CP-Violating Effects in the Higgs Sector of the MSSM

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Outline

- Higgs sector in the MSSM with CP-phases
- Mass of the lightest Higgs boson
- Effective couplings

in coll. with M. Frank, T. Hahn, S. Heinemeyer, W. Hollik and G. Weiglein
based on JHEP **0702** (2007) 047 [arXiv:hep-ph/0611326]

Minimal Supersymmetric Standard Model (MSSM)

- supersymmetric extension of the standard model

  Supersymmetry (SUSY):

  fermionic degrees of freedom $\leftrightarrow$ bosonic degrees of freedom

  $\Rightarrow$ superpartner for the standard model particles

- two Higgs doublets

- explicit SUSY breaking $\Rightarrow$ many new (complex) parameters

Complex Parameters

Complex parameters can lead to CP- or T-violation:

T-operator: antiunitary :

complex conjugation of complex parameters

MSSM: Parameters are complex in general:

They are not forbidden by a symmetry as

CP-symmetry is no fundamental symmetry in nature:

- observation of CP-violation in K- and B-systems
- CP-violation is needed for explanation of baryogenesis

Two Higgs doublets

Two reasons for two Higgs doublets:

- mass generation for both up- and down-type quarks

  problem in contrast to SM:

  charge conjugated Higgs superfield will break supersymmetry

- anomaly cancelations

  problem in contrast to SM:

  introduction of further fermions with non-vanishing hypercharges

The Higgs potential in the MSSM

Higgs potential:

$$V_{\text{Higgs}} = \frac{g^2 + g'^2}{8}(H_1^+ H_1 - H_2^+ H_2)^2 + \frac{g^2}{2}|H_1^+ H_2|^2 + |\mu|^2(H_1^+ H_1 + H_2^+ H_2)$$

$$+ (m_1^2 H_1^+ H_1 + m_2^2 H_2^+ H_2) + (\epsilon_{ij}|m_{12}^2| e^{i\varphi_{m_{12}^2}} H_1^i H_2^j + h.c.)$$

$g,\ g'$:	gauge couplings
μ:	coupl. betw. Higgs superfields
$m_1^2,\ m_2^2,\ m_{12}^2$:	soft breaking parameters

one complex parameter: $m_{12}^2 = |m_{12}^2| e^{i\varphi_{m_{12}^2}}$

The Higgs potential in the MSSM

if $m_{12} = 0$ and $\mu = 0$:

MSSM: further U(1) symmetry:
Peccei-Quinn symmetry

The Higgs potential in the MSSM

if $m_{12} = 0$ and $\mu = 0$:

MSSM: further U(1) symmetry: Peccei-Quinn symmetry

if $m_{12} \neq 0$ and $\mu \neq 0$:

perform a Peccei-Quinn transformation with angle φ_{PQ}

redefine:

$$(m_{12}^2)' = |m_{12}^2| e^{i(\varphi_{m_{12}^2} - \varphi_{\mathrm{PQ}})}$$

$$(\mu)' = |\mu| e^{i(\varphi_\mu - \varphi_{\mathrm{PQ}})}$$

$\Longrightarrow$ physical contents of the Lagrangian does not change

$\Longrightarrow$ m_{12}^2 can always be chosen to be real

Higgs vacuum expectation values

Scalar Higgs doublets in the vacuum state:

$$H_1|_{\text{vac.}} = \begin{pmatrix} v_1 \\ 0 \end{pmatrix} \ , \qquad H_2|_{\text{vac.}} = e^{i\xi} \begin{pmatrix} 0 \\ v_2 \end{pmatrix}$$

$\Longrightarrow$ vacuum expectation values can differ by a phase ξ

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⟹ vacuum expectation values can differ by a phase ξ

Expansion about the vacuum:

$$H_1 = \begin{pmatrix} v_1 + \frac{1}{\sqrt{2}}(\phi_1^0 - i\zeta_1^0) \\ -\phi_1^- \end{pmatrix} \;, \qquad H_2 = e^{i\xi} \begin{pmatrix} \phi_2^+ \\ v_2 + \frac{1}{\sqrt{2}}(\phi_2^0 + i\zeta_2^0) \end{pmatrix}$$

- four real scalar fields: ϕ_1^0, ϕ_2^0, ζ_1^0, ζ_2^0
- two complex scalar fields: $\phi_1^\pm$, $\phi_2^\pm$

} no mass eigenstates

The Higgs sector at Born level

Mass terms: bilinear terms in the Higgs potential:

$$V_{\text{Higgs}}|_{\text{bil.}} = \frac{1}{2}\left(\phi_1^0, \phi_2^0\right) \mathcal{M}_{\phi^0} \begin{pmatrix} \phi_1^0 \\ \phi_2^0 \end{pmatrix} + \ldots \text{ mixing betw. } (\phi_1^0, \phi_2^0), (\zeta_1^0, \zeta_2^0), \ldots$$

$$+ \frac{1}{2}\left(\phi_1^0, \phi_2^0\right) \mathcal{M}_{\phi^0\zeta^0} \begin{pmatrix} \zeta_1^0 \\ \zeta_2^0 \end{pmatrix} + \ldots \text{ mixing betw. } (\phi_1^0, \phi_2^0, \zeta_1^0, \zeta_2^0)$$

Matrix $\mathcal{M}_{\phi^0\zeta^0}$ generates mixing between the ϕ^0- and ζ^0-fields:

$$\mathcal{M}_{\phi^0\zeta^0} = \begin{pmatrix} 0 & m_{12}^2 \sin(\xi) \\ -m_{12}^2 \sin(\xi) & 0 \end{pmatrix}$$

$\Longrightarrow$ no such mixing in case of real parameters

The Higgs sector at Born level

Minimum condition for the vacuum:

$$\frac{\partial V_{\text{Higgs}}}{\partial H_j^i}\Big|_{\text{vac.}} = 0\ ,\quad i,j = 1,2$$

This is fulfilled if terms linear in the Higgs fields vanish:

$$V_{\text{Higgs}}|_{\text{lin}} = -t_{\phi_1^0}\phi_1^0 - t_{\phi_2^0}\phi_2^0 - t_{\zeta_1^0}\zeta_1^0 - t_{\zeta_2^0}\zeta_2^0$$

In particular:

$$t_{\zeta_1^0} = -\frac{v_1}{v_2}t_{\zeta_2^0} = \sqrt{2}\, m_{12}^2\, v_2 \sin(\xi) \stackrel{!}{=} 0$$

$\Longrightarrow$ phase ξ must vanish: $\xi = 0$

at Born level: no CP-violating phases

The Higgs sector at Born level

Physical mass eigenstates:

- 2 CP-even Higgs bosons: H^0, h^0 $\xleftarrow{\text{mixing}}$ ϕ_1^0, ϕ_2^0
- 1 CP-odd Higgs boson: A^0 $\xleftarrow{\text{mixing}}$ ζ_1^0, ζ_2^0
- 2 charged Higgs bosons: $H^\pm$ $\xleftarrow{\text{mixing}}$ $\phi_1^\pm$, $\phi_2^\pm$

Masses of the Higgs bosons:

- not all independent
- lightest Higgs boson: h^0

  upper theoretical Born mass limit: $M_{h^0} \leq M_Z$

The mass of the lightest Higgs boson

Real parameters:

upper theoretical Born mass limit: $M_{h^0} \leq M_Z = 91$ GeV

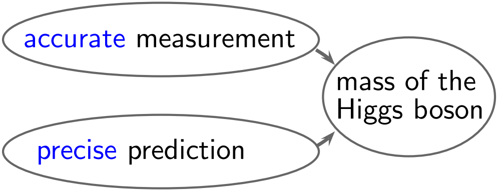
with quantum corrections of higher orders: $M_{h^0} \lesssim 140$ GeV

↖ dependent on the MSSM parameters

Complex parameters:

quantum corrections will also depend on parameter phases

Discovery of the Higgs boson:

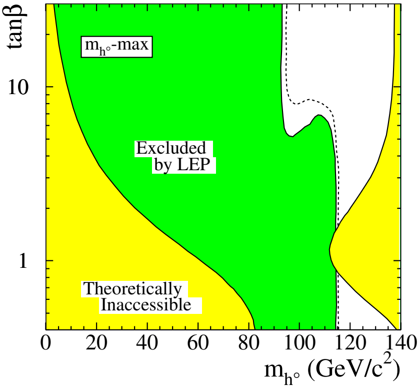


$\Rightarrow$ strong bounds on the MSSM parameter, e.g. on $\tan\beta = \frac{v_2}{v_1}$

The mass of the lightest Higgs boson

Before the discovery of the Higgs boson:

Exclusion of parts of the parameter space



Exclusion limits for $\tan\beta$ in the m_{h^0}-max scenario (real parameters) [LEP Higgs working group]

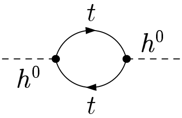
Determination of the Higgs masses

Two-point-function:

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

with the matrix:

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



Real parameters:

$$\hat{\Sigma}_{H^0A^0}(p^2) = \hat{\Sigma}_{h^0A^0}(p^2) = 0$$

no mixing between CP-even and CP-odd states

Determination of the Higgs masses

- One way:

  Propagator matrix:

$$\Delta(p^2) = -\left[\hat{\Gamma}(p^2)\right]^{-1}$$

  Inversion of $\hat{\Gamma}$ $\Rightarrow$ diagonal propagators ($i = H^0,\ h^0,\ A^0$):

$$\Delta_{ii}(p^2) = \frac{i}{p^2 - M^2_{i_{\rm Born}} + \hat{\Sigma}^{\rm eff}_{ii}(p^2)}$$

  with the self energy term:

$$\hat{\Sigma}^{\rm eff}_{ii}(p^2) = \hat{\Sigma}_{ii}(p^2) - i\,\frac{2\hat{\Gamma}_{ij}(p^2)\hat{\Gamma}_{jk}(p^2)\hat{\Gamma}_{ki}(p^2) - \hat{\Gamma}^2_{ki}(p^2)\hat{\Gamma}_{jj}(p^2) - \hat{\Gamma}^2_{ij}(p^2)\hat{\Gamma}_{kk}(p^2)}{\hat{\Gamma}_{jj}(p^2)\hat{\Gamma}_{kk}(p^2) - \hat{\Gamma}^2_{jk}(p^2)}$$

Determination of the Higgs masses

Poles $\mathcal{M}_i^2$ of the diag. propagators:

$$\mathcal{M}_i^2 - M_{i_{\rm Born}}^2 + \hat{\Sigma}_{ii}^{\rm eff}(\mathcal{M}_i^2) = 0$$

Complex pole with phys. mass M and width Γ :

$$\mathcal{M}^2 = M^2 - i M \Gamma$$

Expansion around M^2 up to first order in Γ:

$$M_i^2 - M_{i\rm Born}^2 + {\rm Re}\hat{\Sigma}_{ii}^{\rm eff}(M_i^2) + \frac{{\rm Im}\hat{\Sigma}_{ii}^{\rm eff}(M_i^2)\left({\rm Im}\hat{\Sigma}_{ii}^{\rm eff}\right)'(M_i^2)}{1 + \left({\rm Re}\hat{\Sigma}_{ii}^{\rm eff}\right)'(M_i^2)} = 0$$

Iterative solution $\Rightarrow$ Higgs masses M_i^2

Determination of the Higgs masses

- Second way:

  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:

$$p^2 - \lambda(p^2) = 0$$

Higgs masses at higher orders (incl. CP-phases)

Status:

- Higgs masses at higher order without CP-phases ⇒ good shape (up to leading 3-loop [Martin; Harlander, Kant, Mihaila, Steinhauser])

Including CP-phases:

- Eff. potential approach, up to two-loop leading-log contributions (sfermionic/fermionic contributions) [Pilaftsis, Wagner], [Demir], [Choi, Drees, Lee], [Carena, Ellis, Pilaftsis, Wagner]
- Gaugino contributions [Ibrahim, Nath]
- Effects of imaginary parts at one-loop [Ellis, Lee, Pilaftsis], [Choi, Kalinowski, Liao, Zerwas], [Bernabeu, Binosi, Papavassiliou]

Here: calculation in the Feynman diagrammatic approach

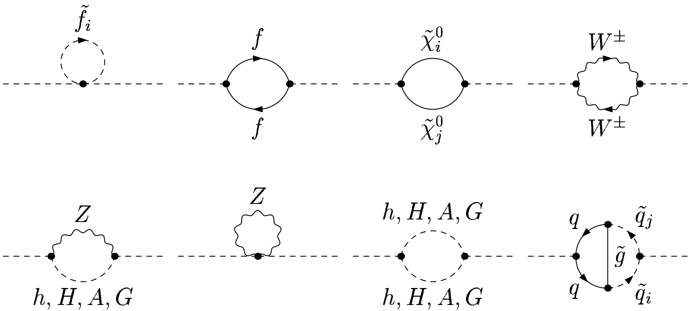
(full one-loop + two-loop $\mathcal{O}(\alpha_t\alpha_s)$) $\alpha_t = \frac{\lambda_t^2}{4\pi}$, λ_t = Yukawa coupl.

Renormalized self energies (SE)

Renormalized SE = Unrenormalized SE + Counterterm part

$$\hat{\Sigma} = \Sigma + \delta\Sigma$$

Feynman diagrams contributing to Σ:



Parameters in the Higgs sector

Original parameters in the Higgs sector:

g	g'	v_1	v_2	$\lvert m_{12}^2\rvert$	m_1^2	m_2^2	ξ

↓ Transformation ↓

e	M_W	M_Z	$\tan\beta$	$M_{H^\pm}$	t_{h^0}	t_{H^0}	t_{A^0}
electr. magn. coupl. const.	gauge boson masses		ratio of vac. exp. values $\tan\beta = \frac{v_2}{v_1}$	mass of $H^\pm$	tadpole parameter of h^0, H^0		tadpole parameter of A^0

Mass matrix counterterm

Renormalization of the parameters:

$$M_x \rightarrow M_x + \delta M_x^{(1)} + \delta M_x^{(2)} + \ldots \qquad x = \{W, Z, H^\pm\}$$

$$\tan\beta \rightarrow \tan\beta + \delta\tan^{(1)}\beta + \delta\tan^{(2)}\beta + \ldots$$

$$t_\phi \rightarrow t_\phi + \delta t_\phi^{(1)} + \delta t_\phi^{(2)} + \ldots \qquad \phi = \{H^0, h^0, A^0\}$$

Renormalization of the neutral Higgs mass matrix $\mathcal{M}_n$:

$$\mathcal{M}_n(M_x, \tan\beta, t_\phi) \rightarrow \mathcal{M}_n(M_x, \tan\beta, t_\phi)$$

$$+ \, \delta\mathcal{M}_n^{(1)}(M_x, \tan\beta, t_\phi, \delta M_x^{(1)}, \delta\tan^{(1)}\beta, \delta t_\phi^{(1)}) + \ldots$$

Higgs mass counterterms

h^0-mass counterterm (α = Born mixing angle of CP-even Higgses h^0, H^0):

$$\delta M_{h^0}^{(1)} = \cos^2(\alpha-\beta)\big(\delta M_{H^\pm}^{2\,(1)} - \delta M_W^{2\,(1)}\big) + \sin^2(\alpha+\beta)\delta M_Z^{2\,(1)}$$
$$+\Big[\big(M_{H^\pm}^2 - M_W^2\big)\sin(2(\alpha-\beta)) + M_Z^2\sin(2(\alpha+\beta))\Big]\cos^2\beta\,\delta\tan^{(1)}\beta$$
$$+\frac{e\sin(\alpha-\beta)}{4M_W\sin\theta_W}\Big[\Big(3+\cos(2(\alpha-\beta))\Big)\delta t_{h^0}^{(1)} + \sin(2(\alpha-\beta))\delta t_{H^0}^{(1)}\Big]$$

“Mass” counterterm for the h^0-A^0-mixing:

$$\delta M_{h^0 A^0}^{(1)} = \frac{e\sin(\alpha-\beta)}{2M_W\sin\theta_W}\delta t_{A^0}^{(1)}$$

Renormalized Higgs self energies at one-loop

Renormalized $h^0 h^0$-self energy:

$$\hat{\Sigma}^{(1)}_{h^0 h^0}(p^2) = \Sigma^{(1)}_{h^0 h^0}(p^2) + \delta Z^{(1)}_{h^0 h^0}(p^2 - M^2_{h^0_{\text{Born}}}) - \delta M^{(1)}_{h^0}$$

with the field renormalization constant:

$$\delta Z^{(1)}_{h^0 h^0} = \sin^2\alpha\, \delta Z^{(1)}_{H_1} + \cos^2\alpha\, \delta Z^{(1)}_{H_2}$$

Field renormalization of the Higgs doublets:

$$H_i \to (\mathbb{1} + \frac{1}{2}\delta Z^{(1)}_{H_i} + \ldots) H_i \qquad i = 1, 2$$

Renormalized $h^0 A^0$-mixing:

$$\hat{\Sigma}^{(1)}_{h^0 A^0}(p^2) = \Sigma^{(1)}_{h^0 A^0}(p^2) - \delta M^{(1)}_{h^0 A^0}$$

Renormalization conditions

Within an $\overline{\textbf{DR}}$/**on-shell** scheme in the Higgs sector:

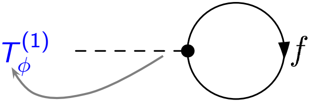
- define the $H^{\pm}$-, W- as well as the Z-mass as **pole mass**

  $\Rightarrow$ directly related to a **physical observable**

$$\delta M_X^{(1)} = \text{Re}\Sigma_{XX}^{(1)}(M_X^2), \qquad X = \{H^{\pm}, W, Z\}$$

- **no** shift of the minimum of the Higgs potential

$$\delta t_\phi^{(1)} = -T_\phi^{(1)}$$



- $\overline{\textbf{DR}}$-scheme for field and $\tan\beta$ renormalization

$$\delta \tan^{(1)}\beta = \delta \tan\beta^{\overline{\text{DR}}}, \qquad \delta Z_{H_i}^{(1)} = \delta Z_{H_i}^{\overline{\text{DR}}}$$

Phases in other sectors

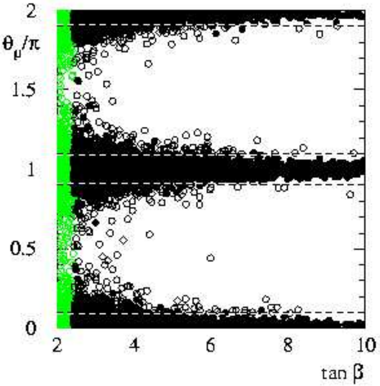
- Sfermion sector:
  - phase φ_{A_f} of the trilinear coupling A_f
- Higgsino sector:
  - phase of μ
- Gaugino sector:
  - phases of the gaugino mass parameters M_1, M_2, M_3
    - one phase can be eliminated (R-Transformation), often φ_{M_2}
    - phase φ_{M_3} is the phase of the gluino mass parameter

      $\Rightarrow$ enters into the Higgs sector at two-loop level

soft breaking parameter

Phase of μ

Constrained by measurements of electric dipole moments:



15 parameter scan:

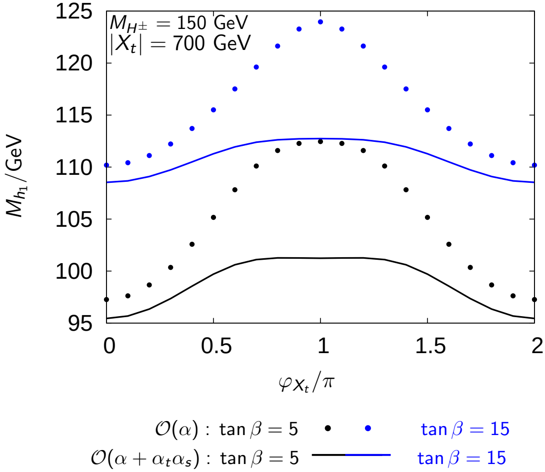
allowed values: black dots

[Barger, Falk, Han, Jiang, Li, Plehn]

- In large areas: The phase of μ is small.

Results: φ_{X_t}-dependence

Size of the squark mixing: $X_t := A_t - \mu^* \cot\beta$



- Higgs mass M_{h_1} does depend on the phase φ_{X_t}, $|X_t| = 700$ GeV.

Results: φ_{X_t}-dependence

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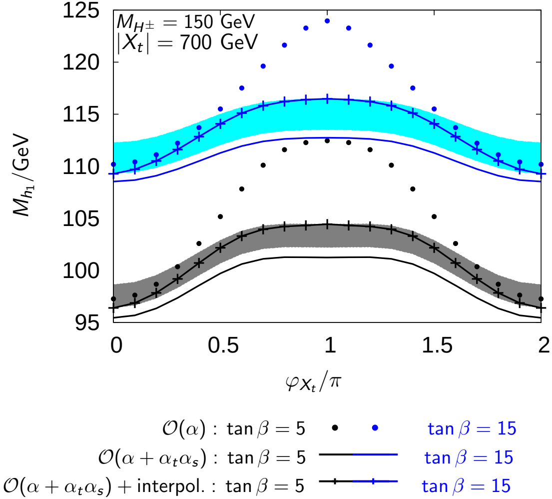


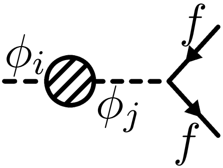
Bands: Estimate of the size of the corrections of $\mathcal{O}(\alpha_b\alpha_s + \alpha_t^2 + \alpha_t\alpha_b + \alpha_b^2)$ [Slavich et al.], FeynHiggs

Interpolation: Size of above 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 the residue is set to 1:

$$\hat{Z}_i = \frac{1}{1 + \left(\text{Re}\hat{\Sigma}_{ii}^{\text{eff}}\right)'(M_i^2)}$$

$\hat{Z}_{ij}$ describes transition $i \to j$:

$$\hat{Z}_{ij} = \frac{\Delta_{ij}(p^2)}{\Delta_{ii}(p^2)}\ \Big|_{p^2=M_i^2}$$

Amplitudes with external Higgs bosons

Mixing between the Higgs bosons:

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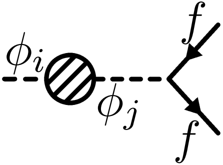


Finite wave function normalization factors needed:

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

Mixing matrix ($\hat{Z}_{ii} = 1$):

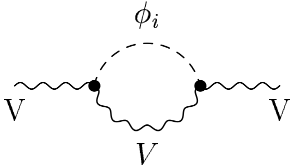
$$\tilde{\mathbf{Z}}_{ij} = \sqrt{\hat{Z}_i}\hat{Z}_{ij}$$

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)

  $\Rightarrow$ further approximations necessary

Amplitudes with internal Higgs bosons

Further approximations ($\hat{=}$ effective potential approach):

$$\tilde{\mathbf{Z}}(\hat{\Sigma}(p^2)) \to \tilde{\mathbf{Z}}(\hat{\Sigma}(0)) = \mathcal{R}$$

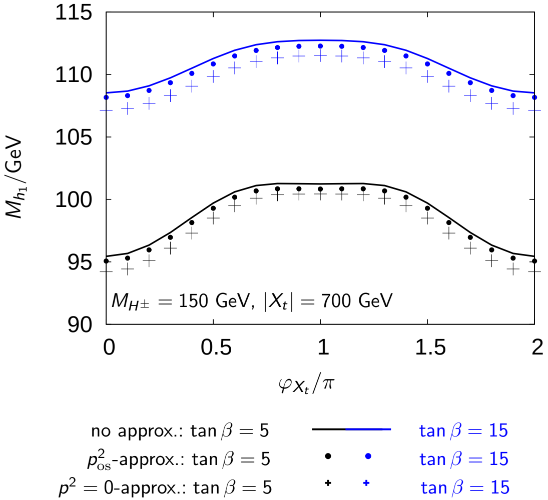
$\mathcal{R}$ diagonalizes matrix $\mathbf{M}(\mathbf{0})$:

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix}_{p^2=0} = \mathcal{R} \begin{pmatrix} H^0 \\ h^0 \\ A^0 \end{pmatrix}, \quad \mathcal{R}\,\mathbf{M}(\mathbf{0})\,\mathcal{R}^\dagger = \begin{pmatrix} M^2_{h_1,p^2=0} & 0 & 0 \\ 0 & M^2_{h_2,p^2=0} & 0 \\ 0 & 0 & M^2_{h_3,p^2=0} \end{pmatrix}$$

Other possibility: use $\mathcal{U}$: $\hat{\Sigma}_{ii}(p^2_{\rm OS} = M^2_{i_{\rm Born}})$, $\hat{\Sigma}_{ij}\left(p^2_{\rm OS} = (M^2_{i_{\rm Born}} + M^2_{j_{\rm Born}})/2\right)$:

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix}_{p^2_{\rm OS}} = \mathcal{U} \begin{pmatrix} H^0 \\ h^0 \\ A^0 \end{pmatrix}, \quad \mathcal{U}\,\mathrm{Re}\left(\mathbf{M}(p^2_{\rm OS})\right)\mathcal{U}^\dagger = \begin{pmatrix} M^2_{h_1,p^2_{\rm OS}} & 0 & 0 \\ 0 & M^2_{h_2,p^2_{\rm OS}} & 0 \\ 0 & 0 & M^2_{h_3,p^2_{\rm OS}} \end{pmatrix}$$

Results: φ_{X_t}-dependence of M_{h_1} (diff. approx.)



- The different approximations apply only for the **one-loop** contributions (two-loop contr. are calculated with $p^2 = 0$).
- The $p^2 = 0$-result differs by up to 1.5 GeV from the full result.
- The p^2_{os}-result differs by less than 0.5 GeV from the full result.

Couplings

One example:

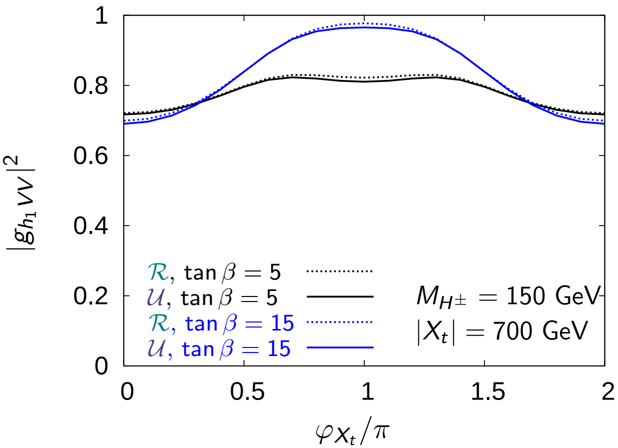
Coupling of two gauge bosons ($V = W,\, Z$) and one Higgs boson:

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

standard model coupling

- only CP-even components of the Higgs bosons couple to V
- all three Higgs bosons can have a CP-even component

Results: φ_{X_t}-dependence of couplings



- Here: $g_{h_1 VV}$ is normalized to the standard model coupling.
- $|g_{h_1 VV}|^2$ does depend on the phase φ_{X_t}.
- $\mathcal{R}_{p^2=0}$ and $\mathcal{U}_{p_{\rm OS}}$ give similar results with only tiny differences.

Summary

- At **Born** level: **no** CP-violation in the Higgs sector
- **Quantum corrections** can **induce** CP-violation.
- **Quantum corrections** have to be taken into account:
  - prediction of Higgs boson masses
  - amplitudes with external Higgs bosons ⇒ $\tilde{\mathbf{Z}}$
  - amplitudes with internal Higgs bosons ⇒ $\mathcal{R}$, $\mathcal{U}$
- The **full one-loop** and the **two-loop $\mathcal{O}(\alpha_t\alpha_s)$** contributions with the **complete phase dependence** are implemented into FeynHiggs.
- **FeynHiggs2.6** is available at www.feynhiggs.de .