CP-violating Loop Effects in the Higgs Sector of the MSSM

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The complex Minimal Supersymmetric Standard Model

Often complex phases in the MSSM are taken to be zero for simplicity. Including complex phases causes the tree level neutral Higgs h, H, A (which are CP eigenstates) to mix to form h_1, h_2, h_3.

This CP violation 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

Higgs Sector of the complex MSSM

At tree level the Higgs sector of the complex MSSM is CP-conserving. (h, H are CP even and A is CP odd.)

Two values are needed to specify the Higgs sector at tree level, often

- The ratio of the vacuum expectation values of the Higgs doublets, $\tan\beta = v_2/v_1$
- One of the Higgs masses. Usually m_A in the real MSSM and $m_{H^\pm}$ in the complex MSSM.

The Loop-corrected neutral Higgs mass matrix is

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

- The presence of complex phases in the loop corrections can lead to non-zero $\hat{\Sigma}_{hA}(p^2), \hat{\Sigma}_{HA}(p^2)$, leading to mixing between all three neutral Higgs bosons.
- The physical masses are labelled by $M_{h_1} \leq M_{h_2} \leq M_{h_3}$

The CPX scenario

The CPX scenario is a MSSM benchmark scenario designed to maximise the effect of complex phases (M. S. Carena et al 2000).

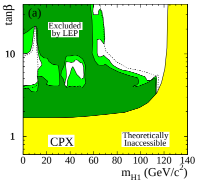
We use (brackets show values used in original analysis by LEP Higgs Working Group)

- $M_{\mathrm{SUSY}} = 500 \mathrm{~GeV}$
- $\mu = 2000 \mathrm{~GeV}$
- $|M_3| = 1000 \mathrm{~GeV}$
- $M_2 = 200 \mathrm{~GeV}$
- $|A_{t,b}^{\mathrm{on-shell}}| = 900 \mathrm{~GeV} \quad (|A_{t,b}^{\overline{\mathrm{MS}}}| = 1000 \mathrm{~GeV})$
- $\phi_{A_t} = \phi_{A_b} = \phi_{M_3} = \frac{\pi}{2}$
- $m_t = 172.6 \mathrm{~GeV} \quad (174.3 \mathrm{~GeV})$

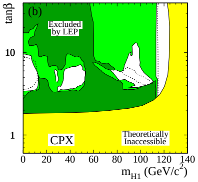
There are two publicly available codes to calculate Higgs masses, couplings and branching ratios in the complex MSSM: *FeynHiggs* (T.Hahn et al) and *CPsuperH* (J.S.Lee et al). Both include some 2-loop corrections. Since they both use different ren. schemes, we can not interpret input parameters such as $\mathrm{abs}(A_t)$, $\arg(A_t)$, M_L^2 and $M_{\tilde{q}_R}$ as having the same meaning in both programs.

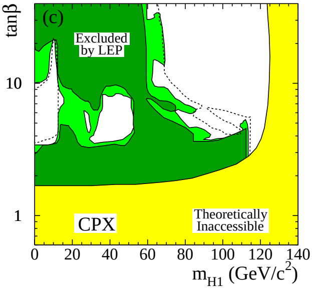
Results of LEP Higgs Working Group and LEP Collaborations for the CPX scenario

CPsuperH



FeynHiggs





Combination

- A point in the CPX scenario parameter space was only said to be excluded by the LEP results if it was excluded by the analysis using *FeynHiggs* and the analysis using *CPsuperH*. [EP JC 46(2006)547]

$h_2 \longrightarrow h_1 + h_1$ Decay Width

- One of the areas that could not be excluded at 95 % CL by the LEP Higgs Working Group is $M_{h_1} \sim 45$ GeV and $\tan\beta \sim 6$.
- As we will see, the decay $h_2 \rightarrow h_1 + h_1$ is very important in this region.
- However, at the time of the LEP analysis, there was no reliable Feynman-diagrammatic result for the $h_2 \rightarrow h_1 + h_1$ decay width .

Here, we show results for $\Gamma(h_a \rightarrow h_b h_b)$, which include

- propagator corrections, which use renormalised self-energies from the program *FeynHiggs*
- full 1-loop vertex corrections

Dealing with external Higgs bosons

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

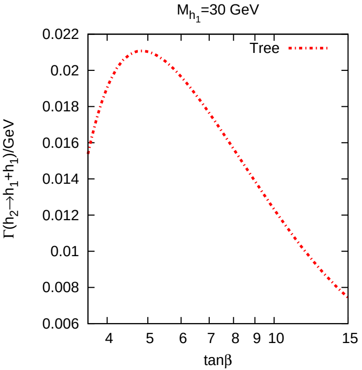
$$
\begin{aligned}
\lim_{p^2 \to \mathcal{M}_{h_1}^2} -\frac{i}{p^2 - \mathcal{M}_{h_1}^2} \left(\hat{\mathbf{Z}} \cdot \hat{\mathbf{\Gamma}}_2 \cdot \hat{\mathbf{Z}}^T \right)_{hh} &= 1 \\
\lim_{p^2 \to \mathcal{M}_{h_2}^2} -\frac{i}{p^2 - \mathcal{M}_{h_2}^2} \left(\hat{\mathbf{Z}} \cdot \hat{\mathbf{\Gamma}}_2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

where $-\hat{\mathbf{\Gamma}}_2(p^2)$ is the inverse of the propagator matrix and $\mathcal{M}_{h_a}^2$ are the poles of the propagator matrix.
The $\hat{\Sigma}_{jk}(p^2)$ were calculated using an expansion about $\mathrm{Re}p^2$:

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

The program *FeynHiggs* (2.6.4) was used for $\hat{\Sigma}_{jk}(\mathrm{Re}p^2)$ and $\hat{\Sigma}'_{jk}(\mathrm{Re}p^2)$.

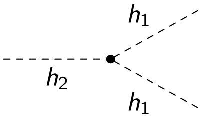
$h_2 \longrightarrow h_1 + h_1$ Decay Width



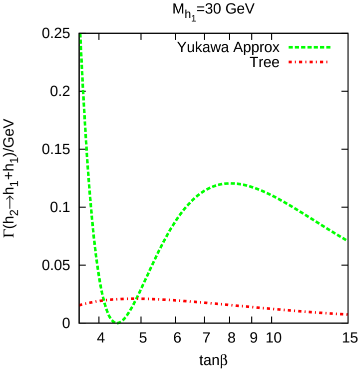
Tree level vertex

- Finite wave function normalisation factors are included by

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

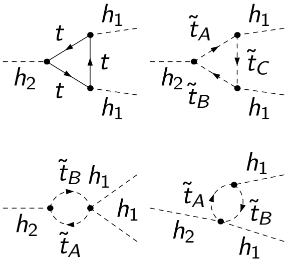


$h_2 \to h_1 + h_1$ Decay Width



Yukawa approximation in vertex

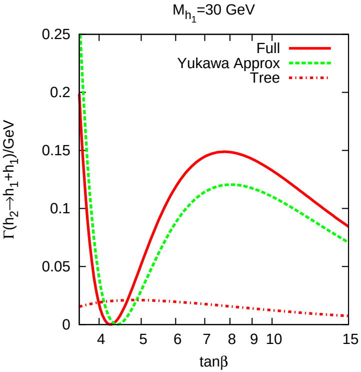
- m_t^4 and m_t^6 terms only
- zero incoming momentum: $p^2 = 0$



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

- Gives compact expressions involving $A_0(m)$ integrals.

$h_2 \longrightarrow h_1 + h_1$ Decay Width



Full 1-loop

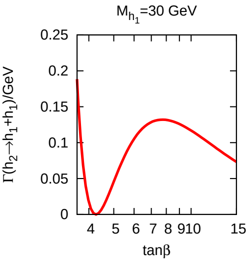
Includes

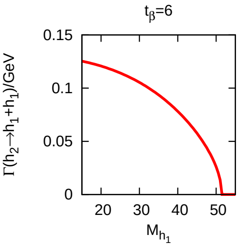
- SM fermions and their superpartners
- neutralinos and charginos
- vector, neutral Higgs, charged Higgs and Goldstone bosons
- Faddeev-Popov ghosts

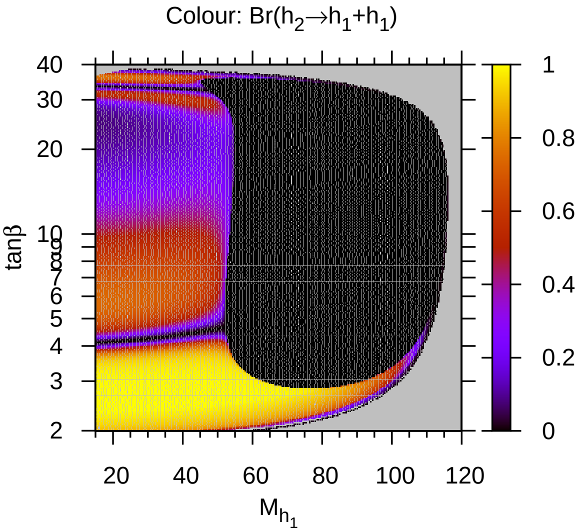
Also includes (strict) 1-loop mixing of h, H, A with G, Z in propagators.

Used the programs *FeynArts* and *FormCalc* (T. Hahn et al).

Contribution to the $h_2 \rightarrow h_1 + h_1$ Branching Ratio

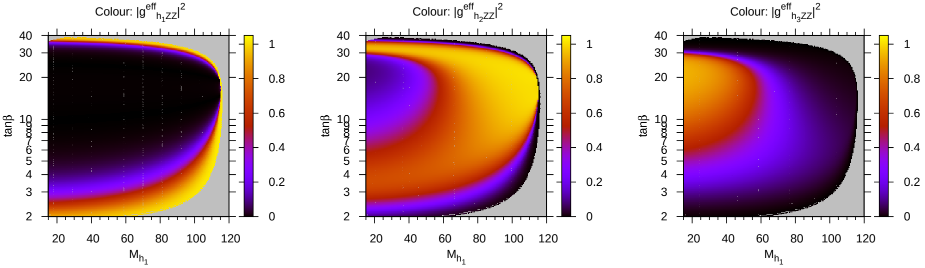






Higgs couplings to Z bosons

- In the region we're interested in, the ratio of the h_1-Z-Z effective coupling squared to the Standard Model, $|g_{h_1 ZZ}|^2$ is suppressed.
  - the h_2 branching ratios will be crucial.

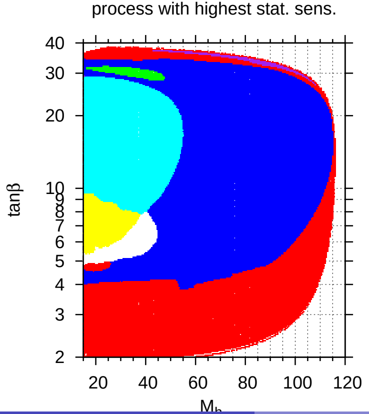


$$
\begin{aligned}
|g_{h_1 ZZ}|^2 + |g_{h_2 ZZ}|^2 + |g_{h_3 ZZ}|^2 &\simeq 1 \\
|g_{h_i ZZ}|^2 &\simeq |g_{h_j h_k Z}|^2
\end{aligned}
$$

where i, j, k are all different

Comparing to the expected limits from the LEP Higgs searches

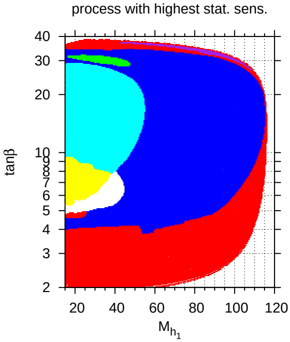
Used *HiggsBounds* (P.Bechtle, O.Brein, S.Heinemeyer, G.Weiglein, K.W.) to compare these theoretical results to the topological cross section limits from the LEP Higgs Working Group. *HiggsBounds* firsts works out which channel has the highest statistical sensitivity, then uses that channel to determine whether the parameter has been excluded (see talk by O. Brein)

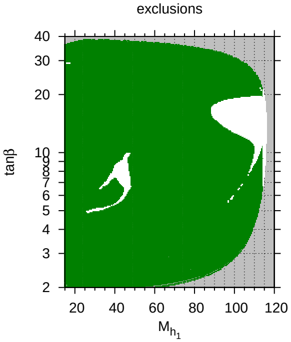


Channel with the highest statistical sensitivity:

- $= h_1 Z \to b\bar{b}Z$
- $= h_2 Z \to b\bar{b}Z$
- $= h_2 Z \to h_1 h_1 Z \to b\bar{b}b\bar{b}Z$
- $= h_2 h_1 \to b\bar{b}b\bar{b}$
- $= h_2 h_1 \to h_1 h_1 h_1 \to b\bar{b}b\bar{b}b\bar{b}$
- $= h_3 h_1 \to b\bar{b}b\bar{b}$
- $=$ other channels

New exclusion plots for the CPX scenario





Channel with the highest statistical sensitivity

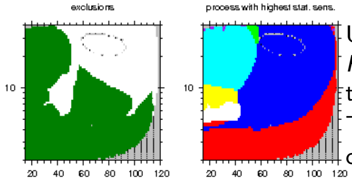
- ■ $= h_1 Z \to b\bar{b}Z$
- ■ $= h_2 Z \to b\bar{b}Z$
- □ $= h_2 Z \to h_1 h_1 Z \to b\bar{b}b\bar{b}Z$
- ■ $= h_2 h_1 \to b\bar{b}b\bar{b}$
- ■ $= h_2 h_1 \to h_1 h_1 h_1 \to b\bar{b}b\bar{b}b\bar{b}$
- ■ $= h_3 h_1 \to b\bar{b}b\bar{b}$
- ■ = other channels

Exclusion region at 95 % CL

green = excluded
white = unexcluded

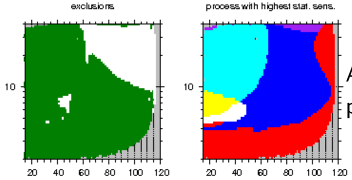
(results for $m_t = 170.9$ GeV are in K.W. and G.Weiglein 2008)

Tentative Comparison to *CPsuperH* (using $|A_t^{\overline{\mathrm{DR}}}| = 1000\ \mathrm{GeV}$)

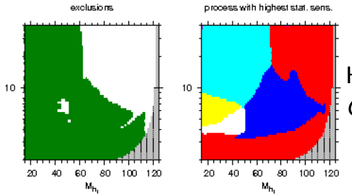


Using $\hat{\Sigma}_{h_i h_j}$ from preliminary new version of *FeynHiggs* (thanks go to T. Hahn for providing this).

Transformation to on-shell parameters uses leading corr. with full phase dependence



As above, except transformation to on-shell parameters is same as in [EP JC 46(2006)547]



Higgs masses, couplings and branching ratios from *CPsuperH*

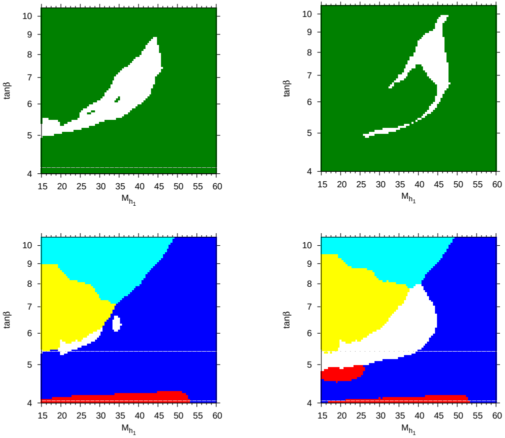
Summary

- Presented results for $h_a \rightarrow h_b + h_c$ decay width, which include 1-loop vertex corrections. These will be incorperated in to the publically available program *FeynHiggs* (as will the results for $h_a \rightarrow f + \bar{f}$).
- Concentrated on the example of $\Gamma(h_2 \rightarrow h_1 + h_1)$ in the *CPX* scenario, showed these new corrections can increase the decay width by factor of 50.
- Looked at the implications of these new corrections to constraints on the mass of the lightest Higgs mass M_{h_1} in the CPX scenario. The results confirm the existence of a 'hole' in the LEP coverage at $M_{h_1} \sim 45\ \mathrm{GeV}$. To cover this hole, we'll need to wait for results from the LHC (possibly) or ILC.

The End

Effect of different approximations for $\Gamma(h_2 \to h_1 h_1)$ (CPX scenario)

Yukawa Approx. | Full



green=excluded

white=unexcluded

■ $= h_1 Z \to b\bar{b}Z$

■ $= h_2 Z \to b\bar{b}Z$

□ $= h_2 Z \to h_1 h_1 Z \to b\bar{b}b\bar{b}Z$

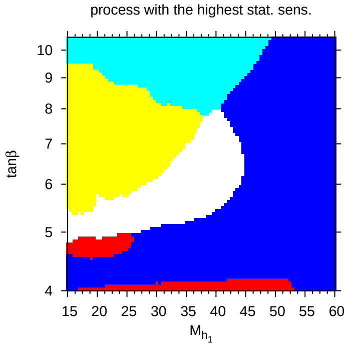
■ $= h_2 h_1 \to b\bar{b}b\bar{b}$

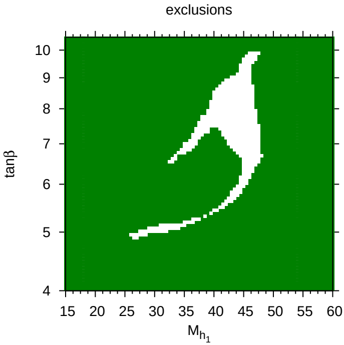
■ $= h_2 h_1 \to h_1 h_1 h_1 \to b\bar{b}b\bar{b}b\bar{b}$

Decay Width $\Gamma(h_a \longrightarrow f\bar{f})$

- $\Gamma(h_a \rightarrow b\bar{b})$, including
  - finite wave ren. 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
  - 1-loop propagator mixing of neutral Higgs with G, Z
- $\Gamma(h_a \rightarrow \tau^+\tau^-)$, including
  - finite wave ren. factors in $\hat{\mathbf{Z}}$
  - full 1-loop vertex corrections (with the option of h_1, h_2, h_3 in loops)
  - QED corrections
  - 1-loop propagator mixing of neutral Higgs with G, Z
- Contribution of other neutral Higgs decay channels are taken from *FeynHiggs*.

New LEP Higgs exclusions for the CPX scenario II





■ $= h_1 Z \to b\bar{b}Z$

■ $= h_2 Z \to b\bar{b}Z$

□ $= h_2 Z \to h_1 h_1 Z \to b\bar{b}b\bar{b}Z$

■ $= h_2 h_1 \to b\bar{b}b\bar{b}$

■ $= h_2 h_1 \to h_1 h_1 h_1 \to b\bar{b}b\bar{b}b\bar{b}$

green $=$ excluded

white $=$ unexcluded