A systematic mass insertion expansion for lepton violating decays in the MSSM

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Based on the work by
A. Crivellin, ZF, W. Materkowska, U. Nierste, S. Pokorski & J. Rosiek
arXiv: hep-ph 17XX.

Outline

1. Motivation
2. Methods for flavor calculations
3. Results
4. Conclusions

Motivation

PHYSICS

- FCNC processes involving leptons are strictly forbidden in the SM ($m_\nu = 0$).
- LFV may serve as clue towards New Physics.

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MATHS

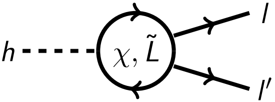
- Use tools that have not been available earlier.
- First systematic discussion of the **mass insertion approximation**.
- Recover the dependency on the Lagrangian parameters.

Upper bounds on LFV processes.

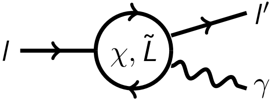
Decay	Experimental upper bound	CL
$\tau \to e\gamma$	3.3×10^{-8}	90%
$\tau \to \mu\gamma$	4.4×10^{-8}	90%
$\mu \to e\gamma$	5.7×10^{-13}	90%
$Z \to \mu e$	7.5×10^{-7}	95%
$Z \to \mu\tau$	1.2×10^{-5}	95%
$Z \to \tau e$	9.8×10^{-6}	95%
$\mu \to e^- e^+ e^-$	1.0×10^{-12}	90%
$\tau \to e^- e^+ e^-$	2.7×10^{-8}	90%
...	$\sim 10^{-8}$	
$H \to e\tau$	6.1×10^{-3}	90%
$H \to \mu\tau$	2.5×10^{-3}	90%
$H \to \mu e$	3.6×10^{-4}	90%

Future sensitivity will improve $\to$ important to have the tools for **fast, precise calculations**.

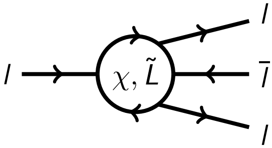
Lepton flavor violating processes



(A)



(B)



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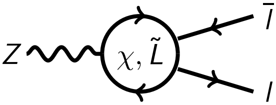

(D)

Mass insertions

Off-diagonal elements, both flavor violating and flavor conserving, of the mass matrices of SUSY particles.

$$\Delta_{LL}^{IJ} = \frac{(M_{LL}^2)^{IJ}}{\sqrt{(M_{LL}^2)^{II}(M_{LL}^2)^{JJ}}} \qquad \Delta_{RR}^{IJ} = \frac{(M_{RR}^2)^{IJ}}{\sqrt{(M_{RR}^2)^{II}(M_{RR}^2)^{JJ}}}$$
$$\Delta_{LR}^{IJ} = \frac{A_l^{IJ}}{\left((M_{LL}^2)^{II}(M_{RR}^2)^{JJ}\right)^{1/4}} \qquad \Delta_{LR}^{\prime IJ} = \frac{A_l^{\prime IJ}}{\left((M_{LL}^2)^{II}(M_{RR}^2)^{JJ}\right)^{1/4}} \quad (1)$$

M_{LL}^2, M_{RR}^2 - slepton soft mass matrices
A_l, A_l' - trilinear terms.

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M_{LL}^2, M_{RR}^2 - slepton soft mass matrices
A_l, A'_l - trilinear terms.
Wilson coefficients

$$\begin{aligned} F^{IJ} &= \frac{1}{(4\pi)^2}\Big(F_{LL}^{IJ}\Delta_{LL}^{IJ} + F_{RR}^{IJ}\Delta_{RR}^{JI} \\ &+ F_{ALR}^{IJ}\Delta_{LR}^{JI} + F_{BLR}^{IJ}\Delta_{LR}^{IJ*} + F_{ALR}^{\prime IJ}\Delta_{LR}^{\prime JI} + F_{BLR}^{\prime IJ}\Delta_{LR}^{\prime IJ*}\Big)\ . \qquad (2) \end{aligned}$$

Our method

1. Expansion in flavor off-diagonal slepton mass insertions (Δ's) performed in the first order in Δ's.
2. Expansion of Δ's coefficients in flavor conserving off-diagonal terms of all SUSY particles
   $\rightarrow$ sleptons (so-called A terms)
   $\rightarrow$ gauginos

We can do this using the Flavor Expansion Theorem (FET) and the newly-developed **Mathematica `MassToMI` package**

J. Rosiek (2015) arXiv: 1509.05030
A. Dedes, *et al* (2015) arXiv: 1504.00960

The use of the symbolic package allows us to:

- perform the required 3rd order MI expansion in a fully automatized way.
- we do not need to make any assumptions upon degeneracy or hierarchy between SUSY particles (contrary to other analyses).
- obtain cancellations between different terms $\rightarrow$ the result is more compact.
- include terms scaling down with SUSY mass scale like v^2/M^2 or slower (M - SUSY mass parameters i.e. M_1, M_2, μ, diagonal soft slepton masses).

To compare our expansion we also performed calculations in the **mass-eigenstates** basis.

F_{MI} - mass-insertion formfactor

F_{ME} - mass-eigenstates formfactor

An example: non-degenerated SUSY spectrum

Transition between the 2nd and 3rd generation

Initial setup ([m] = GeV):

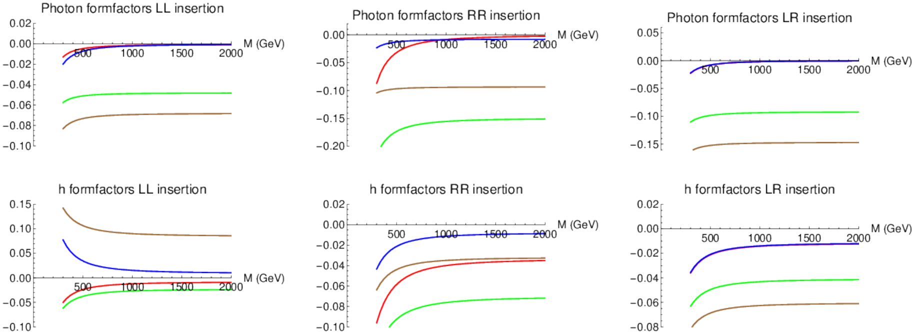
$$\begin{array}{lll} \tan\beta = 5 & m_{\tilde{\mu}_L} = 300 & A_{\mu\mu} = A'_{\mu\mu} = 0.1\sqrt{m_{\tilde{\mu}_L} m_{\tilde{\mu}_R}} \\ \mu = 200 + 100i & m_{\tilde{\tau}_L} = 330 & \\ M_1 = 150 & m_{\tilde{\mu}_R} = 300 & A_{\tau\tau} = A'_{\tau\tau} = 0.1\sqrt{m_{\tilde{\tau}_L} m_{\tilde{\tau}_R}} \\ M_2 = 300 & m_{\tilde{\tau}_R} = 350 & \end{array} \tag{3}$$

Scale up to 2 TeV. Plot

$$\Delta F = \left| \frac{F_{\mathrm{MI}}}{F_{\mathrm{ME}}} \right| - 1 \tag{4}$$

as a function of the average slepton mass.

Accuracy of MI expansion for penguin amplitudes.



L, R: effective couplings, non-degenerated SUSY spectrum (3) for both ME and MI expressions

L, R: ME exressions (3), but universal degenerated spectrum for MI expressions

M - average SUSY mass scale, $(M = M_2 = m_{\tilde{\mu}_L} = m_{\tilde{\mu}_R})$

Results: an example

Bounds on the mass insertions from LFV for SUSY scale $M = 400$ GeV and $\tan\beta = 2$

Process	Δ^{IJ}_{LL}	Δ^{IJ}_{RR}	Δ^{IJ}_{LR}	Δ^{IJ}_{RL}	Δ'^{IJ}_{LR}	Δ'^{IJ}_{LR}
$\tau \to \mu\gamma$	$5.3 \cdot 10^{-1}$	$3.3 \cdot 10^{+0}$	$9.1 \cdot 10^{-2}$	$9.1 \cdot 10^{-2}$	$4.5 \cdot 10^{-2}$	$4.5 \cdot 10^{-2}$
$\tau \to \mu\mu\mu$	$7.5 \cdot 10^{+0}$	$4.0 \cdot 10^{+1}$	$1.3 \cdot 10^{+0}$	$1.3 \cdot 10^{+0}$	$6.4 \cdot 10^{-1}$	$6.4 \cdot 10^{-1}$
$\tau \to \mu e^+ e^-$	$6.7 \cdot 10^{+0}$	$3.6 \cdot 10^{+1}$	$1.1 \cdot 10^{+0}$	$1.1 \cdot 10^{+0}$	$5.6 \cdot 10^{-1}$	$5.6 \cdot 10^{-1}$
$Z^0 \to \tau\mu$	$1.3 \cdot 10^{+3}$	$2.0 \cdot 10^{+5}$	$1.7 \cdot 10^{+4}$	$1.6 \cdot 10^{+4}$	$4.3 \cdot 10^{+3}$	$3.9 \cdot 10^{+3}$
$h \to \tau\mu$	$1.9 \cdot 10^{+2}$	$9.0 \cdot 10^{+2}$	$1.3 \cdot 10^{+3}$	$1.4 \cdot 10^{+3}$	$6.0 \cdot 10^{+0}$	$6.0 \cdot 10^{+0}$

$l \to l'\gamma$ - strongest bounds.

Non-decoupling effects in Higgs decays

First observed by J.F. Gunion, H.E. Haber (2003) arXiv: 0207010

$\rightarrow$ Related to the **2HDM structure** of the MSSM.

Constant in the limit of heavy M but decouple as v^2/M_A^2

The potentially largest contributions to $h \rightarrow ll'$ come from the effects non-decoupling in the limit of large SUSY masses and $\sim A'_l$.

For large SUSY masses and small mixing angles α, β the Higgs decay is more constraining than the $\mu \rightarrow e\gamma$.

Conclusions

1. Newly developed calculation tools used to obtain a full expansion of the amplitudes in terms of mass insertions.
2. Our expansion is completely systematic in powers of v^2/M^2 and v^2/M_A^2
3. We can observe the cancellations between different lower-order terms.
4. Also quantitatively more can be understood than using ME basis.
5. We observed the non-decoupling effects in Higgs decays, where the maximal $BR(h \to ll') \sim \mathcal{O}(10^{-4})$, not much lower than the current experimental sensitivities.

BACKUP

Sources of flavor violation in the MSSM

1. Slepton mass matrix

The slepton and sneutrino mass and mixing matrices are defined as:

$$Z_L^\dagger \begin{pmatrix} (\mathcal{M}_L^2)_{LL} & (\mathcal{M}_L^2)_{LR} \\ (\mathcal{M}_L^2)_{LR}^\dagger & (\mathcal{M}_L^2)_{RR} \end{pmatrix} Z_L = \mathrm{diag}\left(m_{L_1}^2 \ldots m_{L_6}^2\right) \tag{5}$$

$$\left(\mathcal{M}_L^2\right)_{LL} = (M_{LL}^2)^T + \frac{M_Z^2 \cos 2\beta}{2}(1 - 2c_W^2)\hat{1} + \frac{v_1^2 Y_l^2}{2} \tag{6}$$

$$\left(\mathcal{M}_L^2\right)_{RR} = M_{RR}^2 - \frac{M_Z^2 \cos 2\beta}{2} s_W^2 \hat{1} + \frac{v_1^2 Y_l^2}{2} \tag{7}$$

$$\left(\mathcal{M}_L^2\right)_{LR} = \frac{1}{\sqrt{2}}\left(v_2(Y_l \mu^\star - A_l^{'}) + v_1 A_l\right) \tag{8}$$

where $M_{LL}^2, M_{RR}^2, A_l, A_l^{'}$ and $Y_l = -\sqrt{2} m_l / v_1$ are 3×3 matrices in flavor space.

2. Gaugino mass matrices

The neutralino and chargino mass and mixing matrices can be written down as:

$$Z_N^T \begin{pmatrix} M_1 & 0 & \frac{-ev_1}{2c_W} & \frac{ev_2}{2c_W} \\ 0 & M_2 & \frac{ev_1}{2s_W} & \frac{-ev_2}{2s_W} \\ \frac{-ev_1}{2c_W} & \frac{ev_1}{2s_W} & 0 & -\mu \\ \frac{ev_2}{2c_W} & \frac{-ev_2}{2s_W} & -\mu & 0 \end{pmatrix} Z_N = \mathrm{diag}\left(m_{\chi_1^0} \ldots m_{\chi_4^0}\right) \quad (9)$$

$$(Z_-)^T \begin{pmatrix} M_2 & \frac{ev_2}{\sqrt{2}s_W} \\ \frac{ev_1}{\sqrt{2}s_W} & \mu \end{pmatrix} Z_+ = \mathrm{diag}\left(m_{\chi_1}, m_{\chi_2}\right) \quad (10)$$

$\boxed{\textbf{3. Higgs-slepton-slepton vertex}}$ contains the A_l, A'_l terms

$\boxed{\textbf{What are the non-holomorphic } A'_l \textbf{ terms?}}$

$$\mathcal{L} \sim {A'_l}^{IJ} H_i^{2\star} L_i^I R^J + {A'_d}^{IJ} H_i^{2\star} Q_i^I D^J + {A'_u}^{IJ} H_i^{1\star} Q_i^I U^J + H.c. \qquad (11)$$

- Trilinear couplings of the scalar fields
- different in the form from the Yukawa terms in the superpotential

Divided differences

$$
\begin{aligned}
f^{[0]}(x) &= f(x) \\
f^{[1]}(x,y) &= \frac{f^{[0]}(x) - f^{[0]}(y)}{x-y} \\
f^{[2]}(x,y,z) &= \frac{f^{[1]}(x,y) - f^{[1]}(x,z)}{y-z} \\
&\dots
\end{aligned}
\tag{12}
$$

symmetric under permutation of any of its n arguments

$$
f^{[k]}(x_0, \dots, x_k) \equiv f(\{x_0, \dots, x_k\}) \tag{13}
$$

$$
g(\{x_1, x_2\}, \{y_1, y_2, y_3, y_4\}, z) \tag{14}
$$

Divided difference of n-point function is a $(n+1)$-point function

$$
\begin{aligned}
B_0(m_1, \{m_2, m_3\}) &= B_0(\{m_1, m_2\}, m_3) = C_0(m_1, m_2, m_3) \\
B_0(m_1, \{m_2, m_3, m_4\}) &= C_0(m_1, m_2, \{m_3, m_4\}) = D_0(m_1, m_2, m_3, m_4) \\
&\dots
\end{aligned}
$$

We can now find cancellations between different terms.
$\rightarrow$ Identify the lowest non-vanishing order of the mass insertion for every process.

A. Dedes, *et al* (2015), arXiv: 1504.00960