1. Introduction & Renormalization of the cMSSM
2. Stop decays
3. Gluino decays
4. Chargino decays
5. Conclusions
1. Introduction & Renormalization of the cMSSM

Production of SUSY particles at the LHC:
⇒ cascade decays:

\[ \tilde{g} \rightarrow \bar{q}q \rightarrow \bar{q}q \tilde{\chi}_2^0 \rightarrow \bar{q}q \tilde{\tau} \rightarrow \bar{q}q \tau \tilde{\chi}_1^0 \]

Production of uncolored particles via cascade decays often dominates over direct production.
1. Introduction & Renormalization of the cMSSM

Production of SUSY particles at the LHC:
⇒ cascade decays:

\[ \tilde{g} \rightarrow \bar{q}q \rightarrow \bar{q}q\tilde{\chi}_2^0 \rightarrow \bar{q}q\tilde{\tau}\tau \rightarrow \bar{q}q\tau\tau\tilde{\chi}_1^0 \]

Production of uncolored particles via cascade decays often dominates over direct production

Possible: production of Higgs bosons: \( \tilde{t}_2 \rightarrow \tilde{t}_1 h_i, \ldots \)
1. Introduction & Renormalization of the cMSSM

Production of SUSY particles at the LHC:
⇒ cascade decays:

\[ \tilde{g} \rightarrow \bar{q}q \rightarrow \bar{q}q\tilde{\chi}_2^0 \rightarrow \bar{q}q\tilde{\tau}\tau \rightarrow \bar{q}q\tau\tau\tilde{\chi}_1^0 \]

Production of uncolored particles via cascade decays often dominates over direct production

Possible: production of Higgs bosons: \( \tilde{t}_2 \rightarrow \tilde{t}_1 h_i, \ldots \)

Always: production of the lightest SUSY particle: \( \tilde{\chi}_1^0 \)
Production of SUSY particles at the LHC:
⇒ cascade decays:
\[ \tilde{g} \rightarrow \bar{q}q \rightarrow \bar{q}q\tilde{\chi}_2^0 \rightarrow \bar{q}q\tilde{\tau} \rightarrow \bar{q}q\tau\tilde{\chi}_1^0 \]

Production of uncolored particles via cascade decays often dominates over direct production

Possible: production of Higgs bosons: \( \tilde{t}_2 \rightarrow \tilde{t}_1 h, \ldots \)

Always: production of the lightest SUSY particle: \( \tilde{\chi}_1^0 \)

⇒ important source for information on Higgs, LSP
⇒ precision prediction (at least) of BR’s necessary
Complex parameters:

- \( \mu \): Higgsino mass parameter
- \( A_{t,b,\tau} \): trilinear couplings \( X_{t,b,\tau} = A_{t,b} - \mu^* \{ \cot \beta, \tan \beta \} \) complex
- \( M_{1,2} \): gaugino mass parameter (one phase can be eliminated)
- \( m_{\tilde{g}} \): gluino mass

⇒ can induce \( \mathcal{CP} \)-violating effects

Effects of complex parameters in the Higgs sector:

Complex parameters enter via loop corrections:

Result:

\[
(A, H, h) \rightarrow (h_3, h_2, h_1(= \phi))
\]

with

\[
M_{h_3} > M_{h_2} > M_{h_1}
\]
More on complex phases: $\tilde{t}/\tilde{b}$ sector of the MSSM:

Stop, sbottom mass matrices ($X_t = A_t - \mu^*/\tan \beta$, $X_b = A_b - \mu^* \tan \beta$):

\[
M_{\tilde{t}}^2 = \begin{pmatrix}
M_{\tilde{t}L}^2 + m_t^2 + DT_{t1} & m_t X_t^* \\
m_t X_t & M_{\tilde{t}R}^2 + m_t^2 + DT_{t2}
\end{pmatrix} \rightarrow \begin{pmatrix}
m_{\tilde{t}1}^2 & 0 \\
0 & m_{\tilde{t}2}^2
\end{pmatrix}
\]

\[
M_{\tilde{b}}^2 = \begin{pmatrix}
M_{\tilde{b}L}^2 + m_b^2 + DT_{b1} & m_b X_b^* \\
m_b X_b & M_{\tilde{b}R}^2 + m_b^2 + DT_{b2}
\end{pmatrix} \rightarrow \begin{pmatrix}
m_{\tilde{b}1}^2 & 0 \\
0 & m_{\tilde{b}2}^2
\end{pmatrix}
\]

mixing important in stop sector (also in sbottom sector for large $\tan \beta$)

\[SU(2) \text{ relation } \Rightarrow M_{\tilde{t}L} = M_{\tilde{b}L}\]

$\Rightarrow$ relation between $m_{\tilde{t}1}, m_{\tilde{t}2}, \theta_{\tilde{t}}, m_{\tilde{b}1}, m_{\tilde{b}2}, \theta_{\tilde{b}}$. 
More on complex phases: Neutralinos and charginos:

Higgsinos and electroweak gauginos mix

charged:

\[ \tilde{W}^+, \tilde{h}_u^+ \rightarrow \tilde{\chi}^+_1, \tilde{\chi}^+_2, \quad \tilde{W}^-, \tilde{h}_d^- \rightarrow \tilde{\chi}^-_1, \tilde{\chi}^-_2 \]

⇒ charginos: mass eigenstates

mass matrix given in terms of \( M_2, \mu, \tan \beta \)

neutral:

\[ \tilde{\gamma}, \tilde{Z}, \tilde{h}_u^0, \tilde{h}_d^0 \rightarrow \tilde{\chi}^0_1, \tilde{\chi}^0_2, \tilde{\chi}^0_3, \tilde{\chi}^0_4 \]

\[ \tilde{W}^0, \tilde{B}^0 \]

⇒ neutralinos: mass eigenstates

mass matrix given in terms of \( M_1, M_2, \mu, \tan \beta \)

⇒ only one new parameter

⇒ MSSM predicts mass relations between neutralinos and charginos
Examples for processes with (external) stops and Higgs bosons:

- important decay modes of stops
- $A_t$ and $A_b$ directly enter the vertex
- possible source of Higgs bosons at the LHC/ILC
- ...
Examples for processes with (external) stops and Higgs bosons:

- important decay modes of stops
- $A_t$ and $A_b$ directly enter the vertex
- possible source of Higgs bosons at the LHC/ILC
- ...

$\Rightarrow$ higher-order corrections important!
Examples for processes with (external) stops and Higgs bosons:

- important decay modes of stops
- $A_t$ and $A_b$ directly enter the vertex
- possible source of Higgs bosons at the LHC/ILC
- ...

⇒ higher-order corrections important!

⇒ simultaneous renormalization of stop and sbottom sector required!
Examples for processes with (external) stops and Higgs bosons:

- important decay modes of stops
- \( A_t \) and \( A_b \) directly enter the vertex
- possible source of Higgs bosons at the LHC/ILC
- ... 

\[ \Rightarrow \] higher-order corrections important!

\[ \Rightarrow \] simultaneous renormalization of stop and sbottom sector required!

\[ \Rightarrow \] with on-shell properties for external particles!
Examples for processes with (external) stops and Higgs bosons:

- important decay modes of stops
- $A_t$ and $A_b$ directly enter the vertex incl. complex phases!
- possible source of Higgs bosons at the LHC/ILC
- ...

$\Rightarrow$ higher-order corrections important!

$\Rightarrow$ simultaneous renormalization of stop and sbottom sector required!

$\Rightarrow$ including complex phases!
The bigger picture: SUSY decays in the cMSSM

⇒ to get BRs right ⇒ all decays needed
⇒ (nearly) all sectors of the cMSSM enter as external particles
⇒ (nearly) all sectors of the cMSSM have to be renormalized simultaneously
The bigger picture: SUSY decays in the cMSSM

⇒ to get BRs right ⇒ all decays needed
⇒ (nearly) all sectors of the cMSSM enter as external particles
⇒ (nearly) all sectors of the cMSSM have to be renormalized simultaneously

now ready:
– (heavy) stop decays
– gluino decays
– (non-hadronic) chargino decays
2. Heavy Stop Decays

\[ \Gamma(\tilde{t}_2 \rightarrow \tilde{t}_1 h_i) \quad (i = 1, 2, 3) , \]
\[ \Gamma(\tilde{t}_2 \rightarrow \tilde{t}_1 Z) , \]
\[ \Gamma(\tilde{t}_2 \rightarrow t\tilde{\chi}_k^0) \quad (k = 1 \ldots 4) , \]
\[ \Gamma(\tilde{t}_2 \rightarrow t\tilde{g}) , \]
\[ \Gamma(\tilde{\tau}_2 \rightarrow \tilde{b}_i H^+) \quad (i = 1, 2) , \]
\[ \Gamma(\tilde{\tau}_2 \rightarrow \tilde{b}_i W^+) \quad (i = 1, 2) , \]
\[ \Gamma(\tilde{\tau}_2 \rightarrow b\tilde{\chi}_k^+) \quad (k = 1, 2) . \]
Calculation of partial widths and branching ratios:

- all diagrams created with **FeynArts**
  → model file with all counterterms in the cMSSM

- including all **soft/hard QED/QCD diagrams**

- further evaluation with **FormCalc**

- **Dimensional REDuction**

- all **UV** and **IR divergences cancel**

- results will be included into **FeynHiggs** (www.feynhiggs.de)

→ example plots will focus on $\text{BR} (\tilde{t}_2 \rightarrow \tilde{t}_1 h_1), \text{BR} (\tilde{t}_2 \rightarrow t\tilde{\chi}^0_1)$
Feynman diagrams for $\tilde{t}_2 \rightarrow \tilde{t}_1 h_i$

- including $Z-A$ or $G-A$ transition contribution on the external Higgs boson leg
- including all soft/hard QED/QCD diagrams
Feynman diagrams for $\tilde{t}_2 \rightarrow t\tilde{\chi}^0_1$

- including all soft/hard QED/QCD diagrams
Numerical scenarios:

<table>
<thead>
<tr>
<th>Scen.</th>
<th>$M_{H^\pm}$</th>
<th>$m_{\tilde{t}_2}$</th>
<th>$m_{\tilde{t}_1}$</th>
<th>$m_{\tilde{b}_2}$</th>
<th>$\mu$</th>
<th>$A_t$</th>
<th>$A_b$</th>
<th>$M_1$</th>
<th>$M_2$</th>
<th>$M_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>150</td>
<td>650</td>
<td>$0.4 m_{\tilde{t}_2}$</td>
<td>$0.7 m_{\tilde{t}_2}$</td>
<td>200</td>
<td>900</td>
<td>400</td>
<td>200</td>
<td>300</td>
<td>800</td>
</tr>
<tr>
<td>S2</td>
<td>180</td>
<td>1200</td>
<td>$0.6 m_{\tilde{t}_2}$</td>
<td>$0.8 m_{\tilde{t}_2}$</td>
<td>300</td>
<td>1800</td>
<td>1600</td>
<td>150</td>
<td>200</td>
<td>400</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Scen.</th>
<th>$\tan \beta$</th>
<th>$m_{\tilde{t}_1}$</th>
<th>$m_{\tilde{t}_2}$</th>
<th>$m_{\tilde{b}_1}$</th>
<th>$m_{\tilde{b}_2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>2</td>
<td>260.000</td>
<td>650.000</td>
<td>305.436</td>
<td>455.000</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>260.000</td>
<td>650.000</td>
<td>333.572</td>
<td>455.000</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>260.000</td>
<td>650.000</td>
<td>329.755</td>
<td>455.000</td>
</tr>
<tr>
<td>S2</td>
<td>2</td>
<td>720.000</td>
<td>1200.000</td>
<td>769.801</td>
<td>960.000</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>720.000</td>
<td>1200.000</td>
<td>783.300</td>
<td>960.000</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>720.000</td>
<td>1200.000</td>
<td>783.094</td>
<td>960.000</td>
</tr>
</tbody>
</table>

Scenarios chosen such that all decay channels are open

Sven Heinemeyer, SUSY 11 (Fermilab), 29.08.2011
\( \Gamma(\tilde{t}_2 \rightarrow \tilde{t}_1 h_1) \): dependence on \( m_{\tilde{t}_2} \)

\[ \Gamma/\text{GeV} \]

\[ \delta \Gamma/\Gamma^{\text{tree}} \]

⇒ one-loop corrections under control and non-negligible

⇒ size of BR highly scenario dependent

Sven Heinemeyer, SUSY 11 (Fermilab), 29.08.2011
$\Gamma(\tilde{t}_2 \rightarrow \tilde{t}_1 h_1)$: dependence on $\phi_{A_t}$

⇒ one-loop corrections under control and non-negligible
⇒ size of BR highly scenario dependent
\( \Gamma(\tilde{t}_2 \rightarrow t\tilde{\chi}_1^0) \): dependence on \( m_{\tilde{t}_2} \)

⇒ one-loop corrections under control and non-negligible

⇒ size of BR highly scenario dependent
\( \Gamma(\bar{t}_2 \rightarrow t\tilde{\chi}_1^0) \): dependence on \( \phi_{\Delta t} \)

⇒ one-loop corrections under control and non-negligible

⇒ size of BR highly scenario dependent
3. Gluino decays

\[ \Gamma(\tilde{g} \rightarrow \tilde{q}_i q) \quad (i = 1, 2, \ q = t, b, c, s, u, d) \ , \]
\[ \Gamma(\tilde{g} \rightarrow \tilde{q}_i \tilde{q}) \quad (i = 1, 2, \ q = t, b, c, s, u, d) \ , \]
\[ \Gamma(\tilde{g} \rightarrow \tilde{\chi}_k^0 g) \quad (k = 1, 2, 3, 4) \ . \]

No tree-level three-body decays included . . .

⇒ focus on decays involving Stops!

(see previous section)

<table>
<thead>
<tr>
<th>Scen.</th>
<th>(\tan \beta)</th>
<th>(M_{H^\pm})</th>
<th>(M_{\tilde{Q}_L})</th>
<th>(M_{\tilde{q}_R})</th>
<th>(\mu)</th>
<th>(A_t)</th>
<th>(A_b)</th>
<th>(M_1)</th>
<th>(M_2)</th>
<th>(M_3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>20</td>
<td>200</td>
<td>700</td>
<td>800</td>
<td>200</td>
<td>1000</td>
<td>800</td>
<td>200</td>
<td>300</td>
<td>1200</td>
</tr>
</tbody>
</table>
Feynman diagrams for $\tilde{g} \rightarrow \tilde{q}_i q$

- including all soft/hard QED/QCD diagrams
\[ \Gamma(\tilde{g} \rightarrow \tilde{t}_1 t) \]: dependence on \( m_{\tilde{g}} \)

\begin{align*}
\text{\[PRELIMINARY\]} \\
\begin{array}{c@{}c@{}c@{}c@{}c@{}c}
\hline
m_{\tilde{g}}/\text{GeV} & 800 & 1000 & 1200 & 1400 & 1600 & 1800 & 2000 \\
\hline
\Gamma/\text{GeV} & 5 & 10 & 15 & 20 & 25 & 30 & 35 \\
\end{array}
\end{align*}

\begin{align*}
\frac{\delta \Gamma}{\Gamma_{\text{tree}}} & \quad \% \\
\hline
m_{\tilde{g}}/\text{GeV} & 800 & 1000 & 1200 & 1400 & 1600 & 1800 & 2000 \\
\hline
0\% & -5\% & -10\% & -15\% & -20\% & -25\% & -30\% & -35\% & -40\% & -45\% & -50\% \\
\end{align*}

⇒ one-loop corrections under control and non-negligible
⇒ SQCD not sufficient \((r\text{MSSM}: \text{EW calculated for the first time})\)
⇒ size of BR \text{highly} scenario dependent

Sven Heinemeyer, SUSY 11 (Fermilab), 29.08.2011
$\Gamma(\tilde{g} \rightarrow \tilde{t}_1 t)$: dependence on $\varphi_{\tilde{g}}$

$\Rightarrow$ one-loop corrections under control and non-negligible

$\Rightarrow$ size of BR highly scenario dependent
4. Chargino decays

\[ \Gamma(\tilde{\chi}^\pm_2 \rightarrow \tilde{\chi}^\pm_1 h_k) \quad (k = 1, 2, 3) , \]
\[ \Gamma(\tilde{\chi}^\pm_2 \rightarrow \tilde{\chi}^\pm_1 Z) , \]
\[ \Gamma(\tilde{\chi}^\pm_2 \rightarrow \tilde{\chi}^0_1 H^\pm) \quad (i = 1, 2, j = 1, 2, 3, 4) , \]
\[ \Gamma(\tilde{\chi}^\pm_2 \rightarrow \tilde{\chi}^0_1 W^\pm) \quad (i = 1, 2, j = 1, 2, 3, 4) , \]
\[ \Gamma(\tilde{\chi}^\pm_2 \rightarrow \tilde{\ell}^\pm_k \nu_l) \quad (i = 1, 2, l = e, \mu, \tau, k = 1, 2) , \]
\[ \Gamma(\tilde{\chi}^\pm_2 \rightarrow \tilde{\nu}_l l^\pm) \quad (i = 1, 2, l = e, \mu, \tau) . \]

No hadronic decays yet . . .

<table>
<thead>
<tr>
<th>Scen.</th>
<th>tan ( \beta )</th>
<th>( M_{H^\pm} )</th>
<th>( m_{\tilde{\chi}^\pm_2} )</th>
<th>( m_{\tilde{\chi}^\pm_1} )</th>
<th>( M_{\tilde{\ell}_L} )</th>
<th>( M_{\tilde{\ell}_R} )</th>
<th>( A_l )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( S )</td>
<td>20</td>
<td>160</td>
<td>650</td>
<td>350</td>
<td>300</td>
<td>310</td>
<td>400</td>
</tr>
</tbody>
</table>

\[ S_> : \mu > M_2 \quad (\tilde{\chi}^\pm_2 \text{ more higgsino-like}) \]
\[ S_< : \mu < M_2 \quad (\tilde{\chi}^\pm_2 \text{ more gaugino-like}) \]
Feynman diagrams for $\tilde{\chi}_2 \rightarrow \tilde{\chi}_1 h_k$

- including $Z-A$ or $G-A$ transition contribution on the external Higgs boson leg
- including all soft/hard QED/QCD diagrams
Feynman diagrams for $\tilde{\chi}_i^- \rightarrow \tilde{\chi}_j^0 H^-$

- including $W^+ - H^+$ or $G^+ - H^+$ transition contribution on the external Higgs boson leg

- including all soft/hard QED/QCD diagrams
$\Gamma(\tilde{\chi}_2^- \rightarrow \tilde{\chi}_1^- h_1)$: dependence on $m_{\tilde{\chi}_2}^\pm$

$\Rightarrow$ one-loop corrections under control and non-negligible

$\Rightarrow$ size of BR highly scenario dependent
\( \Gamma(\tilde{\chi}_2^\rightarrow \tilde{\chi}_1^0 H^-) \): dependence on \( m_{\tilde{\chi}^\pm_2} \)

\[ \Gamma[\text{GeV}] \]

\[ m_{\tilde{\chi}^\pm_2}[\text{GeV}] \]

\[ \Delta \Gamma/\Gamma[\%] \]

⇒ one-loop corrections under control and non-negligible

⇒ size of BR highly scenario dependent
\[ \Gamma(\tilde{\chi}_2^- \to \tilde{\chi}_1^0 H^-) \): dependence on \( \varphi_{M_2} \)

- \( \Phi \rightarrow \tilde{\chi}_1^0 H^- \)

\( \Gamma[GeV] \)

\( \Delta \Gamma/\Gamma[\%] \)

\( \Rightarrow \) one-loop corrections under control and non-negligible

\( \Rightarrow \) size of BR highly scenario dependent

Sven Heinemeyer, SUSY 11 (Fermilab), 29.08.2011
5. Conclusions

- **Needed:** reliable prediction for SUSY cascades at the LHC
  Of special interest: decays involving Higgs or LSP

- **Our work:**
  Calculation of decay widths and branching ratios
  - all two-body decays
  - full one-loop (incl. hard QED/QCD radiation)
  - in the complex MSSM for arbitrary parameters
  - renormalization of the full cMSSM!

- **Heavy Stop decays:**
  \( \tilde{t}_2 \rightarrow \tilde{t}_1 h_1 \): \( \sim 20\% \),
  \( \tilde{t}_2 \rightarrow t\tilde{\chi}^0_1 \): \( \sim \pm10\% \)

- **Gluino decays:**
  \( \tilde{g} \rightarrow \tilde{t}_1 t \): \( \sim 10\% \), SQCD not sufficient

- **Chargino decays:**
  \( \tilde{\chi}^-_2 \rightarrow \tilde{\chi}^-_1 h_1 \): \( \sim 10\% \),
  \( \tilde{\chi}^-_2 \rightarrow \tilde{\chi}^0_1 H^- \): \( \sim 10\% \)
Higgs Days at Santander 2011
Theory meets Experiment
19.-23. September

contact: Sven.Heinemeyer@cern.ch
http://www.ifca.es/HDays11