Higgs Decays in the Complex MSSM

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The complex Minimal Supersymmetric Standard Model

In its general form, the MSSM includes complex parameters such as

- the trilinear coupling A
- the gluino mass parameter M_3
- the higgsino mass parameter μ

The parameters are often taken to be real for simplicity. However, when the complex phases are included, it leads to some interesting phenomenology

- a new source of CP violation to explain the matter-antimatter asymmetry in the universe
- the possibility of a low mass for the lightest Higgs without conflicting with LEP results

Analysis of LEP results by LEP Higgs Working Group

Two different programs were used to calculate the cMSSM Higgs sector - *FeynHiggs* and *CPH*. A point in the parameter space was said to be excluded only if the analysis with *both* programs found it excluded.

	CPX	*CPX inspired*
$\tan\beta$	0.6–40	0.6–17
$m_{H^+}(\mathrm{GeV}/c^2)$	4–1000	110–190
M_{SUSY} (GeV)	500	500
$\mu(\mathrm{GeV})$	2000	2000
$M_2(\mathrm{GeV})$	200	200
$\mathrm{Abs}(A)(\mathrm{GeV})$	1000($\overline{\mathrm{MS}}$)	1000(on-shell)
$\mathrm{Arg}(A)$	90°	90°
$\mathrm{Abs}(M_3)(\mathrm{GeV}/c^2)$	1000	1000
$\mathrm{Arg}(M_3)$	90°	0°
$m_t(\mathrm{GeV})$	174.3	170.9

The LEP Higgs Working Group analysis found a domain in the *CPX* scenario at $30\ \mathrm{GeV}/c^2 < m_{h_1} < 55\ \mathrm{GeV}/c^2$ which was not excluded at the 95% CL. In this region, the $h_2 \to h_1 + h_1$ branching ratio dominates. However, *FeynHiggs* does not currently have a reliable calculation for the decay width, $\Gamma(h_2 \to h_1 + h_1)$, so $\Gamma(h_2 \to h_1 + h_1)$ from *CPH* was used in both analyses.

Unless otherwise stated, *CPX inspired* parameters are used in this presentation.

The neutral Higgs masses in the complex MSSM

First, find the poles of the 3×3 propagator matrix $\mathbf{\Delta}(p^2)$, which is equivalent to solving $\left|p^2 \mathbb{1} - \mathbf{M}(p^2)\right| = 0$ where

$$\mathbf{M}(p^2) \quad = \begin{pmatrix} m_h^2 - \hat{\Sigma}_{hh}(p^2) & -\hat{\Sigma}_{hH}(p^2) & -\hat{\Sigma}_{hA}(p^2) \\ -\hat{\Sigma}_{hH}(p^2) & m_H^2 - \hat{\Sigma}_{HH}(p^2) & -\hat{\Sigma}_{HA}(p^2) \\ -\hat{\Sigma}_{hA}(p^2) & -\hat{\Sigma}_{HA}(p^2) & m_A^2 - \hat{\Sigma}_{AA}(p^2) \end{pmatrix}$$

In general, the three solutions $\mathcal{M}^2_{h_a}$ are complex. The physical masses, $M^2_{h_a} = \mathrm{Re}\mathcal{M}^2_{h_a}$ and labelled by $M_{h_1} \leq M_{h_2} \leq M_{h_3}$
$\hat{\Sigma}_{jk}(p^2)$ were calculated using an expansion about $\mathrm{Re}p^2$.

$$\hat{\Sigma}_{jk}(p^2) \quad = \quad \hat{\Sigma}_{jk}(\mathrm{Re}p^2) + i\left(\mathrm{Im}p^2\right)\hat{\Sigma}'_{jk}(\mathrm{Re}p^2) + \mathcal{O}\left(\mathrm{Im}p^2\right)^2$$

The program *FeynHiggs* was used for $\hat{\Sigma}_{jk}(\mathrm{Re}p^2)$ and $\hat{\Sigma}'_{jk}(\mathrm{Re}p^2)$. In practice, the eigenvalues of a momentum independent appoximation to $\mathbf{M}(p^2)$ was used as a starting point for iteration.

External Higgs Bosons

Diagrams with external Higgs bosons need finite wave function renormalisation factors, contained in the 3×3 matrix $\hat{\mathbf{Z}}$.

$$\begin{aligned}
\lim_{p^2 \to \mathcal{M}^2_{h_1}} -\frac{i}{p^2 - \mathcal{M}^2_{h_1}} \left(\hat{\mathbf{Z}} \cdot \hat{\mathbf{\Gamma}}_2 \cdot \hat{\mathbf{Z}}^T \right)_{hh} &= 1 \\
\lim_{p^2 \to \mathcal{M}^2_{h_2}} -\frac{i}{p^2 - \mathcal{M}^2_{h_2}} \left(\hat{\mathbf{Z}} \cdot \hat{\mathbf{\Gamma}}_2 \cdot \hat{\mathbf{Z}}^T \right)_{HH} &= 1 \\
\lim_{p^2 \to \mathcal{M}^2_{h_3}} -\frac{i}{p^2 - \mathcal{M}^2_{h_3}} \left(\hat{\mathbf{Z}} \cdot \hat{\mathbf{\Gamma}}_2 \cdot \hat{\mathbf{Z}}^T \right)_{AA} &= 1
\end{aligned}$$

with

$$\hat{\mathbf{Z}} = \begin{pmatrix} \sqrt{Z_h} & \sqrt{Z_h} Z_{hH} & \sqrt{Z_h} Z_{hA} \\ \sqrt{Z_H} Z_{Hh} & \sqrt{Z_H} & \sqrt{Z_H} Z_{HA} \\ \sqrt{Z_A} Z_{Ah} & \sqrt{Z_A} Z_{AH} & \sqrt{Z_A} \end{pmatrix}$$

$-\hat{\mathbf{\Gamma}}_2(p^2)$ is the inverse of the propagator matrix $\mathbf{\Delta}(p^2)$.

External Higgs Bosons

The components of $\hat{\mathbf{Z}}$ are found using,

$$Z_h^{-1} = \frac{\partial}{\partial p^2}\left(\frac{i}{\Delta_{hh}(p^2)}\right)\Bigg|_{p^2=\mathcal{M}^2_{h_1}}$$

$$Z_H^{-1} = \frac{\partial}{\partial p^2}\left(\frac{i}{\Delta_{HH}(p^2)}\right)\Bigg|_{p^2=\mathcal{M}^2_{h_2}}$$

$$Z_A^{-1} = \frac{\partial}{\partial p^2}\left(\frac{i}{\Delta_{AA}(p^2)}\right)\Bigg|_{p^2=\mathcal{M}^2_{h_3}}$$

note

$$\Delta_{ii}(p^2) = \frac{i}{p^2 - m_i^2 + \hat{\Sigma}^{\text{eff}}_{ii}(p^2)}$$

$$Z_{hH} = \frac{\Delta_{hH}}{\Delta_{hh}}\Bigg|_{p^2=\mathcal{M}^2_{h_1}} \qquad Z_{Hh} = \frac{\Delta_{hH}}{\Delta_{HH}}\Bigg|_{p^2=\mathcal{M}^2_{h_2}} \qquad Z_{Ah} = \frac{\Delta_{hA}}{\Delta_{AA}}\Bigg|_{p^2=\mathcal{M}^2_{h_3}}$$

$$Z_{hA} = \frac{\Delta_{hA}}{\Delta_{hh}}\Bigg|_{p^2=\mathcal{M}^2_{h_1}} \qquad Z_{HA} = \frac{\Delta_{HA}}{\Delta_{HH}}\Bigg|_{p^2=\mathcal{M}^2_{h_2}} \qquad Z_{AH} = \frac{\Delta_{HA}}{\Delta_{AA}}\Bigg|_{p^2=\mathcal{M}^2_{h_3}}$$

where Δ_{ij} are components of the 3×3 propagator matrix $\mathbf{\Delta}(p^2)$.

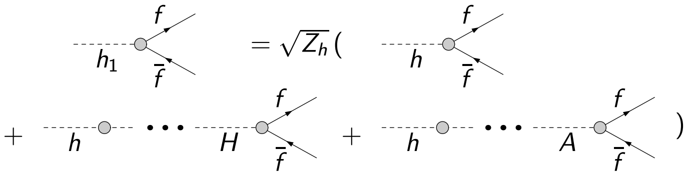
External Higgs Bosons

For a vertex function involving 1,2,3 external Higgs $\hat{\Gamma}_{h_a}, \hat{\Gamma}_{h_a h_b}, \hat{\Gamma}_{h_a h_b h_c}$ respectively,

$$\begin{aligned} \hat{\Gamma}_{h_a} &= \hat{\mathbf{Z}}_{ai} \hat{\Gamma}_i \\ \hat{\Gamma}_{h_a h_b} &= \hat{\mathbf{Z}}_{bj} \hat{\mathbf{Z}}_{ai} \hat{\Gamma}_{ij} \\ \hat{\Gamma}_{h_a h_b h_c} &= \hat{\mathbf{Z}}_{ck} \hat{\mathbf{Z}}_{bj} \hat{\mathbf{Z}}_{ai} \hat{\Gamma}_{ijk} \end{aligned}$$

For example,

$$\hat{\Gamma}_{h_1 f \bar{f}} = \sqrt{Z_h} \left(\hat{\Gamma}_{h f \bar{f}} + Z_{hH} \hat{\Gamma}_{H f \bar{f}} + Z_{hA} \hat{\Gamma}_{A f \bar{f}} \right)$$



Internal Higgs Bosons

For an effective coupling involving internal Higgs bosons, can use the 3×3 unitary rotation matrix **U**, which diagonalises a real, momentum independent appoximation to **M** where

$$\hat{\Sigma}_{kk}(p^2) \rightarrow \mathrm{Re}\left[\hat{\Sigma}_{kk}(m_k^2)\right]$$
$$\hat{\Sigma}_{jk}(p^2) \rightarrow \mathrm{Re}\left[\hat{\Sigma}_{jk}(\frac{1}{2}(m_j^2 + m_k^2))\right]$$

so that **U** diagonalises $\mathbf{M}_U$

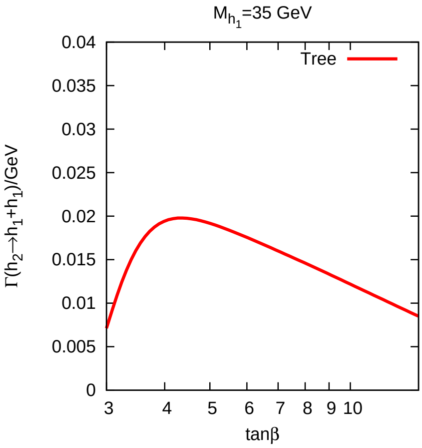
$$\begin{pmatrix} M^2_{h_1,U} & 0 & 0 \\ 0 & M^2_{h_2,U} & 0 \\ 0 & 0 & M^2_{h_3,U} \end{pmatrix} = \mathbf{U} \cdot \mathbf{M}_U \cdot \mathbf{U}^\dagger$$

For example, the h_a-Z-Z coupling is given by a combination of $g_{hZZ}, g_{HZZ}, g_{AZZ}$ using

$$g_{h_a ZZ} = \mathbf{U}_{ak} g_{kZZ}$$

which gives $g^2_{h_1 ZZ} + g^2_{h_2 ZZ} + g^2_{h_3 ZZ} = 1$ as required.

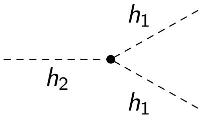
$h_2 \longrightarrow h_1 + h_1$ Decay Width



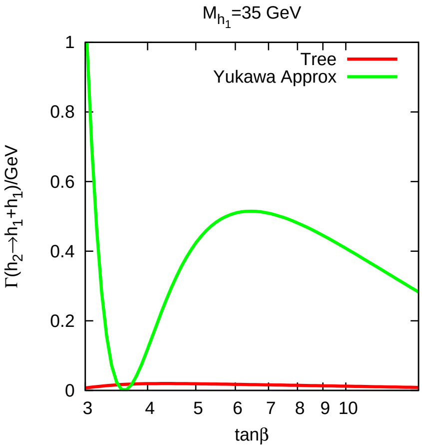
Tree level vertex

- Finite wave function renormalisation factors are included by

$$\Gamma_{h_2 h_1 h_1} = \hat{\mathbf{Z}}_{1k}\hat{\mathbf{Z}}_{1j}\hat{\mathbf{Z}}_{2i}\Gamma^{\text{tree}}_{ijk}$$

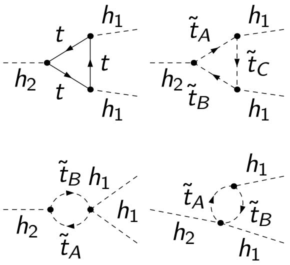


$h_2 \longrightarrow h_1 + h_1$ Decay Width



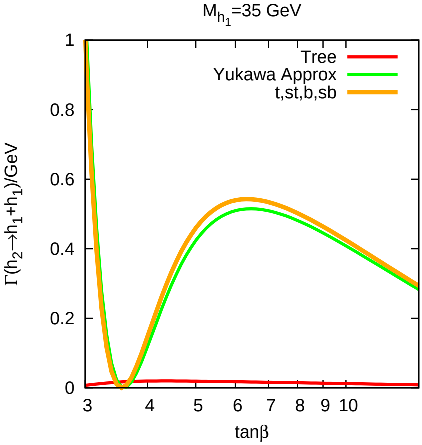
Yukawa approximation in vertex

- m_t^4 terms only
- zero incoming momentum: $p^2 = 0$



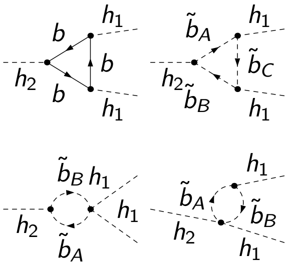
where $\tilde{t}_A, \tilde{t}_B, \tilde{t}_C = \tilde{t}_1, \tilde{t}_2$.

$h_2 \longrightarrow h_1 + h_1$ Decay Width



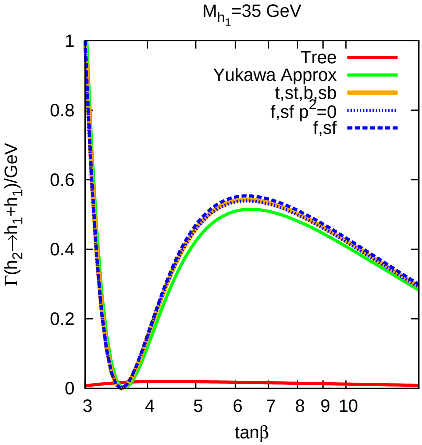
$t, \tilde{t}, b, \tilde{b}$

- loops involving $t, \tilde{t}, b, \tilde{b}$ only
- full momentum dependence



with $\tilde{b}_A, \tilde{b}_B, \tilde{b}_C = \tilde{b}_1, \tilde{b}_2$ and $t, \tilde{t}$ diagrams as before.

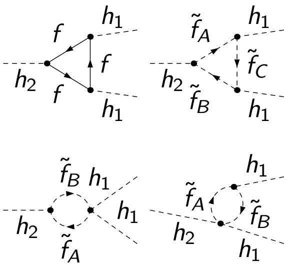
$h_2 \longrightarrow h_1 + h_1$ Decay Width



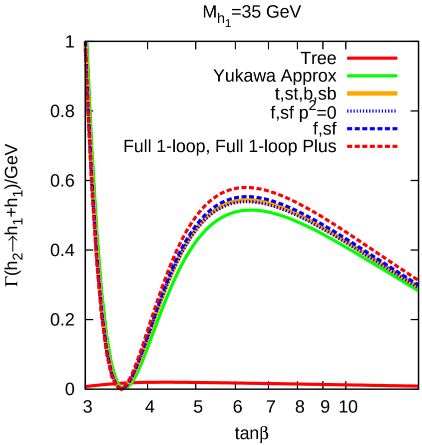
Fermions, Sfermions

Standard model fermions and their superpartners. Two options

- $p^2 = 0$
- full momentum dependence



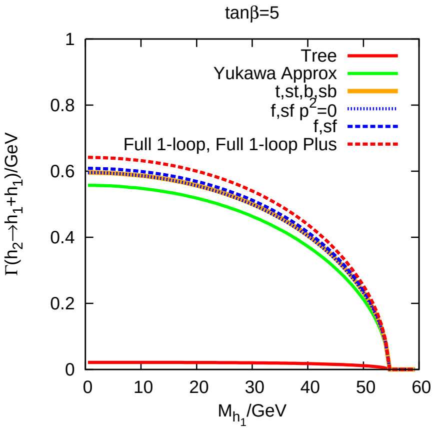
$h_2 \longrightarrow h_1 + h_1$ Decay Width



Full 1-loop and Full 1-loop Plus

- Both options include full 1-loop corrections.
- Full 1-loop Plus has h_1, h_2, h_3 inside loops instead of h, H, A. Transformations with **U** are used to obtain the new couplings. Negligible difference to full 1-loop case.

$\Gamma(h_2 \longrightarrow h_1 + h_1)$ - varying M_{h_1}

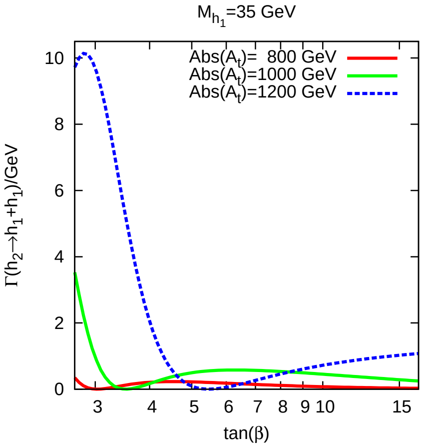


Above $M_{h_1} = 54GeV$,

$$M_{h_2} < 2M_{h_1}$$

so decay is not allowed.

$\Gamma(h_2 \to h_1 + h_1)$ - varying $\mathrm{Abs}(A_t)$



- $\Gamma(h_2 \to h_1 + h_1)$ is strongly dependent on $\mathrm{Abs}(A_t)$.
- Will be particularly relevent for transformations of parameters between on-shell and $\overline{\mathrm{DR}}$ scheme.

Other Ingredients

$\mathrm{Br}(h_a \to h_b h_c)$, $\mathrm{Br}(h_a \to b\bar{b})$, $\mathrm{Br}(h_a \to \tau^+\tau^-)$ are needed when checking parameter points against the LEP exclusions, so two other decay widths were calculated explicitly:

$\Gamma(h_a \to b\bar{b})$, including

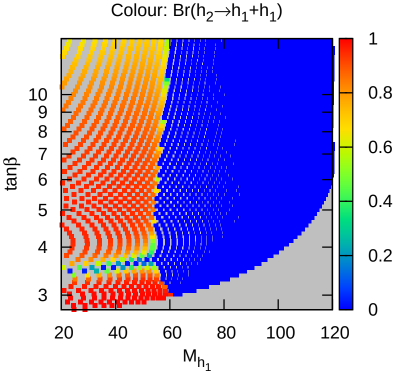
- finite wave renormalisation factors in $\hat{\mathbf{Z}}$
- SM QCD corrections
- Susy QCD corrections - resummation includes full M_3 phase dependence
- full 1-loop vertex corrections (with the option of h_1, h_2, h_3 in loops)
- QED corrections

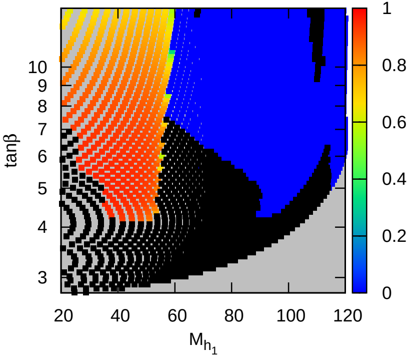
$\Gamma(h_a \to \tau^+\tau^-)$, including

- finite wave renormalisation factors in $\hat{\mathbf{Z}}$
- full 1-loop vertex corrections (with the option of h_1, h_2, h_3 in loops)
- QED corrections

Contribution of other neutral Higgs decay channels are taken from *FeynHiggs*

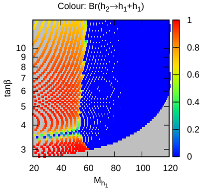
LEP exclusions for the *CPX inspired* scenario from processes involving h_1, h_2

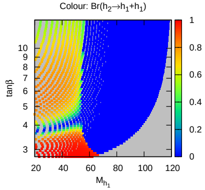


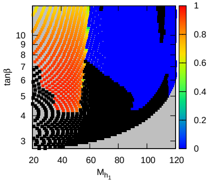


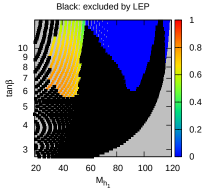
Comparison with the program *CPsuperH*

new results (with current *FH*) | *CPsuperH*









Conversion between on-shell and $\overline{\mathrm{MS}}$ schemes as in hep-ph/0001002.

Summary

- Presented new results for $h_a \rightarrow h_b + h_c$ decay width, which include 1-loop vertex corrections.
- Concentrated on the example of $\Gamma(h_2 \rightarrow h_1 + h_1)$ in the *CPX inspired* scenario, showed these new corrections can increase the decay width by factor of 50.
- Compared to results from momentum independent vertex approximations, which can be used for 'effective' $h_a - h_b - h_c$ couplings, which could be very useful for probing the trilinear neutral Higgs interactions. These approximations proved very successful.
- Looked at the implications of these new corrections to constraints on the mass of the lightest Higgs mass M_{h_1} in the *CPX inspired* scenario. The results confirm the existence of a 'hole' in the LEP coverage at low M_{h_1} $\sim$40 and tanβ $\sim$5.

The End