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Electroweak corrections to Neutralino and Chargino decays in the (N)MSSM

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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:

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

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

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

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

The Next-to-Minimal Supersymmetric Standard Model (NMSSM)

μ-problem: Why is the μ-parameter at the electroweak scale?
$\Longrightarrow$ NMSSM: Introducing a singlet-field $\widehat{S}$ with the terms

$$-\lambda\widehat{S}\widehat{H}_d\widehat{H}_u + \frac{1}{3}\kappa\widehat{S}\widehat{S}\widehat{S} \quad \text{instead of} \quad -\mu\widehat{H}_d\widehat{H}_u$$

generates an effective $\mu = \frac{1}{\sqrt{2}}\lambda v_S$-term (VEV $\langle S\rangle = \frac{1}{\sqrt{2}}v_S$).

Particle content

MSSM + singlet superfield $\widehat{S}$

Mixing with the MSSM particles:

- Neutralinos $\left(\tilde{B}, \tilde{W}_3^0, \tilde{H}_d^0, \tilde{H}_u^0, \tilde{S}\right)$
- Scalars/Pseudoscalars $\left(H_d^0, H_u^0, S\right)$

$\Longrightarrow$ Different Higgs sector with 3 scalars and 2 pseudoscalars
$\Longrightarrow$ Slightly larger lightest Higgs mass m_h possible

Why do we consider the decays $\tilde{\chi}_i^0 \to \tilde{\chi}_j^{\pm} W^{\mp}$ and $\tilde{\chi}_j^{\mp} \to \tilde{\chi}_i^0 W^{\mp}$?

- Neutralino and Chargino decays are prominent decays for the the discovery of SUSY at the LHC and a future linear collider.

The partial widths are obtained from the following interaction Lagrangian:

$$\mathcal{L} = \overline{\tilde{\chi}_j^-} \gamma^\mu \left(P_L O_{Lji} + P_R O_{Rji}\right) \tilde{\chi}_i^0 W_\mu^- + \text{h.c.}$$

In the MSSM as well as in the NMSSM the couplings are given by:

$$O_{Llj} = -g\mathcal{N}_{i2}^* U_{j1} - \frac{1}{\sqrt{2}} g\mathcal{N}_{i3}^* U_{j2}, \qquad O_{Rlj} = -gV_{j1}^* \mathcal{N}_{i2} + \frac{1}{\sqrt{2}} gV_{j2}^* \mathcal{N}_{i4}$$

Decays of a pure Bino $\tilde{B}$ ((N)MSSM) or Singlino $\tilde{S}$ (NMSSM) might be dominated by the NLO contributions!

Calculation of the NLO contributions using an on-shell scheme

Since Neutralinos and Charginos interact electroweak, their masses are measureable with high precision at future colliders:
When performing higher order calculations an on-shell scheme is reasonable!

In the on-shell scheme these decays offer an ideal play ground to tackle the technical questions involved, namely

- UV and IR finiteness
- and in particular gauge invariance!

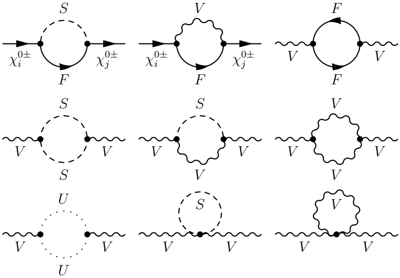
Well-known problem: In the Standard Model the renormalization of mixing matrices using an on-shell scheme is a priori gauge-dependent!

Use Neutralino and Chargino decays to test possible solutions within SUSY.

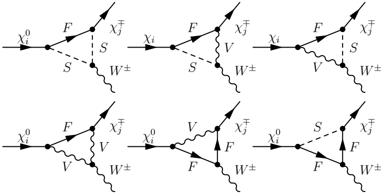
$\Longrightarrow$ Example: Use some kind of pinch technique to address this problem:
Proposal: Yamada, hep-ph/0103046
More details: S.L., Porod, arXiv:1011.6163

Electroweak contributions for $\tilde{\chi}_i^0 \to \tilde{\chi}_j^\pm W^\mp$

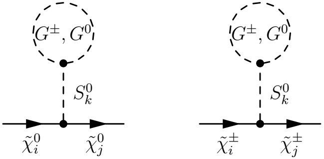
Self energies:



Vertex corrections:

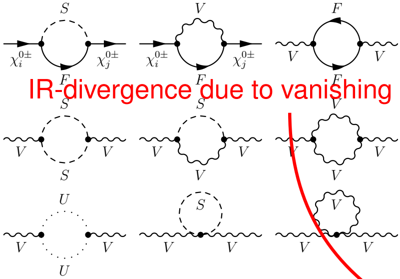


Pinch technique (for $\xi_V \neq 1$ relevant):



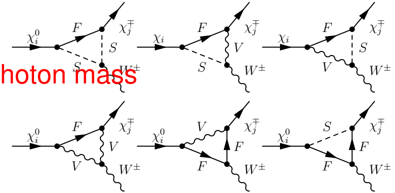
Electroweak contributions for $\tilde{\chi}_i^0 \to \tilde{\chi}_j^{\pm} W^{\mp}$

Self energies:



IR-divergence due to vanishing photon mass

Vertex corrections:



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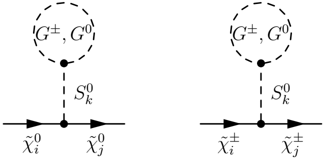
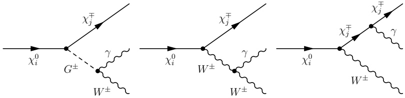


Real photon emission:



NLO corrections in some benchmark scenarios in the NMSSM

We refer to mSUGRA (Djouadi et al. arXiv:0801.4321) and GMSB (Ellwanger et al. arXiv:0803.2962) scenarios:

- mSUGRA 4: GUT scale: $M_0 = 780$ GeV, $M_{1/2} = 775$ GeV, $A_0 = -2250$ GeV
- GMSB 2: $M_{Mess} = 10^{13}$ GeV, $\Lambda = 1.7 \cdot 10^5$ GeV

We define the correction factor

$$\delta = \frac{\Gamma^1 - \Gamma^0}{\Gamma^0} \qquad \text{with} \quad \delta_1 \equiv \text{only squarks/quarks}, \qquad \delta_2 \equiv \text{other sectors} \quad .$$

Sc.	Decay	Γ^0 (in GeV)	Γ^1 (in GeV)	$\delta_{1(\tilde{q},q)}$	δ_2	δ_{1+2}
mSUGRA 4	$\tilde{\chi}_4^0(\tilde{B}) \to \tilde{\chi}_1^-(\tilde{H}^\pm)W^+$	$5.055 \cdot 10^{-2}$	$5.449 \cdot 10^{-2}$	0.8%	7.0%	7.8%
	$\tilde{\chi}_5^0(\tilde{W}) \to \tilde{\chi}_1^-(\tilde{H}^\pm)W^+$	$7.973 \cdot 10^{-1}$	$7.815 \cdot 10^{-1}$	1.2%	-3.2%	-2.0%
GMSB 2	$\tilde{\chi}_4^0(\tilde{H}) \to \tilde{\chi}_1^-(\tilde{W}^\pm)W^+$	7.972	7.738	1.4%	-4.3%	-2.9%
	$\tilde{\chi}_5^0(\tilde{S}) \to \tilde{\chi}_1^-(\tilde{W}^\pm)W^+$	$1.247 \cdot 10^{-2}$	$1.055 \cdot 10^{-2}$	-2.1%	-13.3%	-15.4%

$\Longrightarrow$ For $\tilde{B}$- or $\tilde{S}$-like Neutralino the corrections can be large!
$\Longrightarrow$ δ_2 contributions can be as large or larger than δ_1 contributions!

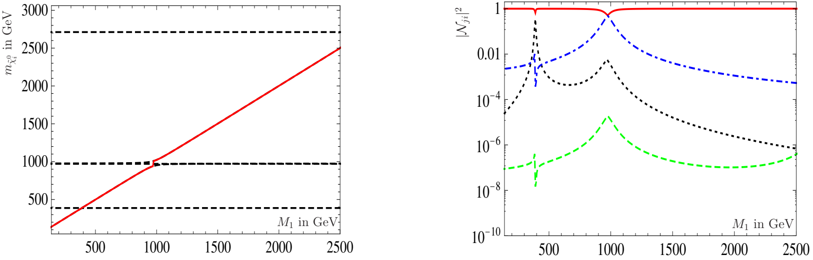
How large can these corrections get?

It might happen, that the Wino-Wino and Higgsino-Higgsino components of

$$O_{Llj} = -g\mathcal{N}^*_{i2}U_{j1} - \frac{1}{\sqrt{2}}g\mathcal{N}^*_{i3}U_{j2}, \qquad O_{Rlj} = -gV^*_{j1}\mathcal{N}_{i2} + \frac{1}{\sqrt{2}}gV^*_{j2}\mathcal{N}_{i4}$$

cancel each other on LO!

To observe this effect we take mSUGRA 1 and vary M_1:
mSUGRA 1: GUT scale: $M_0 = 180$ GeV, $M_{1/2} = 500$ GeV, $A_0 = -1500$ GeV



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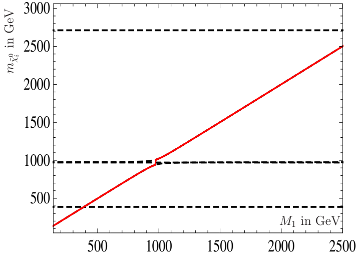
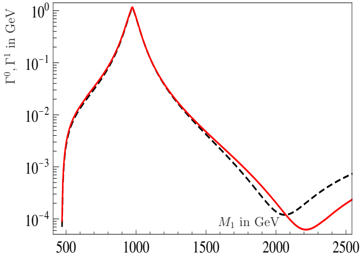
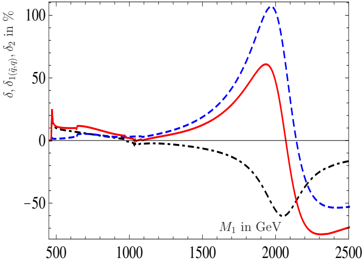




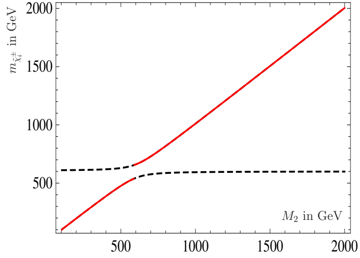
Decay $\tilde{B} \to \tilde{\chi}_1^- (\tilde{W}^\pm) W^+$:

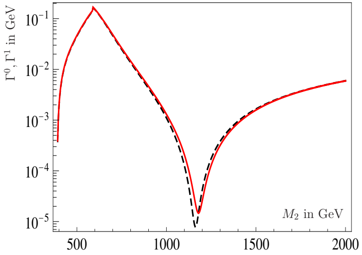
$$\left.\begin{matrix} m_{\tilde{\chi}_i^0}, m_{\tilde{B}} \\ \Gamma^0, \Gamma^1 \\ \delta_{1,(\tilde{q},q)}, \delta_2, \delta \end{matrix}\right\} \quad \text{versus} \quad M_1$$

$\Longrightarrow$ Large corrections $\delta_1 > \delta_2$!



A second example for a Chargino decay $\tilde{W}^- \to \tilde{\chi}_2^0(\tilde{B})W^-$

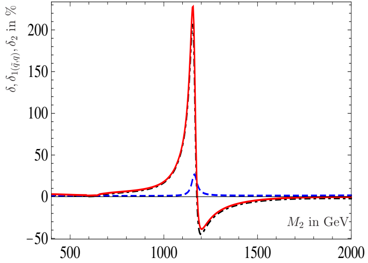




Decay $\tilde{W}^- \to \tilde{\chi}_2^0(\tilde{B})W^-$:

$$\left.\begin{matrix} m_{\tilde{\chi}_i^\pm}, {\color{red} m_{\tilde{W}^\pm}} \\ \Gamma^0, {\color{red}\Gamma^1} \\ {\color{blue}\delta_{1,(\tilde{q},q)}}, \delta_2, {\color{red}\delta} \end{matrix}\right\} \quad \text{versus} \quad M_2$$

$\Longrightarrow$ Large corrections $\delta_1 \ll \delta_2$!



The results can be reproduced with the program CNNDecays (S.L, Porod, arXiv:1011.6163) with SLHA2 in- and output, which can be downloaded from:
www.physik.uni-wuerzburg.de/∼sliebler/CNNDecays.tar.gz

```
# SUSY Les Houches Accord 2 — Neutralino + Chargino NLO Decays into W boson
# S. Liebler, unpublished
# Created: 26.11.2010,  18:04
Block SPINFO                # Program information
     1    CNNDecays         # spectrum calculator
   .......
    1000022      2.10789486E+02   # chi01
    1000023      3.87180852E+02   # chi02
    1000025     −9.71113835E+02   # chi03
    1000035      9.76516110E+02   # chi04
    1000045      2.10157350E+03   # S
    1000024      3.87158709E+02   # chi1+
    1000037      9.77070559E+02   # chi2+
DECAY     1000045      1.68667313E−01     # S
#     BR                    NDA    ID1         ID2
     9.79638284E−01     2      1000037        −24    # BR(S −> chi2+ W−)
     2.03617164E−02     2      1000024        −24    # BR(S −> chi1+ W−)
DECAYNLO     1000045      1.64835565E−01     # S
#     BR                    NDA    ID1         ID2
     9.81192113E−01     2      1000037        −24    # BR(S −> chi2+ W−)
     1.88078869E−02     2      1000024        −24    # BR(S −> chi1+ W−)
   .......
```

Next-to-leading order decay widths for Chargino and Neutralino decays into a W boson using an on-shell scheme . . .

- . . . are a good play ground to tackle gauge invariance in SUSY models.
- . . . are naturally in the range of a few percent.
- . . . can be quite large in case of bino($\tilde{B}$)- and singlino($\tilde{S}$)-like Neutralinos.
- . . . are not necessarily dominated by squark and quark contributions!
  One should take into account full electroweak corrections, if accessible.

All the results can be found in arXiv:1011.6163,
including the program `CNNDecays`!

Thank you for your attention!

If you want to know what happens to R-parity violating Neutralino decays $\tilde{\chi}_i^0 \to l^+W^-$ and their relation to neutrino mixing angles, come to the **“Neutrino masses and lepton flavour violation Working Group”** on Friday!

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Masses for the benchmark scenarios

	$\tilde{\chi}_1^0$		$\tilde{\chi}_2^0$		$\tilde{\chi}_3^0$		$\tilde{\chi}_4^0$		$\tilde{\chi}_5^0$	
	m	C	m	C	m	C	m	C	m	C
mSUGRA 1	210.8	$\tilde{B}$	387.1	$\tilde{W}$	971.1	$\tilde{H}$	976.5	$\tilde{H}$	2101.6	$\tilde{S}$
mSUGRA 3	211.0	$\tilde{B}$	387.4	$\tilde{W}$	942.3	$\tilde{H}$	943.2	$\tilde{H}$	1421.7	$\tilde{S}$
mSUGRA 4	89.1	$\tilde{S}$	215.4	$\tilde{H}$	217.1	$\tilde{H}$	330.5	$\tilde{B}$	608.4	$\tilde{W}$
GMSB 1	472.5	$\tilde{B}$	620.1	$\tilde{S}$	854.1	$\tilde{W}$	1405.4	$\tilde{H}$	1412.4	$\tilde{H}$
GMSB 2	472.5	$\tilde{B}$	855.5	$\tilde{W}$	2352.4	$\tilde{H}$	2355.9	$\tilde{H}$	4062.8	$\tilde{S}$
GMSB 5	203.3	$\tilde{S}$	496.9	$\tilde{B}$	899.6	$\tilde{W}$	1377.7	$\tilde{H}$	1384.0	$\tilde{H}$

	$\tilde{\chi}_1^\pm$		$\tilde{\chi}_2^\pm$	
	m	C	m	C
mSUGRA 1	387.2	$\tilde{W}^\pm$	977.1	$\tilde{H}^\pm$
mSUGRA 3	387.5	$\tilde{W}^\pm$	947.4	$\tilde{H}^\pm$
mSUGRA 4	201.4	$\tilde{H}^\pm$	608.4	$\tilde{W}^\pm$
GMSB 1	854.1	$\tilde{W}^\pm$	1412.4	$\tilde{H}^\pm$
GMSB 2	855.5	$\tilde{W}^\pm$	2355.3	$\tilde{H}^\pm$
GMSB 5	899.6	$\tilde{W}^\pm$	1384.2	$\tilde{H}^\pm$

Gauge dependence