Introduction to Decays in SoftSusy-4.0

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CERN (Re)Interpreting the results of New Physics Searches at the LHC
Workshop– 14/5/2018

See https://softsusy.hepforge.org/ for list of SoftSusy papers and manuals.
Overview for the talk:

1. Introduction
2. SoftSusy Decays Capabilities
3. Decay mode examples, validations and results:
   a) MSSM Susy decays
   b) Higgs decays
   c) $1 \rightarrow 3$ decays
   d) Special Cases - Chargino to Pion decays – NLSP to gravitino decays
   e) NMSSM decays
4. How to use SoftSusy
5. Summary, Conclusions, Future

Introduction – still searching for Susy

- Supersymmetry is *very well theoretically motivated* as a new physics solution for many SM issues – naturalness, (technical) hierarchy, DM, ....
- BUT supersymmetry has *no experimental signatures* – where is it?
- Experimental searches make many assumptions

Given the lack of signals – need to:

1. Search **broad**er parameter space
2. Search **ALL NOOKS AND CORNERS** of available parameter space
3. Search in a more **THEORETICALLY-RIGOROUS** manner

-> will allow discovery or rigorous exclusion of susy parameter space

- Need for *public pheno tools producing theoretical predictions* in the complete susy models across broad ranges of (p)MSSM, NMSSM parameter space -> softsusy, susyhit, sphen, feynhiggs, nmssmtools, etc.
- From experimental point of view exclusions need masses and branching ratios -> *spectrum generators and decay calculators*
Softsusy Decay Calculator

Key Decays Included:

- All MSSM 2 body decays at (at least) tree-level, both sparticle and Higgs boson decays.
- Higgs decays to $\gamma\gamma$ and $Z\gamma$ at leading order (i.e. one-loop) in the MSSM and NMSSM.
- QCD corrections to neutral Higgs decays to quarks (1-loop) and to gluons (2-loop) in the MSSM and NMSSM.
- 3 body decays of gluinos, charginos and neutralinos.
- All NMSSM 2 body decays at tree-level, including both the extended neutralino and extended Higgs sectors.
- Special case decays
  - Next-to-Lightest SUSY Particle (NLSP) 2 body decays to gravitinos in the MSSM at tree level.
  - Chargino decays to pions at small mass splittings.

Advantages:

All in one spectrum generation and decay calculation, straightforward to use, easily linked with other codes.
**Implementation:**

- 2 body and loop decays are *tested hard-coded expressions*
  - susy decays validated extensively against sdecay and sphenon
  - higgs decays against hdecay
  - NMSSM decays against NMSSMTools

- 3 body decays are hard-coded and evaluated via single one-dimensional integration via dgauss.

- Extensively, rigorously tested against many other codes and scanning over (N)MSSM parameter space.

- Output can be read straight into further programs such as Pythia.

**Assumptions:**

- R-parity conservation (RPC)
- No additional CPV relative to SM. CP conservation in extended Higgs sector in NMSSM.
- No additional flavour violation relative to SM
- Only sfermion mixing in 3rd generation.

\[ R_p = (-1)^{(3(B-L)+2S)} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & f_t \end{pmatrix} \]

\[ \theta_u = \theta_d = \theta_c = \theta_s = \theta_e = \theta_\mu = 0 \quad \theta_t, \theta_b, \theta_\tau \neq 0 \]
MSSM Susy decays $1 - \tilde{\tau}_1$

- Validation plots (here compared against sdecay of susyhit) e.g. stop1: $\tilde{\tau}_1$
Higgs decays 1 – BRs at $m_h = 125$ GeV

- Comparison of BRs for SM like higgs – SoftSusy Decays module vs hdecay program of susyhit

NLO QCD corrections included for $h \rightarrow qq$ and $h \rightarrow gg$ decays:
  - 1-loop for $h \rightarrow qq$
  - 2-loop for $h \rightarrow gg$

pMSSM point with $m_h = 125$ GeV

Differences observed due to different mass choices, scale choices and scheme choices
Susy 3 body decays

\[ \Gamma(1 \rightarrow N) = \int \ldots \int_N \frac{S(2\pi)^4 |M|^2}{2m} \delta^{(4)}(P - \sum_{i=1}^{n} p_i) \prod_{i=1}^{n} \frac{d^3 p_i}{(2\pi)^3 2E_i} \]

- Each additional decay particle suppresses \( \Gamma \) (PW)
- 2 body favoured over 3 body, but when 2 body are not kinematically allowed, 3 body decays become important -> key to searching tough regions of parameter space.
- Compressed spectra: \( m_{\text{decay}} - m_{\text{Susy product}} < m_{\text{SM}} \):
  - when \( m_{Zi} - m_{Zj} < m_Z \) no 2 body modes are kinematically available
  - but 3 body modes allowed:
$1 \rightarrow 3$ decays: Gluino example

1 -> 2 Decays forbidden as products (squarks + quarks) heavier than gluino

1 -> 3 Decays to Neutralino and fermion antifermion allowed

Spectrum Plot generated with shaplot of pylha-3.2.0: Buckley arXiv:1305.4194
1 \rightarrow 3$ decays Gluino Mass Scan

![Diagram showing decay rates vs. gluino mass](chart.png)

- $g \rightarrow Z_1 qq$
- $g \rightarrow Z_2 qq$
- $g \rightarrow Z_3 qq$
- $g \rightarrow Z_4 qq$
- $g \rightarrow W_1^+ qq$
- $g \rightarrow W_2^+ qq$
- $g \rightarrow st1 t$
- $g \rightarrow sb1 b$
- $g \rightarrow st2 t$
- $g \rightarrow sb2 b$
- $g \rightarrow sq q$
1 → 3 decays Gluino Mass Scan

- All 3 body decays checked in detail against alternative programs.
- SoftSusy reduces the integrals to 1D integrals and then does adaptive Gaussian integration.
- SPheno has similar approach.
- Susyhit does a 2D integration
- All results match – variation due to input parameter choices
Special cases - Chargino decays to Pions

- **AMSB models** have Wino-like LSP.
- AMSB therefore has characteristically have small chargino-LSP mass splittings.
- Compressed spectra means for $\Delta m < 1\text{GeV}$ **decays to pions** are dominant.
- Beyond that 3 body decays to LSP + lepton pairs are most important.
Special cases - NLSP decays to gravitinos

- In GMSB can get LSP gravitino.
- Couplings inherited from goldstino – can get signatures at LHC.
- Displaced vertex and other signatures.
- Included for gluinos, neutralinos, squarks and sleptons.

\[ \Gamma(NLSP \rightarrow LSP \text{ gravitino}(G) + SM) \propto \frac{(m_{NLSP}^2 - m_{SM}^2)^4}{m_{NLSP}^3 m_G^2 M_{Pl}^2} \]
Add gauge singlet chiral superfield $S$ -> one new SUSY fermion (singlino) and 2 new Susy scalars

$$W = \bar{u}^c h_u \tilde{Q} \tilde{H}_u - \bar{d}^c h_d \tilde{Q} \tilde{H}_d - \bar{e}^c h_e \tilde{L} \tilde{H}_d + \lambda S \tilde{H}_u \tilde{H}_d + \frac{1}{3} \kappa S^3$$

- Singlino $\tilde{S}$ mixes with neutralinos $\chi^0_1, \chi^0_2, \chi^0_3, \chi^0_4$ -> 5 neutralinos
- Scalars form 2 extra higgses bosons, assuming CP conservation in higgs sector -> 1 extra CP even higgs $h_3$
  + 1 extra CP odd higgs $A_2$

NMSSM therefore has extended Higgs sector and extended neutralino sector:

- 7 Higgs bosons: 3 CP even, 2 CP odd, 2 Charged Higgses (H+ and H-)
- 5 Neutralinos: Mix of the 2 Higgsinos, 1 neutral Wino and 1 bino (or equaivalently of 1 Zino and 1 photino) and 1 Singlino

Motivations:
- $\mu$ problem of MSSM resolved in NMSSM - Give $\tilde{S}$ a vev -> dynamically generate $\mu = \lambda \langle S \rangle$ at Susy scale -> No $\mu$ problem!
- Higher higgs masses - masses enhanced by extra $\kappa \langle S \rangle$ term -> larger $m_h$, allows less fine-tuned stop masses!

Ellwanger, Hugonie, Teixeira arXiv:0910.1785
NMSSM Z3 violating point with $m_0 = 400\, GeV$, $m_{1/2} = 350\, GeV$, $\tan\beta = 10$, $\text{sign}(\mu) = +1$, $A_0 = -300\, GeV$, $\lambda = 0.1$, $\kappa = 0.1$, $\lambda(S) = 200\, GeV$ and $\xi_F = 100\, GeV$.

SoftSusy does both Z3 conserving and Z3 violating NMSSM decays.
NMSSM Decays

• 3 CP even neutral Higgs states mix to form physical Higgses.
• For our point we split into MSSM doublet + singlet and $h_2$ is dominantly singlet:

\[ R = \begin{pmatrix} 0.106 & 0.992 & -0.065 \\ 0.029 & 0.063 & 0.998 \\ 0.994 & -0.107 & -0.022 \end{pmatrix} \]
How it works 1

1 input file only required

Choose model
MSSM sugra, amsb,.gmsb
NMSSM etc

Set SM inputs

Set parameters at GUT scale

Set flags for decay process – decays on/off, 1->3, gravitinos etc

Set spectrum generator requirements – precision, no. of loops, gravitino mass,
Output file in SLHA form

**Output file in SLHA form**


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*One Output File with all the information you need generated in 0.2s*

*One such table for each susy and Higgs particle in the (N)MSSM.*

*Can be read straight into other programs – Pythia, Herwig, etc*
SoftSusy is a widely used program already used for spectrum generation and susy parameter calculation in many areas; from experimental searches to fits to data, electroweak, astrophysical observables

SoftSusy-4.0 is a major upgrade to include a decay calculator -> out now!

- SUSY 1->2 at tree-level
- SUSY relevant 1->3 at tree-level
- Higgs 1->2 at tree-level
- Higgs -> VV* -> Vffbar (1->3)
- Higgs -> γγ, Zγ, gg (1-loop)
- Decays to gravitinos
- NMSSM 1->2 at tree-level Susy sector (extended neutralinos)
- NMSSM 1->2 extended higgs sector (tree and 1-loop for h -> γγ, Zγ, gg)

Available at: https://softsusy.hepforge.org/
Conclusions and Future Developments

❖ Main benefits: 1) NMSSM included
2) Ease and Usability – all-in-one
3) Consistency throughout
4) Comparison with other codes -> theoretical error

❖ Currently only RPC, mainly tree-level and not all three body decays included, in future wish to extend to include:
  - 3 body decays of sfermions (work in progress)
  - NMSSM 3 body decays
  - more loop-corrected decays
  - RPV couplings

Download program and manual from http://softsusy.hepforge.org/

Thankyou for Listening!
Any Questions?
Section 6

Extra Slides
What Theoretical Knowledge/Tools are required?

- Require tools to calculate all of these for every point in MSSM/NMSSM Parameter space.

- Can then compare against LHC results to discover/rule out different SUSY parameters/models.
Framework for Susy searches

SoftSusy
SPECTRUM
GENERATOR

• SoftSusy has had a variety of uses, for example here is a small subset:

➢ Susy searches at 7/8/13TeV for CMSSM RPC and RPV benchmark points at LHC.

➢ AMSB searches for long-lived particles – quasi degenerate charginos.

➢ pMSSM studies, mT2 variable study (Allanach, Barr, Dafinca, Gwenlan; arXiv:1105.1024)

➢ Parts are used in GAMBIT – fitting code for BSM, (Athron et al, arXiv:1705.07936v1)

➢ DM global fits (e.g. Bagnaschi et al arXiv:1612.05210, Allanach et al. arXiv:0705:0487)

• SoftSusy is a spectrum generator and decay calculator, determines properties of susy particles:
  - Masses
  - susy parameters (mixings etc)
  - branching ratios

• Softsusy Decay calculator – Extend these uses further into exclusions via decay branching ratios incorporated in the full MSSM/NMSSM.
Uses of SoftSusy

➢ RPV searches in the CMSSM
➢ AMSB searches for long-lived particles – quasi degenerate charginos.
➢ pMSSM studies, mT2 variable study \((\text{Allanach, Barr, Dafinca, Gwenlan; arXiv:1105.1024})\)
➢ Recent ATLAS and CMS searches for stop signatures: \((\text{ATLAS-CONF-2017-037 and -034})\)
➢ Parts are used in GAMBIT – fitting code for BSM, \((\text{Athron et al, arXiv:1705.07936v1})\)
➢ LHC DM Searches and Interpretations \((\text{ATLAS Collaboration, JHEP 1609 (2016) 175})\)
➢ Theoretical analyses of GUT scale boundary conditions – can set own models of susy breaking and implement the running. \((\text{JHEP 0110 (2001) 024})\)
SoftSusy Decay Calculator

- **SOFTSUSY-4.0** (New version!):
  - As before + **DECAY CALCULATOR**
  - Major extension
  - Allows all-in-one spectrum generation and decay calculation
  - All tree-level SUSY and Higgs two body decays in MSSM and NMSSM +
    relevant three body and loop decays!

  - **All-in-One** spectrum generation and decay calculation
  - Ease and Usability
  - Contains all phenomenologically relevant decays:
    - SUSY
    - Higgs
    - Gravitino
    - NMSSM

  All in one place!

  - Provides additional code for decay BRs comparison – improves
    knowledge of theoretical errors and variation involved.
**SoftSusy Spectrum Generator**

1. **SM Inputs (Msbar) at $M_Z$ -> alpha, alphas, $G_F$, mb, mt
2. Susy mass default guesses – definitely wrong
3. Run in MSSM up to GUT scale
4. Compare run values with GUT scale Boundary conditions on masses, e.g. $M_0$, $M_1/2$
5. Take boundary conditions at GUT scale and run back down to $M_Z$
6. Fixed Point Iteration: Repeat 3-5 until get convergence.
7. Output: Susy and Higgs masses, mixings, couplings, gauge couplings at Susy Scale

Threshold corrections:

- $O \left( \log \frac{m_{SUSY}^2}{m_Z^2} \right)$
- $O \left( \frac{m_Z^2}{m_{SUSY}^2} \right)$

Finite terms: $O \left( \frac{m_Z^2}{m_{SUSY}^2} \right)$
Decay calculator Specifics

Decay Calculator (decays.cpp)

- NMSSM switch (bool nmsslslt)
- Calls decay functions with MSSM couplings, 4x4 neutralino mixing Matrix, standard higgs sector (5 higgses)
- Calls decay functions with NMSSM couplings, 5x5 neutralino mixing Matrix, extended higgs sector (7 higgses)
- 1 → 3 decays?
- Gravitinos?
- Partial Widths Branching Ratios (BRs)
- Populates Array of Decays

Masses and parameters from SoftSusy Spectrum calculator

Single Output File (lesHouchesOutput.txt) in SLHA form
SoftSusy Decays *(SOFTSUSY-4.0)*

- All $1 \rightarrow 2$ decays of MSSM SUSY particles.
- All $1 \rightarrow 2$ higgs decays in MSSM.
- Phenomenologically Relevant $1 \rightarrow 3$ decays in MSSM (e.g. for compressed spectra).
- Higgs 1-loop decays: $h \rightarrow \gamma \gamma, Z \gamma, gg$ in MSSM and NMSSM.
- Higgs $1 \rightarrow 3$ decays via $VV^*$: $h \rightarrow VV^* \rightarrow V \ f \bar{f}$.
- Decays to gravitinos in MSSM.
- All $1 \rightarrow 2$ decays of SUSY and higgs particles in NMSSM.
- QCD corrections included for higgs decays to quarks and gluons.
MSSM Susy decays $1 - \chi_4^0$

- Validation plots (here compared against sdecay of susyhit) e.g. neut 4: $\chi_4^0$

Spectrum Plot generated with slhaplot of pyslha-3.2.0:
Buckley arXiv:1305.4194
MSSM Susy decays $1 - \chi_4^0$

- Validation plots (here compared against sdecay of susyhit) e.g. neut 4: $\chi_4^0$

\[
\chi_4^0 \rightarrow \text{leptons and sleptons}
\]

Spectrum Plot generated with slhaplot of pyslha-3.2.0:
Buckley arXiv:1305.4194
MSSM Susy decays $1 - \chi_4^0$

- Validation plots (here compared against sdecay of susyhit) e.g. neut 4: $\chi_4^0$

\[
\chi_4^0 \rightarrow \chi_i^+ \n\]

![Spectrum Plot generated with slhaplot of pyslha-3.2.0: Buckley arXiv:1305.4194](image)
MSSM Susy decays 1 – $\chi_4^0$

- Validation plots (here compared against sdecay of susyhit) e.g. neut 4: $\chi_4^0$

Spectrum Plot generated with slhaplot of pyslha-3.2.0:
Buckley arXiv:1305.4194
Higgs decays 1 – BRs at $m_h = 125$GeV

- Comparison of BRs for SM like higgs – **SoftSusy** Decays module vs hdecay program of susyhit

<table>
<thead>
<tr>
<th>SOFTSUSY with QCD corrections</th>
<th>SOFTSUSY with SUSYHIT’s masses and QCD corrections</th>
<th>HDECAY-3.4 with same QCD corrections</th>
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NLO QCD corrections included for h $\rightarrow$ qq and h $\rightarrow$ gg decays:
- 1-loop for h $\rightarrow$ qq
- 2-loop for h $\rightarrow$ gg
Higgs decays 2 – BRs as mh scanned up to 200GeV

- BRs of lightest higgs as mass scanned – **SoftSusy** Decays plot on left, classic plot from LHC Higgs cross section working group on right:

\[ \text{SoftSusy-4.0} \]

h → VV* → Vq\bar{q}

3 body decay for \( m_h < 2m_V \)

Calculation performed fully analytically including Passarino Veltman Reduction.

- No numerical integration required as all integrals performed by hand.

Formulae hard-coded into SoftSusy.

Included in MSSM and NMSSM

\[
\Gamma(h/H \rightarrow ZZ^*) = \frac{G_F^2 m_h m_W^4 c_W^2}{64\pi^3 \cos^4 \theta_W} F(\epsilon_Z) \left[ 7 - \frac{40}{3} \sin^2 \theta_W + \frac{160}{9} \sin^4 \theta_W \right].
\]

\[
\Gamma(h/H \rightarrow WW^*) = \frac{3G_F^2 m_W^4 m_h^2 c_W^2}{16\pi^3} F(\epsilon_W),
\]

\[
F(\epsilon_V) = \frac{3(1 - 8\epsilon_V^2 + 20\epsilon_V^4)}{\sqrt{4\epsilon_V^2 - 1}} \cos^{-1} \left[ \frac{3\epsilon_V^2 - 1}{2\epsilon_V^3} \right] - (1 - \epsilon_V^2)\left( \frac{47}{2} \frac{e_V^2}{e_V^2} - \frac{13}{2} + \frac{1}{\epsilon_V} \right) - 3(1 - 6\epsilon_V^2 + 4\epsilon_V^4) \log(\epsilon_V).
\]

\[
\epsilon_V = \frac{m_V}{m_h}
\]
$\tilde{g} \rightarrow \tilde{\chi}_i^0 q\bar{q}$

Fermion masses accounted for in:
- Yukawa couplings
- Squark mixing
- Matrix element
- Final state quark masses

Important to account for fermion masses in final states as decays relevant in compressed regions close to thresholds.

Formulae from Baer and Tata, (checked against sPheno - essentially a rewriting of sPheno formulae)

\[
\Gamma(\tilde{g} \rightarrow t\bar{t}\tilde{Z}_i) = \frac{\alpha_s}{8\pi^4 m_{\tilde{g}}} \left[ \Gamma_{\tilde{t}_1} + \Gamma_{\bar{t}_2} + \Gamma_{\tilde{t}_1\bar{t}_2} \right].
\]

\[
\Gamma_{\tilde{t}_1} = \Gamma_{LL}(\tilde{t}_1) \cos^2 \theta_t + \Gamma_{RR}(\tilde{t}_1) \sin^2 \theta_t - \sin \theta_t \cos \theta_t \left[ \Gamma_{L_iR_1}(\tilde{t}_1) + \Gamma_{L_iR_2}(\tilde{t}_1) + \Gamma_{L_2R_1}(\tilde{t}_1) + \Gamma_{L_2R_2}(\tilde{t}_1) \right].
\]

\[
\Gamma_{\tilde{t}_2} = \Gamma_{LL}(\tilde{t}_2) \sin^2 \theta_t + \Gamma_{RR}(\tilde{t}_2) \cos^2 \theta_t + \sin \theta_t \cos \theta_t \left[ \Gamma_{L_iR_1}(\tilde{t}_2) + \Gamma_{L_iR_2}(\tilde{t}_2) + \Gamma_{L_2R_1}(\tilde{t}_2) + \Gamma_{L_2R_2}(\tilde{t}_2) \right].
\]

\[
\Gamma_{\tilde{t}_1\bar{t}_2} = \left[ \Gamma_{LL}(\tilde{t}_1, \tilde{t}_2) + \Gamma_{RR}(\tilde{t}_1, \tilde{t}_2) \right] \sin \theta_t \cos \theta_t + \Gamma_{LR}(\tilde{t}_1, \tilde{t}_2) \cos^2 \theta_t + \Gamma_{RL}(\tilde{t}_1, \tilde{t}_2) \sin^2 \theta_t.
\]

4 diagrams – stop1 and stop2, t and u channel
4 “squared” (i.e. non interference) contributions
6 interference contributions between the different diagrams
\( \tilde{g} \rightarrow \tilde{\chi}_i^+ q' \tilde{q} \)

Fermion masses accounted for in:
- Yukawa couplings
- Squark mixing
- Mt in Matrix element
- Final state quark masses

Important to account for fermion masses in final states as decays relevant in compressed regions close to thresholds.

Formulae from Baer and Tata, (checked against sPheno – essentially a rewriting of sPheno formulae)

4 diagrams – stop1, stop2, sbottom1, sbottom2 for each of \( q' \tilde{q} \) and \( q \tilde{q}' \)
4 “squared” (i.e. non interference) contributions
6 interference contributions between the different diagrams

\[
\Gamma(\tilde{g} \rightarrow t\bar{b} \tilde{W}_i^-) = \frac{\alpha_s}{16\pi^2m_{\tilde{g}}} (\Gamma_{i_1} + \Gamma_{i_2} + \Gamma_{i_1 i_2} + \Gamma_{\tilde{b}_1} + \Gamma_{\tilde{b}_2} + \Gamma_{\tilde{b}_1 \tilde{b}_2} + \Gamma_{\tilde{b}_2 \tilde{b}_1} + \Gamma_{\tilde{b}_2 \tilde{b}_2}).
\]

Mb neglected in matrix element (but accounted for in finite state masses), mt kept throughout.
\[ \tilde{\chi}_i^0 \rightarrow \tilde{\chi}_j^0 q\bar{q} \]

Fermion masses accounted for in:
- Yukawa couplings
- Squark mixing
- Final state quark masses

Calculation in Feynman gauge so get goldstone contribution which is essentially longitudinal component of the Z.

6 diagrams – Z, h, H, A, \( \tilde{q}_1, \tilde{q}_2 \)
6 “squared” (i.e. non interference) contributions (Z, h, H, A, \( \tilde{q}_1, \tilde{q}_2 \))
10 interference contributions between the different diagrams (no CP even CP odd interference or Higgs Z interference as quark masses dropped in matrix element)

\[
\Gamma(\tilde{Z}_i \rightarrow \tilde{Z}_j f\bar{f}) = \frac{N_c}{512\pi^3|m_{\tilde{Z}}|^3} (\Gamma_Z + \Gamma_h + \Gamma_H + \Gamma_A + \Gamma_{hH} + \Gamma_f - 4\Gamma_{h\tilde{f}_1} - 4\Gamma_{h\tilde{f}_2} - 4\Gamma_{H\tilde{f}_1} - 4\Gamma_{A\tilde{f}_1} - 4\Gamma_{A\tilde{f}_2} + 4\Gamma_{Z\tilde{f}_1} + 4\Gamma_{Z\tilde{f}_2} - 4\Gamma_{ZA} - 4\Gamma_{G\tilde{f}_1} - 4\Gamma_{G\tilde{f}_2} + 2\Gamma_{GA} - 4\Gamma_{ZG} - 4\Gamma_{G\tilde{f}_1} - 4\Gamma_{G\tilde{f}_2}).
\]

Quark masses in matrix element approximated to zero as q cannot be top as then 2 body modes are available anyway.

Important to account for fermion masses in final states as decays relevant in compressed regions close to thresholds.

Formulae essentially just a rewriting of those in sPheno
\[ \chi_i^0 \rightarrow \chi_j^+ q' \bar{q} \]

Fermion masses accounted for in:
- Yukawa couplings
- Squark mixing
- Matrix elements
- Final state quark masses

6 diagrams – \( W^+, H^-, \tilde{q}_1^c, \tilde{q}_2^c, \tilde{q}_1, \tilde{q}_2 \)
6 “squared” (i.e. non interference) contributions \( W^+, H^-, \tilde{q}_1^c, \tilde{q}_2^c, \tilde{q}_1, \tilde{q}_2 \)
15 interference contributions between the different diagrams

\[
\Gamma = \frac{N_c}{512\pi^3|m_{Z_i}|^3} \left[ \Gamma_W + \Gamma_{\tilde{f}_1} + \Gamma_{\tilde{f}_2} + \Gamma_{\tilde{f}_3} - 2\Gamma_{\tilde{f}_1,\tilde{f}_2} - 2\Gamma_{\tilde{f}_1,\tilde{f}_3} - 2\Gamma_{\tilde{f}_2,\tilde{f}_3} + 2\Gamma_{WH^*}ight. \\
+ 2\Gamma_{WH} + \Gamma_{H^*} + \Gamma_{G} - 2\Gamma_{W\tilde{f}_1} - 2\Gamma_{W\tilde{f}_2} - 2\Gamma_{W\tilde{f}_3} - 2\Gamma_{W\tilde{f}_4} + 2\Gamma_{H^*G} - 2\Gamma_{G\tilde{f}_1} \\
- 2\Gamma_{G\tilde{f}_2} - 2\Gamma_{G\tilde{f}_3} - 2\Gamma_{G\tilde{f}_4} - 2\Gamma_{H^*\tilde{f}_1} - 2\Gamma_{H^*\tilde{f}_2} - 2\Gamma_{H^*\tilde{f}_3} - 2\Gamma_{H^*\tilde{f}_4} + 2\Gamma_{\tilde{f}_1,\tilde{f}_2} + 2\Gamma_{\tilde{f}_1,\tilde{f}_3} + 2\Gamma_{\tilde{f}_2,\tilde{f}_3}
\]

Quark masses kept throughout matrix elements throughout Dirac algebra – therefore have \( WH^* \) interference too.
Only really relevant for first 2 generations as for t and b then 2 body modes available.
Special cases - Chargino decays to Pions

- Lifetimes of Chargino NLSP long enough to observe in LHC.
- High pT chargino tracks decay to soft pions or leptons + large MET (neutralino LSP).
- Kinks/disappearing tracks observed in one-pronged decays $\tilde{\chi}_1^+ \rightarrow \tilde{\chi}_1^0 \pi^+$.
Gravitino decays - theory

- **Susy -> local symmetry** to incorporate gravity -> spin 2 graviton.
  
  -> spin 3/2 susy partner: **gravitino**.

- Spontaneous susy breaking (SSB) -> massless goldstone fermion of spin 1/2 : **goldstino**.

- In SSB, massless gravitino “eats” massless goldstino -> becomes gravitino’s longitudinal dof -> **gravitino becomes massive**.

- In SSB scenarios, particularly GMSB the gravitino can be LSP.

- Gravitino inherits stronger coupled longitudinal components.

- Decays **NLSP -> LSP gravitino + SM** to be observable at colliders
Gravitino decays - plot

Distances travelled for neutralino NLSP decays to gravitino(G)

\[ \tau = \frac{\bar{h}}{\Gamma} \]

- G \gamma
- G Z
- G h

\[ V_{\tau \gamma}(m) \]

\[ m_{\text{gravitino}} (\text{GeV}) \]

Cern Seminar 14/05/18 Thomas Cridge
NMSSM Key parameters

 Crucially – NMSSM decays not included in most alternative programs – only NMSSMTools or SARAH + SPheno together.

\[ W = \hat{u}^c h_u \hat{Q} \hat{H}_u - \hat{d}^c h_d \hat{Q} \hat{H}_d - \hat{e}^c h_e \hat{L} \hat{H}_d + \lambda \hat{S} \hat{H}_u \hat{H}_d + \frac{1}{3} \kappa \hat{S}^3 \]

- \( \lambda \) - coupling of singlino to higgsinos, neutralino mixing, higgs masses
- \( \kappa \) - contributes to higgs masses
- \( A_\lambda \) - soft susy breaking parameter, trilinear couplings
- \( A_\kappa \) - soft susy breaking parameter, trilinear couplings
- \( \tan \beta = \langle H_u \rangle / \langle H_d \rangle \) - ratio of higgs vevs, neutralino mixing via higgsinos
- \( \mu_{\text{eff}} = \lambda \langle S \rangle \) - higgsino masses, neutralino mixing

N.B. As \( \hat{S} \) is gauge singlet it only couples to non-higgs particles via mixing with other neutralinos.
QCD Corrected Higgs Decays

- Higgs decays to quarks and to gluons include NLO QCD corrections (including susy-QCD corrections), included for both MSSM and NMSSM.

\[ h \rightarrow q\bar{q} \]
- 1-loop corrections are a simple additional multiplicative factor.
- All differences between MSSM and NMSSM are in the tree-level part, the multiplicative factor for the QCD corrections is the same.

\[ \Gamma(h \rightarrow q\bar{q})_{QCD_{corr}} = \Gamma(h \rightarrow q\bar{q})_{tree} \left( 1 + \frac{4\alpha_s(m_h)}{3\pi} \left[ \frac{A(\tilde{\beta})}{\tilde{\beta}} + \frac{3 + 34\tilde{\beta}^2 - 13\tilde{\beta}^4}{16\tilde{\beta}^3} \log \frac{1 + \tilde{\beta}}{1 - \tilde{\beta}} + \frac{3}{8\tilde{\beta}^2} (7\tilde{\beta}^2 - 1) \right] \right). \]

\[ h \rightarrow gg \]
- 2-loop corrections are NLO as process is 1-loop.
- Both QCD and SUSY-QCD corrections included; SUSY-QCD corrections act only on squark loops, QCD corrections act on quark and squark loops.
- All differences between MSSM and NMSSM are in the tree-level part.

\[ \Gamma(\phi \rightarrow gg)_{1-loop+QCD_{corr}} = \frac{G_F^2 m_\phi^3}{128\pi^3} \left[ \frac{3}{8} \left( \delta_{FQCD}^{\phi \rightarrow gg} \right) |I_{loop}^\phi|^2 + \text{Re}(I_{loop}^\phi)^* I_{loop}^\phi \right]. \]

\[ \delta_{FQCD}^{\phi \rightarrow gg} = 1 + \frac{\alpha_s(m_\phi)}{\pi} \left( \frac{95}{4} - \frac{7}{6} N_f \right), \quad \delta_{FQCD}^{\phi \rightarrow Higgs} = 1 + \frac{\alpha_s(m_\phi)}{\pi} \left( \frac{97}{4} - \frac{7}{6} N_f \right), \quad \delta_{QCD} = \frac{17\alpha_s(m_\phi)}{6\pi}. \]