Electroweak corrections to Neutralino decays in supersymmetric models with and without R-parity

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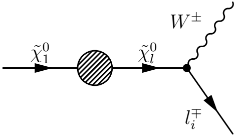
PHYSICS AT THE TERA SCALE
Helmholtz Alliance

Why do we consider R-parity violation at NLO?

Motivation for R-parity violation $\Longrightarrow$ Use L-violating terms to explain current neutrino data (via NLO corrected Neutralino mass matrix).
But:
In R-parity violating models the incomplete NLO correction



$\propto \Lambda_i, \epsilon_i$??

doesn't necessarily show the correlation to neutrino mixing angles as predicted on tree-level! We will discuss the following points:

- Introduction of the $\mu\nu$SSM: Explanation of neutrino data
- Features of LSP decays
- Relation between decay modes and neutrino mixing angles at NLO
- Examples in the NMSSM

Superpotential W in R-parity violating SUSY

All considered models have in common:

$$W_{\text{all}} = (Y_u)_{ij}\,\widehat{Q}_i\widehat{H}_u\widehat{u}^c_j + (Y_d)_{ij}\,\widehat{H}_d\widehat{Q}_i\widehat{d}^c_j + (Y_e)_{ij}\,\widehat{H}_d\widehat{L}_i\widehat{e}^c_j$$

The superpotentials of the MSSM and NMSSM are then given by:

no bilinear coupling!

$$W_{\text{MSSM}} = W_{\text{all}} - \mu\widehat{H}_d\widehat{H}_u$$

$$W_{\text{NMSSM}} = W_{\text{all}} - \lambda\widehat{\Phi}\widehat{H}_d\widehat{H}_u + \frac{1}{3!}\kappa\widehat{\Phi}\widehat{\Phi}\widehat{\Phi} \quad \Leftrightarrow \quad \mu = \lambda\langle\Phi\rangle \text{ after EWSB}$$

Starting with the bilinear model (ϵ_i-term), one can use a similar ansatz:

no bilinear coupling!

$$W_{\text{BRPV}} = W_{\text{all}} - \mu\widehat{H}_d\widehat{H}_u - \epsilon_i\widehat{L}_i\widehat{H}_u$$

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

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

$\mu\nu$SSM: Proposal by D.E. Lopéz-Fogliani and C. Muñoz, 2005

Use right-handed neutrino superfield $\widehat{\nu}^c$ with $L_{\widehat{\nu}^c} = -1$ to solve μ-problem and to generate effective ϵ_i-terms!
Since $L_{\widehat{\nu}^c} = -1$ R-parity already broken before EWSB!

Why do these L-violating terms explain neutrino physics?

In the basis

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

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 5 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

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

with $\Lambda_i = \mu v_i + v_d\epsilon_i$

including $\mu = \lambda \langle\tilde{\nu}^c\rangle$ and $\epsilon_i = \left(Y_\nu\right)_i \langle\tilde{\nu}^c\rangle$.

Remark: Present neutrino data

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

parameter	best fit	2σ
$\Delta m_{21}^2 [10^{-5}\text{eV}^2]$	$7.65^{+0.23}_{-0.20}$	$7.25 - 8.11$
$\lvert\Delta m_{31}^2\rvert [10^{-3}\text{eV}^2]$	$2.40^{+0.12}_{-0.11}$	$2.18 - 2.64$
$\tan^2\theta_{sol}$	$0.438^{+0.046}_{-0.034}$	$0.37 - 0.54$
$\tan^2\theta_{atm}$	$1.00^{+0.33}_{-0.21}$	$0.64 - 1.70$
$\tan^2\theta_R$	$0.010^{+0.017}_{-0.010}$	≤ 0.042

Schwetz, 2008, 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 atmoshperic 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 $\mu\nu$SSM due to singlets states

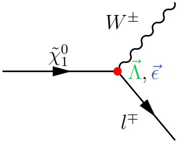
$\Longrightarrow$ Testable at future colliders (LHC and ILC)!

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:

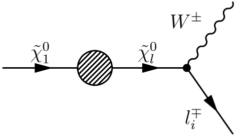
$$\mathcal{L} = \overline{l_i^-}\gamma^\mu\left(O_{Li}P_L + O_{Ri}P_R\right)\tilde{\chi}_1^0 W_\mu^- + h.c.$$

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



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

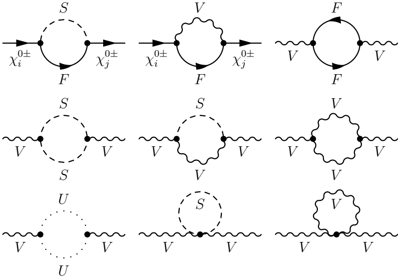
The branching ratios of $\tilde{\chi}_1^0 \to W^\pm l_i$ with the Singlino $\tilde{\chi}_1^0 = \nu^c$ should on tree-level be proportinal to Λ_i, but they aren't after the incomplete one-loop correction:



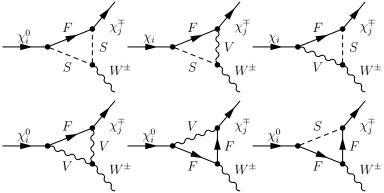
$\propto \Lambda_i, \epsilon_i$??

Electroweak contributions:

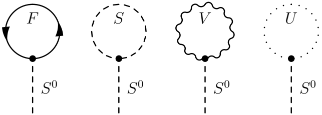
Self energies:



Vertex corrections:

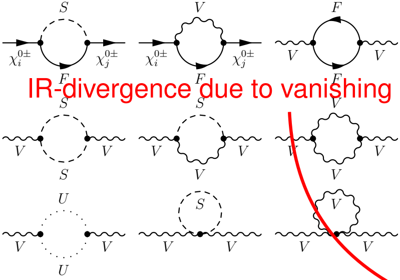


Shifting the vacuum structure:



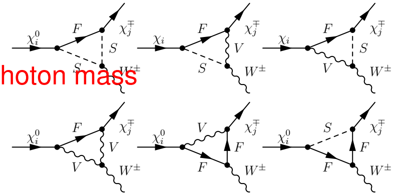
Electroweak contributions:

Self energies:

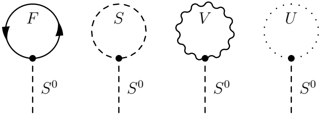


IR-divergence due to vanishing photon mass

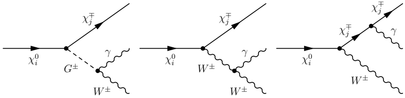
Vertex corrections:

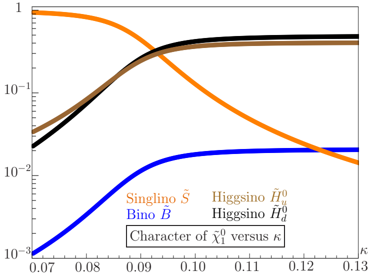


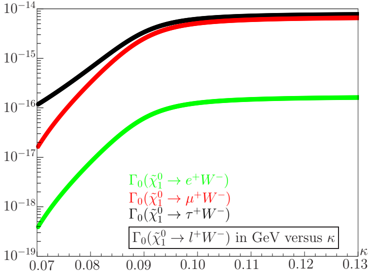
Shifting the vacuum structure:

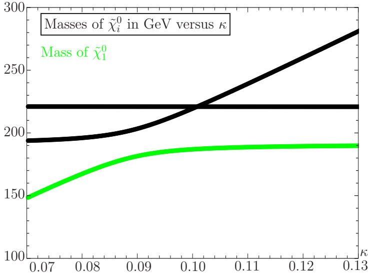


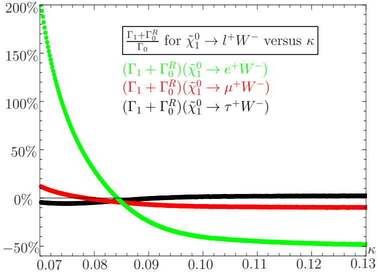
Real photon emission:




Singlino $\tilde{S}$
Higgsino $\tilde{H}_u^0$
Bino $\tilde{B}$
Higgsino $\tilde{H}_d^0$
Character of $\tilde{\chi}_1^0$ versus κ
1
10^{-1}
10^{-2}
10^{-3}
0.07
0.08
0.09
0.10
0.11
0.12
0.13
κ

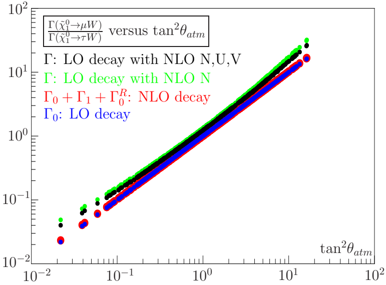

$\Gamma_0(\tilde{\chi}_1^0 \to e^+W^-)$
$\Gamma_0(\tilde{\chi}_1^0 \to \mu^+W^-)$
$\Gamma_0(\tilde{\chi}_1^0 \to \tau^+W^-)$
$\Gamma_0(\tilde{\chi}_1^0 \to l^+W^-)$ in GeV versus κ
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
0.07
0.08
0.09
0.10
0.11
0.12
0.13
κ


Masses of $\tilde{\chi}_i^0$ in GeV versus κ
Mass of $\tilde{\chi}_1^0$
300
250
200
150
100
0.07
0.08
0.09
0.10
0.11
0.12
0.13
κ

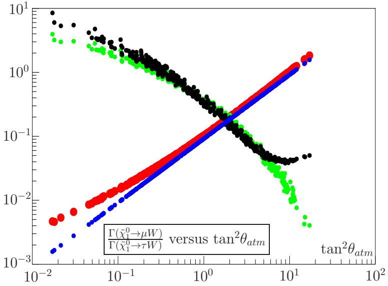

$\frac{\Gamma_1+\Gamma_0^R}{\Gamma_0}$ for $\tilde{\chi}_1^0 \to l^+W^-$ versus κ
$(\Gamma_1 + \Gamma_0^R)(\tilde{\chi}_1^0 \to e^+W^-)$
$(\Gamma_1 + \Gamma_0^R)(\tilde{\chi}_1^0 \to \mu^+W^-)$
$(\Gamma_1 + \Gamma_0^R)(\tilde{\chi}_1^0 \to \tau^+W^-)$
200%
150%
100%
50%
0%
−50%
0.07
0.08
0.09
0.10
0.11
0.12
0.13
κ

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

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



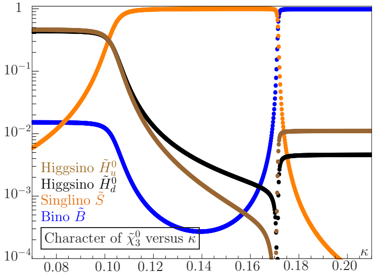
Singlino $\tilde{\chi}_1^0 = \nu^c$

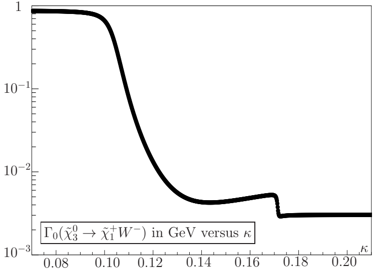


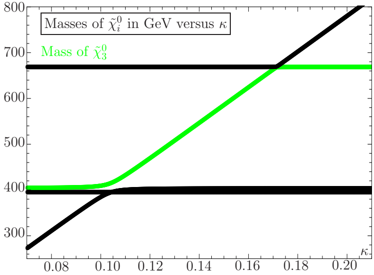
$\Longrightarrow$ The full NLO corrections show the desired behaviour!

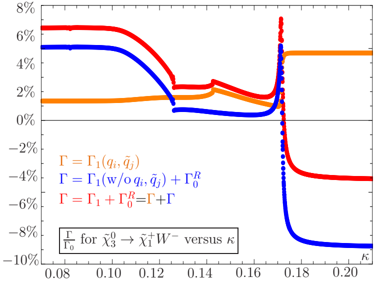
Example in the NMSSM

NLO corrections to $\tilde{\chi}_3^0 \to \tilde{\chi}_1^+ W^-$









Summary:

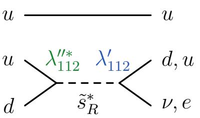
- Electroweak corrections using an on-shell scheme become very important in R-parity violating supersymmetry. (This doesn't imply that the perturbation series is senseless!)
- They preserve the correlations between decay modes and neutrino mixing angles as predicted on tree-level.
- They typcially provide corrections of up to 20% to the decays of Neutralinos and Charginos in the MSSM or NMSSM.
- Electroweak corrections using an on-shell scheme show the same technical behaviour as in the Standard Model.

Thank you for your attention!

Why not adding the following terms $W = W_{\text{MSSM/NMSSM}} + W_{\not{R}}$?

$$W_{\not{R}} = \epsilon_{ab}\left(\frac{1}{2}\lambda_{ijk}\widehat{L}_i^a\widehat{L}_j^b\widehat{e}_k^c + \lambda'_{ijk}\widehat{L}_i^a\widehat{Q}_j^b\widehat{d}_k^c - \epsilon_i\widehat{L}_i^a\widehat{H}_u^b\right) + \frac{1}{2}\lambda''_{ijk}\widehat{u}_i^c\widehat{d}_j^c\widehat{d}_k^c$$

All terms of $W_{\not{R}}$ are invariant under SUSY- and gauge transformations.
$\Longrightarrow$ Strong restrictions from i.e. $p \to \pi^+\nu \;/\; \pi^0 e$:



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

$\Longleftrightarrow$ 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.
My work focuses on models with (effective) ϵ_i-terms.

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 $(Y_\nu)_j$.

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

Most important decay modes:

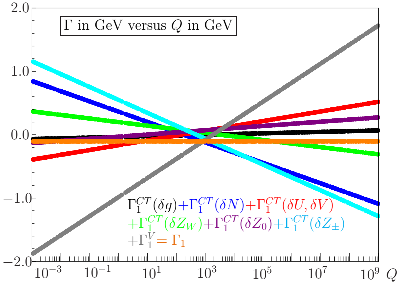
decay	$m_{\tilde{\chi}_1^0} < m_W$	$m_W < m_{\tilde{\chi}_1^0} < m_Z$	$m_Z < m_{\tilde{\chi}_1^0}$
$\tilde{\chi}_1^0 \to Z\nu_i$			●
$\tilde{\chi}_1^0 \to W^{\pm}l^{\mp}$		●	●
$\tilde{\chi}_1^0 \to S_i^0\nu_j$ / $P_i^0\nu_j$	○	○	○
$\tilde{\chi}_1^0 \to l_i^{\pm}l_j^{\mp}\nu_k$	●	●	●
$\tilde{\chi}_1^0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

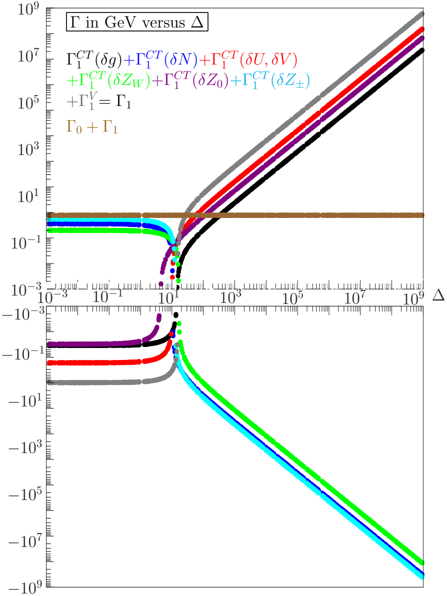
Also present: $\tilde{\chi}_1^0 \to 3\nu$ or $\tilde{\chi}_1^0 \to q_i\bar{q}_j\nu_k$

Notation:

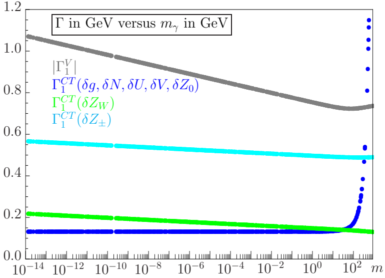
- ● $\Longleftrightarrow$ Link to neutrino physics
- ○ $\Longleftrightarrow$ Masses of scalars and pseudoscalars crucial

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



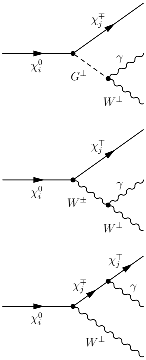


A massless photon produces IR divergences. Therefore one calculates with a photon with mass m_γ. But how to get rid of this dependence on an unphysical mass scale m_γ?

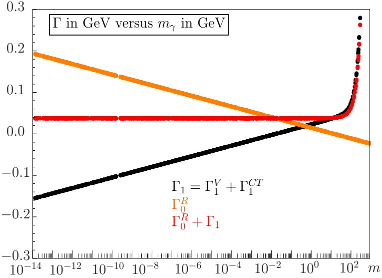


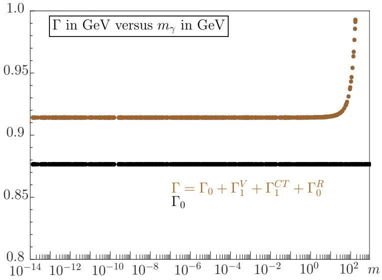
What is missing?

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.

A last problem, which we want to address, are gauge dependences. As in electrodynamics the theory is invariant under gauge transformations. A commonly used gauge fixing are the so called R_ξ-gauges:

$$\mathcal{L}_{\text{fix}} = -\frac{1}{2\xi_\gamma}\left(\partial^\mu A_\mu\right)^2 - \frac{1}{2\xi_Z}\left(\partial^\mu Z_\mu - M_Z \xi_Z' \phi\right)^2 - \frac{1}{2\xi_W}\left(\partial^\mu W_\mu^+ - iM_W \xi_W' \phi^+\right)\left(\partial^\mu W_\mu^- + iM_W \xi_W' \phi^-\right)$$

In the t'Hooft-Feynman-gauge the gauge parameters ξ_V and ξ_V' are choosen equal and appear at several stages in the calculation:

- propagators of the gauge bosons

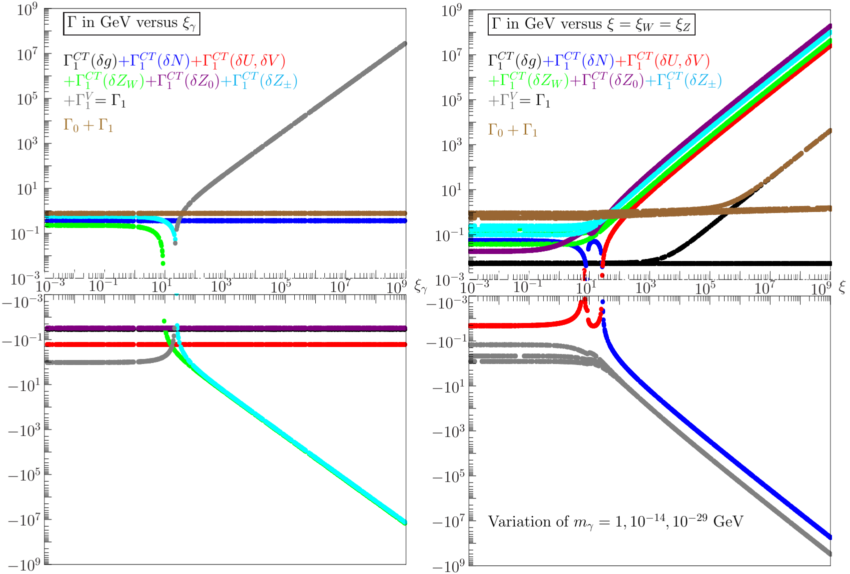
$$G_V^{\mu\nu}(p^2) = \frac{g^{\mu\nu}}{p^2 - m_V^2} - (1 - \xi_V)\frac{p^\mu p^\nu}{(p^2 - m_V^2)(p^2 - \xi_V m_V^2)}$$

- masses of the goldstone bosons and the ghosts

$$m_{G_V} = \xi_V m_V^2 \qquad \text{and} \qquad m_{U_V} = \xi_V m_V^2$$

- scalar-ghost-ghost couplings

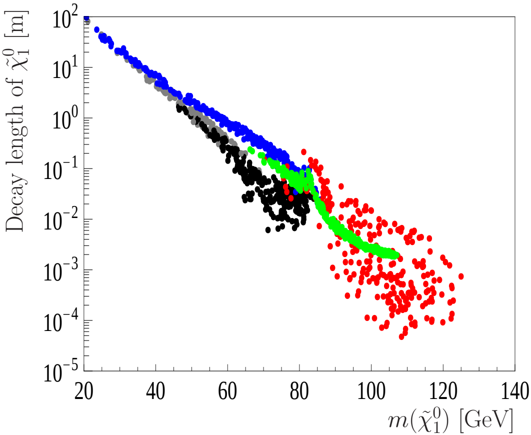
$\Longrightarrow$ The final result should be independent of the parameters ξ_V!


Γ in GeV versus ξ_γ
$\Gamma_1^{CT}(\delta g)+\Gamma_1^{CT}(\delta N)+\Gamma_1^{CT}(\delta U,\delta V)$
$+\Gamma_1^{CT}(\delta Z_W)+\Gamma_1^{CT}(\delta Z_0)+\Gamma_1^{CT}(\delta Z_\pm)$
$+\Gamma_1^V=\Gamma_1$
$\Gamma_0+\Gamma_1$
ξ_γ
Γ in GeV versus $\xi=\xi_W=\xi_Z$
$\Gamma_1^{CT}(\delta g)+\Gamma_1^{CT}(\delta N)+\Gamma_1^{CT}(\delta U,\delta V)$
$+\Gamma_1^{CT}(\delta Z_W)+\Gamma_1^{CT}(\delta Z_0)+\Gamma_1^{CT}(\delta Z_\pm)$
$+\Gamma_1^V=\Gamma_1$
$\Gamma_0+\Gamma_1$
ξ
Variation of $m_\gamma=1,10^{-14},10^{-29}$ GeV

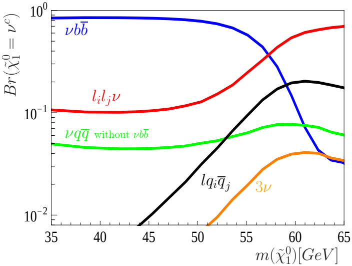
Total decay length and explicit branching ratios?

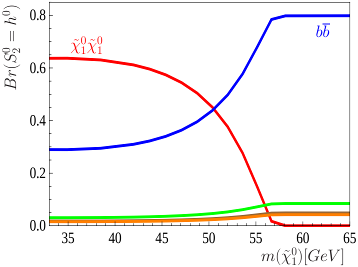
Focus on $\tilde{\chi}_1^0 = \nu^c$:

- $\lambda \in [0.2, 0.5]$
  $\kappa \in [0.025, 0.2]$
  $\mu \in [110, 170]$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

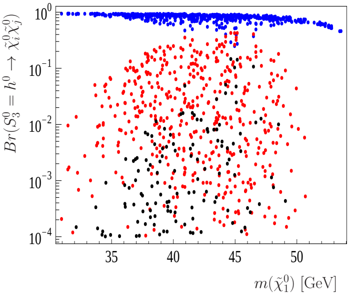


Interesting feature: Decays of the lightest Higgs h^0





Complex behaviour for several light singlinos $\tilde{\chi}_i^0 = \nu_i^c$: Decays of h^0 into $\tilde{\chi}_1^0\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\tilde{\chi}_2^0$ and $\tilde{\chi}_2^0\tilde{\chi}_2^0$



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:

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

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