LFV and Leptogenesis in a minimally flavor violating world

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Outline

- LFV, CPV & Leptogenesis: overview
- Leptonic “Minimal Flavor Violation”
  - Charged LFV
  - Leptogenesis

Observable ?
Testable ?
Viable ?
Correlation with CLFV ?
Introduction: LFV, CPV & Leptogenesis
LFV, CPV, BAU: what’s the connection?

See-saw mechanism for $m_\nu$ (Type I)

$$\mathcal{L} \supset \frac{1}{2} (M_R)_{ij} \nu_R^{T_i} C \nu_R^j - \lambda_{ij}^\nu \nu_R^i (H_c^\dagger L_L^j) + \text{h.c.}$$

- Heavy $\nu_R$ ($M_R \gg v_{\text{ew}}$)
- $M_R$ : L violation
- $\lambda_{ij}^\nu$ : CP and L_i violation
LFV, CPV, BAU: what’s the connection?

See-saw mechanism for $m_\nu$

\[ \mathcal{L} \supset \frac{1}{2} (M_R)_{ij} \nu_R^T C \nu_R^j - \lambda_\nu^i \bar{\nu}_R (H_c L_L^j) + \text{h.c.} \]

Heavy $\nu_R$ ($M_R \gg v_{ew}$)

$M_R$: L violation
$\lambda_\nu$: CP and $L_i$ violation

$m_\nu \sim v_{ew}^2 \lambda_\nu^T M_R^{-1} \lambda_\nu$
LFV, CPV, BAU: what’s the connection?

See-saw mechanism for $m_\nu$

$$\mathcal{L} \supset \frac{1}{2} (M_R)_{ij} \nu_R^{T_i} C \nu_R^j - \lambda^i_\nu \bar{\nu}_R (H_u^+ L_L^j) + \text{h.c.}$$

1) $\mathcal{CP}$ and $\mathcal{L}$ out-of-equilibrium decays of $N_i$ ($T \sim M_R$) $\Rightarrow n_L$

$$\Gamma(N_i \rightarrow l_k H^*) \neq \Gamma(N_i \rightarrow \bar{l}_k H)$$

2) $B+L$ violation (sphalerons) $\Rightarrow$

$$\eta_B \equiv \frac{n_B}{n_\gamma} \neq 0$$
LFV, CPV, BAU: what’s the connection?

See-saw mechanism for $m_\nu$

$$\mathcal{L} \supset \frac{1}{2} (M_R)_{ij} \nu_R^T C \nu_R^j - \lambda^i_j \bar{\nu}_R (H^T_L L_L^j) + \text{h.c.}$$

$M_R$: L violation

$\lambda_\nu$: CP and L violation

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If CP & L_i violation is communicated to particles with mass $\Lambda \sim \text{TeV}$

Observable LFV

Observable lepton EDMs
- Key issue: can we identify signatures for the see-saw scenario?

- Quite hard in general. In this talk, I discuss correlations emerging in the context of a specific scenario, MFV.
Minimal Flavor Violation
MFV hypothesis in the lepton sector

- MFV hypothesis: all flavor-breaking structures are aligned with fermion mass matrices

- Introduced in the quark sector to “explain” absence of large non-standard FCNC from TeV scale physics. (Georgi-Chivukula ‘87)

- Can be formulated in the EFT language, insensitive to UV details of the underlying model (D’ambrosio-Isidori-Giudice-Strumia ‘02)

- Its extension to leptons defines a constrained class of models. Tool to investigate nature / structure of flavor breaking sources (VC-Grinstein-Isidori-Wise ‘05)
MFV hypothesis in the lepton sector

- MFV hypothesis: **all flavor-breaking structures are aligned with fermion mass matrices**

- $m_\nu$ and $m_e (\lambda_e)$ select two eigen-bases in $L_L$ space (related by $U_{PMNS}$)

- MFV($\ell$): BSM flavor structures are “aligned” with $m_\nu$ or $m_e$ in $L_L$ space
  - do not select new eigen-bases
  - FCNC are controlled by lepton masses and $U_{PMNS}$

$$U_{PMNS} \quad \longrightarrow \quad \lambda_e^\dagger \lambda_e \quad \longrightarrow \quad \hat{m}_\nu \, m_\nu$$

$$L_L^i = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}^i$$

i=1,2,3
MFV in models with heavy $\nu_R$

- Spurions in $L_L$ space:

\[
\begin{array}{ccc}
\lambda_e^\dagger \lambda_e & m_\nu^\dagger m_\nu & \lambda_\nu^\dagger \lambda_\nu
\end{array}
\]
MFV in models with heavy $\nu_R$

- Spurions in $L_L$ space:

$$ m_\nu = v^2 \lambda^T \nu \hat{M}_R^{-1} \lambda_\nu $$

$$ \lambda^\dagger \nu \lambda_e \quad m_\nu^\dagger m_\nu \quad \lambda^\dagger \nu \lambda_\nu $$

$$ \nu = \frac{1}{v} \hat{M}_R^{1/2} R \hat{m}_\nu^{1/2} U^\dagger $$

Casas-Ibarra '01

Complex orthogonal matrix
MFV in models with heavy $\nu_R$

- Spurions in $L_L$ space:

\[ m_\nu = v^2 \lambda_\nu^T \hat{M}_R^{-1} \lambda_\nu \]

\[ \lambda_\nu = \frac{1}{v} \hat{M}_R^{1/2} R \hat{m}_\nu^{1/2} U^\dagger \]

- Strict MFV definition (alignment of $m_\nu^\dagger m_\nu$ and $\lambda_\nu^\dagger \lambda_\nu$) ⇒

\[ \hat{M}_R = M_\nu \cdot I \]

\[ R = I \]

- Flavor broken only by Yukawas: $\lambda_e$ and $\lambda_\nu$ [with constrained CP structure].
In this minimal framework (R=I), we investigate the following issues:

- What is the overall normalization of CLFV rates? Does MFV(\ell) alleviate the lepton FCNC problem?

- What pattern of LFV decays is predicted? Can we test it?

- Is thermal leptogenesis viable in such a constrained framework?

- Does successful leptogenesis constrain rate & pattern of LFV decays?

LFV decays: \mu \rightarrow e\gamma, \tau \rightarrow \mu\gamma, \tau \rightarrow e\gamma
Phenomenology of $\ell_i \rightarrow \ell_j \gamma$

- Effective coupling governing $\ell_i \rightarrow \ell_j$ transitions

$$H_{\text{eff}} = \frac{C_W}{\Lambda^2} H^\dagger \tilde{e}_R^i \sigma^{\mu\nu} (??)^{ij} L_L^j F_{\mu\nu}$$

~ TeV
Phenomenology of $\ell_i \rightarrow \ell_j \gamma$

- Effective coupling governing $\ell_i \rightarrow \ell_j$ transitions

$$H_{\text{eff}} = \frac{C_W}{\Lambda^2} \left( \bar{e}_R^i H^\dagger \right) \sigma^{\mu\nu} \left( \begin{array}{c} \phi \\ \phi \end{array} \right)^{ij} L_L^j F_{\mu\nu}$$

$\sim$ TeV

Diagram:
- $\ell \rightarrow \ell' \gamma$
- $\chi^\pm (\chi^0)$
- $\mu$ 
- $\bar{\nu}$ (or $\bar{\beta}$) 
- $e$
Phenomenology of $\ell_i \rightarrow \ell_j \gamma$

- Effective coupling governing $\ell_i \rightarrow \ell_j$ transitions $\propto \lambda_i^\dagger \lambda_j = \frac{M_\nu}{v^2} U \hat{m}_\nu U^\dagger$

$$H_{\text{eff}} = \frac{C_W}{\Lambda^2} H^\dagger \bar{e}_R^i \sigma^{\mu\nu} (\lambda_e \lambda_\nu^\dagger \lambda_\nu)^{ij} L_L^j F_{\mu\nu}$$

$\sim \text{TeV}$
Phenomenology of $\ell_i \rightarrow \ell_j \gamma$

$$B_{\ell_i \rightarrow \ell_j \gamma} = \frac{v^2 M_{\nu}^2}{\Lambda^4} \times |b_{ij}(U_{PMNS}; m_{\text{min}}; \Delta m_{\nu}^2)|^2 \times |c_{RL}^{(1-2)}|^2 I_{PS}$$

(i) Overall normalization controlled by $\frac{v^2 M_{\nu}^2}{\Lambda^4}$. Signals within reach of future searches (MEG, Mu2e, …) if:

$$M_\nu \sim 10^{9-10} \text{ GeV} \times (\Lambda/1 \text{ TeV})^2$$
Phenomenology of $\ell_i \rightarrow \ell_j \gamma$

$$B_{\ell_i \rightarrow \ell_j \gamma} = \frac{v^2 M^2_\nu}{\Lambda^4} \times |b_{ij}(U_{\text{PMNS}}; m_{\text{min}}; \Delta m^2_\nu)|^2 \times |c^{(1-2)}_{RL}|^2 I_{PS}$$

(i) Overall normalization controlled by $\frac{v^2 M^2_\nu}{\Lambda^4}$. Signals within reach of future searches (MEG, Mu2e, ...) if:

$$M_\nu \sim 10^{9-10} \text{GeV} \times (\Lambda/1 \text{ TeV})^2$$

(ii) Signatures: MLFV predicts ratios of $B(\ell_a \rightarrow \ell_b \gamma)$ in terms of $U_{\text{PMNS}}$ and mass splittings with pattern:

$$B(\tau \rightarrow \mu \gamma) >> B(\tau \rightarrow e \gamma) \sim B(\mu \rightarrow e \gamma)$$

(with $\mu \rightarrow e/\tau \rightarrow \mu$ suppression increasing as $s_{13} \rightarrow 0$)
Pattern entirely determined by:

- $\Delta m^2_{\text{atm}} \gg \Delta m^2_{\text{sol}}$
- $\theta_{\text{atm}}, \theta_{\text{sol}} \gg \theta_{13}$

$$b_{ij} = (U^\nu \frac{m}{\nu} U^+)_{ij}$$
This framework can be tested!

- If $s_{13} \geq 0.08$, limits on $B(\mu \rightarrow e\gamma)$ preclude observing $\tau \rightarrow \mu \gamma$ at B factories.
- If $\tau \rightarrow \mu \gamma$ is observed at B factories then $s_{13} < 0.08$.
How does leptogenesis work?

Leptogenesis accounts for

$$\eta_B = \frac{n_B - n_B}{n_\gamma} = (6.3 \pm 0.3) \times 10^{-10}$$

through:

- Out of equilibrium decays of $N_i$ in presence of CPV $\Rightarrow n_L \neq 0$
- EW sphalerons (B+L violation) convert $n_L \leftrightarrow n_B$

Dominant if $\Delta M_{ij} \sim \Gamma_j$ ("resonant leptogenesis")
How does leptogenesis work?

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$$\eta_B = \frac{n_B - n_B}{n_\gamma} = (6.3 \pm 0.3) \times 10^{-10}$$

through:

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How does leptogenesis work?

Leptogenesis accounts for $\eta_B = \frac{n_B - n_B}{n_\gamma} = (6.3 \pm 0.3) \times 10^{-10}$ through:

- Out of equilibrium decays of $N_i$ in presence of CPV $\Rightarrow n_L \neq 0$
- EW sphalerons (B+L violation) convert $n_L \leftrightarrow n_B$

\[ \frac{dn_{N_i}}{dz} = -D_i \left(n_{N_i} - n_{N_i}^{eq}\right), \]

\[ \frac{dn_{L\alpha}}{dz} = -\sum_i \epsilon_{i\alpha} D_i \left(n_{N_i} - n_{N_i}^{eq}\right) - W_\alpha n_{L\alpha} \]

\[ \epsilon_{i\alpha} \equiv \frac{\Gamma(N_i \rightarrow \ell_\alpha \bar{H}) - \Gamma(N_i \rightarrow \bar{\ell}_\alpha H)}{\Gamma(N_i \rightarrow \ell_\alpha \bar{H}) + \Gamma(N_i \rightarrow \bar{\ell}_\alpha H)} \]
Relevance of “Flavor Effects”

Abada, Davidson, Josse-Michaoux, Losada, Riotto ’06

Nardi, Nir, Roulet, Racker ’06

For $T < T_{fl}$, interactions mediated by Yukawa couplings come in equilibrium $\Rightarrow$ project lepton asymmetry onto individual flavors

$N_1 \rightarrow \ell_1 H^*$

$\Gamma_\alpha \sim 10^{-3} \lambda_\alpha^2 T$

$T_\tau \sim 10^{12}$ GeV

$T_\mu \sim 10^9$ GeV

$\ell_{\tau,\mu,e}$
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- For $T < T_{fl}$, interactions mediated by Yukawa couplings come in equilibrium $\Rightarrow$ project lepton asymmetry onto individual flavors

$$N_1 \rightarrow \ell_1 H^* \quad T_\tau \sim 10^{12} \text{ GeV}$$

$$\ell_{\tau,\mu,e} \quad T_\mu \sim 10^9 \text{ GeV}$$

- Key consequences:
  - Washout via inverse decays is typically less effective
  - CP asymmetries $\varepsilon_{i\alpha}$ are sensitive to CPV phases of $U_{PMNS}$

$$\varepsilon_{i\alpha} = \sum_{j \neq i} \frac{1}{8\pi} \text{Im} \left[ (\lambda_{\nu})_{i\alpha}(\lambda_{\nu})^{\dagger}_{\alpha j}(\lambda_{\nu} \lambda_{\nu}^\dagger)_{ij} \right] (g^{(j,i)}(j,i) + g^{(j,i)}(j,i))$$

Functions of $\nu_R$ masses
MFV leptogenesis

- Can happen only in the “flavored-regime”: $M_\nu < 10^{12}$ GeV
Can happen only in the “flavored-regime”: $M_\nu < 10^{12} \text{GeV}$

MFV highly constraints the structure of the $\nu_R$ mass matrix …

$$M_R = M_\nu \left[ 1 + c_1^{(1)} (h_\nu + h_\nu^T) + c_1^{(2)} ((h_\nu)^2 + (h_\nu^T)^2) \
+ c_2^{(2)} h_\nu h_\nu^T + c_3^{(2)} h_\nu^T h_\nu + c_4^{(2)} (h_e + h_e^T) + \ldots \right]$$

$$h_\nu = \lambda_\nu \lambda_\nu^\dagger \hspace{1cm} h_e = \lambda_\nu \lambda_e^\dagger \lambda_e \lambda_\nu^\dagger$$

Structures are fixed by MFV hypothesis (generated by radiative corrections)

Coefficients depend on underlying model. Typically one expects $c_1^{(1)} \sim \log(\Lambda_{\text{GUT}}/M_R)$
MFV leptogenesis

- Can happen only in the “flavored-regime”: $M_\nu < 10^{12}$ GeV

- MFV highly constrains the structure of the $\nu_R$ mass matrix …

\[
M_R = M_\nu \left[ 1 + c^{(1)} (h_\nu + h_\nu^T) + c^{(2)}_1 ((h_\nu)^2 + (h_\nu^T)^2) \\
+ c^{(2)}_2 h_\nu h_\nu^T + c^{(2)}_3 h_\nu^T h_\nu + c^{(2)}_4 (h_e + h_e^T) + \ldots \right]
\]

\[
h_\nu = \lambda_\nu \lambda_\nu^\dagger \quad \quad \quad h_e = \lambda_\nu \lambda_e^\dagger \lambda_e \lambda_\nu^\dagger
\]

Structures are fixed by MFV hypothesis (generated by radiative corrections)

Coefficients depend on underlying model. Typically one expects $c^{(1)} \sim \log(\Lambda_{\text{GUT}}/M_R)$

- … and hence the CP asymmetries:

\[
\epsilon_{i\alpha} \leftrightarrow \text{Im} \left[ (\lambda_\nu)_{i\alpha} (\lambda_\nu^\dagger)_{\alpha j} (\lambda_\nu \lambda_\nu^\dagger)_{ij} \right]
\]

Yukawa couplings in basis in which $M_\nu$ is diagonal
Analytic dependence of CP asymmetries on underlying parameters is understood with EFT + symmetry considerations. But coefficients $c^{(1)}$ and $c^{(2)}$ are determined by UV details.

Numerical analysis with RGE equations

Boundary conditions: $M_R = M_\nu \times I$ and $R = I$ @ $\Lambda_{GUT}$

Parameter space scan:

- $M_\nu \in [10^5, 10^9]$ GeV
- $m_{\nu_{\text{min}}} \in [0, 0.2]$ eV, NH & IH
- $\sin(\theta_{13}) \in [0, 0.2]$
- PMNS phases: $\delta \in [0, 2\pi]$; $\alpha_M, \beta_M \in [0, \pi]$

Results are valid for $\tan(\beta) \sim O(1)$, but keep in mind that $\eta_B \propto [\tan(\beta)]^2$
- Leptogenesis is viable in this setup!! (for NH of light $\nu$ spectrum)
- “Flat” dependence on $M_\nu$

$\eta_B$

$\log_{10} M_\nu$
Highlights of numerical analysis (Uhlig ‘07)

- Leptogenesis not viable for IH of light $\nu$ spectrum
  (due to stronger washout)
Highlights of numerical analysis (Uhlig ‘07)

- CPV with a single PMNS phase?

Dirac phase: no!

Majorana phase: yes!

(understood in terms of $\theta_{13}$ suppression)
Impact on CLFV rates? [through handle on the scale $M_\nu$]

- Successful MFV-Leptogenesis requires in principle $M_\nu < 10^{12}$ GeV (need to be at least in the 2-flavor regime)

- Numerical analysis was performed in the 3-flavor regime $M_\nu < 10^9$ GeV

$$B(\mu \rightarrow e\gamma) \sim 10^{-14} \times \left( \frac{M_\nu}{10^9 \text{GeV}} \right)^2 \left( \frac{1 \text{TeV}}{\Lambda} \right)^4$$

Leptogenesis constraint implies signal within reach of MEG ($\mu \rightarrow e\gamma@10^{-13}$ level) for $\Lambda \leq \text{TeV}$
Conclusions

- The notion of MFV can be introduced in models with heavy $\nu_R$ : $M_R$ is flavor blind and CPV occurs only through $U_{PMNS}$

- CLFV Phenomenology:
  - normalization of rates depends on $(vM_\nu)^2/\Lambda^4$
  - pattern of predictions for ratios of LFV transitions $\mu \rightarrow e/\tau \rightarrow \mu$, … is governed by measured leptonic mass matrices and mixing angles

- Leptogenesis is viable in this scenario (“radiative resonant leptogenesis”)
  - Only in the flavored regime $M_\nu < 10^{12}$ GeV
  - This implies $\mu \rightarrow e \gamma$ rate within reach of MEG if $\Lambda \leq$ TeV
Additional Material
MFV Effective Theory

- Flavor symmetry of $L_{\text{Gauge}} [G_F = \text{SU}(3)^5]$ broken only by $\lambda$'s

Group Theory + Effective Field Theory $\Rightarrow$ investigate consequences of MFV hypothesis in great generality
Washout factors

\[ K_{i\alpha} \equiv \frac{\Gamma(N_i \to \ell_\alpha \bar{H})}{H(T = M_i)} \]

\[ K_\alpha = \sum_i K_{i\alpha} \]

\[ K_e = \left( m_1 c_{12}^2 + m_2 s_{12}^2 + m_3 s_{13}^2 \right) / m_* \]

\[ K_\mu = \left( m_1 c_{23}^2 s_{12}^2 + m_2 c_{12}^2 c_{23}^2 + m_3 s_{23}^2 \right) / m_* \]

\[ K_\tau = \left( m_1 s_{12}^2 s_{23}^2 + m_2 c_{12}^2 s_{23}^2 + m_3 c_{23}^2 \right) / m_* \]

\[ m_* \approx 10^{-3} \text{ eV} \]
Memory Effects

De Simone - Riotto ‘07

- Quantum Boltzmann eqs: “collision” term depends on history of the system

\[
\frac{\partial n_{\ell_i}(X)}{\partial t} = - \int d^3 z \int_0^t dt z \text{Tr} \left[ \Sigma_{\ell_i}(X, z) G_{\ell_i}^<(z, X) - G_{\ell_i}^>(X, z) \Sigma_{\ell_i}(z, X) \right. \\
+ G_{\ell_i}^<(X, z) \Sigma_{\ell_i}^<(z, X) - \Sigma_{\ell_i}^<(X, z) G_{\ell_i}^>(z, X) \bigg].
\]

- Key consequence:
  - CP asymmetries depend on \( z = M_1/T \) (time variable)

\[
\epsilon_1(z) = \epsilon_1^{(0)} \left[ 2 \sin^2 \left( \frac{(M_2 - M_1)z^2}{4H(M_1)} \right) - \frac{\Gamma_2}{M_2 - M_1} \sin \left( \frac{(M_2 - M_1)z^2}{2H(M_1)} \right) \right]
\]

- Effect is important if \( 1/\Delta M_{12} > 1/\Gamma_N \sim 1/H \) (T=M_1)
Impact of memory effects

VC-DeSimone-Isidori-Masina-Riotto

“Memory” effects are controlled by condition

\[ \Delta M_{ji} < \Gamma_i \]

\[ 16\pi c^{(1)} \frac{\Delta m_{ji}}{m_i} < 1 \]

\[ \log_{10} \eta_B \]

\[ \log_{10} (c^{(1)}) \]

Scan over MFV parameter space

Log_{10} (c^{(1)})