FeynHiggs: An MSSM Higgs Physics Tool

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Outline

- FeynHiggs: Overview
- Masses and Mixings
- Comparison with another Tool

Higgs Sector in the MSSM

In the Minimal Supersymmetric Standard Model (MSSM):

- Two Higgs doublets

  $\Rightarrow$ 5 Higgs bosons: at Born level: CP-even, neutral: h^0, H^0
  CP-odd, neutral: A^0
  charged: $H^\pm$

  with quantum corrections: h^0, H^0, A^0 can mix in general
  $\Rightarrow h_1, h_2, h_3$

- Masses of the Higgs bosons are not independent:

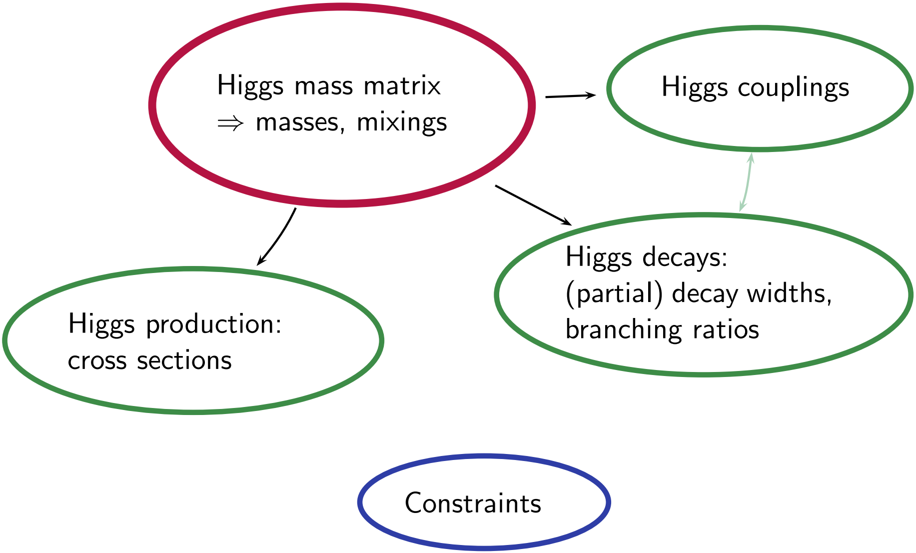
  usuall input: either A^0-mass M_{A^0} oder $H^\pm$-mass $M_{H^\pm}$ and
  $\tan\beta = \frac{v_u}{v_d}$ (ratio of the Higgs vacuum expectation value)

- Lightest Higgs boson: theoretical upper mass bound:

  at Born: $M_{h^0} \leq M_Z = 91$ GeV

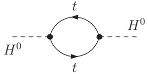
  with quantum corrections: $M_{h_1} \lesssim 135$ GeV

FeynHiggs: Overview



FeynHiggs: Overview

Higgs mass matrix: $$\mathbf{M}(\mathbf{p^2}) = \begin{pmatrix} M^2_{h^0_{\rm Born}} - \hat{\Sigma}_{h^0h^0}(p^2) & -\hat{\Sigma}_{h^0H^0}(p^2) & -\hat{\Sigma}_{h^0A^0}(p^2) \\ -\hat{\Sigma}_{h^0H^0}(p^2) & M^2_{H^0_{\rm Born}} - \hat{\Sigma}_{H^0H^0}(p^2) & -\hat{\Sigma}_{H^0A^0}(p^2) \\ -\hat{\Sigma}_{h^0A^0}(p^2) & -\hat{\Sigma}_{H^0A^0}(p^2) & M^2_{A^0_{\rm Born}} - \hat{\Sigma}_{A^0A^0}(p^2) \end{pmatrix}$$



- Real parameters ($\hat{\Sigma}_{h^0A^0}(p^2) = \hat{\Sigma}_{H^0A^0}(p^2) = 0$):
  - ▷ full one-loop (no NMFV) [Frank, Hahn, Heinemeyer, Hollik, H.R., Weiglein]
    + lead. non-min. flavour viol. (NMFV) [Heinemeyer, Hollik, Merz, Peñaranda]
  - ▷ two-loop: – $\mathcal{O}(\alpha_t\alpha_s)$ [Degrassi, Slavich, Zwirner]
    (more compact than original code [Heinemeyer, Hollik, Weiglein])
    – $\mathcal{O}(\alpha_t^2)$ [Brignole, Degrassi, Slavich, Zwirner]
    – $\mathcal{O}(\alpha_b\alpha_s)$ [Brignole, Degrassi, Slavich, Zwirner]
    – $\mathcal{O}(\alpha_b\alpha_t + \alpha_b^2)$ [Dedes, Degrassi, Slavich]
- Complex parameters ($\hat{\Sigma}_{h^0A^0}(p^2) \neq 0$, $\hat{\Sigma}_{H^0A^0}(p^2) \neq 0$):
  - ▷ full one-loop (no NMFV) [Frank, Hahn, Heinemeyer, Hollik, H.R., Weiglein]
  - ▷ two-loop: – $\mathcal{O}(\alpha_t\alpha_s)$ [Heinemeyer, Hollik, H.R., Weiglein]
    – Interpolation of $\mathcal{O}(\alpha_t^2 + \alpha_b\alpha_t + \alpha_b^2)$ for real parameters

FeynHiggs: Overview

Higgs couplings:

h_i-Z-Z, h_i-W-W, h_i-f-f, h_i-$\tilde{f}$-$\tilde{f}$, h_i-$\tilde{\chi}^0_j$-$\tilde{\chi}^0_k$, h_i-$\tilde{\chi}^\pm_j$-$\tilde{\chi}^\pm_k$, h_i-h_j-Z, h_i-h_j-h_k,
h_i-H^+-H^-, $H^\pm$-f-f, $H^\pm$-$\tilde{f}$-$\tilde{f}$, $H^\pm$-$\tilde{\chi}^0_i$-$\tilde{\chi}^\pm_j$, $H^\pm$-h_i-$W^\pm$

– tree-level + Higgs mixing effects [Frank, Hahn, Heinemeyer, Hollik, H.R., Weiglein]

– h^0-h^0-h^0: + $\mathcal{O}(m_t^4)$-one-loop contributions [Hollik, Peñaranda]

– h^0-b-b: + Δm_b + SM-QCD corrections [Dabelstein], [Carena, Garcia, Nierste, Garcia, Nierste, Wagner], [Braaten, Leveille], [Sakai], [Inami, Kubota], [Dabelstein, Hollik], [Bardin, Vilensky, Khristova], [Drees, Hikasa], [Chankowski, Pokorski, Rosiek], [Coarasa, Jimenez, Sola], [Gorishnii, Kataev, Larin, Surguladze], [Kataev, Kim], [Surguladze], [Chetyrkin, Kwiatkowski], [Larin, van Ritbergen, Vermaseren]

– full one-loop implementation in progress [Weiglein, Williams], [Hahn]

FeynHiggs: Overview

Higgs decays:

- Partial decay width and branching ratios for:

$$h_i \to \quad f\bar{f}, \gamma\gamma, ZZ^{(*)}, WW^{(*)}, gg, \quad h_j Z^*, h_j h_k, H^+H^-, \quad \tilde{f}_j \tilde{f}_k, \quad \tilde{\chi}_j^\pm \tilde{\chi}_k^\pm, \tilde{\chi}_j^0 \tilde{\chi}_k^0,$$

$$H^\pm \to \quad f^{(*)}\bar{f}', \quad h_i W^{\pm *}, \quad \tilde{f}_j \tilde{f}_k', \quad \tilde{\chi}_j^0 \tilde{\chi}_k^\pm$$

  - couplings as before
  - with off-shell effects [Djouadi, Kalinowski, Zerwas]
  - NLO contributions [Vicini et al], [Spira, Djouadi, Graudenz, Zerwas]

- Corresponding channels of an SM Higgs with mass M_{h_i}:

$$h_i^{\text{SM}} \to f\bar{f}, \gamma\gamma, ZZ^{(*)}, WW^{(*)}, gg$$

- $t \to H^+ b, W^+ b$
  - NLO contributions [Coarasa, Garcia, Guasch, Jimenez, Sola], [Campbell, Ellis, Tramontana], [Körner, Mauser], [Carena, Garcia, Nierste, Wagner]

FeynHiggs: Overview

Higgs production:

- Cross-sections (SM total cross-sections multiplied with MSSM effective couplings [Hahn, Heinemeyer, Maltoni, Weiglein, Willenbrock]
  see: http://maltoni.home.cern.ch/maltoni/TeV4LHC/):

▷ $gg \to h_i$: full one-loop + SM NNLO QCD [Catani, de Florian, Grazzini, Nason], [Aglietti, Bonciani, Degrassi, Vicini]

▷ $WW \to h_i$, $ZZ \to h_i$: eff. coupl. + NLO in QCD with MCFM[Campbell, Ellis]

▷ $W \to Wh_i$, $Z \to Zh_i$: eff. coupl. + NNLO in QCD + NLO in EW [Brein, Djouadi, Harlander], [Ciccolini, Dittmaier, Krämer]

▷ $b\bar{b} \to b\bar{b}h_i$: eff. coupl. + NNLO in QCD [Harlander, Kilgore]

▷ $b\bar{b} \to b\bar{b}h_i$, one b tagged: eff. coupl. + NLO in QCD [Campbell, Ellis, Maltoni, Willenbrock], [Dawson, Jackson, Reina, Wackeroth]

▷ $t\bar{t} \to t\bar{t}h_i$: eff. coupl. + NLO in QCD [Beenakker, Dittmaier, Krämer, Plümper, Spira, Zerwas], [Reina, Dawson], [Dawson, Orr, Reina, Wackeroth]

▷ $\tilde{t}\bar{\tilde{t}} \to \tilde{t}\bar{\tilde{t}}h_i$: tree-level + Higgs mixing effects [Sherpa], [FeynHiggs]

▷ $gb \to tH^-$: NLO-SUSY QCD $+\Delta m_b$-effects [Plehn], [Berger, Han, Jiang, Plehn]

FeynHiggs: Overview

Constraints:

- Precision observables:

  ▷ $\Delta\rho$ at $\mathcal{O}(\alpha, \alpha\alpha_s)$, including NMFV effects [Djouadi, Gambino, Heinemeyer, Hollik, Jünger, Weiglein], [Heinemeyer, Hollik, Merz, Peñaranda]

  ▷ M_W, $\sin^2\theta_{\text{eff}}$ via SM formula + $\Delta\rho$ [Awramik, Czakon, Freitas, Weiglein]

  ▷ $BR(b \to s\gamma)$ including NMFV effects [Hahn, Hollik, Weiglein, Peñaranda]

  ▷ $(g_\mu - 2)_{\text{SUSY}}$ including full one- and leading/subleading two-loop SUSY corrections [Moroi], [Degrassi, Giudice], [Heinemeyer, Stöckinger, Weiglein]

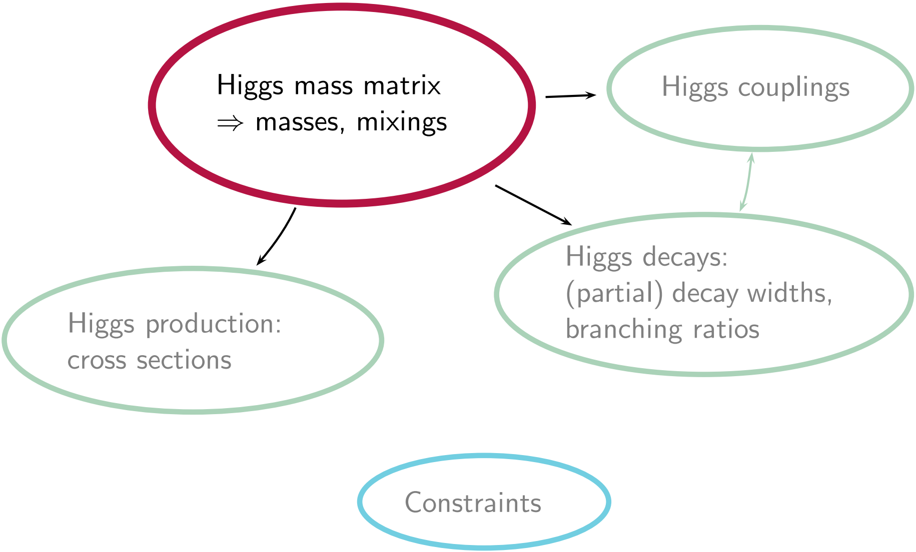
  ▷ EDMs of electron (Th), neutron, Hg [Chang, Keung, Pilaftsis], [Ibrahim, Nath], [Demir, Lebedev, Olive, Pospelov, Ritz], [Olive, Pospelov, Ritz, Santoso]

FeynHiggs: Overview

How to run FeynHiggs?

1. Go to www.feynhiggs.de
2. Download
3. type `./configure`, `make all`, `make install`, `make clean`: library libFH.a is created
4. Run FeynHiggs
   - in the command line mode
   - called from a fortran/C++ code
   - called within a Mathematica program
   - via the web interface

FeynHiggs: Overview



Determination of the Higgs masses

Two-point-function: $-i\hat{\Gamma}(p^2) = p^2 - \mathbf{M}(\mathbf{p^2})$

with the matrix:

$$\mathbf{M}(\mathbf{p^2}) = \begin{pmatrix} M^2_{h^0_{\text{Born}}} - \hat{\Sigma}_{h^0 h^0}(p^2) & -\hat{\Sigma}_{h^0 H^0}(p^2) & -\hat{\Sigma}_{h^0 A^0}(p^2) \\ -\hat{\Sigma}_{h^0 H^0}(p^2) & M^2_{H^0_{\text{Born}}} - \hat{\Sigma}_{H^0 H^0}(p^2) & -\hat{\Sigma}_{H^0 A^0}(p^2) \\ -\hat{\Sigma}_{h^0 A^0}(p^2) & -\hat{\Sigma}_{H^0 A^0}(p^2) & M^2_{A^0_{\text{Born}}} - \hat{\Sigma}_{A^0 A^0}(p^2) \end{pmatrix}$$

Calculate the zeros of the determinant of $\hat{\Gamma}$: $\det[p^2 - \mathbf{M}(\mathbf{p^2})] = 0$

or calculate the eigenvalues $\lambda(p^2)$ of $\mathbf{M}(\mathbf{p^2})$: $\det[\lambda(p^2) - \mathbf{M}(\mathbf{p^2})] = 0$

and solve iteratively: $p^2 - \lambda(p^2) = 0$

$\Rightarrow$ complex pole $\mathcal{M}^2_{h_i} = {M_{h_i}}^2 - i M_{h_i} \Gamma_{h_i}$

with physical mass M_{h_i} and width Γ_{h_i} and $M_{h_1} \leq M_{h_2} \leq M_{h_3}$

FeynHiggs: Results

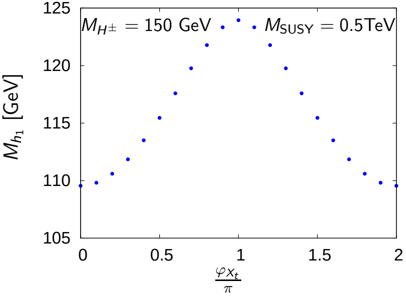
φ_{X_t}-dependence:
(small $M_{H^\pm}$ vs large $M_{H^\pm}$)

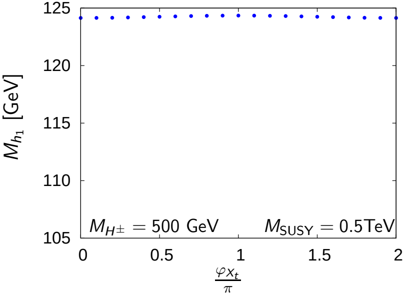
size of the squark mixing:

$X_t := A_t - \mu^* \cot\beta$

$|X_t| = \text{const.} \Rightarrow$ squark masses const.

$|X_t| = 700$ GeV, $\tan\beta = 15$





$\mathcal{O}(\alpha)$ • •

- Higgs mass M_{h_1} depends on φ_{X_t}.
- One-loop corrections are more sensitive to φ_{X_t} for small $M_{H^\pm}$.

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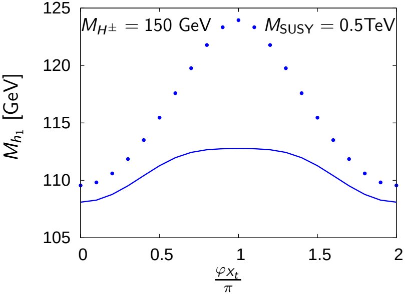

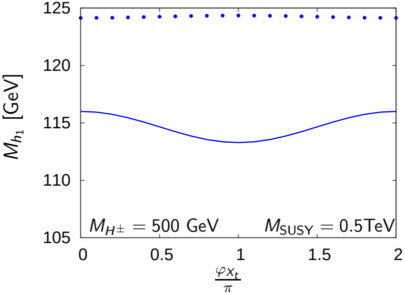

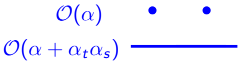

- Higgs mass M_{h_1} depends on φ_{X_t}.
- One-loop corrections are more sensitive to φ_{X_t} for small $M_{H^\pm}$.

FeynHiggs: Results

φ_{X_t}**-dependence:**
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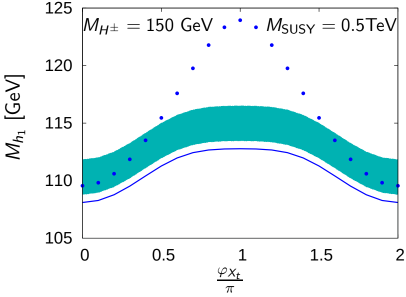

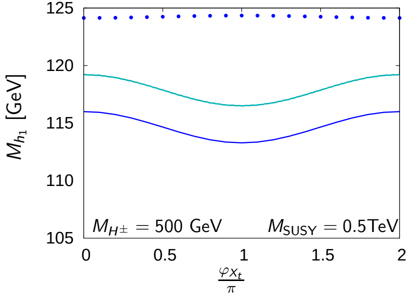

$\mathcal{O}(\alpha)$ • •
$\mathcal{O}(\alpha + \alpha_t\alpha_s)$ ——

Bands: Estimate of the size of the corrections of $\mathcal{O}(\alpha_b\alpha_s + \alpha_t^2 + \alpha_t\alpha_b + \alpha_b^2)$ [Slavich et al.]

FeynHiggs: Results

φ_{X_t}**-dependence:**
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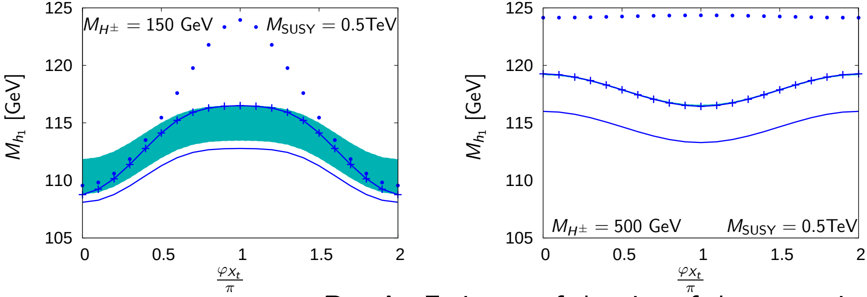
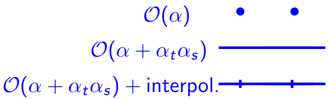




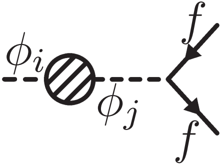
Bands: Estimate of the size of the corrections of $\mathcal{O}(\alpha_b\alpha_s + \alpha_t^2 + \alpha_t\alpha_b + \alpha_b^2)$ [Slavich et al.]

Interpolation: Size of the corrections, known for the MSSM with **real** parameters: Evaluate for $\varphi_{X_t} = 0$ and $\varphi_{X_t} = \pi$ and interpolate

Amplitudes with external Higgs bosons

Mixing between the Higgs bosons:

($\overline{\text{DR}}$/on-shell scheme) $\phi_{\{i,j\}} = H^0,\, h^0,\, A^0$



Finite wave function normalization factors needed:

$$\sqrt{\hat{Z}_i}(\Gamma_i + \hat{Z}_{ij}\Gamma_j + \hat{Z}_{ik}\Gamma_k)$$

- $\hat{Z}_i$ ensures that residuum is set to 1
- $\hat{Z}_{ij}$ describes transition $i \to j$

Definition of mixing matrix $\hat{Z}$ (`ZHiggs in FeynHiggs`):

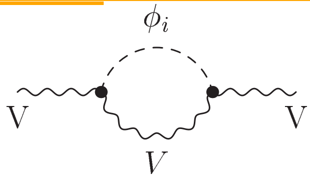
$$\tilde{\mathbf{Z}}_{ij} = \sqrt{\hat{Z}_i}\hat{Z}_{ij}, \quad \hat{Z}_{ii} = 1$$

Vertex with external Higgs boson:

$$\tilde{\mathbf{Z}}_{ii}\Gamma_i + \tilde{\mathbf{Z}}_{ij}\Gamma_j + \tilde{\mathbf{Z}}_{ik}\Gamma_k$$

Amplitudes with internal Higgs bosons

Diagrams with internal Higgs bosons enter precision observables (W-mass, ...):



- Calculation with Born states $\phi_i = H^0,\ h^0,\ A^0$: no problem
- Calculation with $\phi_i = h_1,\ h_2,\ h_3 \Rightarrow$ Inclusion of higher order effects:

One possibility: Use of effective couplings:

Consider $\tilde{\mathbf{Z}}_{ij}$ as mixing matrix:

Problem: $\tilde{\mathbf{Z}}_{ij}$ is a non-unitary matrix (no rotation matrix)

Further approximations necessary (`UHiggs in FeynHiggs`):

effective potential approach: $\tilde{\mathbf{Z}}(\hat{\Sigma}(p^2)) \to \tilde{\mathbf{Z}}(\hat{\Sigma}(0)) = \mathcal{U}$

on-shell approximation: $\tilde{\mathbf{Z}}(\hat{\Sigma}(p^2)) \to \tilde{\mathbf{Z}}(\mathrm{Re}\hat{\Sigma}(p^2_{\mathrm{OS}})) = \mathcal{R}$

$\hat{\Sigma}_{ii}(p^2_{\mathrm{OS}} = M^2_{i_{\mathrm{Born}}})$

$\hat{\Sigma}_{ij}(p^2_{\mathrm{OS}} = (M^2_{i_{\mathrm{Born}}} + M^2_{j_{\mathrm{Born}}})/2)$

Couplings

One example:

Coupling of two gauge bosons ($V = W, Z$) and one Higgs boson:

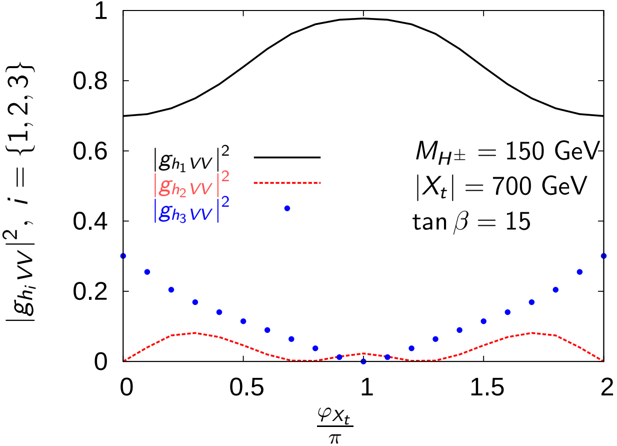
$$g_{h_i VV} = [U_{i1} \cos(\beta - \alpha) + U_{i2} \sin(\beta - \alpha)] \, g_{H_{\text{SM}} VV}$$

standard model coupling ↗

- only CP-even components of the Higgs bosons couple to V

- all three Higgs bosons can have a CP-even component

FeynHiggs: Results: φ_{X_t}-Dependence of Couplings



- Here: $g_{h_i VV}$ is normalized to the standard model coupling.
- $|g_{h_i VV}|^2$ do depend on the phase φ_{X_t}, $|X_t| = 700$ GeV.
- For $\varphi_{X_t} = 0$, h_2 is the CP-odd Higgs boson, for $\varphi_{X_t} = \pi$, it is h_3.

FeynHiggs and CPsuperH

Two programs: input: MSSM parameters
output: Higgs masses

Features (not complete):

FeynHiggs:	CPsuperH [Lee, Pilaftsis, Carena, Choi, Drees, Ellis, Wagner]:
full one-loop corr.	gaugino/higgsino (leading) log one-loop contr.
two-loop corr.:	fermionic/sfermionic contr.:
$\mathcal{O}(\alpha_t\alpha_s)$ complex	up to two-loop (leading) log
$\mathcal{O}(\alpha_b\alpha_s + \alpha^2_{\{t,b\}})$ real	$\mathcal{O}(\alpha_{\{t,b\}}\alpha_s + \alpha^2_{\{t,b\}})$ complex

Input:

on-shell squark parameters	$\overline{\text{DR}}$ squark parameters

FeynHiggs and CPsuperH: Comparison

Input:

on-shell squark parameters	$\overline{\text{DR}}$ squark parameters
FeynHiggs	CPsuperH

Transformation from one scheme to another necessary:

Use relation:

$$X^{\overline{\text{DR}}} + \delta X^{\overline{\text{DR}}} = X^{\text{OS}} + \delta X^{\text{OS}}$$

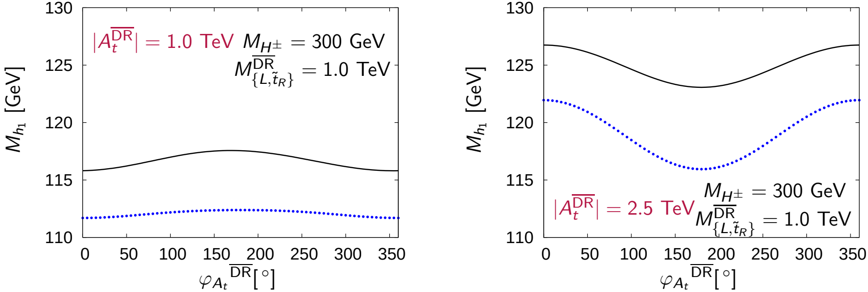
with $X = \{A_t, M_L, M_{\tilde{t}_R}\}$: squark soft breaking parameter

δX^{OS} is then determined by the on-shell counterterms:

$$\delta X^{\text{OS}} = \delta X^{\text{OS}}(\delta m_{\tilde{t}_1}^{\text{OS}}, \delta m_{\tilde{t}_2}^{\text{OS}}, \delta m_t^{\text{OS}}, \delta\theta_{\tilde{t}}^{\text{OS}}, \delta\varphi_{\tilde{t}}^{\text{OS}})$$

FeynHiggs and CPsuperH: Comparison

$\varphi_{A_t}{}^{\overline{\mathrm{DR}}}$**-dependence for different** $|A_t^{\overline{\mathrm{DR}}}|$**:**



CPsuperH ———

FeynHiggs (up to $\mathcal{O}(\alpha_t\alpha_s)$) •

Differences:

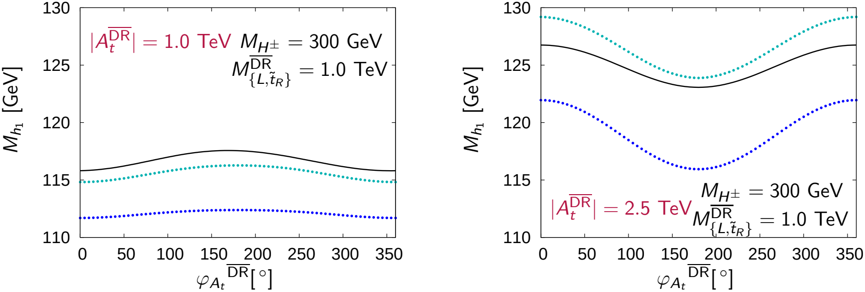
CPsuperH:

(leading) log $\mathcal{O}(\alpha_t^2)$ terms

FeynHiggs: non-log $\mathcal{O}(\alpha_t\alpha_s)$ terms

FeynHiggs and CPsuperH: Comparison

$\varphi_{A_t}{}^{\overline{\mathrm{DR}}}$**-dependence for different** $|A_t^{\overline{\mathrm{DR}}}|$**:**



CPsuperH

FeynHiggs (up to $\mathcal{O}(\alpha_t\alpha_s)$)

FeynHiggs with Interpolation

Differences:

CPsuperH:

(leading) log $\mathcal{O}(\alpha_t^2)$ terms

FeynHiggs: non-log $\mathcal{O}(\alpha_t\alpha_s)$ terms

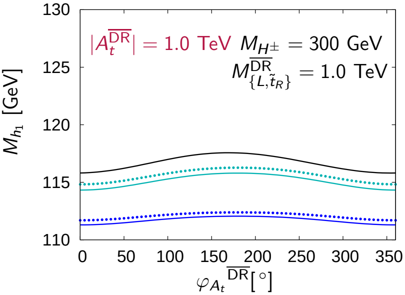
FeynHiggs: non-log $\mathcal{O}(\alpha_t\alpha_s)$ terms

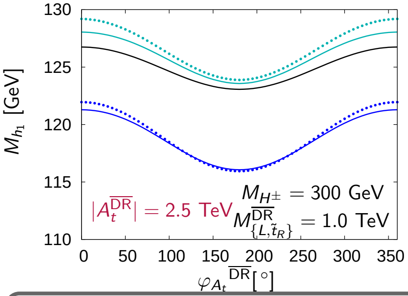
$+$ interpolation of $\mathcal{O}(\alpha_t^2)$ terms

FeynHiggs and CPsuperH: Comparison

$\varphi_{A_t}{}^{\overline{\mathrm{DR}}}$-dependence for different $|A_t^{\overline{\mathrm{DR}}}|$:

Preliminary





CPsuperH ———

FeynHiggs (up to $\mathcal{O}(\alpha_t\alpha_s)$) · ———

FeynHiggs with Interpolation · ———

Parameter transformation: $\mathcal{O}(\alpha_s)$ $\mathcal{O}(\alpha_s + \alpha_t)$

Differences:

CPsuperH:

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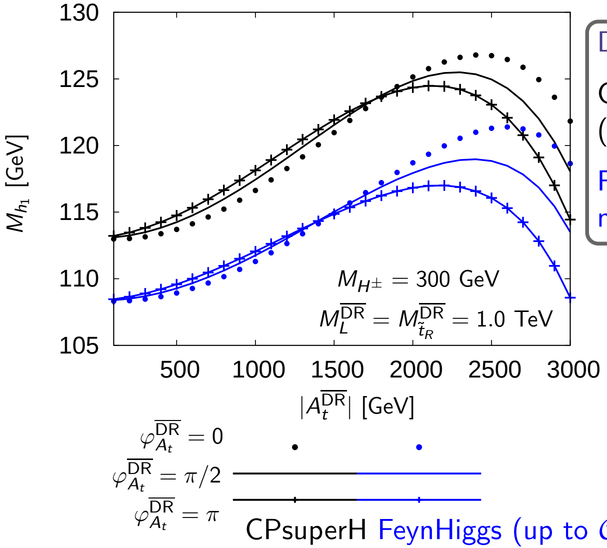
$+$ interpolation of $\mathcal{O}(\alpha_t^2)$ terms

FeynHiggs and CPsuperH: Comparison

$A_t^{\overline{DR}}$-dependence:

Preliminary



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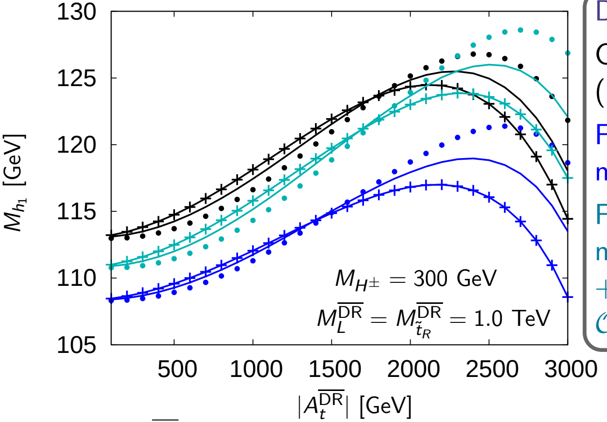
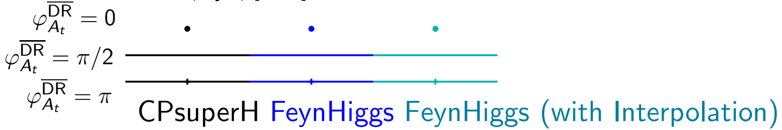
FeynHiggs and CPsuperH: Comparison

Preliminary

$A_t^{\overline{\text{DR}}}$-dependence:





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(leading) log $\mathcal{O}(\alpha_t^2)$ terms

FeynHiggs:
non-log $\mathcal{O}(\alpha_t \alpha_s)$ terms

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$+$ interpolation of
$\mathcal{O}(\alpha_t^2)$ terms

Summary

FeynHiggs (www.feynhiggs.de):

- Core: MSSM Higgs masses and mixing calculation:
  - ▷ In the real MSSM: up to $\mathcal{O}(\alpha_t\alpha_s + \alpha_b\alpha_s + \alpha_t^2 + \alpha_t\alpha_b + \alpha_b^2)$ + including NMFV effects.
  - ▷ In the complex MSSM: up to $\mathcal{O}(\alpha_t\alpha_s)$ + interpolation of the $\mathcal{O}(\alpha_b\alpha_s + \alpha_t^2 + \alpha_t\alpha_b + \alpha_b^2)$ terms.
- Also: Different Higgs decay rates and Higgs production cross sections are given.
- Further: Constraints as the W-mass are calculated.
- Use parameter transformation when comparing to values given by CPsuperH.