Can new generations explain neutrino masses?

(in coll. with A. Aparici, N. Rius, A. Santamaría)

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03/2011

Rencontres de Moriond
Electroweak session
Young Scientist Forum

Neutrinos: new physics needed! (better testable)

- Neutrino masses ($\sum m_\nu \lesssim 1$ eV) $\Rightarrow$ first hint of PBSM.
- From oscillation experiments, the possible hierarchies are:

1. NH: $m_3 \approx \sqrt{|\triangle m^2_{23}|} \approx 0.05$ eV & $m_2 \approx \sqrt{\triangle m^2_{12}} \approx 0.01$ eV.
2. IH: $m_2 \approx m_1 \approx \sqrt{|\triangle m^2_{23}|} \approx 0.05$ eV.
3. Quasi-degenerate: $m_1 \simeq m_2 \simeq m_3$.

- Lepton mixing is compatible with TBM:

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

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Simple explanation: add RH neutrinos and see-saw, but...

- Hierarchy problem for $O(1)$ Yukawas ($\delta m_H^2 \simeq \mu^2/(4\pi)^2$).
- Difficult to test it (sterile ν_R with $m_R \sim \mu \sim 10^{15}\,\mathrm{GeV}$).

Natural SM extension: a complete new family (with ν_R)
(Grimus et al., Babu et al.)

- Theoretically: $\beta_{QCD} < 0 \Longrightarrow n_{gen} \leq 8$.
- EW fits allow 2 extra at most; heavy Higgs better accomm.
- Higgs searches roughly imply that at least $m_H^{5G} \gtrsim 300\,\text{GeV}$.
- New generation leptons E, ν_E and a singlet ν_R:

$$\mathcal{L} \supset \bar{\ell} Y_e e_R \phi + \bar{\ell} Y_\nu \nu_R \tilde{\phi} + \frac{1}{2} \mu \, \overline{\nu_R^c} \nu_R + \text{h.c.}$$

with:

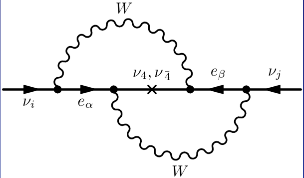
$$Y_\nu = \begin{pmatrix} y_e \epsilon & y_\mu \epsilon & y_\tau \epsilon & y_E \end{pmatrix}^T \text{ where } \epsilon \ll 1$$

- Two massive states at tree level ($m_D \approx y_E v$):

$$m_{4,\bar{4}} = \tfrac{1}{2}(\sqrt{\mu^2 + 4 m_D^2} \mp \mu) \gtrsim 90\,\text{GeV} \longrightarrow y_E \approx \mathcal{O}(1)$$

Two-loop contribution to neutrino masses

- Automatically, at tree level $m_\nu = 0$.
- However, at two loops light neutrino masses are generated:



$$M_{ij} = \frac{g^4}{M_W^4} m_D^2 \, \mu \sum_\alpha V_{i\alpha} V_{4\alpha} m_\alpha^2 \sum_\beta V_{j\beta} V_{4\beta} m_\beta^2 \, I_{\alpha\beta}$$

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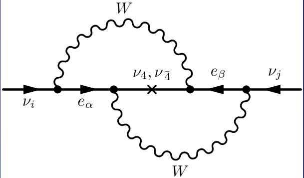

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Huge hierarchies between masses:

$$\frac{m_2}{m_3} \approx \left(\frac{m_\tau}{m_E}\right)^4 \lesssim 10^{-8}, \text{ as } m_E \gtrsim 100\,\text{GeV} \rightarrow \text{ruled-out}$$

The five generations model (two new complete gens.)

$$Y_\nu = \begin{pmatrix} y_E\,\epsilon & y_E\,\epsilon & -y_E\,\epsilon & y_E & 0 \\ 0 & y_F\,\epsilon' & y_F\,\epsilon' & 0 & y_F \end{pmatrix}^T \text{ with } \epsilon,\,\epsilon' \ll 1.$$

Rotation to mass basis in NH (now $m_{D4} \approx y_E v$ & $m_{D5} \approx y_F v$):

$$V \approx \begin{pmatrix} \sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & 0 & \epsilon & 0 \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} & \epsilon & \epsilon' \\ \sqrt{\frac{1}{6}} & -\sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} & -\epsilon & \epsilon' \\ 0 & -\sqrt{3}\epsilon & 0 & 1 & 0 \\ 0 & 0 & -\sqrt{2}\epsilon' & 0 & 1 \end{pmatrix} + \mathcal{O}(\epsilon^2) \to \text{TBM}$$

At tree level: $m_{4,\bar{4}\,(5,\bar{5})} = \frac{1}{2}\left(\sqrt{\mu_{1(2)}^2 + 4 m_{D4(5)}^2} \mp \mu_{1(2)}\right)$.

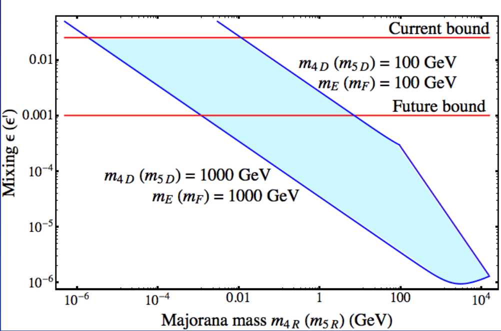
At two loops:

$$m_{2(3)} \approx \frac{g^4 \epsilon^2(')}{(4\pi)^4 M_W^4} m_{D4(5)}^2\, \mu_{1(2)}\, m_{E(F)}^2 \log\left(\frac{m_{E(F)}}{m_{\bar{4}(\bar{5})}}\right)$$

Parameter space for correct mass scale & ratio

$$\rightarrow \frac{m_2}{m_3} \approx \frac{\epsilon^2 m_{D4}^2 \mu_1 m_E^2}{\epsilon'^2 m_{D5}^2 \mu_2 m_F^2}$$

Bounds by $\mu e \gamma$ & μe conv. New cont. to $0\nu\beta\beta$ negligible.



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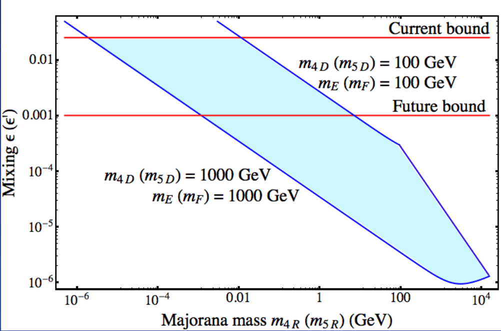


To have right neutrino masses and testability in LFV exp.:

We are in the pseudodirac case.

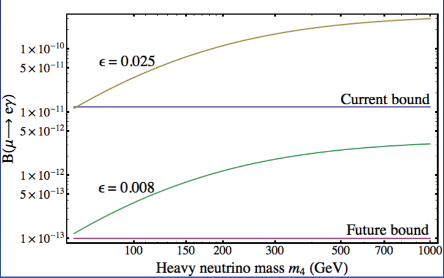
Phenomenological bounds & future LFV signals

- Universality. For example, pion decay, gives:

$$\frac{\Gamma(\pi^+ \to e^+\nu_e)}{\Gamma(\pi^+ \to \mu^+\nu_\mu)} \approx \frac{m_e^2(m_\pi^2 - m_e^2)}{m_\mu^2(m_\pi^2 - m_\mu^2)} \frac{1 - |V_{e4}|^2 - |V_{e5}|^2}{1 - |V_{\mu 4}|^2 - |V_{\mu 5}|^2}(1+\delta R_{e,\mu}) =$$

$$= (1.2310 \pm 0.0037) \cdot 10^{-4} \longrightarrow \epsilon' < 0.04 \text{ (95\% C.L.)}$$

- LFV: $B(\mu \to e\gamma)$ for either hierarchy:



Currently $\epsilon \lesssim 0.03$. Future MEG, μe conv.: $\epsilon \approx \mathcal{O}(10^{-3})$.

Summary & conclusions

- **New families** are **natural, allowed, testable & have nice features:** dyn. EW br. & comp. Higgs, CPV, flavour, DM...
- Small m_ν are natural with new **complete families**.
- Majorana masses $< \mathcal{O}(1)$ TeV are necessary.
- Simplest **4 family model excluded**.
- Viable model with **five generations:**

$\longrightarrow$ ν massless at tree level, **acquire masses at two loops.**

$\longrightarrow$ **TBM** can be accommodated **easily.**

$\longrightarrow$ The **PD limit** of the model **better for LFV testability**.

$\longrightarrow$ **Rich phenomenology:** ν sector, all particles at LHC reach, LFV ($\mu e \to \gamma$, μe conversion) & $0\nu\beta\beta$.

BACK-UP SLIDES

Two-loop integral

$$I_{kn} = \int \frac{d^4p}{(2\pi)^4} \int \frac{d^4q}{(2\pi)^4} \frac{p\cdot q}{(p^2-m_k^2)(q^2-m_n^2)((p+q)^2-m_1^2)((p+q)^2-m_2^2)} \times$$

$$\times \left[\frac{1}{p^2q^2} - \frac{3}{4}\frac{1}{(p^2-M_W^2)(q^2-M_W^2)} \right]$$

If we take $m_{E,F} \gg m_{\bar{4},\bar{5}} > m_W$, we obtain:

$$I_0 \approx -\frac{1}{2^{10}\pi^4 m_{\bar{4}}^2} \ln \frac{m_{\bar{4}}^2}{m_4^2}\,, \qquad k,n = e,\mu,\tau$$

$$I_E \approx -\frac{1}{2^{10}\pi^4 m_E^2} \ln \frac{m_E^2}{m_{\bar{4}}^2}\,, \qquad k \text{ and/or } n = E$$

$$I_F \approx -\frac{1}{2^{10}\pi^4 m_F^2} \ln \frac{m_F^2}{m_{\bar{5}}^2}\,, \qquad k \text{ and/or } n = F$$

Yukawa structure in IH

$$Y_\nu = \begin{pmatrix} -2y_E\epsilon & y_E\,\epsilon & -y_E\,\epsilon & y_E & 0 \\ y_F\,\epsilon' & y_F\,\epsilon' & -y_F\,\epsilon' & 0 & y_F \end{pmatrix}^T$$

$\epsilon, \epsilon' \ll 1$, so $m_{D4} \approx y_E v$ & $m_{D5} \approx y_F v$. Rot. to mass basis (IH):

$$V \approx \begin{pmatrix} \sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & 0 & -2\epsilon & \epsilon' \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} & \epsilon & \epsilon' \\ \sqrt{\frac{1}{6}} & -\sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} & -\epsilon & -\epsilon' \\ \sqrt{6}\epsilon & 0 & 0 & 1 & 0 \\ 0 & -\sqrt{3}\epsilon' & 0 & 0 & 1 \end{pmatrix} + \mathcal{O}(\epsilon^2) \to \text{TBM!}$$

Light neutrino masses are:

$$m_{1(2)} \approx \frac{g^4\epsilon^2(')}{(4\pi)^4 M_W^4}\, m^2_{D4(5)}\, \mu_{1(2)}\, m^2_{E(F)} \log\left(\frac{m_{E(F)}}{m_{\tilde{4}(\tilde{5})}}\right)$$

New families are a natural & welcomed SM extension

- 3 & 4 gens. give same χ^2.
- A heavy Higgs fits better.
- Removes LEP II bound tension.
- Baryogenesis: more CPV.
- DM: hadrons, heavy neutrinos/singlets if stable.
- Composite Higgs & dynamical EW symm. breaking: no hierarchy problem!
- Might solve flavor discrepancies (CPV in B_s-mixing, $B \to K\pi$...).

Bounds & detectability of a new family

- $m_{t'} > 335$ GeV, $m_{b'} > 385$ GeV, $|m_{t'} - m_{b'}| \lesssim 80$ GeV.
- $m_E > 100.8$ GeV, $|m_E - m_{\nu'}| \lesssim 140$ GeV.
- $m_{\nu'}$:

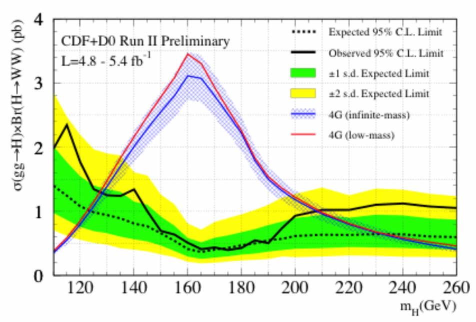
1. unstable (LEP II): 80.5 (M), 90.3 (D), 62.1 GeV (both).
2. stable (inv. Z width): $m_4 > 39.5\,(\mathrm{M}),\ 45\,(\mathrm{D})$ GeV.

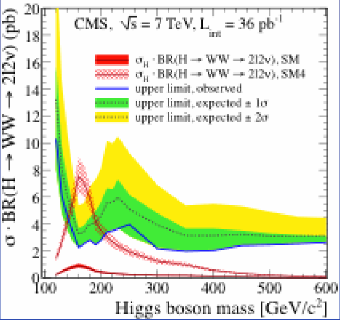
- LHC (with 1 fb^{-1} at 7 TeV) will roughly reach approx.:

1. $m_{b'} \gtrsim 500$ GeV via $b' \to Wt$.
2. $m_E \gtrsim 250$ GeV.
3. $m_{\nu'}$: depends on nature D/M, mixings, hierarchy...

Higgs with new families: better heavier
Early Higgs discovery/exclusion at Tevatron/LHC?

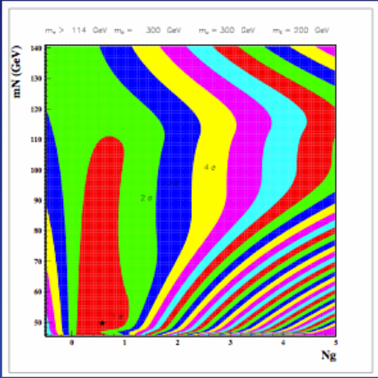
- Higgs exclusion with four families at Tevatron (CDF & D0) and LHC (CMS) (1005.3216, 1102.5429).

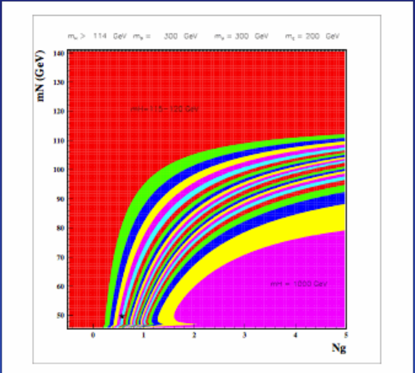




- 95% C.L. excl. Tevatron: 131 GeV $< m_H^{4G} <$ 204 GeV, LHC: 144 GeV $< m_H^{4G} <$ 207 GeV.

How many extra families are allowed?

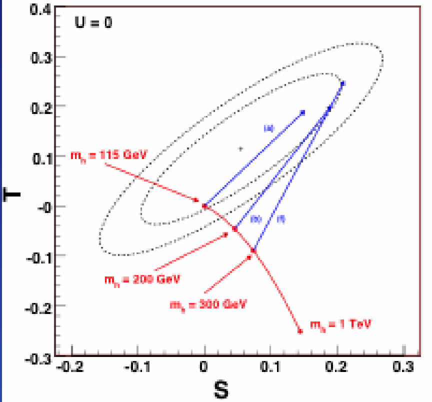




(Novikov et al.)

More on electroweak fits (Kribs et al.)

Higher Higgs mass allowed with extra generations!



$m_\nu = 100$, $m_E = 155$	m_U	m_D	ΔS	ΔT
a	310	260	0.15	0.19
b	320	260	0.19	0.20
f	400	325	0.21	0.25

$0\nu\beta\beta$ with light neutrinos

The $0\nu\beta\beta$ rate is:

$$\Gamma^{0\nu} = \frac{1}{T^{0\nu}_{1/2}} = |m_{ee}|^2 \left|M^{0\nu}\right|^2 G^{0\nu}(Q,Z)$$

$G^{0\nu}(Q,Z)$ is a phase-space factor (for ^{76}Ge is $0.3 \cdot 10^{-25}\, y^{-1} eV^{-2}$), $M^{0\nu}$ is the nuclear matrix element and:

$$m_{ee}(< 0.34\,\text{eV}\,(95\%\,\text{C.L.})) = \left|\sum_i U^2_{ei} m_i\right| =$$

$$= \left|\cos^2\theta_{13}(m_1^2 \cos^2\theta_{12} + m_2^2 e^{2i\phi_1} \sin^2\theta_{12}) + m_3 e^{2i\phi_2} \sin^2\theta_{13}\right|$$

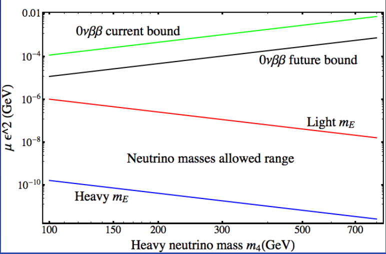
The light neutrino $0\nu\beta\beta$ depends on the hierarchy:

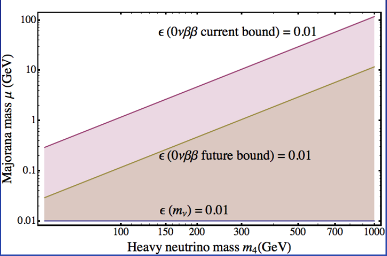
- NH: $|m_{ee}| \leq 5.3 \cdot 10^{-3}$ eV.
- IH: $1.8 \cdot 10^{-2} \leq |m_{ee}| \leq 4.9 \cdot 10^{-2}$ eV.
- Quasi-degenerate: $\cos 2\theta_{12} m_{min} \leq |m_{ee}| \leq m_{min}$.

$0\nu\beta\beta$ with heavy PD neutrinos

Neglect phases & light ν, & $\epsilon = \epsilon'$, $\mu_1 = \mu_2 \equiv \mu$, $m_{4(\tilde{4})} = m_{5(\tilde{5})}$:

$$T^{-1}_{0\nu\beta\beta} \approx \left[\frac{m_p}{\langle m_4 \rangle} - \frac{m_p}{\langle m_{\tilde{4}} \rangle} \right]^2 C^{NN}_{mm} < T^{-1}_{exp} \to \mu^2 < \frac{m_4^4}{\epsilon^4 \, m_P^2 \, C^{NN}_{mm} \, T_{exp}}$$





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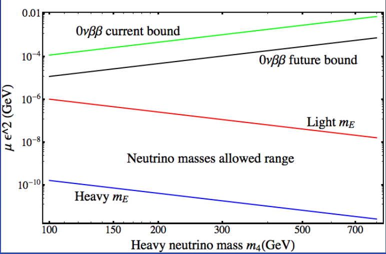

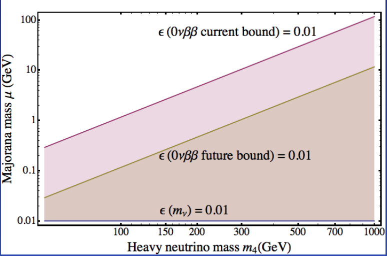

Having the right light neutrinos mass is a stronger bound!

Similarly, cross-sections for $pp \to \ell^+_\alpha \ell^+_\beta X$ are too small for LHC.