Enhancing lepton flavor violation with the Z-penguin

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Based on work in collaboration with
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ArXiv:1202.1825 [hep-ph]

Outline of the talk

- $l_i \to 3l_j$ in the MSSM
- Some mass scaling considerations
- $l_i \to 3l_j$ in the MSSM revisited
- Beyond MSSM
- Final remarks

$l_i \to 3l_j$ in the MSSM

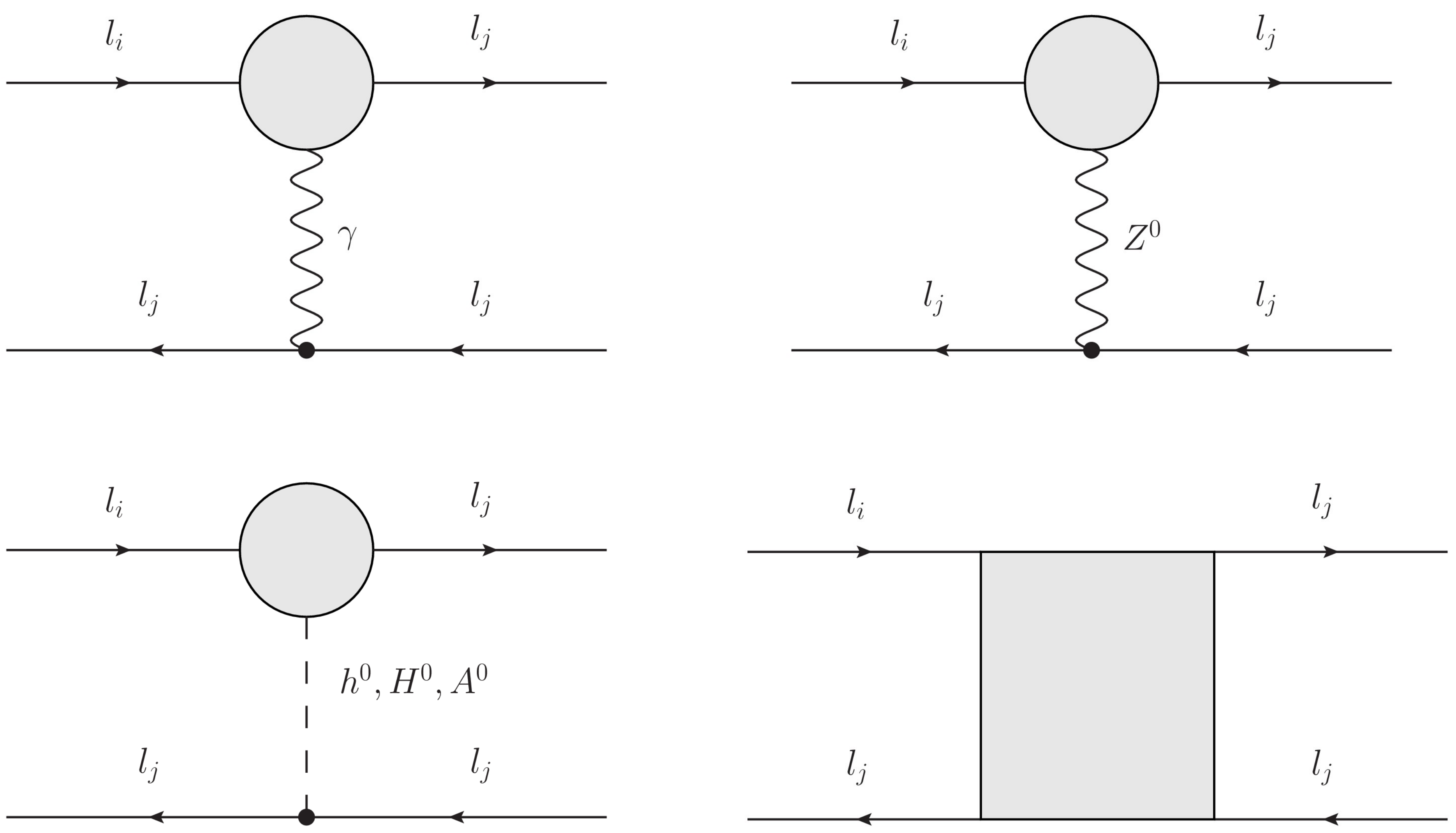
In supersymmetry, the additional degrees of freedom provided by the superparticles typically increase the flavor violating signals to observable levels.

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



$l_i \to 3l_j$ in the MSSM

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

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\begin{aligned}
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+ \quad & \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) \\
+ \quad & \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) \\
+ \quad & \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) \\
- \quad & \frac{1}{2}\left(\hat{B}_3^L B_4^{L*} + \hat{B}_3^R B_4^{R*} + h.c.\right) \\
+ \quad & \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\} \\
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- In most parts of parameter space: Photon penguins

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

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

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

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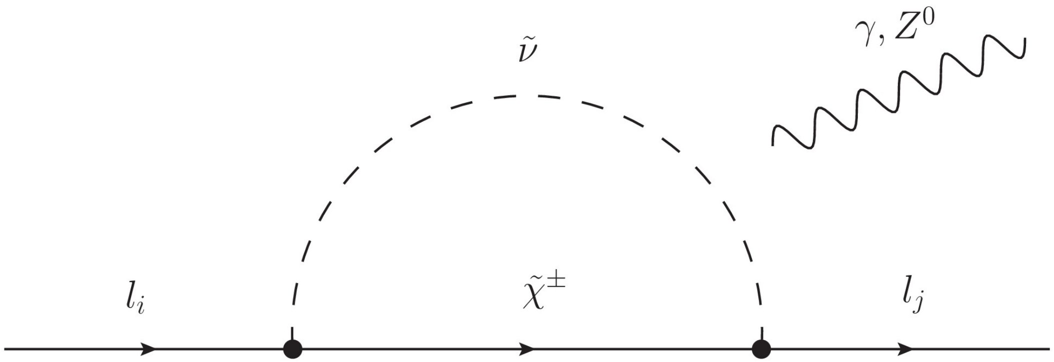
- For large $\tan\beta$ and a light pseudoscalar: Higgs penguins

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

Mass scaling considerations

Let us give a more detailed look...

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



One finds:

$$A_a^{(c)L,R} = \frac{1}{m_{\tilde{\nu}}^2} \mathcal{O}_{A_a}^{L,R} s(x^2)$$

γ - penguin

$$F_X = \frac{1}{g^2 \sin^2\theta_W m_Z^2} \mathcal{O}_{F_X}^{L,R} t(x^2)$$

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...

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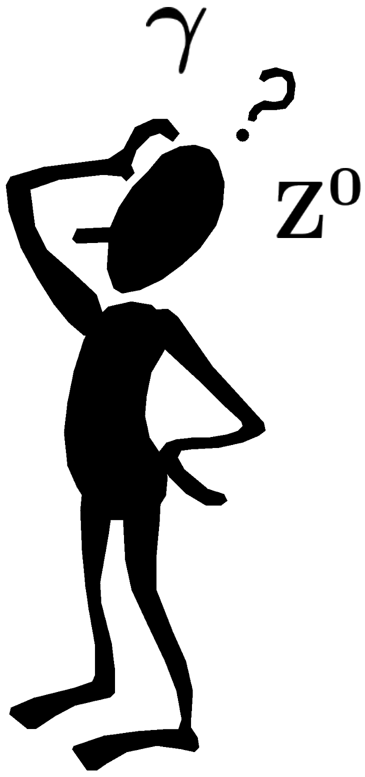
So...

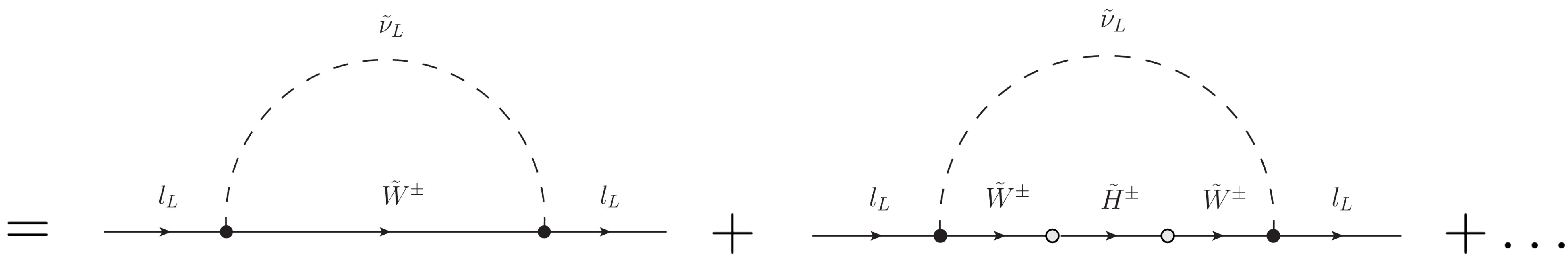
Why the Z-penguins are not the dominant contribution in the MSSM?



$l_i \to 3l_j$ in the MSSM revisited

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

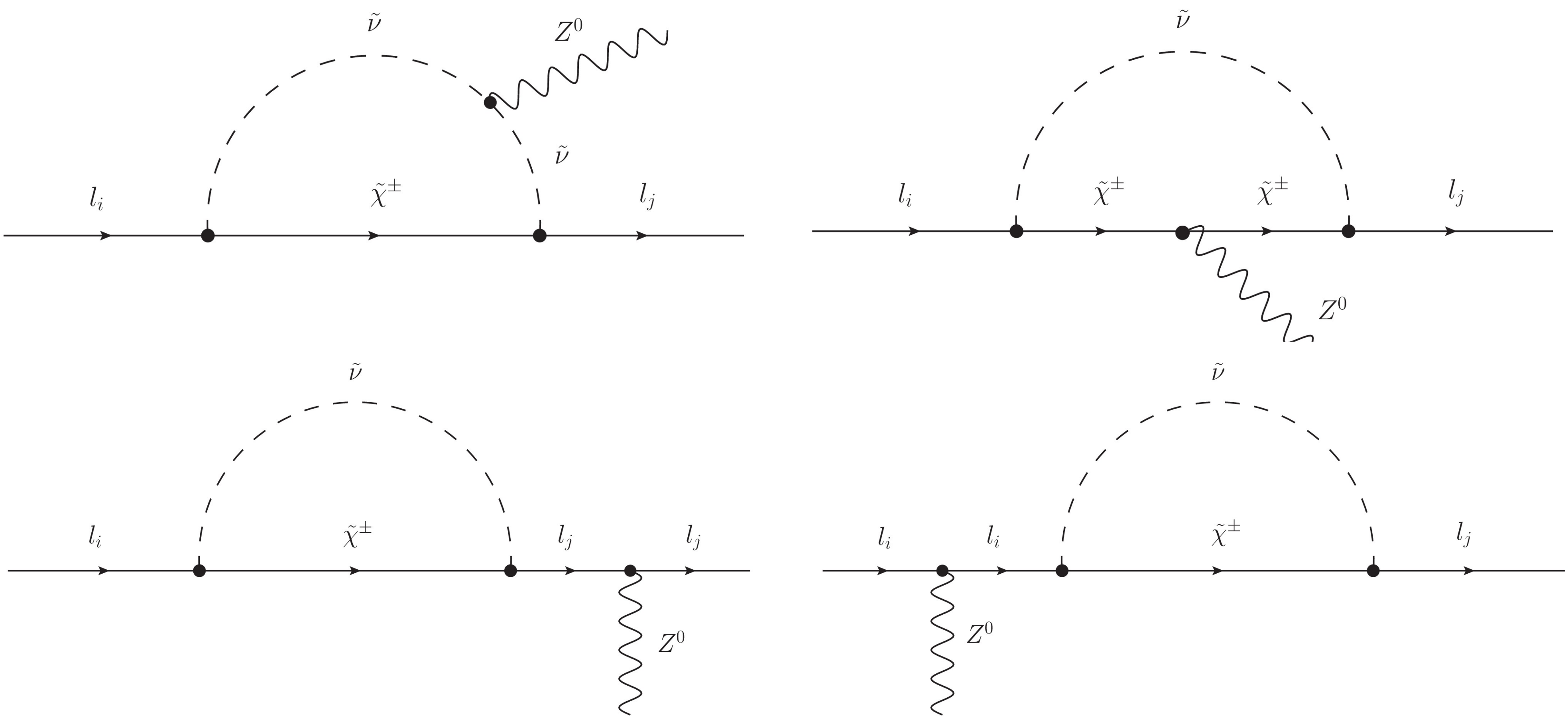
$$F_L = F_L^{(0)} + \theta^2_{\tilde{\chi}^\pm} F_L^{(2)} + \ldots$$



Important: There is no order 1!

$l_i \to 3l_j$ in the MSSM revisited

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



$l_i \to 3l_j$ 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

Beyond the MSSM

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

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

Beyond the MSSM

Example 1: Supersymmetric inverse seesaw. See Cédric's talk.

Example 2: MSSM + Trilinear R-parity violation

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Example 2: MSSM + Trilinear R-parity violation

$$W_R = W_{MSSM} + \frac{1}{2}\lambda_{ijk}\hat{L}_i\hat{L}_j\hat{E}^c_k$$

- Sneutrino-lepton loops are also possible in this case
- The new couplings break the cancellation since

$$\sum_k Z_V^{ki} Z_V^{kj*} \lambda_{jki}\lambda_{jkj} \neq 0$$

Great enhancement due to Z-boson penguins!

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Example 2: MSSM + Trilinear R-parity violation

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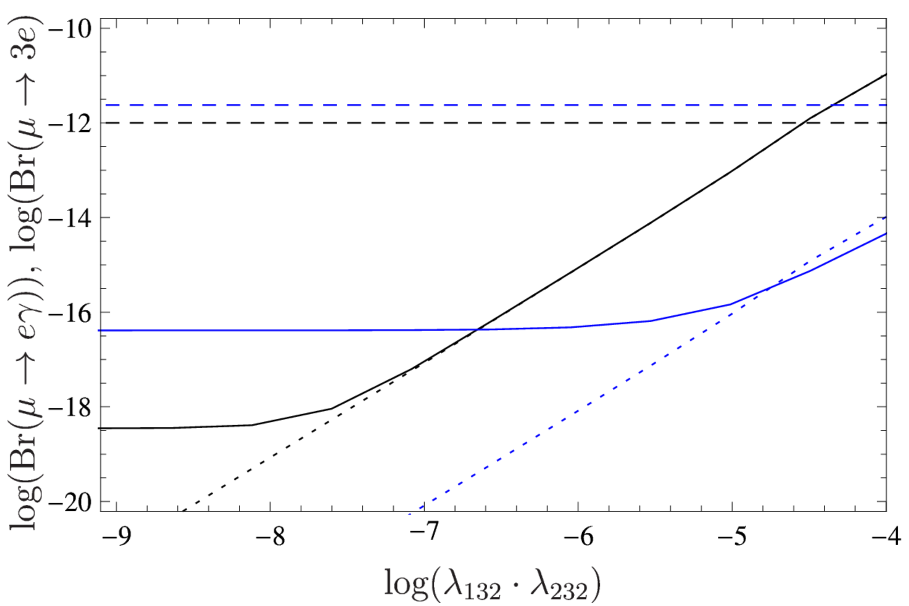

Black: $\mu \to 3e$
Blue: $\mu \to e\gamma$

Final remarks

- In the MSSM the Z-penguin contribution to $l_i \to 3l_j$ is usually neglected or regarded as sub-dominant. And that's totally correct!
- However, in many extensions of the lepton sector the Z-penguin becomes dominant, enhancing the signal by many orders of magnitude.
- In fact, one can easily find $BR(\mu \to 3e) \gg BR(\mu \to e\gamma)$
- $BR(\mu \to 3e)$ can be the most constraining observable!
- LFV studies should be re-considered and bounds re-evaluated.

Thank you!

Backup slides

Photon penguin contributions

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

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

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

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

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

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

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

Z-penguin contributions

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

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

$$\begin{aligned}
F_L^{(n)} &= -\frac{1}{16\pi^2}\Big\{N^R_{iBX}N^{R*}_{jAX}\Big[2E^{R(n)}_{BA}C_{24}(m^2_{\tilde{l}_X}, m^2_{\tilde{\chi}^0_A}, m^2_{\tilde{\chi}^0_B}) - E^{L(n)}_{BA}m_{\tilde{\chi}^0_A}m_{\tilde{\chi}^0_B}C_0(m^2_{\tilde{l}_X}, m^2_{\tilde{\chi}^0_A}, m^2_{\tilde{\chi}^0_B})\Big] \\
&+ N^R_{iAX}N^{R*}_{jAY}\Big[2Q^{\tilde{l}}_{XY}C_{24}(m^2_{\tilde{\chi}^0_A}, m^2_{\tilde{l}_X}, m^2_{\tilde{l}_Y})\Big] + N^R_{iAX}N^{R*}_{jAX}\Big[Z^{(l)}_L B_1(m^2_{\tilde{\chi}^0_A}, m^2_{\tilde{l}_X})\Big]\Big\} \\
F_R^{(n)} &= F_L^{(n)}\Big|_{L\leftrightarrow R} \\
F_L^{(c)} &= -\frac{1}{16\pi^2}\Big\{C^R_{iBX}C^{R*}_{jAX}\Big[2E^{R(c)}_{BA}C_{24}(m^2_{\tilde{\nu}_X}, m^2_{\tilde{\chi}^-_A}, m^2_{\tilde{\chi}^-_B}) - E^{L(c)}_{BA}m_{\tilde{\chi}^-_A}m_{\tilde{\chi}^-_B}C_0(m^2_{\tilde{\nu}_X}, m^2_{\tilde{\chi}^-_A}, m^2_{\tilde{\chi}^-_B})\Big] \\
&+ C^R_{iAX}C^{R*}_{jAY}\Big[2Q^{\tilde{\nu}}_{XY}C_{24}(m^2_{\tilde{\chi}^-_A}, m^2_{\tilde{\nu}_X}, m^2_{\tilde{\nu}_Y})\Big] + C^R_{iAX}C^{R*}_{jAX}\Big[Z^{(l)}_L B_1(m^2_{\tilde{\chi}^-_A}, m^2_{\tilde{\nu}_X})\Big]\Big\} \\
F_R^{(c)} &= F_L^{(c)}\Big|_{L\leftrightarrow R}
\end{aligned}$$

Z-penguin contributions

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

However, note that in the decay width one has

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