CLFV beyond minimal SUSY

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Outline of the talk

- Introduction
  - Why to study CLFV beyond minimal SUSY?
- Enhancing CLFV with the Z-penguin
  - $l_i \to 3l_j$ in the MSSM
  - Some mass scaling considerations
  - $l_i \to 3l_j$ in the MSSM revisited
  - Other observables
- CLFV in R-parity violating SUSY
  - $H \to \mu\tau$
  - Exotic muon decays
- Final remarks

Introduction

Why do we care about CLFV?

The observation of CLFV would be a clear signal of physics beyond the Standard Model (BSM)

- New interactions

Renormalizable: $(Y_\nu)_{ij} \, L_i H \nu_{Rj}$

Non-renormalizable: $\frac{c_{ij}}{\Lambda^2} H^\dagger H L_i H e_{Rj}$

- New sectors (coupled to the charged leptons)

Example: sleptons in SUSY: $\left(m_L^2\right)_{ij}$

LFV : Where to look for?

$l_i \to l_j \gamma$

$l_i \to 3 l_j$

$l_i \to l_j l_k l_k$

$\mu - e$ conversion in nuclei

BSM

LFV at colliders

$M \to l_i l_j$

LFV : Where to look for?

Everywhere!

ratio	LHT	MSSM (dipole)	MSSM (Higgs)	SM4
$\frac{\text{Br}(\mu^- \to e^- e^+ e^-)}{\text{Br}(\mu \to e\gamma)}$	$0.02 \ldots 1$	$\sim 6 \cdot 10^{-3}$	$\sim 6 \cdot 10^{-3}$	$0.06 \ldots 2.2$
$\frac{\text{Br}(\tau^- \to e^- e^+ e^-)}{\text{Br}(\tau \to e\gamma)}$	$0.04 \ldots 0.4$	$\sim 1 \cdot 10^{-2}$	$\sim 1 \cdot 10^{-2}$	$0.07 \ldots 2.2$
$\frac{\text{Br}(\tau^- \to \mu^- \mu^+ \mu^-)}{\text{Br}(\tau \to \mu\gamma)}$	$0.04 \ldots 0.4$	$\sim 2 \cdot 10^{-3}$	$0.06 \ldots 0.1$	$0.06 \ldots 2.2$
$\frac{\text{Br}(\tau^- \to e^- \mu^+ \mu^-)}{\text{Br}(\tau \to e\gamma)}$	$0.04 \ldots 0.3$	$\sim 2 \cdot 10^{-3}$	$0.02 \ldots 0.04$	$0.03 \ldots 1.3$
$\frac{\text{Br}(\tau^- \to \mu^- e^+ e^-)}{\text{Br}(\tau \to \mu\gamma)}$	$0.04 \ldots 0.3$	$\sim 1 \cdot 10^{-2}$	$\sim 1 \cdot 10^{-2}$	$0.04 \ldots 1.4$
$\frac{\text{Br}(\tau^- \to e^- e^+ e^-)}{\text{Br}(\tau^- \to e^- \mu^+ \mu^-)}$	$0.8 \ldots 2$	~ 5	$0.3 \ldots 0.5$	$1.5 \ldots 2.3$
$\frac{\text{Br}(\tau^- \to \mu^- \mu^+ \mu^-)}{\text{Br}(\tau^- \to \mu^- e^+ e^-)}$	$0.7 \ldots 1.6$	~ 0.2	$5 \ldots 10$	$1.4 \ldots 1.7$
$\frac{\text{R}(\mu\text{Ti} \to e\text{Ti})}{\text{Br}(\mu \to e\gamma)}$	$10^{-3} \ldots 10^{2}$	$\sim 5 \cdot 10^{-3}$	$0.08 \ldots 0.15$	$10^{-12} \ldots 26$

Table taken from A. J. Buras et al., JHEP 1009 (2010) 104 [arXiv:1006.5356]

LFV : How to look for?

In order to unravel the physics behind LFV (and neutrino masses!) we must:

- Search for LFV in as many observables as possible: they might have information about different sectors of the theory

- Study the relations among different observables (ratios, correlations, hierarchies...)

- Understand the origin of such relations: what is the underlying physics?

This is exactly what we want to address in case of SUSY models

Not only in the MSSM!

Beyond the minimal SUSY

Neutrinos are massless in the MSSM

High-energy extensions

Examples: standard seesaw (types-I, -II, -III)

The new degrees of freedom decouple

Only RGE effects at low energies

Deeply studied in the literature

[Minimal SUSY]

Low-energy extensions

Examples: low-scale seesaw, R-parity violation...

The new degrees of freedom are present at low energies

New particles and/or interactions

The common lore might be wrong

[Non-Minimal SUSY]

Enhancing CLFV with the Z-penguin

$l_i \to 3l_j$ in the MSSM

In supersymmetry, the additional degrees of freedom provided by the superparticles typically increase the flavor violating signals to observable levels.

The most popular example in the leptonic sector is the radiative decay $\mu \to e\gamma$ (why the most popular? see later...), but other interesting processes have been studied in the literature. For example:

$$l_i \to 3l_j$$

- J. Hisano et al., PRD 53 (1996) 2442
- E. Arganda and M.J. Herrero, PRD 73 (2006) 055003

$l_i \to 3l_j$ in the MSSM

A brief détour...

Experimental limits

$l_i \to l_j \gamma$	$l_i \to 3l_j$
$\text{Br}(\mu \to e\gamma) < 0.57 \cdot 10^{-12}$	$\text{Br}(\mu \to 3e) < 1.0 \cdot 10^{-12}$
$\text{Br}(\tau \to e\gamma) < 3.3 \cdot 10^{-8}$	$\text{Br}(\tau \to 3e) < 2.7 \cdot 10^{-8}$
$\text{Br}(\tau \to \mu\gamma) < 4.4 \cdot 10^{-8}$	$\text{Br}(\tau \to 3\mu) < 2.1 \cdot 10^{-8}$

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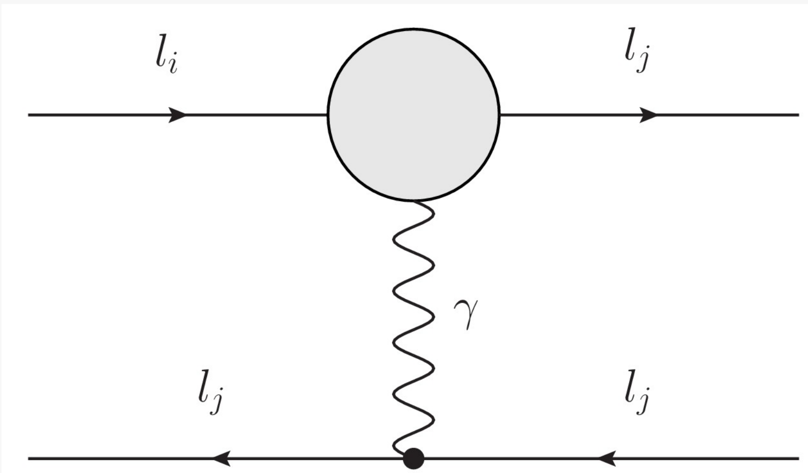
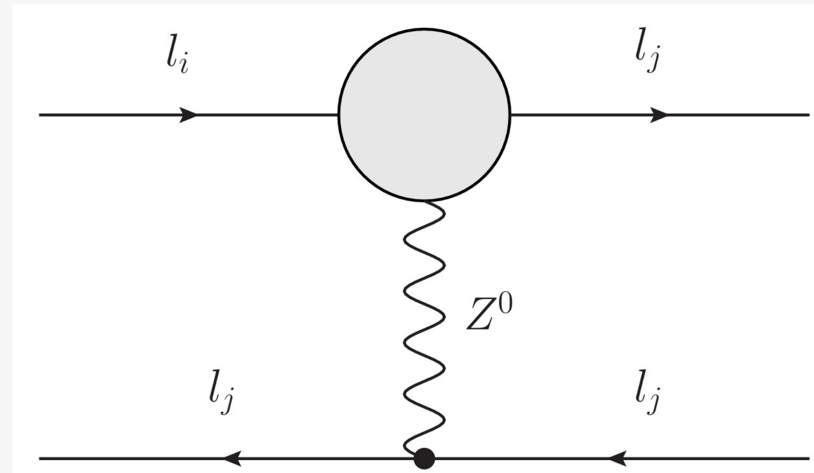
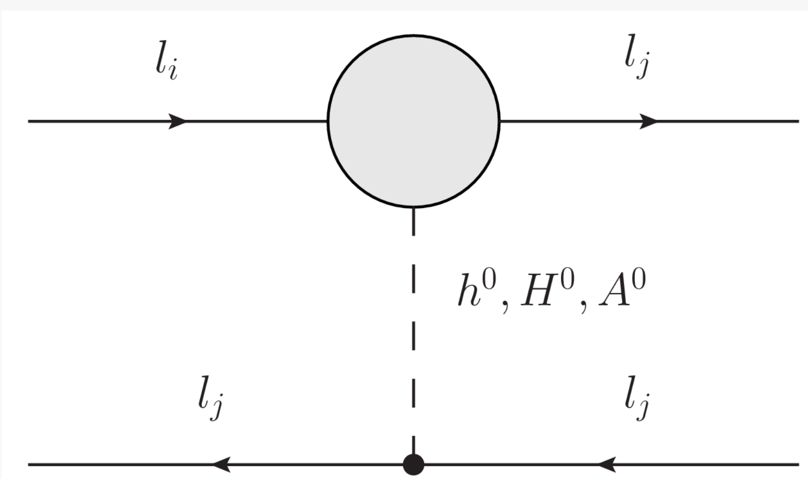
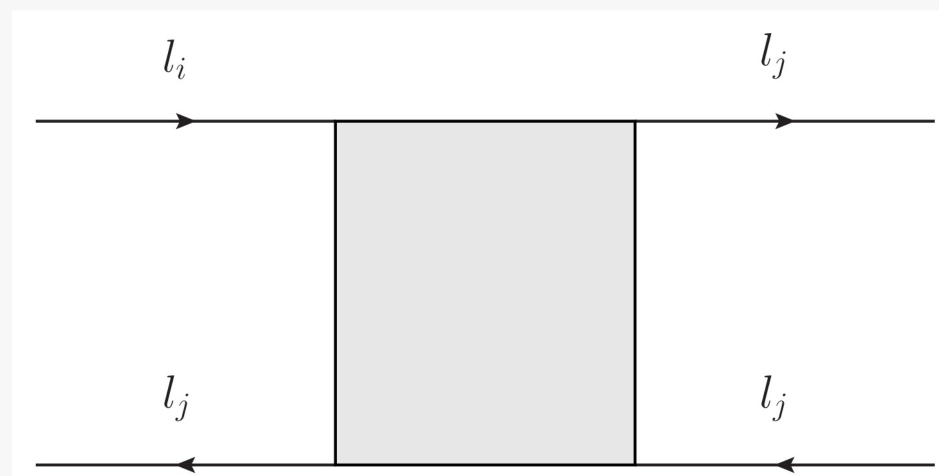
$l_i \to 3l_j$ in the MSSM









$l_i \to 3l_j$ in the MSSM

$$
\begin{aligned}
\Gamma \; = \; & \frac{e^4}{512\pi^3} m_{l_j}^5 \Big[\left|A_1^L\right|^2 + \left|A_1^R\right|^2 - 2\left(A_1^L A_2^{R*} + A_2^L A_1^{R*} + h.c.\right) \\
+ \; & \left(\left|A_2^L\right|^2 + \left|A_2^R\right|^2\right)\left(\frac{16}{3}\log\frac{m_{l_j}}{m_{l_i}} - \frac{22}{3}\right) \\
+ \; & \frac{1}{6}\left(\left|B_1^L\right|^2 + \left|B_1^R\right|^2\right) + \frac{1}{3}\left(\left|\hat{B}_2^L\right|^2 + \left|\hat{B}_2^R\right|^2\right) \\
+ \; & \frac{1}{24}\left(\left|\hat{B}_3^L\right|^2 + \left|\hat{B}_3^R\right|^2\right) + 6\left(\left|B_4^L\right|^2 + \left|B_4^R\right|^2\right) \\
- \; & \frac{1}{2}\left(\hat{B}_3^L B_4^{L*} + \hat{B}_3^R B_4^{R*} + h.c.\right) \\
+ \; & \frac{1}{3}\left\{2\left(\left|F_{LL}\right|^2 + \left|F_{RR}\right|^2\right) + \left|F_{LR}\right|^2 + \left|F_{RL}\right|^2\right\} \\
+ \; & \text{interference terms}\Big]
\end{aligned}
$$

$l_i \to 3l_j$ in the MSSM

$$
\begin{aligned}
\Gamma &= \frac{e^4}{512\pi^3} m_{l_j}^5 \left[\left|A_1^L\right|^2 + \left|A_1^R\right|^2 - 2\left(A_1^L A_2^{R*} + A_2^L A_1^{R*} + h.c.\right) \right. \\
&+ \left(\left|A_2^L\right|^2 + \left|A_2^R\right|^2\right) \left(\frac{16}{3} \log \frac{m_{l_j}}{m_{l_i}} - \frac{22}{3}\right) \\
&+ \frac{1}{6}\left(\left|B_1^L\right|^2 + \left|B_1^R\right|^2\right) + \frac{1}{3}\left(\left|\hat{B}_2^L\right|^2 + \left|\hat{B}_2^R\right|^2\right) \\
&+ \frac{1}{24}\left(\left|\hat{B}_3^L\right|^2 + \left|\hat{B}_3^R\right|^2\right) + 6\left(\left|B_4^L\right|^2 + \left|B_4^R\right|^2\right) \\
&- \frac{1}{2}\left(\hat{B}_3^L B_4^{L*} + \hat{B}_3^R B_4^{R*} + h.c.\right) \\
&+ \frac{1}{3}\left\{2\left(\left|F_{LL}\right|^2 + \left|F_{RR}\right|^2\right) + \left|F_{LR}\right|^2 + \left|F_{RL}\right|^2\right\} \\
&+ \left. \text{interference terms} \right]
\end{aligned}
$$

$l_i \to 3l_j$ in the MSSM

What contribution dominates?

$l_i \to 3l_j$ in the MSSM

What contribution dominates?

- In most parts of parameter space: Photon penguins

J. Hisano et al., PRD 53 (1996) 2442
E. Arganda and M.J. Herrero, PRD 73 (2006) 055003

$$\frac{BR(l_i \to 3l_j)}{BR(l_i \to l_j\gamma)} = \frac{\alpha}{3\pi}\left(\log\frac{m_{l_i}^2}{m_{l_j}^2} - \frac{11}{4}\right) \quad \Rightarrow \quad BR(l_i \to l_j\gamma) \gg BR(l_i \to 3l_j)$$

... and that, together with the good experimental perspectives, has made $\mu \to e\gamma$ so attractive for the pheno community

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- For large $\tan\beta$ and a light pseudoscalar: Higgs penguins

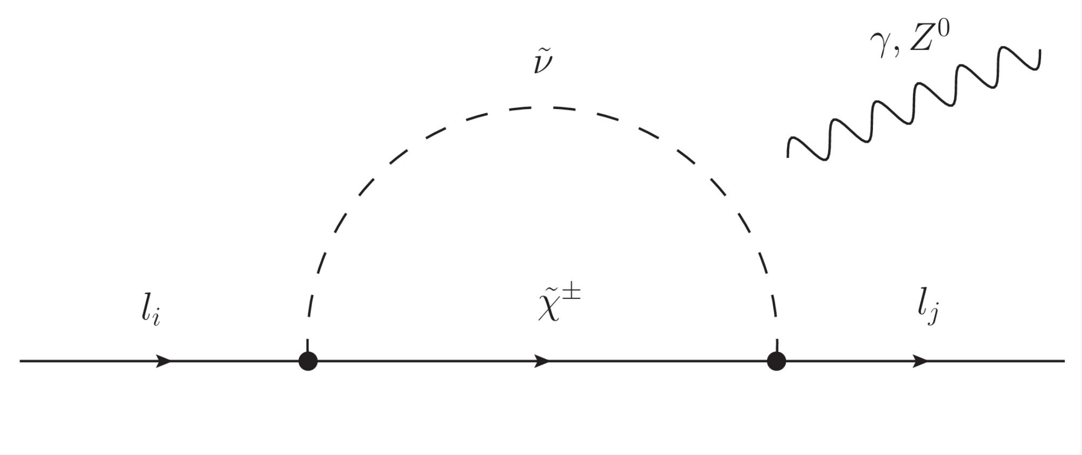
K.S. Babu, C. Kolda, PRL 89 (2002) 241802

Mass scaling considerations

M. Hirsch, F. Staub, AV, PRD 85 (2012) 113013

Let us give a more detailed look...

Consider the γ- and Z-penguins originated by chargino-sneutrino loops.



One finds:

$$A_a^{(c)L,R} = \frac{1}{m_{\tilde{\nu}}^2} \mathcal{O}_{A_a}^{L,R} s(x^2) \qquad F_X = \frac{1}{g^2 \sin^2\theta_W m_Z^2} \mathcal{O}_{F_X}^{L,R} t(x^2)$$

γ - penguin **Z - penguin**

Mass scaling considerations

In fact, the mass scalings

$$A \sim m_{SUSY}^{-2} \qquad\qquad F \sim m_Z^{-2}$$

are quite intuitive. These are the lowest mass scales in the penguins (recall, for example, the H-penguins $\sim m_H^{-2}$)

Then, by doing a very simple estimate...

$$\frac{F}{A} \sim \frac{m_{SUSY}^2}{g^2 \sin^2 \theta_W \, m_Z^2} \sim 500 \qquad \text{for } m_{SUSY} \sim 300\text{GeV}$$

And, remember... $\Gamma(l_i \to 3 l_j) \propto A^2 \, , \, F^2$

Mass scaling considerations

These considerations lead us to the expectation

$$F \gg A$$

So...

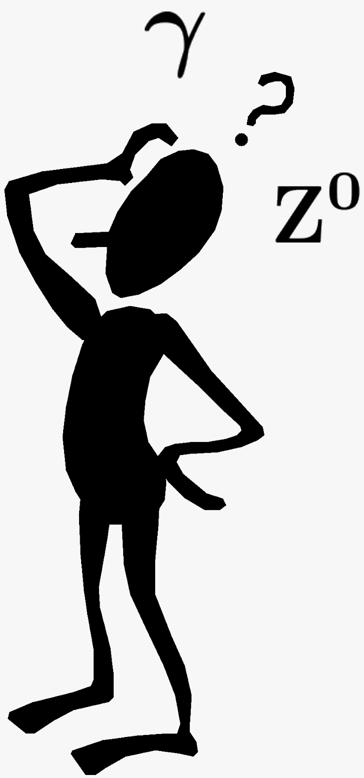
Mass scaling considerations

These considerations lead us to the expectation

$$F \gg A$$

So...

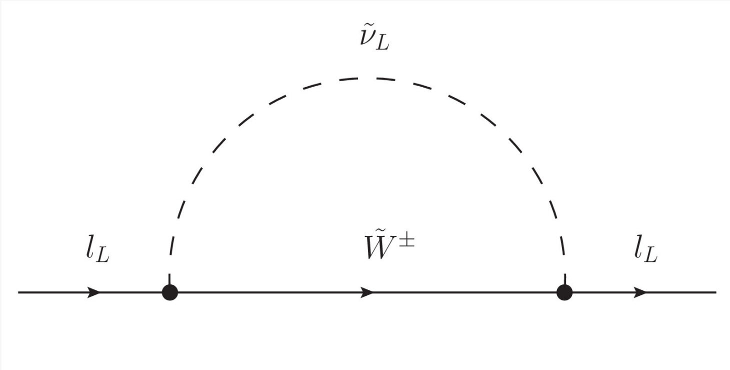
Why the Z-penguins are not the dominant contribution in the MSSM?

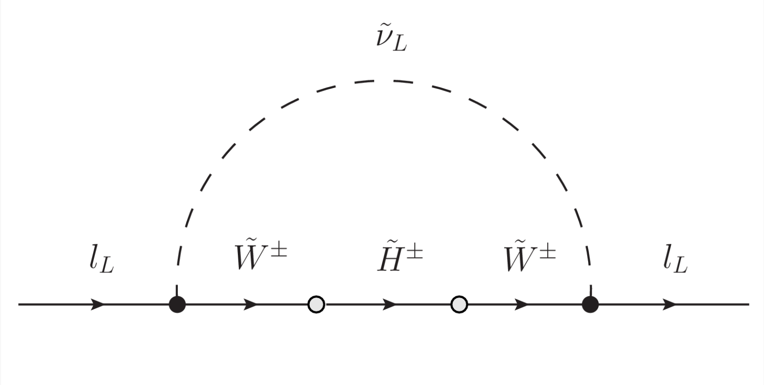


$l_i \to 3l_j$ in the MSSM revisited

Consider F_L, the dominant contribution within the Z-penguins, obtained when the external leptons are L-handed, and make an expansion on the chargino mixing angle.

$$F_L = F_L^{(0)} + \frac{1}{2}\theta^2_{\tilde{\chi}^\pm} F_L^{(2)} + \ldots$$

$=$ 

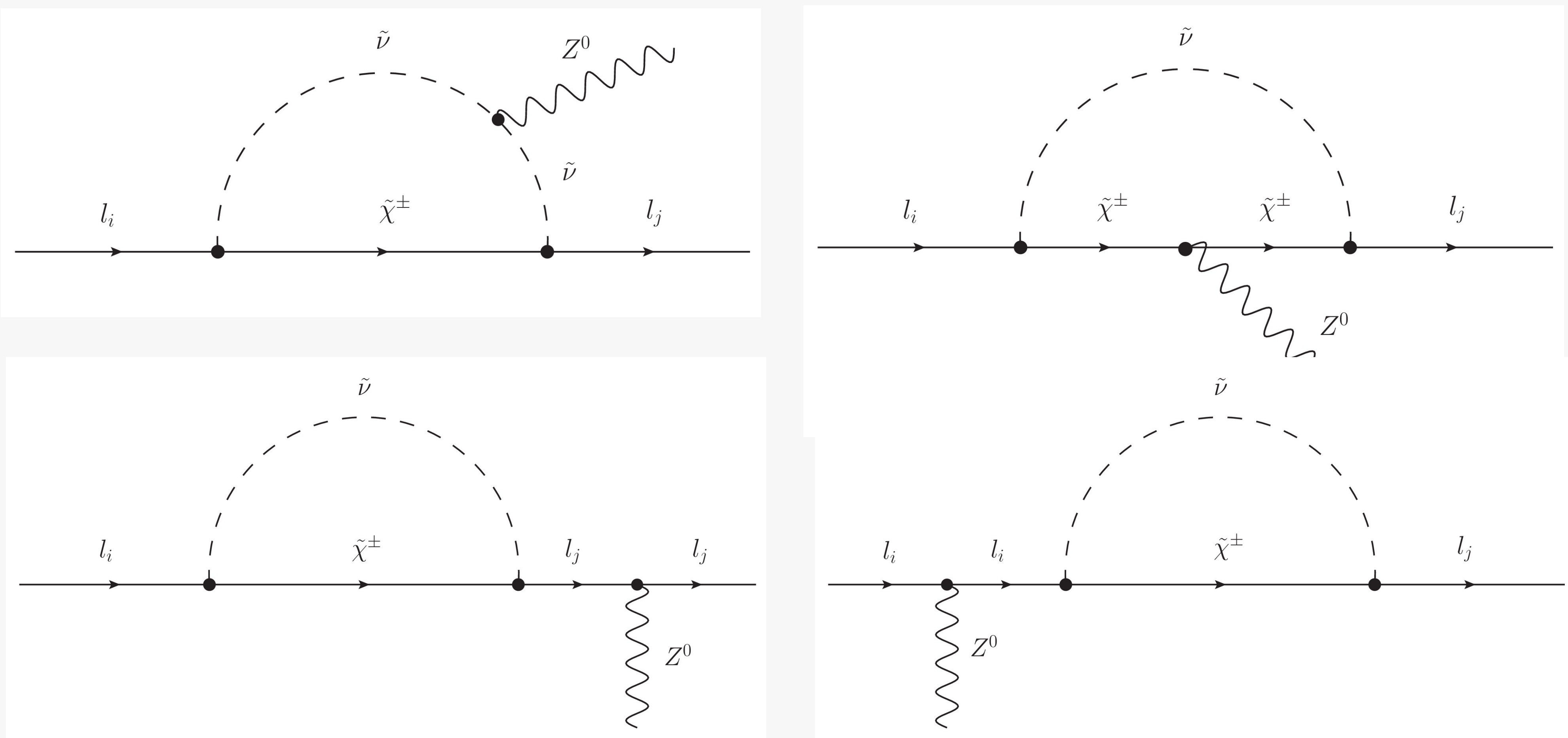
$+$ 

$+ \ldots$

Important: There is no order 1!

$l_i \to 3l_j$ in the MSSM revisited

$$\mathbf{F} = \mathbf{F_1} + \mathbf{F_2} + \mathbf{F_3} + \mathbf{F_4}$$



$l_i \to 3l_j$ in the MSSM revisited

When you sum the four diagrams that contribute to $F_L^{(0)}$:

$$\begin{aligned} F_L^{(0)} &= F_{L,1}^{(0)} + F_{L,2}^{(0)} + F_{L,3}^{(0)} + F_{L,4}^{(0)} \\ &= \frac{1}{2} g^3 c_W Z_V^{ki} Z_V^{kj*} X_1^k + \frac{1}{2} g^2 g' s_W Z_V^{ki} Z_V^{kj*} X_2^k \end{aligned}$$

X_1^k and X_2^k are combinations of PV functions, with different combinations of chargino and sneutrino masses. However, one finds that the masses cancel out and they just become numerical constants. Therefore...

$l_i \to 3l_j$ in the MSSM revisited

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X_1^k and X_2^k are combinations of PV functions, with different combinations of chargino and sneutrino masses. However, one finds that the masses cancel out and they just become numerical constants. Therefore...

$$\Rightarrow \quad F_L^{(0)} \propto \sum_k Z_V^{ki} Z_V^{kj*} = 0$$

It vanishes exactly!

Side comment: This cancellation was also found in Lunghi et al. Nucl. Phys. B 568 (2000) 120 when looking into $B \to X_s l^+ l^-$ in supersymmetry

$l_i \to 3l_j$ in the MSSM revisited

In **conclusion**, the Z-penguins are not dominant in the MSSM because the leading-order term vanishes and the first non-zero contribution is suppressed by two chargino insertions. This cancellation is not found in the photon penguins.

How can we break the cancellation?

- Additional states that mix with the sneutrinos
- New lepton couplings

$l_i \to 3l_j$ can be greatly enhanced!

$l_i \to 3l_j$ in the MSSM revisited

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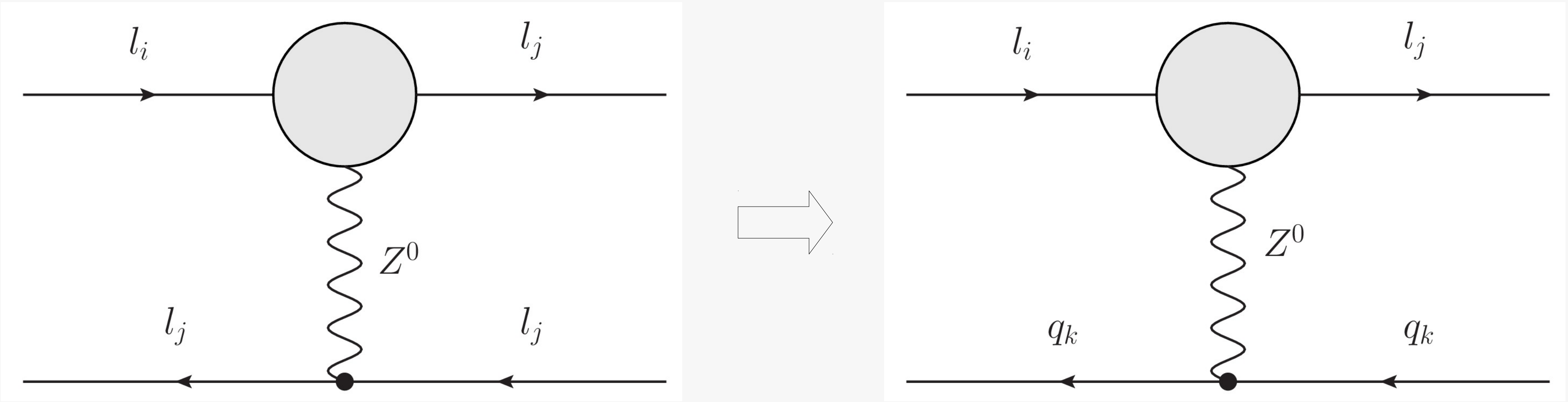
In fact... only $l_i \to 3l_j$?

Other observables



$\mu - e$ conversion in nuclei

$\tau \to P^0 l_i$

Same $Z^0 - l_i - l_j$ 1-loop effective coupling!

References:

E. Arganda, M.J. Herrero and A.M. Teixeira, JHEP 0710 (2007) 104
E. Arganda, M.J. Herrero and J. Portolés, JHEP 0806 (2008) 079

Other observables

Another brief détour...

Experimental limits

$\mu - e$ conversion	$\tau \to P^0 l_i$
$\mathrm{CR}_{\mathrm{Au}(197,79)} < 7 \cdot 10^{-13}$	$\mathrm{Br}(\tau \to \pi \mu) < 5.8 \cdot 10^{-8}$
$\mathrm{CR}_{\mathrm{Ti}(48,22)} < 4.3 \cdot 10^{-12}$	$\mathrm{Br}(\tau \to \eta \mu) < 5.1 \cdot 10^{-8}$
$< 10^{-18} - 10^{-16}$ (future)	...

Enhancing CLFV with the Z-penguin

Hirsch et al., Enhancing $l_i \to 3l_j$ with the Z^0-penguin [arXiv:1202.1825]

Dreiner at al., New bounds on trilinear R-parity violation from lepton flavor violating observables [arXiv:1204.5925]

Hirsch et al., Phenomenology of the minimal supersymmetric $U(1)_{B-L} \times U(1)_R$ extension of the standard model [arXiv:1206.3516]

Abada et al., Enhancing lepton flavour violation in the supersymmetric inverse seesaw beyond the dipole contribution [arXiv:1206.6497]

Ilakovac et al., Charged Lepton Flavour Violation in Supersymmetric Low-Scale Seesaw Models [arXiv:1212.5939]

$\mu - e$ conversion in nuclei and $\mu \to 3e$ are the most constraining observables in these models

Open issues

- Non-decoupling behavior?

Advocated for H-penguins in E. Arganda et al, PRD 71 (2005) 035011. See also the recent M. Arana-Catania et al, arXiv:1304.3371

Similar results found for the Z-penguin

- Non-SUSY contributions?

In most models where the Z-penguins are enhanced other non-SUSY contributions may also play a role. Which one is more important?

See for example A. Ilakovac, A. Pilaftsis PRD 80 (2009) 091902 : box contributions in models with light right-handed neutrinos

- Other examples?

In fact, SUSY is not responsible for the Z-penguin dominance. Is it possible to find simpler models (without SUSY) leading to the same qualitative results?

CLFV in R-parity violating SUSY

R-parity violation

$$\mathcal{W} = \mathcal{W}_{MSSM} + \epsilon_i \hat{L}_i \hat{H}_u + \frac{1}{2}\lambda_{ijk}\hat{L}_i\hat{L}_j\hat{E}^c_k + \frac{1}{2}\lambda'_{ijk}\hat{L}_i\hat{Q}_j\hat{D}^c_k$$

(+ B violating term)

- No theoretical argument in favor of R-parity

R-parity is introduced by hand

- In fact, R-parity does not solve proton decay

Non-renormalizable operators can also induce fast proton decay and some of them are not forbidden by R-parity.

S. Weinberg, Phys. Rev. D 26, 287 (1982)
N. Sakai and T. Yanagida, Nucl. Phys. B 197, 533 (1982)

- There is no need to remove ALL the RPV couplings

Neutrino masses

RPV provides an explanation for neutrino masses.

Simplest example: Bilinear RPV

$$\mathcal{W} \supset \epsilon \hat{L} \hat{H}_u \qquad \Rightarrow \qquad \nu - \tilde{H}_u^0 \text{ mixing}$$

Neutrino mass is generated due to the mixing between the neutrinos and the MSSM neutralinos.

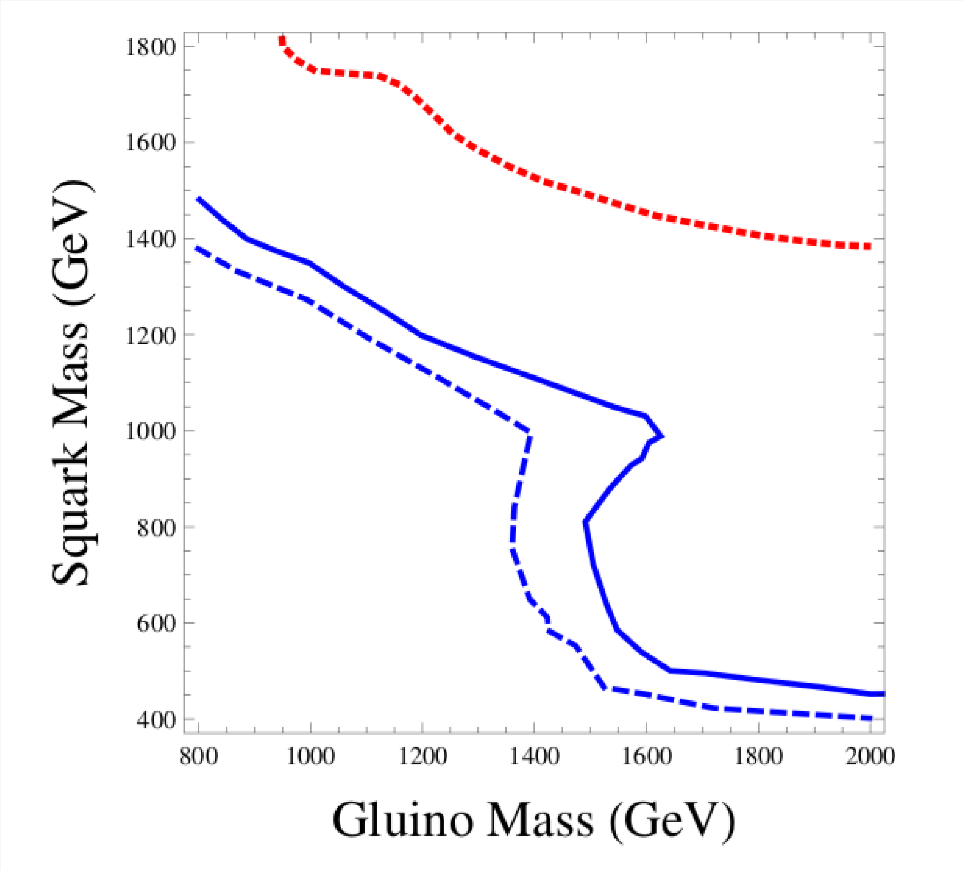
$$M_N = \begin{pmatrix} 0 & m \\ m^T & \mathcal{M}_{\chi^0} \end{pmatrix} \qquad m \sim \epsilon \ll \mathcal{M}_{\chi^0}$$

Electroweak scale seesaw: $m_\nu^0 = -m^T \cdot \mathcal{M}_{\chi^0}^{-1} \cdot m$

RPV and LHC bounds

Less missing energy...
less stringent constraints!

P. W. Graham et al, JHEP 1207 (2012) 149
M. Hanussek, J. S. Kim, PRD 85 (2012) 115021



$m(\tilde{\chi}_1^0) = 50\,\mathrm{GeV}$

Blue: $\tilde{\chi}_1^0 \to \nu b\bar{b}$

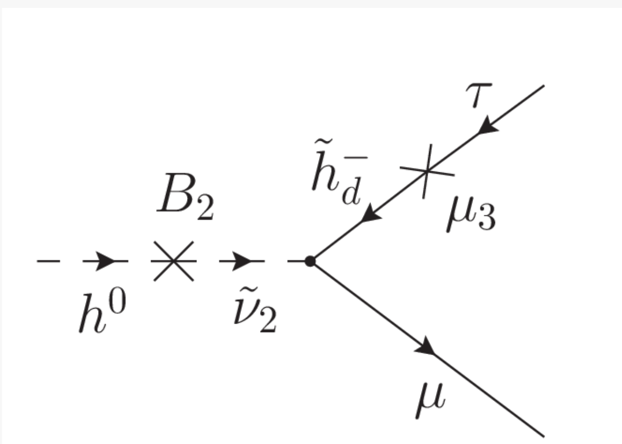
Red: stable $\tilde{\chi}_1^0$

Plot taken from P. W. Graham et al, JHEP 1207 (2012) 149

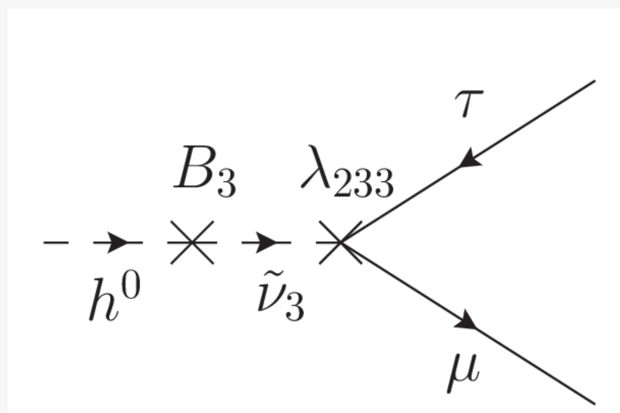
$H \to \mu\tau$ in RPV

A. Arhrib, Y. Cheng, O. Kong
EPL 101 (2013) 31003 [arXiv:1208.4669] and PRD 87 (2013) 015025 [arXiv:1210.8241]

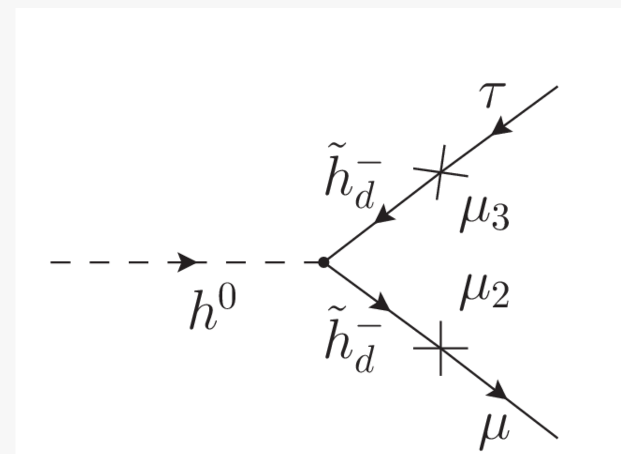
The particles-sparticles mixing induced by RPV lead to
tree-level LFV Higgs decays



$B\epsilon$ contribution



$B\lambda$ contribution



ϵ^2 contribution

Note: $\mathcal{L}_{soft} \supset B \tilde{L} H_u$

$H \to \mu\tau$ in RPV

A. Arhrib, Y. Cheng, O. Kong
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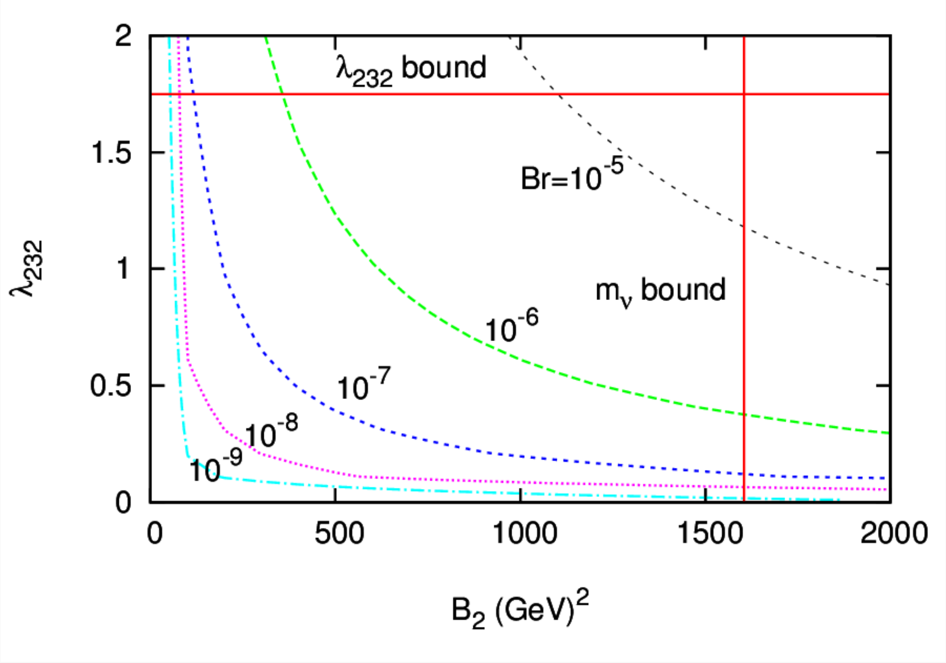


RPV Parameter Combinations	Br with Neutrino Mass $\lesssim 1$ eV Constraint
$B_2\,\mu_3$	1×10^{-15}
$B_3\,\mu_2$	1×10^{-13}
$B_1\,\lambda_{123}$	1×10^{-5}
$B_1\,\lambda_{132}$	3×10^{-5}
$B_2\,\lambda_{232}$	3×10^{-5}
$B_3\,\lambda_{233}$	3×10^{-5}
$\mu_2\,\mu_3$	2×10^{-18}
$B_1\,A^\lambda_{123}$	5×10^{-11}
$B_1\,A^\lambda_{132}$	5×10^{-11}
$B_2\,A^\lambda_{232}$	5×10^{-11}
$B_3\,A^\lambda_{233}$	5×10^{-11}

Current limits: $\text{Br} \lesssim 0.1$ Harnik et al, JHEP 1303 (2013) 026 [arXiv:1209.1397]

LHC sensitivity: $\text{Br} \sim 10^{-3}$ Davidson, Verdier, PRD 86 (2012) 111701 [arXiv:1211.1248]

$20\,fb^{-1}$ at $\sqrt{s} = 8\,\text{TeV}$

Spontaneous R-parity violation

Extended RPV models sometimes break R-parity spontaneously

The first models of spontaneous R-parity violation broke lepton number by the VEV of a left-handed sneutrino

C.S. Aulakh and R.N. Mohapatra
Phys. Lett. B 119 (1982) 136
$\text{MSSM with } \langle \tilde{\nu}_L^i \rangle = v_i \neq 0$

$\Rightarrow$

L violation
Neutrino masses
Goldstone boson, J

$$J = Im\Big(\sum_i \frac{v_i}{v_L} \tilde{\nu}_L^i + \frac{v_L}{v^2} (v_d H_d^0 - v_u H_u^0) \Big) \quad \Rightarrow \quad \textbf{Doublet majoron}$$

Ruled out by LEP: Large contribution to the invisible Z width

Spontaneous R-parity violation

However, one can build more sofisticated models where R-parity is broken by the VEV of a gauge singlet

A. Masiero and J.W.F. Valle, Phys. Lett. B 251, 273 (1990)

$$\mathcal{W} = \mathcal{W}_{\rm MSSM} + Y_\nu^i \hat{L}_i \hat{\nu}^c \hat{H}_u - h_0 \hat{H}_d \hat{H}_u \hat{\Phi} + h \hat{\Phi} \hat{\nu}^c \hat{S} + \frac{\lambda}{3!} \hat{\Phi}^3$$

$$J \simeq Im \left(\frac{v_S}{V} \tilde{S} - \frac{v_R}{V} \tilde{\nu}_R \right)$$

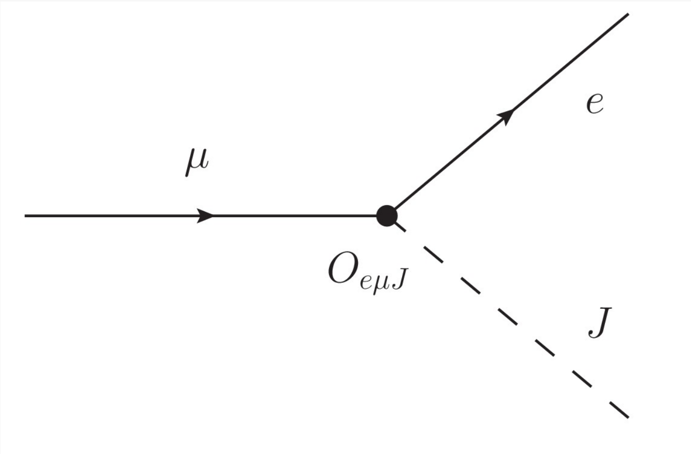
Singlet majoron
It evades the invisible Z width bound

Note: One can also gauge B-L, see for example V. Barger et al, PRL 102 (2009) 181802

Exotic muon decays

N. Rius, J.C. Romao and J.W.F. Valle, Nuc. Phys. B 363, 369 (1991)
TRIUMF experiment: A. Jodidio et al, Phys. Rev. D 34, 1967 (1986)

$$\mu \to eJ$$



$$O_{e\mu J} \sim \frac{1}{v_R} \times \text{RPV parameters}$$

- The branching ratio can be measurable for low values of v_R
- Possible improvement: $\mu \to eJ\gamma$ does not have the background coming from $\mu \to e\nu\nu$
- Current experimental bound: $\text{Br}(\mu \to eJ) \lesssim 10^{-5}$ [TRIUMF]

Exotic muon decays

M. Hirsch, J. Meyer, W. Porod, AV, PRD 79 (2009) 055023

$$\mu \to e J \gamma$$

$$\text{Br}(\mu \to e J \gamma) = \frac{\alpha}{2\pi} \mathcal{I}(x_{min}, y_{min}) \text{Br}(\mu \to e J)$$

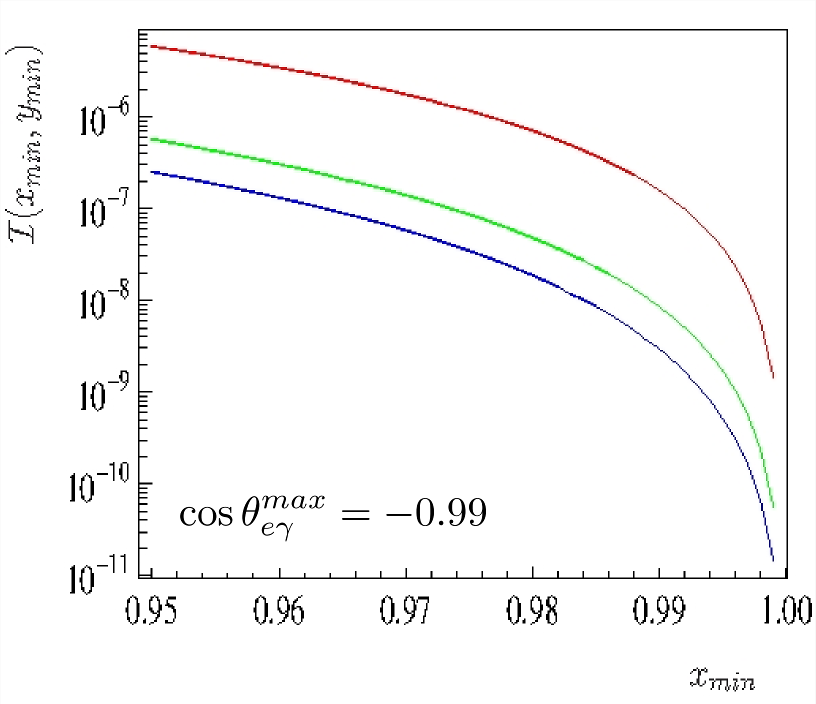
$\mathcal{I}(x_{min}, y_{min})$ is a phase space integral that depends on

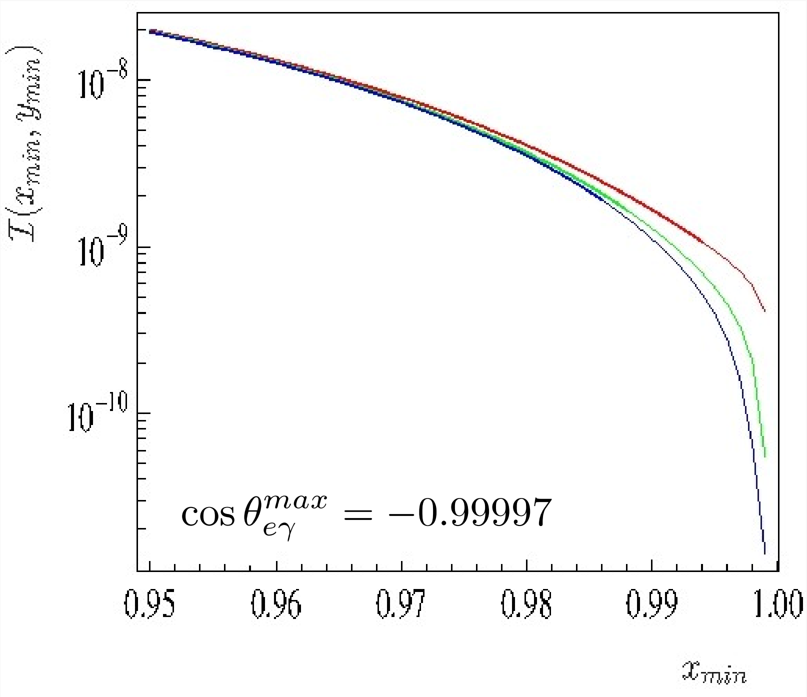
- Kinematics
- Experimental cuts ($x_{min} \equiv \frac{2E_e^{min}}{m_\mu}$ and $y_{min} \equiv \frac{2E_\gamma^{min}}{m_\mu}$)

Can the MEG experiment look for this decay?

Exotic muon decays

M. Hirsch, J. Meyer, W. Porod, AV, PRD 79 (2009) 055023





MEG experiment :

$$x_{min} = 0.995$$

$$y_{min} = 0.99$$

$$\cos\theta_{e\gamma}^{max} = -0.99997$$
$$(|\pi - \theta_{e\gamma}| \leq 8.4\,\mathrm{mrad})$$

$$\Rightarrow \quad \mathcal{I} \simeq 6 \cdot 10^{-10}$$

MEG suffers from small phase space integral

Exotic muon decays

M. Hirsch, J. Meyer, W. Porod, AV, PRD 79 (2009) 055023

$\mu \to e J \gamma$

Strategy: Relax the kinematical cuts

Problem: Leads to a dramatic increase of the background

Accidental background due to positron annihilation in flight → Better timing resolution?

Prompt background due to muon radiative decay $\mu \to e \nu \nu \gamma$ → Kinematical information might allow to discriminate

Final remarks

Final remarks

- In the MSSM neutrinos are massless: we definitely need to go beyond!
- **Example 1:** Z-penguins in models with extended lepton sector. One expects $\mathrm{CR}_{\mu-e}\,,\ \mathrm{Br}(\mu \to 3e) \gg \mathrm{Br}(\mu \to e\gamma)$
- **Example 2:** RPV SUSY. More exotic signatures can be found.

It is in fact quite easy to find a non-standard CLFV phenomenology!

Thank you!

Backup slides

Photon penguin contributions

E. Arganda and M.J. Herrero, PRD 73 (2006) 055003

$$A_a^{L,R} = A_a^{(n)L.R} + A_a^{(c)L,R}, \quad a = 1,2$$

$$\begin{aligned}
A_1^{(n)L} &= \frac{1}{576\pi^2} N_{iAX}^R N_{jAX}^{R*} \frac{1}{m_{\tilde{l}_X}^2} \frac{2 - 9x_{AX} + 18x_{AX}^2 - 11x_A^3 + 6x_{AX}^3 \log x_{AX}}{(1-x_{AX})^4} \\
A_2^{(n)L} &= \frac{1}{32\pi^2} \frac{1}{m_{\tilde{l}_X}^2} \left[N_{iAX}^L N_{jAX}^{L*} \frac{1 - 6x_{AX} + 3x_{AX}^2 + 2x_{AX}^3 - 6x_{AX}^2 \log x_{AX}}{6(1-x_{AX})^4} \right. \\
&+ N_{iAX}^R N_{jAX}^{R*} \frac{m_{l_i}}{m_{l_j}} \frac{1 - 6x_{AX} + 3x_{AX}^2 + 2x_{AX}^3 - 6x_{AX}^2 \log x_{AX}}{6(1-x_{AX})^4} \\
&+ \left. N_{iAX}^L N_{jAX}^{R*} \frac{m_{\tilde{\chi}_A^0}}{m_{l_j}} \frac{1 - x_{AX}^2 + 2x_{AX} \log x_{AX}}{(1-x_{AX})^3} \right] \\
A_a^{(n)R} &= \left. A_a^{(n)L} \right|_{L \leftrightarrow R}
\end{aligned}$$

where $x_{AX} = m_{\tilde{\chi}_A^0}^2 / m_{\tilde{l}_X}^2$

Photon penguin contributions

E. Arganda and M.J. Herrero, PRD 73 (2006) 055003

$$A_1^{(c)L} = -\frac{1}{576\pi^2} C^R_{iAX} C^{R*}_{jAX} \frac{1}{m^2_{\tilde{\nu}_X}} \frac{16 - 45x_{AX} + 36x^2_{AX} - 7x^3_A + 6(2 - 3x_{AX})\log x_{AX}}{(1 - x_{AX})^4}$$

$$\begin{aligned} A_2^{(c)L} &= -\frac{1}{32\pi^2} \frac{1}{m^2_{\tilde{\nu}_X}} \left[C^L_{iAX} C^{L*}_{jAX} \frac{2 + 3x_{AX} - 6x^2_{AX} + x^3_{AX} + 6x_{AX}\log x_{AX}}{6\,(1 - x_{AX})^4} \right. \\ &+ C^R_{iAX} C^{R*}_{jAX} \frac{m_{l_i}}{m_{l_j}} \frac{2 + 3x_{AX} - 6x^2_{AX} + x^3_{AX} + 6x_{AX}\log x_{AX}}{6\,(1 - x_{AX})^4} \\ &+ \left. C^L_{iAX} C^{R*}_{jAX} \frac{m_{\tilde{\chi}^-_A}}{m_{l_j}} \frac{-3 + 4x_{AX} - x^2_{AX} - 2\log x_{AX}}{(1 - x_{AX})^3} \right] \end{aligned}$$

$$A_a^{(c)R} = A_a^{(c)L}\Big|_{L\leftrightarrow R}$$

$$\text{where } x_{AX} = m^2_{\tilde{\chi}^-_A} / m^2_{\tilde{\nu}_X}$$

Z-penguin contributions

E. Arganda and M.J. Herrero, PRD 73 (2006) 055003

$$F_{L(R)} = F_{L(R)}^{(n)} + F_{L(R)}^{(c)}$$

$$\begin{aligned}
F_L^{(n)} &= -\frac{1}{16\pi^2}\left\{N_{iBX}^R N_{jAX}^{R*}\left[2E_{BA}^{R(n)} C_{24}(m^2_{\tilde{l}_X}, m^2_{\tilde{\chi}^0_A}, m^2_{\tilde{\chi}^0_B}) - E_{BA}^{L(n)} m_{\tilde{\chi}^0_A} m_{\tilde{\chi}^0_B} C_0(m^2_{\tilde{l}_X}, m^2_{\tilde{\chi}^0_A}, m^2_{\tilde{\chi}^0_B})\right]\right.\\
&+ \left. N_{iAX}^R N_{jAY}^{R*}\left[2Q_{XY}^{\tilde{l}} C_{24}(m^2_{\tilde{\chi}^0_A}, m^2_{\tilde{l}_X}, m^2_{\tilde{l}_Y})\right] + N_{iAX}^R N_{jAX}^{R*}\left[Z_L^{(l)} B_1(m^2_{\tilde{\chi}^0_A}, m^2_{\tilde{l}_X})\right]\right\}\\
F_R^{(n)} &= \left. F_L^{(n)}\right|_{L\leftrightarrow R}\\
F_L^{(c)} &= -\frac{1}{16\pi^2}\left\{C_{iBX}^R C_{jAX}^{R*}\left[2E_{BA}^{R(c)} C_{24}(m^2_{\tilde{\nu}_X}, m^2_{\tilde{\chi}^-_A}, m^2_{\tilde{\chi}^-_B}) - E_{BA}^{L(c)} m_{\tilde{\chi}^-_A} m_{\tilde{\chi}^-_B} C_0(m^2_{\tilde{\nu}_X}, m^2_{\tilde{\chi}^-_A}, m^2_{\tilde{\chi}^-_B})\right]\right.\\
&+ \left. C_{iAX}^R C_{jAY}^{R*}\left[2Q_{XY}^{\tilde{\nu}} C_{24}(m^2_{\tilde{\chi}^-_A}, m^2_{\tilde{\nu}_X}, m^2_{\tilde{\nu}_Y})\right] + C_{iAX}^R C_{jAX}^{R*}\left[Z_L^{(l)} B_1(m^2_{\tilde{\chi}^-_A}, m^2_{\tilde{\nu}_X})\right]\right\}\\
F_R^{(c)} &= \left. F_L^{(c)}\right|_{L\leftrightarrow R}
\end{aligned}$$

Z-penguin contributions

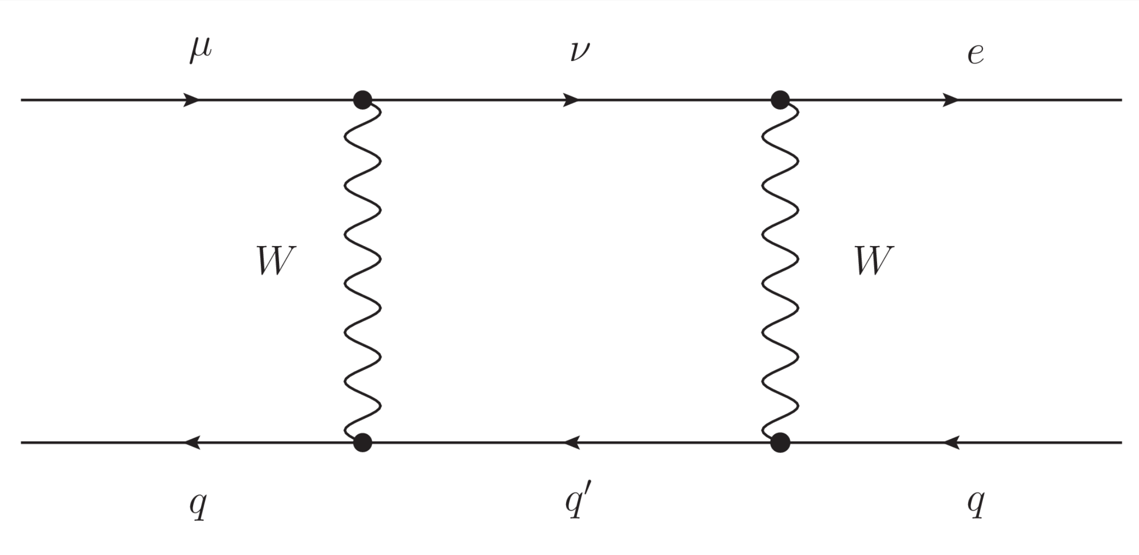
E. Arganda and M.J. Herrero, PRD 73 (2006) 055003

However, note that in the decay width one has

$$
\begin{aligned}
F_{LL} &= \frac{F_L Z_L^{(l)}}{g^2 \sin^2\theta_W m_Z^2} \\
F_{RR} &= F_{LL}|_{L\leftrightarrow R} \\
F_{LR} &= \frac{F_L Z_R^{(l)}}{g^2 \sin^2\theta_W m_Z^2} \\
F_{RL} &= F_{LR}|_{L\leftrightarrow R}
\end{aligned}
$$

Beyond the MSSM: Inverse Seesaw

Furthermore, for $\mu - e$ conversion in nuclei...



A. Ilakovac, A. Pilaftsis
PRD 80 (2009) 091902

D. N. Dinh, A. Ibarra, E. Molinaro, S. T. Petcov
JHEP 1208 (2012) 125

R. Alonso, M. Dhen, M. B. Gavela, T. Hambye
JHEP 1301 (2013) 118

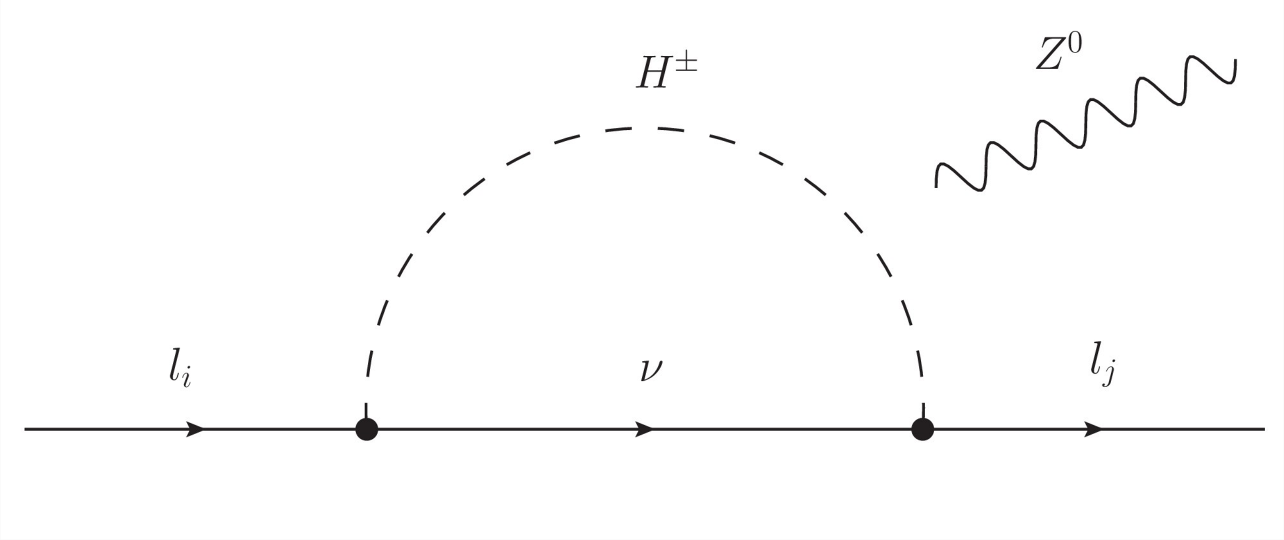
A. Ilakovac, A. Pilaftsis, L. Popov
arXiv:1212.5939

- Non-supersymmetric contribution
- Relevant for light singlet neutrinos
- Not completely understood in the literature

Non-SUSY scenarios

Is this effect restricted to SUSY models?
Is this effect related to some fundamental property of SUSY?

NO



The same behavior is found for this contribution: same Z-penguin enhancement!