Supersymmetric Decays in **SoftSusy**

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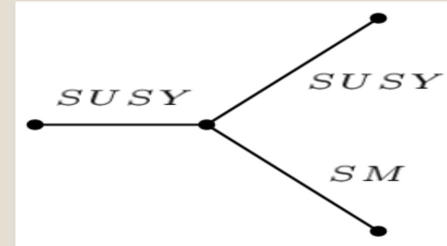
See https://softsusy.hepforge.org/ for list of SoftSusy papers and manuals.

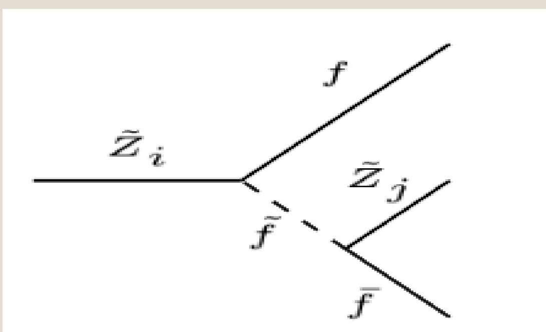
Overview for the talk:

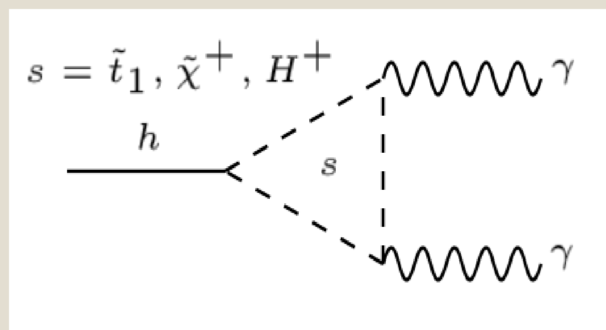
1. Searches for Supersymmetry
2. Analysis Context, Motivations for Decay Calculator
3. How it works
4. Capabilities
5. Decay modes, validation, uses:
   - MSSM Susy decays
   - Higgs decays
   (- Gravitino decays)
   - $1 \rightarrow 3$ decays
   - NMSSM decays
6. Summary

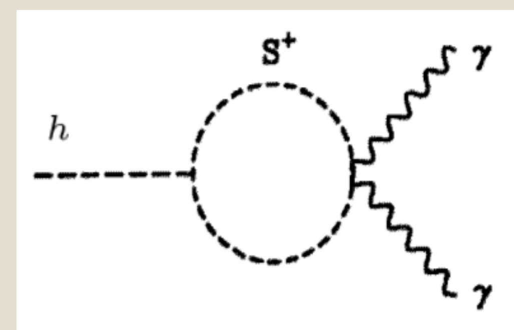
Searches for Susy



- Lots of ways to search for susy
- Look for new particles via susy decays: SUSY → SUSY + SM
- Look for effects of new virtual particles:
  - e.g. sfermion intermediates in 1 → 3 decays
  - stops in h → γγ, Zγ, gg loops

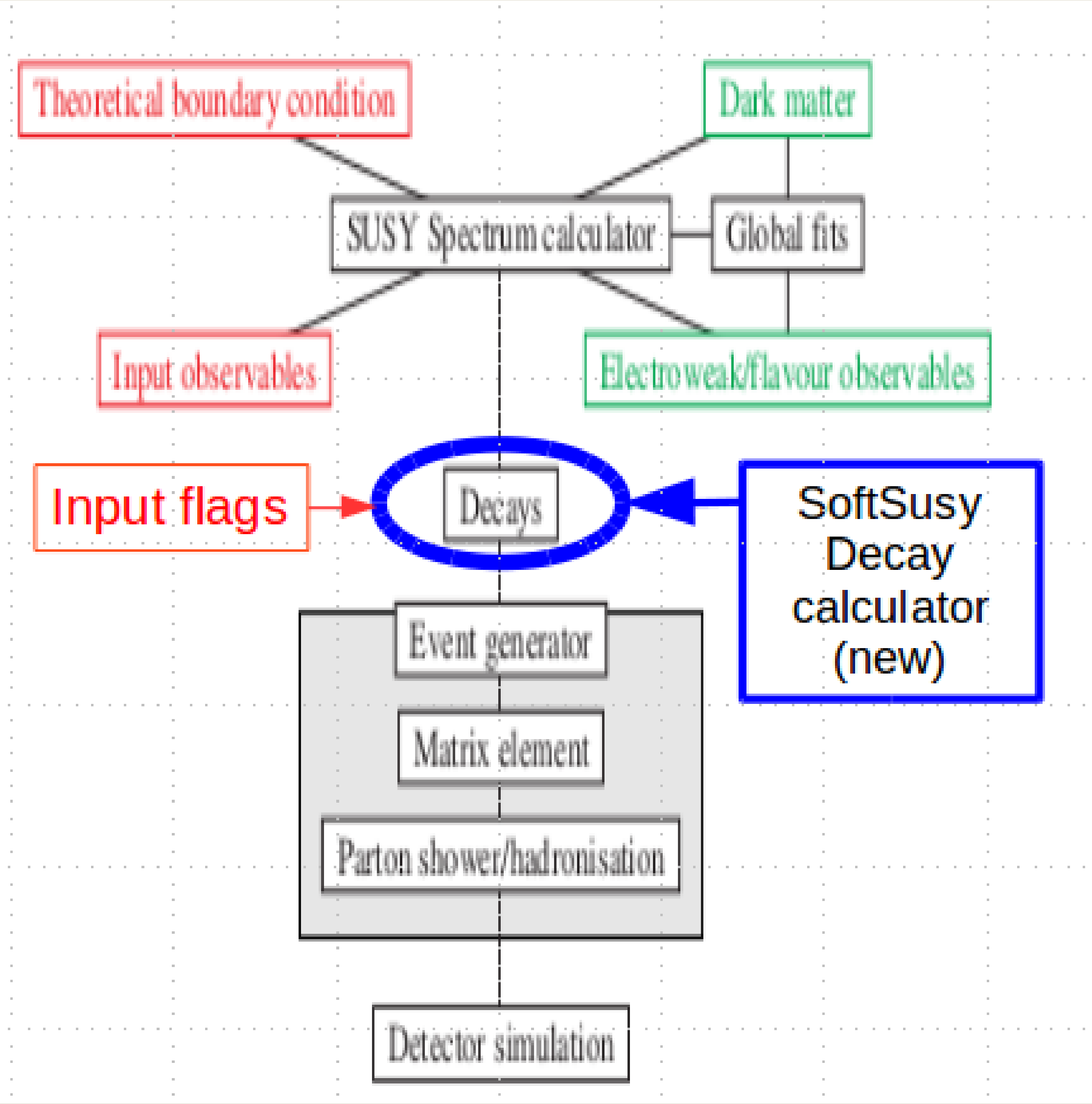






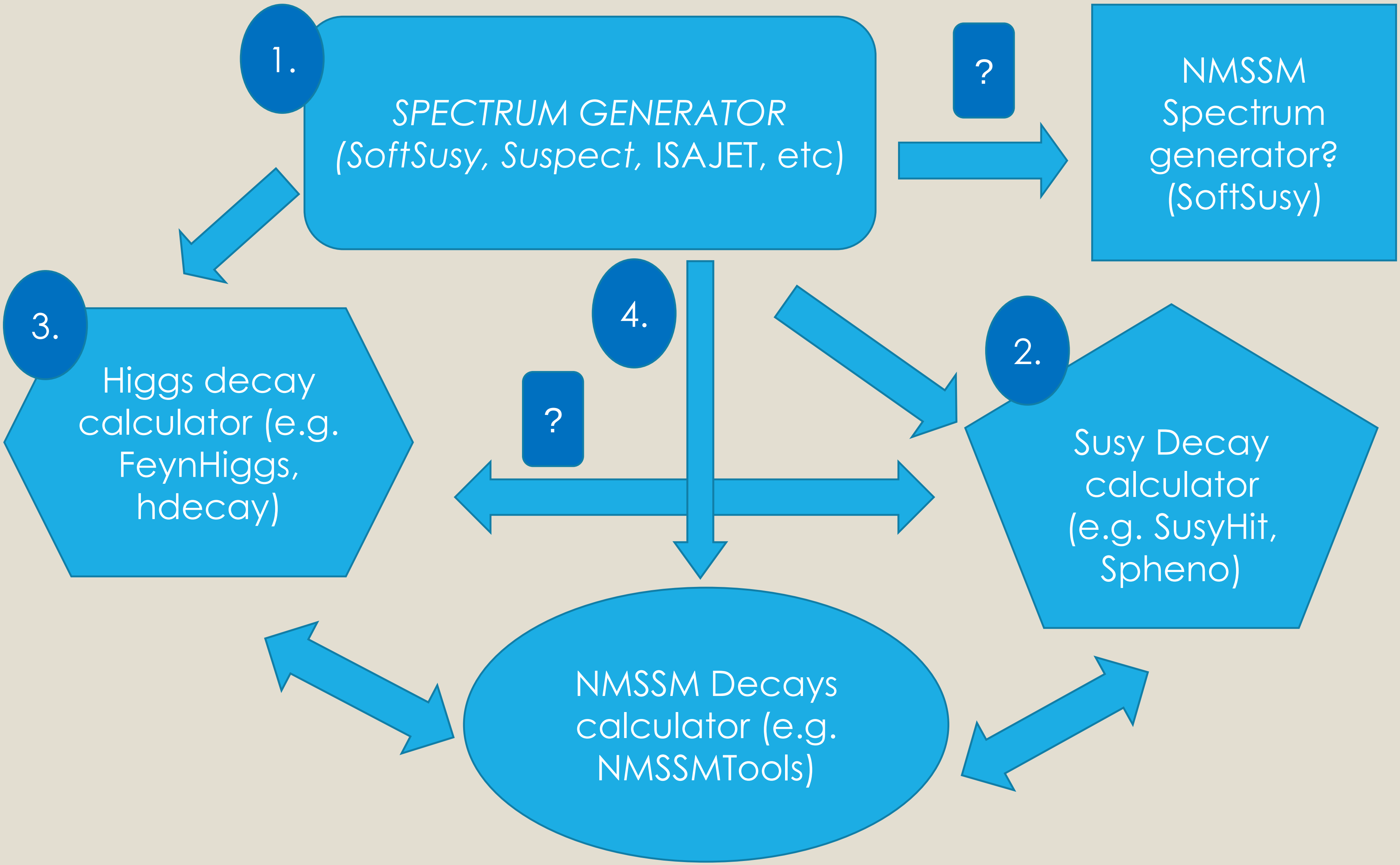
- So far cMSSM significantly constrained, although still room for pMSSM.

Framework for Susy searches



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

Current setup and programs



Motivations for SoftSusy Decay Calculator

- 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.

How it works – 1 Input File

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,

lesHouchesInputexample - 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)
ADDITIONAL DECAY FLAGS
- PARTIAL WIDTHS
- 1 -> 3 DECAYS
- GRAVITINO DECAYS
# The default is that without this, SOFTSUSY will only calculate the spectrum
    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
```

1 Output file in SLHA form

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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}
```

1 Output file in SLHA form

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```
#        PDG          Width
DECAY 35           3.00125008e-01   # H_0 (heavy higgs) decays
#        PW                BR                NDA   PDG1          PDG2
         2.78264729e-11    9.27162754e-11    2     2             -2            # H -> u ub
         1.80296909e-10    6.00739373e-10    2     1             -1            # H -> d db
         7.79140519e-06    2.59605330e-05    2     4             -4            # H -> c cb
         8.64306061e-08    2.87982020e-07    2     3             -3            # H -> s sb
         4.42931827e-05    1.47582446e-04    2     5             -5            # H -> b bb
         2.07374757e-02    6.90961271e-02    2     6             -6            # H -> t tb
         6.95536206e-13    2.31748834e-12    2     11            -11           # H -> e- e+
         2.97363271e-08    9.90798043e-08    2     13            -13           # H -> mu- mu+
         8.41000528e-06    2.80216744e-05    2     15            -15           # H -> tau- tau+
         3.45243551e-03    1.15033250e-02    2     1000022       1000022       # H -> ~chi_10 ~chi_10
         1.97235209e-02    6.57176853e-02    2     1000022       1000023       # H -> ~chi_10 ~chi_20
         3.58278886e-04    1.19376552e-03    2     1000022       1000025       # H -> ~chi_10 ~chi_30
         1.83054243e-02    6.09926657e-02    2     1000023       1000023       # H -> ~chi_20 ~chi_20
         1.34984061e-04    4.49759456e-04    2     1000023       1000025       # H -> ~chi_20 ~chi_30
         1.14619819e-07    3.81906925e-07    2     1000025       1000025       # H -> ~chi_30 ~chi_30
         1.20851258e-03    4.02669736e-03    2     1000024       -1000024      # H -> ~chi_1+ ~chi_1-
         2.55910284e-04    8.52678972e-04    2     25            25            # H -> h h
         1.12799806e-05    3.75842742e-05    2     22            22            # H -> gamma gamma
         9.80376043e-05    3.26655898e-04    2     21            21            # H -> gluon gluon
         8.36105100e-06    2.78585615e-05    2     23            22            # H -> Z gamma
         1.60542630e-01    5.34919204e-01    2     24            -24           # H -> W+ W-
         7.52274315e-02    2.50653659e-01    2     23            -23           # H -> Z Z
#
```

```
# Z3 = 1, SoftHiggsOut = 0
Block MASS                    # Mass spectrum
```

```
  3  1     9.86565237e-01    # S_{3,1}
  3  2    -1.12405729e-01    # S_{3,2}
```

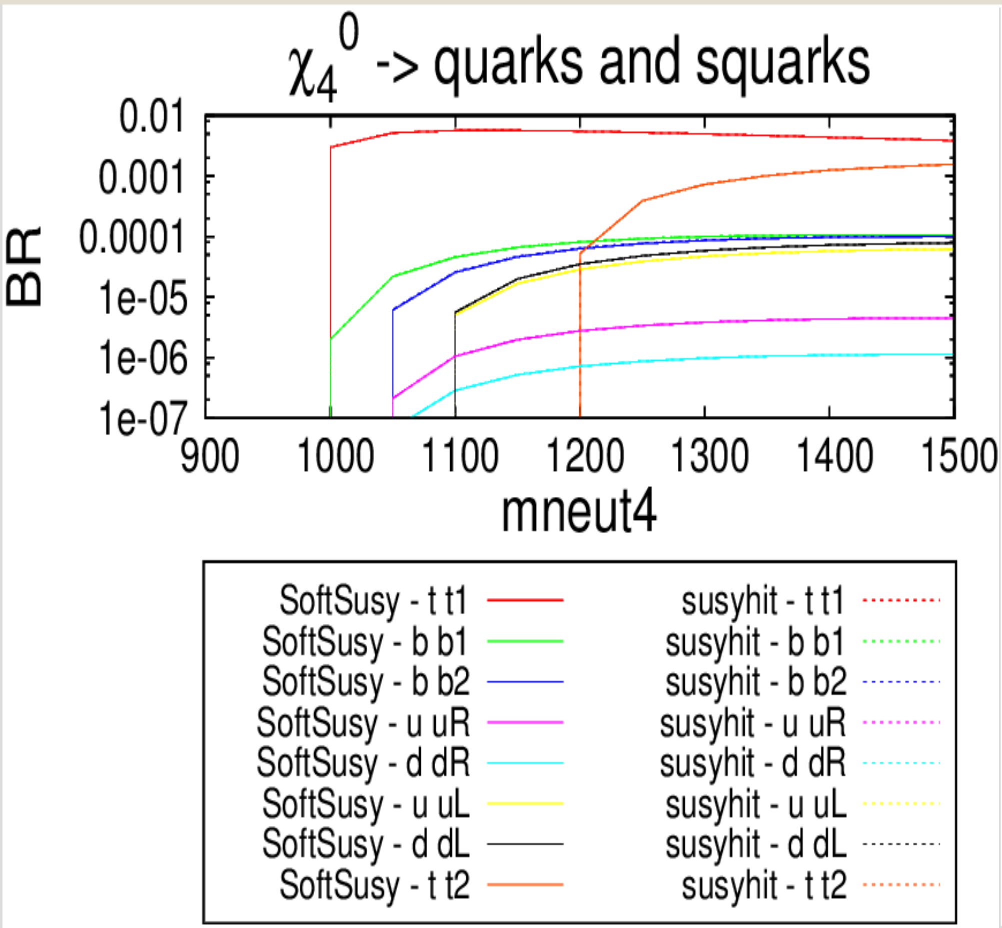
SoftSusy Decay Capabilities

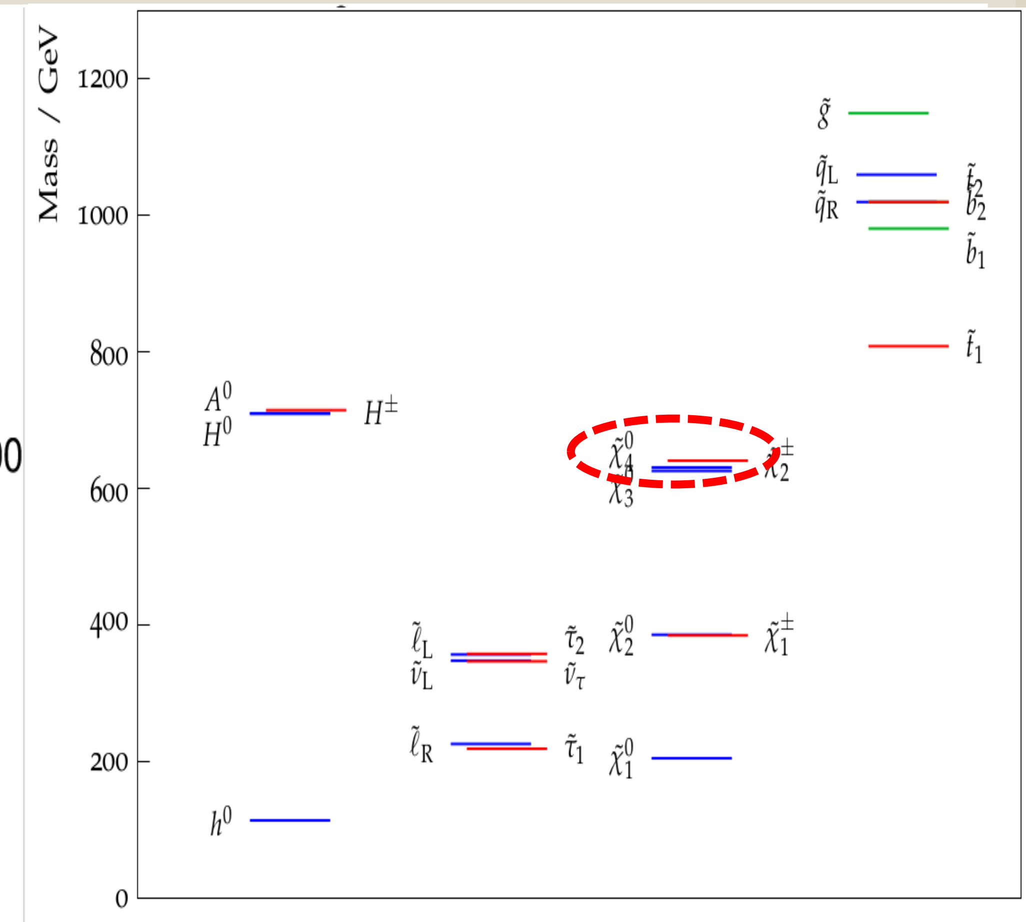
- All 1 → 2 decays of MSSM SUSY particles.
- All 1 → 2 higgs decays in MSSM.
- Phenomenologically Relevant 1 → 3 decays in MSSM (e.g. for compressed spectra)
- Higgs 1-loop decays: h -> γγ, Zγ, gg in MSSM and NMSSM
- Higgs 1 → 3 decays via VV*: h -> VV* -> V f fbar
- Decays to gravitinos in MSSM
- All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

MSSM Susy decays – χ_4^0

- Validation plots e.g. neut 4

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





MSSM Susy decays – χ_4^0

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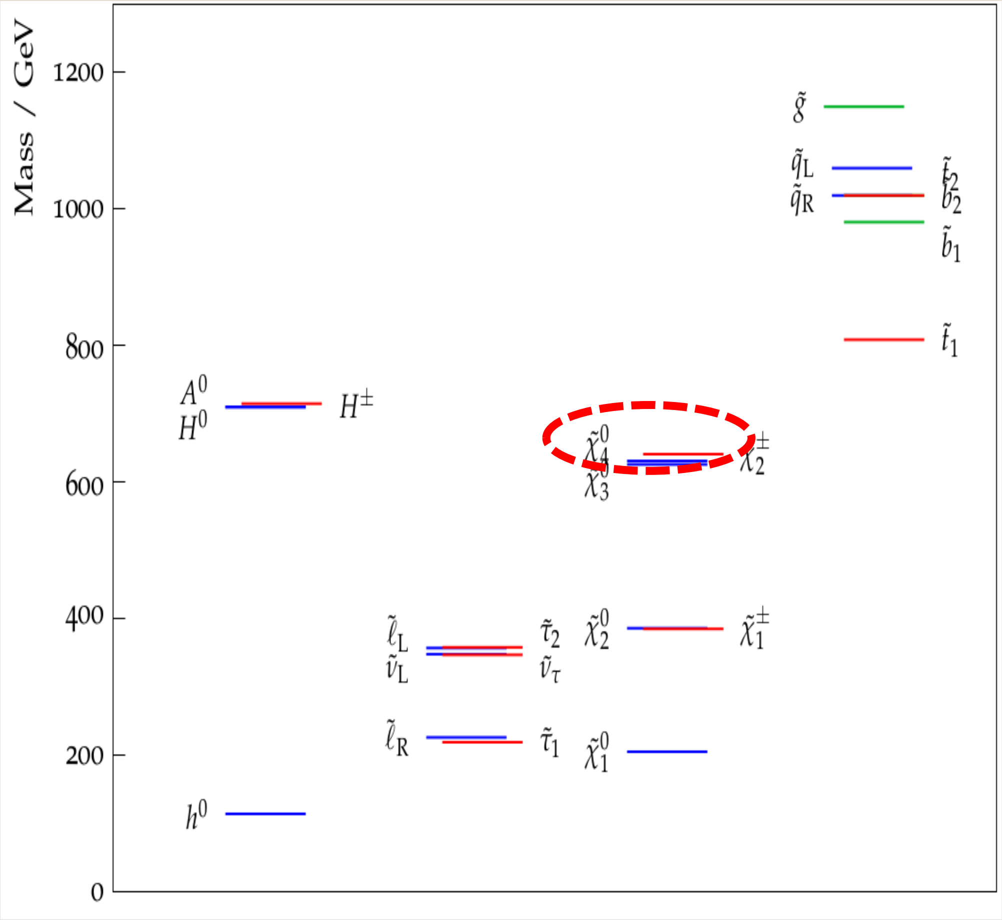
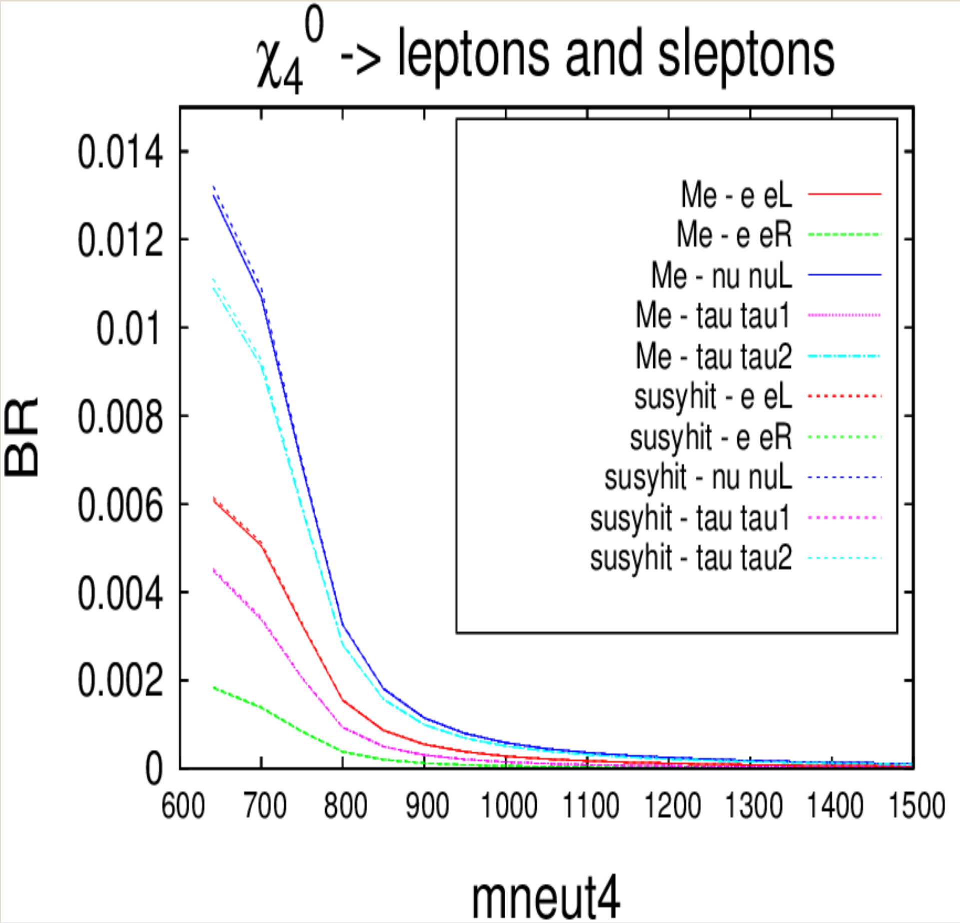
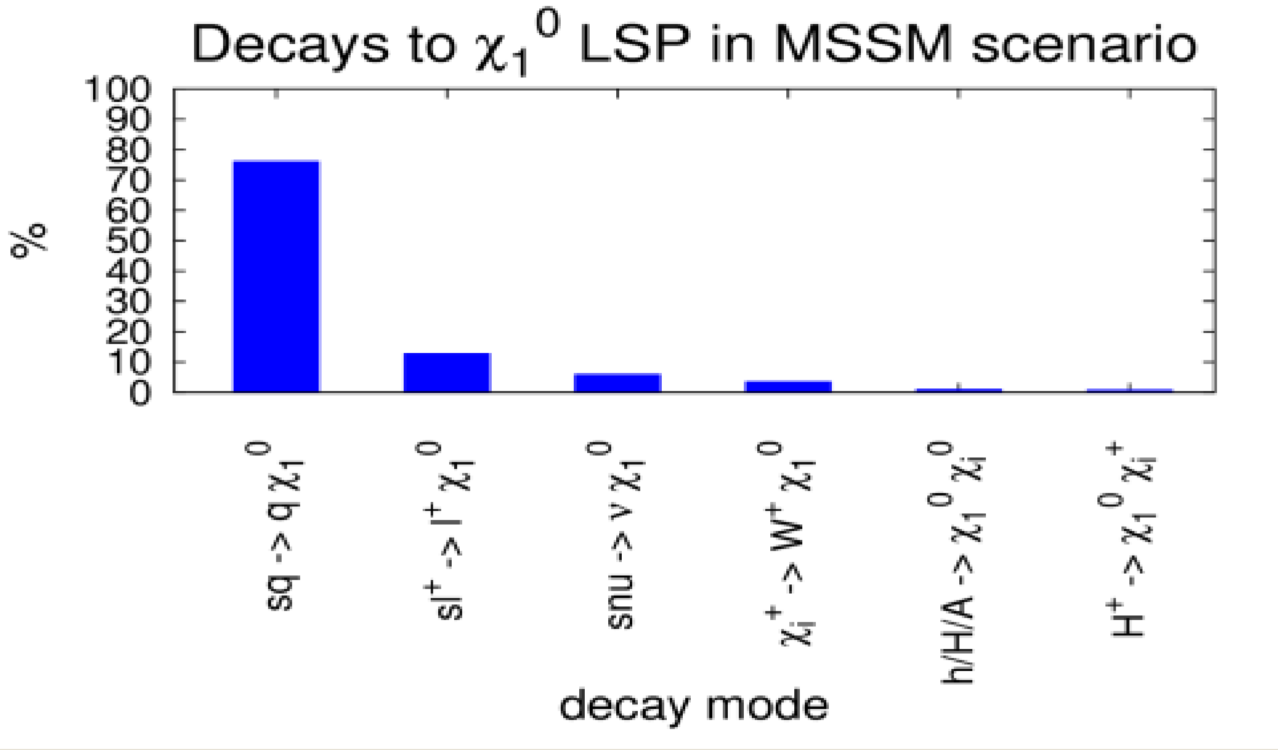




MSSM Susy decays 2 – DM as χ_1^0 LSP

- DM search – e.g. suppose DM is lightest neutralino, may want to look at decays into neutralino1.
- Can examine which particle types are produced in association and in what percentages to look for signals.



$$m_{\chi_1^0} = 204 \text{ GeV}$$

NLSP $= \tilde{\tau}_1$

Partial Width for

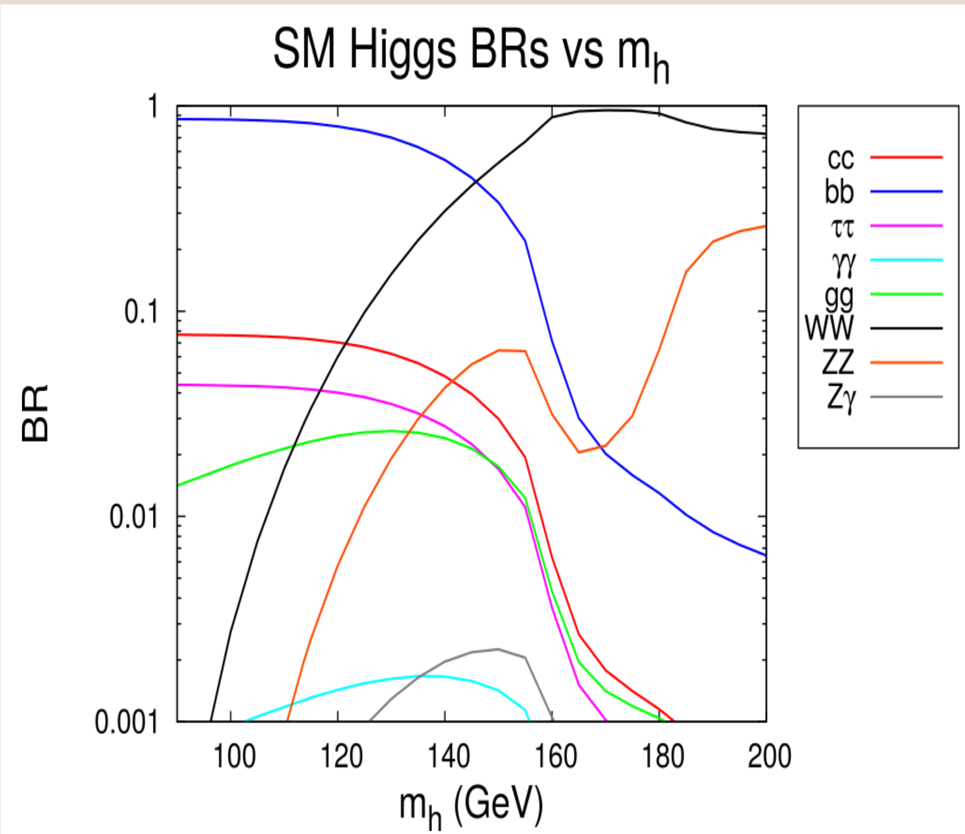
$\tilde{\tau}_1 \rightarrow \tau\ \chi_1^0$

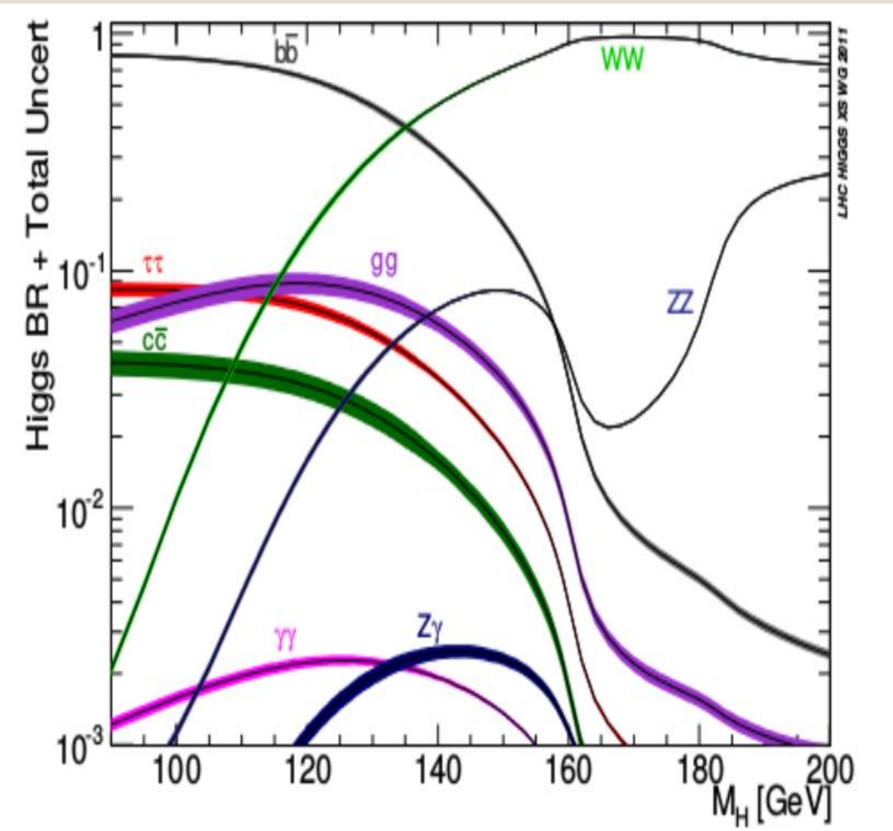
$\Gamma = 7.7 \times 10^{-3}$ GeV

lifetime = 8.6s

Higgs decays – 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:

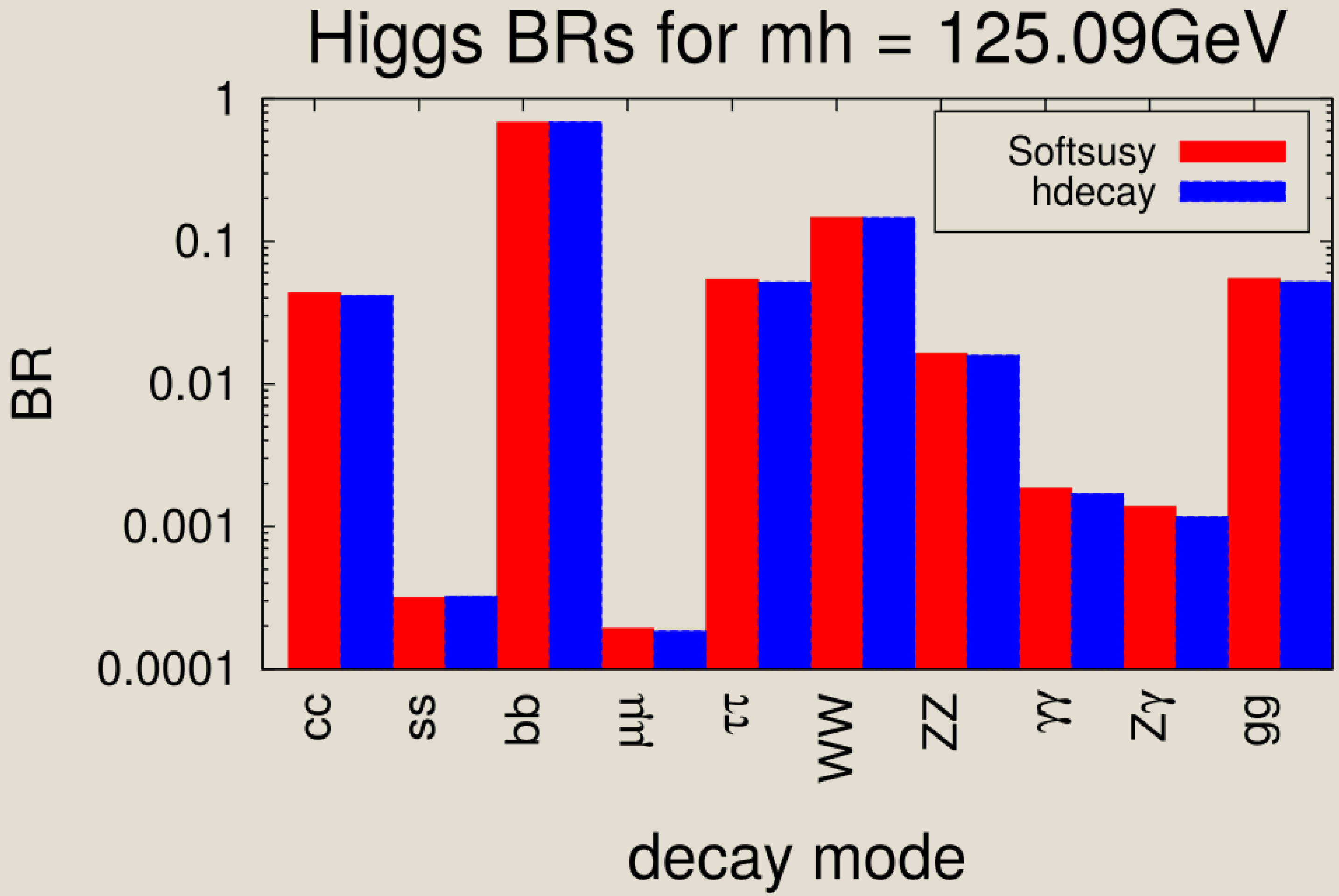




Denner, Heinemeyer, Puljak, Rebuzzi, Spira "Standard Model Higgs Boson Branching ratios with Uncertainties", arXiv:1107.5909

Higgs decays 1 – BRs at mh = 125.09GeV

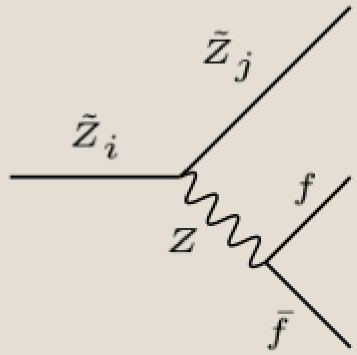
- Comparison of BRs for SM like higgs – SoftSusy Decays module vs hdecay program

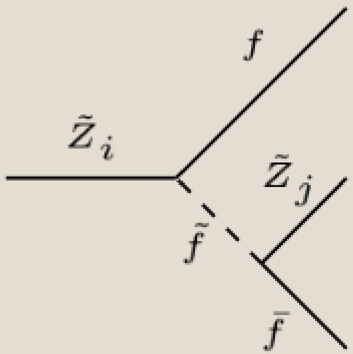


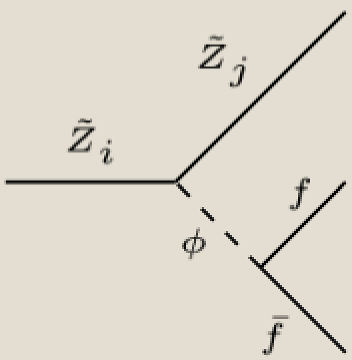
1 → 3 decays

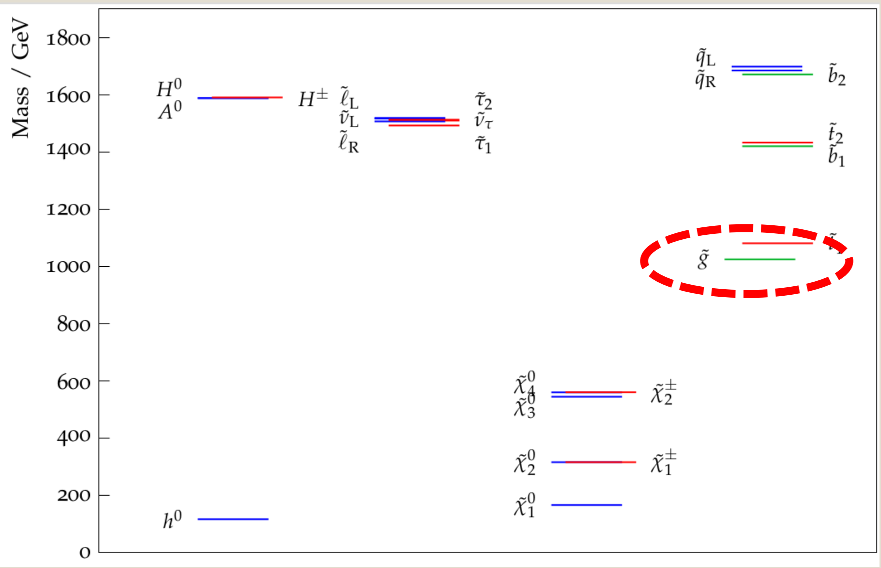
$$\Gamma(1 \to N) = \int \cdots \int_N \frac{S(2\pi)^4 \langle |M|^2 \rangle}{2m} \delta^{(4)}\left(P - \sum_{i=1}^{n} p_i\right) \prod_{i=1}^{n} \frac{d^3 p_i}{(2\pi)^3 2E_i}$$

- Each additional decay particle suppresses Γ (PW)
- 1 -> 2 favoured over 1 -> 3, but when 1 -> 2 not allowed, 1 -> 3 important.
- E.g. Compressed spectra: $m_{decay} - m_{Susy\ product} < m_{SM}$



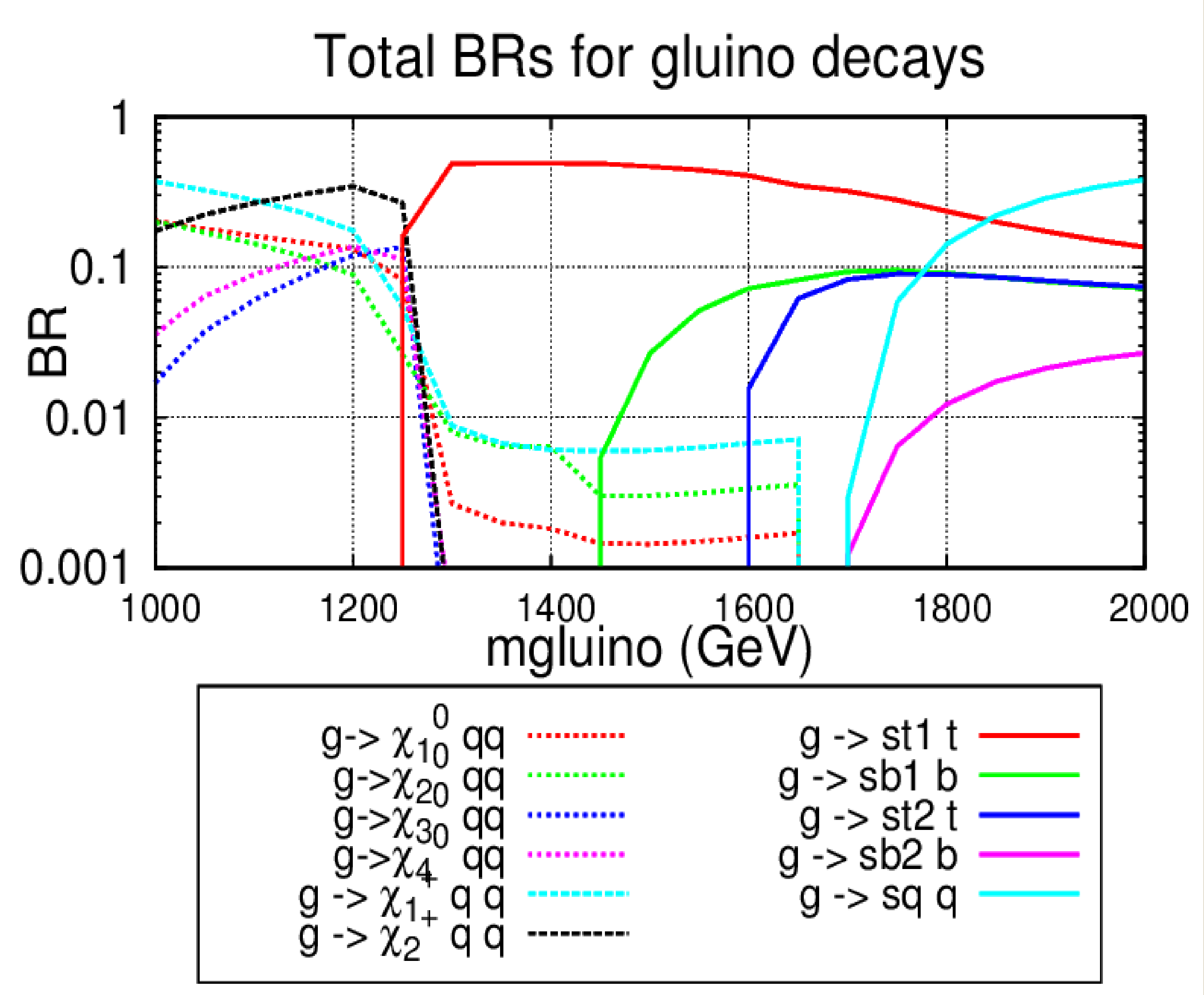






Spectrum Plot generated with slhaplot of pyslha-3.2.0: Buckley arXiv:1305.4194

1 → 3 decays Plot

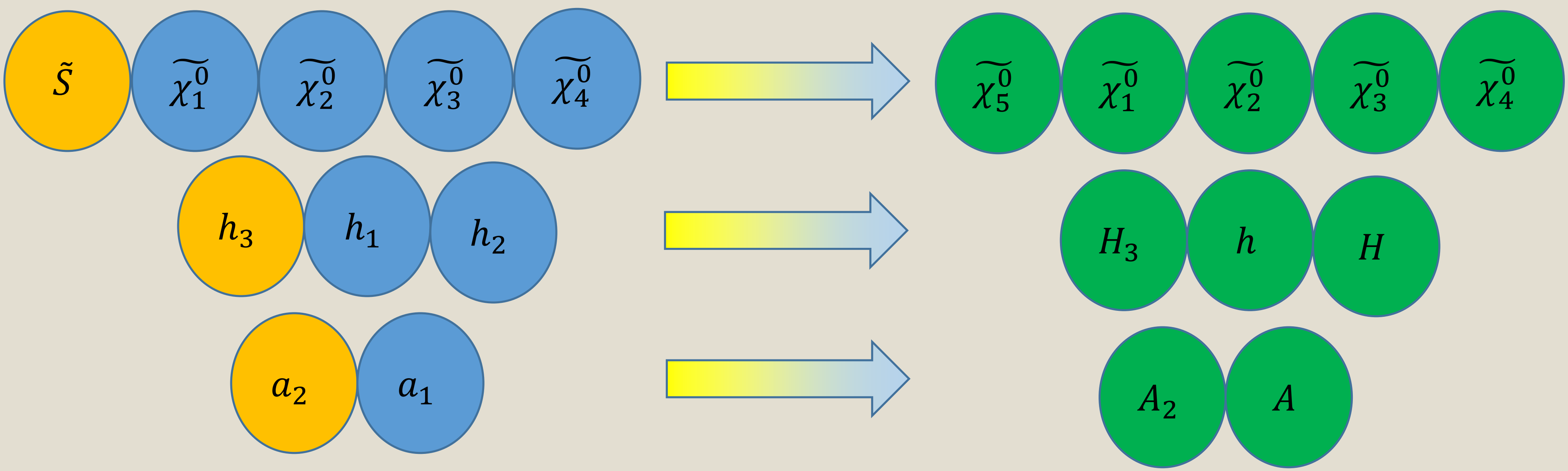


NMSSM – theory

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

    -> Mix with 2 CP even higgses and 1 CP odd higgs of MSSM



NMSSM – theory and motivations

- μ problem
  - Sets scale of higgsino/higgs masses

$$W = \hat{u}^c \mathbf{h_u} \hat{Q} \hat{H}_u - \hat{d}^c \mathbf{h_d} \hat{Q} \hat{H}_d - \hat{e}^c \mathbf{h_e} \hat{L} \hat{H}_d + \mu \hat{H}_u \hat{H}_d$$

  - Have to set μ to EW/SUSY scale by hand -> fine-tuned
  - NMSSM:

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

  - Give $\tilde{S}$ a vev -> dynamically generate $\mu = \lambda\langle S\rangle$ at Susy scale
  - ---- > No μ problem!

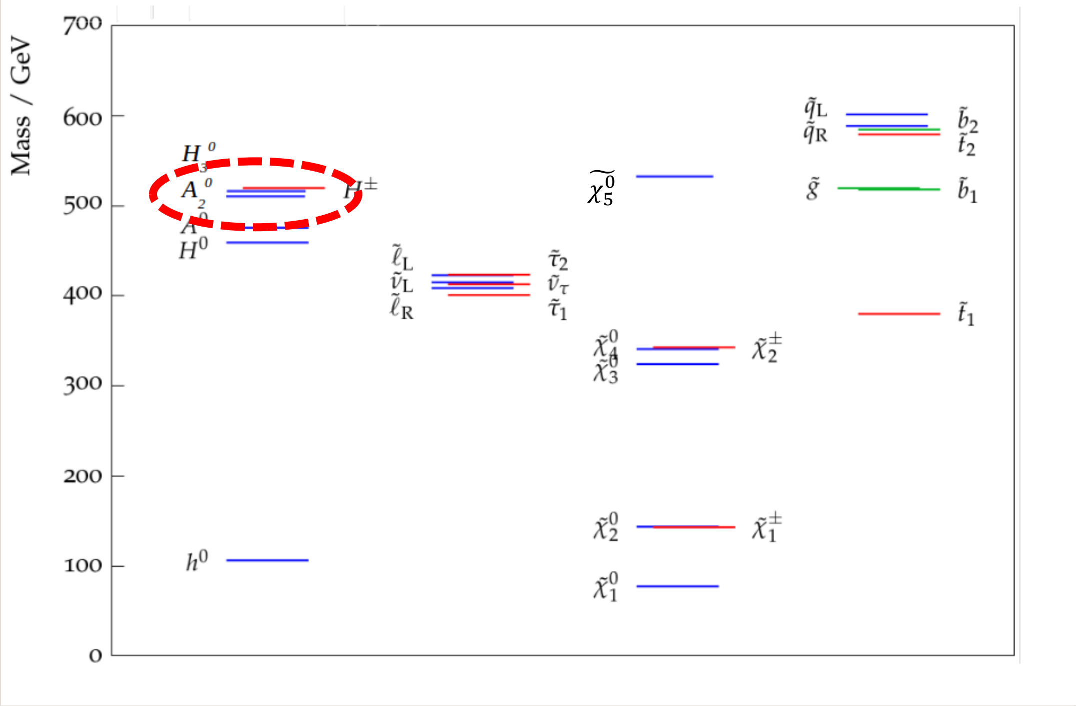
Ellwanger, Hugonie, Teixeira
arXiv:0910.1785

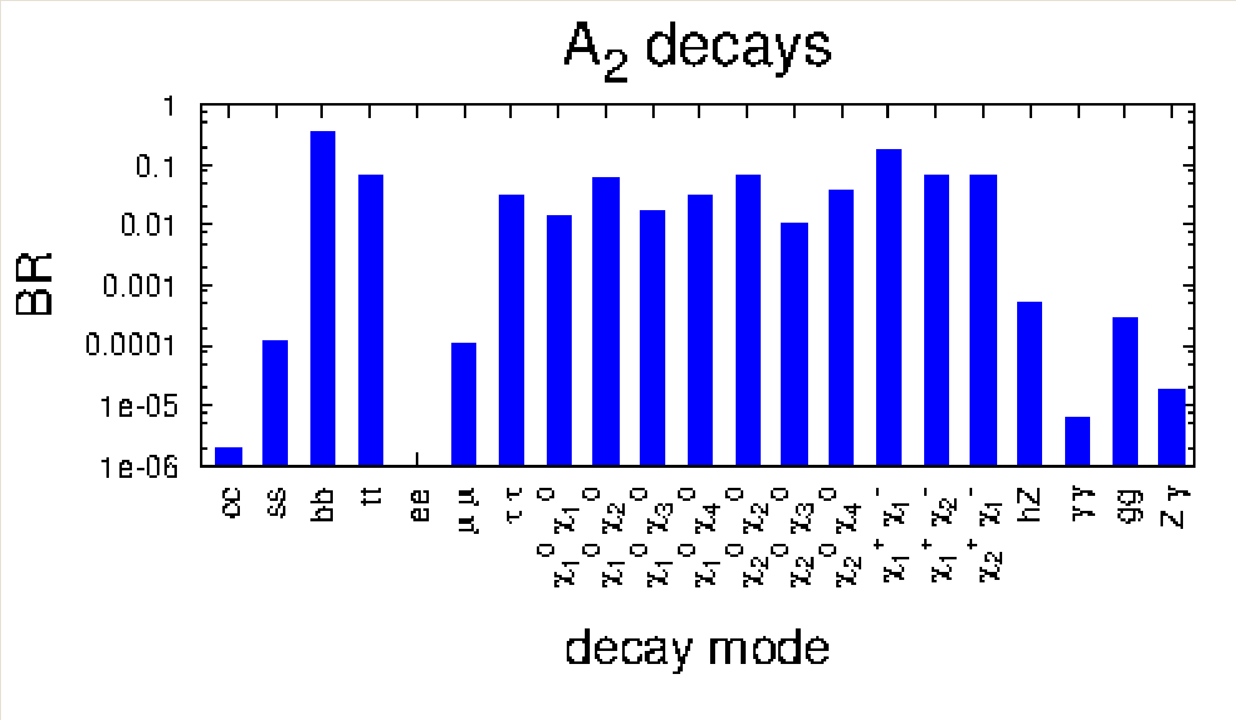
- Higher higgs masses:
  - MSSM at tree-level: mh < mZ -> Problem getting mh near 125GeV
  - NMSSM: masses enhanced by extra $\kappa\langle S\rangle$ term -> larger mh

\- Allows less fine-tuned stop masses!

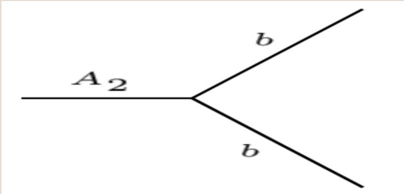
NMSSM Decays – A_2

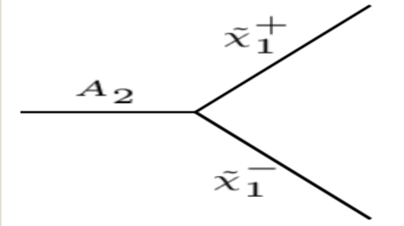
- New heavier CP odd higgs, A_2 in NMSSM.
- Consider it's decays with right-hand spectrum.





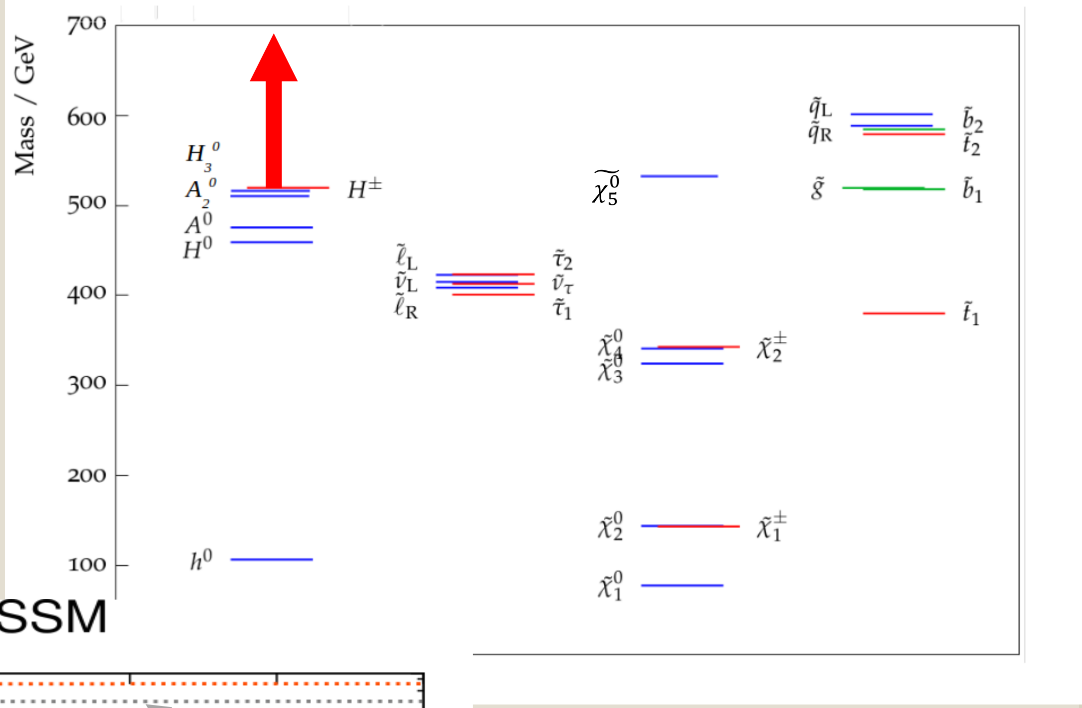
- Note no NMSSM specific decays open initially.

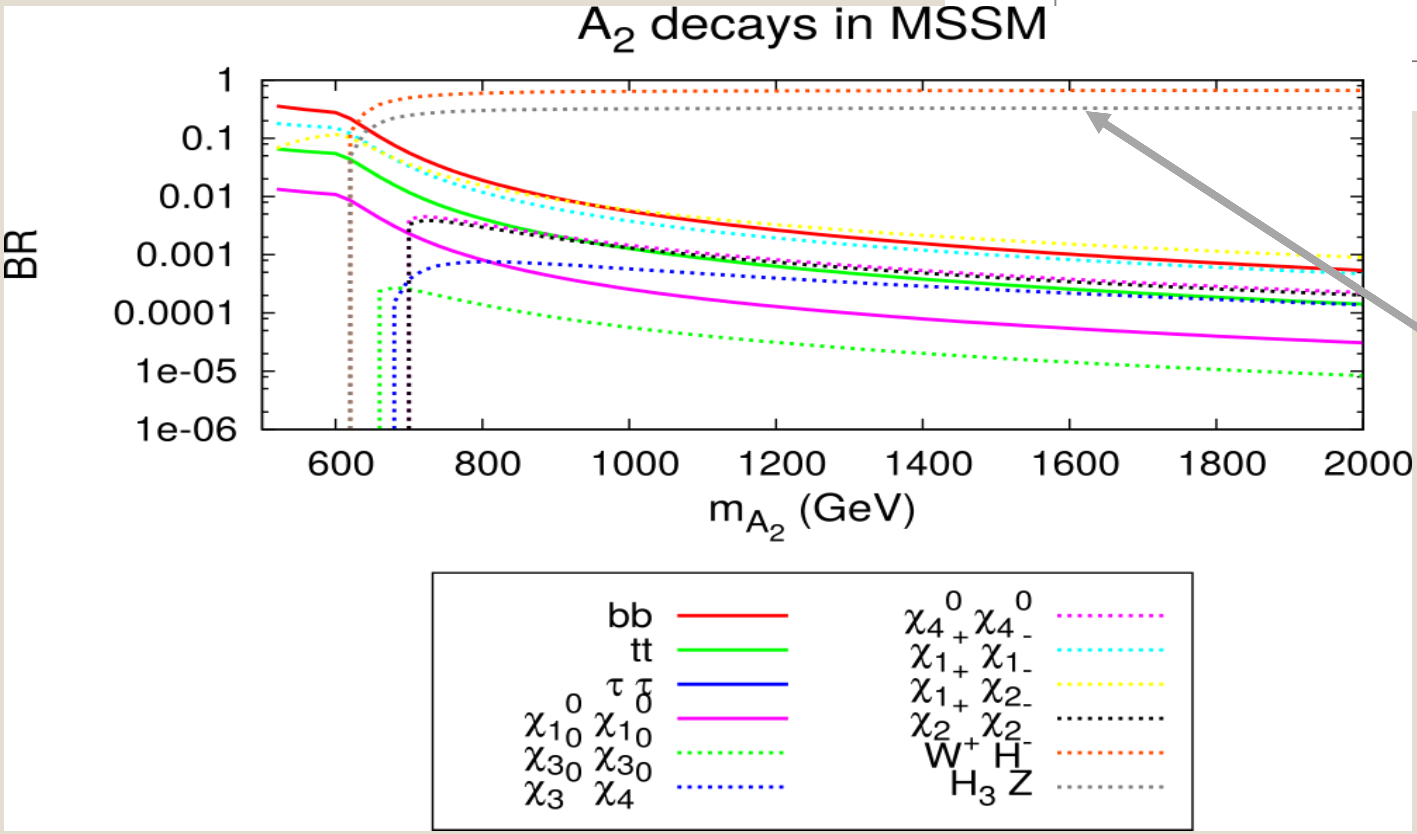




NMSSM Decays – A_2 scan

- Again as raise its mass other modes become available.





- Decay to Heaviest CP even higgs H_3 and Z boson becomes important once allowed.

Summary and Conclusions

- Softsusy-4.0 will include a **decay calculator -> OUT SOON!**
- This will calculate the decays:

  -> **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)

QCD Corrections included here

Thankyou for Listening! Any Questions?

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

Aside on CMSSM and pMSSM

CMSSM assumes at the GUT scale that:
- all the scalar particles have the same mass m_0
- all the gauginos have the same mass $m_{1/2}$
- all the trilinear couplings are the same A_0
- other free free parameter is $\tan\beta = v2/v1$
- sign(μ) (higgsino mass term) not fixed

PMSSM reduces no. of free parameters to 19 by assuming:

- no new source of CP-violation

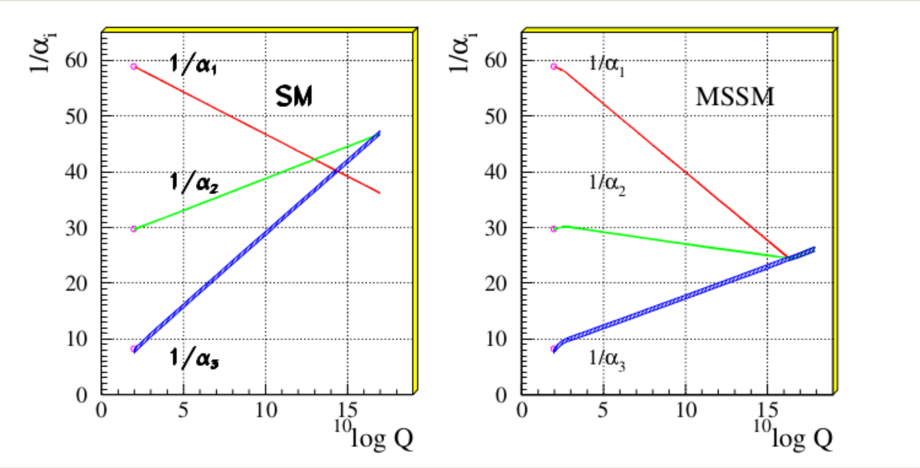
- no Flavour Changing Neutral Currents

- first and second generation universality

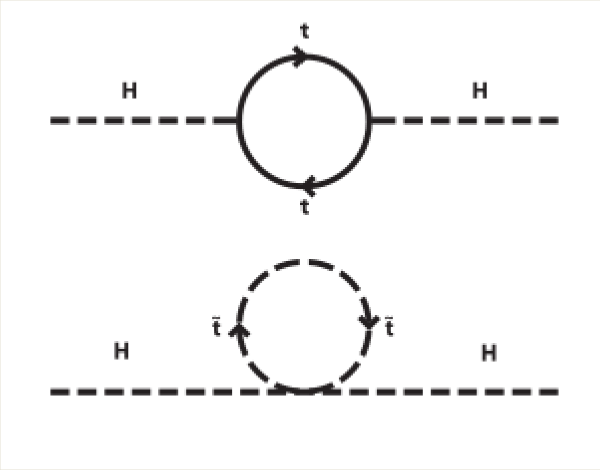
The large parameter space of pMSSM makes searches challenging.

Motivations for Supersymmetry

- Technical Hierarchy Problem – corrections to higgs masses
- Gauge Coupling Unification



[Figure: D.I. Kazakov, hep-ph/0012288 p 12 .]



$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}[\Lambda_{\mathrm{UV}}^2 + \ldots].$$

$$\Delta m_H^2 = 2 \times \frac{\lambda_S}{16\pi^2}[\Lambda_{\mathrm{UV}}^2 + \ldots].$$

- Dark Matter – χ_1^0 LSP
- GUTs and Susy String Theories

Searches for Supersymmetry

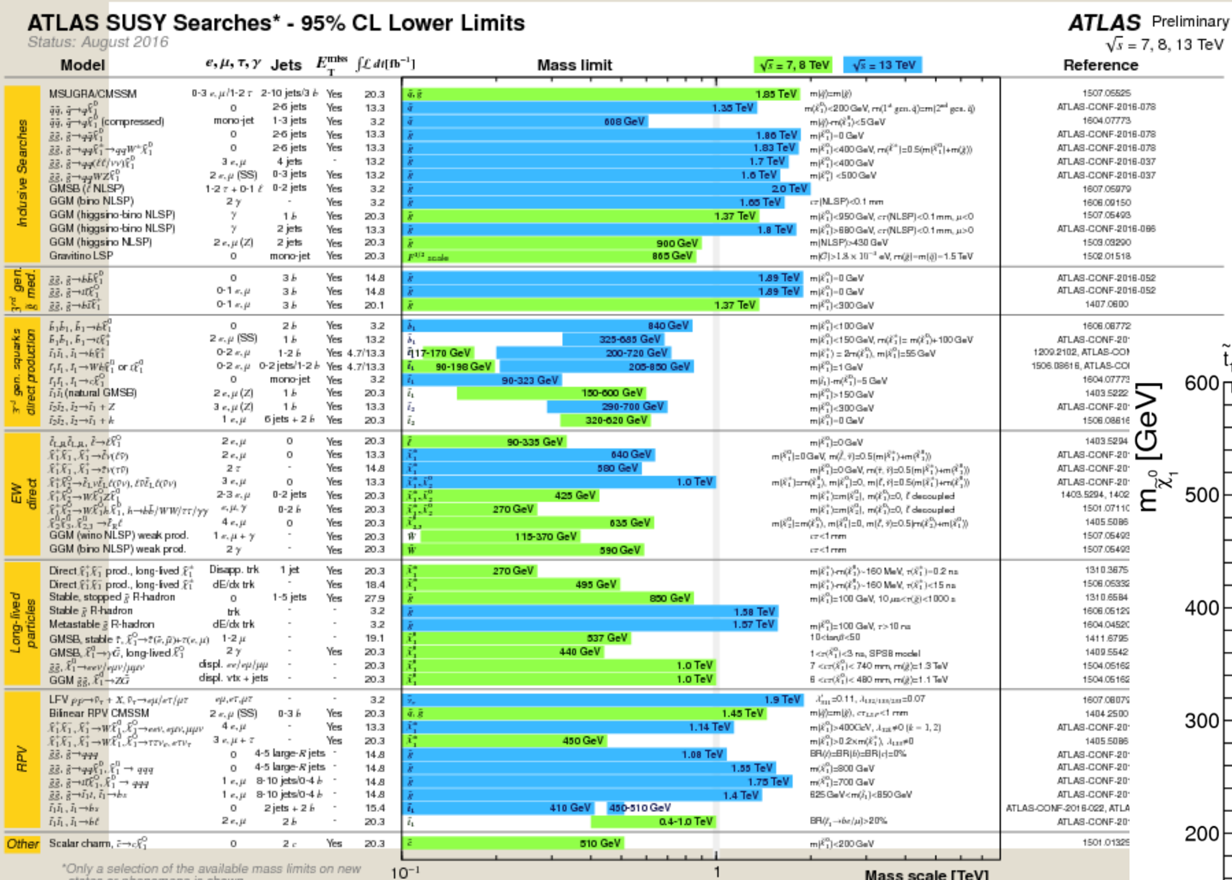
- Susy predicts whole swathe of new particles – on top of the usual 17 SM particles we get another 32 particles.
- Breaking mechanism unknown - add in soft terms by hand to break susy.

$$\mathcal{L} = \mathcal{L}_{\text{SUSY}} + \mathcal{L}_{\text{soft}},$$

- "120 new parameters" - search large parameter space
- 5 parameters (m0, m1/2, A0, tanbeta, sign(mu)) in mSUGRA
- 4 parameters in AMSB (m0, m3/2, tanbeta, sign(mu))
- 6 parameters for GMSB (Λ, M, n5, tanbeta, sign(mu), Cgrav).
- Our lack of knowledge => don't know masses or couplings => searches for susy particles over wide mass ranges and large parameter spaces.

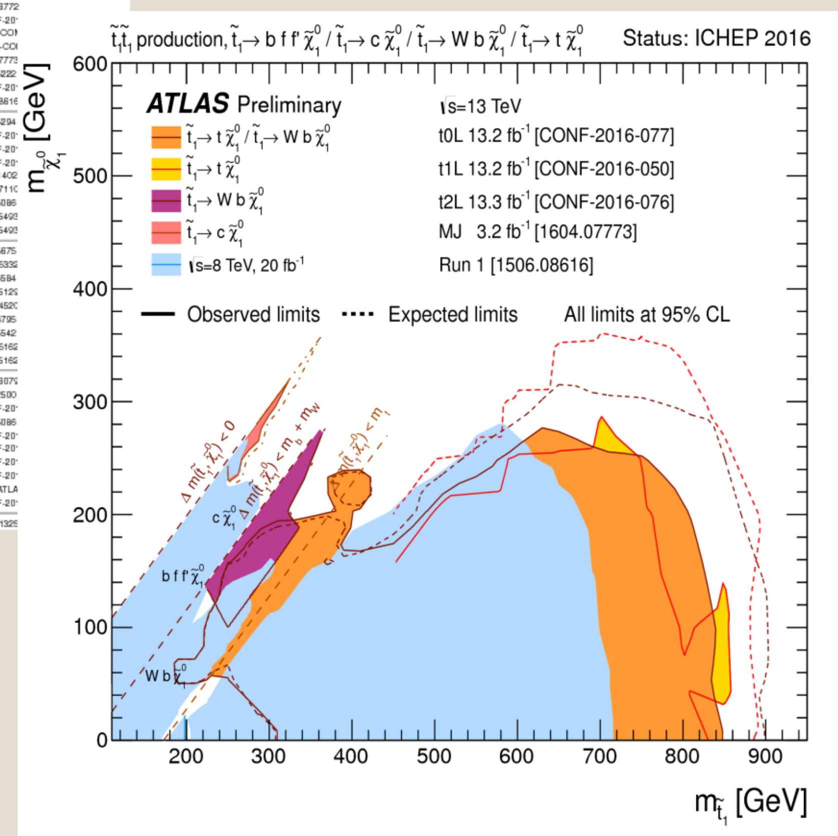
Particle Type	Spin	R_p	Label
gluino	$\frac{1}{2}$	-1	$\tilde{g}$
squark	0	-1	$\tilde{u}_L$ $\tilde{u}_R$ $\tilde{d}_L$ $\tilde{d}_R$ $\tilde{c}_L$ $\tilde{c}_R$ $\tilde{s}_L$ $\tilde{s}_R$ $\tilde{t}_1$ $\tilde{t}_2$ $\tilde{b}_1$ $\tilde{b}_2$
slepton	0	-1	$\tilde{e}_L$ $\tilde{e}_R$ $\tilde{\nu}_e$ $\tilde{\mu}_L$ $\tilde{\mu}_R$ $\tilde{\nu}_\mu$ $\tilde{\tau}_1$ $\tilde{\tau}_2$ $\tilde{\nu}_\tau$
chargino	$\frac{1}{2}$	-1	$\chi_1^{+/-}$ $\chi_2^{+/-}$
neutralino	$\frac{1}{2}$	-1	χ_1^0 χ_2^0 χ_3^0 χ_4^0
Higgs bosons	0	+1	h^0 H^0 H^+ H^- A^0

Constraint Plots



ATLAS SUSY Summary Plot

ICHEP 2016

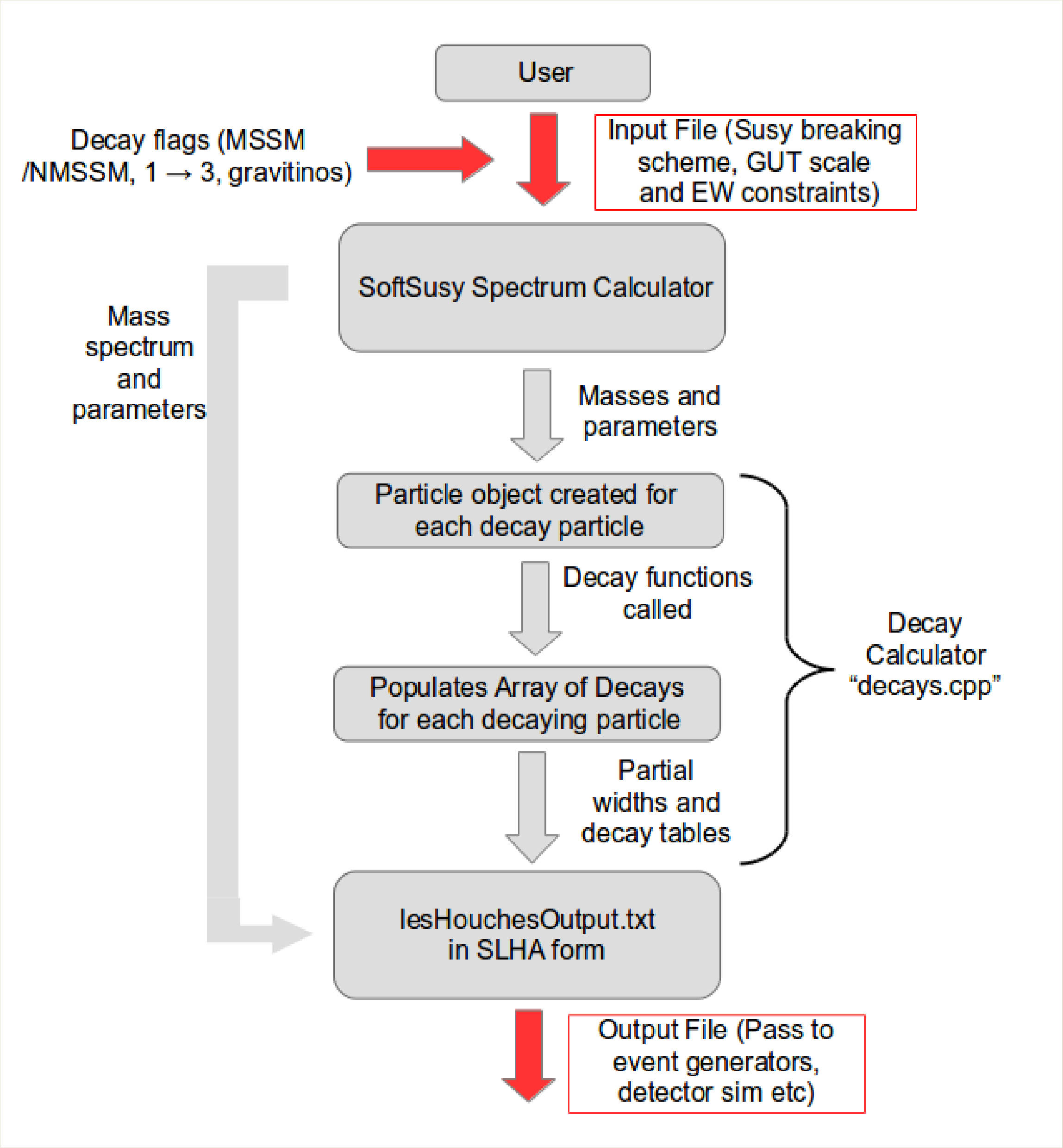


https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SUSY/index.html#ATLAS_SUSY_Stop_tLSP

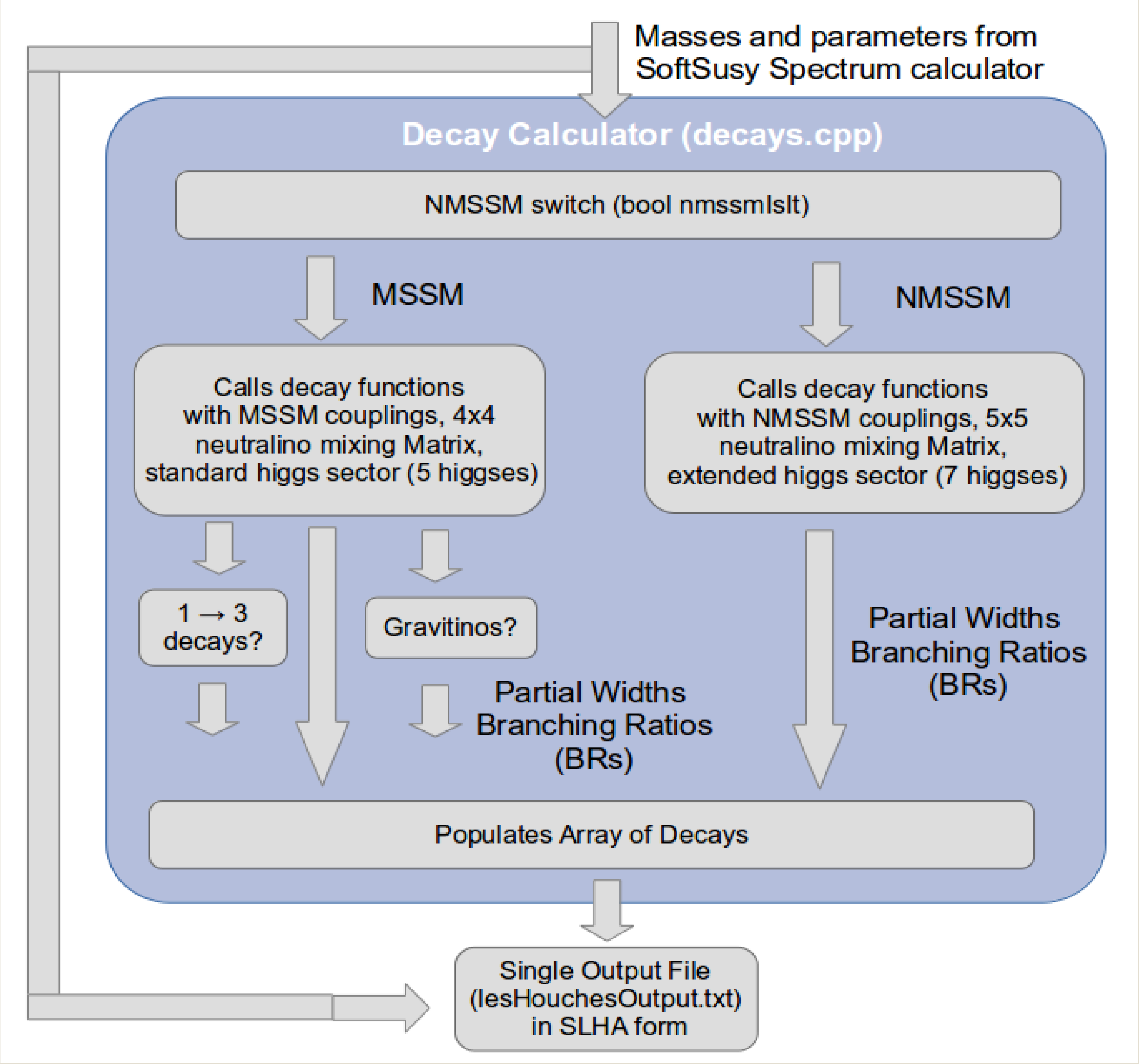
	Softsusy (3.7.4)	Susyhit (1.5)	FeynHiggs (2.11.1)	SPheno (3.3.6)	Isajet (7.84)	Pythia (8.2)	NMSSM-Tools (4.6.0)	Herwig++ (2.7)
Production Cross-sections	✗	✗	✓ (LHC and Tevatron)	✓ (e+e- only)	✓ (pp, ppbar, e+e-)	✓	✗	✓
Spectrum calculator	✓	✓	✓ (for Higgses)	✓	✓	✗	✓	✗
Highest order loop corrections in spectrum	3	2 (Suspect)	2 (although some resummation to all orders)	2	2	-	2	-
NMSSM	✓	✗	✗	✗	✗	-	✓	-
FV	✓	✓	✓	✓	✗	-	✗	-
RPV	✓	✗	✗	✓	✗	-	✗	-
Neutrino masses and mixings	✓	✗	✗	✓	✓	-	✗	-
Experiment constraints	✗ (Except EW)	✓ (Suspect)	✓	✓	✓	-	✓	-
Decay calculator	NEW	✓	✓	✓	✓	✓	✓	✓
Susy decays	NEW	✓ (Sdecay)	✗	✓	✓	✓	✓	✓
Higgs decays	NEW	✓ (Hdecay- up to 3- loop corrections)	✓	✓	✓	✓	✓	✓
Loop corrections to widths	NEW – only h-> qq so far	✓	✓	Only via running couplings (+g Qcd corrections for h ->qq)	✓	Only via running couplings	✓ (1-loop SM QCD corrections)	✓
NMSSM	NEW	✗	✗	✗	✗	✗	✓	✗
RPV	Not yet - maybe in future	✗	✗	✓	✗	✓	✗	✓

Allanach, Kraml, Porod “Comparison of SUSY mass spectrum calculations”, arXiv:hep-ph/0207314

How it works 2 – What happens next?



How it works 3 – Decay calculator Specifics



Assumptions made

- R-parity conservation (RPC)

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

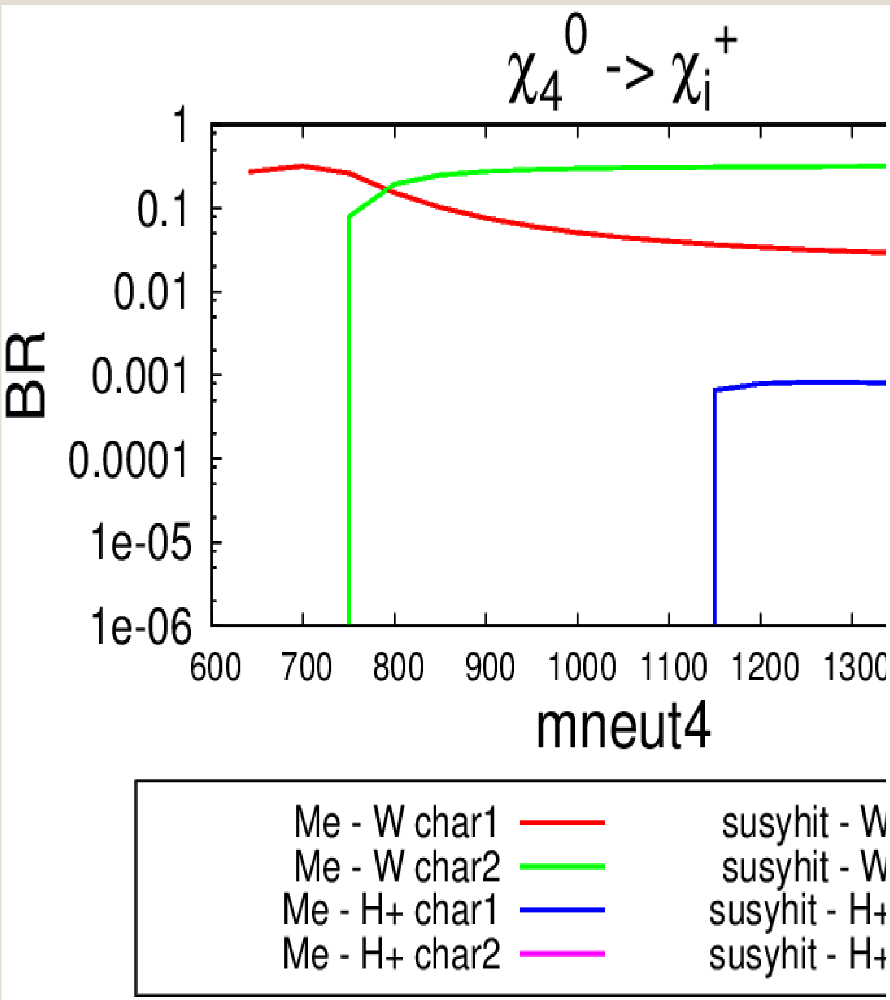
- No additional CPV relative to SM
- No additional flavour violation relative to SM
- Only sfermion mixing in 3rd generation.

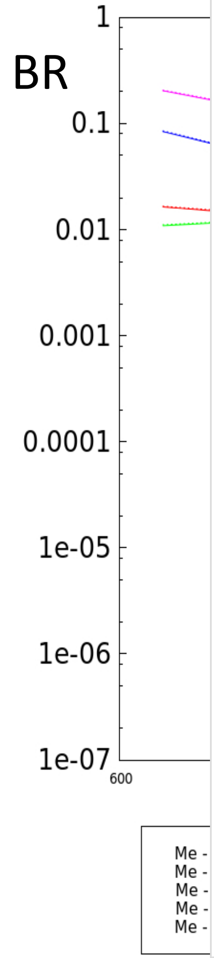
$$\theta_u = \theta_d = \theta_c = \theta_s = \theta_e = \theta_\mu = 0$$

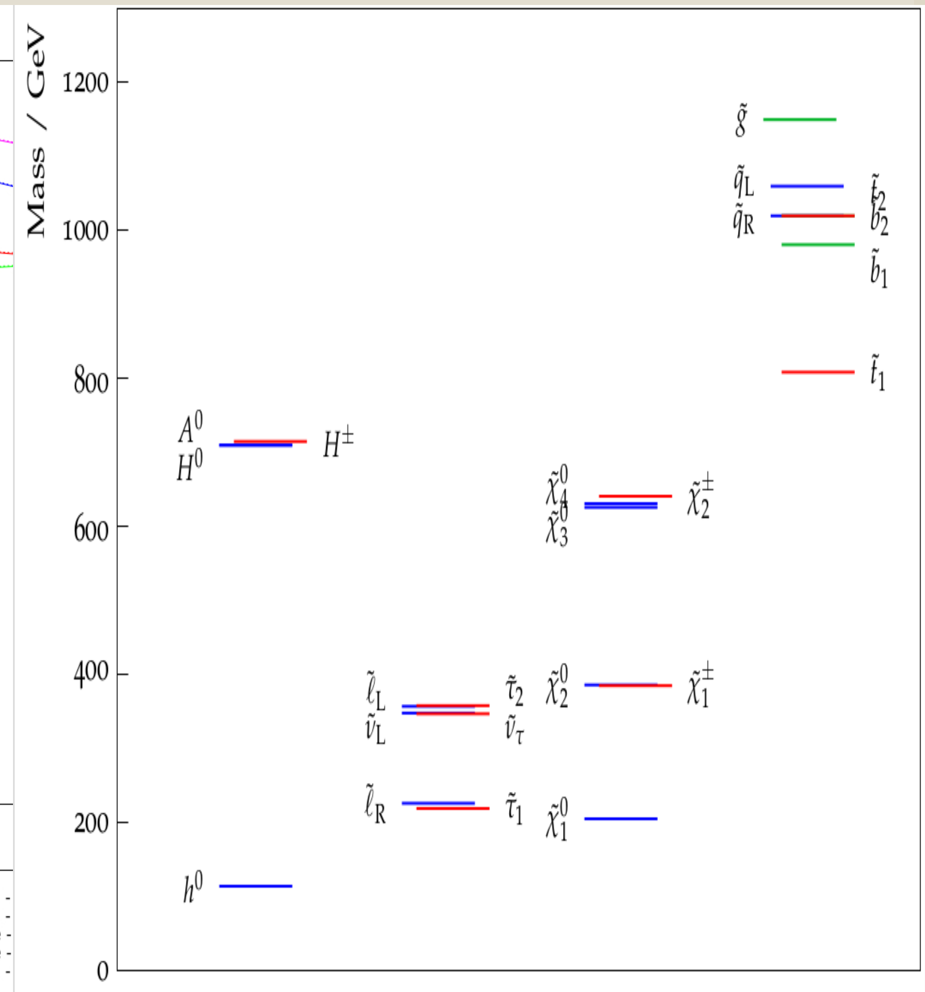
$$\theta_t, \theta_b, \theta_\tau \neq 0$$

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

MSSM Susy decays 2 (continued) – χ_4^0





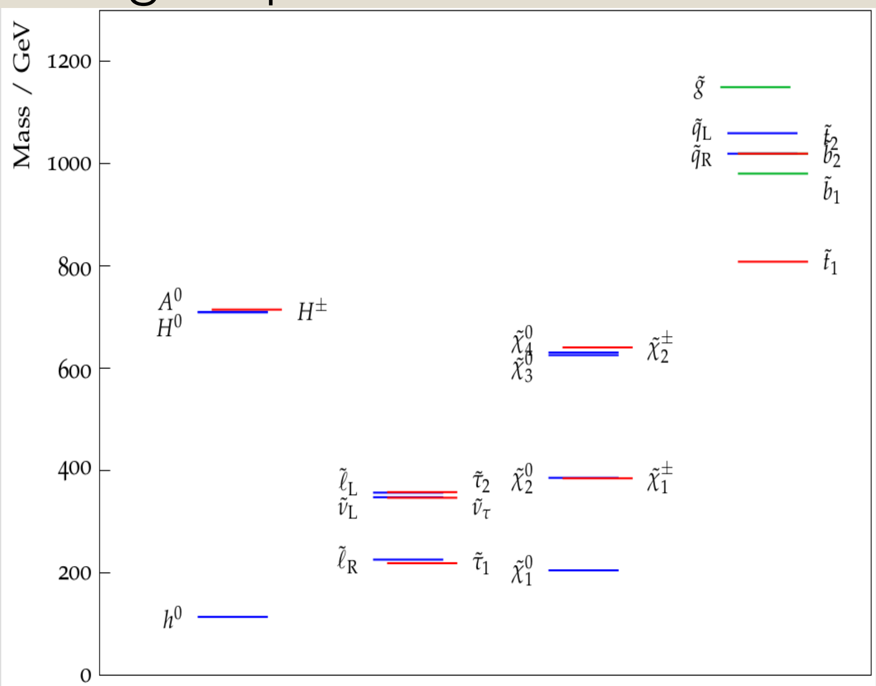


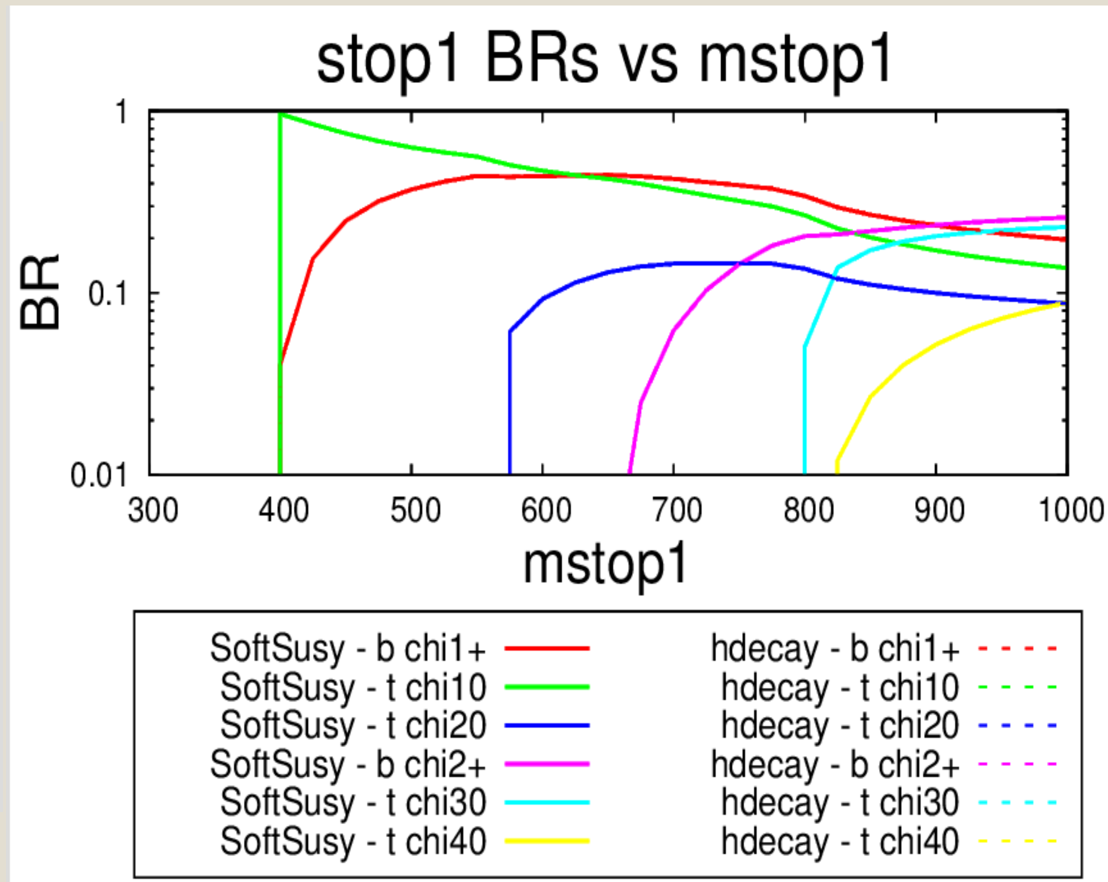
Spectrum Plot generated with slhaplot of pyslha-3.2.0: Buckley arXiv:1305.4194

MSSM Susy decays 1 – stop1

- Validation plots

  e.g. stop1

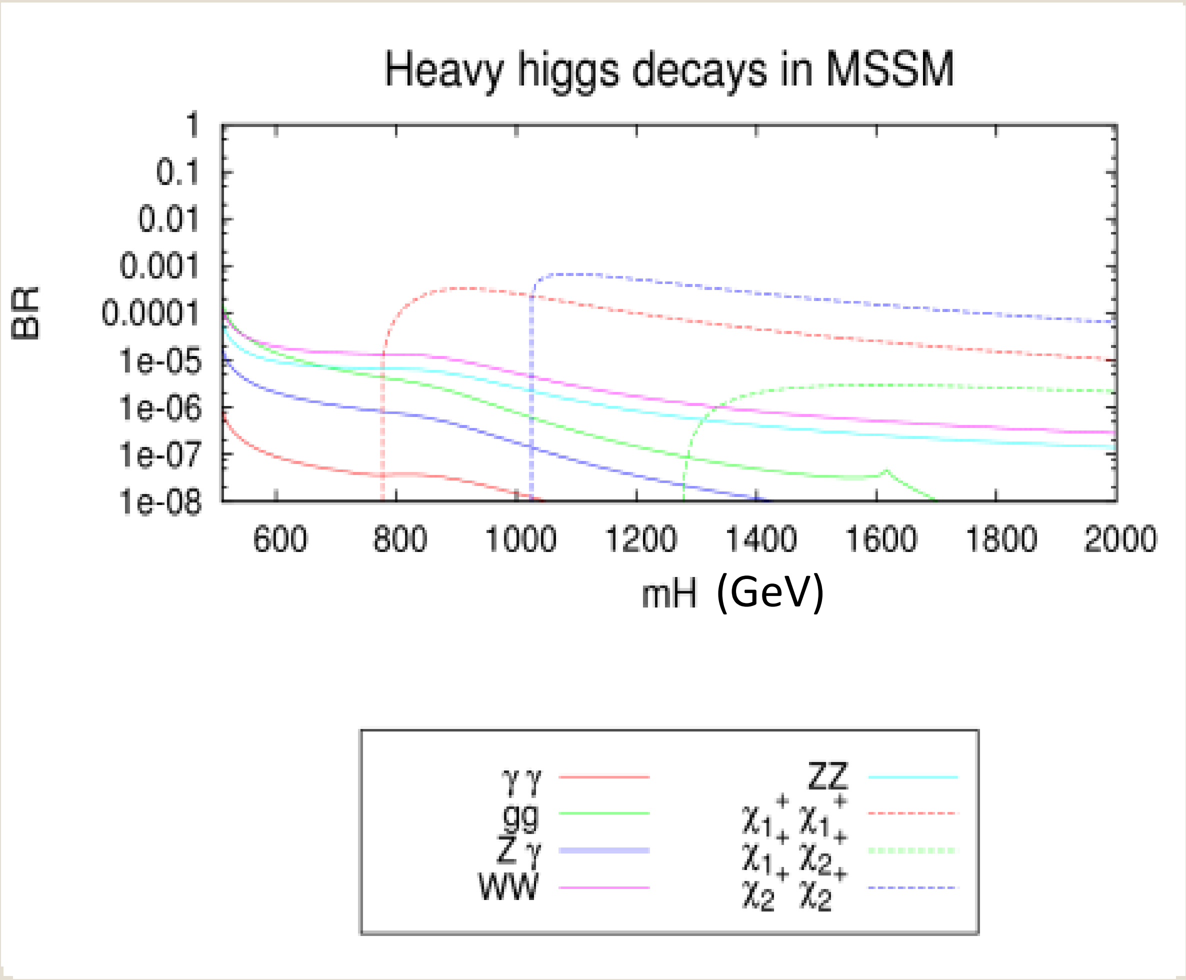


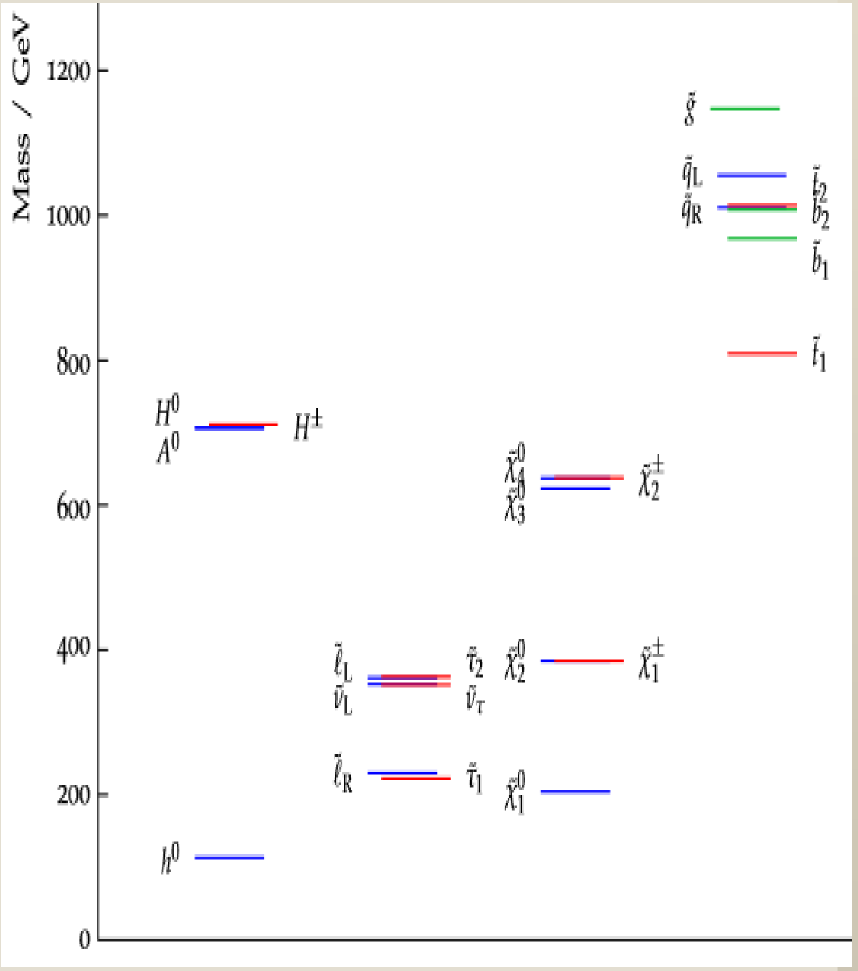


of solid lines ->

excellent agreement!

Higgs decays 3 - H

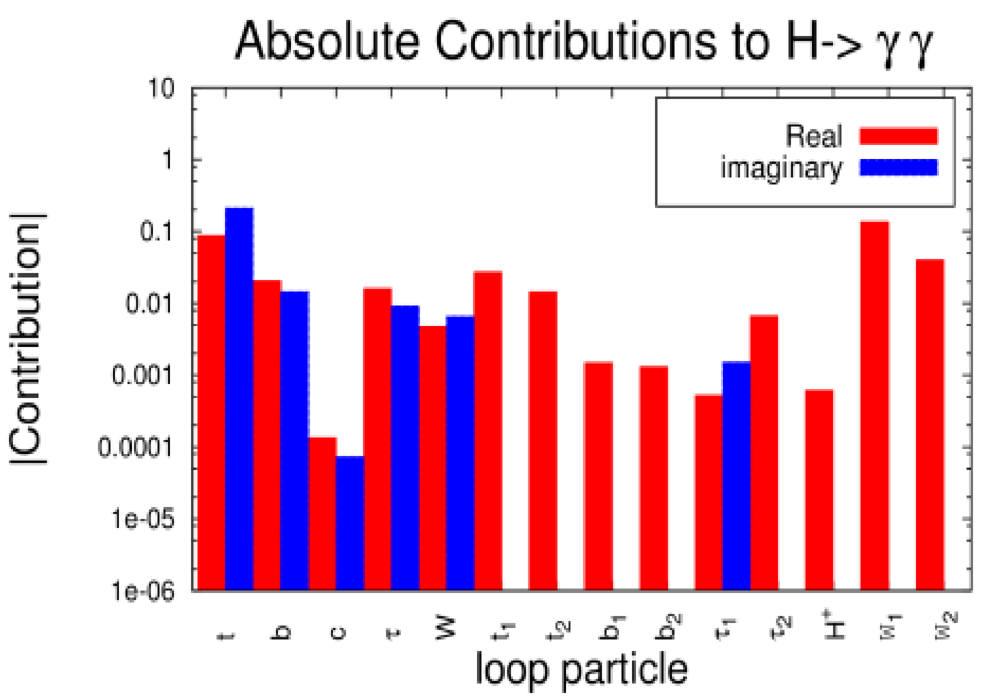


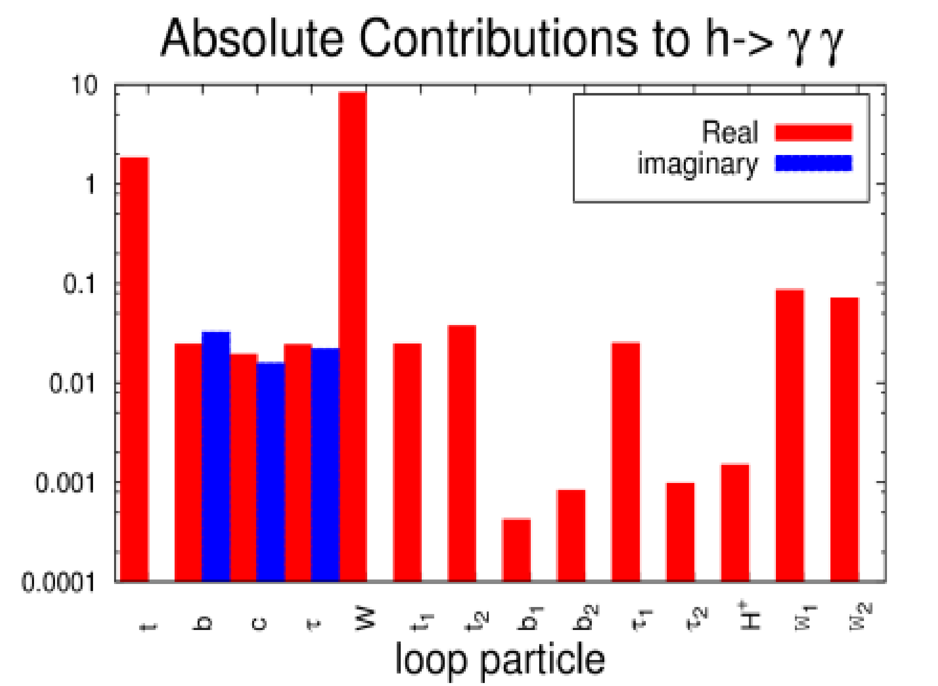


Spectrum Plot generated with slhaplot of pyslha-3.2.0: Buckley arXiv:1305.4194

Higgs decays 4 – h, H -> γγ

- Contributions to h → gamma gamma in MSSM at mh =125GeV and for heavier higgs at mH = 706.4GeV.

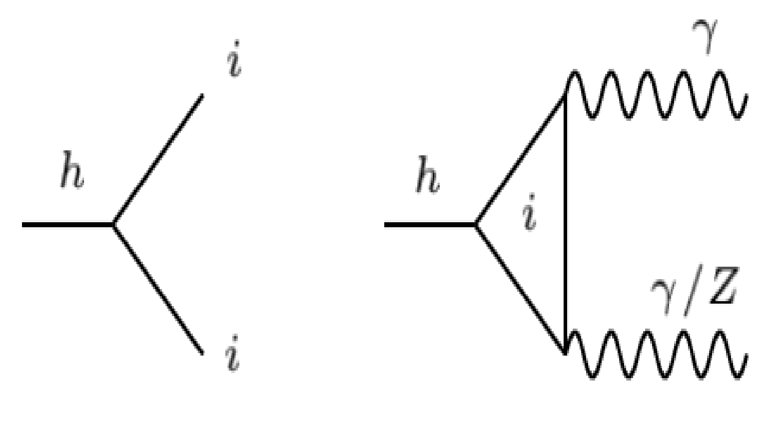




Imaginary parts of loop integrals:

$$f(\tau) = \begin{cases} [\sin^{-1}(\frac{1}{\sqrt{\tau}})]^2, \; for & \tau \geq 1, \\ -\frac{1}{4}[ln(\frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}}) - i\pi]^2, \; for & \tau < 1 \end{cases}$$

$$\Gamma(\phi \rightarrow \gamma\gamma) = \frac{g^2 \alpha_{em}^2 m_\phi^3}{1024\pi^3 m_W^2} ||\Sigma I_{loop}^{\phi}|^2$$



$$I_{\tilde{t}_1}^h = \frac{4}{3}\tau(1 - \tau f(\tau))[R^1_{\tilde{t}_L\tilde{t}_L}\cos^2\theta_t + R^1_{\tilde{t}_R\tilde{t}_R}\sin^2\theta_t - 2R^1_{\tilde{t}_L\tilde{t}_R}\cos\theta_t\sin\theta_t]$$

$$I_{\tilde{t}_2}^h = \frac{4}{3}\tau(1 - \tau f(\tau))[R^2_{\tilde{t}_L\tilde{t}_L}\sin^2\theta_t + R^2_{\tilde{t}_R\tilde{t}_R}\cos^2\theta_t + 2R^2_{\tilde{t}_L\tilde{t}_R}\cos\theta_t\sin\theta_t]$$

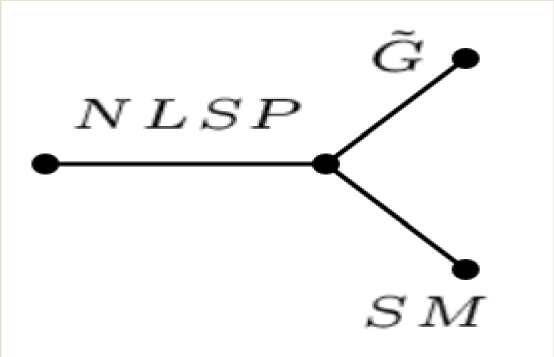
$$\tau = 4m_i^2/m_{\phi 0}^2$$

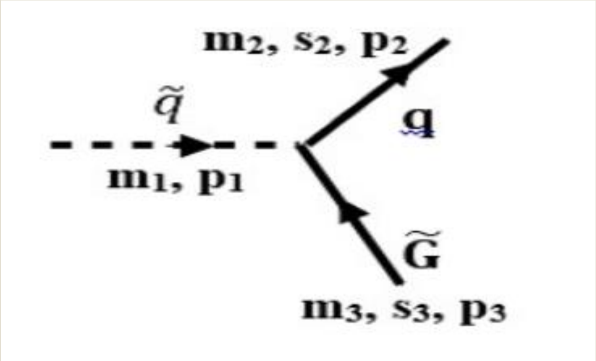
$$m_h > 2m_i \rightarrow \tau = \frac{4m_i^2}{m_h^2} < 1 \rightarrow$$

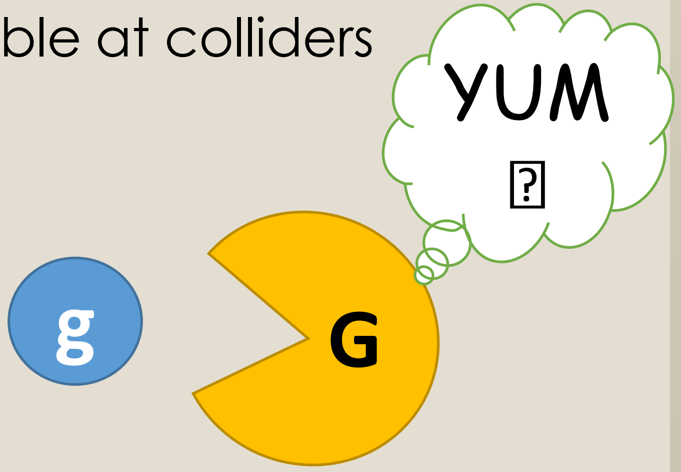
If h -> 2*loop particle can occur get imaginary part of loop integral!

Gravitino decays - theory

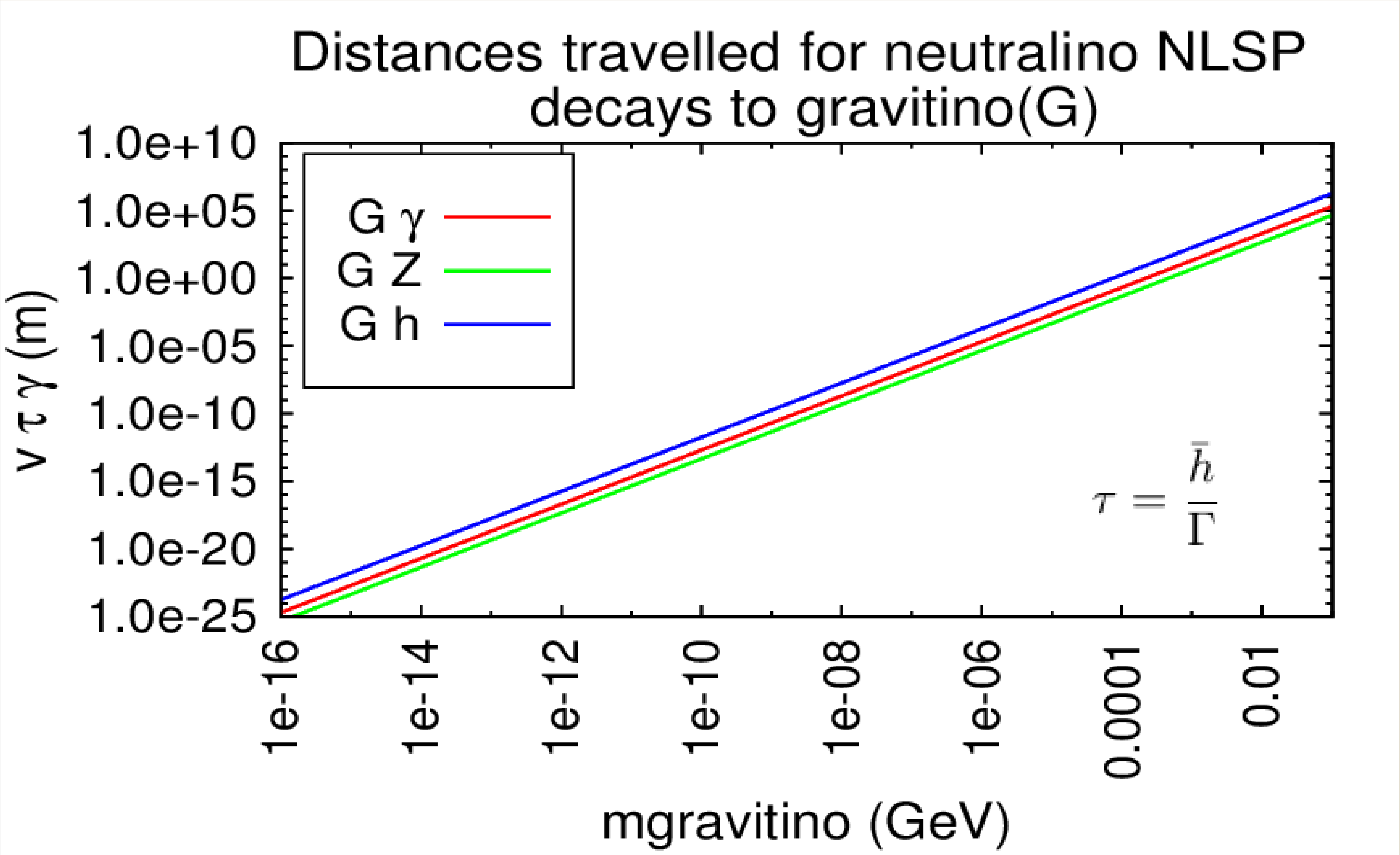
- Susy -> local symmetry to incorporate gravity -> spin 2 graviton.
  -> spin 3/2 susy partner: gravitino.
- Spontaneous susy breaking (SSB) -> massless goldstone fermion of spin 1/2 : goldstino.
- In EWSB, massless gravitino "eats" massless goldstino -> becomes gravitino's longitudinal dof -> gravitino becomes massive.
- In SSB scenarios, particularly GMSB the gravitino can be LSP.
- Decays to gravitinos are usually gravitational strength –> essentially decoupled.
- Goldstino dofs couple much more strongly -> gravitino inherits stronger coupled longitudinal components.
- Decays **NLSP -> LSP gravitino + SM** to be observable at colliders







Gravitino decays - plot



NMSSM Key parameters

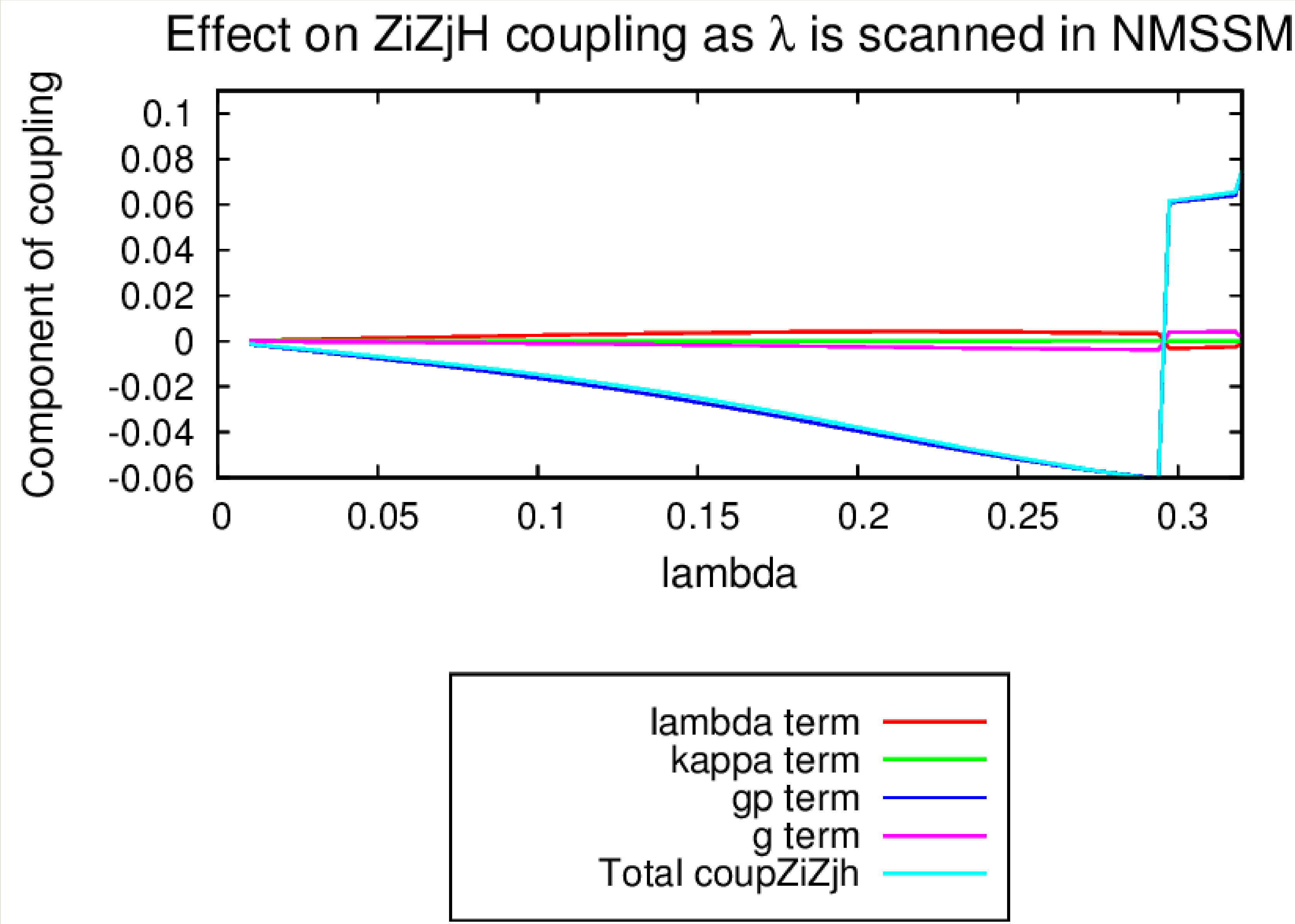
Crucially – NMSSM decays not included in most alternative programs – only NMSSMTools or SARAH + SPheno together.

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

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
$\tan\beta = \langle Hu \rangle / \langle Hd \rangle$	- ratio of vevs of higgses, neutralino mixing via higgsinos
$\boldsymbol{\mu_{eff} = \lambda \langle S \rangle}$	- higgsino masses, neutralino mixing

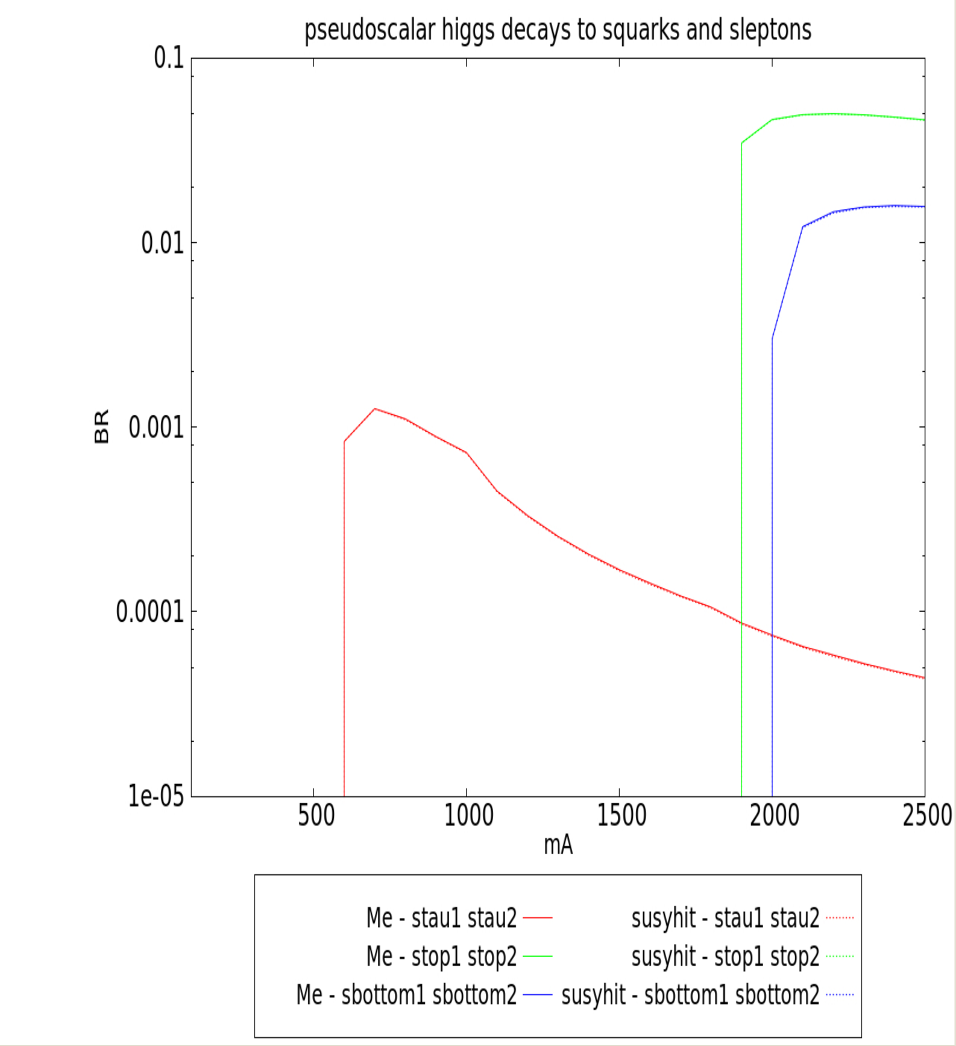
N.B. As $\tilde{S}$ is gauge singlet it only couples to non-higgs particles via mixing with other neutralinos.

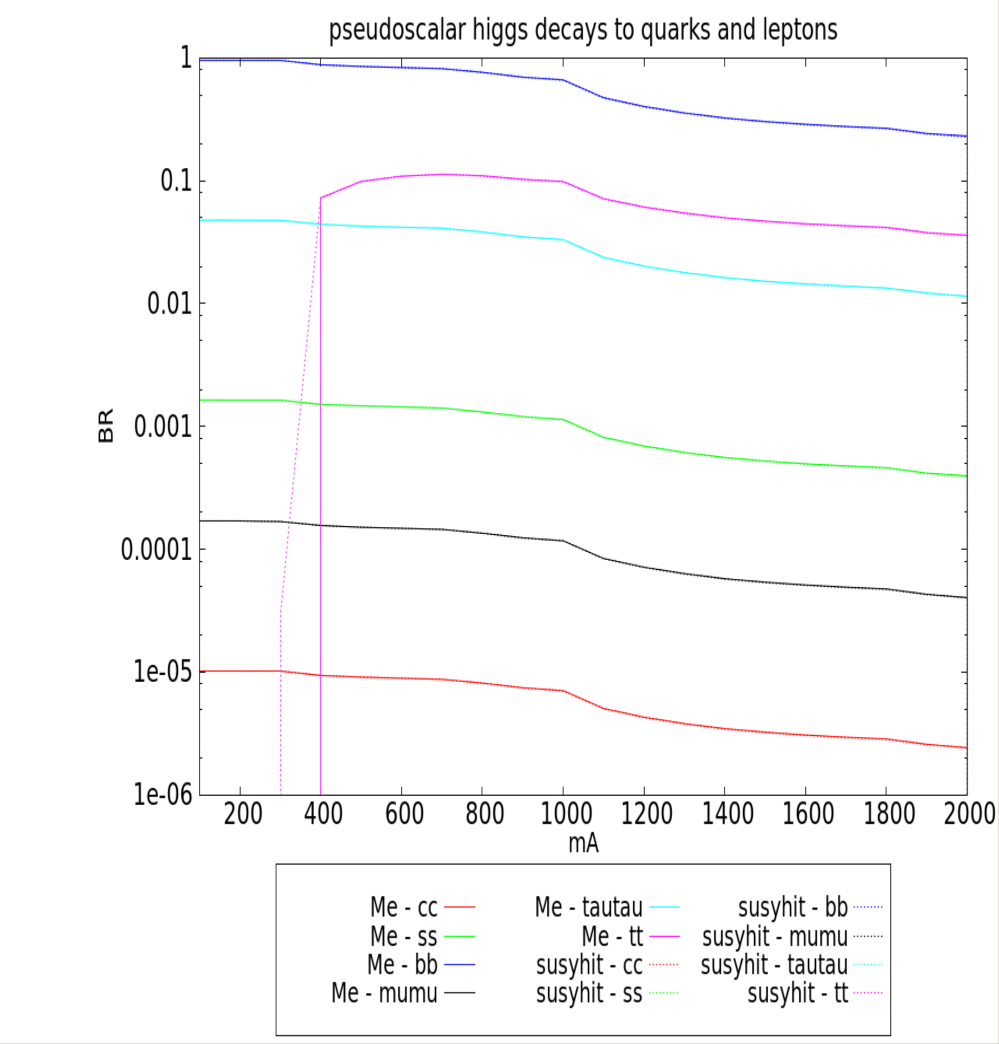
NMSSM Scan Decays



Higgs decays 3 – A decays validation

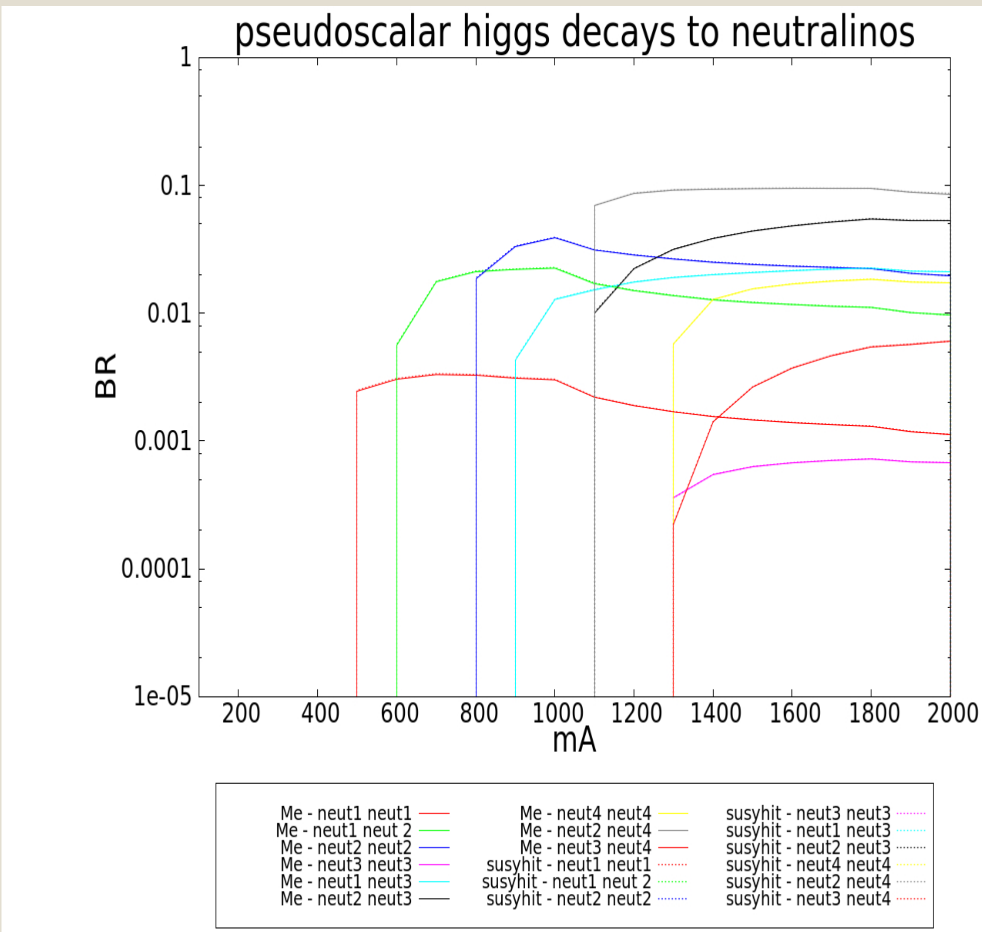
- Pseudoscalar higgs validation plots

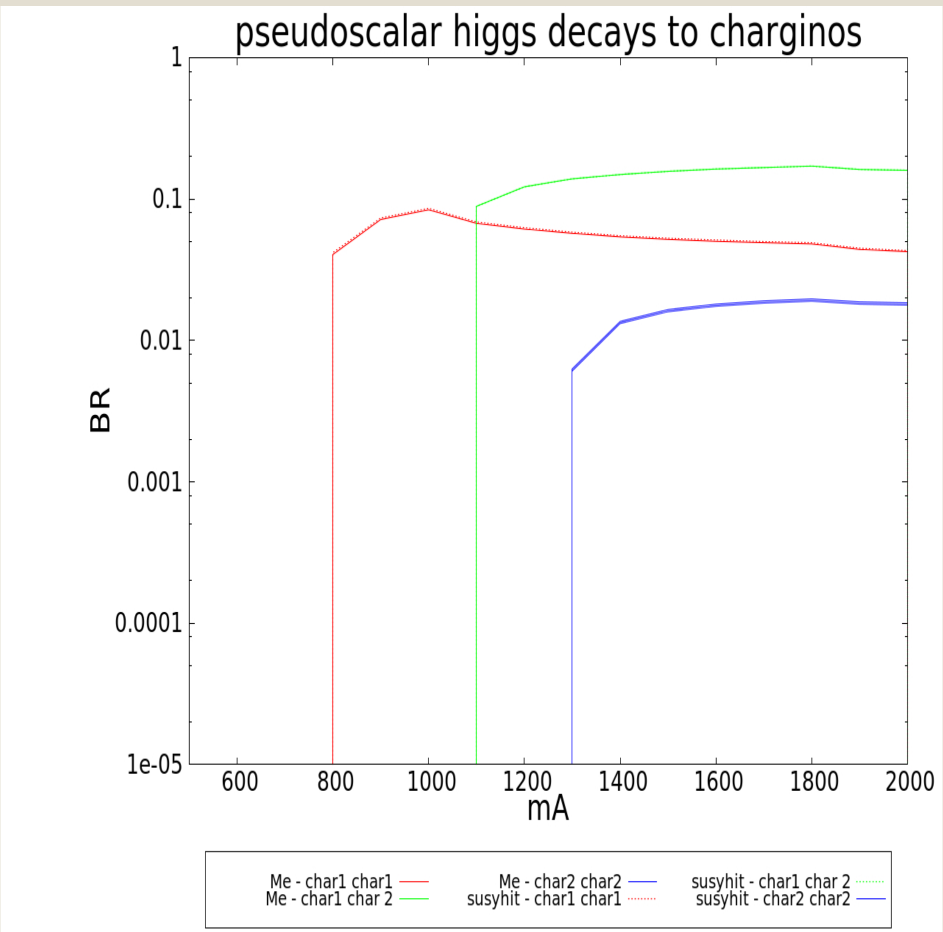




Higgs decays 3 – A decays validation 2

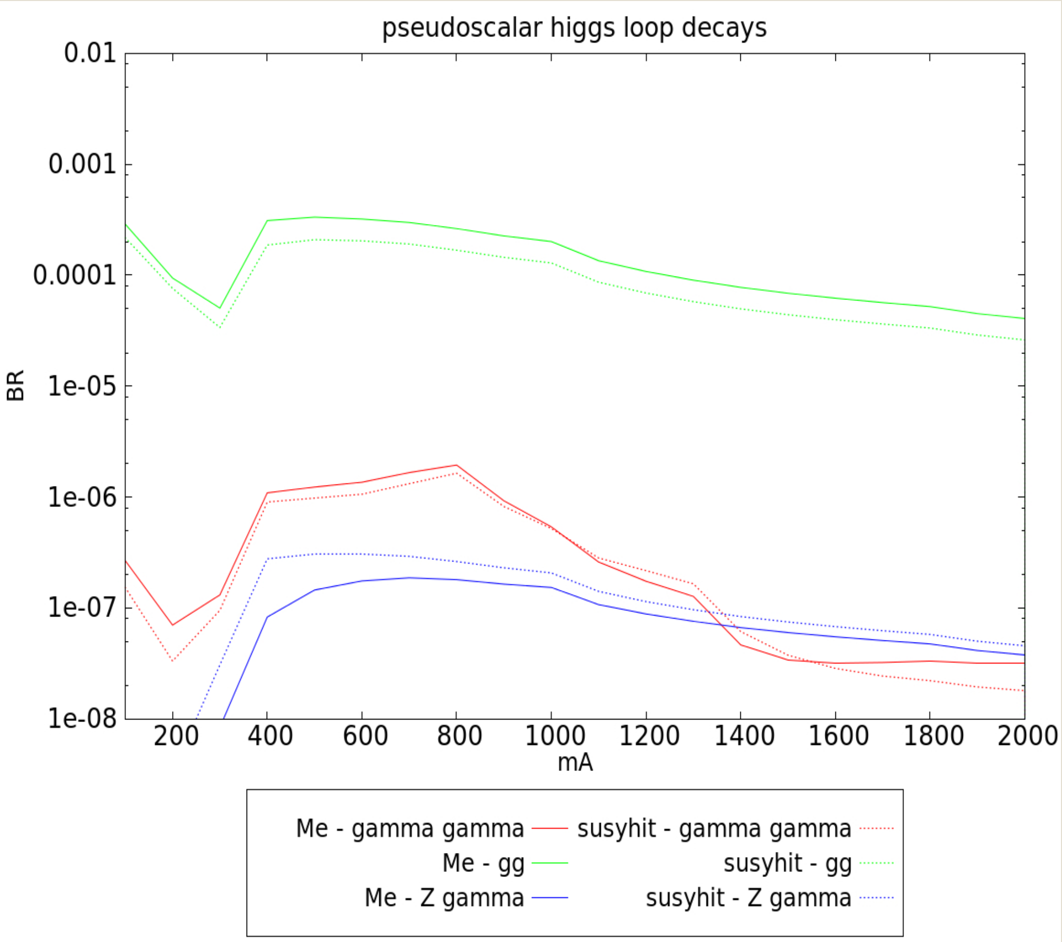
- Pseudoscalar higgs validation plots

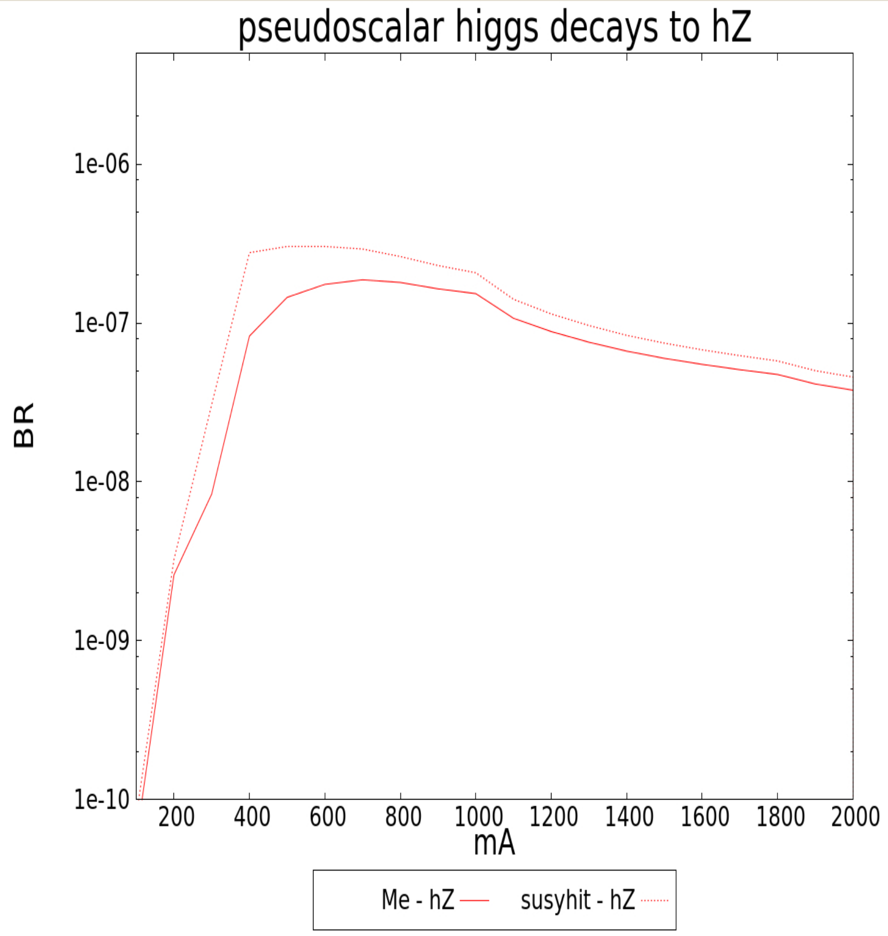




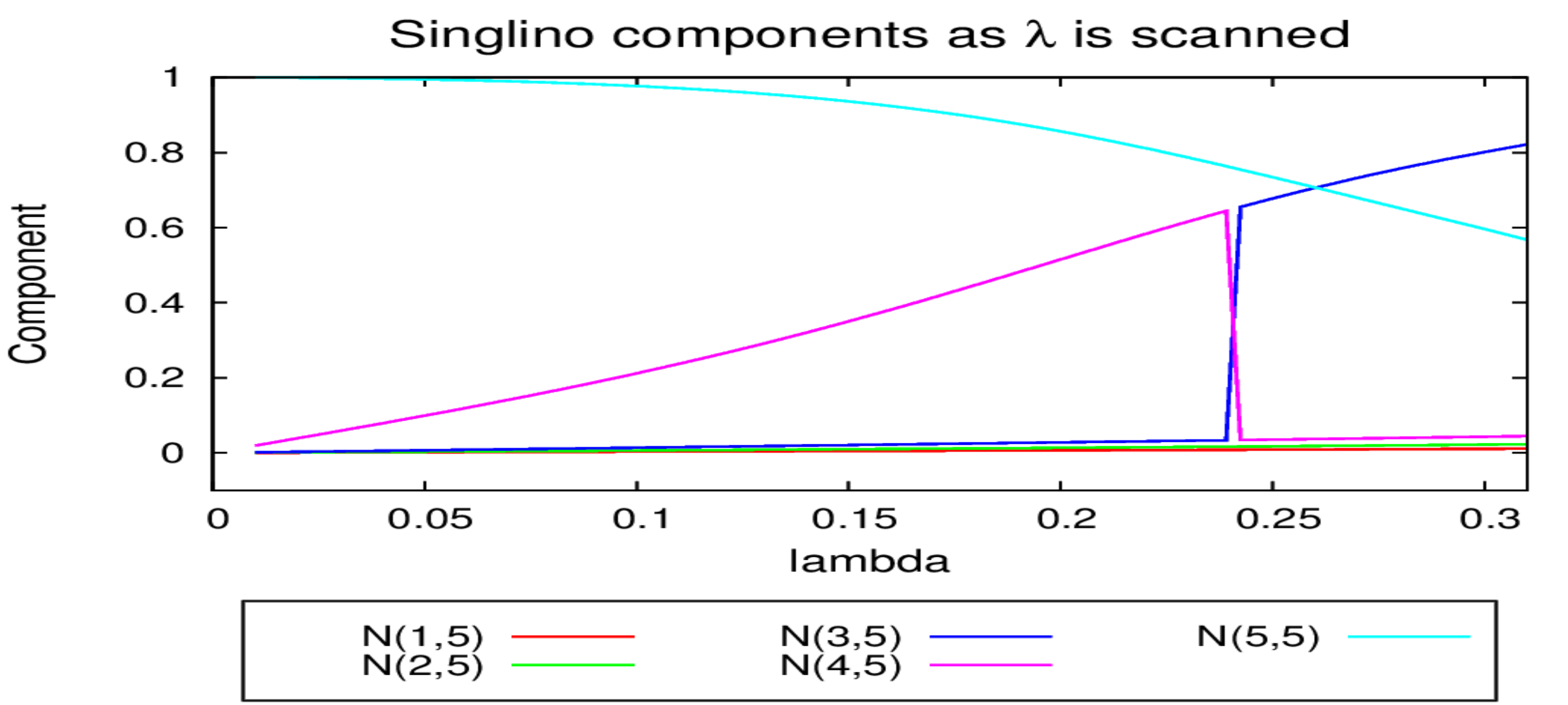
Higgs decays 3 – A decays validation 3

- Pseudoscalar higgs validation plots





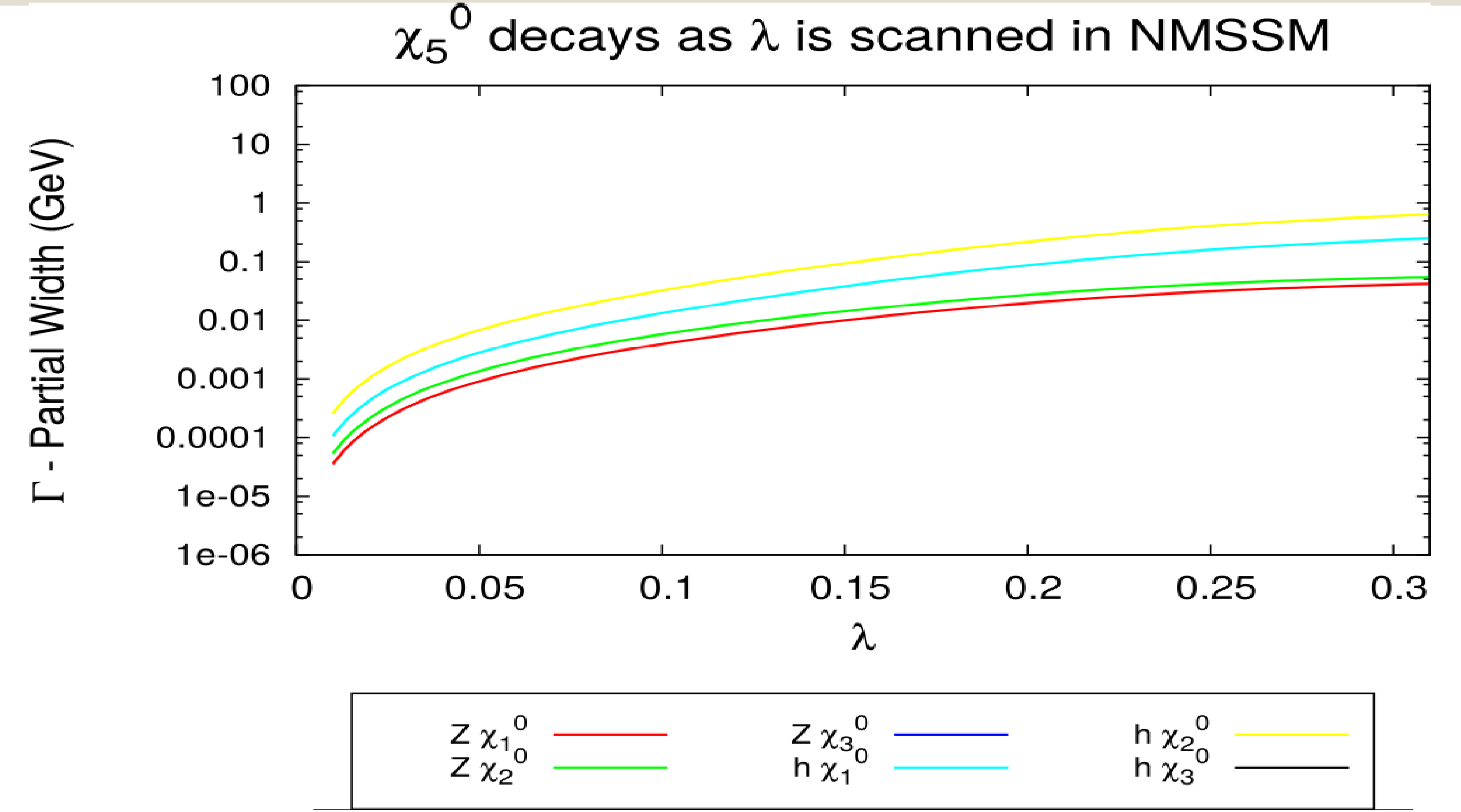
NMSSM - χ^0 singlino components



$$\mathcal{M}_{\tilde{\psi}^0} = \begin{pmatrix} M_1 & 0 & -M_Z c_\beta s_W & M_Z s_\beta s_W & 0 \\ 0 & M_2 & M_Z c_\beta c_W & -M_Z s_\beta c_W & 0 \\ -M_Z c_\beta s_W & M_Z c_\beta c_W & 0 & -\mu & -\lambda v_2 \\ M_Z s_\beta s_W & -M_Z s_\beta c_W & -\mu & 0 & -\lambda v_1 \\ 0 & 0 & 0 & 0 & 2\kappa s + \mu' \end{pmatrix}.$$

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

NMSSM Scan Decays



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