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Correlating neutralino decay modes with neutrino mixing angles

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Outline

1. Supersymmetry with and without R-parity
2. Neutrino physics in models with broken R-parity
3. LSP properties in models with broken R-parity
4. Summary

The Minimal Supersymmetric Standard Model (MSSM)

1. Particle content:
   - Each SM fermion has a scalar as superpartner.
   - There are two Higgs and two fermionic Higgsino doublets.
   - Each gauge boson has a fermionic superpartner, called gaugino.
2. Particle mixing: Particles like the neutral Higgsinos and the neutral gauginos mix to e.g. four Neutralinos:

$$\left(\psi^0\right)^T = \left(\tilde{B}, \tilde{W}_3^0, \tilde{H}_d^0, \tilde{H}_u^0\right) \qquad \longrightarrow \qquad \left(F^0\right)^T = \left(\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0\right)$$

3. Particle interactions: Interactions in supersymmetric theories are described by the superpotential W, which is in the MSSM given by:

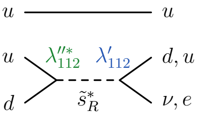
$$W_{\text{MSSM}} = \left(Y_u\right)_{ij} \widehat{Q}_i \widehat{H}_u \widehat{u}_j^c + \left(Y_d\right)_{ij} \widehat{H}_d \widehat{Q}_i \widehat{d}_j^c + \left(Y_e\right)_{ij} \widehat{H}_d \widehat{L}_i \widehat{e}_j^c - \mu \widehat{H}_d \widehat{H}_u$$

Remark: $\widehat{L}_i = (\widehat{\nu}_i, \widehat{e}_i)^T,\ \widehat{Q}_i = (\widehat{u}_i, \widehat{d}_i)^T,\ \widehat{H}_u = (\widehat{H}_u^+, \widehat{H}_u^0)^T,\ \widehat{H}_d = (\widehat{H}_d^0, \widehat{H}_d^-)^T$

Similar to the SM, the MSSM does not provide an explanation for neutrino masses. Nevertheless there are more terms $W_{\not R}$, which are invariant under SUSY- and gauge-transformations:

$$W_{\not R} = \frac{1}{2}\lambda_{ijk}\widehat{L}_i\widehat{L}_j\widehat{e}^c_k + \lambda'_{ijk}\widehat{L}_i\widehat{Q}_j\widehat{d}^c_k - \epsilon_i\widehat{L}_i\widehat{H}_u + \frac{1}{2}\lambda''_{ijk}\widehat{u}^c_i\widehat{d}^c_j\widehat{d}^c_k$$

$\Longrightarrow$ Strong restrictions from i.e. $p \to \pi^+\nu \;/\; \pi^0 e$:



$$\Longrightarrow \qquad \lambda'_{112}\lambda''^{*}_{112} \leq 2\cdot 10^{-27}\left(\frac{m_{\tilde{s}_R}}{100\text{GeV}}\right)^2$$

$\Longleftrightarrow$ All terms in $W_{\not R}$ are forbidden by R-parity $P_R = (-1)^{3(B-L)+2s}$, which is $P_R = +1$ for SM particles and $P_R = -1$ for SUSY partners.

Idea:

But allowing only L-violating terms explains neutrino physics and leads to a phenomenology, which is testable at the LHC.
We will now focus on the phenomenology of models with (effective) ϵ_i-terms.

Generation of a Majorana mass term for ν_i via the L-violating terms

In the basis

$$\left(\psi^0\right)^T = \left(\tilde{B}, \tilde{W}_3^0, \tilde{H}_d^0, \tilde{H}_u^0, \nu_1, \nu_2, \nu_3\right)$$

one can write $\mathcal{L}_{\text{neutral}}^{\text{mass}} = -\frac{1}{2}\left(\psi^0\right)^T \mathcal{M}_n \psi^0 + h.c.$ with

$$\mathcal{M}_n = \begin{pmatrix} M_n & m \\ m^T & 0 \end{pmatrix}.$$

- M_n mixes the 4 heavy states
- m mixes the heavy states with the neutrinos

This leads to an effective neutrino mass matrix m_{eff}, which is at NLO given by

$$(m_{\text{eff}})_{ij} = -\left(m^T M_n^{-1} m\right)_{ij} = a\Lambda_i\Lambda_j + b\left(\Lambda_i\epsilon_j + \epsilon_i\Lambda_j\right) + c\epsilon_i\epsilon_j$$

with $\Lambda_i = \mu v_i + v_d\epsilon_i$ and $\langle\tilde{\nu}_i\rangle = \frac{1}{\sqrt{2}}v_i$

Remark: Present neutrino data

From neutrino oscillations: mass differences $\Delta m^2_{ij} = m_i^2 - m_j^2$ between the different mass eigenstates and mixing angles:

parameter	best fit	2σ
$\Delta m^2_{21}[10^{-5}\text{eV}^2]$	$7.59^{+0.23}_{-0.18}$	$7.22 - 8.03$
$\|\Delta m^2_{31}\|[10^{-3}\text{eV}^2]$	$2.40^{+0.12}_{-0.11}$	$2.18 - 2.64$
$\tan^2\theta_{12} = \tan^2\theta_{sol}$	$0.466^{+0.033}_{-0.042}$	$0.41 - 0.56$
$\tan^2\theta_{23} = \tan^2\theta_{atm}$	$1.00^{+0.33}_{-0.21}$	$0.64 - 1.70$
$\tan^2\theta_{13} = \tan^2\theta_{R}$	$0.013^{+0.013}_{-0.009}$	≤ 0.041

[Schwetz et al., 2010, arXiv:0808.2016]

Example for fitting the neutrino data with the parameters of (m_{eff}):

$$\tan^2\theta_{atm} \approx \left(\frac{\Lambda_2}{\Lambda_3}\right)^2, \quad \tan^2\theta_{sol} \approx \left(\frac{\tilde{\epsilon}_1}{\tilde{\epsilon}_2}\right)^2, \qquad \tan^2\theta_R \approx \left(\frac{\Lambda_1}{\sqrt{{\Lambda_2}^2 + {\Lambda_3}^2}}\right)^2,$$

$\Longrightarrow$ Alignment parameter Λ_i fits atmospheric and ϵ_i solar scale.

What features do these R-parity violating models have?

- Neutrino data is explainable ($\not{R}$ via L-violating terms).
- Lightest supersymmetric particle (LSP) is not stable any more.
  $\Longrightarrow$ Decay length of **mm** up to several **km** $\Longleftrightarrow$ Displaced vertices
- Decay modes of LSP are correlated with the neutrino mixing angles.
- Special phenomenology in some of these models due to singlets states

$\Longrightarrow$ Testable at the LHC!

All the properties above are for example given in the $\mu\nu$SSM, which will be discussed in the following: [D.E. Lopéz-Fogliani and C. Muñoz, 2005]

$$W_{\mu\nu\text{SSM}} = (Y_u)_{ij}\,\widehat{Q}_i\widehat{H}_u\widehat{u}_j^c + (Y_d)_{ij}\,\widehat{H}_d\widehat{Q}_i\widehat{d}_j^c + (Y_e)_{ij}\,\widehat{H}_d\widehat{L}_i\widehat{e}_j^c$$

$$-\lambda\widehat{\nu}^c\widehat{H}_d\widehat{H}_u + (Y_\nu)_i\,\widehat{L}_i\widehat{H}_u\widehat{\nu}^c + \frac{1}{3!}\kappa\widehat{\nu}^c\widehat{\nu}^c\widehat{\nu}^c$$

$$\Leftrightarrow \mu = \lambda\left\langle\tilde{\nu}^c\right\rangle, \quad \epsilon_i = (Y_\nu)_i\left\langle\tilde{\nu}^c\right\rangle \text{ after EWSB}$$

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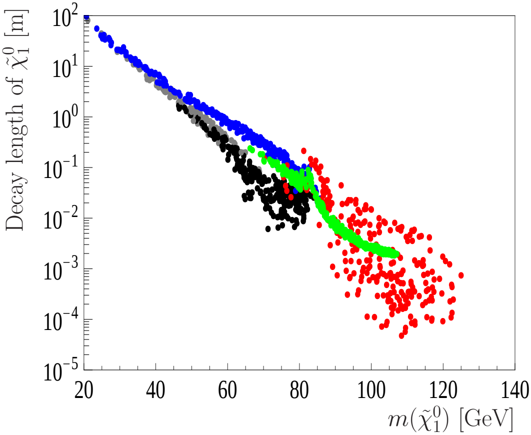
Total decay length for a singlino-type LSP $\tilde{\chi}_1^0 = \nu^c$

- $\lambda \in [0.2, 0.5]$
  $\kappa \in [0.025, 0.2]$
  $\mu \in [110, 170]$GeV
- SPS1a' (ν^c)
  SPS1a' (mixture)
  SPS3 (ν^c)
  SPS3 (mixture)
  SPS4 (mixture)
- $\{m(S_1^0), m(P_1^0)\} > m(\tilde{\chi}_1^0)$ by appropriate choice of $T_\kappa \in [-20, -0.05]$GeV

[Bartl, Hirsch, S.L, Porod, Vicente, arXiv:0903.3596]



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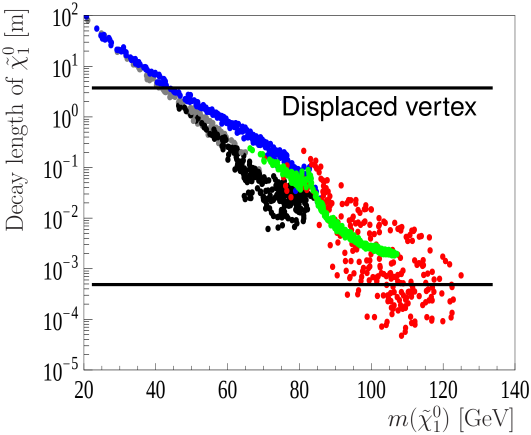


Decay modes of the lightest neutralino $\tilde{\chi}_1^0$ as LSP

Most important decay modes:

decay	$m_{\tilde{\chi}_1^0} < m_W$	$m_W < m_{\tilde{\chi}_1^0} < m_Z$	$m_Z < m_{\tilde{\chi}_1^0}$
$\tilde{\chi}_1^0 \to Z\nu_i$			•
$\tilde{\chi}_1^0 \to W^{\pm}l^{\mp}$		•	•
$\tilde{\chi}_1^0 \to S_i^0\nu_j$ / $P_i^0\nu_j$	○	○	○
$\tilde{\chi}_1^0 \to l_i^{\pm}l_j^{\mp}\nu_k$	•	•	•
$\tilde{\chi}_1^0 \to q_i\bar{q}_j l_k$	•	•	•

Also present: $\tilde{\chi}_1^0 \to 3\nu$ or $\tilde{\chi}_1^0 \to q_i\bar{q}_j\nu_k$

Notation:

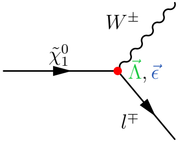
- • $\Longleftrightarrow$ Link to neutrino physics
- ○ $\Longleftrightarrow$ Masses of scalars and pseudoscalars crucial

Where does the correlation come from?

Consider the lightest neutralino $\tilde{\chi}_1^0 = \tilde{W}_3^0$ as LSP in the $\mu\nu$SSM.
Two-body decay: At tree level the left-handed W-$\tilde{\chi}_1^0$-l_i-coupling reads:

$$\mathcal{L} = \overline{l_i^-}\gamma^\mu \left(O_{Li}P_L + O_{Ri}P_R\right)\tilde{\chi}_1^0 W_\mu^- + h.c.$$

$$O_{Li} \approx \frac{g}{\sqrt{2}}\left[\frac{g\Lambda_i}{\det_+}N_{12} - \left(\frac{\epsilon_i}{\mu} + \frac{g^2 v_u \Lambda_i}{2\mu \det_+}\right)N_{13} - \sum_{j=1}^{5} N_{1j}\xi_{ij}\right]$$

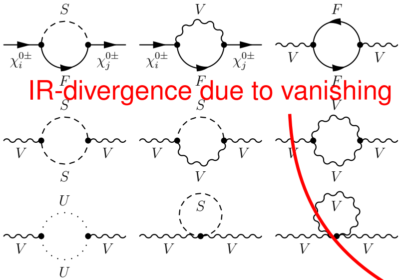


$$\Longrightarrow \frac{Br\left(\tilde{\chi}_1^0 \to W^-\mu^+\right)}{Br\left(\tilde{\chi}_1^0 \to W^-\tau^+\right)} \propto \left|\frac{O_{L2}}{O_{L3}}\right|^2 = \left(\frac{\Lambda_2}{\Lambda_3}\right)^2 \approx \tan^2\theta_{atm}$$

To maintain this correlation after calculating the one-loop Neutralino mass matrix one has to perform a complete NLO correction to the decay $\tilde{\chi}_1^0 \to W^\pm l^\mp$.

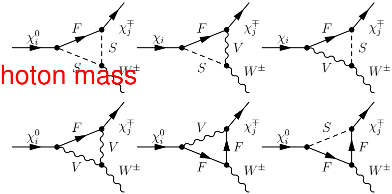
Electroweak contributions

Self energies:

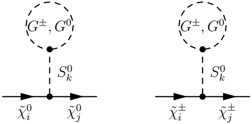


IR-divergence due to vanishing photon mass

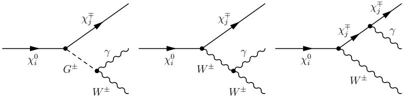
Vertex corrections:

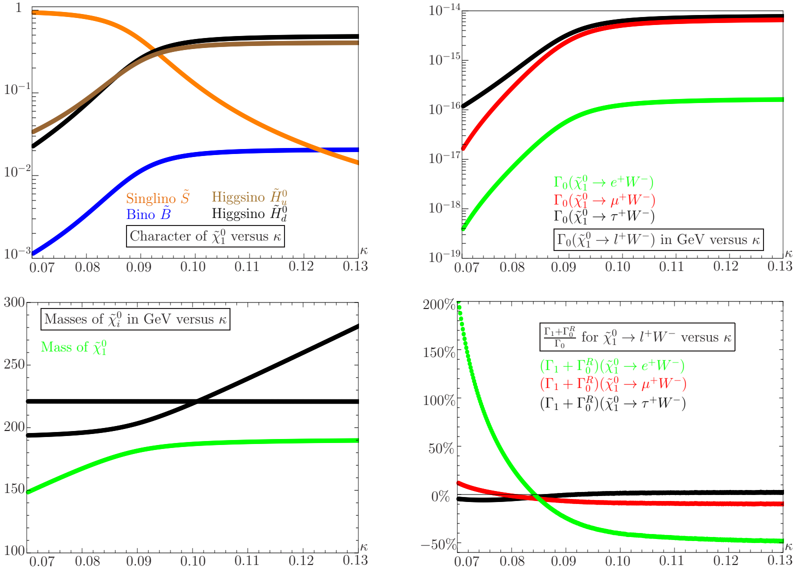


Pinch technique (for $\xi_V \neq 1$ relevant):



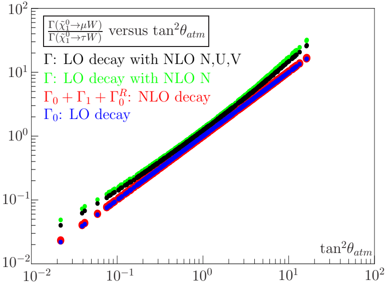
Real photon emission:



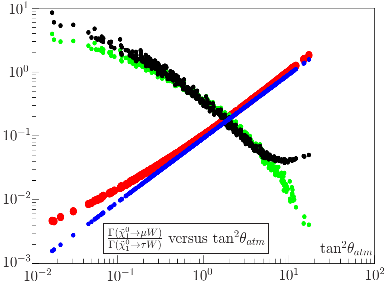

Singlino $\tilde{S}$
Higgsino $\tilde{H}_u^0$
Bino $\tilde{B}$
Higgsino $\tilde{H}_d^0$
Character of $\tilde{\chi}_1^0$ versus κ
$\Gamma_0(\tilde{\chi}_1^0 \to e^+W^-)$
$\Gamma_0(\tilde{\chi}_1^0 \to \mu^+W^-)$
$\Gamma_0(\tilde{\chi}_1^0 \to \tau^+W^-)$
$\Gamma_0(\tilde{\chi}_1^0 \to l^+W^-)$ in GeV versus κ
Masses of $\tilde{\chi}_i^0$ in GeV versus κ
Mass of $\tilde{\chi}_1^0$
$\frac{\Gamma_1+\Gamma_0^R}{\Gamma_0}$ for $\tilde{\chi}_1^0 \to l^+W^-$ versus κ
$(\Gamma_1+\Gamma_0^R)(\tilde{\chi}_1^0 \to e^+W^-)$
$(\Gamma_1+\Gamma_0^R)(\tilde{\chi}_1^0 \to \mu^+W^-)$
$(\Gamma_1+\Gamma_0^R)(\tilde{\chi}_1^0 \to \tau^+W^-)$
κ
0.07 0.08 0.09 0.10 0.11 0.12 0.13
1
10^{-1}
10^{-2}
10^{-3}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
300
250
200
150
100
200%
150%
100%
50%
0%
−50%

Finally we can compare the ratios of decay widths $\tilde{\chi}^0_1 \to l^+ W^-$ with the neutrino mixing angles:

Bino $\tilde{\chi}^0_1 = \tilde{B}$



Singlino $\tilde{\chi}^0_1 = \nu^c$



$\Longrightarrow$ The full NLO corrections show the behaviour predicted on tree-level!

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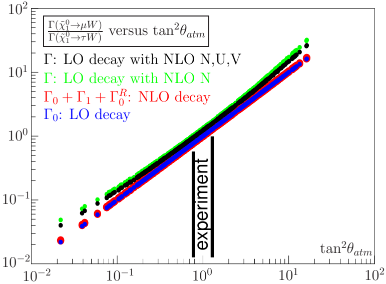

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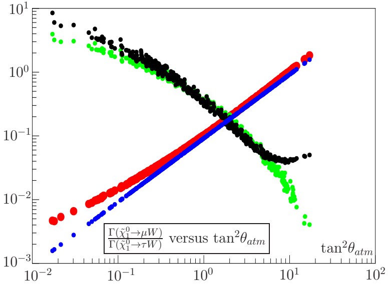


$\Longrightarrow$ The full NLO corrections show the behaviour predicted on tree-level!

Models with broken R-parity via (effective) ϵ_i-terms in SUSY theories ...

- ... provide an alternative ansatz to explain neutrino masses and mixings.
- ... show interesting correlations between decay modes and neutrino mixing angles. To maintain these tree-level relations a full NLO calculation is necessary. If some singlet neutralinos are light, interesting decay chains at the LHC could occur.
- ... are in complete agreement with experimental bounds on lepton flavor violating decays due to the smallness of L-violating parameters.
- ... can show interesting decay chains for e.g. the lightest SUSY Higgs.

Thank you for your attention!

Particle content of the $\mu\nu$SSM

MSSM + right-handed neutrino superfield $\widehat{\nu}^c$ with $L_{\widehat{\nu}^c} = -1$

The new, R-parity violating terms induce a mixing of the following flavor eigenstates to mass eigenstates:

- Neutralinos $\left(\tilde{B}, \tilde{W}_3^0, \tilde{H}_d^0, \tilde{H}_u^0, \nu^c, \nu_1, \nu_2, \nu_3\right)$

  $\Longrightarrow$ 5 heavy states including Singlino ν^c and three light states

- Scalars/Pseudoscalars $(H_d^0, H_u^0, \tilde{\nu}^c, \tilde{\nu}_1, \tilde{\nu}_2, \tilde{\nu}_3)$

  $\Longrightarrow$ Singlet scalar/pseudoscalar state $\tilde{\nu}^c$

Similar to BRPV and SRPV:

- Charginos $\left(\tilde{W}^-, \tilde{H}_d^-, e, \mu, \tau\right)$
- Charged Scalars $(H_d^-, H_u^+, \tilde{e}, \tilde{\mu}, \tilde{\tau}, \tilde{e}^c, \tilde{\mu}^c, \tilde{\tau}^c)$

Definition of the matrix $\xi = m^T M_n^{-1}$

The complete diagonalization of the neutral fermion mass matrix reads

$$\widehat{\mathcal{M}}_n = \mathcal{N}^* \mathcal{M}_n \mathcal{N}^\dagger \quad \text{with} \quad \mathcal{M}_n = \begin{pmatrix} M_n & m \\ m^T & 0 \end{pmatrix}$$

and can be done approximately with $\xi = m^T M_n^{-1}$ in the form

$$\mathcal{N}^* = \begin{pmatrix} N^* & 0 \\ 0 & \mathcal{V}^T \end{pmatrix} \begin{pmatrix} 1 - \frac{1}{2}\xi^\dagger \xi & \xi^\dagger \\ -\xi & 1 - \frac{1}{2}\xi\xi^\dagger \end{pmatrix}$$

resulting in

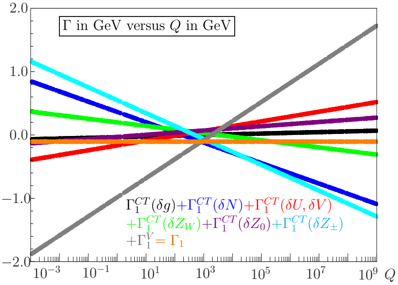
$$\mathcal{N}^* \mathcal{M}_n \mathcal{N}^\dagger \approx \begin{pmatrix} N^* & 0 \\ 0 & \mathcal{V}^T \end{pmatrix} \begin{pmatrix} M_n & 0 \\ 0 & -m^T M_n^{-1} m \end{pmatrix} \begin{pmatrix} N^\dagger & 0 \\ 0 & \mathcal{V} \end{pmatrix} \quad ,$$

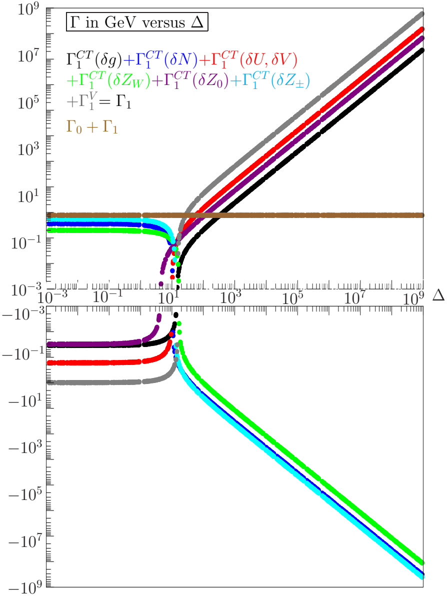
where in the 1-$\mu\nu$SSM the matrix ξ is given by

$$\xi_{ij} = K_\Lambda^j \Lambda_i - \frac{1}{\mu} \delta_{j3} \epsilon_i$$

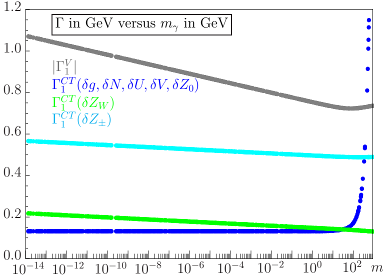
with K_Λ^j neither proportional to v_j nor $(Y_\nu)_j$.

Let's have a look at the dependence of the UV parameter Δ and the renormalization scale Q for a NMSSM Neutralino decay.



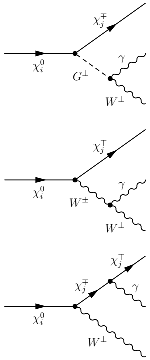


A massless photon produces IR divergences. Therefore one calculates with a photon with mass m_γ. But how to get rid of this dependence on an unphysical mass scale m_γ?

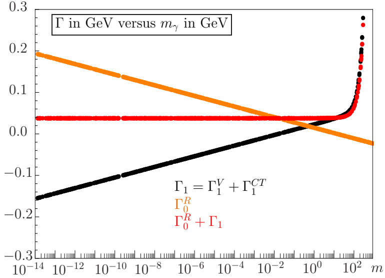


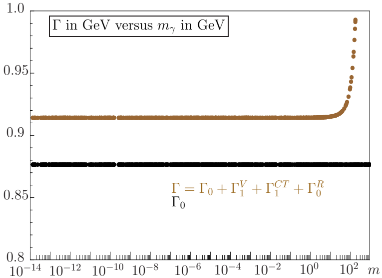
What is missing?

We have to take into account the real corrections coming from the emission of a photon with mass m_γ!



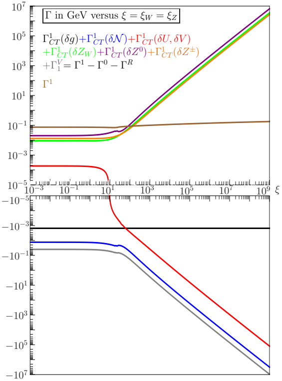
This can either be done by considering a cut-off energy for the real correction or by calculating the full hard photon emission, what was done here:

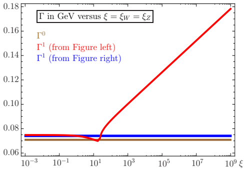


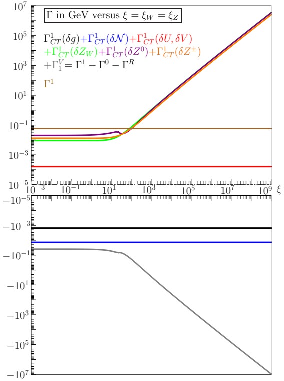


$\Longrightarrow$ The final decay width is IR finite.

Gauge dependence







Considering the possible extension of bilinear R-parity breaking, one can compare displaced vertex signals, completely invisible final state branching ratios for LSP decays and lightest Higgs decays:

	Displaced vertex	Comment	BR(Invis.)	Higgs decays
BRPV	Yes	Visible	≤ 10 %	standard
SRPV	Yes/No	anti-correlates with invisible	any	non-standard (invisible)
$\mu\nu$SSM	Yes/No	anti-correlates with non-standard Higgs	≤ 10 %	non-standard

Combining the NMSSM with BRPV results in the superpotential:

$$W_{\text{NMSSM+BRPV}} = W_{\text{all}} - \lambda \widehat{S}\widehat{H}_d\widehat{H}_u - \epsilon_i \widehat{L}_i \widehat{H}_u + \frac{1}{3!}\kappa\widehat{S}\widehat{S}\widehat{S}$$

This model is very hard to distinguish from the $\mu\nu$SSM, since in both a light singlet scalar/neutralino can be present.