LFV decays in MSSM with Non-Holomorphic Soft Terms

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1. MSSM with NonHolomorphic soft breaking terms (NHSSM)
2. LFV and Analyzing Charge Breaking Minima in NHSSM
3. Results
4. Conclusion & Outlook

Different parts of SUSY Lagrangian

Supersymmetry : dominant paradigm in BSM physics and for good reason!

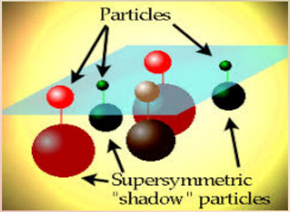
SUSY links two different class of particles namely fermions and bosons $\Leftrightarrow$ solves several problems with the Standard Model in its minimal / non-minimal versions.

The Lagrangian density :

$$\boxed{\mathcal{L}_{MSSM} = \mathcal{L}_{SUSY} + \mathcal{L}_{SOFT}}$$

$$\boxed{\mathcal{L}_{SUSY} = \mathcal{L}_{gauge} + \mathcal{L}_{matter} + \mathcal{L}_{Higgs-Yukawa}}$$

Superpotential : $W_{MSSM} =$
$\mathbf{y_u} Q \cdot H_u \bar{U} - \mathbf{y_d} Q \cdot H_d \bar{D} - \mathbf{y_e} L \cdot H_d \bar{E} + \mu H_u \cdot H_d$



$$\begin{aligned}
-\mathcal{L}^{MSSM}_{soft} = & \frac{1}{2}(M_3 \tilde{g}\tilde{g} + M_2 \tilde{W}\tilde{W} + M_1 \tilde{B}\tilde{B} + c.c) \\
& + (\tilde{q}_{iL} \cdot h_u \mathbf{A_u}_{ij} \tilde{u}^*_{jR} + \tilde{q}_{iL} \cdot h_d \mathbf{A_d}_{ij} \tilde{d}^*_{jR} + \tilde{\ell}_{iL} \cdot h_d \mathbf{A_e}_{ij} \tilde{e}^*_{jR} + h.c.) \\
& + \tilde{q}^\dagger_{iL} \mathbf{m^2_q}_{ij} \tilde{q}_{jL} + \tilde{\ell}^\dagger_{iL} \mathbf{m^2_L}_{ij} \tilde{\ell}_{jL} + \tilde{u}_{iR} \mathbf{m^2_u}_{ij} \tilde{u}^\dagger_{jR} + \tilde{d}_{iR} \mathbf{m^2_d}_{ij} \tilde{d}^\dagger_{jR} \\
& + \tilde{e}_{iR} \mathbf{m^2_e}_{ij} \tilde{e}^\dagger_{jR} + m^2_{h_u} h^*_u h_u + m^2_{h_d} h^*_d h_d + (B_\mu h_u . h_d + c.c)
\end{aligned}$$

$\mathcal{L}^{MSSM}_{soft}$ is usually claimed to include **all possible** "soft supersymmetry breaking" terms.

Are there any more possible soft terms? [Ref : S. Martin, Phys. Rev D, 2000]

Nature	Term	order of magnitude	origin
"may be" soft	$\phi^2\phi^*$	$\frac{\lvert F\rvert^2}{M^3} \sim \frac{m_w^2}{M}$	$\frac{1}{M^3}[XX^*\Phi^2\Phi^*]_D$

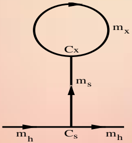
Non Holomorphic Trilinear Interactions :

$$-\mathcal{L}'^{\phi^2\phi^*}_{soft} \supset \tilde{q}\cdot h_d^*\mathbf{A'_u}\tilde{u}^* + \tilde{q}\cdot h_u^*\mathbf{A'_d}\tilde{d}^* + \tilde{\ell}\cdot h_u^*\mathbf{A'_e}\tilde{e}^* + h.c$$

Not considered generally due to high scale suppressions ($1/M$ factor) mainly in gravity mediated scenario,

Reappearance of divergences:

In presence of a gauge singlet, these terms may lead to large radiative corrections. $\sim \frac{m_X^2}{m_s^2} ln(\frac{m_X^2}{m_s^2})$
m_s : mass of the singlet field, m_X : mass of some heavy field.



However if $m_s \sim m_X$, then there is no problem. [Hetherington, 2001]
MSSM contains no singlet under the entire gauge group, so we can always include NH terms with the usual soft terms.

Structure of the Slepton Mass Matrices

The general form of 6×6 sleptom mass squared matrix is written in electroweak basis $\Longrightarrow$ $(\tilde{e}_L, \tilde{\mu}_L, \tilde{\tau}_L, \tilde{e}_R, \tilde{\mu}_R, \tilde{\tau}_R)$

$$M^2_{\tilde{\ell}} = \begin{pmatrix} M^2_{\tilde{\ell}LL} & M^2_{\tilde{\ell}LR} \\ M^2_{\tilde{\ell}RL} & M^2_{\tilde{\ell}RR} \end{pmatrix}$$

Each block is a 3×3 matrix where we defined,

$$\begin{aligned} M^2_{\tilde{\ell}LL_{ij}} &= M^2_{\tilde{L}_{ij}} + (M^2_Z(-\tfrac{1}{2} + \sin^2\theta_W)\cos 2\beta + m^2_{\ell_i})\delta_{ij} \\ M^2_{\tilde{\ell}RR_{ij}} &= M^2_{\tilde{e}_{ij}} + (-M^2_Z \sin^2\theta_W \cos 2\beta + m^2_{\ell_i})\delta_{ij}. \end{aligned}$$

The main difference between generic MSSM and MSSM with non-holomorphic soft terms $\Longrightarrow$

$$A^{\tilde{\ell}}_{ij} = \begin{pmatrix} A_e - (\mu + A'_e)\tan\beta & A_{e\mu} - A'_{e\mu}\tan\beta & A_{e\tau} - A'_{e\tau}\tan\beta \\ A_{\mu e} - A'_{\mu e}\tan\beta & A_\mu - (\mu + A'_\mu)\tan\beta & A_{\mu\tau} - A'_{\mu\tau}\tan\beta \\ A_{\tau e} - A'_{\tau e}\tan\beta & A_{\tau\mu} - A'_{\tau\mu}\tan\beta & A_\tau - (\mu + A'_\tau)\tan\beta \end{pmatrix}$$

$$\text{with } M^2_{\tilde{\ell}RL} = (M^2_{\tilde{\ell}LR})^\dagger$$

Our analysis however would only explore the effects of non-diagonal holomorphic or non-holomorphic trilinear couplings that induce mixing in the slepton mass squared matrices ($M^2_{\tilde{\ell}LR} = \sqsubseteq_l A_{ij}$) and in the couplings.

Flavors & Lepton Flavor Violation

Three copies of the leptonic SU(2) doublet.

$$\begin{bmatrix} \nu_e \\ e^- \end{bmatrix} \begin{bmatrix} \nu_\mu \\ \mu- \end{bmatrix} \begin{bmatrix} \nu_\tau \\ \tau^- \end{bmatrix}$$

Gauge and Yukawa interactions

Is lepton flavor a conserved quantity?

We already know the answer : NO !

$\Rightarrow$ from neutrino flavor oscillations.

- However charge Lepton Flavor Violation (cLFV) has never been observed. $\mu^- \to e^-\gamma$, $\tau^- \to \mu^-\mu^+\mu^-$, $h \to \mu^-\tau^+$, $\pi^0 \to e^-\mu^+$, $K_L^0 \to \pi^0 e^-\mu^+$ have never been shown up in any experiments.
- The observation of cLFV would be a clear signal of (non-trivial) physics beyond the Standard Model.
- Within the SM (+ Dirac neutrino mass model), since neutrino masses are the only source of LFV, all cLFV amplitudes are strongly suppressed.
- In fact, many BSM models predict large cLFV rates.
- Flavor violating Higgs decays are a very interesting channels, being probed at the LHC.

To Avoid any Charge Breaking Minima

- Absence of any FCNC significantly constrains the off-diagonal elements in the mass and trilinear coupling matrices.
- However, the Charge and Color Breaking(CCB) constraints are more robust than the corresponding FCNC data.
- The third generation of sfermions are the most important candidate in connection with the CCB minima in MSSM.
- With NH terms there can be significant changes in all of the Yukawa couplings through loops.

The total tree level scalar potential involving Higgs, selectron, smuon and stau fields, assuming μ to be real and y_{ij}'s or A_{ij}'s are real symmetric matrix, reduces to,

$$V_{\tilde{l},H} = A\phi^2 + B\phi^3 + C\phi^4$$

where,

Holomorphic

$$A = \frac{1}{2}\sum_{e,\mu,\tau}(M^2_{\tilde{L}_{ii}} + M^2_{\tilde{e}_{ii}}) + \sum_{i\neq j}(M^2_{\tilde{L}_{ij}} + M^2_{\tilde{e}_{ij}}) + m^2_{H_d} + |\mu|^2 ,$$

$$B = \sum_{e,\mu,\tau} A_i + 2\sum_{i\neq j} A_{ij},$$

$$C = \frac{5}{4}\Big(\sum_{e,\mu,\tau} y_i^2 + \frac{2}{5}\sum_{i\neq j} y_{ij}^2\Big) .$$

Non-Holomorphic

$$A = \frac{1}{2}\sum_{e,\mu,\tau}(M^2_{\tilde{L}_{ii}} + M^2_{\tilde{e}_{ii}}) + \sum_{i\neq j}(M^2_{\tilde{L}_{ij}} + M^2_{\tilde{e}_{ij}}) + m^2_{H_u} + m^2_{H_d} + 2|\mu|^2 - 2B\mu$$

$$B = \sum_{e,\mu,\tau} A_i - (A'_i + \mu y_i) + 2\sum_{i\neq j}\{A_{ij} - (A'_{ij} + \mu y_{ij})\},$$

$$C = \frac{g_1^2 + g_2^2}{8} + \frac{5}{4}\Big(\sum_{e,\mu,\tau} y_i^2 + \frac{2}{5}\sum_{i\neq j} y_{ij}^2\Big) .$$

To Avoid any Charge Breaking Minima :

Considering all the three generations of slepton :

Avoiding the Charge Breaking Minima → Condition for Holomorphic Trilinear terms

$$\Big(\sum_{e,\mu,\tau} A_i + 2\sum_{i\neq j} A_{ij}\Big)^2 < 5\Big(\sum_{e,\mu,\tau} y_i^2 + \frac{2}{5}\sum_{i\neq j} {y_{ij}}^2\Big) \times \Big[\frac{1}{2}\sum_{e,\mu,\tau}(M^2_{\tilde{L}_{ii}} + M^2_{\tilde{e}_{ii}}) + \sum_{i\neq j}(M^2_{\tilde{L}_{ij}} + M^2_{\tilde{e}_{ij}}) + m^2_{H_d} + |\mu|^2\Big]$$

With NH terms in V_{soft}, the condition is :

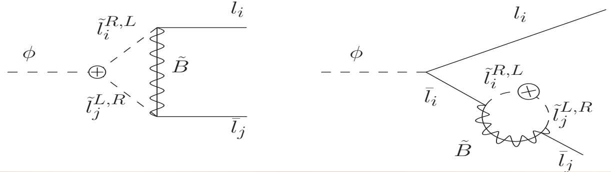
$$\Big(\sum_{e,\mu,\tau}\{A_i - (A'_i + \mu y_i)\} + 2\sum_{i\neq j}\{A_{ij} - (A'_{ij} + \mu y_{ij})\}\Big)^2 < \Big(\frac{g_1^2 + g_2^2}{2} + 5\sum_{e,\mu,\tau} y_i^2 + 2\sum_{i\neq j} {y_{ij}}^2\Big) \times \Big[\frac{1}{2}\sum_{e,\mu,\tau}(M^2_{\tilde{L}_{ii}} + M^2_{\tilde{e}_{ii}}) + \sum_{i\neq j}(M^2_{\tilde{L}_{ij}} + M^2_{\tilde{e}_{ij}}) + m^2_{H_u} + m^2_{H_d} + 2|\mu|^2 - 2B\mu\Big]$$

- No off-diagonal entries in the slepton bilinear mass term, i.e. $M^2_{\tilde{L}_{ij}} = M^2_{\tilde{e}_{ij}} = 0$.
- Only source of flavor violation → A_{ij} & A'_{ij}.

Flavor changing Higgs decays : $\phi(h, H, A) \to \ell_i \bar{\ell}_j$

The Higgs mediated penguin diagrams, induced by $\phi - \tilde{\ell}_i - \bar{\tilde{\ell}}_j$ vertex, may effectively contribute in $\phi - \ell_i - \bar{\ell}_j$ vertices through loops leading to Higgs flavor violating decays. Effective Lagrangian representing the interaction between neutral Higgs boson and charged leptons is given by,

$$-\mathcal{L}_{eff} = \bar{e}^i_R y_{e_{ii}} \left[\delta_{ij} H^0_d + (\epsilon_1 \delta_{ij}(A_{ij} H^0_d - (\mu + A'_{ij}) H^{0*}_u)) + \epsilon_{2ij}(A_{ij} H^0_d - A'_{ij} H^{0*}_u)\right] \ell^j_L + h.c.$$



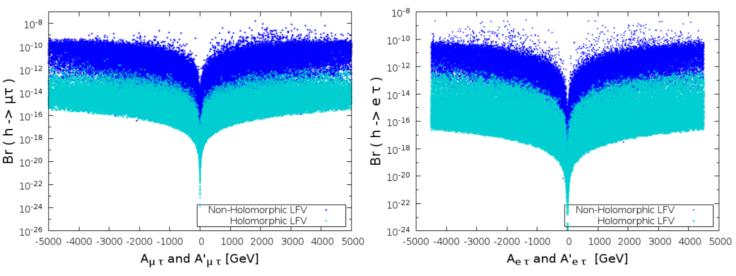
The first term $\to$ the usual Yukawa interaction.
The $\epsilon_1 \to$ the corrections to the charged lepton Yukawa couplings from flavor conserving loops.
The last term $\to$ source of flavor violation through the insertion of $(A_{ij} - A'_{ij} \tan\beta)$ in slepton arms inside the loops. ϵ_2 describes different loop functions involving neutralino and slepton masses owing to various cLFV processes.

Flavor changing Higgs decays : $\phi(h,H,A) \to \ell_i \bar{\ell}_j$

$$-\mathcal{L}^{\text{eff}}_{i\neq j} = (2G_F^2)^{1/4} \frac{m_{E_i}\kappa^E_{ij}}{\cos^2\beta} \left(\bar{e}^i_R\, \ell^j_L\right) [\cos(\alpha-\beta)h + \sin(\alpha-\beta)H - iA] + \text{h.c.}$$

$$\kappa^E_{ij} = \frac{\epsilon_2(A_{ij} - A'_{ij}\tan\beta)}{[1 + (\epsilon_1(A_{ii} - (\mu + A'_{ii})\tan\beta)) + \epsilon_2(A_{ii} - A'_{ii}\tan\beta))]}$$

$\Rightarrow$ The non-holomorphic trilinear couplings via $\tan\beta$ enhancement may have greater importance towards Higgs mediated processes.



The variation of $Br(h \to \mu\tau)$ with $A_{\mu\tau}$ and $A'_{\mu\tau}$ and $Br(h \to e\tau)$ with $A_{e\tau}$ and $A'_{e\tau}$. Some of the parameters are : $M_1 = [100, 1000]$, $M_2 = 1500$, $M_3 = 2800$, $\mu = 800$, $m_A = 1500$ (all in GeV) and $\tan\beta = 40$.

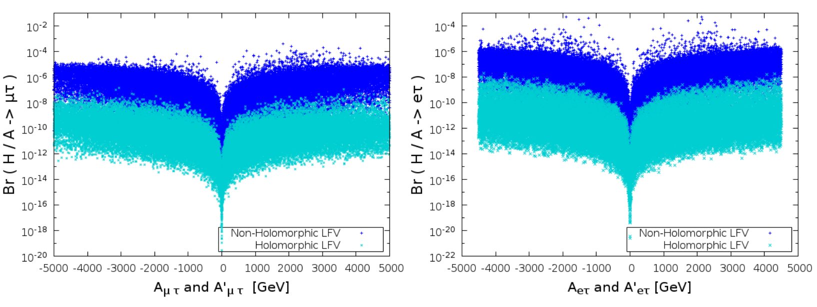
Case of Heavier Higgs - CP even and CP odd

$$\mathrm{Br}(\phi_k \to \mu\tau) = \tan^2\beta\ (|\kappa^E_{\tau\mu}|^2)\ C_\Phi\ \mathrm{Br}(\phi_k \to \tau\tau)\,,$$

The coefficients C_Φ are given by:

$$C_{h/H} = \left[\frac{\cos/\sin(\beta-\alpha)}{\sin/\cos\alpha}\right]^2,\quad C_A = 1.$$

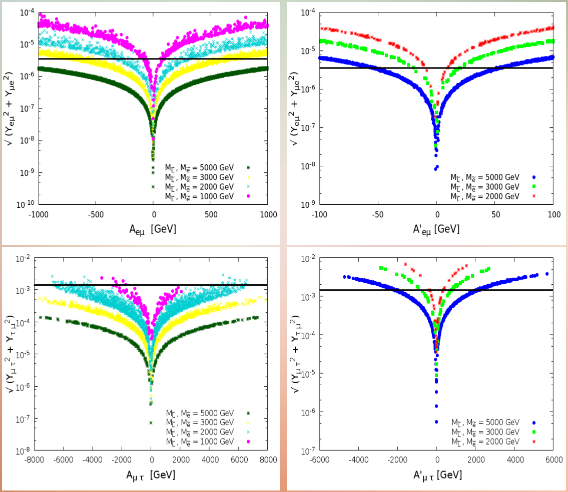
Unlike the case of LFV h-decay, the LFV branching ratios of H/A as shown here may scale as high as 10^{-4}. This may be of significance in relation to a future high energy collider.



$Br(H/A \to e/\mu\tau)$ **as a function of** $A^{(\prime)}_{\mu\tau}$ **and** $A^{(\prime)}_{e\tau}$ **are shown with** $m_H, m_A = 1.5$ **TeV.**

Direct constraints on Y_{ij} from LFV Higgs decay limits of LHC

Multi-parameter scattered plots are quite limited in emphasizing the degree of importance of the Yukawa coupling bounds. Hence, $M_1 = 400$ GeV and ($M_{\tilde{L}}$ & $M_{\tilde{e}}$) to have the specific values 1, 2, 3 and 5 TeV for MSSM and 2, 3 and 5 TeV for NHSSM.



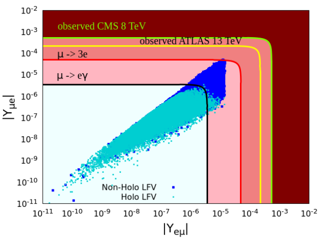
$\sqrt{Y_{e\mu}^2 + Y_{\mu e}^2}$
$< 3.6 \times 10^{-6}$,
(from $\mu \to e\gamma$ limit.)

$\sqrt{Y_{e\tau}^2 + Y_{\tau e}^2}$
$< 2.26 \times 10^{-3}$,
(from $H \to e\tau$ LHC 13 TeV results)

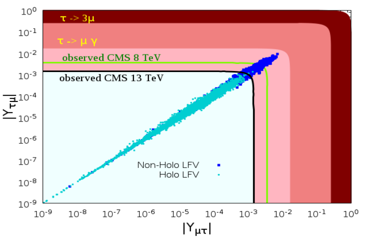
$\sqrt{Y_{\mu\tau}^2 + Y_{\tau\mu}^2}$
$< 1.5 \times 10^{-3}$,
(from $H \to \mu\tau$ LHC 13 TeV results)

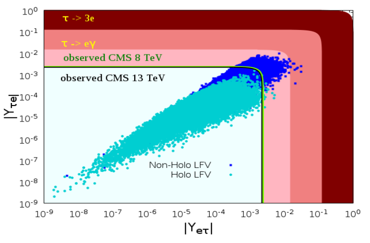
$\sqrt{Y_{ij}^2 + Y_{ji}^2}$ vs. A_{ij} (left panel) and A'_{ij} (right panel). Black horizontal lines in each plot denote the corresponding upper limits on the off-diagonal Yukawa couplings.

LHC searches of $h \to \ell_i \bar{\ell}_j$:-



- Constraints on the flavour violating Yukawa couplings, $|Y_{ij}|$ and $|Y_{ji}|$ from LHC results.
- The different light and deep red shaded regions are restricted by the upper bounds of flavor violating LFV decays.
- For first two generation, $Br(\mu \to e\gamma)$ gives the actual bound, the 13 TeV results are not so constraining.





Wrap-up

For most of the cLFV observables, the standard trilinear couplings A turn out to be inadequate to produce any significant result for the present or even the future experimental sensitivities.

- Specific non-holomorphic supersymmetry breaking terms i.e., $A'_{f,ij}$ may imprint significant contributions to cLFV processes like $\ell_j \to \ell_i \gamma$ or $\ell_j \to 3\ell_i$, $\phi \to \ell_i \bar{\ell}_j$.
- A reasonable off-diagonal NH trilinear couplings together with the diagonal ones may lead to potentially dangerous unphysical charge breaking minima. We derived the condition for having a charge preserving global minima for both trilinear couplings.
- NH couplings is better suited in achieving larger rates for all flavor violating observables which can potentially be tested in the near future.
- In particular, $\mu \to e\gamma$ would be more favourable to test A' involving first two generation Sleptons while MSSM heavier Higgs searches into flavor violation modes may strongly be influenced by $A'_{e\tau}$ or $A'_{\mu\tau}$.

Questions, Comments, Suggestions !!

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