Confronting Flavor Symmetries and extended Scalar Sectors with Lepton Flavor Violation Phenomenology

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Interplay between the extended Standard Models

- There are different way to extend the Standard Models
- Extend scalar sectors (additional Higgs doublets, ...)
- Impose Flavor symmetries (to explain the neutrino masses and mixings)
- ...

Interplay between the extended Standard Models

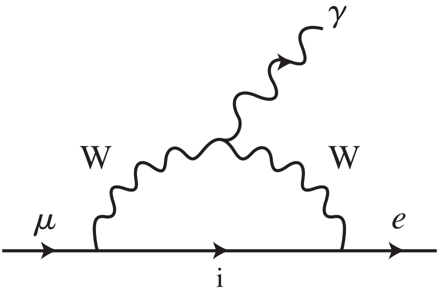

Figure: LFV-diagram in SM (Bo He, T. P. Cheng and Ling-Fong Li ,02)

The Branching ratio is extremely small ($\lesssim 10^{-45}$). However, extension of the SM generically violate Lepton Flavor. $\Rightarrow$ larger Branching ratio is possible

Interplay between the extended Standard Models

- more scalars $\Rightarrow$ Lepton Flavor Violation (LFV) processes (which are quite strongly constrained)
- in general, the 3×3 yukawa coupling matrices hold a lot of freedom in their 18 parameters $\Rightarrow$ the models cannot be easily ruled out by LFV constraint
- impose more structure on the yukawa coupling matrices via flavor symmetries $(SM \times G_f)$ $\Rightarrow$ reduce the free parameters in the yukawa coupling matrices $\Rightarrow$ the LFV constraint becomes stronger and might be possible to rule out some models

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2. fit the model to neutrino data $\Rightarrow$ allow us to extract certain ranges for the model parameters
3. additional scalars compared to the SM $\Rightarrow$ mediate LFV-processes $\Rightarrow$ the branching ratios can be predicted using the fitted parameter values
4. if this prediction does not fit with present (future) LFV-bounds $\Rightarrow$ we are (will be) able to exclude the particular flavor symmetry imposed (in a certain scenario)

Constraining one particular model: The Ma-model

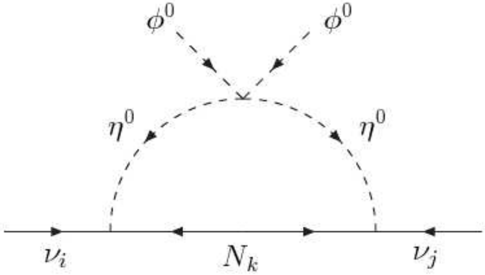
The basic ingredients apart from the SM are:

- 3 heavy right-handed (Majorana) neutrinos N_k, which are singlets under $SU(2)$ and have no hypercharge
- a second Higgs doublet η with SM-like quantum numbers that does not obtain a VEV
- an additional Z_2-parity under which all SM-particles are even, while N_k as well as η are odd

(E. Ma ,06)

Features of the Ma-model

- radiatively generated neutrino masses $\Rightarrow$ naturally small



- stable Dark Matter candidates due to the Z_2-parity
- apart from these points, it is essentially an oridinaly THDM

(E. Ma ,08)

Flavor Symmetry Models we use

- A_4-**model** which predicts the tri-bimaximal mixing ($\theta_{13} = 0, \theta_{23} = \pi/4$, $\tan\theta_{12} = 1/\sqrt{2}$).

- D_4-**model** which predicts the $\mu - \tau$ symmetry ($\theta_{13} = 0, \theta_{23} = \pi/4$), where θ_{12} is determined by parameters in the neutrino mass matrix.

The A_4-model (model 1)

Field	$l_{1,2,3}$	e_1^c	e_2^c	e_3^c	$N_{1,2,3}$	ϕ	η	φ_S	φ_T	χ
A_4	$\underline{\mathbf{3}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}''$	$\underline{\mathbf{1}}'$	$\underline{\mathbf{3}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{3}}$	$\underline{\mathbf{3}}$	$\underline{\mathbf{1}}$
$Z_4^{\rm aux}$	i	i	i	i	-1	1	1	i	-1	i

$$\begin{aligned}
\mathcal{L}_l \;=\;& y_1^e \frac{\phi}{\Lambda}(l_1\varphi_{T1} + l_2\varphi_{T3} + l_3\varphi_{T2})e_1^c + y_2^e\frac{\phi}{\Lambda}(l_3\varphi_{T3} \\
& + l_1\varphi_{T2} + l_2\varphi_{T1})e_2^c + y_3^e\frac{\phi}{\Lambda}(l_2\varphi_{T2} + l_1\varphi_{T3} + l_3\varphi_{T1})e_1^c \\
& + \frac{\eta}{\Lambda}\Big[y_1[(2l_1N_1 - l_2N_3 - l_3N_2)\varphi_{S1} \\
& + (2l_3N_3 - l_1N_2 - l_2N_1)\varphi_{S3} + (2l_2N_2 - l_1N_3 - l_3N_1)\varphi_{S2}] \\
& + y_2(l_1N_1 + l_2N_3 + l_3N_2)\chi\Big] + M(N_1N_1 + N_2N_3 + N_3N_2).
\end{aligned}$$

The A_4-model (model 1)

The right-handed neutrino masses are degenerate, $M_{1,2,3} = M$.
The Yukawa coupling reads

$$h = \begin{pmatrix} -a & -a & 2a+b \\ b-a & 2a & -a \\ 2a & b-a & -a \end{pmatrix}.$$

$\Rightarrow$ three free parameters (a, b, M) to fit all observables:

$$\Delta m^2_{\odot} = (b^4 - (3a+b)^4)\Lambda^2_{1,2,3},\ \Delta m^2_A = -24ab(9a^2+b^2)\Lambda^2_{1,2,3},$$

$$\tan\theta_{12} = \frac{1}{\sqrt{2}},\ \theta_{13} = 0,\ \text{and } \theta_{23} = \frac{\pi}{4}.$$

The D_4-model (model 2)

Field	l_1	$l_{2,3}$	e_1^c	$e_{2,3}^c$	N_1	N_2	N_3	ϕ	η	φ_e	χ_e	φ_ν	$\psi_{1,2}$
D_4	$\mathbf{1_1}$	$\mathbf{2}$	$\mathbf{1_1}$	$\mathbf{2}$	$\mathbf{1_3}$	$\mathbf{1_2}$	$\mathbf{1_4}$	$\mathbf{1_1}$	$\mathbf{1_1}$	$\mathbf{1_3}$	$\mathbf{1_4}$	$\mathbf{1_3}$	$\mathbf{2}$
Z_2^{aux}	1	1	1	1	-1	-1	-1	1	1	1	1	-1	-1

$$
\begin{aligned}
\mathcal{L}_l \;=\;& l_1 e_1^c \frac{\phi}{\Lambda^2}(y_1^e \varphi_e^2 + y_2^e \chi_e^2 + y_3^e \varphi_\nu^2 + 2 y_4^e \psi_1 \psi_2) \\
& + y_5^e (l_2 e_2^c + l_3 e_3^c) \frac{\phi}{\Lambda} \varphi_e + y_6^e (l_2 e_2^c - l_3 e_3^c) \frac{\phi}{\Lambda} \chi_e \\
& + y_1 l_1 N_1 \frac{\eta}{\Lambda} \varphi_\nu + y_2 (l_2 \psi_1 + l_3 \psi_2) N_1 \frac{\eta}{\Lambda} \\
& + y_3 (l_2 \psi_2 - l_3 \psi_1) N_2 \frac{\eta}{\Lambda} + y_4 (l_2 \psi_1 - l_3 \psi_2) N_3 \frac{\eta}{\Lambda} \\
& + \frac{1}{2} M_1 N_1 N_1 + \frac{1}{2} M_2 N_2 N_2 + \frac{1}{2} M_3 N_3 N_3 .
\end{aligned}
$$

The D_4-model (model 2)

The right-handed neutrino masses are M_1, M_2, M_3.
The Yukawa coupling matrix can be written as

$$h = \begin{pmatrix} a & 0 & 0 \\ b & -c & d \\ -b & -c & d \end{pmatrix}.$$

$\Rightarrow$ seven free parameters $(a, b, c, d, M_1, M_2, M_3)$ to fit all neutrino observables:

$$\Delta m_\odot^2 = (a^2 + 2b^2)^2 \Lambda_1^2,\ \ \Delta m_A^2 = 4(c^2\Lambda_2 + d^2\Lambda_3)^2,$$

$$\tan\theta_{12} = \frac{a}{\sqrt{2}b},\ \ \theta_{13} = 0,\ \text{and}\ \theta_{23} = \frac{\pi}{4}.$$

The four benchmark scenarios for the scalar sector

In the form $(m_1, m_2, \lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5)$:

$$\alpha : \quad (100i\mathrm{GeV}, 75\mathrm{GeV}, 0.24, 0.10, 0.10, -0.15, -0.10)$$

$$\beta : \quad (100i\mathrm{GeV}, 98.5\mathrm{GeV}, 0.24, 0.30, 0.09, -0.18, -0.11)$$

$$\gamma : \quad (100i\mathrm{GeV}, 950\mathrm{GeV}, 0.24, 0.50, 0.02, -0.12, -0.10)$$

$$\delta : \quad (100i\mathrm{GeV}, 550\mathrm{GeV}, 0.24, 0.30, 0.02, -0.05, -0.01)$$

These four scenarios are consistent with:

- collider experiments (direct searches @ LEP) $m(h^0) > 112.9$ GeV and $m(H^\pm) > 78.6$ GeV, both at 95% confidence level.
- lightest scalar as the Dark Matter candidate (H^0) from WMAP-data
- ρ parameter
- W- and Z-boson decay widths
- consistency and perturbativity of the scalar sector

The χ^2-fit for Scenario α with Model 1

The minimization of the χ^2-function then yields the following best-fit values for the three parameters:

$$a = 0.0189,\ b = -0.691,\ M = 2.42 \cdot 10^6\ \text{GeV}.$$

For the above parameters, this yields in the form ${}^{+1\sigma,+3\sigma}_{-1\sigma,-3\sigma}$:

$$\begin{aligned} a &: \quad {}^{+0.0003,+0.0009}_{-0.0003,-0.0009}, \\ b &: \quad {}^{+0.003,+0.009}_{-0.003,-0.009}, \\ M &: \quad {}^{+0.02,+0.05}_{-0.02,-0.05} \cdot 10^6\ \text{GeV}. \end{aligned}$$

LFV Diagram in this model

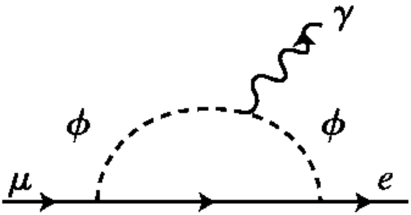


Figure: LFV diagram in Ma-model (Bo He, T. P. Cheng and Ling-Fong Li ,02)

LFV-experiments

Experiment	Status	Process	BR-Limit
MEGA	Past	$\mu \to e\gamma$	$1.2 \cdot 10^{-11}$
MEG	Future	$\mu \to e\gamma$	$1.0 \cdot 10^{-13}$
BELLE	Past	$\tau \to \mu\gamma$	$4.5 \cdot 10^{-8}$
Babar	Past	$\tau \to e\gamma$	$1.1 \cdot 10^{-7}$
MECO	Cancelled	$\mu\mathrm{Al} \to e\mathrm{Al}$	$2.0 \cdot 10^{-17}$
SINDRUM II	Past	$\mu\mathrm{Ti} \to e\mathrm{Ti}$	$6.1 \cdot 10^{-13}$
PRISM/PRIME	Future	$\mu\mathrm{Ti} \to e\mathrm{Ti}$	$5.0 \cdot 10^{-19}$
SINDRUM II	Past	$\mu\mathrm{Au} \to e\mathrm{Au}$	$7.0 \cdot 10^{-13}$
SINDRUM II	Past	$\mu\mathrm{Pb} \to e\mathrm{Pb}$	$4.6 \cdot 10^{-11}$

Our Results

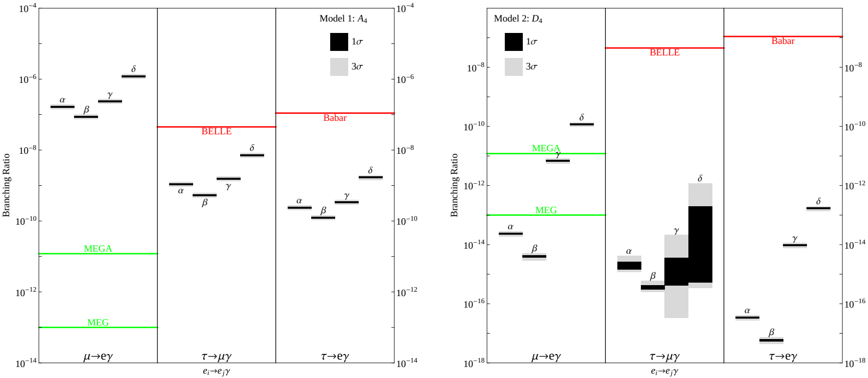


Figure: The numerical results of our analysis for Model 1 and 2

Conclusions

- models with an extended scalar sectors and discrete flavour symmetries can easily get into trouble with LFV-bounds
- we have shown that with the Ma-model (with A_4 and D_4 symmetry)
- models with a lot of structure can easily be excluded
- models with many parameters can at least be strongly constrained, if not excluded as well
- these considerations are not restricted to Ma-like models, but should also be correct in a much wider class of theories