HEPHY VIENNA

Institute for High Energy Physics

HFOLD a program package for calculating two-body MSSM Higgs decays at full one-loop level

Wolfgang Frisch, Helmut Eberl

Tools 2010, Winchester, UK

2nd July 2010

Outline

- HFOLD - Higgs Full One-Loop Decays
- Motivation
- The MSSM
- Higgs decays
- Details of program
- Numerics
- Outlook

Motivation

- All SUSY-QCD corrections to MSSM 1->2 Higgs decays are known, but the calculation of the full electroweak corr. has just started.
- No complete full one-loop code public available
- Total one-loop widths are necessary for 1->3 processes at one-loop level with resonant propagators

The Minimal Supersymmetric Standard Model

- The MSSM is the mininal supersymmetric extension of the Standard Model
  - minimal (=1) set of SUSY generator
  - minimal (=2) set of Higgs doublets

- The SM particles and their supersymmetric partners are located in chiral and vector multiplets

- The Superpotential is the source of the yukawa interactions

$$W_{\mathrm{MSSM}} = \overline{u}\mathbf{y_u}QH_u - \overline{d}\mathbf{y_d}QH_d - \overline{e}\mathbf{y_e}LH_d + \mu H_u H_d$$

$\mathbf{y_u}, \mathbf{y_d}, \mathbf{y_e}$ are the 3 x 3 Yukawa matrices μ can be complex

- Supersymmetry is broken in Nature, therefore one has to introduce SUSY breaking terms in the Lagrangian

$$\mathcal{L}_{soft} = -m^2_{ij}\phi^*_i\phi_j - \left(b_{ij}\phi_i\phi_j + A_{ijk}\phi_i\phi_j\phi_k + \frac{M_a}{2}\lambda_a\lambda_a + h.c.\right)$$

5 phys. Higgs bosons

Chiral supermultiplets:

Names		spin 0	spin 1/2	$SU(3)_C,\ SU(2)_L,\ U(1)_Y$
squarks, quarks	Q	$(\widetilde{u}_L\ \ \widetilde{d}_L)$	$(u_L\ \ d_L)$	$(\,\mathbf{3},\ \mathbf{2}\,,\ \frac{1}{6})$
(×3 families)	$\overline{u}$	$\widetilde{u}^*_R$	$u^\dagger_R$	$(\,\overline{\mathbf{3}},\ \mathbf{1},\ -\frac{2}{3})$
	$\overline{d}$	$\widetilde{d}^*_R$	$d^\dagger_R$	$(\,\overline{\mathbf{3}},\ \mathbf{1},\ \frac{1}{3})$
sleptons, leptons	L	$(\widetilde{\nu}\ \ \widetilde{e}_L)$	$(\nu\ \ e_L)$	$(\,\mathbf{1},\ \mathbf{2}\,,\ -\frac{1}{2})$
(×3 families)	$\overline{e}$	$\widetilde{e}^*_R$	$e^\dagger_R$	$(\,\mathbf{1},\ \mathbf{1},\ 1)$
Higgs, higgsinos	H_u	$(H^+_u\ \ H^0_u)$	$(\widetilde{H}^+_u\ \ \widetilde{H}^0_u)$	$(\,\mathbf{1},\ \mathbf{2}\,,\ +\frac{1}{2})$
	H_d	$(H^0_d\ \ H^-_d)$	$(\widetilde{H}^0_d\ \ \widetilde{H}^-_d)$	$(\,\mathbf{1},\ \mathbf{2}\,,\ -\frac{1}{2})$

4 neutralinos

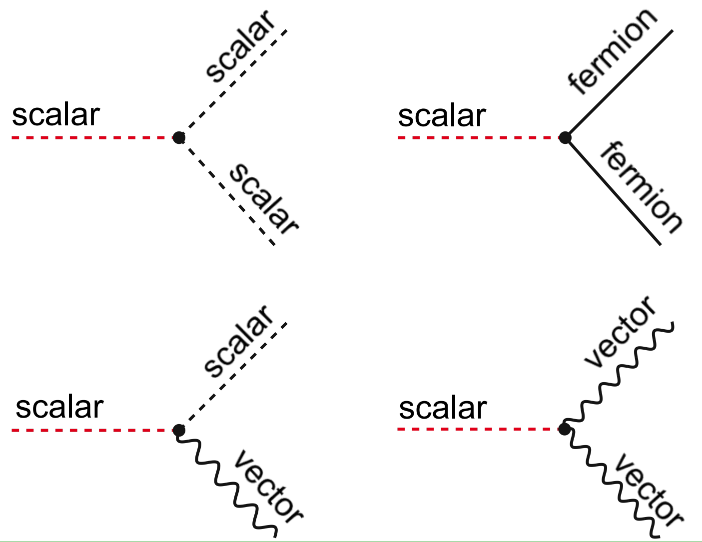
2 charginos

Vector supermultiplets:

Names	spin 1/2	spin 1	$SU(3)_C,\ SU(2)_L,\ U(1)_Y$
gluino, gluon	$\widetilde{g}$	g	$(\,\mathbf{8},\ \mathbf{1}\,,\ 0)$
winos, W bosons	$\widetilde{W}^\pm\ \ \widetilde{W}^0$	$W^\pm\ \ W^0$	$(\,\mathbf{1},\ \mathbf{3}\,,\ 0)$
bino, B boson	$\widetilde{B}^0$	B^0	$(\,\mathbf{1},\ \mathbf{1}\,,\ 0)$

Two-body Higgs decays

possible tree-level structures:



MSSM Higgs decay channels

$$\phi = h^0, H^0, A^0$$

$$\begin{array}{rcl} \phi & \rightarrow & f\,\bar{f} \\ \phi & \rightarrow & \tilde{f}_i\,\bar{\tilde{f}}_j \\ \phi & \rightarrow & \tilde{\chi}^0_k\,\tilde{\chi}^0_l \\ \phi & \rightarrow & \tilde{\chi}^+_r\,\tilde{\chi}^-_s \\ H^0 & \rightarrow & Z^0\,Z^0,\ W^+\,W^- \\ H^0 & \rightarrow & h^0\,h^0 \\ A^0 & \rightarrow & h^0\,Z^0 \\ H^+ & \rightarrow & f\,\bar{f}' \\ H^+ & \rightarrow & \tilde{f}_i\,\bar{\tilde{f}}'_j \\ H^+ & \rightarrow & \tilde{\chi}^0_k\,\tilde{\chi}^-_s \\ H^+ & \rightarrow & h^0\,W^+ \end{array}$$

Loop induced: $h^0 \rightarrow \gamma\gamma,\ gg$

Higgs sector in the MSSM

$$H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix} \qquad H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}$$

- electroweak SSB $\langle H_d^0 \rangle = v_d$ $\langle H_u^0 \rangle = v_u$
- tree-level: 2 free parameters $\tan\beta = \frac{v_u}{v_d}, m_A$
- upper bound for $m_{h^0}^{\max} \leq m_Z |\cos 2\beta|$
- one-loop corr. important for m_{h^0} leading terms $\sim \frac{m_t^4}{m_W^2}$

$$m_{h^0}^{\text{corr}} \leq 135 \text{ GeV}$$

The Higgs sector in the decoupling limit

- The decoupling is reached for large values of $M_A >> M_Z$
- The $H^0, A^0, H^\pm$ become heavy and degenerate in mass
- The light CP-even Higgs boson reaches its maximal mass value
- Higgs couplings to vector bosons and fermions can be enhanced or suppressed

Higgs couplings to gauge bosons

From the Lagrangian with the covariant derivatives

$$\mathcal{L} = (D^\mu H_u)^\dagger D_\mu H_u + (D^\mu H_d)^\dagger D_\mu H_d$$

we get the gauge boson masses

$$m_W^2 = \frac{v^2 g^2}{4}, \qquad m_{Z^0}^2 = \frac{v^2}{4}(g^2 + g'^2) = \frac{m_W^2}{\cos^2\theta_W}, \qquad \text{and} \quad v^2 = v_u^2 + v_d^2$$

and the couplings with one and two gauge bosons to the Higgs bosons, e.g.

$$g_{h^0WW} = g m_W \sin(\beta - \alpha)$$
$$g_{H^0WW} = g m_W \cos(\beta - \alpha)$$
$$g_{h^0ZZ} = \frac{g}{\cos\theta_W} m_Z \sin(\beta - \alpha)$$
$$g_{H^0ZZ} = \frac{g}{\cos\theta_W} m_Z \cos(\beta - \alpha)$$

$$\cos(\beta - \alpha) \simeq \frac{m_Z \sin 4\beta}{2m_A}$$
$$\cos(\beta - \alpha) \rightarrow 0$$
$$\sin(\beta - \alpha) \rightarrow 1$$

couplings proportional to

$\cos(\beta - \alpha)$	$\sin(\beta - \alpha)$
$H^0W^+W^-$	$h^0W^+W^-$
$H^0Z^0Z^0$	$h^0Z^0Z^0$
$Z^0A^0h^0$	$Z^0A^0H^0$
$W^\pm H^\mp h^0$	$W^\pm H^\mp H^0$
$ZW^\pm H^\mp h^0$	$ZW^\pm H^\mp H^0$
$\gamma W^\pm H^\mp h^0$	$\gamma W^\pm H^\mp G^0$

In decoupling limit: 0 1

Higgs couplings to fermions

$$-\mathcal{L} = h_t \left(\bar{t}P_L t H_u^0 - \bar{t}P_L b H_u^+\right) + h_b \left(\bar{b}P_L b H_d^0 - \bar{b}P_L t H_d^-\right) + \text{h.c.}$$

Yukawa couplings $h_b = \frac{\sqrt{2}m_b}{v_d} = \frac{\sqrt{2}m_b}{v\cos\beta}, \quad h_t = \frac{\sqrt{2}m_t}{v_u} = \frac{\sqrt{2}m_t}{v\sin\beta}$

$$h^0 b\bar{b} : -\frac{\sin\alpha}{\cos\beta} = \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha) \rightarrow 1$$

$$h^0 t\bar{t} : \frac{\cos\alpha}{\sin\beta} = \sin(\beta-\alpha) - \cot\beta\cos(\beta-\alpha) \rightarrow 1$$

$$H^0 b\bar{b} : \frac{\cos\alpha}{\cos\beta} = \cos(\beta-\alpha) + \tan\beta\cos(\beta-\alpha) \rightarrow \tan\beta$$

$$H^0 t\bar{t} : \frac{\sin\alpha}{\sin\beta} = \cos(\beta-\alpha) - \cot\beta\cos(\beta-\alpha) \rightarrow -\cot\beta$$

Decoupling limit

A^0 as H^0, but $\propto \gamma^5$

From loops we get effectively $h_b H_d^0 \bar{b}b - h_b \Delta_b \cot\beta H_u^{0*} \bar{b}b + \ldots$. The term Δ_b prop. to $\tan\beta$ can be resummed [1].

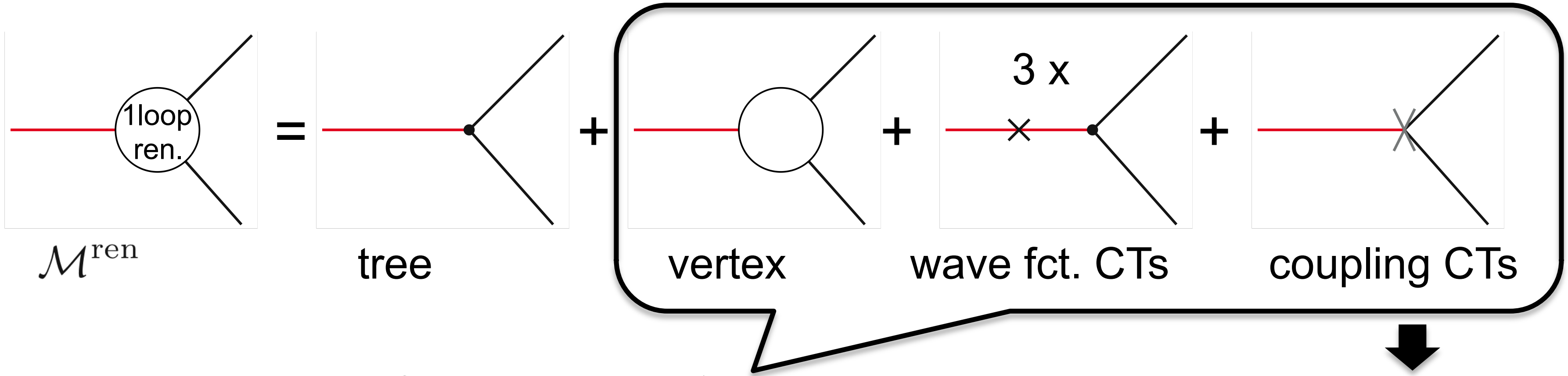
$$h_b \rightarrow \frac{h_b}{1+\Delta_b}$$

$$\Delta_b = \frac{2\alpha_s}{3\pi} m_{\tilde{g}} \mu \tan\beta I(m_{\tilde{b}_1}, m_{\tilde{b}_2}, m_{\tilde{g}}) + \frac{h_t^2}{16\pi^2} \mu A_t \tan\beta I(m_{\tilde{t}_1}, m_{\tilde{t}_2}, \mu) - \frac{g_2^2}{16\pi^2} \mu M_2 \tan\beta \left[U_{11}^{\tilde{t}} U_{11}^{\tilde{t}*} I(m_{\tilde{t}_1}, M_2, \mu) + U_{21}^{\tilde{t}} U_{21}^{\tilde{t}*} I(m_{\tilde{t}_2}, M_2, \mu)\right]$$

$$I(a,b,c) = \frac{a^2b^2\log(\frac{a^2}{b^2}) + b^2c^2\log(\frac{b^2}{c^2}) + c^2a^2\log(\frac{c^2}{a^2})}{(a^2-b^2)(b^2-c^2)(a^2-c^2)}$$

[1] M. Carena et al, 1999, 2000

Renormalization



$$\mathcal{M}^{\rm ren} = \mathcal{M}^0 + \mathcal{M}^1$$

only UV div. parts
technical trick

automatic check of
RGE invariance

DRbar scheme: UV divergence Δ = 0

(note: tree-level couplings given at scale Q)

$$\Gamma^2 = \text{kinematics} \times \left(|\mathcal{M}^0|^2 + 2\text{Re}(\mathcal{M}^{0\dagger}\mathcal{M}^1) + \mathcal{O}(2\text{loop}) \right)$$

always on-shell masses

Public available programs

- HDecay, hep-ph/9704448 by Djouadi, Kalinowski, Spira
  - RGE improvements via running masses
  - Off-shell decays
- FeynHiggs 2.7 by Heinemeyer, Hollik, Weiglein, Hahn, MSSM Higgs mass calculator
  - Higgs decays into fermions are calculated at full one-loop level, flavor violating case
- SPheno, hep-ph/0301101 by Porod, MSSM spectrum calculator
  - Higgs decays into pairs of quarks have RGE improvements
- ISAJET,.....

Status of our calculations

- flavor conserving MSSM for real input parameters
- all necessary amplitudes are calculated using FeynArts 3.2/FormCalc 5.3
- SUSY spectrum is calculated using SPHENO
- the renormalization is done in the DRbar-scheme following the SPA convention
- own written counter term file for the relevant terms of the MSSM
- automatic generation of fortran code of each channel
- general R_ξ gauge implementation for W,Z-boson
- hard Bremsstrahlung included with generic formulas
- “naïve” h_b = Yuk(4,3) resummation included
- easy usable Mathematica link
- In- and output in Les Houches Format

SUSY Parameter Analysis project*

http//spa.desy.de/spa

- For the LHC and even more for the ILC, MSSM observables will be measured with high accuracy
- Calculations including higher-orders are necessary, to get information on fundamental SUSY parameters and SUSY-breaking mechanism
- A well-defined theoretical framework is needed when higher-order corrections are included.
- The aim of the SPA convention is to provide such a theoretical framework
- SPA convention provides a clear base for calculating masses, couplings, mixing angles, decay widths and production cross sections.
- Program repository on the web:

  LHC+ILC tools, Les Houches Accord
- Reference point SPS1a'

* J. A. Aguillar-Saavedra et al., EPJ C46 (2006) 43; see also J. Kalinowski, Acta Phys. Polon. B37 (2006), 1215

SPA convention

- Masses of SUSY particles and Higgs bosons defined as pole masses
- All SUSY Lagrangian parameters are in the DRbar scheme at Q = 1TeV
- All elements in mass matrices, rotation matrices and corresponding mixing angles are def. DRbar at Q , except (h^0 –H^0) mixing angle is defined on-shell with p = m_{h0}
- SM input parameters: $G_{\mathrm{Fermi}}, \alpha, M_Z, \alpha_s(M_Z)$ and fermion masses
- Decay widths/branching ratios and production cross section are calculated for the set of parameters specified above

Linear R_ξ gauge

The gauge fixing Lagrangian is

$$\mathcal{L}^{GF} = -\frac{1}{\xi_W} F^+ F^- \frac{1}{\xi_A} |F^A|^2 , \quad \text{with} \quad A = Z, \gamma, g \, ,$$

with $F^+ = \partial_\mu W^{\mu +} + i\xi_W m_W G^+$, $F^Z = \partial_\mu Z^\mu + \xi_Z m_Z G^0, F^\gamma = \gamma_\mu A^\mu$, and $F^g = \gamma_\mu G^{a\mu}$.

The Higgs-ghost propagators are $i/(q^2 - \xi_V m_V^2)$ and the vector-boson propagator in the R_ξ gauge reads

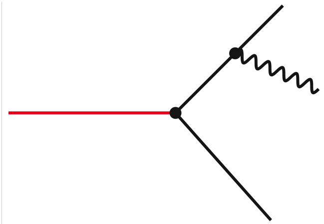
$$D_V^{\mu\nu} = \frac{-i \left(g^{\mu\nu} - (1-\xi_V) \frac{q^\mu q^\nu}{q^2 - \xi m_V^2} \right)}{q^2 - m_V^2}$$

and can be split in a form with single propagators, $L_x f[x] = \frac{f[x] - f[x\xi]}{x}$,

$$D_V^{\mu\nu}|_\xi = \frac{-i\, g^{\mu\nu}}{q^2 - m_V^2} + \frac{i}{m_V^2} \left(\frac{q^\mu q^\nu}{(q^2 - m_V^2)} - \frac{q^\mu q^\nu}{(q^2 - \xi m_V^2)} \right) = D_V^{\mu\nu}|_{\xi=1} + L_{m_V^2} \frac{i\, q^\mu q^\nu}{(q^2 - m_V^2)}$$

This second form we used in order to check gauge independence using the automatic tools FA and FC for W and Z. For the massless particles γ and Gluon we performed analytic proofs of gauge invariance.

Bremsstrahlung

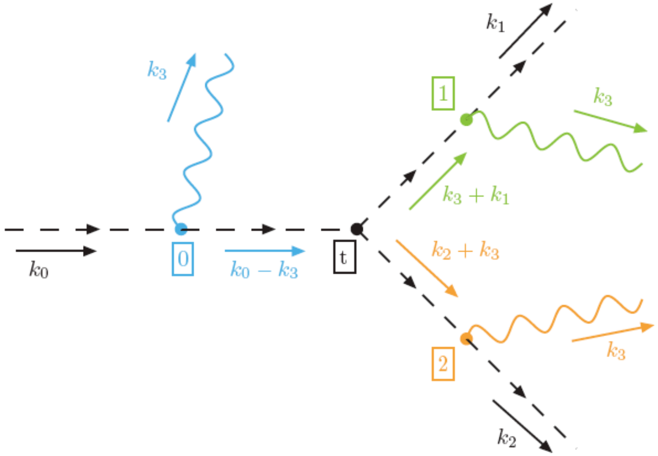


In order to cancel the IR divergencies we have included real photon/gluon radiation:

- soft radiation – dependent on cut ΔE, automatized in FormCalc
- hard radiation – analytic results for integrals used from [1]
  four generic structures analytically derived and used

$$\Gamma^{\text{total}} = \Gamma(\phi \to p_1 p_2) + \Gamma(\phi \to p_1 p_2\, \gamma/g)$$

The simplest case is scalar -> scalar scalar γ/g:



$$\int \overline{|\mathcal{M}|^2} \quad \to \quad 4|g_t|^2 \times$$

$$\Big[- g_0^2 m_0^2 I_{00} - g_0 g_1 (m_0^2 + m_1^2 - m_2^2) I_{10}$$
$$- g_1^2 m1^2 I_{11} - g_0 g_2 (m_0^2 - m_1^2 + m_2^2) I_{20}$$
$$- g_1 g_2 (m_0^2 - m_1^2 - m_2^2) I_{21} - g_2^2 m_2^2 I_{22}$$
$$- g_0 (g_1 + g_2) I_0 - g_1 (g_0 - g_2) I_1 - g_2 (g_0 - g_1) I_2 \Big]$$

The integrals I_{ij} depend on $\log \lambda$, λ is the auxiliary mass for γ/g.

[1] A. Denner, Fortschr. Phys. 41 (1993) 307

All numerical results preliminary

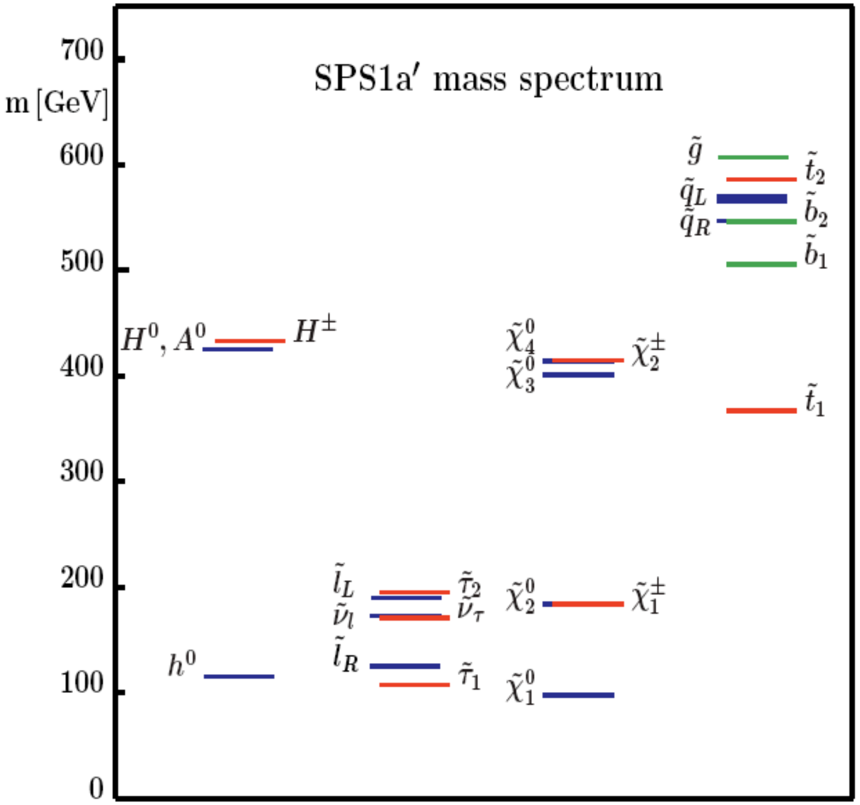
Reference point SPS1a'

$$\text{mSUGRA point: } M_{1/2} = 250 \text{ GeV}, \ M_0 = 70 \text{ GeV}, \ A_0 = -300 \text{ GeV},$$
$$\tan\beta = 10, \ \text{sign}\mu = +1$$

Note, the point SPS1a' is close to the original Snowmass point SPS1a (has $M_0 = 100$ GeV, $A_0 = -100$ GeV).

Parameter	SPS1a′ value	Parameter	SPS1a′ value
g'	0.3636	M_1	103.3
g	0.6479	M_2	193.2
g_s	1.0844	M_3	571.7
Y_τ	0.1034	A_τ	−445.2
Y_t	0.8678	A_t	−565.1
Y_b	0.1354	A_b	−943.4
μ	396.0	$\tan\beta$	10.0
M_{H_d}	159.8	$\lvert M_{H_u}\rvert$	378.3
M_{L_1}	181.0	M_{L_3}	179.3
M_{E_1}	115.7	M_{E_3}	110.0
M_{Q_1}	525.8	M_{Q_3}	471.4
M_{U_1}	507.2	M_{U_3}	387.5
M_{D_1}	505.0	M_{D_3}	500.9

DRbar parameter at Q = 1 TeV



MSSM Higgs decays at SPS1a'

H^0	FH 2.65	HDECAY	tree*	sqcd*	full*	sqcd/full
$t\bar{t}$	0.040132	0.046685	0.025642	0.034871	0.031492	0.903116
$b\bar{b}$	0.638195	0.660744	0.504388	0.626518	0.620139	0.989818

H^0	FH 2.65	HDECAY	tree*	full*	tree/full
$\tau\bar{\tau}$	0.087343	0.088975	0.084946	0.086736	1.021073
$\tilde{\chi}_1^+\tilde{\chi}_1^-$	0.044219	0.030739	0.014502	0.017172	1.184131
$\tilde{\chi}_1^0\tilde{\chi}_1^0$	0.013708	0.014807	0.013897	0.013299	0.956968
$\tilde{\chi}_2^0\tilde{\chi}_1^0$	0.044657	0.042718	0.037066	0.037994	1.025028
$\tilde{\chi}_2^0\tilde{\chi}_2^0$	0.017010	0.011779	0.005485	0.006589	1.201235
$\tilde{\tau}_1\tilde{\tau}_1$	0.010339	0.010663	0.011072	0.012911	1.166045
$\tilde{\tau}_1\tilde{\tau}_2$	0.010847	0.010228	0.010027	0.012683	1.264867
h^0h^0	0.011322	0.009004	0.009592	0.011366	1.184922
Z^0Z^0	0.000102	0.001834	0.000834	0.000722	0.865899
W^+W^-	0.000217	0.003773	0.001716	0.002035	1.185894

* The On-shell Higgs masses calculated using FH 2.65

MSSM Higgs decays at SPS1a'

A^0	FH 2.65	HDECAY	tree*	sqcd*	full*	sqcd/full
$t\bar{t}$	0.129248	0.130480	0.091412	0.116383	0.102741	0.882784
$b\bar{b}$	0.6347855	0.661894	0.505094	0.627339	0.622234	0.991862

A^0	FH 2.65	HDECAY	tree*	full*	tree/full
$\tau\bar{\tau}$	0.086827	0.089097	0.085032	0.087083	1.024118
$\tilde{\chi}_1^+\tilde{\chi}_1^-$	0.248475	0.208640	0.157644	0.188297	1.194444
$\tilde{\chi}_1^0\tilde{\chi}_1^0$	0.020982	0.022525	0.013897	0.013299	0.956968
$\tilde{\chi}_2^0\tilde{\chi}_1^0$	0.099111	0.096063	0.088606	0.090732	1.023992
$\tilde{\chi}_2^0\tilde{\chi}_2^0$	0.098491	0.082084	0.005485	0.006589	1.201235

* The On-shell Higgs masses calculated using FH 2.65

MSSM Higgs decays at SPS1a’

H^+	FH 2.65	HDECAY	tree*	sqcd*	full*	sqcd/full
$t\bar{b}$	0.592691	0.519319	0.468341	0.58647	0.531737	0.906674

H^+	FH 2.65	HDECAY	tree*	full*	tree/full
$\tau\nu_\tau$	0.088582	0.090915	0.086906	0.076974	0.885723
$\tilde{\chi}_1^+\tilde{\chi}_1^0$	0.129379	0.127584	0.116956	0.113783	0.972870
$\tilde{\chi}_1^+\tilde{\chi}_2^0$	0.000874	0.000797	0.000587	0.000522	0.890147
$\tilde{\nu}_\mu\tilde{\mu}_1$	0.036808	0.036546	0.036777	0.04274	1.162136
$\tilde{\nu}_\mu\tilde{\mu}_1$	0.000165	0.000271	0.000211	0.000356	1.682552
h^0W^+	0.001776	0.002035	0.001667	0.001719	1.031060

* The On-shell Higgs masses calculated using FH 2.65

HFOLD

Program description:

The program code is written in Fortran 77

•At the program start the input file **hfold.in** is read with the following options:

- name of Les Houches input file
- selection of higgs particle: h^0 = 1, H^0 = 2, A^0 = 3 ,H^+ = 4, All = 5
- contribution: tree = 0, full one loop = 1, SQCD = 2
- bremsstrahlung: off = 0, hard bremsstrahlung = 1, soft bremsstrahlung = 2
- Higgs masses calculator: tree level masses = 0, approximation= 1, FeynHiggs masses = 2
- Name of output file

Outlook

- Bottom Yukawa coupling resummation to improve, see [1]
- Decay with vanishing tree-level, use of $(\text{one-loop})^2$, see e.g. [2]
- Extension to complex MSSM
- h^0 loop decays – two-loop improvements?
- leading (strong) two-loop contributions?
- developed technique applicable for any 1 to 2 and 2 to 2 processes

First version of the program will be on the web soon!

[1] L. Hofer, U. Nierste, D. Scherer, 2009, [2] S. Bejar, talk at HEPTOOLS meeting, Lisbon 2009

Thank you for your attention!