Higgs decays in the complex MSSM

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Outline

1. Introduction
   - The Higgs sector of the MSSM
   - Higgs decays
2. Higher order corrections
3. Preliminary results
   - Formfactors
   - The decay width
4. Summary

The Higgs sector of the MSSM

- In the MSSM, the Higgs sector needs to contain two Higgs doublets, which leads to 5 physical Higgs states:

$$h, H, A, H^+, H^-$$

- At tree level the Higgs sector is described by tanβ and M_A
- The tree level masses m_h and m_H are found by diagonalising the Higgs mass matrix

$$M_H^{2,tree} = \begin{pmatrix} M_A^2 \sin^2\beta + M_Z^2 \cos^2\beta & -\left(M_A^2 + M_Z^2\right)\sin\beta\cos\beta \\ -\left(M_A^2 + M_Z^2\right)\sin\beta\cos\beta & M_A^2\cos^2\beta + M_Z^2\sin^2\beta \end{pmatrix}$$

$\downarrow$ diagonalisation, α

$$M_H^{2,tree} = \begin{pmatrix} m_H^{2,tree} & 0 \\ 0 & m_h^{2,tree} \end{pmatrix}$$

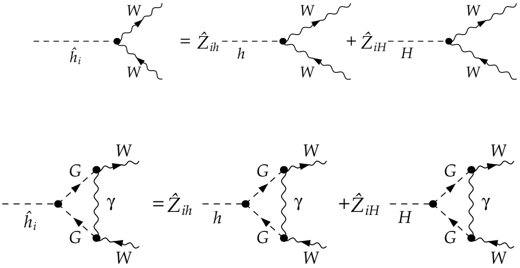
The MSSM with complex parameters

- In general, some of the parameters of the MSSM can be complex. For instance,
  - gluino mass parameter M_3
  - trilinear coupling parameter A
- When complex phases are included, interesting (non-excluded) phenomenology can result
- Complex phases allow mixing between all three neutral Higgs bosons

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

Higgs propagator corrections I

- At tree level there is no CP-violation in the Higgs sector of the MSSM with complex parameters
- Finite wavefunction normalisation factors have been used to give external particles the correct on-shell properties to take Higgs mixing into account



$$\begin{pmatrix} \hat{\Gamma}_1 \\ \hat{\Gamma}_2 \\ \hat{\Gamma}_3 \end{pmatrix} = \hat{Z} \begin{pmatrix} \hat{\Gamma}_h \\ \hat{\Gamma}_H \\ \hat{\Gamma}_A \end{pmatrix}$$

Higgs propagator corrections II

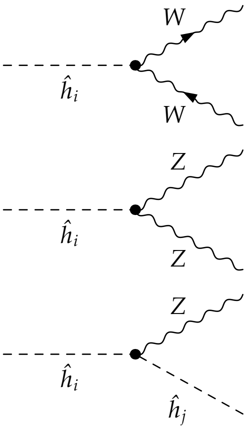
- The non-unitary $\hat{Z}$ matrix is given by

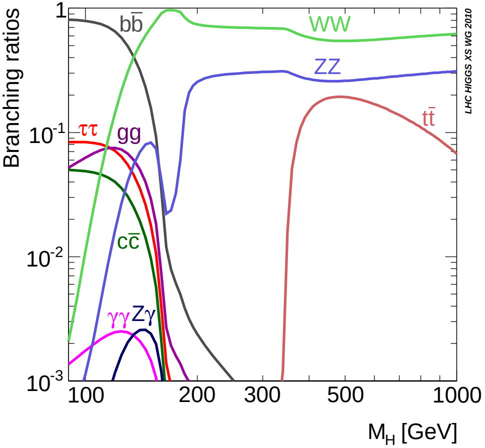
$$\hat{Z} = \begin{pmatrix} \sqrt{Z_h} & \sqrt{Z_h}Z_{hH} & \sqrt{Z_h}Z_{hA} \\ \sqrt{Z_H}Z_{Hh} & \sqrt{Z_H} & \sqrt{Z_h}Z_{HA} \\ \sqrt{Z_h}Z_{Ah} & \sqrt{Z_A}Z_{AH} & \sqrt{Z_A} \end{pmatrix}$$

- When producing a Higgs i, $\sqrt{Z_i}$ is a normalisation factor (dependent on the ii propagator), and Z_{ij} involves the ij propagator and takes account of diagrams where there is a tree level Higgs j connected directly to the vertex.
- These corrections can be very important numerically. They are calculated using `FeynHiggs`*, which includes the dominant two-loop contributions as well as the full one-loop corrections.

* `FeynHiggs` can be found at **www.feynhiggs.de**

Higgs decays at the LHC





Branching ratios in the SM*

* **Figure from: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections**

Decay widths and formfactors

- Loop corrections to the Higgs vertex can be represented using an effective coupling

$$T^{\mu\nu} = Ag^{\mu\nu} + Bp^{\mu}q^{\nu} + C\epsilon^{\mu\nu\rho\sigma}p_{\sigma}q_{\rho}$$

- The formfactors B and C arising from loop corrections are small – too small to affect the decay width
- The decay width can be considered to be

$$\Gamma \propto |A|^2$$

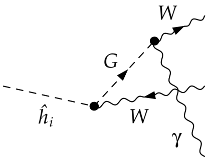
- By studying the behaviour of the formfactor A, we can understand the behaviour of the width

Virtual corrections

- The programs `FeynArts`, `FormCalc` and `LoopTools`* have been used in order to calculate the loop corrections
- Masses and weak boson field renormalisation constants are renormalised on-shell, and Higgs field renormalisation constants are calculated in the $\overline{DR}$ scheme
- The LO result is parametrised in terms of $\alpha(M_Z)$, and the charge renormalisation constant is adjusted accordingly

* Programs can be found at **www.feynarts.de**

Real corrections



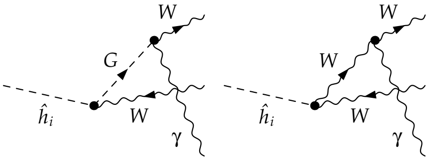
$$\Gamma_{real} = \Gamma_0 \frac{\alpha}{\pi}\left[-\left\{\frac{1+\beta_0^2}{\beta_0}\log\frac{1+\beta_0}{1-\beta_0} - 2\right\}\log\frac{\lambda^2}{M_W^2\beta_0} + 2(2-\log 2) + \right.$$

$$\left.\frac{1+\beta_0^2}{\beta_0}\left(\mathrm{Li}_2\frac{2\beta_0}{\beta_0-1} - \mathrm{Li}_2\frac{2\beta_0}{\beta_0+1} + \mathrm{Li}_2\frac{1-\beta_0}{2} + \frac{1}{2}\log(1-\beta_0^2)\log\frac{1+\beta_0}{1-\beta_0}\right)\right] +$$

$$\frac{M_{h_i}\alpha|S|^2}{16\sin^2\theta_W(1-\beta_0^2)}\frac{\alpha}{\pi}\left[\left(\beta_0^4+\beta_0^2-\beta_0^6-1\right)\log\frac{1+\beta_0}{1-\beta_0} + 2\beta_0^5 + 2\beta_0 - \frac{4}{3}\beta_0^3\right]$$

$$\beta_0 = \sqrt{1-\frac{4M_W^2}{M_{h_i}^2}}$$

Real corrections



In order to include these corrections when considering the formfactors, we let

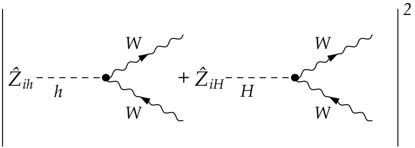
$$\begin{aligned} \Gamma_0 &\propto |A_0|^2 \\ \Gamma_{real} &\propto K_{real}|A_0|^2 \end{aligned}$$

Higgs propagator-type corrections: Improved Born Approximation

- Propagator factors are included at leading order, but the correction is kept strictly at one-loop level

$$|A_{cor}|^2 = |A_{h_2}|^2 + 2\text{Re}[A^*_{H,tree} \Delta A_H]$$

LO:



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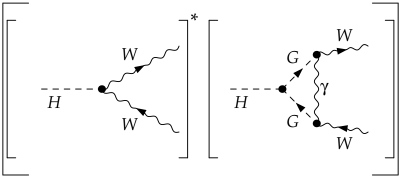
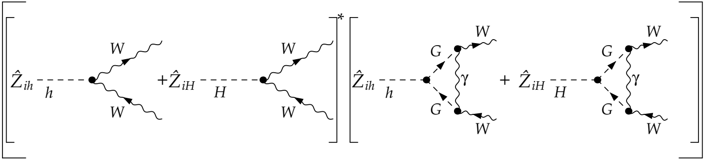
CORN: 2 Re



- This gives a correction of 0 to h_3 decay

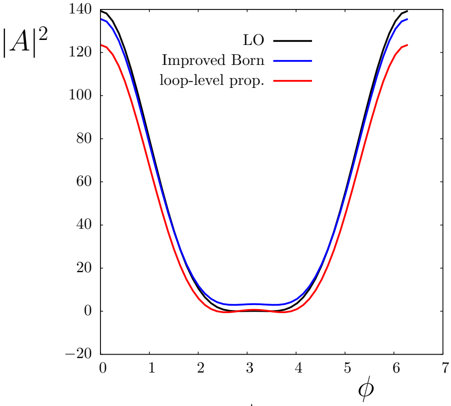
Higgs propagator-type corrections: At loop level

$\hat{Z}$ factors are applied at loop level as well as at leading order

CORN: 2 Re 

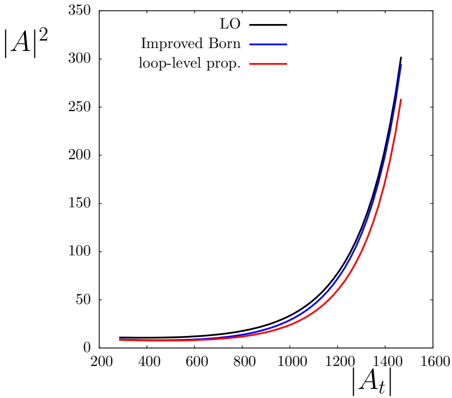
Several methods of applying these corrections were investigated in order to ensure IR-safety

The effect of propagator-type corrections



$h_2 \to W^+W^-$

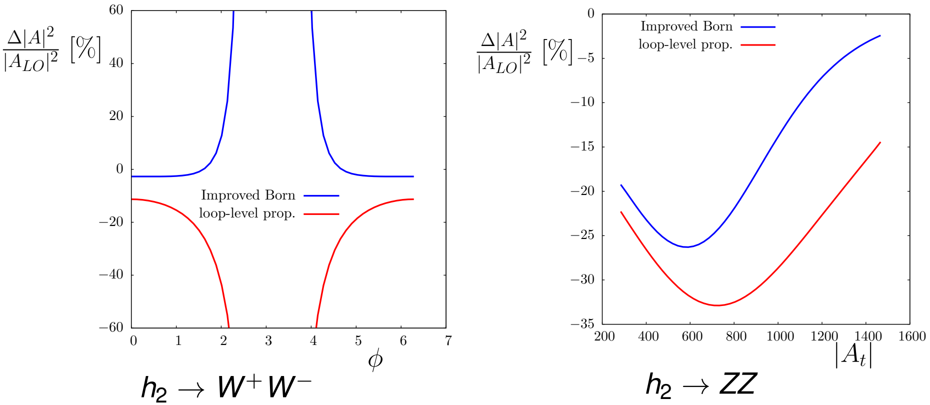
where $A_t = |A_t| \exp(i\phi)$



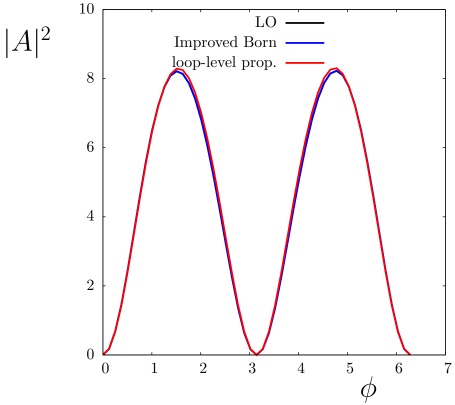
$h_2 \to ZZ$

The effect of propagator-type corrections

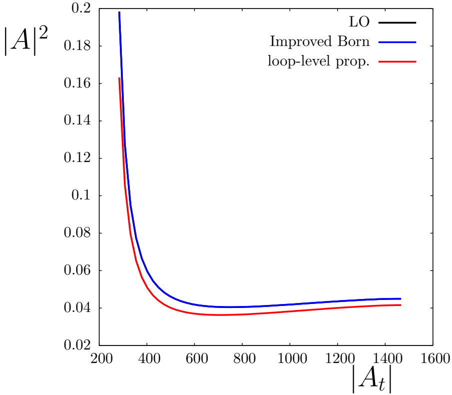
The propagator-type contributions can have a dramatic effect on the behaviour of the corrections



The effect of propagator-type corrections



$h_3 \to W^+W^-$



$h_3 \to ZZ$

Scanning over formfactors

- Once interesting 'benchmark' scenarios have been identified, we can scan around these points in order to discover which parameters have the largest effect on the correction

Parameter Scans

- In order to find the region of parameter space where the cross section (and corrections) are reasonable and which is experimentally allowed, we perform adaptive parameter scans*
- 9 parameters are varied in order to maximise the size of the corrections
  - $M_{H^\pm}$, $\tan\beta$, M_{SUSY}, $m_{\tilde{t}}$, μ, M_2, $|A_t|$, $|M_3|$
  - ϕ, where $A_t = |A_t|e^{i\phi}$ and $M_3 = |M_3|e^{i\phi}$
- All thresholds are avoided
- HiggsBounds** is used to ensure that the scenario being studied is not already experimentally excluded
- Limits on the sfermion and chargino masses are imposed

* **hep-ph/04072340**, O. Brein

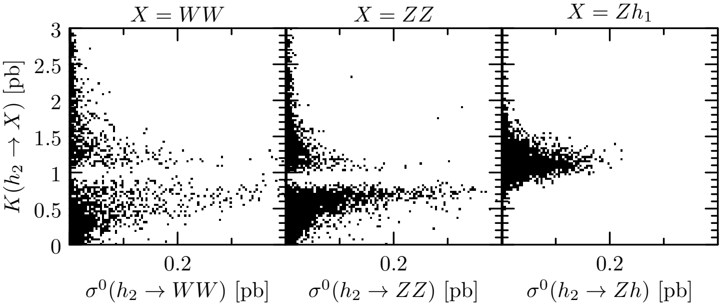
** **arXiv:0811.4169[hep-ph]**, P. Bechtle, O. Brein, S. Heinemeyer, G. Weiglein, K.E. Williams

Parameter Scans: Outlook

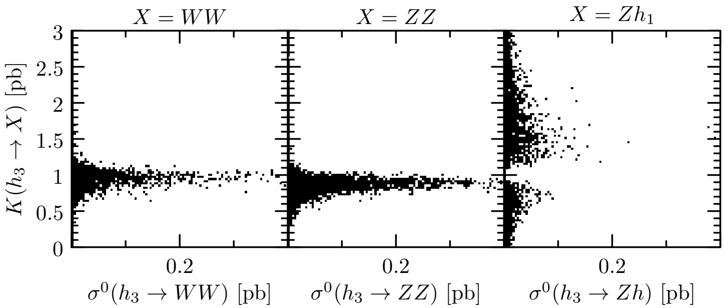
Additions are being made to the parameter scans

- The corrected partial width $\Gamma_{h_i \to h_j h_k}$ will be included
- Further limits will be imposed from the electroweak precision data
  - $g_\mu - 2$
  - $\Delta\rho$
  - Electric dipole moments (electron, neutron, mercury)
  - $B \to X_s \gamma$

Scans of the decay width for h_2



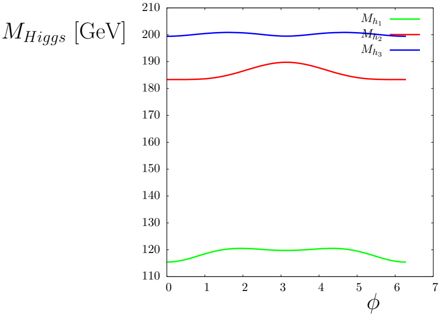
Scans of the decay width for h_3

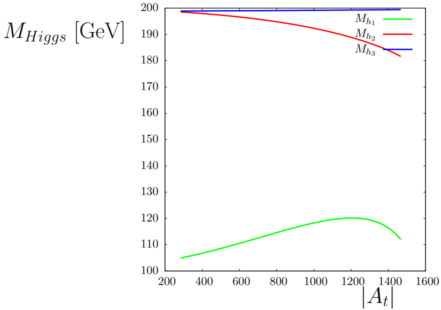


Summary

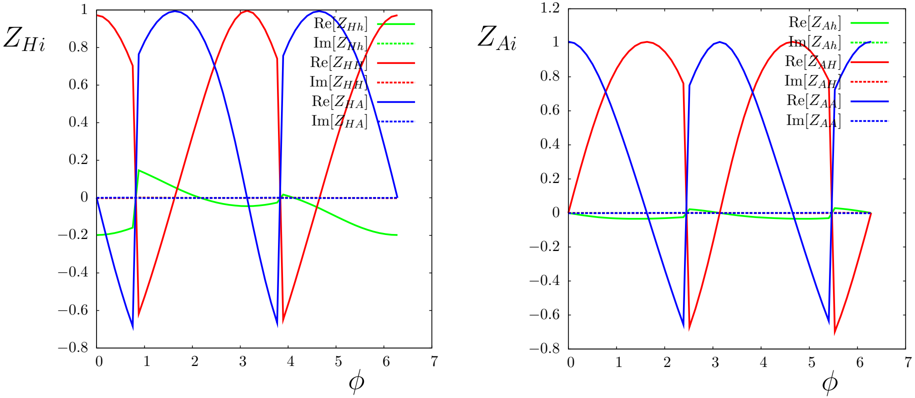
- The decays $h_i \to WW$, $h_i \to ZZ$ and $h_i \to Zh_j$ can be important in the complex MSSM
- Mixing between the neutral MSSM Higgs bosons can be very significant – including this effect at loop level can dramatically alter the corrections
- The full corrections to these decays have been calculated and scans are being performed to discover the most interesting areas of parameter space
- The corrections to the decay width can be phenomenologically relevant

Backup: Higgs masses





Backup: Propagator factors



Backup: Propagator factors