Lepton Flavor Violating Higgs Decays in Supersymmetry without R Parity

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Lepton Flavor Violation and R Parity

Why lepton flavor violation (LFV):

- In the Standard Model
- In neutrino oscillation experiments
- The observation of lepton flavor violation as a hint to physics beyond the Standard Model

Among the possible LFV sources, R-parity violation (RPV) is the one which interests us.

Lepton Flavor Violation and R Parity

What is R parity:

- Keeps baryon and lepton number conservation
- Makes lightest supersymmetric particle (LSP) a possible dark matter candidate

Without R parity:

- A richer phenomenology
- A convenient approach to lepton flavor violation which gives neutrino masses and mixings
- Metastable dark matter is still possible. F. Takayama *et al.* (2000)

$h^0 \to \mu^\pm \tau^\mp$

We investigate thoroughly LFV Higgs to $\mu^\pm \tau^\mp$ decay in supersymmetry (SUSY) without R parity:

- Full diagrammatic calculations up to one-loop level
- All the needed effective couplings and decay amplitudes are derived analytically.
- We diagonalize all the mass matrices numerically and deal directly with the mass eigenstates.

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Why $h^0 \to \mu^\pm \tau^\mp$:

- Especially interesting at the moment with Higgs being discovered
- Lack for a comprehensive consideration of R-parity violation

The key features of $h^0 \to e^\pm \mu^\mp$ and $h^0 \to e^\pm \tau^\mp$ are also discussed.

A Generic Supersymmetric Model without R Parity

Superpotential with minimal superfields spectrum:

$$W = \epsilon_{ab}\Big[\mu_\alpha \hat{H}_u^a \hat{L}_\alpha^b + h_{ik}^u \hat{Q}_i^a \hat{H}_u^b \hat{U}_k^C + \lambda'_{\alpha jk} \hat{L}_\alpha^a \hat{Q}_j^b \hat{D}_k^C + \frac{1}{2}\lambda_{\alpha\beta k} \hat{L}_\alpha^a \hat{L}_\beta^b \hat{E}_k^C\Big] + \frac{1}{2}\lambda''_{ijk} \hat{U}_i^C \hat{D}_j^C \hat{D}_k^C$$

- We have four $\hat{L}$ superfields.
- We choose a flavor basis such that only $\hat{L}_0$ bears a nonzero vacuum expectation value (VEV) and thus can be identified as usual $\hat{H}_d$ in the minimal supersymmetric standard model (MSSM).

Soft Supersymmetry Breaking Terms

The soft SUSY breaking terms $V_{\rm soft}$:

$$\epsilon_{ab} B_\alpha H_u^a \tilde{L}_\alpha^b + \epsilon_{ab}\left[A_{ij}^U \tilde{Q}_i^a H_u^b \tilde{U}_j^\dagger + A_{ij}^D H_d^a \tilde{Q}_i^b \tilde{D}_j^\dagger + A_{ij}^E H_d^a \tilde{L}_i^b \tilde{E}_j^\dagger\right] + \text{h.c.}$$

$$+\epsilon_{ab}\left[A_{ijk}^{\lambda'} \tilde{L}_i^a \tilde{Q}_j^b \tilde{D}_k^\dagger + \frac{1}{2} A_{ijk}^{\lambda} \tilde{L}_i^a \tilde{L}_j^b \tilde{E}_k^\dagger\right] + \frac{1}{2} A_{ijk}^{\lambda''} \tilde{U}_i^\dagger \tilde{D}_j^\dagger \tilde{D}_k^\dagger + \text{h.c.}$$

$$+\tilde{Q}^\dagger \tilde{m}_Q^2 \tilde{Q} + \tilde{U}^\dagger \tilde{m}_U^2 \tilde{U} + \tilde{D}^\dagger \tilde{m}_D^2 \tilde{D} + \tilde{L}^\dagger \tilde{m}_L^2 \tilde{L} + \tilde{E}^\dagger \tilde{m}_E^2 \tilde{E} + \tilde{m}_{H_u}^2 |H_u|^2$$

$$+\frac{M_1}{2}\tilde{B}\tilde{B} + \frac{M_2}{2}\tilde{W}\tilde{W} + \frac{M_3}{2}\tilde{g}\tilde{g} + \text{h.c.}$$

- $\tilde{m}_L^2$ is given by a 4×4 matrix with zeroth components. $\tilde{m}_{L_{00}}^2$ corresponds to $\tilde{m}_{H_d}^2$ in MSSM while $\tilde{m}_{L_{0k}}^2$'s give new mass mixings.

Corrections to Higgs Boson Masses

Following corrections to Higgs Boson masses are considered:

- Tree-level contributions from the RPV terms
- The radiative corrections from third generation quarks and squarks

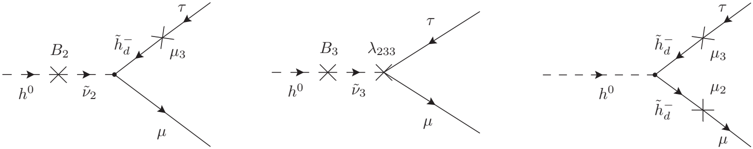
We implement full one-loop radiative corrections from third generation quarks and squarks to matrix elements which are most relevent to Higgs states. M. Carena *et al.* (2000)

Specifically, key two-loop corrections to elements directly related to light Higgs are also implemented. S. Heinemeyer *et al.* (1999)

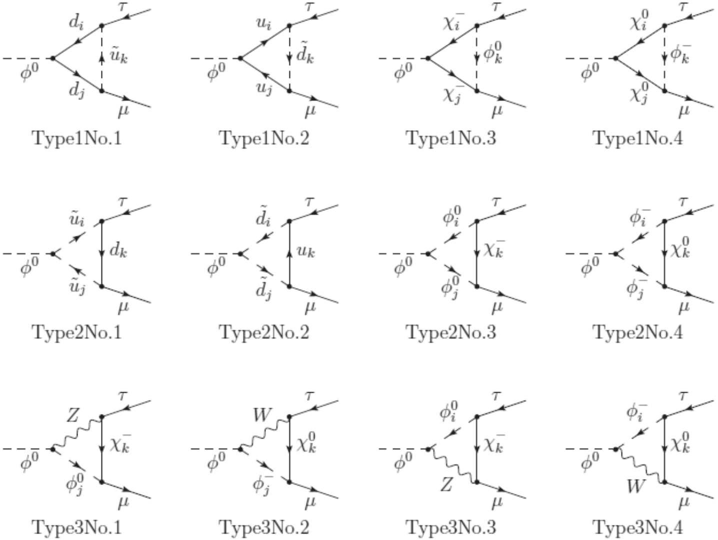
Tree Level Feynman Diagrams

In the framework of SUSY without R parity, we can have LFV Higgs decays at tree level.

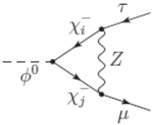
We show these tree diagrams by means of the mass insertion approximation:



One-Loop Feynman Diagrams (1)



One-Loop Feynman Diagrams (2)



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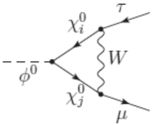

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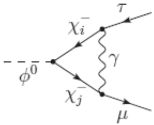

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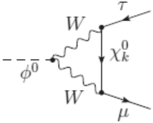

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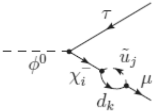

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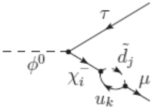

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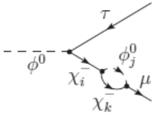

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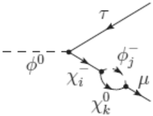

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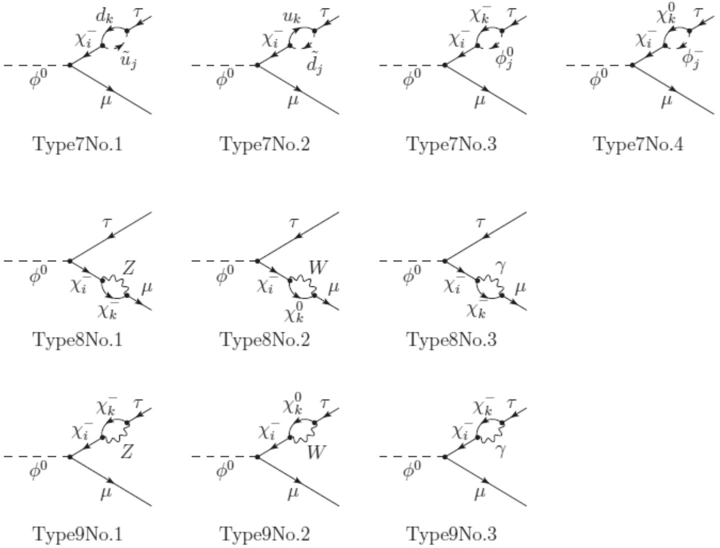

d_k τ χ_i^- $\tilde{u}_j$ ϕ^0 μ
Type7No.1
u_k τ χ_i^- $\tilde{d}_j$ ϕ^0 μ
Type7No.2
χ_k^- τ χ_i^- ϕ_j^0 ϕ^0 μ
Type7No.3
χ_k^0 τ χ_i^- ϕ_j^- ϕ^0 μ
Type7No.4
τ ϕ^0 χ_i^- Z μ χ_k^-
Type8No.1
τ ϕ^0 χ_i^- W μ χ_k^0
Type8No.2
τ ϕ^0 χ_i^- γ μ χ_k^-
Type8No.3
χ_k^- τ χ_i^- Z ϕ^0 μ
Type9No.1
χ_k^0 τ χ_i^- W ϕ^0 μ
Type9No.2
χ_k^- τ χ_i^- γ ϕ^0 μ
Type9No.3

Conditions and Assumptions

Adopted parameter space:

Free parameters	Range
$\|\mu_0\|$, M_2, $\|A_u\|$, $\|A_d\|$ and $\left\|A^\lambda\right\|$	$\leq$ 2500 GeV
A_e	zero, since its influence is negligible
$\tan\beta$	3 to 60
$\tilde{m}_E^2 = \tilde{m}_L^2$ (without zeroth component)	$\leq$ (2500 GeV)^2 $\times$ identity matrix
$\tilde{m}_{L_{00}}^2$	Constrained only by mass eigenvalues below

Mass eigenvalues output	Range
Light Higgs mass	123 to 127 GeV
Heavy Higgs/sneutrino masses	200 GeV to 3 TeV
Charged Higgs/slepton masses	200 GeV to 3 TeV

- The total decay width of light Higgs is the RPV decay rate of $h^0 \to \mu^\pm\tau^\mp$ plus MSSM one.
- $M_2 = \frac{1}{3.5} M_3 = 2M_1$; $\tilde{m}_Q^2 = \tilde{m}_U^2 = \tilde{m}_D^2 = (0.8M_3 \times \text{identity matrix})^2$

Constraints on RPV Parameters

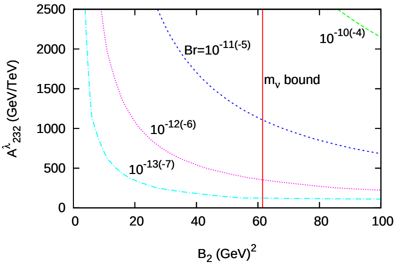
Bounds in whole analysis:

- Indirect neutrino mass bound $\sum_i m_{\nu_i} \lesssim 1\text{eV}$ D. N. Spergel *et al.* (2003)
- Just in case, branching ratios with solid neutrino mass bounds, i.e. $m_{\nu_e} < 3\text{eV}$, $m_{\nu_\mu} < 190\text{keV}$ and $m_{\nu_\tau} < 18.2\text{MeV}$ are also listed.
  S. Eidelman *et al.* (2004)

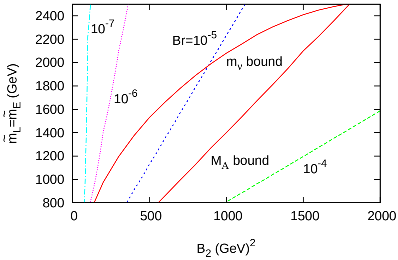
Other constraints:

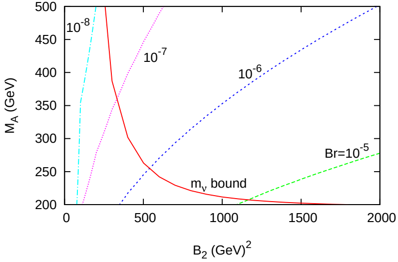
- Additional "1% of B_0" as upper bound of B_i by hand in the circumstance of extraordinary loose bounds
- LFV charged lepton decays (e.g., $\tau^- \to \mu^- e^+ e^-$, $\mu \to e\gamma$)
- Semileptonic decays (e.g., $D^+ \to \bar{K}^0 l_i^+ \nu_i$)
- experimental values of CKM matrix elements

Contributions from $B_i\,\lambda$ and $B_i\,A^\lambda$ Combinations



All three panels: *Branching ratios from $B_2\,A^\lambda_{232}$ (upper-left) and $B_2\,\lambda_{232}$ (lower ones) with $M_2 = 2500$ GeV, $\mu_0 = 1800$ GeV $= A_u = -A_d$ and $\tan\beta$=60. The Solid red line (m_ν bound) comes from demanding that the 22 element of the neutrino mass matrix $<$ 1 eV.*





Results

We pull together the most interesting RPV parameter combinations and corresponding branching ratios:

The most interesting RPV parameter combinations

RPV Parameter Combinations	With Neutrino Mass $\lesssim$1eV Constraint	With Relaxed Neutrino Mass Bounds
$B_2\,\mu_3$	1×10^{-15}	9×10^{-6}
$B_3\,\mu_2$	1×10^{-13}	7×10^{-4}
$B_1\,\lambda_{123}$	1×10^{-5}	4×10^{-5}
$B_1\,\lambda_{132}$	3×10^{-5}	7×10^{-5}
$B_2\,\lambda_{232}$	3×10^{-5}	6×10^{-2}
$B_3\,\lambda_{233}$	3×10^{-5}	3×10^{-2}
$B_2\,A^{\lambda}_{232}$	$5 \times 10^{-11(-5)}$	7×10^{-7}
$B_3\,A^{\lambda}_{233}$	$5 \times 10^{-11(-5)}$	1×10^{-7}

- The numbers in the parentheses indicate the branching ratios in the case of $A^{\lambda} = 2500$ TeV.

Conclusion

- Constraints from neutrino mass give stringent bounds for most RPV parameter combinations.
- Even with RPV parameters only, notable contributions to LFV Higgs decays are possible.
- $h^0 \to e^\pm \tau^\mp$ is expected to be able to give roughly the same order of branching ratio with that of $h^0 \to \mu^\pm \tau^\mp$.
- $h^0 \to e^\pm \mu^\mp$ is suppressed due to constraint from two-loop Barr-Zee diagrams. A. Goudelis *et al.* (2012); G. Blankenburg *et al.* (2012); R. Harnik *et al.* (2012)

The branching ratio can become even larger if we allow more free parameters or a larger parameter space.

Conclusion

Generally speaking, a heavy SUSY spectrum is preferred.

- An exception: in the extreme case that A^{λ} is larger than around hundreds of TeV
- A smaller value of the Higgs mass parameter M_A is favored.

In a Higgs factory, the cross-section of a 125 GeV SM Higgs boson is roughly 200 fb near the threshold. With a luminosity of 500 fb^{-1}, we may have several raw events.

At a higher energy (e.g., 3 TeV) the cross-section is about 500 fb. With a luminosity of 1000 fb^{-1}, we may have several tens of raw events.

Thank you for your attention!