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Constraints on the (low scale) type-III seesaw

In collaboration with E. Fernandez-Martinez, M. Filaci, J. Hernandez-Garcia and J. Lopez-Pavon

(work in progress)

Corfu Summer Institute
Workshop on the Standard Model and beyond
Corfu, 31/08-09/09 2018

Fermion masses

After LHC discovery of the Higgs boson and precise measurement of Yukawa couplings the BEH mechanism is well established as the mechanism to give mass to charged fermions

However: what about neutrinos?

from oscillation experiments -> they are massive and their mass is very light

The SM must be extended

Neutrino masses

The simplest extension -> add ν_R and Dirac mass $Y\bar{L}\phi\nu_R$
is not satisfactory:

- extreme lightness of neutrino masses not explained
- lepton number conservation must be imposed

otherwise, Majorana mass is allowed $M\bar{\nu_R}\nu_R$

-> new scale in the SM -> BSM physics!

M can be at any scale, lighter or heavier than EW scale

If M>EW -> Seesaw mechanism
lightness of neutrino mass arise naturally

Seesaw mechanism

Minkowsky77
Gell-Mann Ramond Slansky 79
Yanagida 79
Mohapatra Senjanovic 80

Simplest: type I seesaw
-> add heavy fermion singlets N

$$\mathcal{L} = \mathcal{L}_{\mathcal{SM}} + \mathcal{L}_{\mathcal{K}} - \frac{1}{2}\overline{N_i}M_{ij}N_j - Y_{i\alpha}\overline{N_i}\widetilde{\phi}^\dagger L_\alpha + h.c.$$

$$\begin{pmatrix} 0 & \frac{v}{\sqrt{2}}Y \\ \frac{v}{\sqrt{2}}Y^T & M \end{pmatrix}$$

$$m_\nu = \frac{v^2}{2} Y M^{-1} Y^T$$

Light neutrino mass for $Y \sim 1$ and $M \sim M_{GUT}$

Drawback: impossible to test!
- both directly -> never produce heavy states
- neither indirectly -> NP effects suppressed by the large M:

$$c^{d=6} = \epsilon = \frac{v^2}{2} Y^\dagger M^{-2} Y$$

Seesaw mechanism

O(1) Yukawa not necessary: $M \sim \mathrm{TeV}$ with $Y \sim 10^{-6}$ (Y_e)

It seems better, but:
- N produced via Yukawa couplings -> difficult direct prod.
- moreover: NP effects now suppressed by Y^2 $\sim Y^2/M^2$

Can we build testable models?
YES

2 ways:
- use different seesaw particle, which can be gauge-produced at accelerators
- try to have low scale with large Yukawa

we will do both

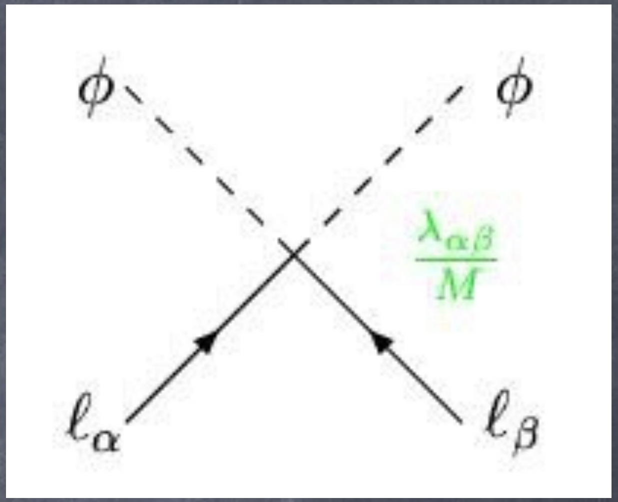
Other seesaws

type I is only one of the possible realization of neutrino masses
Let's adopt an effective operator approach:

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{c^{d=5}}{\Lambda}\mathcal{O}_5 + \sum_i \frac{c_i^{d=6}}{\Lambda^2}\mathcal{O}_{6,i} + \dots$$

O5 unique! $\frac{c_{\alpha\beta}^{d=5}}{\Lambda}\left(\bar{L^c}_\alpha \tilde{\phi}^*\right)\left(\tilde{\phi}^\dagger L_\beta\right)$

Weinberg 79



Many ways of getting it:
- tree-level
- 1 loop
- ...

3 possibilities:
- fermion SU(2)-singlets -> typeI seesaw
- scalar SU(2)-triplets -> typeII seesaw
- fermion SU(2)-triplets -> typeIII seesaw

Other seesaws

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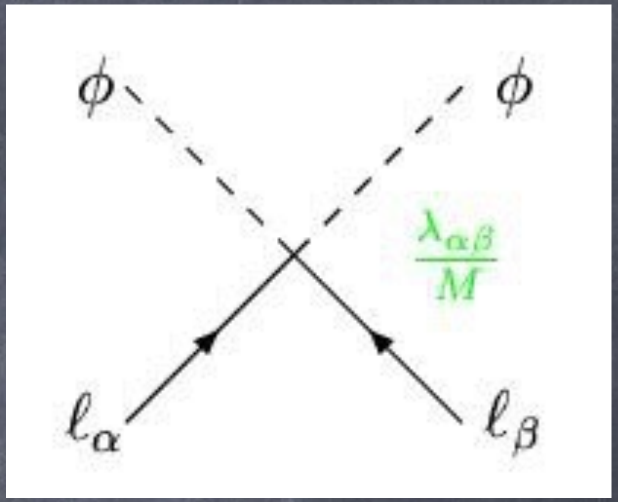

Many ways of getting it:
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3 possibilities:
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Type-III seesaw

Foot Lew He Joshi 89 Ma 98 ...

Add to the SM fermionic SU(2) triplets:

$$\vec{\Sigma} = (\Sigma_1, \Sigma_2, \Sigma_3)$$

$$\mathcal{L} = \mathcal{L}_{\rm SM} + i\overline{\Sigma}_R \not{D} \Sigma_R - \frac{1}{2}\left(\overline{\Sigma^i_R}\,(M_\Sigma)_{ij}\,\Sigma^{cj}_R - (Y_\Sigma)_{i\alpha}\,\overline{\Sigma^i_R}\tilde{\phi}^\dagger \tau \ell^\alpha_L\right) + \text{h.c.}$$

$$\Sigma^\pm = \frac{1}{\sqrt{2}}(\Sigma_1 \pm i\Sigma_2) \qquad \psi = \Sigma^{+c} + \Sigma^-$$

$$\Sigma^0 = \Sigma_3$$

$$\mathcal{L}_M = -\begin{pmatrix}\overline{\ell_L} & \overline{\psi_L}\end{pmatrix}\begin{pmatrix} m_\ell & Y_\Sigma^\dagger \\ 0 & M_\Sigma \end{pmatrix}\begin{pmatrix}\ell_R \\ \psi_R\end{pmatrix} - \begin{pmatrix}\overline{\nu_L^c} & \overline{\Sigma^0}\end{pmatrix}\begin{pmatrix} 0 & m_D^T \\ m_D & M_\Sigma \end{pmatrix}\begin{pmatrix}\nu_L \\ \Sigma^{0c}\end{pmatrix} + \text{h.c.}$$

Σ^0 exactly behaves like ν_R

-> all the neutrino mass phenomenology studied for typeI seesaw models can be applied here

-> additionally richer phenomenology from charged states

Type-III seesaw

Advantages:

- LHC: triplets can be Drell-Yann produced (if M is small) independently of the strength of Y
- Richer pheno: FCNC for charged leptons at tree-level relevant only if Y is large and M small

$$c^{d=6} = \epsilon = \frac{v^2}{2} Y^\dagger M^{-2} Y$$

We can have large Y and low M if
neutrino mass suppression comes from a symmetry ->
-> Lepton Number

Requirement of approximate L conservation

Approximate L conservation

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{c^{d=5}}{\Lambda_{LN}} \mathcal{O}_5 + \sum_i \frac{c_i^{d=6}}{\Lambda_{LF}^2} \mathcal{O}_{6,i} + \ldots$$

Neutrino mass
L violating

flavour changing operator
L conserving

Standard seesaw: $\Lambda_{LN} = \Lambda_{LF} = M$

We consider models where $M = \Lambda_{LF} << \Lambda_{LN}$

Inverse seesaw models (initially for type-I)

Mohapatra 86 Mohapatra Valle 86 Bernabeu Santamaria Vidal Mendez Valle 87
Branco Grimus Lavoura 89 Malinsky Romao Valle 05 Buchmueller Wyler 90
Gavela Hambye Hernandez^2 09

1) General case - Eff. ops. analysis

Consider type-III seesaw, add a certain number of triplets, integrate them out, generate effective operators, calculate all possible processes, compare with experiments and put bounds

$$\mathcal{O}_{\alpha\beta}^{d=6} = \left(\bar{L}_\alpha \vec{\tau} \tilde{\phi}\right) i\gamma^\mu D_\mu \left(\tilde{\phi}^\dagger \vec{\tau} L_\beta\right)$$

-> non-unitarity of the leptonic mixing matrix $N = (1-\eta)U_{PMNS}$

-> FCNC for charged leptons at tree-level $\sim (NN^\dagger)^2 \sim (1-4\eta)$

$$\eta < \begin{pmatrix} 1.5\cdot 10^{-3} & 0.9\cdot 10^{-7} & 0.6\cdot 10^{-3} \\ 0.9\cdot 10^{-7} & 2.0\cdot 10^{-3} & 0.6\cdot 10^{-3} \\ 0.6\cdot 10^{-3} & 0.6\cdot 10^{-3} & 2.0\cdot 10^{-3} \end{pmatrix}$$

Abada CB Bonnet Gavela Hambye 07

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new bounds: $\eta < \begin{pmatrix} 3.6\cdot 10^{-4} & 3.0\cdot 10^{-7} & 2.8\cdot 10^{-4} \\ 3.0\cdot 10^{-7} & 5.8\cdot 10^{-4} & 5.4\cdot 10^{-4} \\ 2.8\cdot 10^{-4} & 5.4\cdot 10^{-4} & 9.2\cdot 10^{-4} \end{pmatrix}$

CB, Fernandez-Martinez, Filaci, Hernandez-Garcia, Lopez-Pavon, in preparation

1) General case - Eff. ops. analysis

In this case we are assuming large Y and small M
-> approximate L conservation, but we do not see it directly

Also at the LHC: searches for triplets like these

$$M_\Sigma > 840 \text{ GeV} \quad (\text{if } Y_e = Y_\mu = Y_\tau)$$ CMS2017

but: how can we know they are responsible for neutrino masses?

2) Inverse type-III with 3 triplets

Approximate L conservation fixes the pattern of Y and M:

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$$m_D = \frac{v}{\sqrt{2}} \begin{pmatrix} Y_e & Y_\mu & Y_\tau \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \qquad M = \begin{pmatrix} 0 & \Lambda & 0 \\ \Lambda & 0 & 0 \\ 0 & 0 & \Lambda' \end{pmatrix}$$

$$L_e = L_\mu = L_\tau = L_1 = 1 \quad L_2 = -1 \quad L_3 = 0$$

$$m_\nu = \frac{v^2}{2} Y^T M^{-2} Y = 0$$

$$\eta = \frac{v^2}{4\Lambda^2} \begin{pmatrix} |Y_e|^2 & Y_e Y_\mu^* & Y_e Y_\tau^* \\ Y_\mu Y_e^* & |Y_\mu|^2 & Y_\mu Y_\tau^* \\ Y_\tau Y_e^* & Y_\tau Y_\mu^* & |Y_\tau|^2 \end{pmatrix} \neq 0$$

large effects even with conserved L

2) Inverse type-III with 3 triplets

Approximate L conservation fixes the pattern of Y and M:

Kersten Smirnov 07

Abada CB Bonnet Gavela Hambye 07

$$m_D = \frac{v}{\sqrt{2}} \begin{pmatrix} Y_e & Y_\mu & Y_\tau \\ \epsilon_1 Y'_e & \epsilon_1 Y'_\mu & \epsilon_1 Y'_\tau \\ \epsilon_2 Y''_e & \epsilon_2 Y''_\mu & \epsilon_2 Y''_\tau \end{pmatrix} \qquad M = \begin{pmatrix} \mu_1 & \Lambda & \mu_3 \\ \Lambda & \mu_2 & \mu_4 \\ \mu_3 & \mu_4 & \Lambda' \end{pmatrix}$$

=3

$$L_e = L_\mu = L_\tau = L_1 = 1 \quad L_2 = -1 \quad L_3 = 0$$

$$m_\nu = \frac{v^2}{2} Y^T M^{-2} Y \neq 0$$

=3

$$\eta = \frac{v^2}{4\Lambda^2} \begin{pmatrix} |Y_e|^2 & Y_e Y_\mu^* & Y_e Y_\tau^* \\ Y_\mu Y_e^* & |Y_\mu|^2 & Y_\mu Y_\tau^* \\ Y_\tau Y_e^* & Y_\tau Y_\mu^* & |Y_\tau|^2 \end{pmatrix} \neq 0$$

large effects even with conserved L

2) Inverse type-III with 3 triplets

Compute $m_\nu = \frac{v^2}{2} Y M^{-1} Y^T$ with these specific Y and M

$$Y_\tau = \frac{1}{m_{e\mu}^2 - m_{ee} m_{\mu\mu}} \left(Y_e \left(m_{e\mu} m_{\mu\tau} - m_{e\tau} m_{\mu\mu} \right) + \right.$$
$$+ Y_\mu \left(m_{e\mu} m_{e\tau} - m_{ee} m_{\mu\tau} \right) - \sqrt{Y_e^2 m_{\mu\mu} - 2 Y_e Y_\mu m_{e\mu} + Y_\mu^2 m_{ee}} \times$$
$$\left. \times \sqrt{m_{e\tau}^2 m_{\mu\mu} - 2 m_{e\mu} m_{e\tau} m_{\mu\tau} + m_{ee} m_{\mu\tau}^2 + m_{e\mu}^2 m_{\tau\tau} - m_{ee} m_{\mu\mu} m_{\tau\tau}} \right)$$

$$m_{\alpha\beta}(\Theta_{12},\ \Theta_{23},\ \Theta_{13},\ \delta,\ \phi_1,\ \phi_2,\ \Delta m_{12}^2,\ \Delta m_{23}^2,\ m_0)$$

This is the footprint of the seesaw!

It must be taken into account when performing the fit

3) Inverse type-III with 2 triplets

Gavela Hambye Hernandez^2 09
Eboli Gonzales-Fraile Gonzales-Garcia 11

$$m_D = \frac{v}{\sqrt{2}} \begin{pmatrix} Y_e & Y_\mu & Y_\tau \\ 0 & 0 & 0 \end{pmatrix} \qquad M = \begin{pmatrix} 0 & \Lambda \\ \Lambda & 0 \end{pmatrix}$$

$$m_D = \frac{v}{\sqrt{2}} \begin{pmatrix} Y_e & Y_\mu & Y_\tau \\ \epsilon_1 Y'_e & \epsilon_1 Y'_\mu & \epsilon_1 Y'_\tau \end{pmatrix} \qquad M = \begin{pmatrix} \mu_1 & \Lambda \\ \Lambda & \mu_2 \end{pmatrix}$$

$$Y_\mu = \frac{m_{e\mu} \pm \sqrt{m_{e\mu}^2 - m_{ee} m_{\mu\mu}}}{m_{ee}} Y_e. \qquad Y_\tau = \frac{m_{e\tau} \pm \sqrt{m_{e\tau}^2 - m_{ee} m_{\tau\tau}}}{m_{ee}} Y_e.$$

$$m_{ee} m_{\mu\tau} = m_{e\mu} m_{e\tau} - s_\mu s_\tau \sqrt{\left(m_{e\mu}^2 - m_{ee} m_{\mu\mu}\right)\left(m_{e\tau}^2 - m_{ee} m_{\tau\tau}\right)}$$

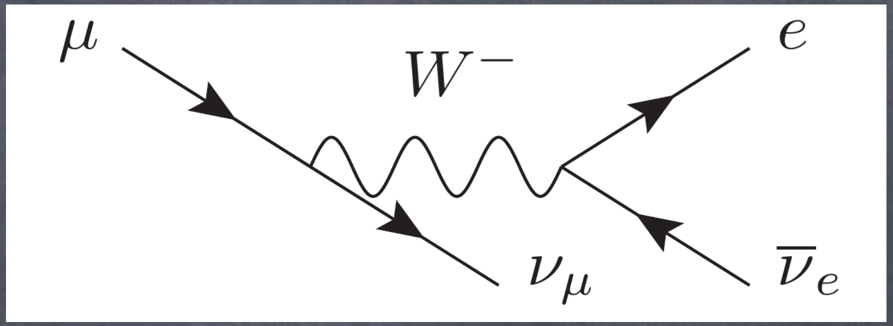
More constrained scenario, we expect more stringent bounds

Observables for the fit

26 observables in the fit, as a function of $\alpha,\ M_Z,\ G_F$

G_F receives non-unitary corrections (measured in muon decay):

$$G_F = G_\mu(1+\eta_{ee}+\eta_{\mu\mu})$$



- W mass
- ratios of Z fermionic decays
- invisible width of Z
- ratios of weak decays constraining EW universality
- weak decays costraining CKM unitarity
- LFV processes: $\mu \to e(\mathrm{Ti}),\ \tau \to e\gamma,\ \tau \to \mu\gamma$

Parameters

1) General case:

$\eta_{ee}\ \eta_{\mu\mu}\ \eta_{\tau\tau}\ \eta_{e\mu}\ \eta_{e\tau}\ \eta_{\mu\tau}$ (9 parameters)

2) 3 triplets:

$|\theta_e|\ |\theta_\mu|\ \varphi_e\ \varphi_\mu$ $\delta\ \phi_1\ \phi_2\ m_0$

3) 2 triplets:

$|\theta_e|$ $\delta\ \phi\ (m_0 = 0)$

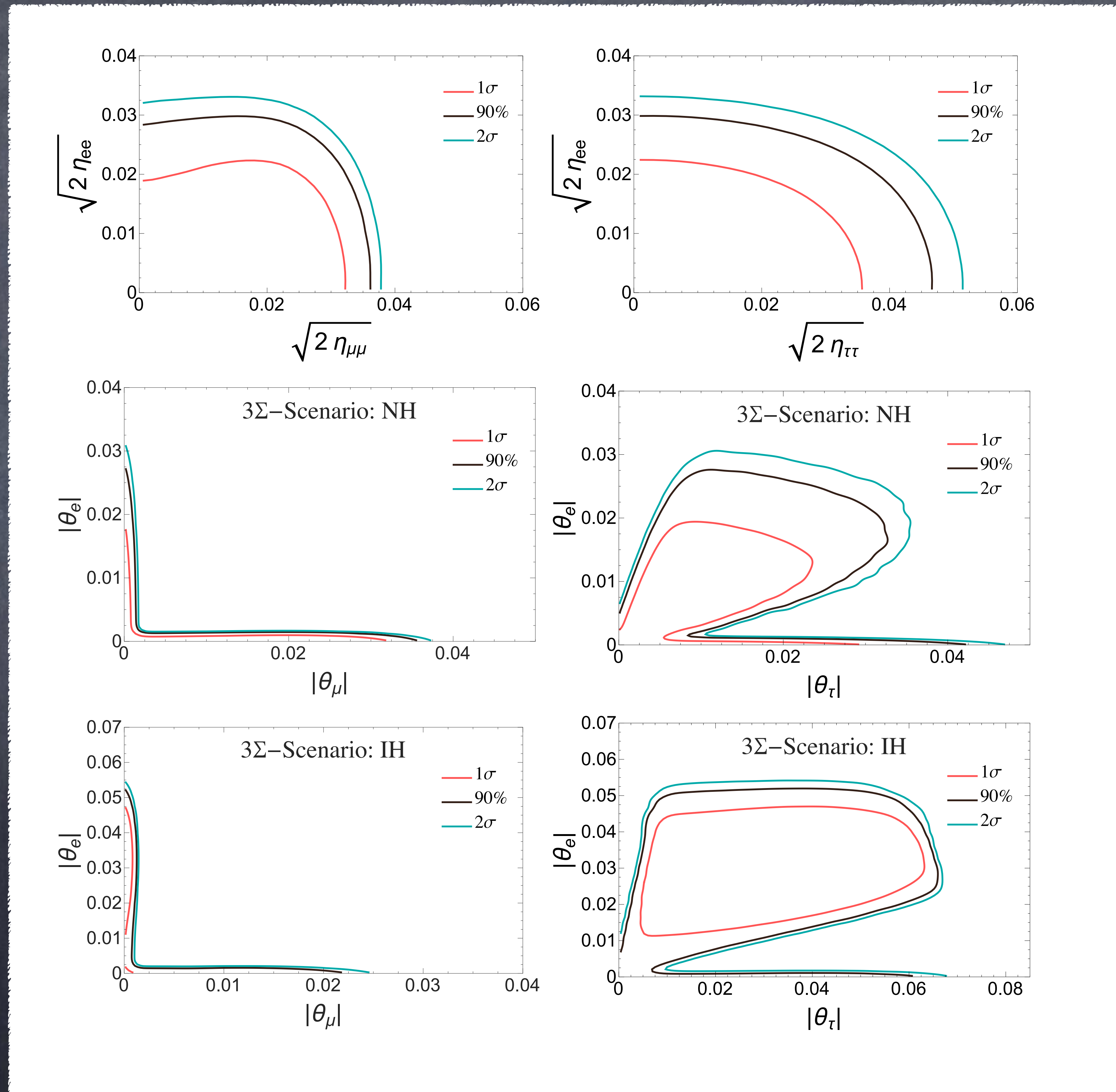
In (2) and (3) consider both NH and IH

PRELIMINARY Results PRELIMINARY

General

3 triplets NH

3 triplets IH



PRELIMINARY Results PRELIMINARY

		General		3 triplets		2 triplets	
		LFC	LFV	NH	IH	NH	IH
$\sqrt{2\eta_{ee}},\ \lvert\theta_e\rvert$	1σ	$< \mathbf{0.015}$	—	$< 3.7 \cdot 10^{-3}$	$0.032^{+0.010}_{-0.012}$	$< 6.9 \cdot 10^{-4}$	$< 2.6 \cdot 10^{-3}$
	2σ	$< \mathbf{0.027}$	—	< 0.025	< 0.050	$< 8.4 \cdot 10^{-4}$	$< 3.2 \cdot 10^{-3}$
$\sqrt{2\eta_{\mu\mu}},\ \lvert\theta_\mu\rvert$	1σ	$< \mathbf{0.028}$	—	< 0.027	$< 1.5 \cdot 10^{-5}$	$< 1.0 \cdot 10^{-3}$	$< 5.5 \cdot 10^{-4}$
	2σ	$< \mathbf{0.034}$	—	< 0.034	< 0.020	$< 1.2 \cdot 10^{-3}$	$< 6.6 \cdot 10^{-4}$
$\sqrt{2\eta_{\tau\tau}},\ \lvert\theta_\mu\rvert$	1σ	$< \mathbf{0.024}$	—	< 0.024	$0.040^{+0.018}_{-0.036}$	$< 7.7 \cdot 10^{-3}$	$< 2.0 \cdot 10^{-3}$
	2σ	$< \mathbf{0.043}$	—	< 0.042	< 0.066	$< 9.3 \cdot 10^{-3}$	$< 2.3 \cdot 10^{-3}$
$\sqrt{2\eta_{e\mu}},\ \sqrt{\lvert\theta_e\theta_\mu\rvert}$	1σ	< 0.016	$< \mathbf{6.5 \cdot 10^{-4}}$	$< 6.5 \cdot 10^{-4}$	$< 6.5 \cdot 10^{-4}$	$< 6.5 \cdot 10^{-4}$	$< 6.5 \cdot 10^{-4}$
	2σ	< 0.024	$< \mathbf{7.7 \cdot 10^{-4}}$	$< 7.7 \cdot 10^{-4}$	$< 7.7 \cdot 10^{-4}$	$< 7.7 \cdot 10^{-4}$	$< 7.7 \cdot 10^{-4}$
$\sqrt{2\eta_{e\tau}},\ \sqrt{\lvert\theta_e\theta_\tau\rvert}$	1σ	$< \mathbf{0.012}$	< 0.107	$< 1.9 \cdot 10^{-3}$	$0.036^{+0.010}_{-0.023}$	$< 2.3 \cdot 10^{-3}$	$< 1.6 \cdot 10^{-3}$
	2σ	$< \mathbf{0.024}$	< 0.127	< 0.023	< 0.052	$< 2.8 \cdot 10^{-3}$	$< 1.9 \cdot 10^{-3}$
$\sqrt{2\eta_{\mu\tau}},\ \sqrt{\lvert\theta_\mu\theta_\tau\rvert}$	1σ	$< \mathbf{0.022}$	< 0.115	< 0.023	$< 7.9 \cdot 10^{-4}$	$< 2.1 \cdot 10^{-3}$	$< 8.2 \cdot 10^{-4}$
	2σ	$< \mathbf{0.033}$	< 0.137	< 0.032	< 0.032	$< 2.5 \cdot 10^{-3}$	$< 9.7 \cdot 10^{-4}$

from Schwartz inequality :

$$|\eta_{\alpha\beta}| \leq \sqrt{\eta_{\alpha\alpha}\eta_{\beta\beta}}$$

from LFV processes:

μ to e conversion in Ti, $\tau \to e\gamma$ and $\tau \to \mu\gamma$

PRELIMINARY Results PRELIMINARY

		General		3 triplets		2 triplets	
		LFC	LFV	NH	IH	NH	IH
$\sqrt{2\eta_{ee}}$, $\lvert\theta_e\rvert$	1σ	$< \mathbf{0.015}$	—	$< 3.7 \cdot 10^{-3}$	$0.032^{+0.010}_{-0.012}$	$< 6.9 \cdot 10^{-4}$	$< 2.6 \cdot 10^{-3}$
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PRELIMINARY Results PRELIMINARY

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Future perspectives

Analyse the 3 and 2 triplets case at the LHC

> 2 triplets case studied in Eboli, Gonzales-Fraile, Gonzales-Garcia '11

- perform the study in the 3 triplets scenario

- use present LHC bounds on triplets typeIII-like
  to place direct constraint on the approximate L-conserving
  type-III seesaw

Conclusions

- Low-scale seesaws with approximate Lepton Number symmetry are very interesting scenarios
- We are studying the typeIII seesaw with approximate L-symmetry with 2 and 3 triplets
- We are placing new bounds on the parameters of these models
- We will study LHC phenomenology
- In case of signal (at the LHC or in LFV processes) the correlations typical of these models will make them *really* testable

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Ευχαριστώ!

Thank you!

Back up

Observable	SM prediction	Experimental value
$M_W \simeq M_W^{\rm SM}\,(1-0.20\,(\eta_{ee}+\eta_{\mu\mu}))$	(80.363 ± 0.006) GeV	(80.385 ± 0.015) GeV
$R_l \simeq R_l^{\rm SM}\,(1-0.18\,(\eta_{ee}+\eta_{\mu\mu}))$	20.740 ± 0.010	20.804 ± 0.050
$R_c \simeq R_c^{\rm SM}\,(1-0.11\,(\eta_{ee}+\eta_{\mu\mu}))$	0.17226 ± 0.00003	0.1721 ± 0.0030
$R_b \simeq R_b^{\rm SM}\,(1+0.06\,(\eta_{ee}+\eta_{\mu\mu}))$	0.21576 ± 0.00003	0.21629 ± 0.00066
$\sigma^0_{\rm had} \simeq \sigma^{0\,\rm SM}_{\rm had}\,(1-0.55\,(\eta_{ee}+\eta_{\mu\mu})-0.53\eta_{\tau\tau})$	(41.479 ± 0.008) nb	(41.541 ± 0.037) nb
$\Gamma_{\rm inv} \simeq \Gamma_{\rm inv}^{\rm SM}\,(1+0.33\,(\eta_{ee}+\eta_{\mu\mu})+1.32\eta_{\tau\tau})$	(0.50166 ± 0.00005) GeV	(0.4990 ± 0.0015) GeV
$R^\pi_{\mu e} \simeq (1+(\eta_{\mu\mu}-\eta_{ee}))$	1	1.0042 ± 0.0022
$R^\pi_{\tau\mu} \simeq (1+(\eta_{\tau\tau}-\eta_{\mu\mu}))$	1	0.9941 ± 0.0059
$R^W_{\mu e} \simeq (1+(\eta_{\mu\mu}-\eta_{ee}))$	1	0.992 ± 0.020
$R^W_{\tau\mu} \simeq (1+(\eta_{\tau\tau}-\eta_{\mu\mu}))$	1	1.071 ± 0.025
$R^K_{\mu e} \simeq (1+(\eta_{\mu\mu}-\eta_{ee}))$	1	0.9956 ± 0.0040
$R^K_{\tau\mu} \simeq (1+(\eta_{\tau\tau}-\eta_{\mu\mu}))$	1	0.978 ± 0.014
$R^l_{\mu e} \simeq (1+(\eta_{\mu\mu}-\eta_{ee}))$	1	1.0040 ± 0.0032
$R^l_{\tau\mu} \simeq (1+(\eta_{\tau\tau}-\eta_{\mu\mu}))$	1	1.0029 ± 0.0029
$\left\|V^\beta_{ud}\right\| \simeq \sqrt{1-\|V_{us}\|^2}(1-\eta_{\mu\mu})$	$\sqrt{1-\|V_{us}\|^2}$	0.97417 ± 0.00021
$\left\|V_{us}^{\tau\to K\nu_\tau}\right\| \simeq \|V_{us}\|\,(1-\eta_{ee}-\eta_{\mu\mu}+\eta_{\tau\tau})$	$\|V_{us}\|$	0.2212 ± 0.0020
$\left\|V_{us}^{\tau\to K,\pi}\right\| \simeq \|V_{us}\|\,(1-\eta_{\mu\mu})$	$\|V_{us}\|$	0.2232 ± 0.0019
$\left\|V_{us}^{K_L\to\pi e\overline{\nu}_e}\right\| \simeq \|V_{us}\|\,(1-\eta_{\mu\mu})$	$\|V_{us}\|$	0.2237 ± 0.0011
$\left\|V_{us}^{K_L\to\pi\mu\overline{\nu}_\mu}\right\| \simeq \|V_{us}\|\,(1-\eta_{ee})$	$\|V_{us}\|$	0.2240 ± 0.0011
$\left\|V_{us}^{K_S\to\pi e\overline{\nu}_e}\right\| \simeq \|V_{us}\|\,(1-\eta_{\mu\mu})$	$\|V_{us}\|$	0.2229 ± 0.0016
$\left\|V_{us}^{K^\pm\to\pi e\overline{\nu}_e}\right\| \simeq \|V_{us}\|\,(1-\eta_{\mu\mu})$	$\|V_{us}\|$	0.2247 ± 0.0012
$\left\|V_{us}^{K\pm\to\pi\mu\overline{\nu}_\mu}\right\| \simeq \|V_{us}\|\,(1-\eta_{ee})$	$\|V_{us}\|$	0.2245 ± 0.0014
$\left\|V_{us}^{K,\pi\to\mu\nu}\right\| \simeq \|V_{us}\|\,(1-\eta_{\mu\mu})$	$\|V_{us}\|$	0.2315 ± 0.0010

TABLE I. List of observables input to the global fit. The first column contains the leading dependence on the non-unitarity parameters η, the second column contains the loop-corrected SM expectation, and the third column the experimental measurement used in the fit.

Observable	Experimental bound	Future sensitivity
$\tau \to \mu\gamma$	$< 4.4 \cdot 10^{-8}$ [5]	$< 3 \cdot 10^{-9}$ [6]
$\tau \to e\gamma$	$< 3.3 \cdot 10^{-8}$ [5]	$< 3 \cdot 10^{-9}$ [6]
$\mu \to e$ (Ti)	$< 4.3 \cdot 10^{-12}$ [7]	$< 10^{-18}$ [8]