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

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Outline

HFOLD - Higgs Full One-Loop Decays

Motivation

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

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Brief introduction in the MSSM

- Supersymmetry relates bosons and fermions
- MSSM solves the hierarchy problem
- The MSSM is the minimal supersymmetric extension of the SM
  - Minimal (=1) set of Susy generators $Q, \overline{Q}$
  - Minimal (=2) number of Higgs doublets H_1, H_2
- MSSM requires many new parameters:
  m_A, $tan\beta$, μ, M_1, M_2, M_3, A_l, A_u, A_d, M_E, M_L, M_D, M_Q, M_U
  - MSUGRA:m_0, $m_{1/2}$, A_0, $tan\beta$, $sign(\mu)$

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The MSSM particle spectrum

Neutral Photino, Zino, Higgsinos

$$\tilde{\gamma}, \tilde{Z}^0, \tilde{H}_1^0, \tilde{H}_2^0$$

Charged Higgsinos and gauginos

$$\tilde{H}_1^-, \tilde{H}_2^+, \tilde{W}^+, \tilde{W}^-$$

2 Higgs doublets

$$H_1 = (H_1^0, H_1^-),\ H_2 = (H_2^+, H_2^0)$$

Neutralinos

$$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$$

Charginos

$$\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$$

5 physical Higgs particles

$$h^0, H^0, A^0, H^\pm$$

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The Higgs sector in the MSSM

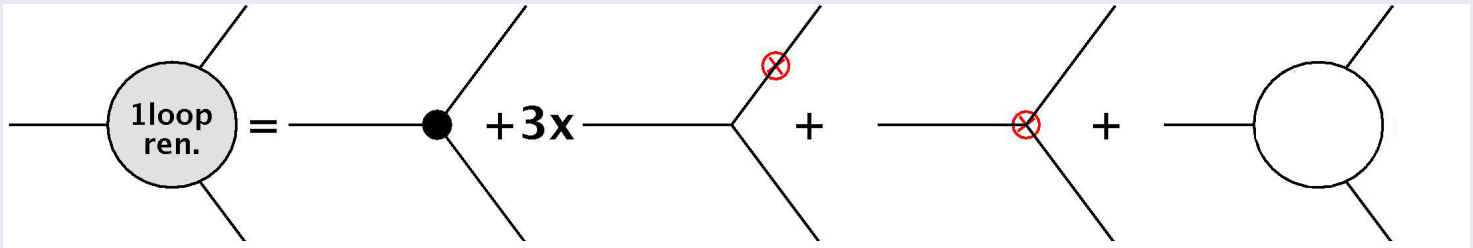
- $H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}$, $H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}$
- SSB : $< H_u >= v_u$, $< H_d >= v_d$
- tree-level: 2 free parameters $\tan\beta = \frac{v_u}{v_d}$, m_A
- upper bound for $m_{h^0}^{\max} \leq m_Z |\cos 2\beta|$
- one-loop corr. important for m_{h^0} leading terms $\sim \frac{m_t^4}{m_W^2}$
  $m_{h^0}^{\max} \leq 135$ GeV

Parameter regimes in the MSSM Higgs sector

- Decoupling-Regime $M_A \gg M_Z$
  - h^0 approaches its maximal mass
  - $M_H \simeq M_A \simeq M_{H^\pm}$ become very heavy and degenerate in mass
  - H^0 decouples from gauge bosons $g_{HVV} \to 0$
  - h^0 coupling to gauge bosons becomes SM-like $g_{hVV} \to 1 = g_{H_{SM}VV}$
  - h^0 coupling to up, down-type fermions becomes SM-like $g_{huu}, g_{hdd} \to 1$
  - H^0 coupling to up, down-type fermions becomes suppresed/enhanced by $tan\beta$,$g_{Huu} \propto -cot\beta$, $g_{Hdd} \propto tan\beta$
  - decoupling regime occurs more quickly if $tan\beta$ is large

Renormalization

Renormalization - Shifts in masses, couplings and fields



$$\mathscr{M}^{1L} = \mathscr{M}^{tree} + \mathscr{M}^{WFR} + \mathscr{M}^{CT} + \mathscr{M}^{vertex}$$

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- Technical trick - transition to the $\overline{DR}$ scheme

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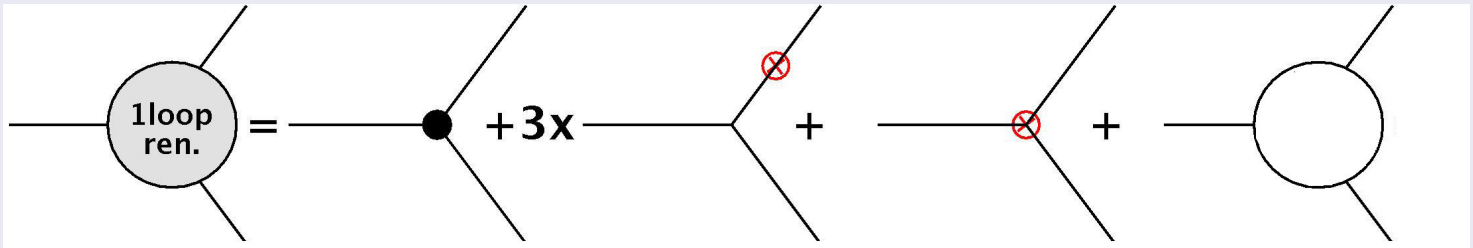

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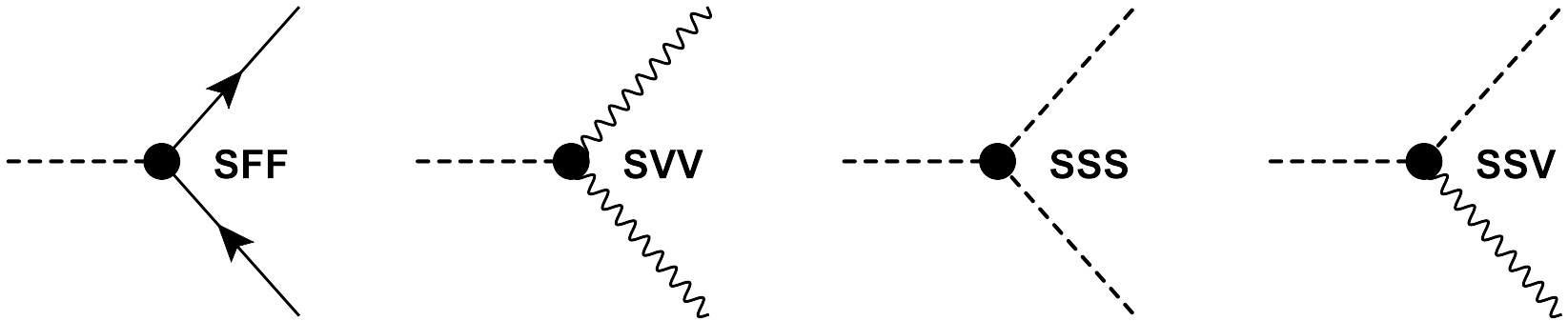
Renormalized processes

Generic Higgs couplings



h^0	H^0	A^0	H^+
$u_i\bar{u}_i, d_i\bar{d}_i, e_i\bar{e}_i$	$u_i\bar{u}_i, d_i\bar{d}_i, e_i\bar{e}_i$	$u_i\bar{u}_i, d_i\bar{d}_i, e_i\bar{e}_i$	$u_i\bar{d}_i, \bar{e}_i\nu_e$
X	$h^i h^i, Z^0Z^0, W^+W^-$	h^0Z^0, H^0Z^0	h^i, W^+
$\tilde{u}_i\bar{\tilde{u}}_j, \tilde{d}_i\bar{\tilde{d}}_j, \tilde{e}_i\bar{\tilde{e}}_j$	$\tilde{u}_i\bar{\tilde{u}}_j, \tilde{d}_i\bar{\tilde{d}}_j, \tilde{e}_i\bar{\tilde{e}}_j$	$\tilde{u}_i\bar{\tilde{u}}_j, \tilde{d}_i\bar{\tilde{d}}_j, \tilde{e}_i\bar{\tilde{e}}_j$	$\tilde{u}_i\bar{\tilde{d}}_j, \bar{\tilde{e}}_i\tilde{\nu}_e$
$\tilde{\chi}_i^0\tilde{\chi}_j^0, \tilde{\chi}_i^+\tilde{\chi}_j^-$	$\tilde{\chi}_i^0\tilde{\chi}_j^0, \tilde{\chi}_i^+\tilde{\chi}_j^-$	$\tilde{\chi}_i^0\tilde{\chi}_j^0, \tilde{\chi}_i^+\tilde{\chi}_j^-$	$\tilde{\chi}_i^0\tilde{\chi}_j^+$

Public available packages that calculate MSSM Higgs decays

- HDECAY, *hep-ph/9704448* by Djouadi, Kalinowski, Spira , RGE improvement
- FeynHiggs 2.7 by Heinemeyer, Hollik, Weiglein, Hahn, MSSM Higgs mass calculator (Higgs decays into fermions are calc. at full one-loop level, flavor viloating case)
- SPHENO, *hep-ph/0301101v4,* MSSM spectrum calculator, MSSM Higgs decay widths at tree-level, Higgs-quark-quark decays RGE improvement

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- 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 $\overline{DR}$-scheme following the SPA convention
- hard Bremsstrahlung included with generic formulas
- general R_ξ-gauge included for the W and Z boson
- "naïve" hb = Yuk(4,3) resummation included
- easy usable Mathematica link In- and output in Les Houches Format

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The SPA convention

- 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.

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- All elements in mass matrices, rotation matrices and corresponding mixing angles are def. $\overline{DR}$-scheme at Q , except (h^0 -H^0) - mixing angle is defined on-shell with $p = m_{h^0}$
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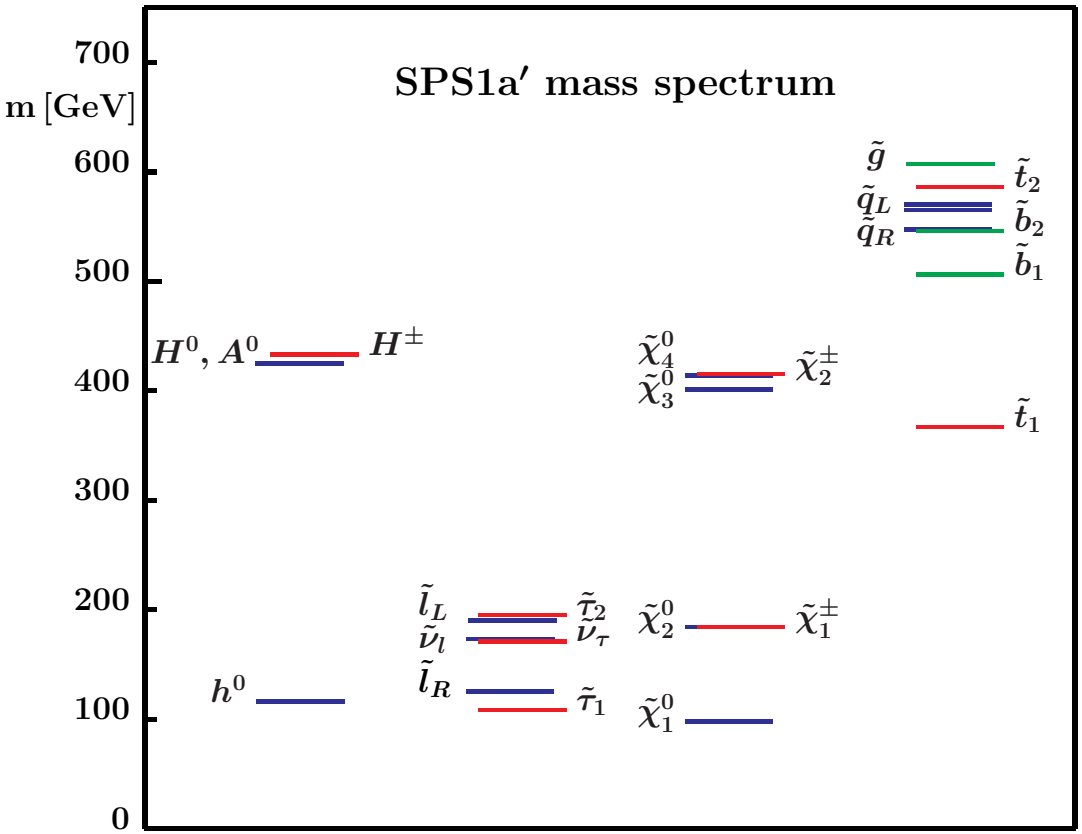
Reference point SPS1a'

- SPS1a' : m_0=70, $m_{1/2}$=250, $tan\beta$=10, $sign(\mu)$=+1, A_0=−300



Partial and total decay widths of H^0 at SPS1a'

Decays into quarks

H^0	BRtree	BRfull	HF-tree	HF-sqcd	HF-full	1-sqcd/full	FH27	HD	SP
$b\bar{b}$	0.5546	0.6157	0.4652	0.6262	0.6216	-.0073	0.6062	0.6293	0.5310
$t\bar{t}$	0.0549	0.0620	0.0460	0.0631	0.0564	-.1188	0.0561	0.0765	0.0716

EW decay modes

H^0	BRtree	BRfull	HF-tree	HF-full	1-tree/full	FH27	HD	SP
$\tau\bar{\tau}$	0.1058	0.0872	0.0887	0.0914	0.0288	0.0978	0.0871	0.0888
$\tilde{\chi}_1^0\tilde{\chi}_1^0$	0.0172	0.0142	0.0144	0.0140	-.0297	0.0121	0.0136	0.0145
$\tilde{\chi}_1^0\tilde{\chi}_2^0$	0.0539	0.0445	0.0452	0.0465	0.0273	0.0426	0.0438	0.0449
$\tilde{\chi}_2^0\tilde{\chi}_2^0$	0.0205	0.0169	0.0172	0.0206	0.1684	0.0208	0.0175	0.0171
$\tilde{\chi}_1^+\tilde{\chi}_1^-$	0.0515	0.0425	0.0432	0.0527	0.1808	0.0521	0.0454	0.0447
$\tilde{\tau}_1\tilde{\tau}_1$	0.0212	0.0174	0.0177	0.0184	0.0370	0.0182	0.0091	0.0177
$\tilde{\tau}_1\tilde{\tau}_2$	0.0206	0.0170	0.0173	0.0191	0.0932	0.0183	0.0265	0.0174
$\tilde{\tau}_2\tilde{\tau}_2$	0.0044	0.0037	0.0037	0.0035	-.0641	0.0044	0.0013	0.0038
h^0h^0	0.0110	0.0091	0.0092	0.0091	-.0168	0.0094	0.0086	0.0088

Total widths

$\Gamma^{tree}_{H^0}$	$\Gamma^{sqcd}_{H^0}$	$\Gamma^{full}_{H^0}$	$\Gamma^{FH}_{H^0}$	$\Gamma^{HD}_{H^0}$	$\Gamma^{SP}_{H^0}$
0.8389	1.0171	1.0274	0.9597	0.9950	0.8890

Partial and total decay widths of A^0 at SPS1a'

Decays into quarks

A^0	BRtree	BRfull	HF-tree	HF-sqcd	HF-full	1-sqcd/full	FH27	HD	SP
$b\bar{b}$	0.3741	0.4361	0.4665	0.6282	0.6250	-.0052	0.6087	0.6264	0.5319
$t\bar{t}$	0.0862	0.0965	0.1074	0.1389	0.1289	-.0780	0.1805	0.1664	0.1573

EW decay modes

A^0	BRtree	BRfull	HF-tree	HF-full	1-tree/full	FH27	HD	SP
$\tau\bar{\tau}$	0.0713	0.0617	0.0889	0.0919	0.0321	0.0980	0.0872	0.0889
$\tilde{\chi}_1^0\tilde{\chi}_1^0$	0.0170	0.0147	0.0212	0.0205	-.0303	0.0181	0.0201	0.0214
$\tilde{\chi}_1^0\tilde{\chi}_2^0$	0.0755	0.0654	0.0942	0.0972	0.0308	0.0890	0.0920	0.0945
$\tilde{\chi}_2^0\tilde{\chi}_2^0$	0.0729	0.0631	0.0909	0.1166	0.2203	0.0975	0.0922	0.0904
$\tilde{\chi}_1^+\tilde{\chi}_1^-$	0.1800	0.1558	0.2245	0.2862	0.2156	0.2395	0.0000	0.0000
$\tilde{\tau}_1\tilde{\tau}_2$	0.0225	0.0195	0.0280	0.0297	0.0551	0.0292	0.0275	0.0280
h^0Z	0.0020	0.0018	0.0025	0.0016	-.5671	0.0010	0.0016	0.0016

Total widths

$\Gamma^{tree}_{A^0}$	$\Gamma^{sqcd}_{A^0}$	$\Gamma^{full}_{A^0}$	$\Gamma^{FH}_{A^0}$	$\Gamma^{HDecay}_{A^0}$	$\Gamma^{SPheno}_{A^0}$
1.2471	1.4405	1.5256	1.3920	1.3783	1.2752

Partial and total decay widths of H^+ at SPS1a'

Decays into quarks

H^+	BRtree	BRfull	HF-tree	HF-sqcd	HF-full	1-sqcd/full	FH27	HD	SP
$t\bar{b}$	0.6171	0.6813	0.4649	0.6170	0.5685	-.0854	0.5321	0.6585	0.4649

EW decay modes

H^+	BRtree	BRfull	HF-tree	HF-full	1-tree/full	FH27	HD	SP
$\tau\nu_\tau$	0.1203	0.1001	0.0906	0.0804	-.1278	0.0922	0.0889	0.0906
$\tilde{\chi}_1^+\tilde{\chi}_1^0$	0.1712	0.1424	0.1290	0.1253	-.0292	0.1194	0.1262	0.1305
$\tilde{\nu}_\tau\tilde{\tau}_1$	0.0809	0.0673	0.0610	0.0611	0.0026	0.0630	0.0597	0.0609

Total widths

$\Gamma^{tree}_{H^+}$	$\Gamma^{sqcd}_{H^+}$	$\Gamma^{full}_{H^+}$	$\Gamma^{FH}_{H^+}$	$\Gamma^{HDecay}_{H^+}$	$\Gamma^{SPheno}_{H^+}$
0.7534	0.9057	0.8414	0.8132	0.9416	0.7542

Conclusion and outlook

- Package is working and will be ready for download soon at http://wwwhephy.oeaw.ac.at/tools/
- Study NUHM scenarios, where decays into squarks are possible and loop corrections are important
- Bottom Yukawa coupling resummation to improve Hofer, Nierste, Scherer hep-ph/0907.5408
- Extension to the complex MSSM
- Start calculating $2 \longrightarrow 3$ and $1 \longrightarrow 3$ processes at one loop with resonant progators
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Thank you for your attention