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

Karina Williams, in collaboration with Georg Weiglein, Oliver Brein, Philip Bechtle and Sven Heinemeyer

IPPP, University of Durham

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Supersymmetry

- Supersymmetry is a symmetry connecting bosons and fermions.
- Solves 'naturalness' problem - cancellation of quadratic divergences.
- Exact supersymmetry: particles and sparticles have the same mass.
- Sparticles have not been observed - SUSY is broken.
- Softly broken SUSY - quadratic divergences still cancel.

Minimal Supersymmetric Standard Model

- Minimum number of superpartners
- 2 Higgs Doublets
- No assumption about SUSY breaking mechanism - all terms that break SUSY softly are added to Lagrangian
- Has more than 100 free parameters (in addition to those in the SM)
- Gives unification of gauge couplings
- Conserves R Parity - SUSY particles can not decay in to only SM particles - lightest SUSY particle is a Dark Matter Candidate
- Predicts that the lightest Higgs Mass < 140 GeV - within the reach of the LHC
- Higgs mass is given in terms of other parameters - lightest Higgs mass will be a good electroweak precision observable - can be exploited by the LHC and ILC.

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

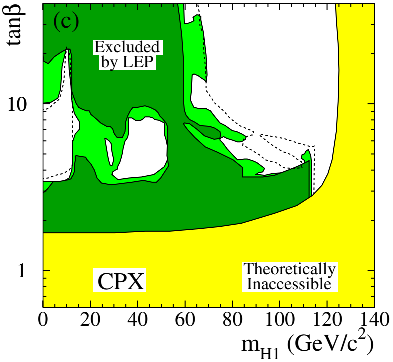
CPX scenario - chosen to maximise the effect of complex phases. We use

- $M_{\mathrm{SUSY}} = 500\ \mathrm{GeV}, \mu = 2000\ \mathrm{GeV}, |M_3| = 1000\ \mathrm{GeV}, M_2 = 200\ \mathrm{GeV}$
- $|A_{t,b}^{\mathrm{on-shell}}| = 900\ \mathrm{GeV} \quad (|A_{t,b}^{\overline{\mathrm{MS}}}| = 1000\ \mathrm{GeV})$
- $\phi_{A_t} = \phi_{A_b} = \phi_{M_3} = \frac{\pi}{2}$
- $m_t = 170.9\ \mathrm{GeV} \quad (174.3\ \mathrm{GeV})$

(brackets show values used in original analysis)

Analysis of LEP results by LEP Higgs Working Group

Exclusions in the CPX scenario (from hep-ex/0602042)



- M_{h_1} is the mass of the lightest neutral Higgs and $\tan\beta$ is the ratio of vacuum expectation values.
- 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 $\tan\beta \sim 6$.

$h_2 \longrightarrow h_1 + h_1$ Decay Width

In this region, the $h_2 \rightarrow h_1 + h_1$ decay width is very important.

However, at the time, there was no reliable Feynman-diagrammatic result for this decay width.

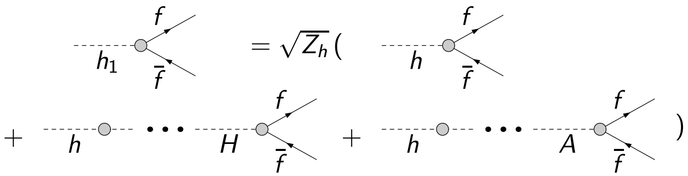
Here, we show results for $\Gamma(h_a \rightarrow h_b h_b)$, which include

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

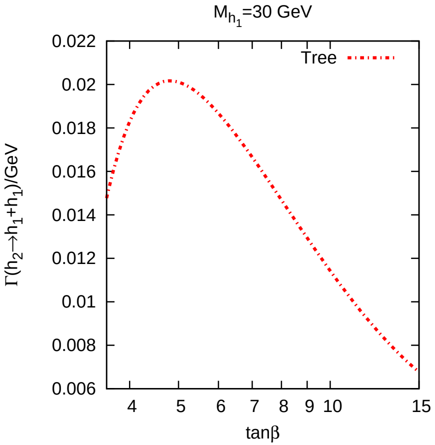
Propagator Corrections

- We use $\overline{\mathrm{DR}}$ renormalisation for the Higgs field ren. constants
- Therefore, diagrams with external Higgs bosons need finite wave function renormalisation factors (involving the renormalised Higgs self-energies) contained in the 3×3 matrix $\hat{\mathbf{Z}}$.
- For example, for a vertex function involving an external Higgs h_1

$$\hat{\Gamma}_{h_1 f\bar{f}} = \hat{\mathbf{Z}}_{ai}\hat{\Gamma}_i \quad = \quad \sqrt{Z_h}\left(\hat{\Gamma}_{hf\bar{f}} + Z_{hH}\hat{\Gamma}_{Hf\bar{f}} + Z_{hA}\hat{\Gamma}_{Af\bar{f}}\right)$$



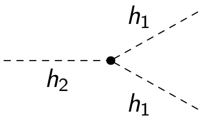
$h_2 \longrightarrow h_1 + h_1$ Decay Width



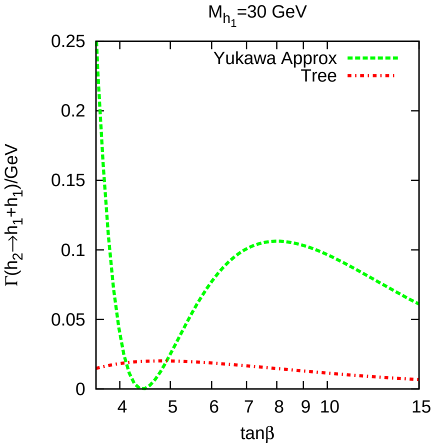
Tree level vertex

- Finite wave function renormalisation factors are included by

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

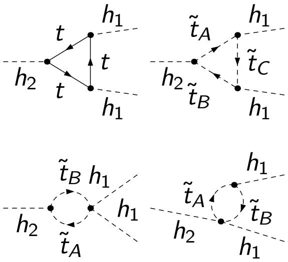


$h_2 \longrightarrow h_1 + h_1$ Decay Width



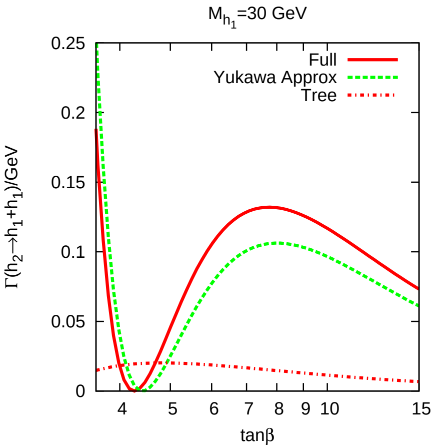
Yukawa approximation in vertex

- 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

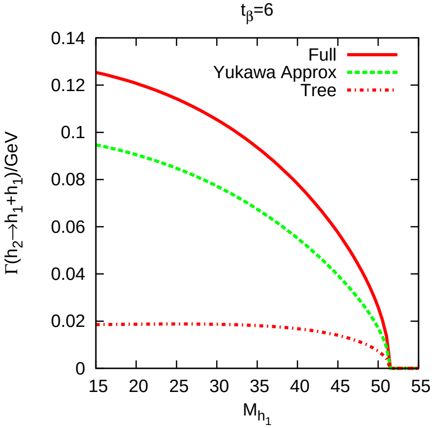


Full 1-loop

Includes

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

$h_2 \rightarrow h_1 + h_1$ Decay Width - varying M_{h_1}

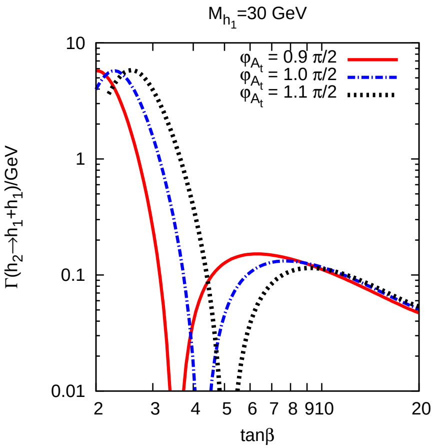


Above $M_{h_1} = 52 GeV$,

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

so decay is not allowed.

$h_2 \to h_1 + h_1$ Decay Width - varying $\mathrm{Arg}(A_t)$

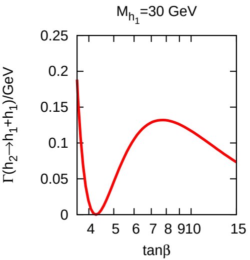


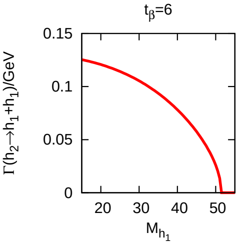
$\Gamma(h_2 \to h_1 + h_1)$ is strongly dependent on $\mathrm{Arg}(A_t)$.

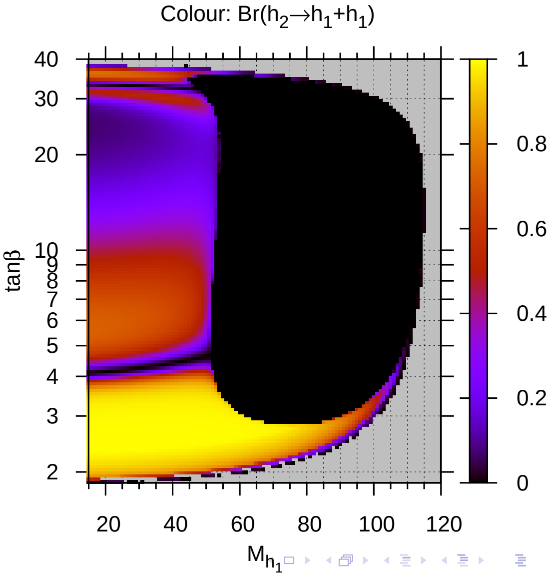
Ingredients

- Neutral Higgs Masses
  - using neutral Higgs self-energies from *FeynHiggs*
  - has full phase dependence at order $\alpha_t \alpha_s$ (arXiv:0710.4891)
- $\Gamma(h_a \to h_b h_b)$, 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)
- $\Gamma(h_a \to b\bar{b})$, 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
- $\Gamma(h_a \to \tau^+\tau^-)$, 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
- Contribution of other neutral Higgs decay channels are taken from *FeynHiggs*
- Effective couplings of neutral Higgs bosons to Z bosons

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

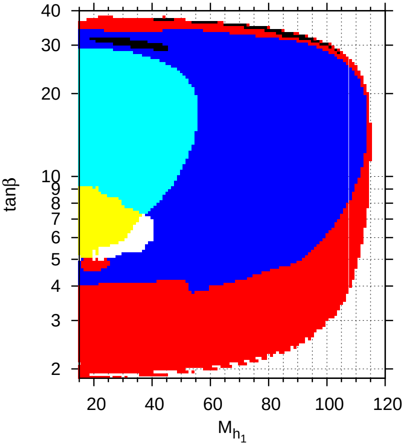






Comparing to the LEP Higgs predictions

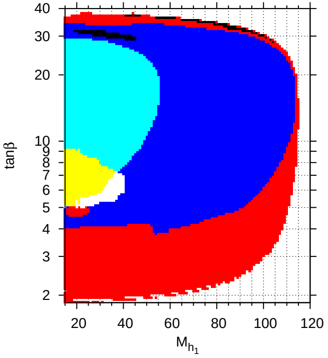
The theoretical prediction for each channel is compared to the experimental prediction for that channel at LEP.

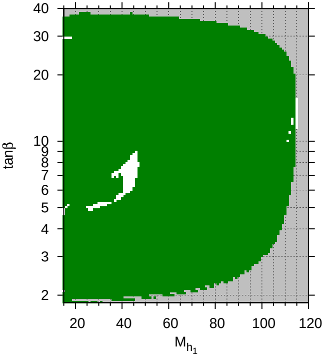


Channel with the highest statistical sensitivity:

- ■ (red) $= h_1 Z \to b\bar{b}Z$
- ■ (blue) $= h_2 Z \to b\bar{b}Z$
- □ $= h_2 Z \to h_1 h_1 Z \to b\bar{b}b\bar{b}Z$
- ■ (cyan) $= h_2 h_1 \to b\bar{b}b\bar{b}$
- ■ (yellow) $= h_2 h_1 \to h_1 h_1 h_1 \to b\bar{b}b\bar{b}b\bar{b}$
- ■ (black) $=$ other channels

New LEP Higgs exclusions for the CPX scenario





Channel with the highest statistical sensitivity

- ■ $= h_1 Z \to b\bar{b}Z$ (red)
- ■ $= h_2 Z \to b\bar{b}Z$ (blue)
- □ $= h_2 Z \to h_1 h_1 Z \to b\bar{b}b\bar{b}Z$
- ■ $= h_2 h_1 \to b\bar{b}b\bar{b}$ (cyan)
- ■ $= h_2 h_1 \to h_1 h_1 h_1 \to b\bar{b}b\bar{b}b\bar{b}$ (yellow)
- ■ = other channels (black)

Exclusion region at 95 % CL

green = excluded
white = unexcluded

Program *HiggsBounds*

Takes, as input,

- neutral Higgs masses
- normalised $e^+e^- \to h_i Z$ and $e^+e^- \to h_j h_i$ cross sections
- $h_i \to b\bar{b}$, $h_i \to \tau\bar{\tau}$ and $h_j \to h_i h_i$ branching ratios

and compares these to the cross section limits from the LEP Higgs searches.

- generalised to models with any number of neutral Higgs - can be used to check any theoretical model against the LEP Higgs results
- a web version and downloadable version will be made publically available
- soon to include Tevatron data

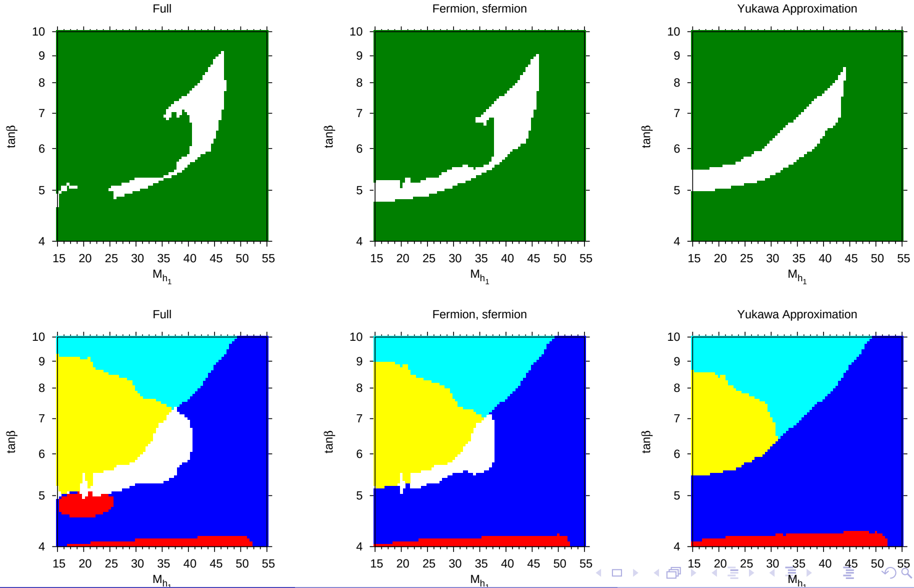
Summary

- Presented results for $h_a \to h_b + h_c$ decay width, which include 1-loop vertex corrections.
- Concentrated on the example of $\Gamma(h_2 \to h_1 + h_1)$ 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 $M_{h_1} \sim 45$. To cover this hole, we'll need to wait for results from the LHC (possibly) or ILC.
- Discussed the new program *HiggsBounds*, which will allow physicists to compare their Higgs sector predictions with the LEP and Tevatron limits.

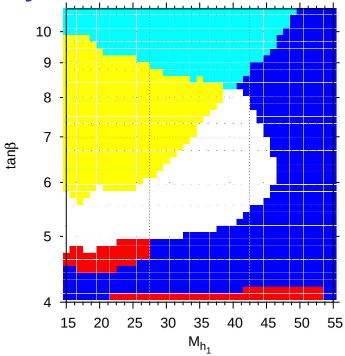
The End

Will the LHC get enough evidence to finally track down a Higgs Boson or could a very light Higgs still escape detection?

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

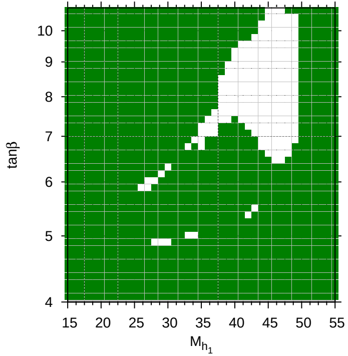


New LEP Higgs exclusions for the CPX scenario but $m_t = 174.3$ GeV



Channel with the highest statistical sensitivity

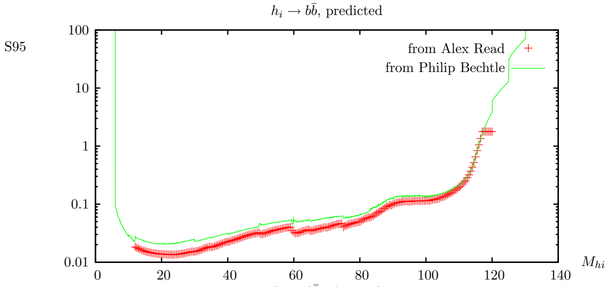
- ■ $= h_1 Z \to b\bar{b}Z$ (red)
- ■ $= h_2 Z \to b\bar{b}Z$ (blue)
- □ $= h_2 Z \to h_1 h_1 Z \to b\bar{b}b\bar{b}Z$
- ■ $= h_2 h_1 \to b\bar{b}b\bar{b}$ (cyan)
- ■ $= h_2 h_1 \to h_1 h_1 h_1 \to b\bar{b}b\bar{b}b\bar{b}$ (yellow)
- ■ $=$ other channels



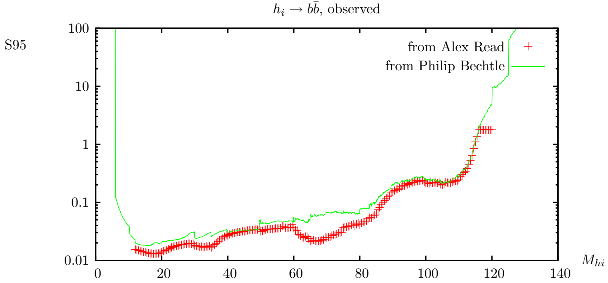
Is this channel excluded at 95 % CL?

green = yes
white = no

LEP results



predicted S95 values for $e^+e^- \longrightarrow h_iZ \longrightarrow b\bar{b}Z$



observed S95 values for $e^+e^- \longrightarrow h_iZ \longrightarrow b\bar{b}Z$

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

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

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 $\mathrm{Re}p^2$.

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

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,

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

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

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

note

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

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

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

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,

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