Introduction to Decays in **SoftSusy-4.0**

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In collaboration with Professor Ben Allanach

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

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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 → 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

Based on paper: B.C. Allanach and T.C. on arXiv:hep-ph/1703.09717 and Computer Physics Communications (CPC 220C (2017) pp. 417-502) + more to come!

Introduction – still searching for Susy

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

Simplified Models

Reduced Parameter spaces

100% Branching Ratios

- Given the lack of signals – need to:
  1. Search **b r o a d e r** 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, spheno, 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 γγ and Zγ 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.

SoftSusy Decay Calculator

Implementation:

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

  Some example results and validation later in this talk

- 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)

$$R_p = (-1)^{(3(B-L)+2S)}$$

- No additional CPV relative to SM. CP conservation in extended Higgs sector in NMSSM.

$$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & f_t \end{pmatrix}$$

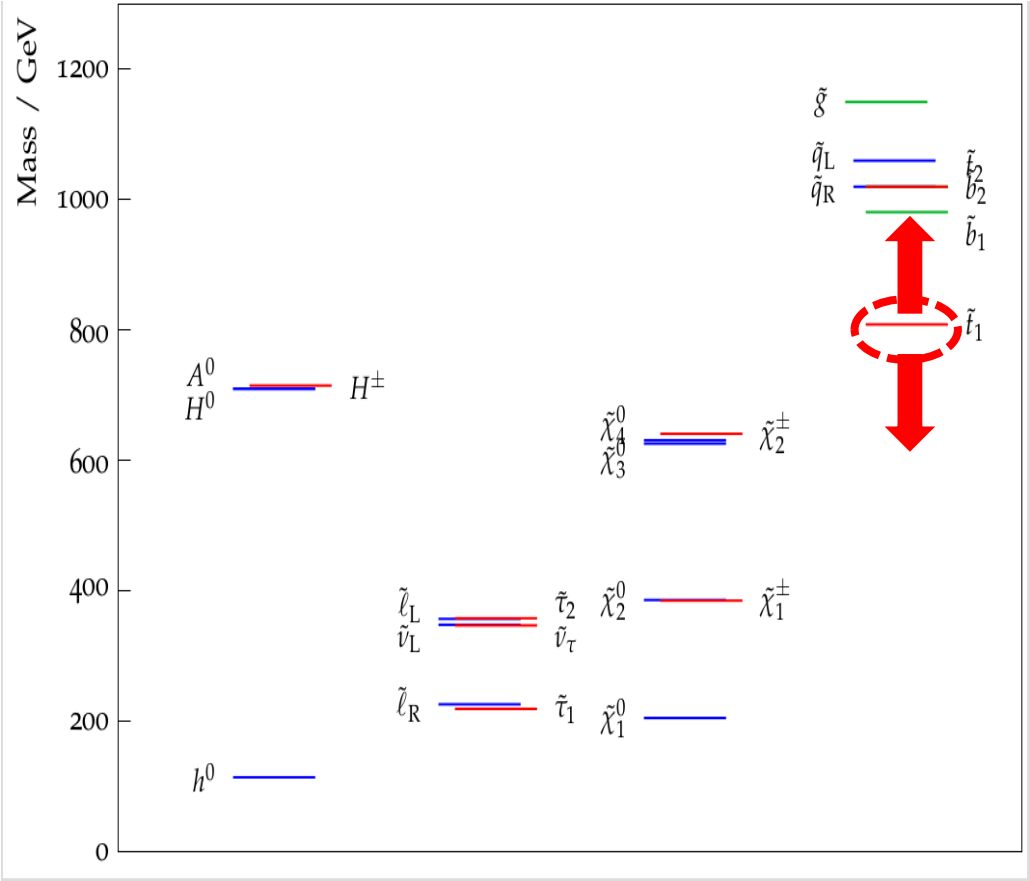
- No additional flavour violation relative to SM

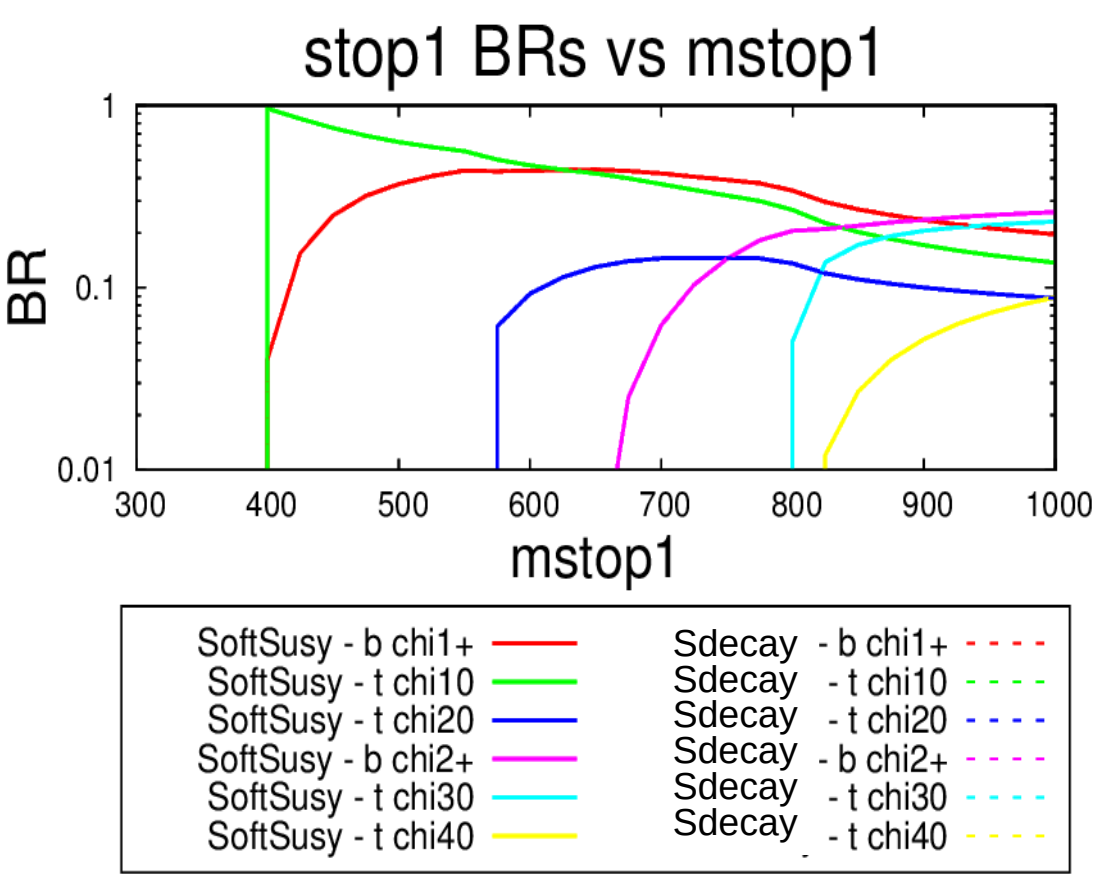
$$\theta_u = \theta_d = \theta_c = \theta_s = \theta_e = \theta_\mu = 0 \qquad \theta_t, \theta_b, \theta_\tau \neq 0$$

- Only sfermion mixing in 3rd generation.

MSSM Susy decays 1 – $\tilde{t}_1$

- Validation plots (here compared against sdecay of susyhit) e.g. stop1: $\tilde{t}_1$

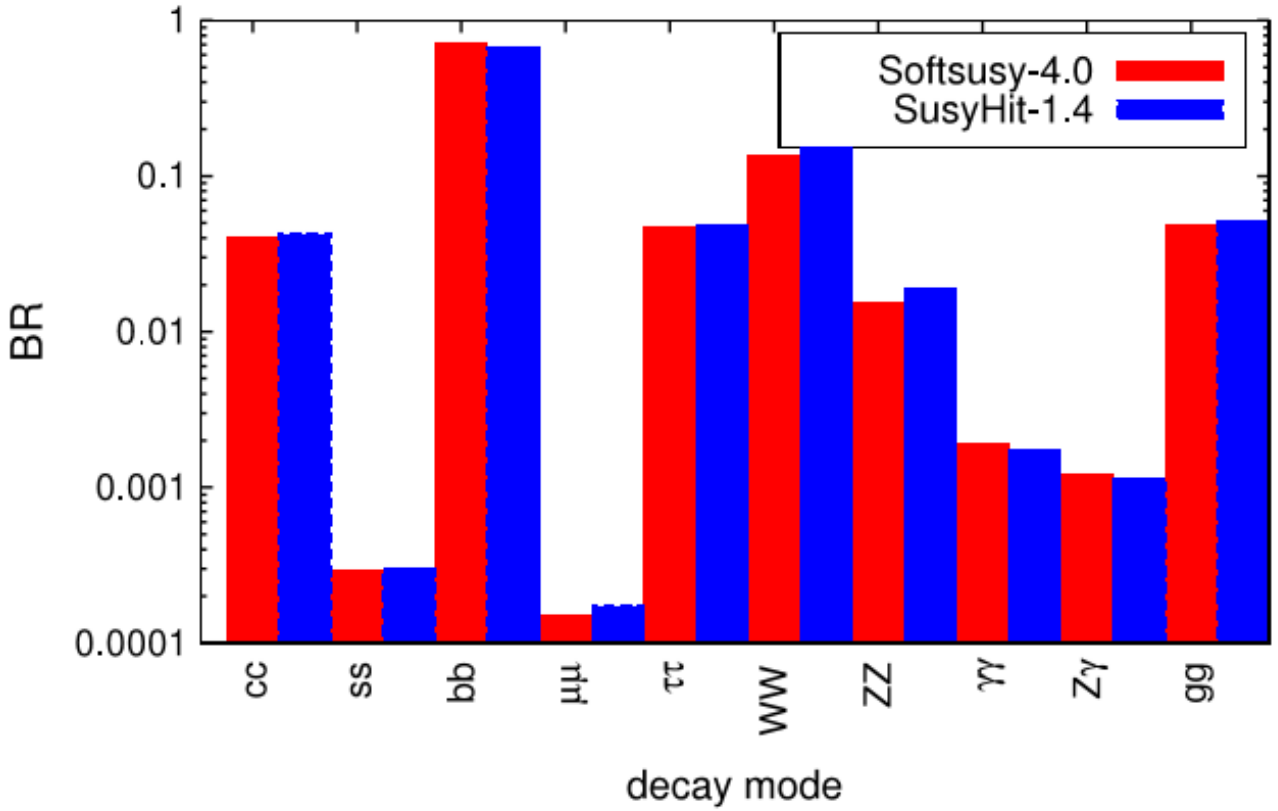




Higgs decays 1 – BRs at mh = 125GeV

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

B.C. Allanach, T. Cridge / Computer Physics Communications 220 (2017) 417–502



NLO QCD corrections included for h -> qq and h -> gg decays:
- 1-loop for h -> qq
- 2-loop for h -> gg

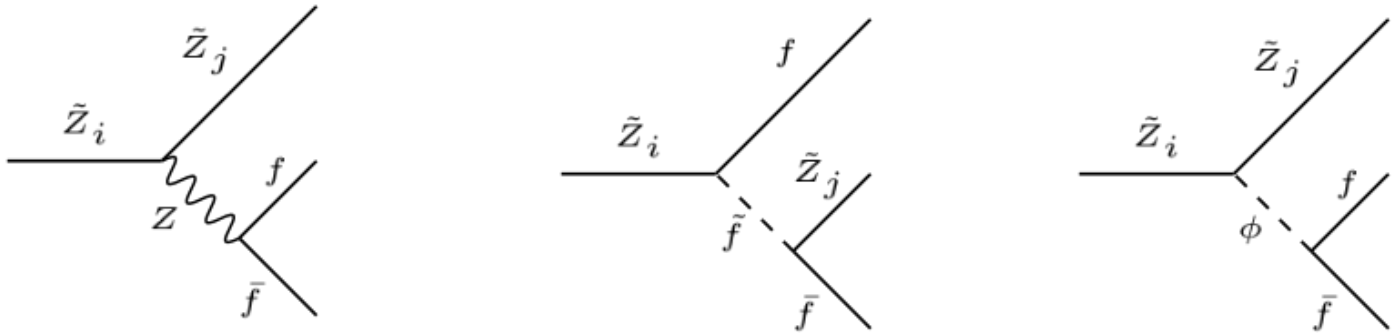
pMSSM point with mh = 125 GeV

Differences observed due to different mass choices, scale choices and scheme choices

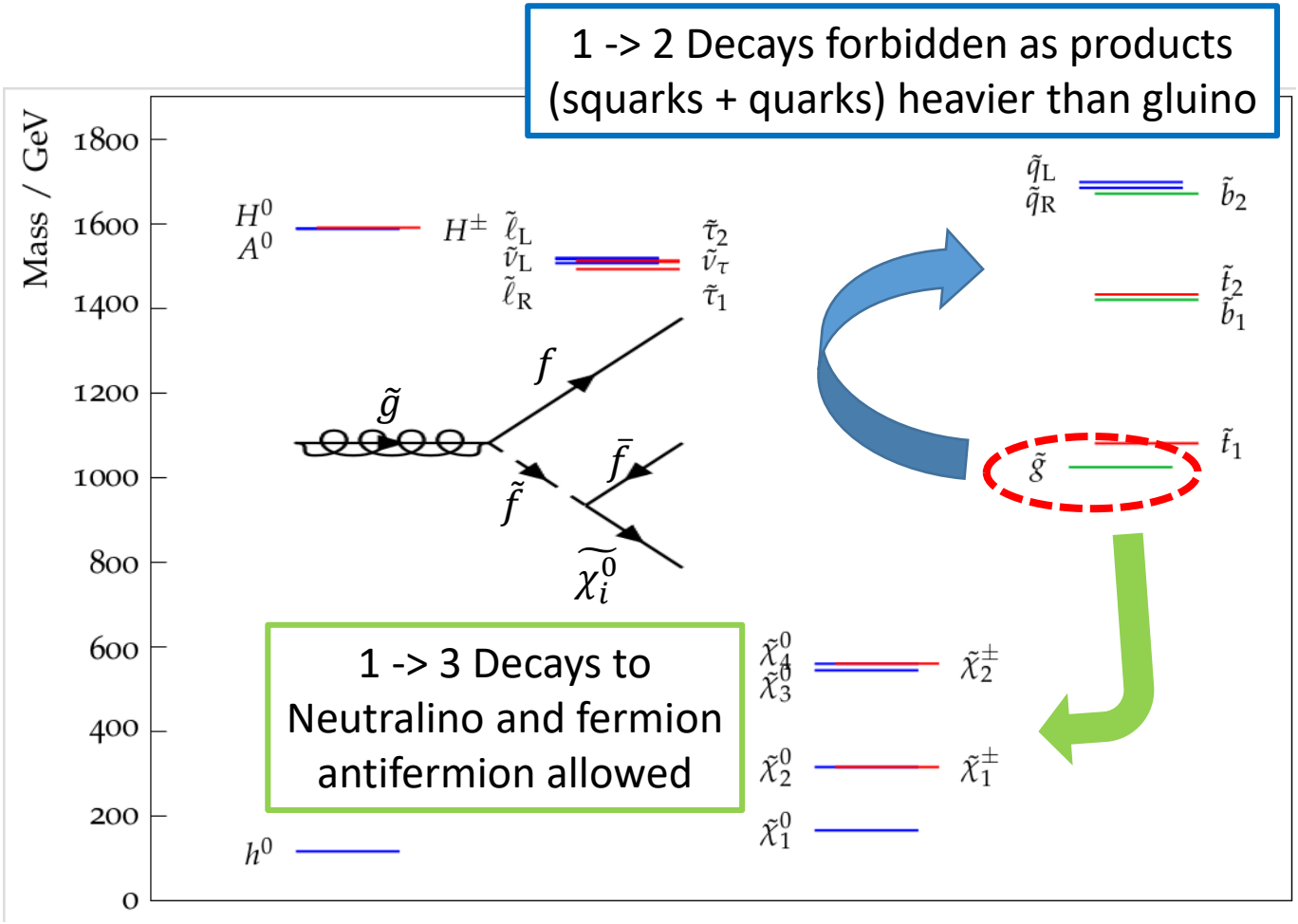
Susy 3 body decays

$$\Gamma(1 \to N) = \int \cdots \int_N \frac{S(2\pi)^4 \langle |M|^2 \rangle}{2m} \delta^{(4)}(P - \sum_{i=1}^{n} p_i) \prod_{i=1}^{n} \frac{d^3 p_i}{(2\pi)^3 2E_i}$$

- Each additional decay particle suppresses Γ (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: $m_{decay} - m_{Susy\ product} < m_{SM}$:
  - when mZi – mZj < mZ no 2 body modes are kinematically available
  - but 3 body modes allowed:

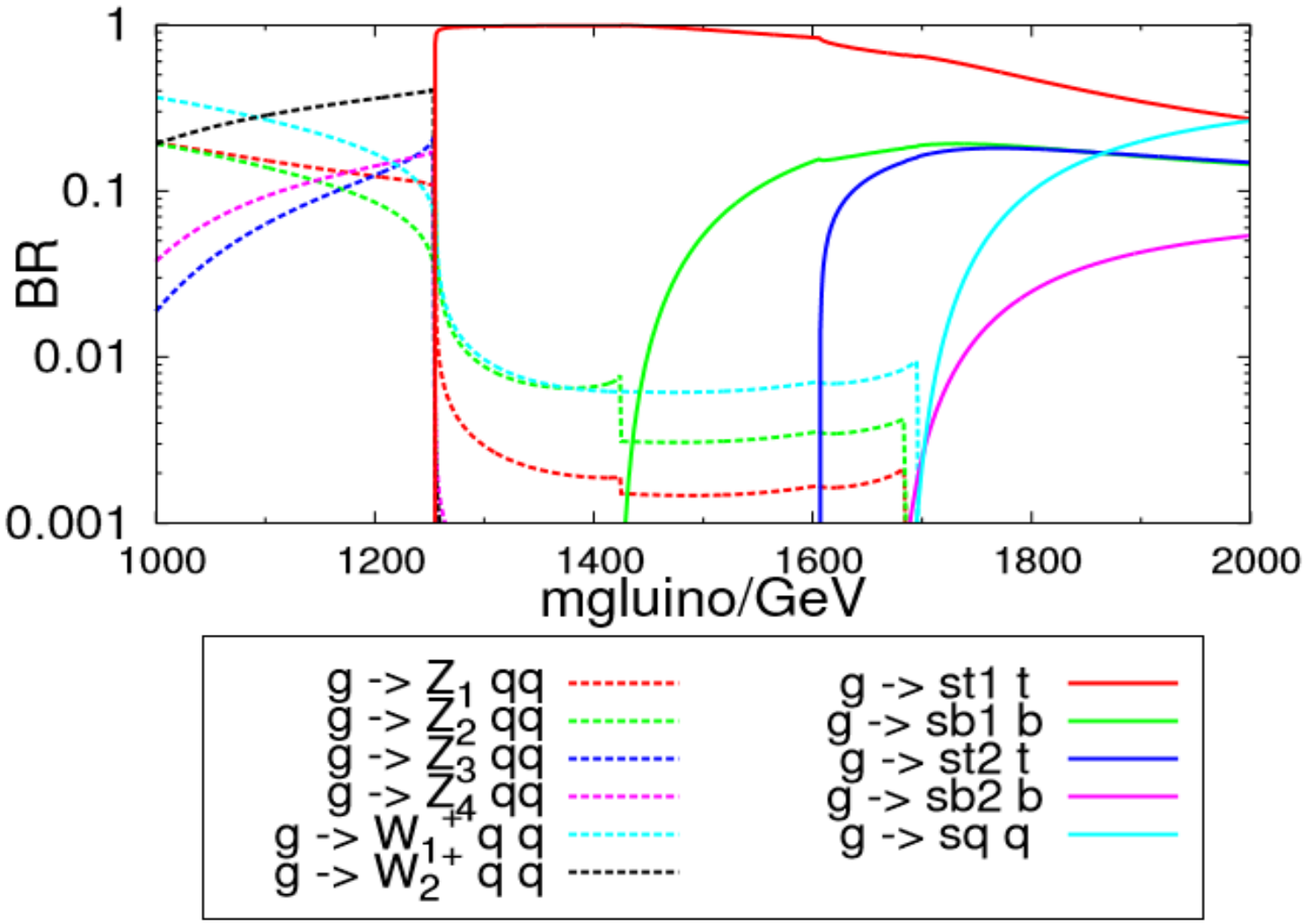


1 → 3 decays: Gluino example



Spectrum Plot generated with slhaplot of pyslha-3.2.0: Buckley arXiv:1305.4194

1 → 3 decays Gluino Mass Scan



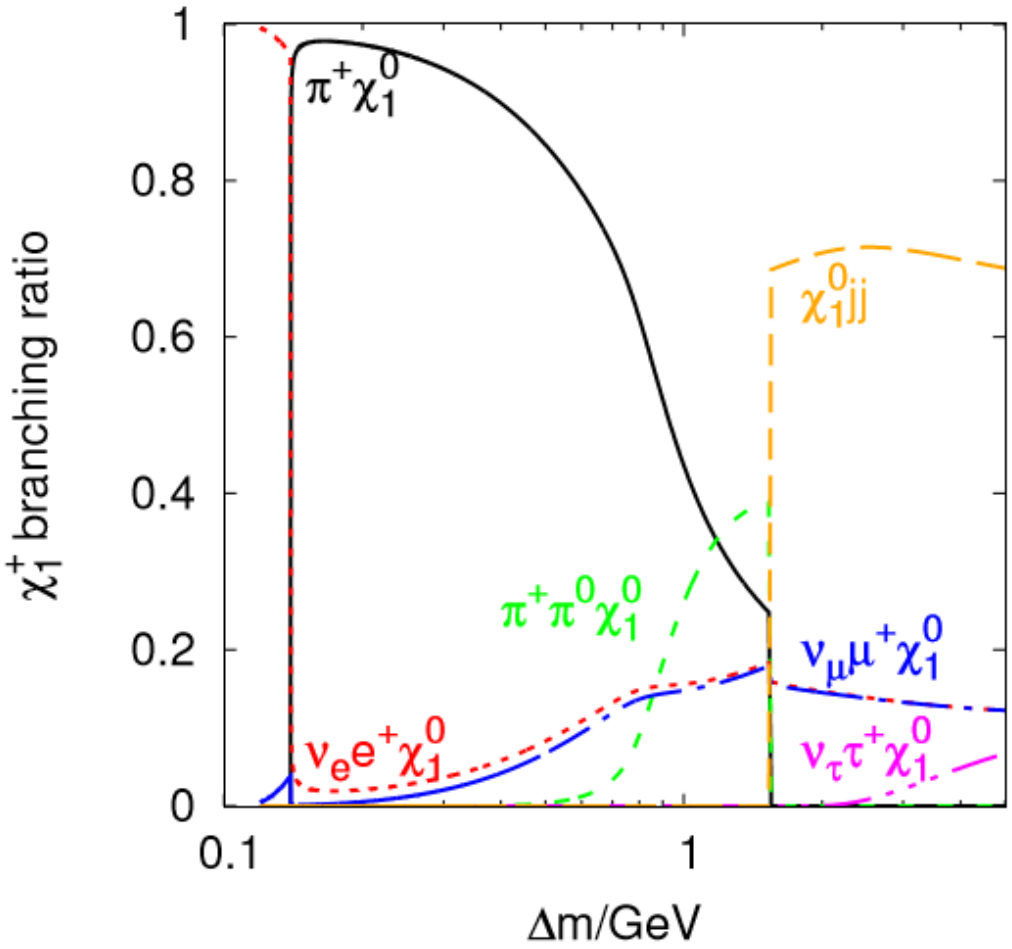
1 → 3 decays Gluino Mass Scan

SOFTSUSY		sPHENO-3.38		SUSYHIT-1.4		mode
PW/GeV	BR	PW/GeV	BR	PW/GeV	BR	
2.90e-04	2.26e-02	2.89e-04	2.32e-02	2.89e-04	2.32e-02	$\tilde{g} \to \tilde{Z}_1 u\bar{u}$
3.21e-04	2.51e-02	3.19e-04	2.56e-02	3.19e-04	2.56e-02	$\tilde{g} \to \tilde{Z}_2 u\bar{u}$
1.35e-07	1.06e-05	1.35e-07	1.08e-05	1.35e-07	1.08e-05	$\tilde{g} \to \tilde{Z}_3 u\bar{u}$
5.52e-06	4.31e-04	5.49e-06	4.40e-04	5.49e-06	4.40e-04	$\tilde{g} \to \tilde{Z}_4 u\bar{u}$
9.06e-05	7.07e-03	9.02e-05	7.22e-03	9.02e-05	7.24e-03	$\tilde{g} \to \tilde{Z}_1 d\bar{d}$
3.07e-04	2.40e-02	3.06e-04	2.45e-02	3.06e-04	2.45e-02	$\tilde{g} \to \tilde{Z}_2 d\bar{d}$
1.75e-07	1.36e-05	1.74e-07	1.39e-05	1.74e-07	1.40e-05	$\tilde{g} \to \tilde{Z}_3 d\bar{d}$
6.67e-06	5.21e-04	6.64e-06	5.31e-04	6.64e-06	5.33e-04	$\tilde{g} \to \tilde{Z}_4 d\bar{d}$
2.90e-04	2.26e-02	2.89e-04	2.32e-02	2.89e-04	2.32e-02	$\tilde{g} \to \tilde{Z}_1 c\bar{c}$
3.21e-04	2.51e-02	3.19e-04	2.56e-02	3.19e-04	2.56e-02	$\tilde{g} \to \tilde{Z}_2 c\bar{c}$
1.35e-07	1.05e-05	1.41e-07	1.13e-05	1.35e-07	1.08e-05	$\tilde{g} \to \tilde{Z}_3 c\bar{c}$
5.52e-06	4.31e-04	5.50e-06	4.40e-04	5.49e-06	4.40e-04	$\tilde{g} \to \tilde{Z}_4 c\bar{c}$
9.06e-05	7.07e-03	9.02e-05	7.22e-03	9.02e-05	7.24e-03	$\tilde{g} \to \tilde{Z}_1 s\bar{s}$
3.07e-04	2.40e-02	3.06e-04	2.45e-02	3.06e-04	2.45e-02	$\tilde{g} \to \tilde{Z}_2 s\bar{s}$
1.75e-07	1.36e-05	1.77e-07	1.42e-05	1.74e-07	1.40e-05	$\tilde{g} \to \tilde{Z}_3 s\bar{s}$
6.67e-06	5.21e-04	6.64e-06	5.32e-04	6.64e-06	5.33e-04	$\tilde{g} \to \tilde{Z}_4 s\bar{s}$
1.47e-03	1.15e-01	1.47e-03	1.17e-01	1.44e-03	1.15e-01	$\tilde{g} \to \tilde{Z}_1 t\bar{t}$
2.56e-04	1.99e-02	2.46e-04	1.97e-02	2.67e-04	2.15e-02	$\tilde{g} \to \tilde{Z}_2 t\bar{t}$
3.48e-04	2.71e-02	3.10e-04	2.48e-02	3.34e-04	2.68e-02	$\tilde{g} \to \tilde{Z}_3 t\bar{t}$
6.13e-04	4.79e-02	5.66e-04	4.53e-02	5.21e-04	4.18e-02	$\tilde{g} \to \tilde{Z}_4 t\bar{t}$
1.27e-04	9.93e-03	1.25e-04	1.00e-02	1.25e-04	1.00e-02	$\tilde{g} \to \tilde{Z}_1 b\bar{b}$
7.80e-04	6.09e-02	7.74e-04	6.20e-02	7.74e-04	6.21e-02	$\tilde{g} \to \tilde{Z}_2 b\bar{b}$
2.20e-05	1.72e-03	1.77e-05	1.42e-03	1.78e-05	1.43e-03	$\tilde{g} \to \tilde{Z}_3 b\bar{b}$
3.48e-05	2.72e-03	3.24e-05	2.60e-03	3.23e-05	2.60e-03	$\tilde{g} \to \tilde{Z}_4 b\bar{b}$
6.28e-04	4.90e-02	6.24e-04	5.00e-02	6.24e-04	5.01e-02	$\tilde{g} \to \tilde{W}_1^- u\bar{d}$
6.28e-04	4.90e-02	6.24e-04	5.00e-02	6.24e-04	5.01e-02	$\tilde{g} \to \tilde{W}_1^+ d\bar{u}$
6.28e-04	4.90e-02	6.24e-04	5.00e-02	6.24e-04	5.01e-02	$\tilde{g} \to \tilde{W}_1^- c\bar{s}$
6.28e-04	4.90e-02	6.24e-04	5.00e-02	6.24e-04	5.01e-02	$\tilde{g} \to \tilde{W}_1^+ s\bar{c}$
1.20e-05	9.36e-04	1.19e-05	9.56e-04	1.19e-05	9.58e-04	$\tilde{g} \to \tilde{W}_2^- u\bar{d}$
1.20e-05	9.36e-04	1.19e-05	9.56e-04	1.19e-05	9.58e-04	$\tilde{g} \to \tilde{W}_2^+ d\bar{u}$
1.20e-05	9.36e-04	1.19e-05	9.56e-04	1.19e-05	9.58e-04	$\tilde{g} \to \tilde{W}_2^- c\bar{s}$
1.20e-05	9.36e-04	1.19e-05	9.56e-04	1.19e-05	9.58e-04	$\tilde{g} \to \tilde{W}_2^+ s\bar{c}$
9.29e-04	7.25e-02	9.21e-04	7.38e-02	9.21e-04	7.39e-02	$\tilde{g} \to \tilde{W}_1^- t\bar{b}$
9.29e-04	7.25e-02	9.21e-04	7.38e-02	9.21e-04	7.39e-02	$\tilde{g} \to \tilde{W}_1^+ b\bar{t}$
1.35e-03	1.05e-01	1.27e-03	1.01e-01	1.27e-03	1.02e-01	$\tilde{g} \to \tilde{W}_2^- t\bar{b}$
1.35e-03	1.05e-01	1.27e-03	1.01e-01	1.27e-03	1.02e-01	$\tilde{g} \to \tilde{W}_2^+ b\bar{t}$

- 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

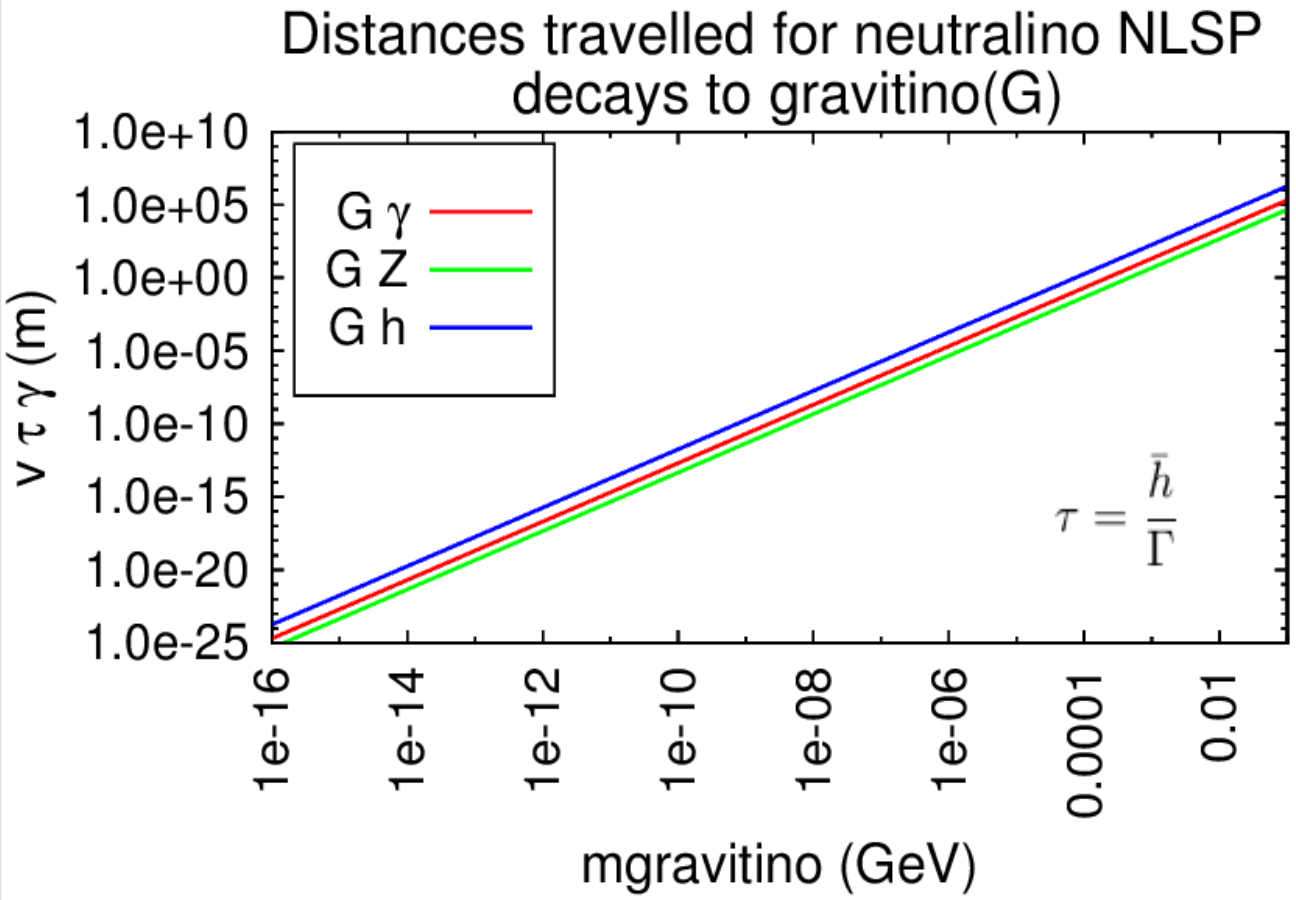
Special cases - Chargino decays to Pions

- **AMSB models** have Wino-like LSP.
- AMSB therefore has characteristically have small chargino-LSP mass splittings.
- Compressed spectra means for $\Delta m < 1GeV$ **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.



$$\Gamma(NLSP \rightarrow LSP\ gravitino(G) + SM) \propto \frac{(m_{NLSP}^2 - m_{SM}^2)^4}{m_{NLSP}^3 m_G^2 M_{Pl}^2}$$

NMSSM Theory

- Add gauge singlet chiral superfield S -> one new SUSY fermion (singlino) and 2 new Susy scalars

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

  - Singlino $\tilde{S}$ mixes with neutralinos $\widetilde{\chi_1^0}, \widetilde{\chi_2^0}, \widetilde{\chi_3^0}, \widetilde{\chi_4^0}$ -> 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

Ellwanger, Hugonie, Teixeira arXiv:0910.1785

- NMSSM therefore has **extended Higgs sector** and **extended neutralino sector**:

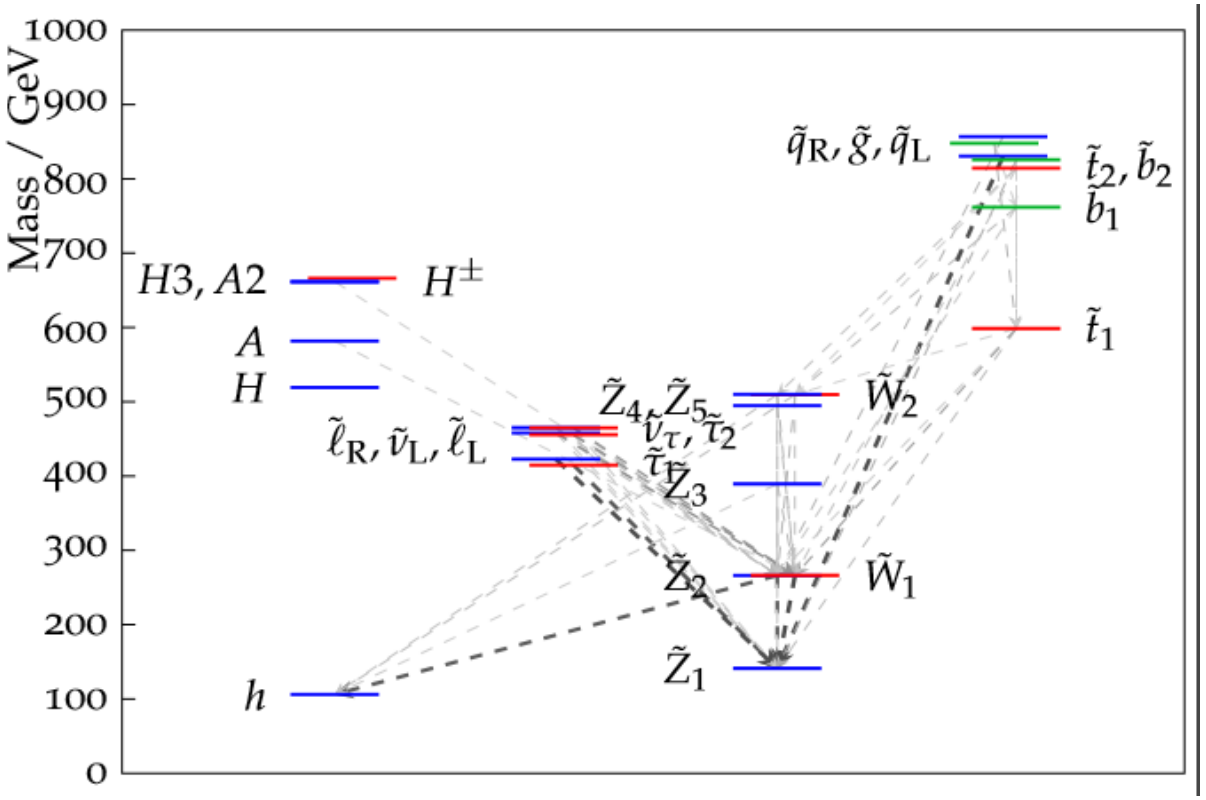
-> **7 Higgs bosons**: 3 CP even, 2 CP odd, 2 Charged Higgses (H+ and H-)

-> **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:

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

NMSSM Decays



SoftSusy does both Z3 conserving and Z3 violating NMSSM decays.

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

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:

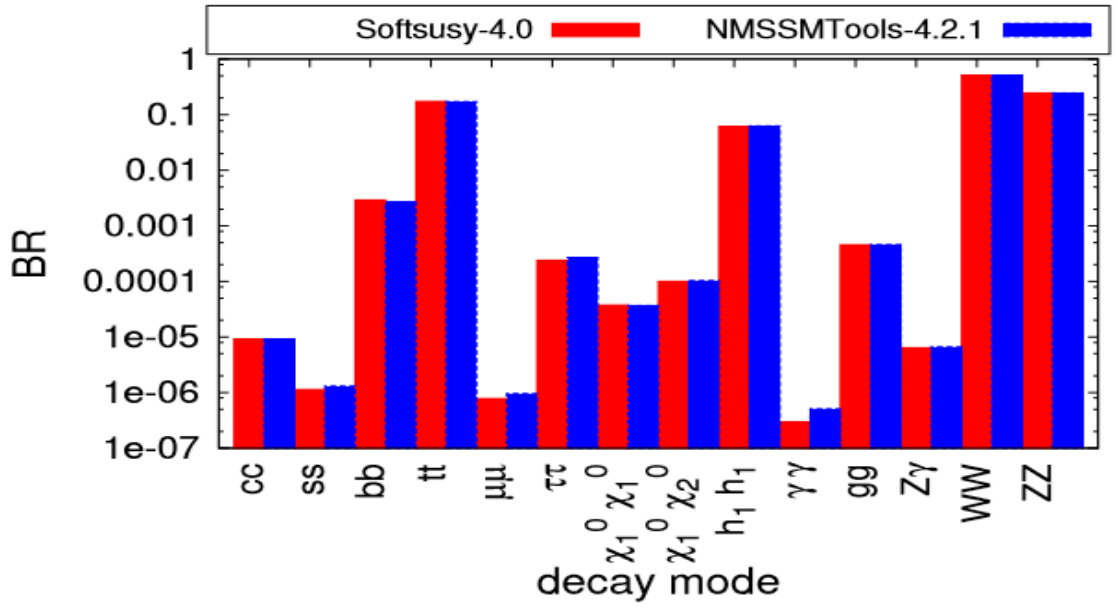
$$R = \begin{pmatrix} 0.106 & 0.992 & -0.065 \\ 0.029 & 0.063 & 0.998 \\ 0.994 & -0.107 & -0.022 \end{pmatrix}$$

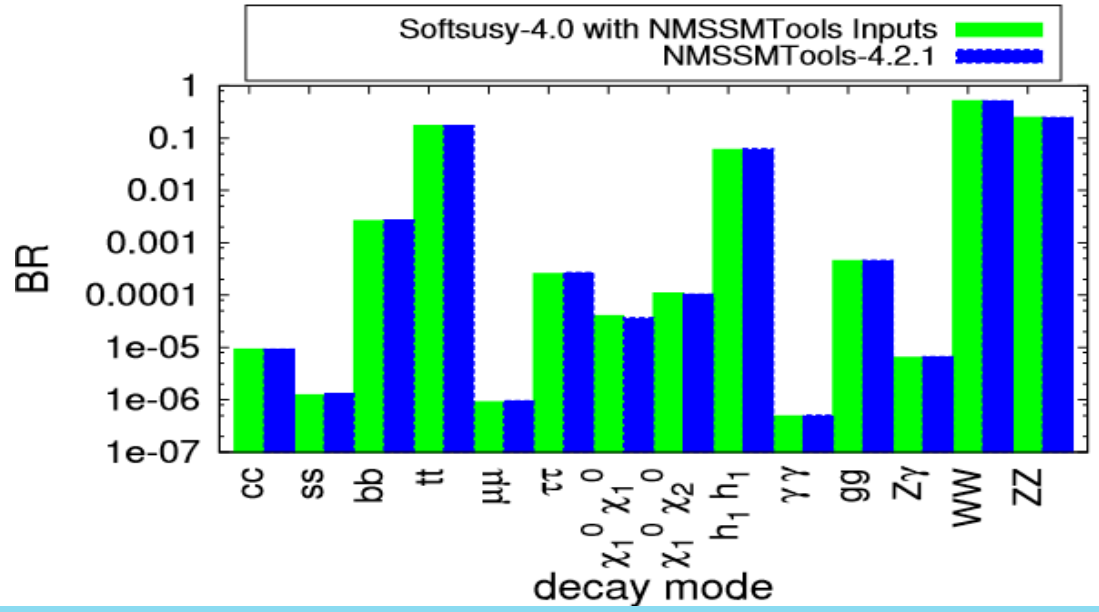
$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = R \begin{pmatrix} H_u \\ H_d \\ S \end{pmatrix}$$

Physical Basis

3x3 Mixing Matrix

Gauge Basis





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,

*lesHouchesInput - Mousepad

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```
# Example input in SLHA format, and suitable for input to
# SOFTSUSY (v1.8 or higher): CMSSM10.1.1 input - see arXiv:1109.3859
Block MODSEL                    # Select model
    1    1                      # sugra
Block SMINPUTS                  # Standard Model inputs
    1   1.279340000e+02         # alpha^(-1) SM MSbar(MZ)
    2   1.166370000e-05         # G_Fermi
    3   1.172000000e-01         # alpha_s(MZ) SM MSbar
    4   9.118760000e+01         # MZ(pole)
    5   4.250000000e+00         # mb(mb) SM MSbar
    6   1.743000000e+02         # mtop(pole)
    7   1.777000000e+00         # mtau(pole)
Block MINPAR                    # Input parameters
    1   1.250000000e+02         # m0
    2   5.000000000e+02         # m12
    3   1.000000000e+01         # tan beta at MZ, in DRbar scheme, Feynman gauge
    4   1.000000000e+00         # sign(mu)
    5   0.000000000e+00         # A0
Block SOFTSUSY                  # Optional SOFTSUSY-specific parameters
    0   1.000000000e+00         # Calculate decays in output (only for RPC (N)MSSM)
# The default is that without this, SOFTSUSY will only calculate the spectrum
   24   1.000000000e-06         # If decay BR is below this number, don't output
   25   1.000000000e+00         # If set to 0, don't calculate 3-body decays (1=default)
   26   0.000000000e+00         # If set to 1, output partial widths (0=default)
    1   1.000000000e-03         # Numerical precision: suggested range 10^(-3...-6)
    2   0.000000000e+00         # Quark mixing parameter: see manual
    3   0.000000000e+00         # Additional verbose output?
    4   1.000000000e+00         # Change electroweak symmetry breaking scale?
    5   1.000000000e+00         # Include 2-loop scalar mass squared/trilinear RGEs
    6   1.000000000e-04         # Numerical precision
    7   2.000000000e+00         # Number of loops in Higgs mass computation
   10   0.000000000e+00         # Force it to SLHA***1*** output?
   11   1.000000000e+19         # Gravitino mass
   12   0.000000000e+00         # Print spectrum even when point disallowed
   13   0.000000000e+00         # Set a tachyonic A^0 to zero mass
#   19   1.000000000e+00          # Include 3-loop SUSY RGEs
#   20   3.100000000e+01          # Include 2-loop g/Yuk corrections: 31 for all
#   22   1.000000000e+00          # Include 2-loop sparticle mass thresholds
#   23   0.000000000e+00          # No expansion of 2-loop gluino terms
```

Output file in SLHA form

SLHA: arXiv:hep-ph/0311123

SLHA2: arXiv:hep-ph/0801.0045

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```
# SOFTSUSY3.7.4 SLHA compliant output
# B.C. Allanach, Comput. Phys. Commun. 143 (2002) 305-331, hep-ph/0104
Block SPINFO          # Program information
     1    SOFTSUSY    # spectrum calculator
     2    3.7.4       # version number
Block MODSEL  # Select model
     1    1   # sugra
     3    1   # NMSSM
     9    0   # call micrOmegas (default: 0 = no)
    13    1   # sparticle decays via NMSDECAY (default: 0)
    12    4.52388280e+02   # parameter output scale
Block SMINPUTS             # Standard Model inputs
     1    1.27918000e+02   # alpha_em^(-1)(MZ) SM MSbar
     2    1.16639000e-05   # G_Fermi
     3    1.18900000e-01   # alpha_s(MZ)MSbar
     4    9.11876000e+01   # MZ(pole)
     5    4.20000000e+00   # mb(mb)
     6    1.70900000e+02   # Mtop(pole)
     7    1.77700000e+00   # Mtau(pole)
Block MINPAR               # SUSY breaking input parameters
     3    1.00000000e+01   # tanb, DRbar, Feynman gauge
     4    1.00000000e+00   # sign(mu)
     1    4.00000000e+02   # m0
     2    2.00000000e+02   # m12
     5   -3.00000000e+02   # A0
Block EXTPAR               # scale of SUSY breaking BCs
     0    2.70752239e+16   # MX scale
# SOFTSUSY-specific non SLHA information:
# MIXING=2 Desired accuracy=1.00000000e-04 Achieved accuracy=8.5461764
# 3-loop RGE corrections are off. 2-loop Yukawa/g3 thresholds are off
# 2-loop SUSY QCD computation of squark/gluino pole masses are off
# Z3 = 1, SoftHiggsOut = 0
Block MASS                         # Mass spectrum
```

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```
# Z3 = 1, SoftHiggsOut = 0
Block MASS                         # Mass spectrum
# PDG code      mass               particle
         24     8.03773761e+01     # MW
         25     1.06125456e+02     # h0(1)
         35     4.59243769e+02     # h0(2)
         45     5.13842116e+02     # h0(3)
         36     4.75604020e+02     # A0(1)
         46     5.17643738e+02     # A0(2)
         37     5.19733930e+02     # H+
    1000021     5.19588431e+02     # ~g
    1000022     7.72506034e+01     # ~neutralino(1)
    1000023     1.43487708e+02     # ~neutralino(2)
    1000024     1.42956970e+02     # ~chargino(1)
    1000025    -3.24123822e+02     # ~neutralino(3)
    1000035     3.40829262e+02     # ~neutralino(4)
    1000037     3.42811793e+02     # ~chargino(2)
    1000045     5.37613642e+02     # ~neutralino(5)
    1000001     6.01605489e+02     # ~d_L
    1000002     5.96553856e+02     # ~u_L
    1000003     6.01602918e+02     # ~s_L
    1000004     5.96551264e+02     # ~c_L
    1000005     5.18172073e+02     # ~b_1
    1000006     3.80037250e+02     # ~t_1
    1000011     4.22929545e+02     # ~e_L
    1000012     4.15128928e+02     # ~nue_L
    1000013     4.22932704e+02     # ~mu_L
    1000014     4.15121260e+02     # ~numu_L
    1000015     4.00955036e+02     # ~stau_1
    1000016     4.12825312e+02     # ~nu_tau_L
    2000001     5.88855759e+02     # ~d_R
    2000002     5.88251698e+02     # ~u_R
    2000003     5.88853082e+02     # ~s_R
    2000004     5.88249079e+02     # ~c_R
    2000005     5.84772590e+02     # ~b_2
    2000006     5.79368559e+02     # ~t_2
    2000011     4.08716920e+02     # ~e_R
    2000013     4.08690387e+02     # ~mu_R
    2000015     4.23561796e+02     # ~stau_2
Block NMHmix                     # CP even Higgs mixing matrix
  1  1      1.07097084e-01   # S_{1,1}
  1  2      9.92977500e-01   # S_{1,2}
  1  3     -5.02583210e-02   # S_{1,3}
  2  1      1.23366318e-01   # S_{2,1}
  2  2      3.68868055e-02   # S_{2,2}
  2  3      9.91675408e-01   # S_{2,3}
  3  1      9.86565237e-01   # S_{3,1}
  3  2     -1.12405729e-01   # S_{3,2}
```

Output file in SLHA form

SLHA: arXiv:hep-ph/0311123

SLHA2: arXiv:hep-ph/0801.0045

```
#     PDG          Width
DECAY 35           2.22170713e+00   # heavy higgs decays
#     BR                 NDA   PDG1          PDG2        Comments
      5.06774318e-06     2      4          -4          # H -> c cb
      3.07203043e-04     2      3          -3          # H -> s sb
      7.75300359e-01     2      5          -5          # H -> b bb
      1.41115765e-01     2      6          -6          # H -> t tb
      2.09145471e-04     2      13         -13         # H -> mu- mu+
      6.51058377e-02     2      15         -15         # H -> tau- tau+
      3.12257645e-03     2      1000022     1000022    # H -> ~chi_10 ~chi_10
      7.36883175e-03     2      1000022     1000023    # H -> ~chi_10 ~chi_20
      2.46467076e-03     2      25          25         # H -> h h
      3.21818444e-05     2      1000012    -1000012    # H -> ~nu_eL ~nu_eL*
      1.04662821e-04     2      2000011    -2000011    # H -> ~e_R- ~e_R+
      3.22870171e-05     2      1000014    -1000014    # H -> ~nu_muL ~nu_muL*
      1.04613078e-04     2      2000013    -2000013    # H -> ~mu_R- ~mu_R+
      6.26454473e-06     2      1000013    -2000013    # H -> ~mu_L- ~mu_R+
      8.85412879e-06     2      2000013    -1000013    # H -> ~mu_R- ~mu_L+
      5.82149371e-05     2      1000016    -1000016    # H -> ~nu_tauL ~nu_tauL*
      2.09873868e-05     2      1000015    -1000015    # H -> ~tau_1- ~tau_1+
      1.80021745e-03     2      1000015    -2000015    # H -> ~tau_1- ~tau_2+
      1.80021745e-03     2      2000015    -1000015    # H -> ~tau_2- ~tau_1+
      1.38212167e-06     2      22          22         # H -> gamma gamma
      3.17220840e-04     2      21          21         # H -> gluon gluon
      4.79030916e-04     2      24         -24         # H -> W+ W-
      2.34232999e-04     2      23         -23         # H -> Z Z
```

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

Summary

- **`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)

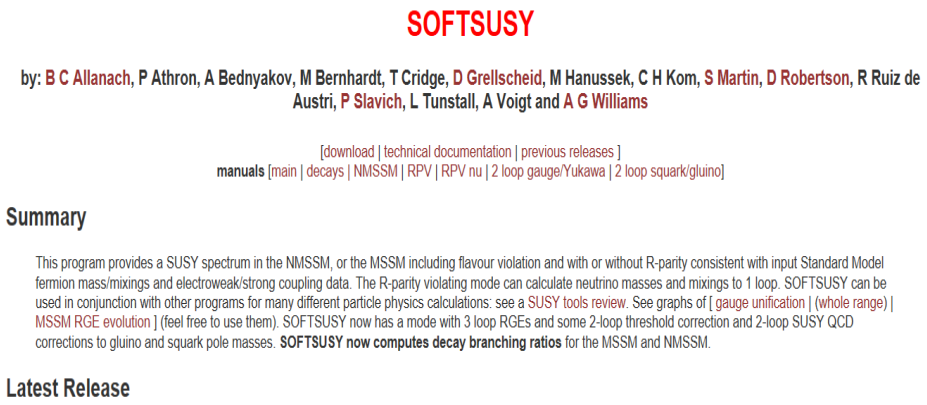
  -> Decays to **gravitinos**

  -> **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)

NLO QCD Corrections included here

Available at: https://softsusy.hepforge.org/


SOFTSUSY

by: B C Allanach, P Athron, A Bednyakov, M Bernhardt, T Cridge, D Grellscheid, M Hanussek, C H Kom, S Martin, D Robertson, R Ruiz de Austri, P Slavich, L Tunstall, A Voigt and A G Williams

[download | technical documentation | previous releases]
manuals [main | decays | NMSSM | RPV | RPV nu | 2 loop gauge/Yukawa | 2 loop squark/gluino]

Summary

This program provides a SUSY spectrum in the NMSSM, or the MSSM including flavour violation and with or without R-parity consistent with input Standard Model fermion mass/mixings and electroweak/strong coupling data. The R-parity violating mode can calculate neutrino masses and mixings to 1 loop. SOFTSUSY can be used in conjunction with other programs for many different particle physics calculations: see a SUSY tools review. See graphs of [gauge unification | (whole range) | MSSM RGE evolution] (feel free to use them). SOFTSUSY now has a mode with 3 loop RGEs and some 2-loop threshold correction and 2-loop SUSY QCD corrections to gluino and squark pole masses. **SOFTSUSY now computes decay branching ratios** for the MSSM and NMSSM.

Latest Release

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

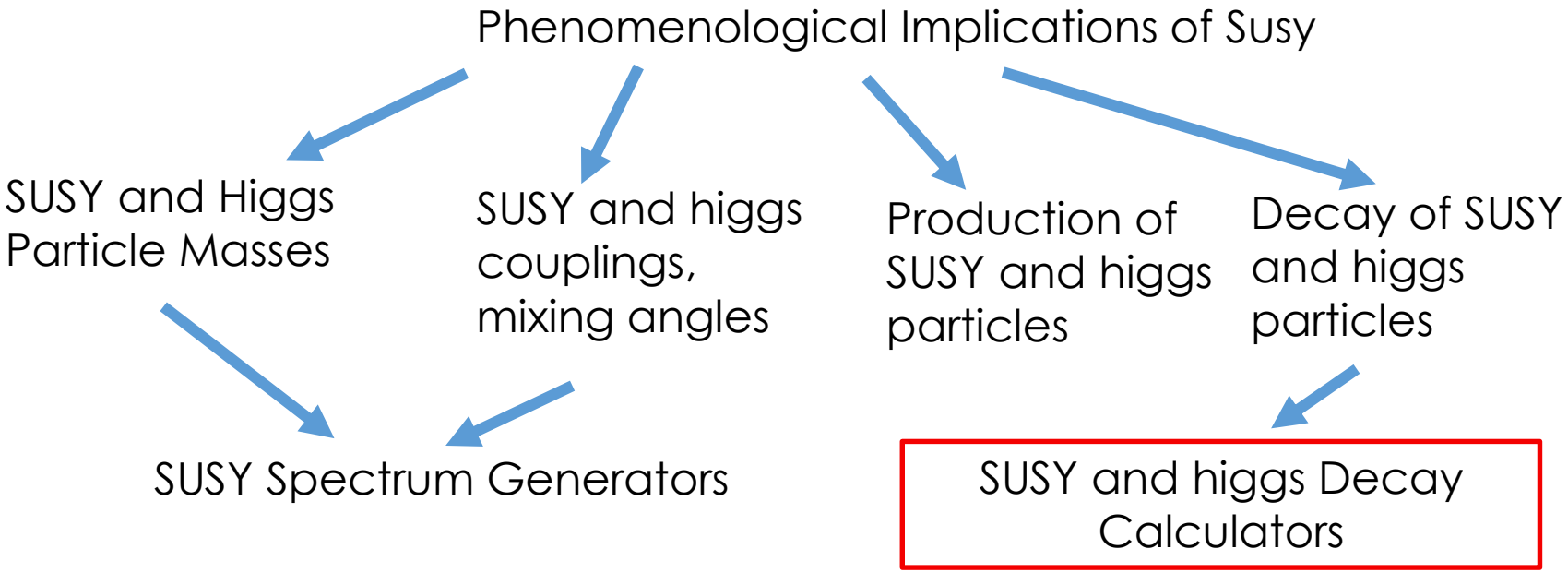
Thankyou for Listening!
Any Questions?

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

Section 6

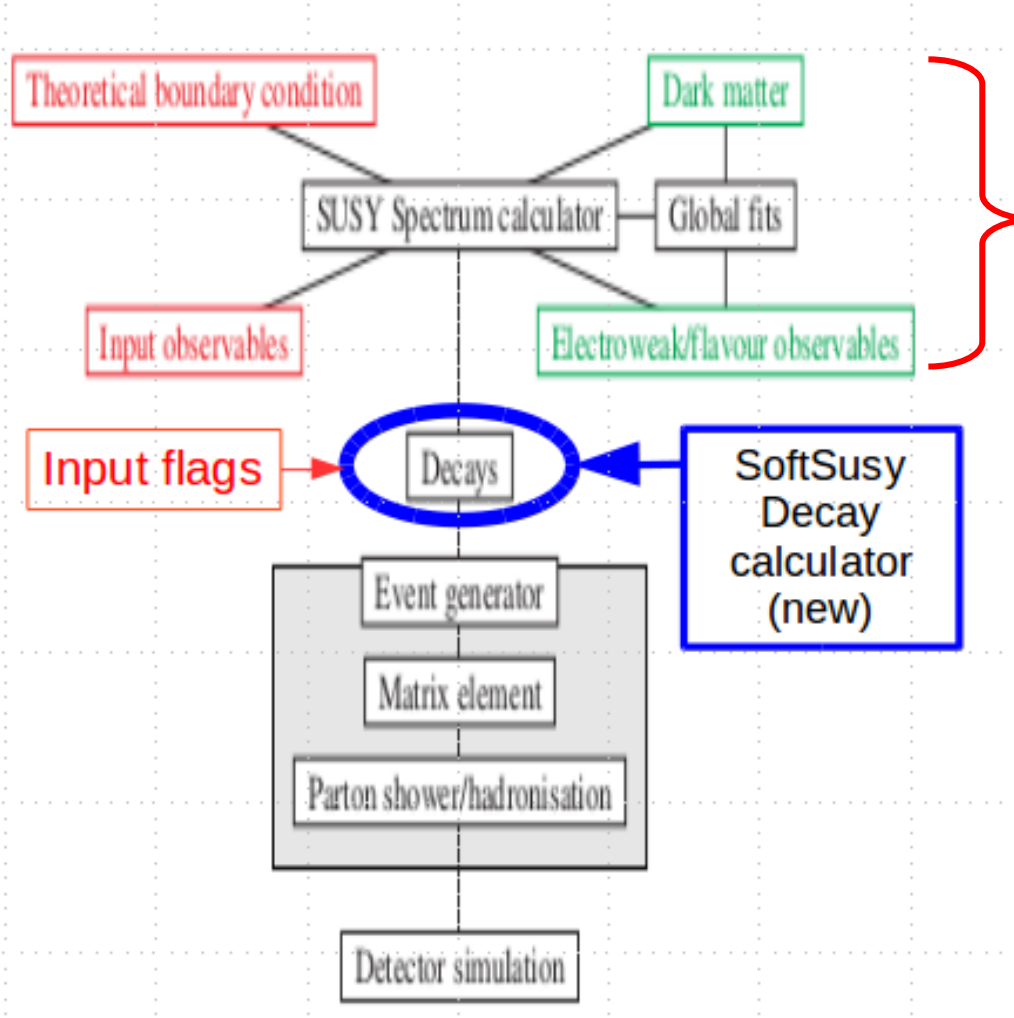
Extra Slides

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 *([1] B.C. Allanach, Comput. Phys. Commun. 143 (2002) 305331, hep-ph/0104145)*

SoftSusy Decay calculator (new)

B.C. Allanach, "SUSY Predictions and SUSY Tools at the LHC", arXiv:0805.2088[hep-ph]

SoftSusy

- 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 ← Added for SoftSusy-4.0
- Softsusy Decay calculator – Extend these uses further into exclusions via decay branching ratios incorporated in the full MSSM/NMSSM.

Uses of SoftSusy

- Susy searches at 7/8/13TeV for CMSSM benchmark points at LHC. *(CERN-EP-2017-246)*
- RPV searches in the CMSSM
- AMSB searches for long-lived particles – quasi degenerate charginos.
- pMSSM studies, mT2 variable study *(Allanach, Barr, Dafinca, Gwenlan; arXiv:1105.1024)*
- Recent ATLAS and CMS searches for stop signatures: *(ATLAS-CONF-2017-037 and -034)*
- 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)*
- LHC DM Searches and Interpretations *(ATLAS Collaboration, JHEP 1609 (2016) 175)*
- Theoretical analyses of GUT scale boundary conditions – can set own models of susy breaking and implement the running. *(JHEP 0110 (2001) 024)*
- Fine-tuning calculation of different susy breaking *(Eur.Phys.J. C76 (2016) no.8, 450)*

SoftSusy Decay Calculator

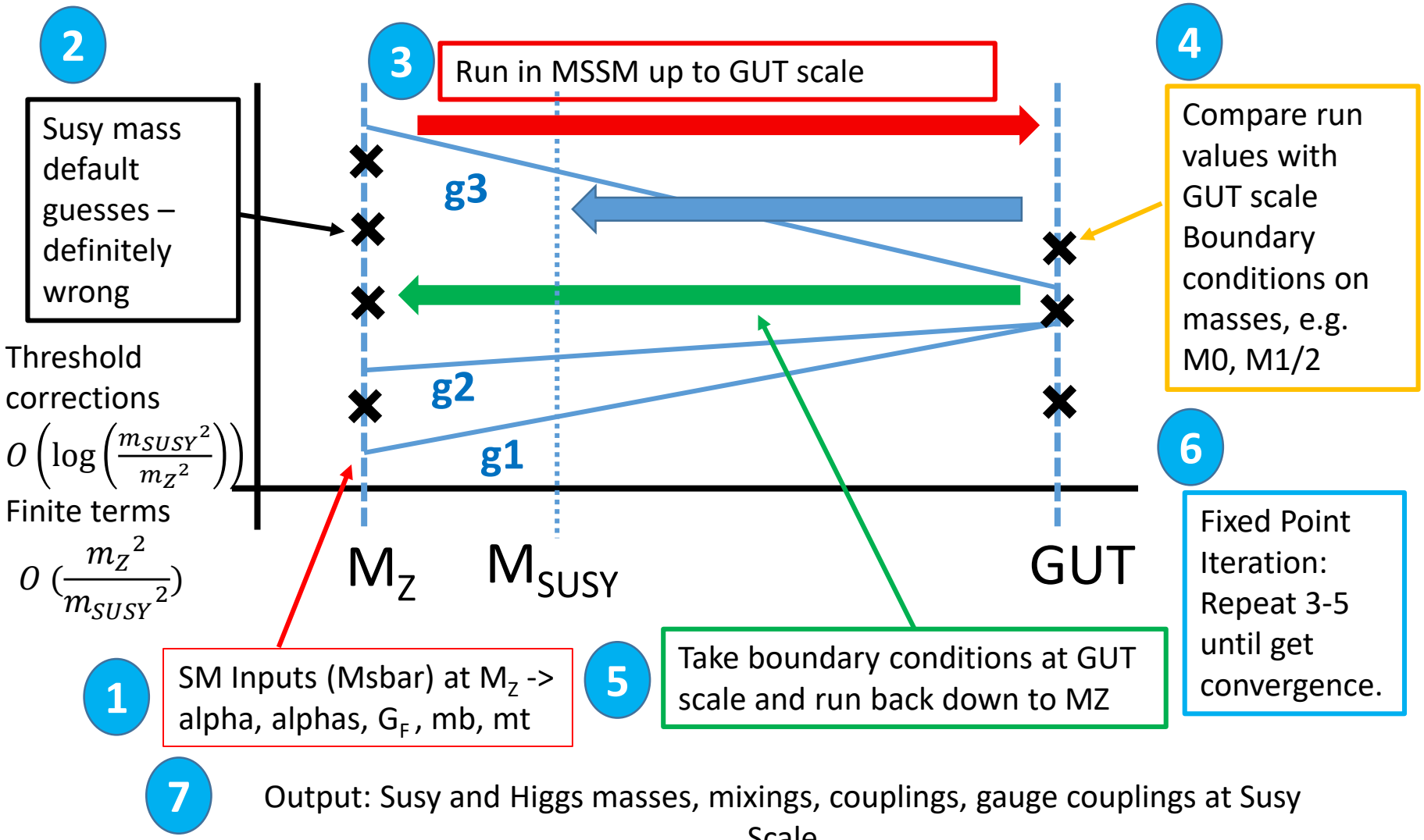
- **SOFTSUSY-4.0** (New version!):
  - As before + **DECAY CALCULATOR**
  - Major extension
  - Allows all-in-one spectrum generation and decay calculation
  - All tree-level SUSY and Higgs two body decays in MSSM and NMSSM + relevant three body and loop decays!

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

All in one place!

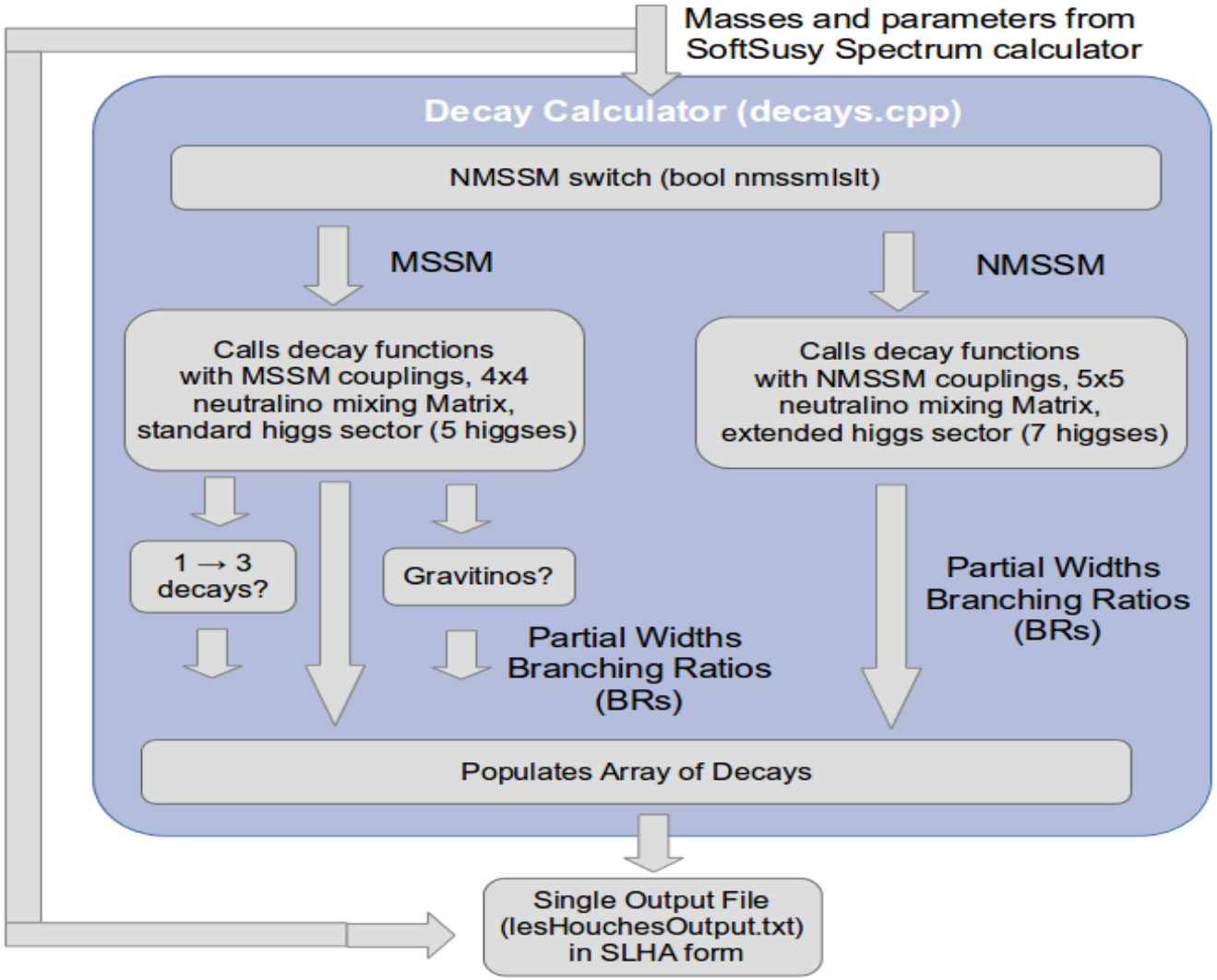
- Provides additional code for decay BRs comparison – improves knowledge of theoretical errors and variation involved.

SoftSusy Spectrum Generator



7 Output: Susy and Higgs masses, mixings, couplings, gauge couplings at Susy Scale

Decay calculator Specifics

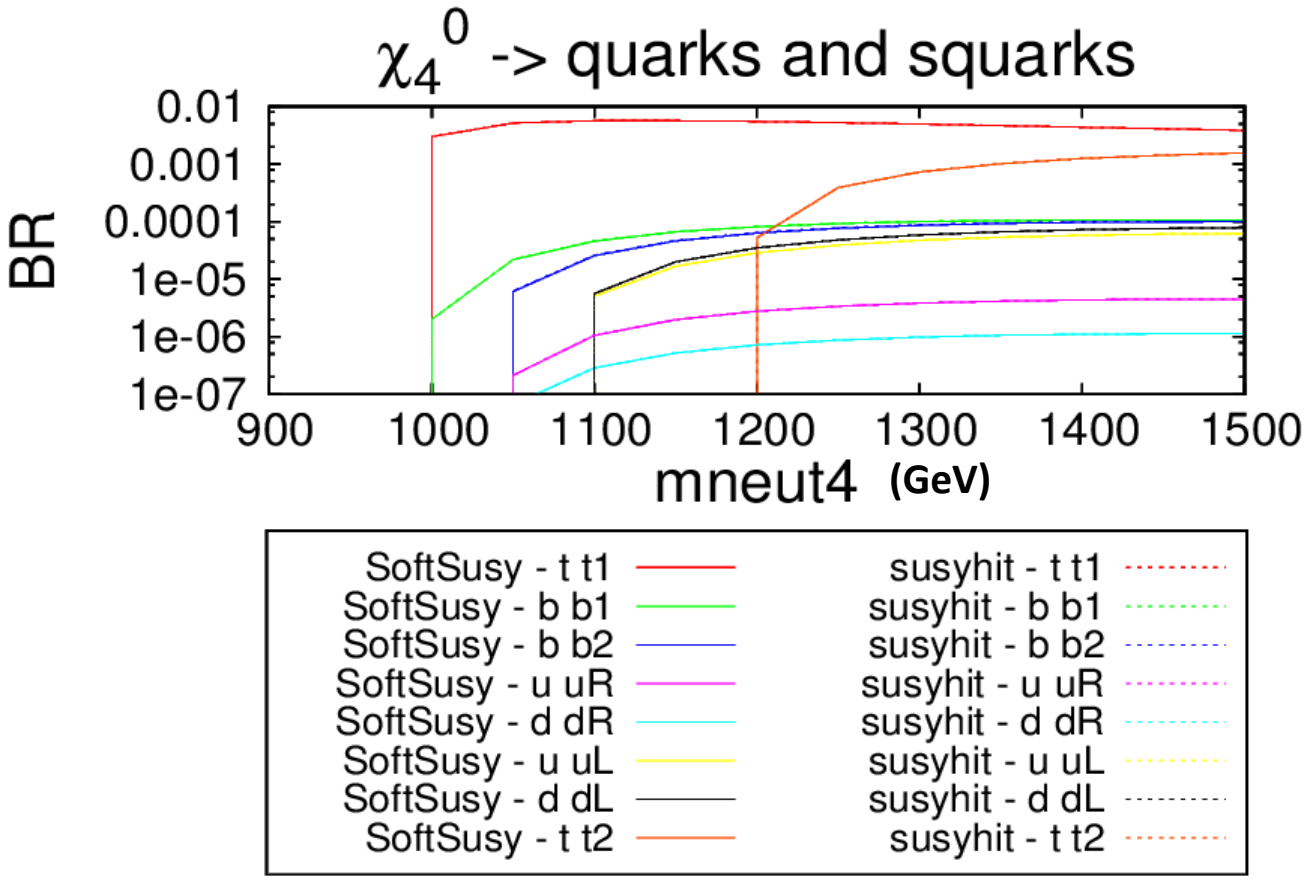


SoftSusy Decays (`SOFTSUSY-4.0`)

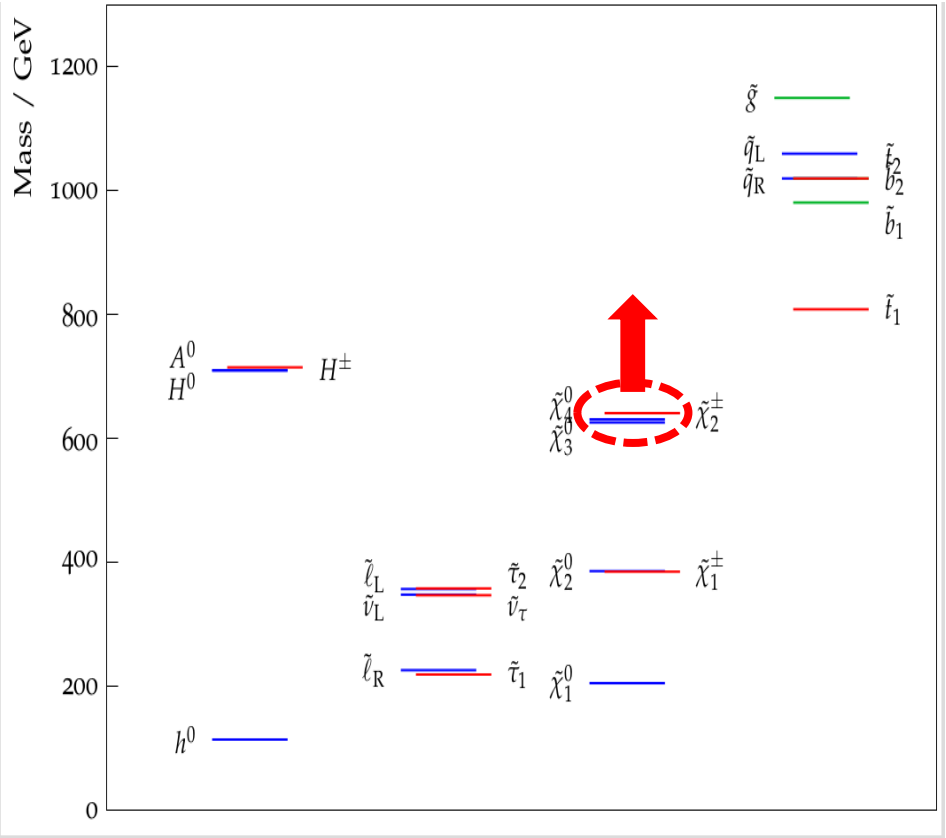
- All 1 → 2 decays of MSSM SUSY particles.
- All 1 → 2 higgs decays in MSSM.
- Phenomenologically Relevant 1 → 3 decays in MSSM (e.g. for compressed spectra).
- Higgs 1-loop decays: h -> γγ, Zγ, gg in MSSM and NMSSM.
- Higgs 1 → 3 decays via VV*: h -> VV* -> V f fbar.
- Decays to gravitinos in MSSM.
- All 1 → 2 decays of SUSY and higgs particles in NMSSM.
- QCD corrections included for higgs decays to quarks and gluons.

MSSM Susy decays 1 – χ_4^0

- Validation plots (here compared against sdecay of susyhit) e.g. neut 4: χ_4^0



Spectrum Plot generated with slhaplot of pyslha-3.2.0:
Buckley arXiv:1305.4194



MSSM Susy decays 1 – χ_4^0

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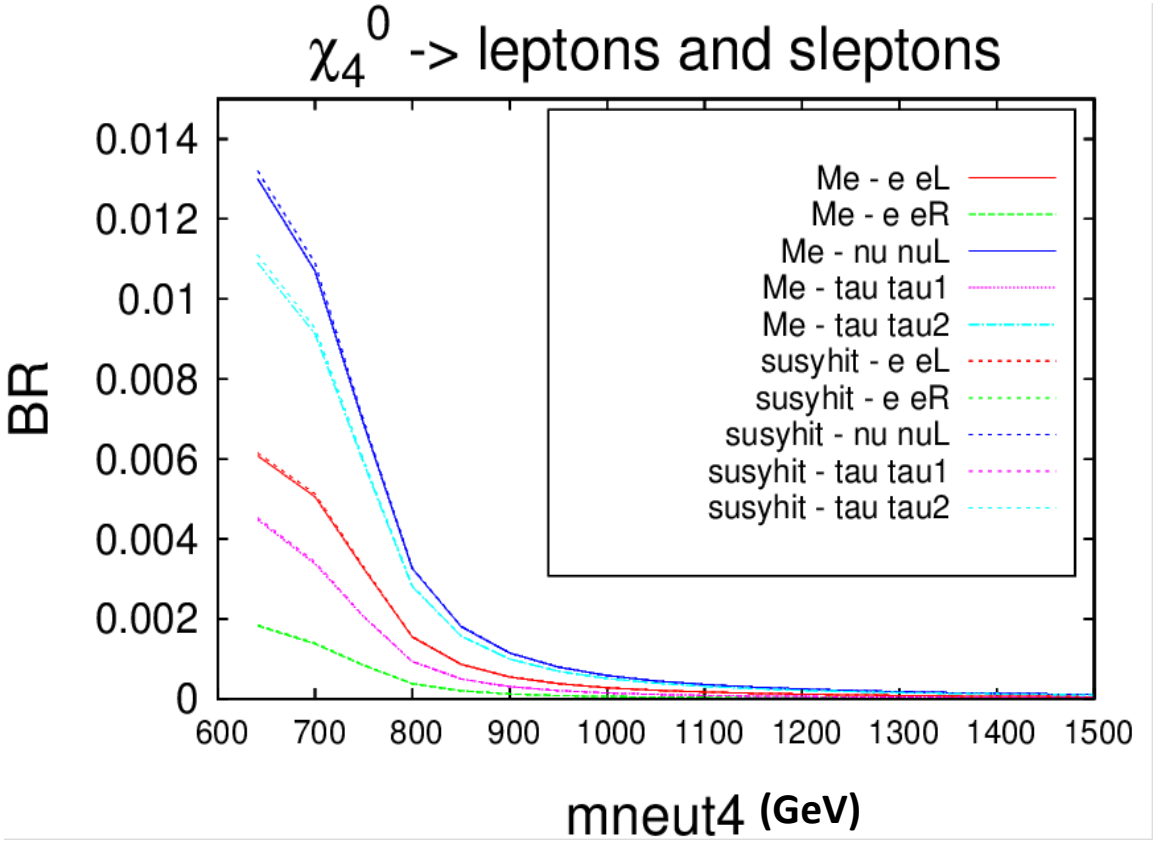

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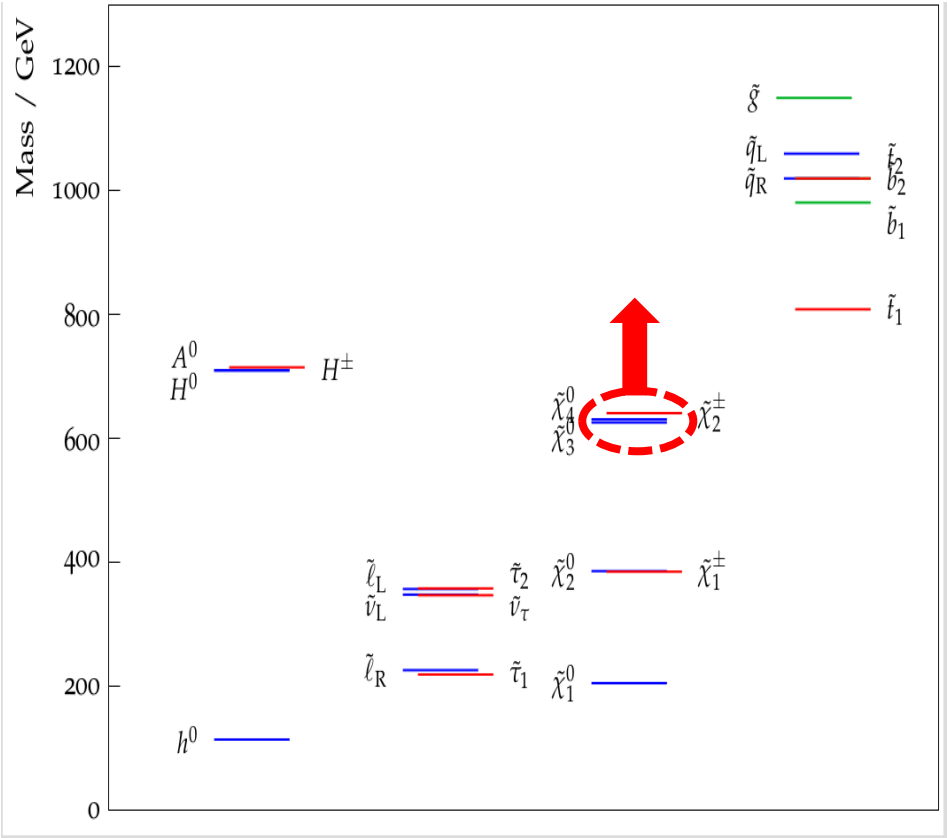
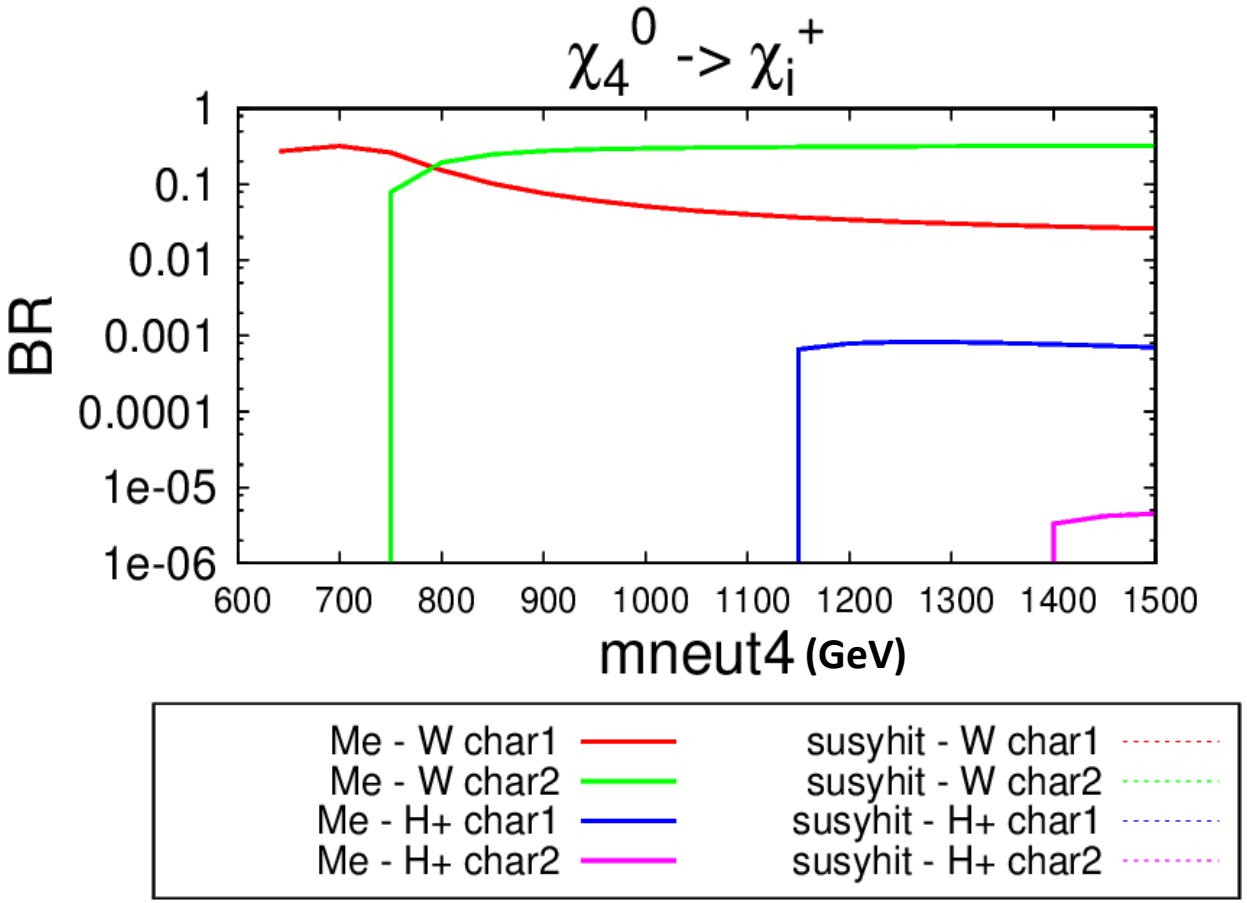
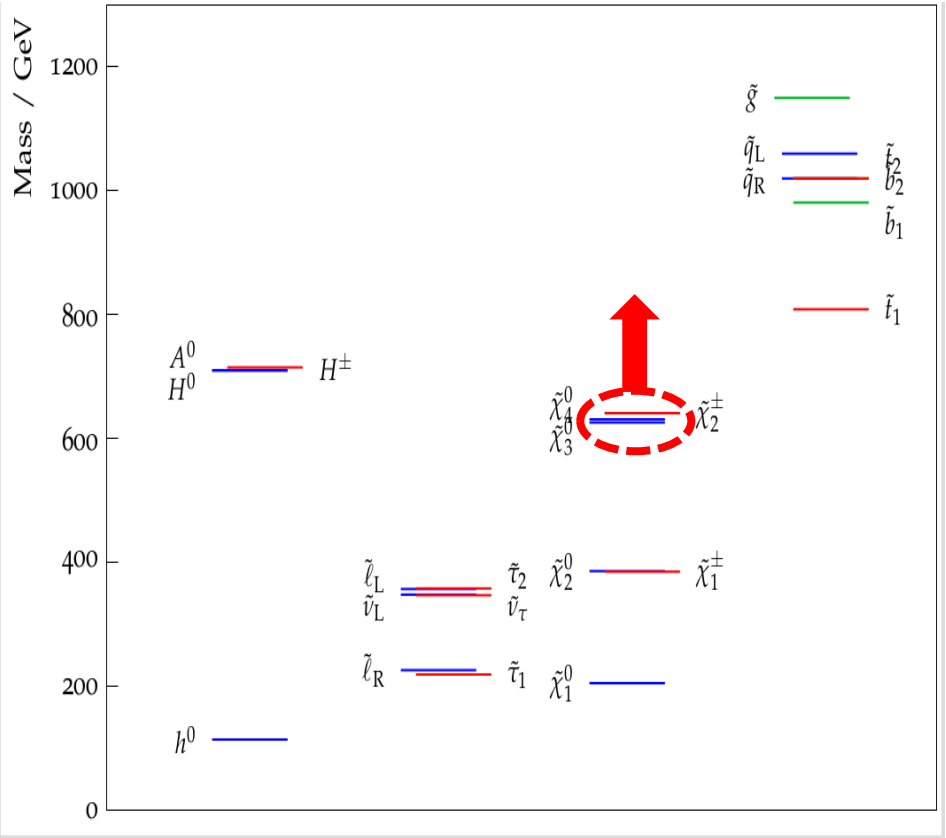


MSSM Susy decays 1 – χ_4^0

- Validation plots (here compared against sdecay of susyhit) e.g. neut 4: χ_4^0

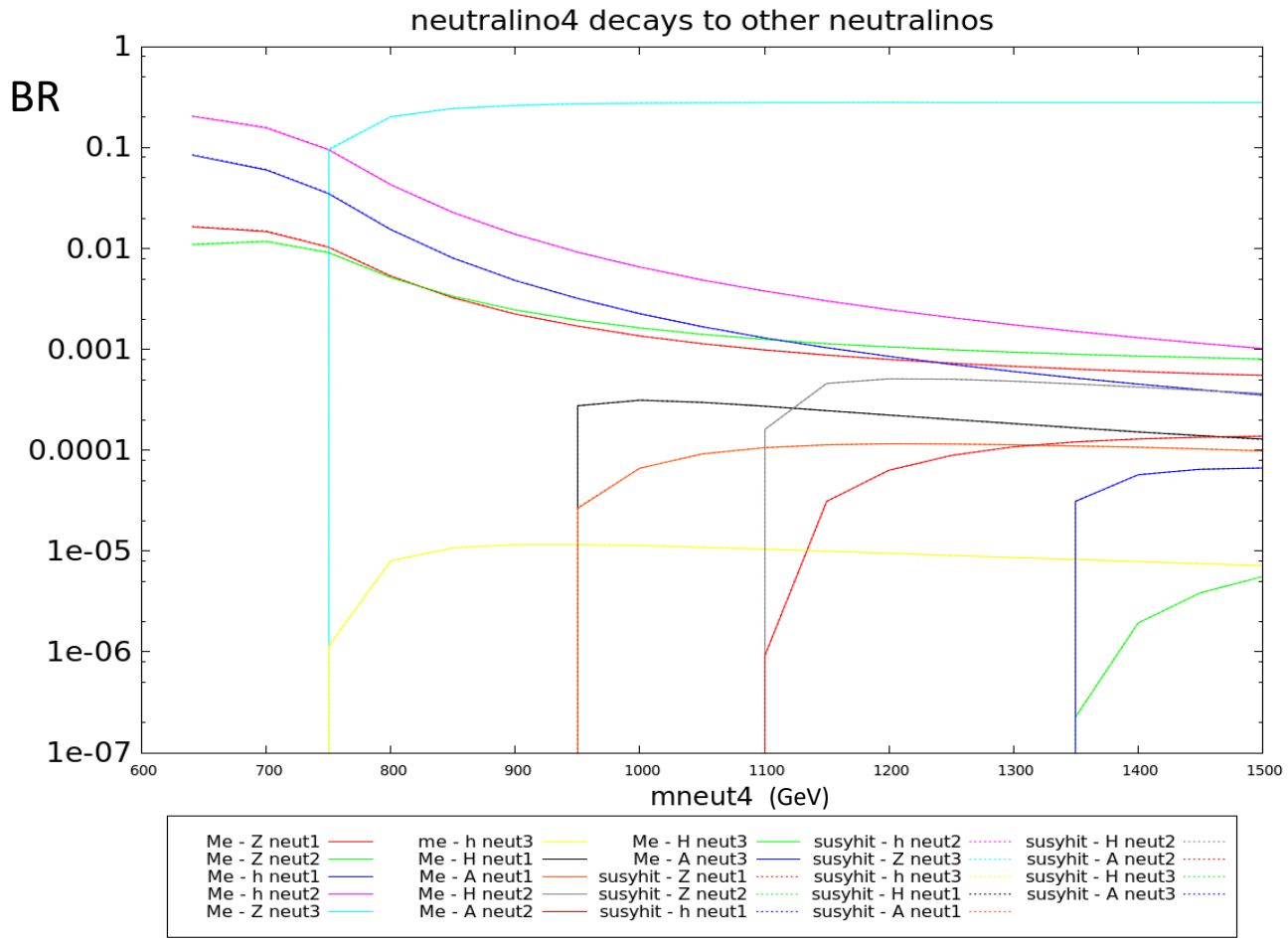


Spectrum Plot generated with slhaplot of pyslha-3.2.0:
Buckley arXiv:1305.4194

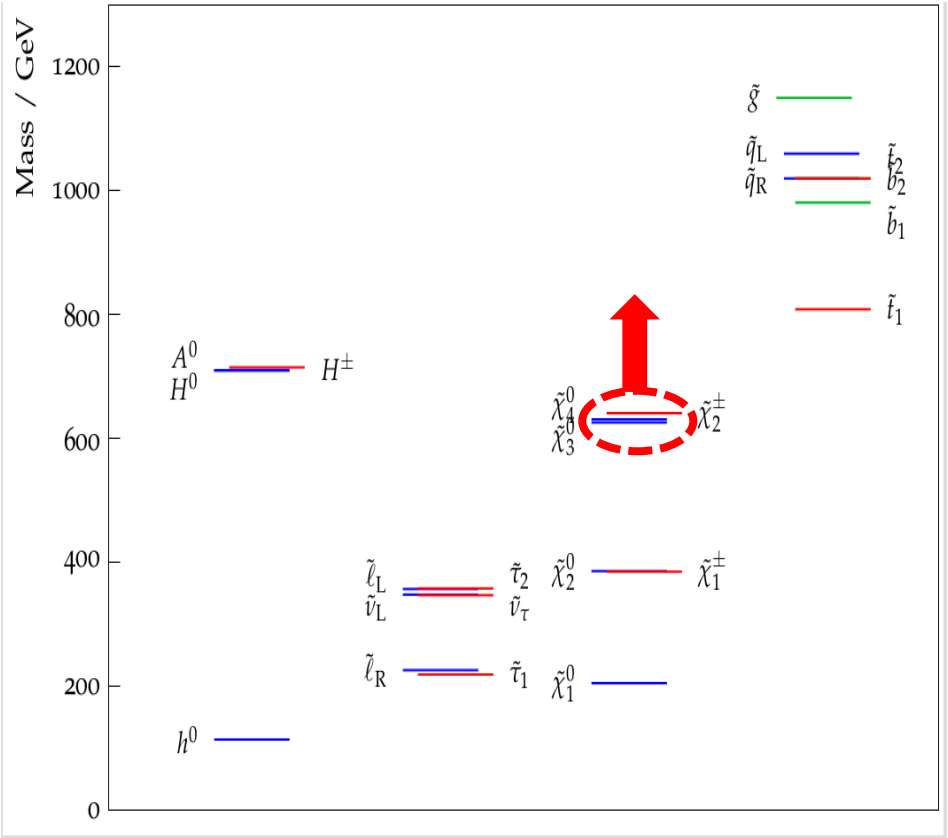


MSSM Susy decays 1 – χ_4^0

- Validation plots (here compared against sdecay of susyhit) e.g. neut 4: χ_4^0



Spectrum Plot generated with slhaplot of pyslha-3.2.0: Buckley arXiv:1305.4194



Higgs decays 1 – BRs at mh = 125GeV

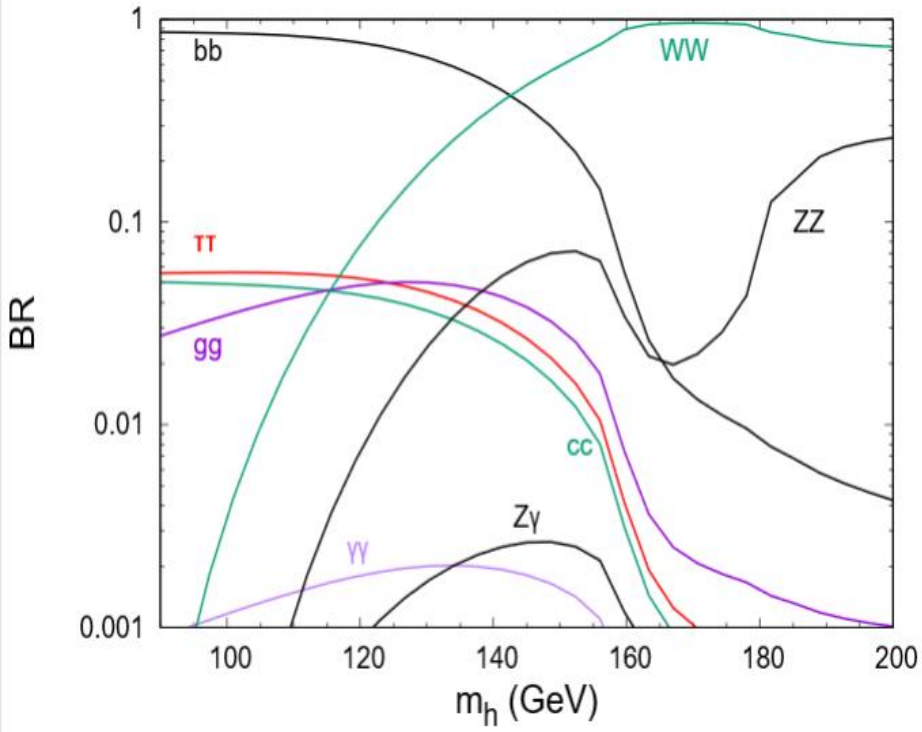
- Comparison of BRs for SM like higgs – **`SoftSusy`** Decays module vs hdecay program of susyhit

SOFTSUSY with QCD corrections		SOFTSUSY with SUSYHIT's masses and QCD corrections		HDECAY-3.4 with same QCD corrections		mode
PW/GeV	BR	PW/GeV	BR	PW/GeV	BR	
2.25e-04	4.03e-02	2.25e-04	4.31e-02	2.25e-04	4.24e-02	$h \to cc$
1.62e-06	2.91e-04	1.62e-06	3.11e-04	1.63e-06	3.06e-04	$h \to ss$
3.96e-03	7.10e-01	3.60e-03	6.90e-01	3.61e-03	6.80e-01	$h \to bb$
8.52e-07	1.53e-04	9.17e-07	1.76e-04	9.19e-07	1.73e-04	$h \to \mu\mu$
2.61e-04	4.67e-02	2.59e-04	4.97e-02	2.60e-04	4.90e-02	$h \to \tau\tau$
1.06e-05	1.89e-03	9.24e-06	1.77e-03	9.24e-06	1.74e-03	$h \to \gamma\gamma$
2.71e-04	4.86e-02	2.72e-04	5.22e-02	2.72e-04	5.13e-02	$h \to gg$
6.74e-06	1.21e-03	5.88e-06	1.13e-03	6.11e-06	1.15e-03	$h \to Z\gamma$
7.61e-04	1.36e-01	7.61e-04	1.46e-01	8.22e-04	1.55e-01	$h \to WW^*$
8.44e-05	1.51e-02	8.44e-05	1.62e-02	1.02e-04	1.92e-02	$h \to ZZ^*$

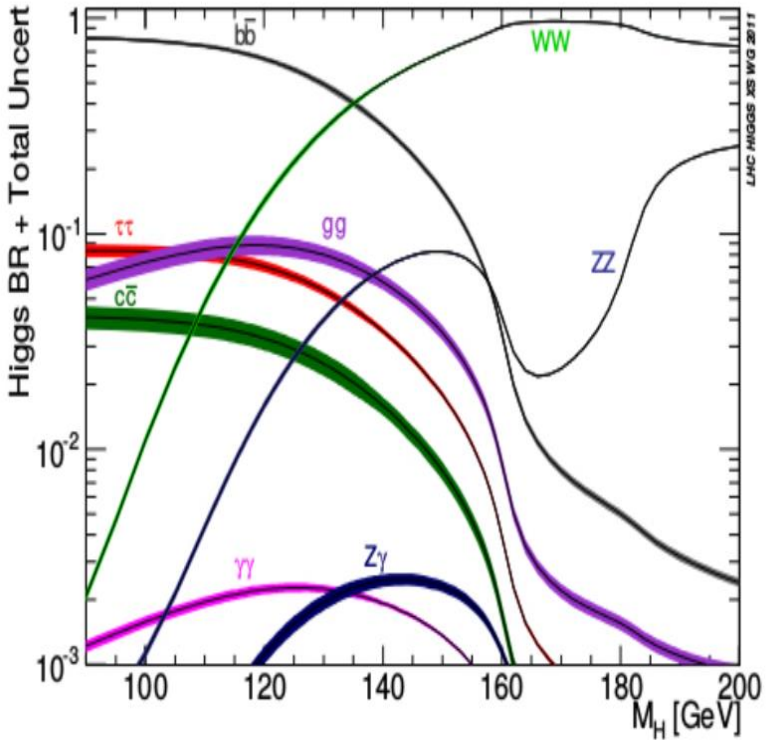
NLO QCD corrections included for h -> qq and h -> gg decays:
- 1-loop for h -> qq
- 2-loop for h -> gg

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:

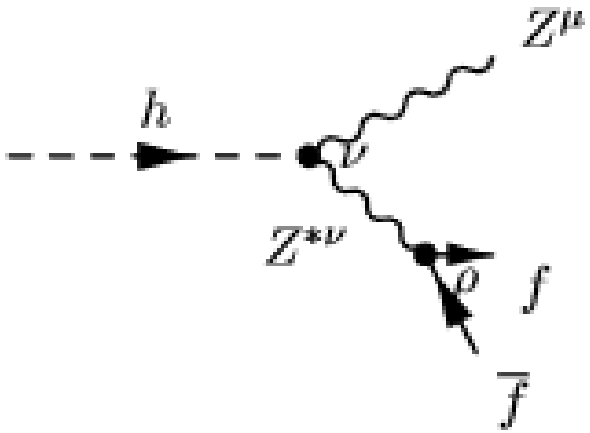


`SoftSusy-4.0`



Denner, Heinemeyer, Puljak, Rebuzzi, Spira "Standard Model Higgs Boson Branching ratios with Uncertainties", arXiv:1107.5909

$h \to VV^* \to Vq\bar{q}$



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

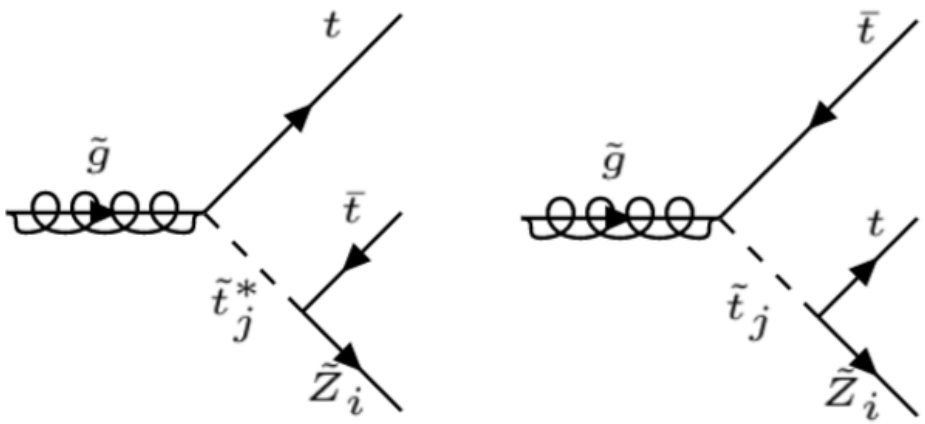
$$\Gamma(h/H \to ZZ^*) = \frac{G_F^2 m_{h/H} m_W^4 c_{h/HVV}^2}{64\pi^3 \cos^4\theta_W} F(\epsilon_Z)\left[7 - \frac{40}{3}\sin^2\theta_W + \frac{160}{9}\sin^4\theta_W\right],$$

$$\Gamma(h/H \to WW^*) = \frac{3G_F^2 m_W^4 m_{h/H} c_{h/HVV}^2}{16\pi^3} F(\epsilon_W),$$

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

$$\epsilon_V = {}^{m_V}/_{m_h}$$

$\tilde{g} \to \widetilde{\chi_i^0} q\bar{q}$



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.

<u>4 diagrams – stop1 and stop2, t and u channel</u>
4 "squared" (i.e. non interference) contributions
6 interference contributions between the different diagrams

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

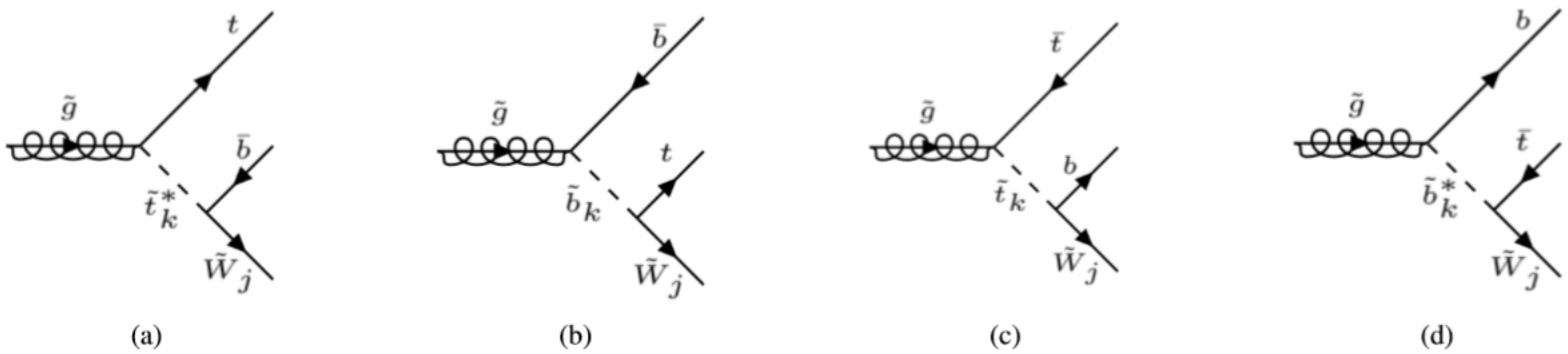
$$\Gamma_{\tilde{t}_1} = \Gamma_{LL}(\tilde{t}_1)\cos^2\theta_t + \Gamma_{RR}(\tilde{t}_1)\sin^2\theta_t - \sin\theta_t\cos\theta_t\left[\Gamma_{L_1R_1}(\tilde{t}_1) + \Gamma_{L_1R_2}(\tilde{t}_1) + \Gamma_{L_2R_1}(\tilde{t}_1) + \Gamma_{L_2R_2}(\tilde{t}_1)\right].$$

$$\Gamma_{\tilde{t}_2} = \Gamma_{LL}(\tilde{t}_2)\sin^2\theta_t + \Gamma_{RR}(\tilde{t}_2)\cos^2\theta_t + \sin\theta_t\cos\theta_t\left[\Gamma_{L_1R_1}(\tilde{t}_2) + \Gamma_{L_1R_2}(\tilde{t}_2) + \Gamma_{L_2R_1}(\tilde{t}_2) + \Gamma_{L_2R_2}(\tilde{t}_2)\right].$$

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

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

$\tilde{g} \to \widetilde{\chi_i^{\pm}} q' \bar{q}$



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.

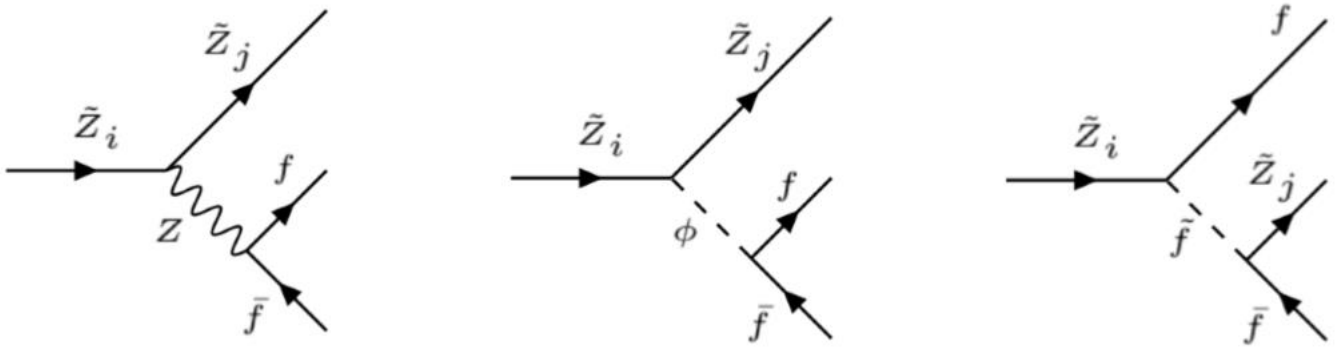
<u>4 diagrams – stop1, stop2, sbottom1, sbottom2 for each of $q'\bar{q}$ and $q\bar{q}'$</u>
4 "squared" (i.e. non interference) contributions
6 interference contributions between the different diagrams

$$\Gamma(\tilde{g} \to t\bar{b}\tilde{W}_i^-) = \frac{\alpha_s}{16\pi^2 m_{\tilde{g}}}(\Gamma_{\tilde{t}_1} + \Gamma_{\tilde{t}_2} + \Gamma_{\tilde{t}_1\tilde{t}_2} + \Gamma_{\tilde{b}_1} + \Gamma_{\tilde{b}_2} + \Gamma_{\tilde{t}_1\tilde{b}_1} + \Gamma_{\tilde{t}_1\tilde{b}_2} + \Gamma_{\tilde{t}_2\tilde{b}_1} + \Gamma_{\tilde{t}_2\tilde{b}_2}).$$

Mb neglected in matrix element (but accounted for in finite state masses), mt kept throughout.

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

$\widetilde{\chi_i^0} \to \widetilde{\chi_j^0} q\bar{q}$



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.

<u>6 diagrams – Z, h, H, A, $\widetilde{q_1}$, $\widetilde{q_2}$</u>

6 "squared" (i.e. non interference) contributions (Z, h, H, A, $\widetilde{q_1}$, $\widetilde{q_2}$)

10 interference contributions between the different diagrams (no CP even CP odd interference or Higgs Z interference as quark masses dropped in matrix element)

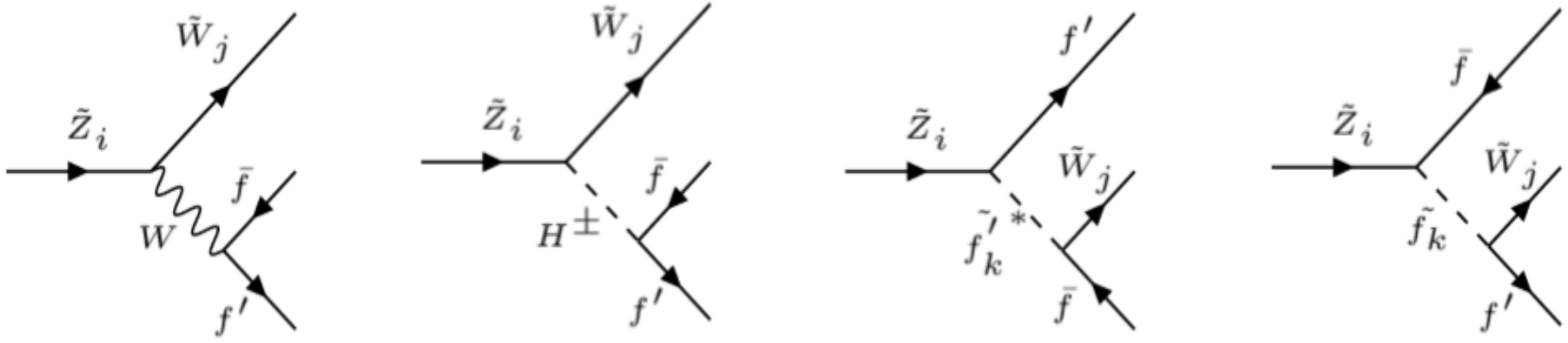
$$\Gamma(\tilde{Z}_i \to \tilde{Z}_j f\bar{f}) = \frac{N_c}{512\pi^3|m_{\tilde{Z}_i}|^3}(\Gamma_Z + \Gamma_h + \Gamma_H + \Gamma_A + \Gamma_{hH} + \Gamma_{\tilde{f}} - 4\Gamma_{h\tilde{f}_1} - 4\Gamma_{h\tilde{f}_2} - 4\Gamma_{H\tilde{f}_1} - 4\Gamma_{H\tilde{f}_2} - 4\Gamma_{A\tilde{f}_1} - 4\Gamma_{A\tilde{f}_2}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

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

$\widetilde{\chi_i^0} \to \widetilde{\chi_j^+} q' \bar{q}$



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

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

<u>6 diagrams – W+-, H+-, $\widetilde{q'_1}$,$\widetilde{q'_2}$, $\widetilde{q_1}$, $\widetilde{q_2}$</u>

6 "squared" (i.e. non interference) contributions W+-, H+-, $\widetilde{q'_1}$,$\widetilde{q'_2}$, $\widetilde{q_1}$, $\widetilde{q_2}$

15 interference contributions between the different diagrams

$$\Gamma = \frac{N_c}{512\pi^3|m_{Z_i}|^3}\Big[\Gamma_W + \Gamma_{\tilde{f}_1} + \Gamma_{\tilde{f}_2} + \Gamma_{\tilde{f}'_1} + \Gamma_{\tilde{f}'_2} - 2\Gamma_{\tilde{f}'_1\tilde{f}_1} - 2\Gamma_{\tilde{f}'_1\tilde{f}_2} - 2\Gamma_{\tilde{f}'_2\tilde{f}_1} - 2\Gamma_{\tilde{f}'_2\tilde{f}_2} + 2\Gamma_{WH^\pm}$$
$$+ 2\Gamma_{WG} + \Gamma_{H^\pm} + \Gamma_G - 2\Gamma_{W\tilde{f}'_1} - 2\Gamma_{W\tilde{f}'_2} - 2\Gamma_{W\tilde{f}_1} - 2\Gamma_{W\tilde{f}_2} + 2\Gamma_{H^\pm G} - 2\Gamma_{G\tilde{f}'_1}$$
$$- 2\Gamma_{G\tilde{f}'_2} - 2\Gamma_{G\tilde{f}_1} - 2\Gamma_{G\tilde{f}_2} - 2\Gamma_{H^\pm\tilde{f}'_1} - 2\Gamma_{H^\pm\tilde{f}'_2} - 2\Gamma_{H^\pm\tilde{f}_1} - 2\Gamma_{H^\pm\tilde{f}_2} + 2\Gamma_{\tilde{f}'_1\tilde{f}'_2} + 2\Gamma_{\tilde{f}_1\tilde{f}_2}$$

Quark masses kept throughout matrix elements throughout Dirac algebra – therefore have WH^+interference too.

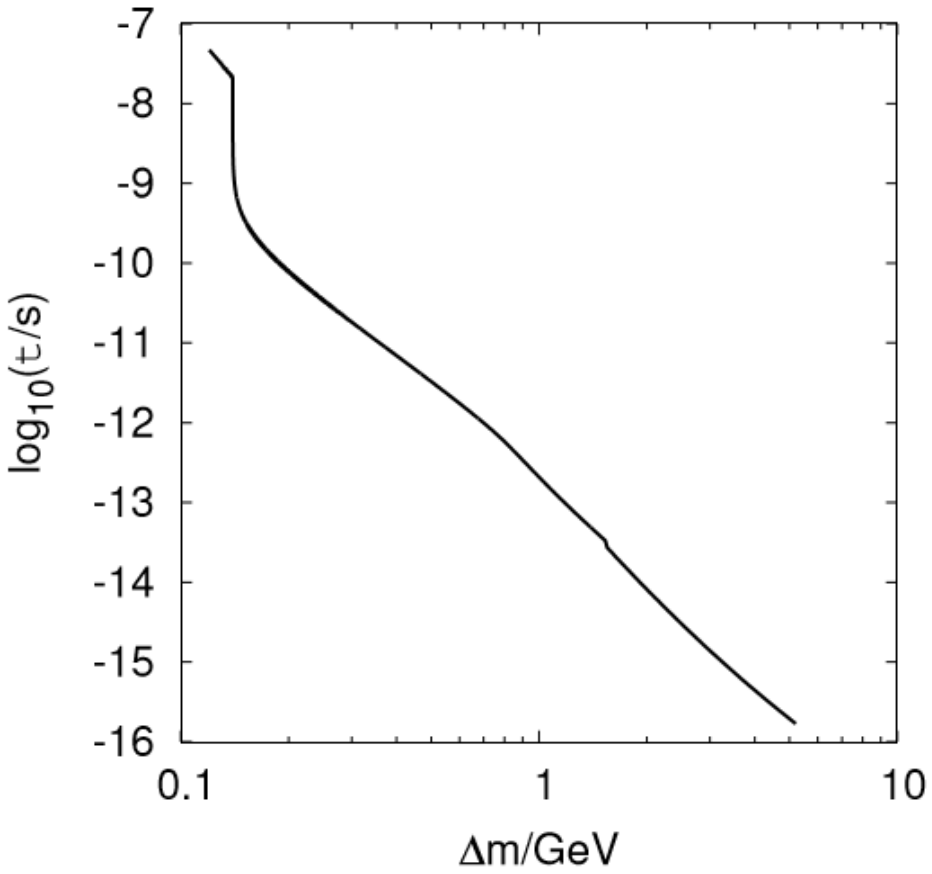
Only really relevant for first 2 generations as for t and b then 2 body modes available.

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

Special cases - Chargino decays to Pions

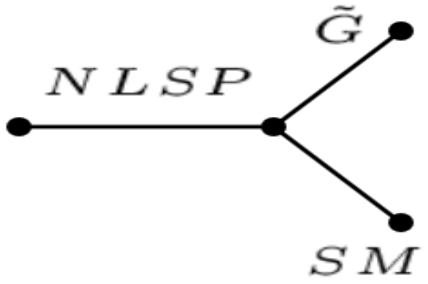
- Lifetimes of Chargino NLSP long enough to observe in LHC.
- High pT chargino tracks decay to soft pions or leptons + large MET (neutralino LSP).
- Kinks/disappearing tracks observed in one-pronged decays $\tilde{\chi}_1^+ \rightarrow \tilde{\chi}_1^0 \pi^+$.

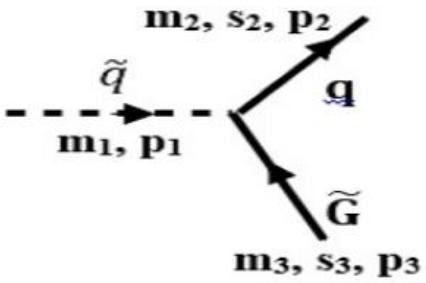


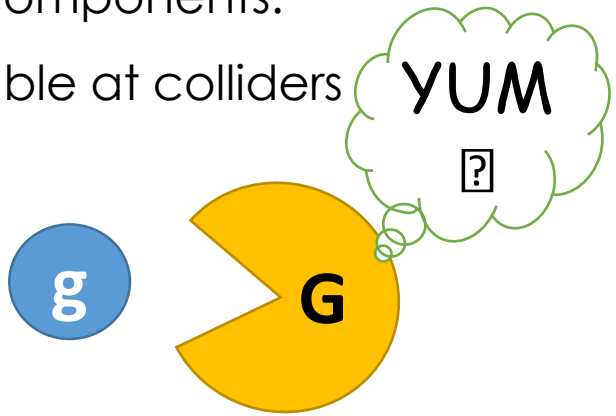
Gravitino decays - theory

- Susy -> local symmetry to incorporate gravity -> spin 2 graviton.

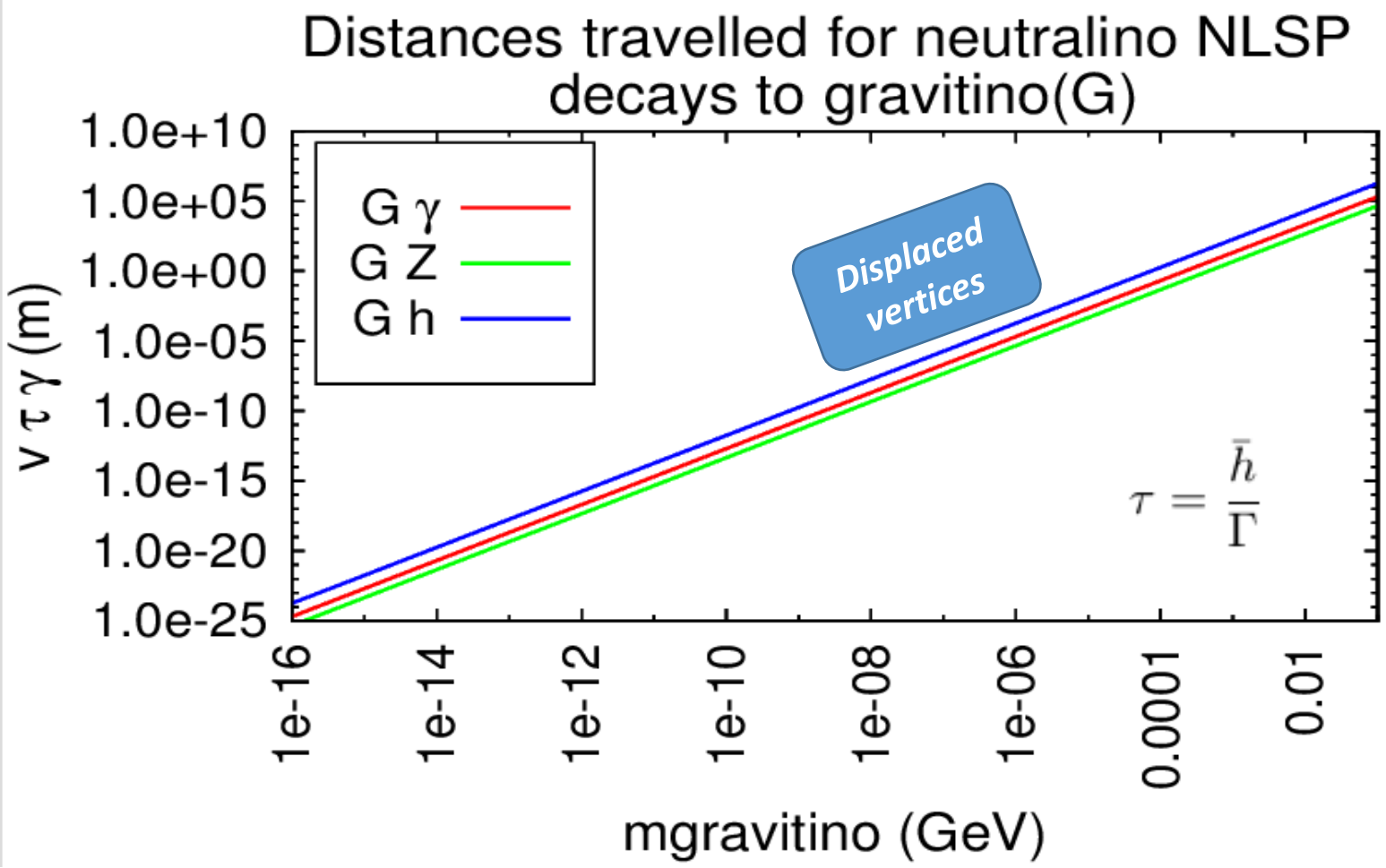
  -> spin 3/2 susy partner: gravitino.
- Spontaneous susy breaking (SSB) -> massless goldstone fermion of spin 1/2 : goldstino.
- In SSB, massless gravitino "eats" massless goldstino -> becomes gravitino's longitudinal dof -> gravitino becomes massive.
- In SSB scenarios, particularly GMSB the gravitino can be LSP.
- Gravitino inherits stronger coupled longitudinal components.
- Decays **NLSP -> LSP gravitino + SM** to be observable at colliders







Gravitino decays - plot



NMSSM Key parameters

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

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

λ - coupling of singlino to higgsinos, neutralino mixing, higgs masses

κ - contributes to higgs masses

$\boldsymbol{A_\lambda}$ - soft susy breaking parameter, trilinear couplings

$\boldsymbol{A_\kappa}$ - soft susy breaking parameter, trilinear couplings

$\boldsymbol{tan\beta = \langle H_u \rangle / \langle H_d \rangle}$ - ratio of higgs vevs, neutralino mixing via higgsinos

$\boldsymbol{\mu_{eff} = \lambda \langle S \rangle}$ - higgsino masses, neutralino mixing

N.B. As $\tilde{S}$ is gauge singlet it only couples to non-higgs particles via mixing with other neutralinos.

QCD Corrected Higgs Decays

Must use pole masses with QCD corrections (not running masses) or you will double count $\mathcal{O}(\alpha_s)$ effects

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

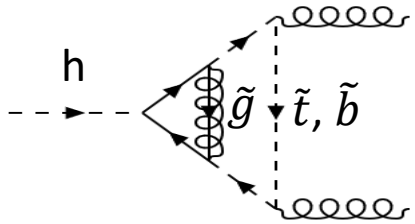
$h \to q\bar{q}$

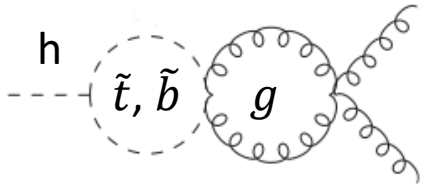
- 1-loop corrections are a simple additional multiplicative factor.
- All differences between MSSM and NMSSM are in the tree-level part, the multiplicative factor for the QCD corrections is the same.

$$\Gamma(h \to qq)_{QCDcorr} = \Gamma(h- > qq)_{tree}\left(1 + \frac{4\alpha_s(m_h)}{3\pi}\left[\frac{A(\tilde{\beta})}{\tilde{\beta}} + \frac{3 + 34\tilde{\beta}^2 - 13\tilde{\beta}^4}{16\tilde{\beta}^3}\log\frac{1+\tilde{\beta}}{1-\tilde{\beta}} + \frac{3}{8\tilde{\beta}^2}(7\tilde{\beta}^2 - 1)\right]\right).$$

$h \to gg$

- 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.





$$\Gamma(\phi \to gg)_{1-loop+QCDcorr} = \frac{\alpha_s^2(m_\phi)}{128\pi^3}\frac{G_F}{\sqrt{2}}m_\phi^3\frac{9}{8}\left[\delta^{\phi}_{FQCD}|I^{\phi}_{looptot}|^2 + Re[(I^{\phi}_{looptot})^* I^{\phi}_{sqtot}]\delta_{SQCD}\right].$$

$$\delta^{CPevenHiggs}_{FQCD} = 1 + \frac{\alpha_s(m_\phi)}{\pi}\left(\frac{95}{4} - \frac{7}{6}N_f\right), \quad \delta^{CPoddHiggs}_{FQCD} = 1 + \frac{\alpha_s(m_\phi)}{\pi}\left(\frac{97}{4} - \frac{7}{6}N_f\right). \quad \delta_{SQCD} = \frac{17\alpha_s(m_\phi)}{6\pi}.$$