Higgs-boson decay to four fermions in the Two-Higgs-Doublet Model

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based on arXiv:1704.02645 and upcoming

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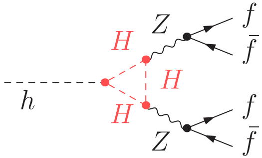
Higgs-boson decay to four fermions

- One of the best measured Higgs-decay channels
- Higgs decay to four charged leptons: very clean channel
- Beyond-Standard-Model effects?



Two-Higgs-Doublet Model

Higgs potential:

$$V = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 + m_{12}^2 (\Phi_1^\dagger \Phi_2 + \text{h.c.})$$
$$+\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2)$$
$$+\lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \lambda_5 \left[(\Phi_1^\dagger \Phi_2)^2 + (\Phi_2^\dagger \Phi_1)^2\right]$$

- CP conserving
- invariant under $\Phi_1 \to -\Phi_1$ for $m_{12}^2 = 0$

with the complex scalar $SU(2)$ doublets:

$$\Phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1^+ \\ v_1 + \eta_1 + \mathrm{i}\chi_1 \end{pmatrix} \qquad \Phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_2^+ \\ v_2 + \eta_2 + \mathrm{i}\chi_2 \end{pmatrix}$$

Two-Higgs-Doublet Model

Higgs potential:

$$V = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 + m_{12}^2 (\Phi_1^\dagger \Phi_2 + \text{h.c.})$$
$$+\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2)$$
$$+\lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \lambda_5 \left[(\Phi_1^\dagger \Phi_2)^2 + (\Phi_2^\dagger \Phi_1)^2 \right]$$

- CP conserving
- invariant under $\Phi_1 \to -\Phi_1$ for $m_{12}^2 = 0$
- m_{11}^2, m_{22}^2 fixed by minimum condition
  m_{12}^2, λ_1, ..., λ_5 free parameters

$\Rightarrow$ enough free parameters to define all Higgs masses independently

$\Rightarrow$ all Higgs masses can be chosen as pole masses (on-shell)

Higgs-mass eigenstates

CP-even Higgs bosons:

$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \eta_1 \\ \eta_2 \end{pmatrix}$$

CP-odd Higgs bosons:

$$\begin{pmatrix} G^0 \\ A^0 \end{pmatrix} = \begin{pmatrix} \cos\beta_n & \sin\beta_n \\ -\sin\beta_n & \cos\beta_n \end{pmatrix} \begin{pmatrix} \chi_1 \\ \chi_2 \end{pmatrix} \quad \text{with} \quad \tan\beta_n = \tan\beta = \frac{v_2}{v_1} \text{ at LO}$$

Charged Higgs bosons:

$$\begin{pmatrix} G^\pm \\ A^\pm \end{pmatrix} = \begin{pmatrix} \cos\beta_c & \sin\beta_c \\ -\sin\beta_c & \cos\beta_c \end{pmatrix} \begin{pmatrix} \phi_1^\pm \\ \phi_2^\pm \end{pmatrix} \quad \text{with} \quad \tan\beta_c = \tan\beta \text{ at LO}$$

Input parameters

Originally:

$$\overbrace{m_{11}^2 \quad m_{22}^2 \quad m_{12}^2 \quad \lambda_1 \quad \lambda_2 \quad \lambda_4}^{\text{parameters of Higgs potential}} \qquad \overbrace{v_1 \quad v_2}^{\text{vacuum expectation values}} \qquad \overbrace{g \quad g'}^{\text{gauge couplings}} \qquad \overbrace{\lambda_3 \quad \lambda_5}^{\text{parameters of Higgs potential}}$$

Chosen:

$$\underbrace{\overbrace{t_h \quad t_H}^{\text{tadpole parameters}}}_{\text{Minimum condition}} \quad \underbrace{\overbrace{M_h \quad M_H \quad M_A \quad M_{H^+}}^{\text{Higgs masses}} \quad \overbrace{M_W \quad M_Z}^{\text{gauge-boson masses}} \quad \overbrace{e}^{\text{electric charge}}}_{\text{on-shell}} \quad \underbrace{\overbrace{\tan\beta}^{=\frac{v_2}{v_1}} \quad \lambda_3/\overset{\text{mixing angle}\ \downarrow}{\alpha} \quad \lambda_5}_{\overline{\text{MS}}}$$

Renormalization

see also [Santos, Barroso 97, Kanemura, Okada, Senaha, Yuan hep-ph/0408364; Lopez-Val, Sola 0908.2898; Degrande 1406.3030; Krause, Mühlleitner, Lorenz, Santos, Ziesche 1605.04853; Denner, Jenniches, Lang, Sturm 1607.07352; Krause, Mühlleitner, Santos, Ziesche 1609.04185]

On-shell renormalization:

- Masses M_h, M_H, M_A, M_{H^+}, M_W, M_Z: Pole masses
- Fields exploiting matrix-valued renormalization:

$$\begin{pmatrix} H_0 \\ h_0 \end{pmatrix} = \begin{pmatrix} 1 + \frac{1}{2}\delta Z_H & \frac{1}{2}\delta Z_{Hh} \\ \frac{1}{2}\delta Z_{hH} & 1 + \frac{1}{2}\delta Z_h \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix} \text{ etc.}$$

  $\rightarrow$ no mixing of external on-shell fields

- Electric charge: via $ee\gamma$ vertex in the Thomson limit

$\overline{\text{MS}}$ renormalization:

- $\tan\beta$
- λ_3 or α
- λ_5

} $\rightarrow$ renormalization-scale dependent parameter

Remark about mixing angles

A priori: at NLO not well-defined:

can be absorbed by field-renormalization constants

$\rightarrow$ no need to renormalize mixing angles

But: If original parameters replaced by mixing angles

$\rightarrow$ fixed via the relation between original parameter and α

Tadpole renormalization

Two variants:

a) Vanishing renormalized tadpoles: $t_{S,0} = \overbrace{t_S}^{=0} + \delta t_S$

Condition: $\delta t_S + (\text{explicit tadpole loops}) = 0$

$\Rightarrow$ no explicit tadpole diagrams need to be included

Disadvantage: $t_{S,0} = \delta t_S$ enters in relations between bare input parameters

$\rightarrow$ potentially gauge-dependent terms enter relations between renormalized parameters and observables

b) Vanishing bare tadpoles: $t_{S,0} = 0$ [Fleischer, Jegerlehner 80; Actis, Ferroglia, Passera, Passarino hep-ph/0612122]

Explicit tadpole diagrams have to be taken into account

Advantage: no gauge-dependent δt_S enters in relations between bare input parameters

$\rightarrow$ relation between renormalized parameters and observables are gauge independent

Four possibilities for λ_3/α and β

- Scheme $\lambda_{3_{\overline{\text{MS}}}}$:

  λ_3 $\overline{\text{MS}}$, $\tan\beta$ $\overline{\text{MS}}$
  tadpole scheme: $t_S = 0$

- Scheme $\alpha_{\overline{\text{MS}}}$:

  α instead of λ_3: α $\overline{\text{MS}}$, $\tan\beta$ $\overline{\text{MS}}$
  tadpole scheme: $t_S = 0$

- Scheme FJ:

  α $\overline{\text{MS}}$, $\tan\beta$ $\overline{\text{MS}}$
  tadpole scheme: $t_{S,0} = 0$

- Scheme FJ λ_3:

  λ_3 $\overline{\text{MS}}$, $\tan\beta$ $\overline{\text{MS}}$
  tadpole scheme: $t_{S,0} = 0$

see also [Krause, Mühlleitner, Lorenz, Santos, Ziesche 1605.04853; Denner, Jenniches, Lang, Sturm 1607.07352]

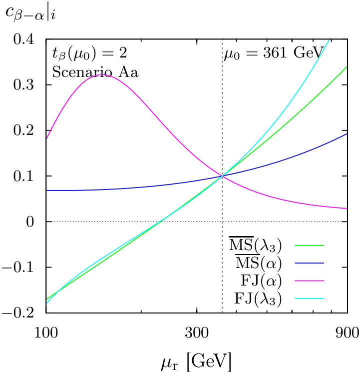
Running of $\cos(\beta-\alpha)$ in different schemes

[Altenkamp, Dittmaier, HR 1704.02645]

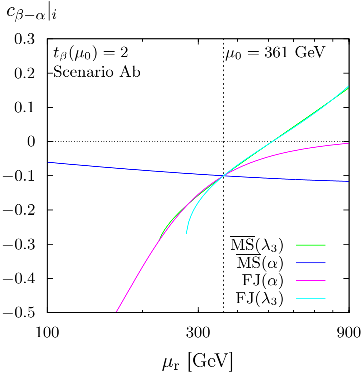
Scenario A: $M_h = 125$ GeV, $M_H = 300$ GeV, $M_{A_0} = M_{H^+} = 460$ GeV, $\lambda_5 = -1.9$, $\tan\beta = 2$

$\mu_0 = M_h + M_H + M_A + 2M_{H^+}$ for 2HDM type 1

Aa: $\cos(\beta-\alpha)|_{\substack{\text{input}\\\text{scheme}}}(\mu_0) = 0.1$:



Ab: $\cos(\beta-\alpha)|_{\substack{\text{input}\\\text{scheme}}}(\mu_0) = -0.1$:

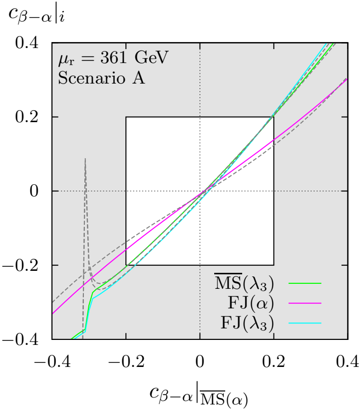


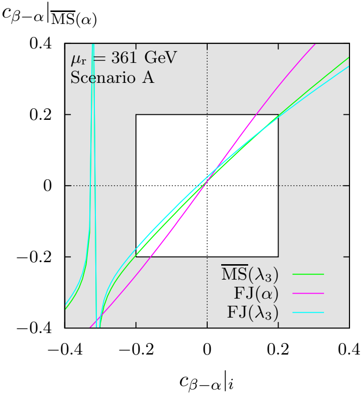
$\Rightarrow$ sizeable running effects

Conversion of parameters

[Altenkamp, Dittmaier, HR 1704.02645]

Conversion: $p_{\mathrm{RS2}} = p_{\mathrm{RS1}} + \delta p_{\mathrm{RS1}}(p_{\mathrm{RS1}}) - \delta p_{\mathrm{RS2}}(p_{\mathrm{RS2}})$





- Scenarios depend on the chosen renormalization scheme.

Conversion of parameters

[Altenkamp, Dittmaier, HR 1704.02645]

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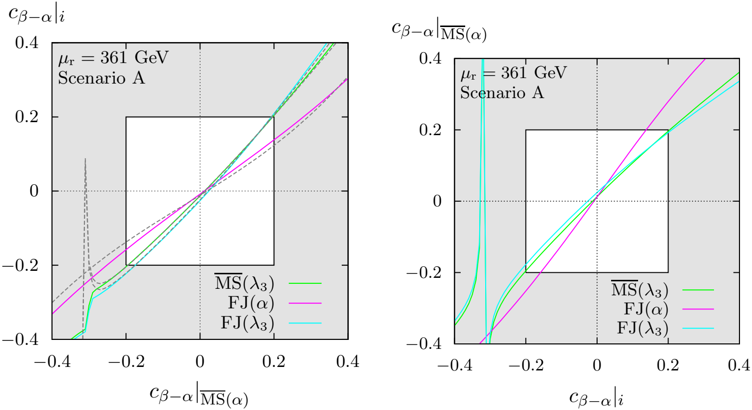


- Peak region: λ_3 is a bad input parameter if $\cos(2\alpha) \approx 0$,

  (to avoid the issue: choose different λ_i).

Implementation in PROPHECY4F

PROPHECY4F: A Monte Carlo generator for a
Proper description of the Higgs decay into 4 fermions

[Bredenstein, Denner, Dittmaier, Weber hep-ph/0604011; hep-ph/0607060; hep-ph/0611234]

→ use the functionality of PROPHECY4F for 2HDM:

Implementation:

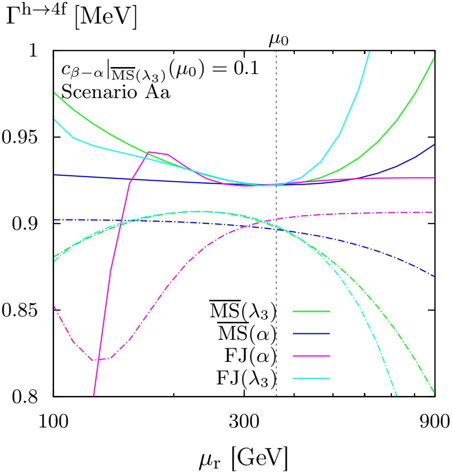
- model file generation with and without FeynRules [Christensen, Duhr 0806.4194]
- virtual EW diagrams: generation with FeynArts [Küblbeck, Böhm, Denner 90; Hahn hep-ph/0012260]

  virtual QCD diagrams: obtained by proper rescaling of Higgs couplings

  real diagrams: obtained by rescaling of Higgs coupling $g_{hVV} = \sin(\beta - \alpha) g_{hVV}^{SM}$
- amplitude reduction with inhouse mathematica routines or FormCalc [Hahn, Perez-Victoria hep-ph/9807565]
- W/Z resonances treated in complex-mass scheme
- evaluation of loop integrals with Collier [Denner, Dittmaier, Hofer 1604.06792]
- infrared divergences treated with dipole subtraction [Catani, Seymour hep-ph/9605323; Dittmaier hep-ph/9904440]

μ dependence of $\Gamma(h \to 4f)$

[Altenkamp, Dittmaier, HR 1704.02645]



$\mu_0 = (M_h + M_H + M_{A_0} + 2M_{H^+})/5$

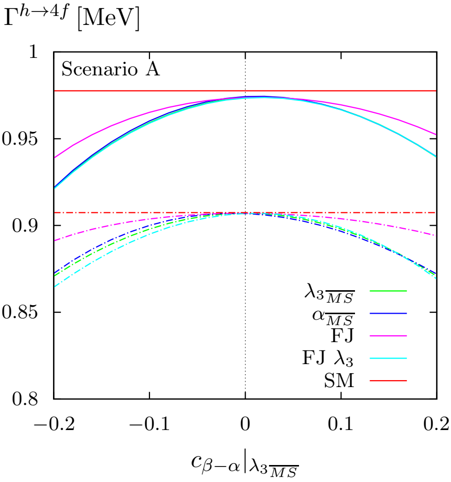
LO: dashed

NLO EW: solid

- Scheme λ_3 $\overline{\rm MS}$ used
- Clear plateau around $\mu_r = \mu_0$ at NLO
- Scale dependence reduced from LO to NLO

$\cos(\beta-\alpha)$ dependence of $\Gamma(h \to 4f)$

[Altenkamp, Dittmaier, HR 1704.02645]



$\mu_0 = (M_h + M_H + M_{A_0} + 2M_{H^+})/5$

LO: dashed

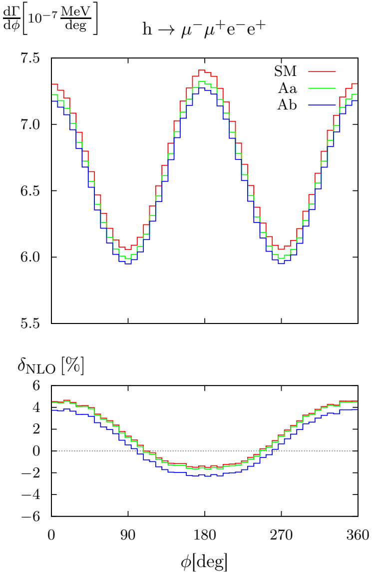
NLO: solid

- Scheme λ_3 $\overline{\text{MS}}$ used:

$\Gamma^{h\to 4f}_{\text{2HDM, LO}}\big|_{\lambda_3,\overline{\text{MS}}} = s^2_{\beta-\alpha}\Gamma^{h\to 4f}_{\text{SM, LO}}$

Example distribution

[Altenkamp, Dittmaier, HR 1704.02645]



$\mu_0 = (M_h + M_H + M_{A_0} + 2M_{H^+})/5$

- Scheme λ_3 $\overline{\text{MS}}$ used
- negligible shape differences between SM and 2HDM

Summary

- PROPHECY4F: Extended to the 2HDM (available on request):

  Features:

  - 4 different renormalization schemes:
    - ⋆ Different options for α/λ_3 and $\tan\beta$
    - ⋆ Masses and field-strength-renormalization constants on-shell, λ_5 $\overline{\text{MS}}$

      Note: m_{12}^2 is not an input parameter
  - Consistent conversion of parameters between the different ren. schemes
  - Running of $\overline{\text{MS}}$ parameters

- Effects of running and conversion of parameters can be sizeable
- Deviation from the SM about 0 to -6%

  NLO corrections contribute 1–2%.

Mixing angles and field renormalization

$$\begin{pmatrix} \varphi_{1,0} \\ \varphi_{2,0} \end{pmatrix} = \mathbf{R}_\varphi(\theta_0) \begin{pmatrix} h_{1,0} \\ h_{2,0} \end{pmatrix} = \begin{pmatrix} c_{\theta,0} & -s_{\theta,0} \\ s_{\theta,0} & c_{\theta,0} \end{pmatrix} \begin{pmatrix} h_{1,0} \\ h_{2,0} \end{pmatrix},$$

$$\begin{pmatrix} h_{1,0} \\ h_{2,0} \end{pmatrix} = \begin{pmatrix} 1 + \frac{1}{2}\delta Z_{\mathrm{h_1h_1}} & \frac{1}{2}\delta Z_{\mathrm{h_1h_2}} \\ \frac{1}{2}\delta Z_{\mathrm{h_2h_1}} & 1 + \frac{1}{2}\delta Z_{\mathrm{h_2h_2}} \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}, \qquad \theta_0 = \theta + \delta\theta.$$

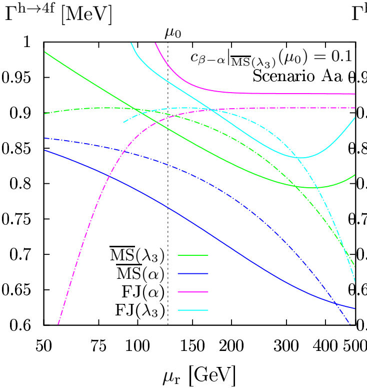
$$\begin{pmatrix} \varphi_{1,0} \\ \varphi_{2,0} \end{pmatrix} = \left[\begin{pmatrix} c_\theta & -s_\theta \\ s_\theta & c_\theta \end{pmatrix} \begin{pmatrix} 1 + \frac{1}{2}\delta Z_{\mathrm{h_1h_1}} & \frac{1}{2}\delta Z_{\mathrm{h_1h_2}} \\ \frac{1}{2}\delta Z_{\mathrm{h_2h_1}} & 1 + \frac{1}{2}\delta Z_{\mathrm{h_2h_2}} \end{pmatrix} + \begin{pmatrix} -s_\theta & -c_\theta \\ c_\theta & -s_\theta \end{pmatrix} \delta\theta \right] \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$$

$$= \begin{pmatrix} c_\theta & -s_\theta \\ s_\theta & c_\theta \end{pmatrix} \begin{pmatrix} 1 + \frac{1}{2}\delta Z_{\mathrm{h_1h_1}} & \frac{1}{2}(\delta Z_{\mathrm{h_1h_2}} - 2\delta\theta) \\ \frac{1}{2}(\delta Z_{\mathrm{h_2h_1}} + 2\delta\theta) & 1 + \frac{1}{2}\delta Z_{\mathrm{h_2h_2}} \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}.$$

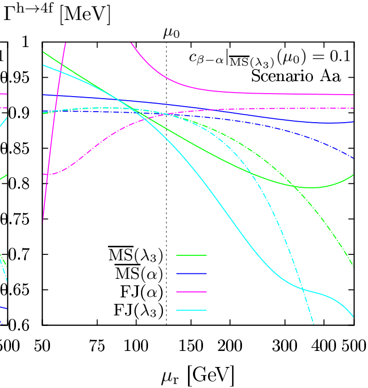
μ dependence of $\Gamma(h \to 4f)$

[Altenkamp, Dittmaier, HR 1704.02645]

with conversion:



without conversion:



$\mu_0 = M_h$

LO: dashed
NLO EW: solid

Scheme λ_3 $\overline{\mathrm{MS}}$ used