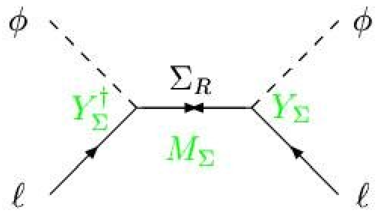
Antusch, CB, Fernández-Martínez, Gavela, López-Pavón 2006

Low-energy effects of see-saw: type III



$$\mathcal{L}_{\Sigma,SM} \;=\; i\,\overline{\vec{\Sigma}_R}\,\not{D}\,\vec{\Sigma}_R - \frac{1}{2}\overline{\vec{\Sigma}_R}M_\Sigma\vec{\Sigma}^c_R - \overline{\vec{\Sigma}_R}Y_\Sigma(\widetilde{\phi}^\dagger\vec{\tau}\ell_L) + \text{h.c.}$$

Low-energy effects of see-saw: type III



$$\mathcal{L}_{\Sigma,SM} = i\,\overline{\vec{\Sigma}_R} \not{D} \vec{\Sigma}_R - \frac{1}{2}\overline{\vec{\Sigma}_R} M_\Sigma \vec{\Sigma}_R^c - \overline{\vec{\Sigma}_R} Y_\Sigma (\tilde{\phi}^\dagger \vec{\tau} \ell_L) + \text{h.c.}$$

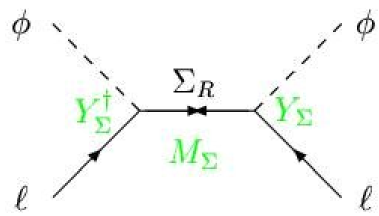
Integrate out Σ_R

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \delta\mathcal{L}^{d=5} + \delta\mathcal{L}^{d=6} + \cdots$$

$$\frac{1}{2}\, c_{\alpha\beta}^{d=5} \left(\overline{\ell_{L\alpha}^c}\,\tilde{\phi}^*\right)\left(\tilde{\phi}^\dagger\, \ell_{L\beta}\right) + \text{h.c.}$$

$$c^{d=5} = Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma$$

Low-energy effects of see-saw: type III



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Integrate out Σ_R

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \delta\mathcal{L}^{d=5} + \delta\mathcal{L}^{d=6} + \cdots$$

$$\frac{1}{2}\, c^{d=5}_{\alpha\beta} \left(\overline{\ell^c_{L\alpha}}\,\tilde{\phi}^*\right)\left(\tilde{\phi}^\dagger\,\ell_{L\beta}\right) + \text{h.c.}$$

$$c^{d=6}_{\alpha\beta} \left(\overline{\ell_{L\alpha}}\,\vec{\tau}\tilde{\phi}\right) i\not{D} \left(\tilde{\phi}^\dagger \vec{\tau} \ell_{L\beta}\right)$$

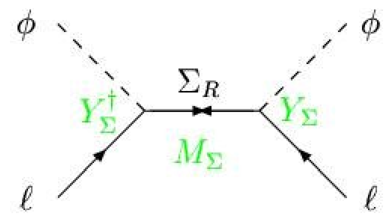
$$c^{d=5} = Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma$$

$$c^{d=6} = Y_\Sigma^\dagger \frac{1}{|M_\Sigma|^2} Y_\Sigma$$

It renormalises kinetic energy
for neutrinos and charged leptons
and corrects gauge couplings

Abada, CB, Bonnet, Gavela, Hambye 07

Low-energy effects of see-saw: type III



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Integrate out Σ_R

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \delta\mathcal{L}^{d=5} + \delta\mathcal{L}^{d=6} + \cdots$$

$$\frac{1}{2}\,c_{\alpha\beta}^{d=5}\left(\overline{\ell_{L\alpha}^c}\tilde{\phi}^*\right)\left(\tilde{\phi}^\dagger\,\ell_{L\beta}\right) + \text{h.c.}$$

$$c_{\alpha\beta}^{d=6}\left(\overline{\ell_{L\alpha}}\vec{\tau}\tilde{\phi}\right)i\not{D}\left(\tilde{\phi}^\dagger\vec{\tau}\ell_{L\beta}\right)$$

$$c^{d=5} = Y_\Sigma^T\frac{1}{M_\Sigma}Y_\Sigma$$

$$c^{d=6} = Y_\Sigma^\dagger\frac{1}{|M_\Sigma|^2}Y_\Sigma$$

Same coeffs as in type I

It renormalises kinetic energy for neutrinos and charged leptons and corrects gauge couplings

Abada, CB, Bonnet, Gavela, Hambye 07

Low-energy effects of see-saw: type III

$$\mathcal{L}^{d\leq 6}_{\rm leptons} = i\overline{\nu_L}_\alpha \partial\!\!\!/ \left(\delta_{\alpha\beta}+\epsilon^{\Sigma}_{\alpha\beta}\right)\nu_{L\beta} + i\overline{l_L}_\alpha \partial\!\!\!/ \left(\delta_{\alpha\beta}+2\epsilon^{\Sigma}_{\alpha\beta}\right) l_{L\beta} - \frac{1}{2}\left[\overline{\nu_L{}^c}_\alpha\, m_{\nu\,\alpha\beta}\,\nu_{L\beta} + \text{h.c.}\right]$$
$$-\overline{\ell}_\alpha\, m_{l\,\alpha\beta}\,\ell_\beta + \frac{1}{\sqrt{2}} g\left[\overline{l_L}_\alpha W\!\!\!\!/^{\,-}\left(\delta_{\alpha\beta}+2\epsilon^{\Sigma}_{\alpha\beta}\right)\nu_{L\beta} + \text{h.c.}\right]$$
$$-\frac{g}{2}\overline{l_L}_\alpha W\!\!\!\!/^{\,3}\left(\delta_{\alpha\beta}+4\epsilon^{\Sigma}_{\alpha\beta}\right) l_{L\beta} + \frac{g}{2}\overline{\nu_L}_\alpha W\!\!\!\!/^{\,3}\nu_{L\alpha} - \frac{g'}{2}\overline{l_L}_\alpha B\!\!\!/\, l_{L\beta} - \frac{g'}{2}\overline{\nu_L}_\alpha B\!\!\!/\,\nu_{L\alpha}\,,$$

$$J^{-\,CC}_\mu \equiv \overline{l_L}\,\gamma_\mu\, N\,\nu,$$
$$J^{Z}_\mu(\text{neutrinos}) \equiv \frac{1}{2}\overline{\nu}\,\gamma_\mu\,(N^\dagger N)^{-1}\,\nu$$
$$J^{Z}_\mu(\text{leptons}) \equiv \frac{1}{2}\overline{l}\,\gamma_\mu\,(N N^\dagger)^2\, l.$$

N is not unitary

new processes:
ex. $\mu \rightarrow eee$ @ tree level

Abada, CB, Bonnet, Gavela, Hambye 2007

Low-energy effects of see-saw: type II

$$\mathcal{L}_\Delta = (D_\mu \Delta)^\dagger (D^\mu \Delta) + \left(\overline{\widetilde{\ell}_L} Y_\Delta (\vec{\tau} \cdot \vec{\Delta}) \ell_L + \mu_\Delta \widetilde{\phi}^\dagger (\vec{\tau} \cdot \vec{\Delta}^\dagger) \phi + \text{h.c.} \right)$$
$$- \left\{ \Delta^\dagger M_\Delta{}^2 \Delta + \frac{1}{2} \lambda_2 \left(\Delta^\dagger \Delta \right)^2 + \lambda_3 \left(\phi^\dagger \phi \right) \left(\Delta^\dagger \Delta \right) + \frac{\lambda_4}{2} \left(\Delta^\dagger \vec{T} \Delta \right)^2 + \lambda_5 \left(\Delta^\dagger \vec{T} \Delta \right) \phi^\dagger \vec{\tau} \phi \right\}$$

Low-energy effects of see-saw: type II

$$\mathcal{L}_\Delta = (D_\mu\Delta)^\dagger (D^\mu\Delta) + \left(\widetilde{\overline{\ell_L}} Y_\Delta (\vec{\tau}\cdot\vec{\Delta})\ell_L + \mu_\Delta \tilde{\phi}^\dagger(\vec{\tau}\cdot\vec{\Delta}^\dagger)\phi + \text{h.c.}\right)$$
$$-\left\{\Delta^\dagger {M_\Delta}^2 \Delta + \frac{1}{2}\lambda_2 \left(\Delta^\dagger\Delta\right)^2 + \lambda_3\left(\phi^\dagger\phi\right)\left(\Delta^\dagger\Delta\right) + \frac{\lambda_4}{2}\left(\Delta^\dagger\vec{T}\Delta\right)^2 + \lambda_5\left(\Delta^\dagger\vec{T}\Delta\right)\phi^\dagger\vec{\tau}\phi\right\}$$

Integrate out Δ

D=5 $\quad c^{d=5} = 4Y_\Delta \frac{\mu_\Delta}{|M_\Delta|^2} \quad \rightarrow \quad m_\nu = -2Y_\Delta v^2 \frac{\mu_\Delta}{|M_\Delta|^2}$

m_ν proportional both to μ and Y_Δ linearly dependent on Y_Δ

Low-energy effects of see-saw: type II

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m_ν proportional both to μ and Y_Δ linearly dependent on Y_Δ

$c^{d=5}$ is different with respect to fermionic cases $$c^{d=5} = Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma$$

Low-energy effects of see-saw: type II

Abada, CB, Bonnet, Gavela, Hambye 07

D=6

$$\delta\mathcal{L}_{\phi D} = \frac{|\mu_\Delta|^2}{|M_\Delta|^4}\left(\phi^\dagger \vec{\tau}\,\tilde{\phi}\right)\left(\overleftarrow{D_\mu}\overrightarrow{D^\mu}\right)\left(\tilde{\phi}^\dagger \vec{\tau}\,\phi\right)$$

It renormalises M_Z

$$\delta\mathcal{L}_{6\phi} = -2\left(\lambda_3 + \lambda_5\right)\frac{|\mu_\Delta|^2}{|M_\Delta|^4}\left(\phi^\dagger\phi\right)^3$$

It renormalises v

$$\delta\mathcal{L}_{4F} = \frac{1}{{M_\Delta}^2}\left(\overline{\widetilde{\ell_L}}\,Y_\Delta\,\vec{\tau}\,\ell_L\right)\left(\overline{\ell_L}\,\vec{\tau}\,Y_\Delta^\dagger\,\widetilde{\ell_L}\right)$$

It renormalises G_F

Low-energy effects of see-saw: type II

Abada, CB, Bonnet, Gavela, Hambye 07

D=6

$$\delta\mathcal{L}_{\phi D} = \frac{|\mu_\Delta|^2}{|M_\Delta|^4}\left(\phi^\dagger \vec{\tau}\,\tilde{\phi}\right)\left(\overleftarrow{D_\mu}\overrightarrow{D^\mu}\right)\left(\tilde{\phi}^\dagger \vec{\tau}\,\phi\right)$$

It renormalises M_Z

$$\delta\mathcal{L}_{6\phi} = -2\,(\lambda_3+\lambda_5)\,\frac{|\mu_\Delta|^2}{|M_\Delta|^4}\left(\phi^\dagger\phi\right)^3$$

It renormalises v

$$\delta\mathcal{L}_{4F} = \frac{1}{{M_\Delta}^2}\left(\overline{\tilde{\ell}_L}\,Y_\Delta\,\vec{\tau}\,\ell_L\right)\left(\overline{\ell_L}\,\vec{\tau}\,Y_\Delta^\dagger\,\tilde{\ell}_L\right)$$

It renormalises G_F

→ It generates 4-fermions interactions

→ It is not suppressed by μ

Low-energy effects of see-saw: type II

Abada, CB, Bonnet, Gavela, Hambye 07

D=6

$$\delta\mathcal{L}_{\phi D} = \frac{|\mu_\Delta|^2}{|M_\Delta|^4}\left(\phi^\dagger \vec{\tau}\tilde{\phi}\right)\left(\overleftarrow{D_\mu}\overrightarrow{D^\mu}\right)\left(\tilde{\phi}^\dagger\vec{\tau}\phi\right)$$

It renormalises M_Z

$$\delta\mathcal{L}_{6\phi} = -2\left(\lambda_3+\lambda_5\right)\frac{|\mu_\Delta|^2}{|M_\Delta|^4}\left(\phi^\dagger\phi\right)^3$$

It renormalises v

$$\delta\mathcal{L}_{4F} = \frac{1}{M_\Delta{}^2}\left(\overline{\tilde{\ell}_L}\, Y_\Delta\, \vec{\tau}\,\ell_L\right)\left(\overline{\ell_L}\,\vec{\tau}\, Y_\Delta^\dagger\, \tilde{\ell}_L\right)$$

It renormalises G_F

→ It generates 4-fermions interactions

→ It is not suppressed by μ

$c^{d=6}$ is common to all cases: $$c^{d=6} = Y_\Sigma^\dagger \frac{1}{|M_\Sigma|^2} Y_\Sigma$$

Can we distinguish among different models?

- d=5 operator is common to all models for Majorana ν masses but $c^{d=5}$ is different for fermionic and scalar models

- d=6 operator permit to discriminate among different models and $c^{d=6}$ is common to all models

  but generically if $Y \approx O(1)$ → $c^{d=6} \approx (c^{d=5})^2$ → very suppressed
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We need to decouple d=5 from d=6

Notice: d=5 operator violates lepton number
d=6 operators conserve it

→ natural from the point of view of symmetries…

See-saw @ low scale

Light Majorana mass should vanish:

- inversely proportional to a Majorana scale ≈ *1/M*
- directly proportional to it ≈ μ

ANSATZ:
When the breaking of L take place @ a small scale μ with $\mu << M$ the d=5 op. is suppressed with μ while the d=6 is unsuppressed

$$c^{d=5} = f(Y)\frac{\mu}{M^2}$$

$$c^{d=6} = g(Y)\,\frac{1}{|M|^2}$$

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- Multiple seesaw (for 1 generation)

$$\begin{pmatrix} 0 & m_{D_1} & 0 \\ m_{D_1} & 0 & M_{N_1} \\ 0 & M_{N_1} & \mu \end{pmatrix}$$

$$\mu << M_N \quad m_D << M_N$$

$$m_\nu \approx \frac{m_{D_1}^2}{M_{N_1}} \frac{\mu}{M_{N_1}}$$

Our ansatz confirmed by Kersten, Smirnov 2007

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Which are the experimental signatures and the present bounds?

Bounds on Yukawas type I

W decays, invisible Z decay, universality tests, rare lepton decays

$\rightarrow$ bounds on $|NN^\dagger|$

Antusch, CB, Fernández-Martínez, Gavela, López-Pavón 2006

$$||NN^\dagger| - 1|_{\alpha\beta} = \frac{v^2}{2}|c^{d=6}|_{\alpha\beta} = \frac{v^2}{2}|Y_N^\dagger \frac{1}{|M_N|^2} Y_N|_{\alpha\beta}$$

$$\frac{v^2}{2}|Y_N^\dagger \frac{1}{|M_N|^2} Y_N|_{\alpha\beta} \lesssim \begin{pmatrix} 10^{-2} & 7.0\cdot 10^{-5} & 1.6\cdot 10^{-2} \\ 7.0\cdot 10^{-5} & 10^{-2} & 1.0\cdot 10^{-2} \\ 1.6\cdot 10^{-2} & 1.0\cdot 10^{-2} & 10^{-2} \end{pmatrix}$$

$$|Y| \leq 5\cdot 10^{-1}\frac{M}{1TeV}$$ or stronger

Bounds on Yukawas type III

W decays, invisible Z decay, universality tests,
charged leptons Z decays, rare lepton decays (like $\mu\to e\gamma$ and $\mu\to eee$)

→ bounds on $|NN^\dagger|$

Abada, CB, Bonnet, Gavela, Hambye 2007

$$||NN^\dagger| - 1|_{\alpha\beta} = \frac{v^2}{2}|c^{d=6}|_{\alpha\beta} = \frac{v^2}{2}|Y_N^\dagger \frac{1}{|M_N|^2} Y_N|_{\alpha\beta}$$

$$\frac{v^2}{2}|c^{d=6}|_{\alpha\beta} = \frac{v^2}{2}|Y_\Sigma^\dagger \frac{1}{M_\Sigma^\dagger}\frac{1}{M_\Sigma} Y_\Sigma|_{\alpha\beta} \lesssim \begin{pmatrix} 3\cdot 10^{-3} & < 1.1\cdot 10^{-6} & < 1.2\cdot 10^{-3} \\ < 1.1\cdot 10^{-6} & 4\cdot 10^{-3} & < 1.2\cdot 10^{-3} \\ < 1.2\cdot 10^{-3} & < 1.2\cdot 10^{-3} & 4\cdot 10^{-3} \end{pmatrix}$$

Better bounds on off-diag elements due to tree-level $\mu\to eee$ and similar

$$|Y| \leq 1.6\cdot 10^{-1}\frac{M}{1TeV}$$ or stronger

Bounds on Yukawas type II

Process	Constraint on	Bound $\left(\times\left(\frac{M_\Delta}{1\,\mathrm{TeV}}\right)^2\right)$
M_W	$\lvert Y_{\Delta\mu e}\rvert^2$	$< 7.3 \times 10^{-2}$
$\mu^- \to e^+e^-e^-$	$\lvert Y_{\Delta\mu e}\rvert\lvert Y_{\Delta ee}\rvert$	$< 1.2 \times 10^{-5}$
$\tau^- \to e^+e^-e^-$	$\lvert Y_{\Delta\tau e}\rvert\lvert Y_{\Delta ee}\rvert$	$< 1.3 \times 10^{-2}$
$\tau^- \to \mu^+\mu^-\mu^-$	$\lvert Y_{\Delta\tau\mu}\rvert\lvert Y_{\Delta\mu\mu}\rvert$	$< 1.2 \times 10^{-2}$
$\tau^- \to \mu^+e^-e^-$	$\lvert Y_{\Delta\tau\mu}\rvert\lvert Y_{\Delta ee}\rvert$	$< 9.3 \times 10^{-3}$
$\tau^- \to e^+\mu^-\mu^-$	$\lvert Y_{\Delta\tau e}\rvert\lvert Y_{\Delta\mu\mu}\rvert$	$< 1.0 \times 10^{-2}$
$\tau^- \to \mu^+\mu^-e^-$	$\lvert Y_{\Delta\tau\mu}\rvert\lvert Y_{\Delta\mu e}\rvert$	$< 1.8 \times 10^{-2}$
$\tau^- \to e^+e^-\mu^-$	$\lvert Y_{\Delta\tau e}\rvert\lvert Y_{\Delta\mu e}\rvert$	$< 1.7 \times 10^{-2}$
$\mu \to e\gamma$	$\lvert\Sigma_{l=e,\mu,\tau} Y_{\Delta}{}^{\dagger}_{l\mu} Y_{\Delta el}\rvert$	$< 4.7 \times 10^{-3}$
$\tau \to e\gamma$	$\lvert\Sigma_{l=e,\mu,\tau} Y_{\Delta}{}^{\dagger}_{l\tau} Y_{\Delta el}\rvert$	< 1.05
$\tau \to \mu\gamma$	$\lvert\Sigma_{l=e,\mu,\tau} Y_{\Delta}{}^{\dagger}_{l\tau} Y_{\Delta\mu l}\rvert$	$< 8.4 \times 10^{-1}$

Abada, CB, Bonnet, Gavela, Hambye 2007

$$|Y| \leq 10^{-1} \frac{M}{1TeV}$$

or stronger

Conclusions

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- We have calculated D=6 ops for the 3 types of see-saw: they are different → with low scale they can be used to distinguish
- D=6 bounded from 4-fermions interactions and unitarity deviations

$$|Y| \leq 10^{-1} \frac{M}{1TeV}$$

→ keep tracking these deviations in the future: they are excellent windows for new physics