SUSY Benchmark Activities in WG3

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WG3: Exotic Higgs Decays at Fermilab

22 May 2015

$\mathcal{B}$enchmarck $\mathcal{S}$earches for $\mathcal{S}$USY $\mathcal{M}$odels

▷ Scan:

- Identify relevant parameters of the SUSY Higgs sector in question (MSSM, NMSSM, ...)
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- Theory: perturbativity of parameters, correct minimum (no charge/colour breaking min) etc.
- Experiment: compatibility with Higgs data from LEP, Tevatron, LHC; with LHC SUSY searches; with low-energy observables; with relic density
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▷ Tools: Use state-of-the art tools

* Production/Decay ($\rightarrow$ rates): include higher order corrections, off-shell decays
* Specify tools used: reproducable results
* Ideal: use tools recommended by LHCXSWG (however, not available for all models yet)

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▷ Bechmark identification: Among resulting scenarios from scan, compatible with the constraints

* select benchmarks according to criteria (exotic final states; light stops; Higgs-to-Higgs etc)

$\mathcal{N}$MSSMCALC

- **NMSSMCALC:** Fortran package for the calculation in the real & complex NMSSM of the
  - ⋆ loop-corrected NMSSM Higgs boson masses at one-loop and at two-loop at $\mathcal{O}(\alpha_t \alpha_s)$
  - ⋆ NMSSM Higgs boson decay widths and branching ratios

- **Input and output files** feature the SUSY Les Houches Accord (SLHA) Skands eal; Allanach eal

- **Decay Widths:** extension of HDECAY to the NMSSM Djouadi,Kalinowski,MM,Spira

- **Reference:**

  NMSSMCALC: A Program Package for the Calculation of Loop-Corrected Higgs Boson Masses and Decay Widths in the (Complex) NMSSM

  J. Baglio, R. Gröber, MMM, D.T. Nhung, H. Rzehak, M. Spira, J. Streicher and K. Walz

  Comput. Phys. Commun. **185** (2014) 12 [arXiv:1312.4788]

The $\mathcal{NMSSM}$ $\mathcal{H}$iggs $\mathcal{S}$ector

- **The Z_3 invariant NMSSM:**

$$
\begin{aligned}
V_{\text{Higgs}} \;=\; & |\lambda(H_u^+ H_d^- - H_u^0 H_d^0) + \kappa S^2|^2 \\
& + (m_{H_u}^2 + |\lambda S|^2)(|H_u^0|^2 + |H_u^+|^2) + (m_{H_d}^2 + |\lambda S|^2)(|H_d^0|^2 + |H_d^-|^2) \\
& + \frac{g_1^2 + g_2^2}{8}(|H_u^0|^2 + |H_u^+|^2 - |H_d^0|^2 - |H_d^-|^2)^2 + \frac{g_2^2}{2}|H_u^+ H_d^{0*} + H_u^0 H_d^{-*}|^2 \\
& + m_S^2 |S|^2 + (\lambda A_\lambda (H_u^+ H_d^- - H_u^0 H_d^0) S + \frac{1}{3}\kappa A_\kappa S^3 + h.c.)
\end{aligned}
$$

- **Tadpole parameters:**

$$
\left.\frac{\partial V}{\partial \phi_i}\right|_{\text{min}} = t_{\phi_i} \; , \qquad\qquad \phi = (h_d, h_u, h_s)
$$

Minimization condition requires: $t_{\phi_i} = 0$ at tree-level

- **Parameter basis:**

◇ exploit tadpole conditions to replace $m_{H_u}^2, m_{H_d}^2, m_S^2$ by $t_{h_u}, t_{h_d}, t_{h_s}$

◇ replace g, g', v_u, v_d by $e, M_W, M_Z, \tan\beta = v_u/v_d$

◇ replace A_λ by $M_{H_\pm}$

$\rightsquigarrow$ parameter set: $t_{h_u}, t_{h_d}, t_{h_s}, e, M_W, M_Z, M_{H^\pm}, \tan\beta, \lambda, \kappa, v_s, A_\kappa$

The $\mathcal{NMSSM}$ $\mathcal{H}$iggs $\mathcal{S}$ector

- **The Z_3 invariant NMSSM:**

$$\begin{aligned} V_{\text{Higgs}} &= |\lambda(H_u^+ H_d^- - H_u^0 H_d^0) + \kappa S^2|^2 \\ &+(m_{H_u}^2 + |\lambda S|^2)(|H_u^0|^2 + |H_u^+|^2) + (m_{H_d}^2 + |\lambda S|^2)(|H_d^0|^2 + |H_d^-|^2) \\ &+\frac{g_1^2 + g_2^2}{8}(|H_u^0|^2 + |H_u^+|^2 - |H_d^0|^2 - |H_d^-|^2)^2 + \frac{g_2^2}{2}|H_u^+ H_d^{0*} + H_u^0 H_d^{-*}|^2 \\ &+m_S^2|S|^2 + (\lambda A_\lambda (H_u^+ H_d^- - H_u^0 H_d^0) S + \frac{1}{3}\kappa A_\kappa S^3 + h.c.) \end{aligned}$$

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$\rightsquigarrow$ complex NMSSM: $t_{h_u}, t_{h_d}, t_{h_s}, t_{a_d}, t_{a_s}, e, M_W, M_Z, M_{H^\pm}, \tan\beta, |\lambda|, |\kappa|, v_s, \text{Re}|A_\kappa|, \varphi_y$

Program Description

- **Webpage:**
  http://www.itp.kit.edu/∼/maggie/NMSSMCALC

- **Files:** wrap file: `nmssmcalc.f`, makefile for compilation, additional help files
  - ⋆ 3 main files:
    `CalcMasses.F (mass corrections),`
    `bhdecay.f and bhdecay_c.f (decay widths and BRs)`
  - ⋆ input files
    `inp.dat` (in SLHA format), `bhdecay.in` (setting of CKM parameters and flags)

- **Input file `inp.dat`:** in SLHA format
  - ⋆ Flags: CP-conserving/violating, 1-/2-loop mass corrections, OS/$\overline{\text{DR}}$ sheme in top/stop sector (for 2-loop corrections)
  - ⋆ Block SMINPUTS: SM input parameters
  - ⋆ Block EXTPAR: soft SUSY breaking parameters, NMSSM specific parameters, $\tan\beta$, $M_{H^\pm}$
  - ⋆ complex NMSSM: additionally blocks IMEXTPAR (imaginary parts of complex parameters) and CMPLX (phase φ_u)

http://www.itp.kit.edu/~maggie/NMSSMCALC

NMSSMCALC
Calculator of One-Loop Higgs Mass Corrections and of Higgs Decay Widths in the CP-conserving and the CP-violating NMSSM

The program package NMSSMCALC calculates the one-loop corrected Higgs boson masses and the Higgs decay widths and branching ratios within the CP-conserving and the CP-violating NMSSM. The decay calculator is based on an extension of the program HDECAY 6.10 now.

Released by: Julien Baglio, Ramona Gröber, Margarete Mühlleitner, Dao Thi Nhung, Heidi Rzehak, Michael Spira, Juraj Streicher and Kathrin Walz
Program: NMSSMCALC version 1.02

When you use this program, please cite the following references:

NMSSMCALC:	Julien Baglio, Ramona Gröber, Margarete Mühlleitner, Dao Thi Nhung, Heidi Rzehak, Michael Spira, Juraj Streicher and Kathrin Walz, in arXiv:1312.4788
One-Loop Masses:	K. Ender, T. Graf, M. Mühlleitner, H. Rzehak, in Phys. Rev. D85 (2012)075024
	T. Graf, R. Gröber, M. Mühlleitner, H. Rzehak, K. Walz, in JHEP 1210 (2012) 122
HDECAY:	A. Djouadi, J. Kalinowski, M. Spira, Comput.Phys.Commun. 108 (1998) 56
An update of HDECAY:	A. Djouadi, J. Kalinowski, Margarete Muhlleitner, M. Spira, in arXiv:1003.1643

Informations on the Program:

- Short explanations on the program are given here.
- To be advised about future updates or important modifications, send an E-mail to nmssmcalc@itp.kit.edu.

$\mathcal{O}$utput $\mathcal{F}$ile: $\mathcal{S}$LHA $\mathcal{F}$ormat

```
#          PDG              Width
DECAY         25     1.21947660E-03   # H1 decays
#           BR          NDA       ID1        ID2
      8.94709020E-01    2           5         -5    # BR(H1-> b       bb      )
      9.11419262E-02    2         -15         15    # BR(H1-> tau+    tau-    )
      3.22958606E-04    2         -13         13    # BR(H1-> mu+     mu-     )
      3.59782553E-04    2           3         -3    # BR(H1-> s       sb      )
      4.31960949E-03    2           4         -4    # BR(H1-> c       cb      )
      6.44006108E-03    2          21         21    # BR(H1-> g       g       )
      6.67678437E-05    2          22         22    # BR(H1-> gam     gam     )
      1.57221386E-05    2          22         23    # BR(H1-> Z       gam     )
      2.40306420E-03    2          24        -24    # BR(H1-> W+      W-      )
      2.21087590E-04    2          23         23    # BR(H1-> Z       Z       )
#
#          PDG              Width
DECAY         35     3.46721521E-03   # H2 decays
#           BR          NDA       ID1        ID2
      5.07441591E-01    2           5         -5    # BR(H2-> b       bb      )
      5.34626924E-02    2         -15         15    # BR(H2-> tau+    tau-    )
      1.89262743E-04    2         -13         13    # BR(H2-> mu+     mu-     )
      2.07858646E-04    2           3         -3    # BR(H2-> s       sb      )
      3.28719643E-02    2           4         -4    # BR(H2-> c       cb      )
      8.82149227E-02    2          21         21    # BR(H2-> g       g       )
      2.90260048E-03    2          22         22    # BR(H2-> gam     gam     )
      1.61708014E-03    2          23         22    # BR(H2-> Z       gam     )
      2.16347150E-01    2          24        -24    # BR(H2-> W+      W-      )
      2.67510177E-02    2          23         23    # BR(H2-> Z       Z       )
```

$\mathcal{O}$utput $\mathcal{F}$ile: $\mathcal{S}$LHA $\mathcal{F}$ormat

```
#
BLOCK DCINFO  # Decay Program information
     1    BHDECAY     # decay calculator
     2    1.03        # version number
#
BLOCK SPINFO  # Spectrum calculator information
     1    CalcMasses  # loop Higgs mass calculator
     2    2.00          # version number
#
BLOCK MODSEL  # Model selection
     3      1    # NMSSM
     5      0    # CP-conserving
#
BLOCK SMINPUTS  # Standard Model inputs
         2     1.16637000E-05   # G_F [GeV^-2]
         3     1.18400000E-01   # alpha_S(M_Z)^MSbar
         4     9.11876000E+01   # M_Z pole mass
         5     4.19000000E+00   # mb(mb)^MSbar
         6     1.73500000E+02   # mt pole mass
         7     1.77682000E+00   # mtau pole mass
#
BLOCK EXTPAR  # Input parameters - non-minimal models
         0     1.25044872E+03   # input
         1     8.62372896E+02   # M1
         2     2.01462610E+02   # M2
         3     2.28530595E+03   # M3
        11     1.82404356E+03   # At
        12    -1.53864055E+03   # Ab
```

$\mathcal{S}$earch for $\mathcal{NMSSM}$ $\mathcal{B}$enchmarks

- **Benchmarks -1:**
  - $*$ $h \to ss$ or $h \to aa$ with s, a the lightest CP-even, CP-odd scalar $\leftarrow$ mainly singlet-like
  - $*$ further decays into SM quarks and leptons

- **Benchmarks -2:**
  - $*$ $h \to \tilde{\chi}_1^0 \tilde{\chi}_2^0$, $\tilde{\chi}_2^0 \tilde{\chi}_2^0$
  - $*$ $\tilde{\chi}_1^0$: LSP, mainly singlino neutralino, $\tilde{\chi}_2^0$: mainly bino neutralino
  - $*$ $\tilde{\chi}_2^0 \to s\tilde{\chi}_1^0$ or $\tilde{\chi}_2^0 \to \gamma\tilde{\chi}_1^0 \rightsquigarrow$ final state: 2 fermions + MET or 1γ + MET

$\mathcal{W}$ork in $\mathcal{P}$rogress

$\mathcal{S}$earch for $\mathcal{NMSSM}$ $\mathcal{B}$enchmarks - $\mathcal{S}$can

Mixing angle $\tan\beta$ and NMSSM couplings λ, κ:

$$1 \le \tan\beta \le 30 \,, \qquad 0 \le \lambda \le 0.7 \,, \qquad -0.7 \le \kappa \le 0.7$$

with perturbativity requirement

$$\sqrt{\lambda^2 + \kappa^2} \le 0.7$$

Soft SUSY breaking trilinear NMSSM couplings and μ_{eff}:

$$-2 \text{ TeV} \le A_\lambda \le 2 \text{ TeV} \,, \; -2 \text{ TeV} \le A_\kappa \le 2 \text{ TeV} \,, \; -1 \text{ TeV} \le \mu_{\text{eff}} \le 1 \text{ TeV}$$

Remaining Parameters:

$$-2 \text{ TeV} \le A_U, A_D, A_L \le 2 \text{ TeV}$$

$$600 \text{ GeV} \le M_{\tilde{t}_R} = M_{\tilde{Q}_3} \le 3 \text{ TeV} \,, \; 600 \text{ GeV} \le M_{\tilde{\tau}_R} = M_{\tilde{L}_3} \le 3 \text{ TeV} \,, \; M_{\tilde{b}_R} = 3 \text{ TeV}$$

$$M_{\tilde{u}_R,\tilde{c}_R} = M_{\tilde{d}_R,\tilde{s}_R} = M_{\tilde{Q}_{1,2}} = M_{\tilde{e}_R,\tilde{\mu}_R} = M_{\tilde{L}_{1,2}} = 3 \text{ TeV}$$

$$100 \text{ GeV} \le M_1 \le 1 \text{ TeV} \,, \; 200 \text{ GeV} \le M_2 \le 1 \text{ TeV} \,, \; 1.3 \text{ TeV} \le M_3 \le 3 \text{ TeV}$$

$\mathcal{NMSSM}$ $\mathcal{S}$can

- **Conditions on the parameter scan:**

  - At least one CP-even Higgs boson $H_i \equiv h$ with: 124 GeV $\lesssim M_h \lesssim 127$ GeV
  - Compatibility with μ_{XX}^{exp} $(X = b, \tau, \gamma, W, Z)$: $|\mu_{XX}^{\text{scan}}(h) - \mu_{XX}^{\text{exp}}| \leq 2\sigma$
  - Relic density $\Omega_c h^2$ below PLANCK result $(\Omega_c h^2)^{\text{NMSSM}} \leq 0.1187 \pm 0.0017$ [PLANCK]

Constraints from low-energy observables, from LEP, Tevatron and LHC searches [NMSSMTools]

- **Signal can be superposition of two Higgs boson rates close in mass: h and $\Phi = H_i, A_j$**

$$\mu_{XX}(h) \equiv R_\sigma(h)\, R_{XX}^{BR}(h) \;+\; \sum_{\substack{\Phi \neq h \\ |M_\Phi - M_h| \leq \delta}} R_\sigma(\Phi)\, R_{XX}^{BR}(\Phi)\, F(M_h, M_\Phi, d_{XX})$$

δ : mass resolution in the respective XX final state

$F(M_h, M_\Phi, d_{XX})$: Gaussian weighting function

d_{XX}: experimental resolution of final state XX [NMSSMTools]

$\mathcal{E}$xperimental $\mathcal{S}$ignal $\mathcal{R}$ates

Based on: ATLAS-CONF-2013-034; CMS-PAS-HIG-13-005; combination à la Espinosa,MMM,Grojean,Trott

channel	best fit value	$2 \times 1\sigma$ error
$VH \to Vbb$	0.97	± 1.06
$H \to \tau\tau$	1.02	± 0.7
$H \to \gamma\gamma$	1.14	± 0.4
$H \to WW$	0.78	± 0.34
$H \to ZZ$	1.11	± 0.46

How MSSM Higgs BRs are Calculated for the LHCHXSWG

Sven Heinemeyer, IFCA (CSIC, Santander)

Fermilab, 05/2015

BR co-convenors:
Ansgar Denner, Alexander Mück, Ivica Puljak, Daniela Rebuzzi

Main idea:

Use best code for individual decay widths

Codes used:

– FeynHiggs
– FeynHiggs/Prophecy4f
– Hdecay

Tool for combination:

the "Script"

Author: Daniela Rebuzzi (with some help from S.H.)

New, interesting decays/scenarios?

From my email with Stefania :-)

Stefania:

For the specific case of the MSSM, we are thinking to decays of the type $h \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 \to \gamma \tilde{G}$ (with $\tilde{G}$ the gravitino and $\tilde{\chi}_1^0$ mainly bino).

Sven:

I understand that BR($\tilde{\chi}_1^0 \to \gamma \tilde{G}$) $= 1$ is assumed, but that the parameters $m_{\tilde{\chi}_1^0}$, $m_{3/2}$ and the neutralino mixing matrix are still relevant. The longer the life time the better? Probably up to a certain limit that gives you displaced photons (with a decay length ctau). What are your preferred values?

BR($h\tilde{\chi}_1^0 \tilde{\chi}_1^0$) is in principle evaluated in our machinery. So far it did not play a role, because in the benchmark scenarios so far $m_{\tilde{\chi}_1^0} > M_h/2$.

Sven: (cont.)

So we need a scenario with $M_1 \neq M_2$ at the GUT scale, equivalent to $M_1 \neq M_2/2$ at the EW scale. The easiest would be to treat M_1 and M_2 independent paraemters.

One could start with a known benchmark scenario but just keep M_1 as a free parameter, then scan M_A, $\tan\beta$ and M_1, evaluate BR$(h\tilde{\chi}_1^0\tilde{\chi}_1^0)$ and ctau to find interesting regions.

Thoughts?

Thank You For Your Attention!

$\mathcal{I}$nterpretation within $\mathcal{SUSY}$: The $\mathcal{NMSSM}$ $\mathcal{H}$iggs $\mathcal{S}$ector

- **Supersymmetric Higgs Sector:** SUSY & anomaly-free theory $\Rightarrow$ 2 complex Higgs doublets

- **Most economic version:** Minimal Supersymmetric Extension of the SM (MSSM):

  2 complex Higgs doublets

- **Next-to-Minimal Supersymmetric Extension of the SM: NMSSM**

  Fayet; Kaul eal; Barbieri eal; Dine eal; Nilles eal; Frere eal; Derendinger eal; Ellis eal;
  Drees; Ellwanger eal; Savoy; Elliott eal; Gunion eal; Franke eal; Maniatis; Djouadi eal; Mahmoudi eal; ...

  2 complex Higgs doublets plus one complex singlet field $\rightsquigarrow$

- **Solution of the μ-problem:** μ must be of $\mathcal{O}$(EWSB scale) Kim,Nilles

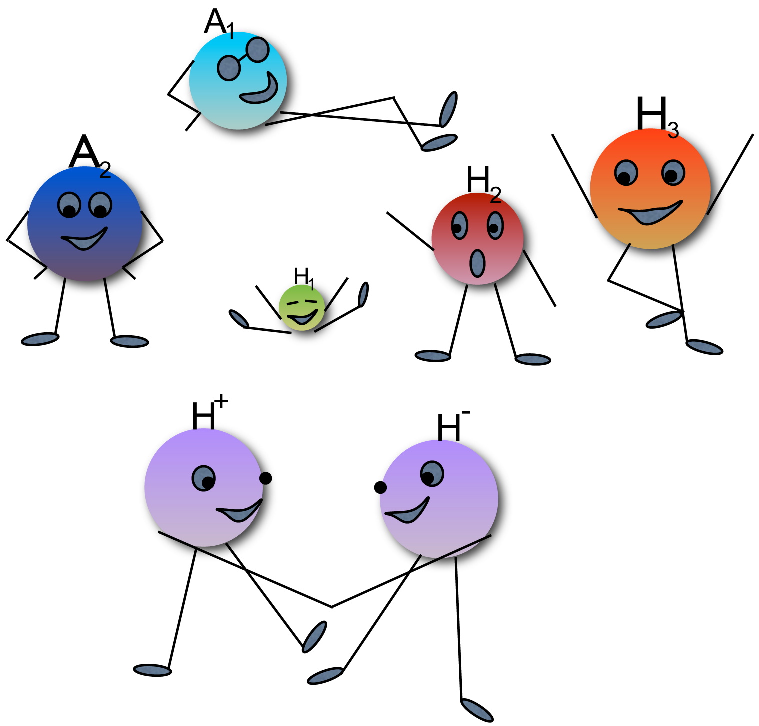
  μ generated dynamically through the VEV of scalar component of an additional chiral superfield field $\hat{S}$: $\mu = \lambda\langle S\rangle$ from: $\lambda\hat{S}\hat{H}_u\hat{H}_d$

The $\mathcal{NMSSM}$ $\mathcal{H}$iggs $\mathcal{S}$ector

- **Enlarged Higgs and neutralino sector:** 2 complex Higgs doublets $\hat{H}_u, \hat{H}_d$, 1 complex singlet $\hat{S}$

7 Higgs bosons:	$H_1, H_2, H_3, A_1, A_2, H^+, H^-$
5 neutralinos:	$\tilde{\chi}_i^0$ $(i = 1, ..., 5)$

- **Higgs mass eigenstates:**
  superpositions of doublet and singlet components $\rightsquigarrow$
  the more singlet-like
  the smaller couplings to SM particles



- **Significant changes of Higgs boson phenomenology**
  - ∗ light Higgses not excluded, Higgs-to-Higgs decays
  - ∗ degenerate Higgs bosons around 125 GeV possible
  - ∗ very light singlino-like lightest SUSY particle (LSP)
  - ∗ $\rightsquigarrow$ invisible Higgs decays
  - ∗ tree-level CP violation ...

$\mathcal{O}$ne $\mathcal{L}$oop $\mathcal{C}$orrections

- **One-Loop masses:** obtained in Feynman diagrammatic approach

  [Ender($\rightarrow$ Walz),Graf,MMM,Rzehak]

- **Renormalization scheme:**

$$\underbrace{t_{h_u}, t_{h_d}, t_{h_s}, e, M_W, M_Z, M_{H^\pm},}_{\text{on-shell}} \underbrace{\tan\beta, \lambda, \kappa, v_s, A_\kappa}_{\overline{\text{DR}}}$$

- **Complex NMSSM:** obtained in Feynman diagrammatic approach [Graf,Gröber,MMM,Rzehak,Walz]

$\mathcal{T}$he $\mathcal{H}$iggs $\mathcal{S}$ector at $\mathcal{T}$ree $\mathcal{L}$evel of the $\mathcal{C}$omplex $\mathcal{N}$MSSM

- **Two complex Higgs doublets and one complex singlet field**

$$H_d = \begin{pmatrix} \frac{1}{\sqrt{2}}(v_d + h_d + ia_d) \\ h_d^- \end{pmatrix} , \quad H_u = e^{i\varphi_u} \begin{pmatrix} h_u^+ \\ \frac{1}{\sqrt{2}}(v_u + h_u + ia_u) \end{pmatrix} , \quad S = \frac{e^{i\varphi_s}}{\sqrt{2}}(v_s + h_s + ia_s)$$

- **Superpotential:**

$$W = \hat{u} Y_u (\hat{Q}^T \epsilon \hat{H}_u) - \hat{d} Y_d (\hat{Q}^T \epsilon \hat{H}_d) - \hat{e} Y_e (\hat{L}^T \epsilon \hat{H}_d) + \lambda \hat{S} (\hat{H}_u^T \epsilon \hat{H}_d) + \frac{1}{3} \kappa \hat{S}^3$$

- **Soft SUSY breaking Lagrangian:**

$$\mathcal{L}_{\text{soft}} = -m_{H_u}^2 H_u^\dagger H_u - m_{H_d}^2 H_d^\dagger H_d - m_S^2 |S|^2 - \left(\lambda A_\lambda (H_u^T \epsilon H_d) S + \frac{1}{3} \kappa A_\kappa S^3 + h.c. \right) + ...$$

- **MSSM μ term:** generated dynamically

$$\lambda S (H_u^T \epsilon H_d) \rightarrow \frac{\lambda v_s}{\sqrt{2}} e^{i\varphi_s} (H_u^T \epsilon H_d) \equiv \mu (H_u^T \epsilon H_d)$$

$\mathcal{T}$he $\mathcal{H}$iggs $\mathcal{S}$ector at $\mathcal{T}$ree $\mathcal{L}$evel of the $\mathcal{C}$omplex $\mathcal{N}$MSSM

- **Tadpole parameters:**

$$\left.\frac{\partial V}{\partial \phi_i}\right|_{\text{min}} = t_{\phi_i} \;, \qquad\qquad \phi = (a, a_s, h_d, h_u, h_s)$$

Minimization condition requires: $t_{\phi_i} = 0$ at tree-level

- **Phase combinations** appearing in tadpoles and mass matrices at tree level

$$\begin{aligned} \varphi_x &= \varphi_{A_\lambda} + \varphi_\lambda + \varphi_s + \varphi_u \\ \varphi_y &= \varphi_\kappa - \varphi_\lambda + 2\varphi_s - \varphi_u \\ \varphi_z &= \varphi_{A_\kappa} + \varphi_\kappa + 3\varphi_s \end{aligned}$$

$t_{a_d} = 0$, $t_{a_s} = 0 \rightsquigarrow$ eliminate φ_x and $\varphi_z \rightsquigarrow$ only φ_y

$\mathcal{O}$ne $\mathcal{L}$oop $\mathcal{C}$orrections

- **One-Loop masses:** obtained in Feynman diagrammatic approach

  [Ender(→ Walz),Graf,MMM,Rzehak]

- **Renormalization scheme:**

$$\underbrace{t_{h_u}, t_{h_d}, t_{h_s}, e, M_W, M_Z, M_{H^\pm}}_{\text{on-shell}}, \underbrace{\tan\beta, \lambda, \kappa, v_s, A_\kappa}_{\overline{\text{DR}}}$$

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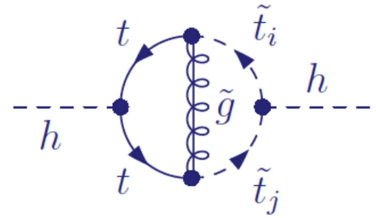
$$\underbrace{t_{h_u}, t_{h_d}, t_{h_s}, t_{a_d}, t_{a_s}, e, M_W, M_Z, M_{H^\pm}}_{\text{on-shell}}, \underbrace{\tan\beta, |\lambda|, |\kappa|, v_s, |A_\kappa|, \varphi_s, \varphi_u, \varphi_\lambda, \varphi_\kappa}_{\overline{\text{DR}}}$$

$\mathcal{T}$wo-$\mathcal{L}$oop $\mathcal{C}$orrections

- **Two-loop order $\mathcal{O}(\alpha_t\alpha_s)$:** with $\alpha_t = \frac{y_t^2}{4\pi}$ [MMM,Nhung,Rzehak,Walz]

  largest contribution $\sim m_t^2\alpha_t\alpha_s$

  NMSSM specific contributions that are proportional to λ



- **Approximations:**
  - ◇ vanishing gauge couplings:

    $e, M_W, M_Z \to 0$ but $\sin\theta_W, v = 2M_W \sin\theta_W/e$ fixed
  - ◇ In two-loop diagrams of charged Higgs self-energy: $m_b = 0$
  - ◇ vanishing external momenta in all self-energies (neutral Higgs bosons, charged Higgs bosons, gauge bosons): $p, M_{H^\pm} \to 0$

- **Renormalization** at $\mathcal{O}(\alpha_t\alpha_s)$

$$\underbrace{t_{h_d}, t_{h_u}, t_{h_s}, t_{a_d}, t_{a_s}, M_{H^\pm}^2, v}_{\text{on-shell scheme}}, \underbrace{\tan\beta, |\lambda|, v_s, |\kappa|, \mathrm{Re}A_\kappa, s_{\varphi_y}}_{\overline{\text{DR}}\text{ scheme}}$$

- **Top/Stop sector renormalization** at $\mathcal{O}(\alpha_s)$: 2 options: On-shell and $\overline{\text{DR}}$ scheme

$\mathcal{D}$ecay $\mathcal{W}$idths

- **Decay Widths:**
  - ⋆ include dominant higher order QCD corrections
  - ⋆ down-type leptons: HO SUSY-EW, down-type quarks: SUSY-QCD, bottoms: SUSY-QCD&EW
  - ⋆ off-shell decays into VV $(V = Z, W)$, V+Higgs, Higgs pair, $t\bar{t}$; $H^+ \to t\bar{b}$
  - ⋆ real NMSSM: SUSY-QCD to decays into stop, sbottom pairs

$\mathcal{S}$uperposition of $\mathcal{S}$ignal $\mathcal{R}$ates

$$R_{pp,H_i} = \frac{\sigma_{\text{incl}}^{\text{NMSSM}}}{\sigma_{\text{incl}}^{\text{SM}}} \cdot \frac{\text{BR}(H_i \to pp)^{\text{NMSSM}}}{\text{BR}(H_i \to pp)^{\text{SM}}} \qquad \text{with} \quad i = 1..5.$$

$$R_{pp,H_i}^{\text{combined}} = \sum_{k=1}^{5} R_{pp,H_k} \cdot \underbrace{\exp\left(\frac{-(M_{H_k} - M_{H_i})^2}{2\,(d_p \cdot M_{H_k})^2}\right)}_{F_p(M_{H_k})}$$

This weighting factor depends on the mass difference and on a factor d_p which is decay specific:

p	$\tau\tau$	WW	bb	ZZ	$\gamma\gamma$
d_p	0.2	0.2	0.1	0.02	0.02