Higgs decaying to four fermions in the Two-Higgs-Doublet Model

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in collaboration with Lukas Altenkamp and Stefan Dittmaier

based on arXiv:1704.02645 and arXiv:1710.07598

CP3 Origins, SDU, Odense

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Status

- Discovery of a Higgs boson
- Many searches for new particles
  $\rightarrow$ Many exclusion limits
- Open questions:
  - Dark matter
  - Matter-antimatter asymmetry
  - ...

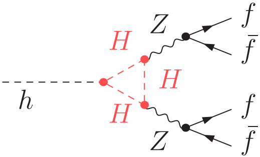
  $\rightarrow$ Models addressing these questions often require an extended Higgs sector

$\Rightarrow$ ⋆ Study properties of discovered Higgs boson
⋆ Continue searching, also for additional Higgs bosons

$\rightarrow$ Need precise theory predictions

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

Simple extension of the Standard Model:

- Only one Higgs doublet added to the Standard Model
- Simplest extension containing a charged Higgs boson

  (3 neutral, 2 charged) h H A $H^{\pm}$
- Embedded in other, more “complete” theories,
  e.g. supersymmetric extensions such as the MSSM

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 $m_{12}^2 = 0$ (softly broken by $m_{12}^2 \neq 0$)

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:

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

- CP conserving
- invariant under $\Phi_1 \to -\Phi_1$ for $m_{12}^2 = 0$ (softly broken by $m_{12}^2 \neq 0$)
- 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:

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

Charged Higgs bosons:

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

Input parameters

Originally:

parameters of Higgs potential: $\overbrace{m_{11}^2 \quad m_{22}^2 \quad m_{12}^2 \quad \lambda_1 \quad \lambda_2 \quad \lambda_4}^{\text{parameters of Higgs potential}}$

vacuum expectation values: $\overbrace{v_1 \quad v_2}$

gauge couplings: $\overbrace{g \quad g'}$

parameters of Higgs potential: $\overbrace{\lambda_3 \quad \lambda_5}$

Chosen:

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

Renormalization

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

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; Denner, Lang, Uccirati, 1705.06053; Denner, Dittmaier, Lang 1808.03466]

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

$\rightarrow$ mixing angle fixed via the relation between original parameter and the mixing angle

Tadpole renormalization

Two variants:

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

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

Now: 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 $\lambda_{3_{\overline{\text{MS}}}}$: see [Altenkamp, Dittmaier, H.R. 1704.02645]

  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]

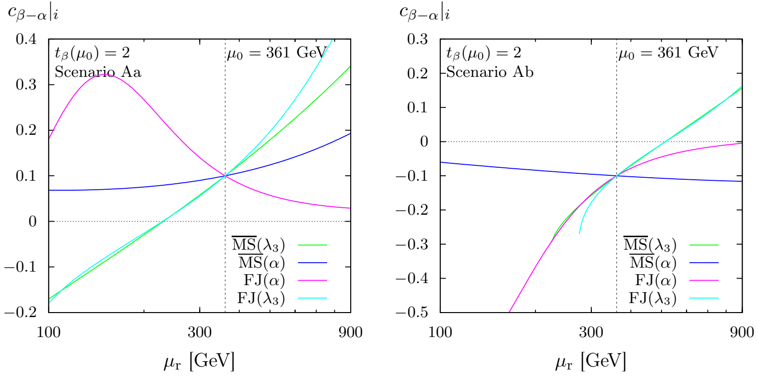
Running of $\cos(\beta-\alpha)$ in different schemes

[Altenkamp, Dittmaier, H.R. 1704.02645, 1710.07598]

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, see [Haber , Stål, 1507.04281]

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

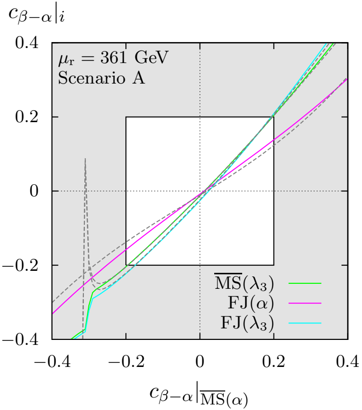


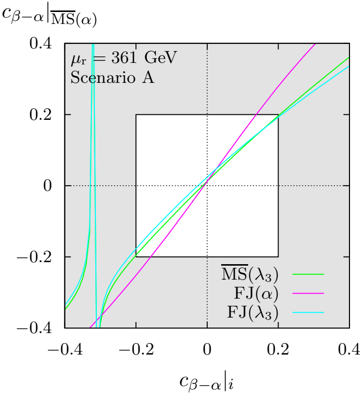
$\Rightarrow$ sizeable running effects

Conversion of parameters

[Altenkamp, Dittmaier, H.R. 1704.02645, 1710.07598]

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.

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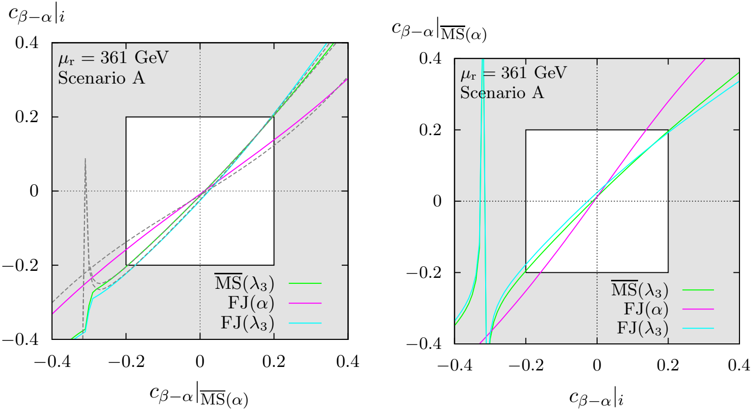

- Peak region: λ_3 is a bad input parameter if $\cos(2\alpha) \approx 0$,
  (to avoid the issue: choose different λ_i).

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

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- model file generation with and without FeynRules [Christensen, Duhr 0806.4194]

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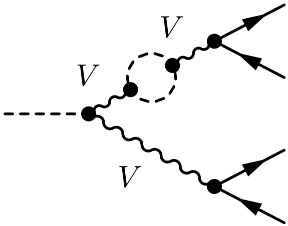

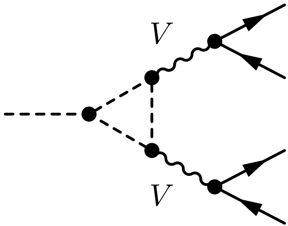

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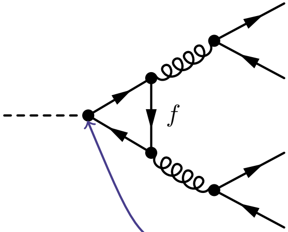
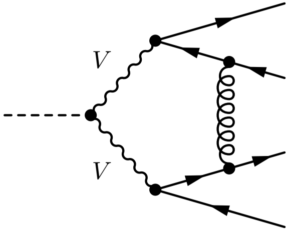
  virtual QCD diagrams: obtained by proper rescaling of Higgs couplings





depends on type of 2HDM: 4 types implemented

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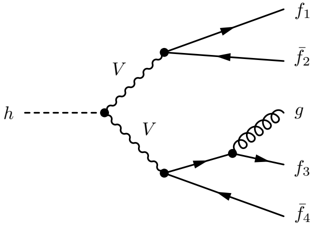
  real diagrams: obtained by rescaling of Higgs coupling $g_{hVV} = \sin(\beta - \alpha) g_{hVV}^{\text{SM}}$



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- amplitude reduction with inhouse mathematica routines or FormCalc

  [Hahn, Perez-Victoria hep-ph/9807565]

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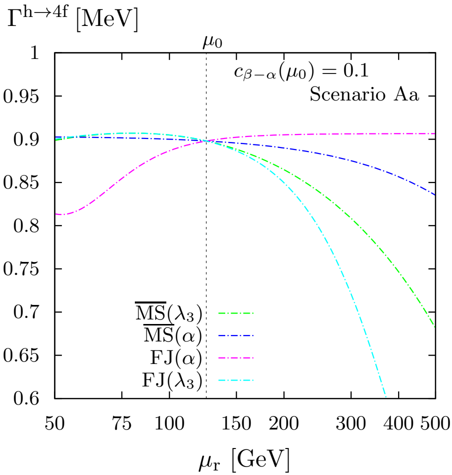
- infrared divergences treated with dipole subtraction [Catani, Seymour hep-ph/9605323; Dittmaier hep-ph/9904440]

μ_r dependence of $\Gamma(h \to 4f)$

[Altenkamp, Dittmaier, H.R. 1704.02645]



"naive" scale: $\mu_0 = M_h$

leading order (LO): dashed
next-to LO (NLO) electroweak (EW): solid

- No conversion: scenario interpreted as given in respective scheme
- No clear plateau around $\mu_r = \mu_0$ at NLO

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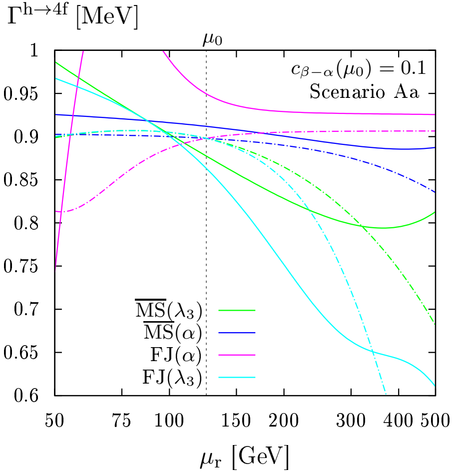

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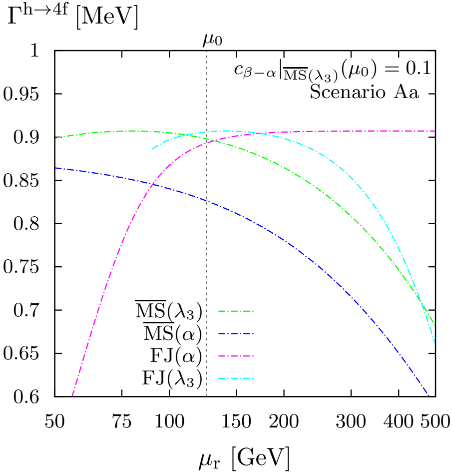

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- Scheme λ_3 $\overline{MS}$ used
- With conversion: Sizeable effects already at LO
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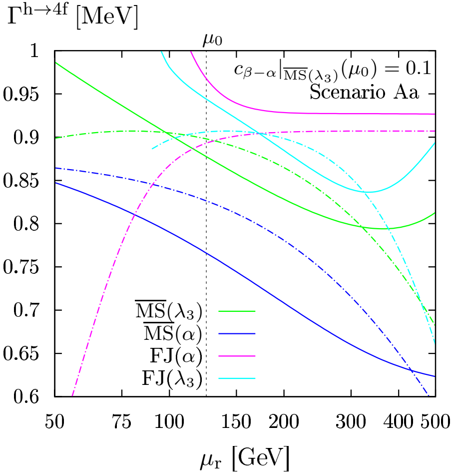

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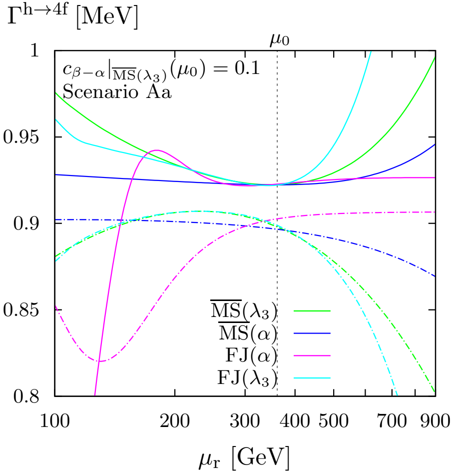


$\mu_0 = (M_h + M_H + M_{A_0} + 2M_{H^+})/5$

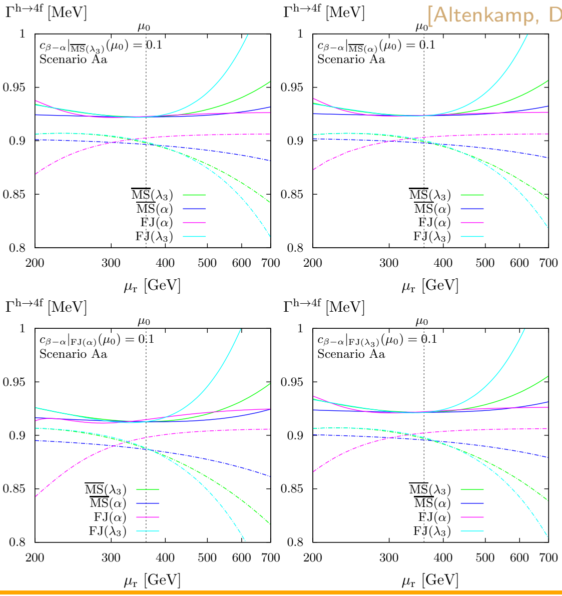
LO: dashed

NLO EW: solid

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

μ_r dependence of $\Gamma(h \to 4f)$

[Altenkamp, Dittmaier, H.R. 1710.07598]



For all input schemes:

- Clear plateau
- Reduction of scale dependence from LO to NLO

An on-shell renormalization of α, β

[Denner, Dittmaier, Lang 1808.03466]

Idea:

- Use ratio of matrix elements, e.g. $\frac{\mathcal{M}_{H\to ZZ}}{\mathcal{M}_{h\to ZZ}}$
- Ensure: Matrix elements evaluated
  at phase-space points in physical region:
  - problematic for $\frac{\mathcal{M}_{H\to ZZ}}{\mathcal{M}_{h\to ZZ}}$ if h is SM like
  - introduce new fields and decouple them:

    ⋆ two right-handed fermion singlets ν_{1R}, ν_{2R}

    ⋆ additional Z_2 symmetry: $\nu_{1R} \to -\nu_{1R}$, $\nu_{2R} \to \nu_{2R}$

    $\Rightarrow \nu_{jR}$ couples only to Φ_j

$\mathcal{L}_{\nu_R} = \Sigma_{j=1}^{2} \mathrm{i}\bar{\nu}_{\mathrm{jR}} \partial \nu_{\mathrm{jR}} - \left[\mathrm{y}_{\nu_\mathrm{j}} \bar{\mathrm{L}}_{\mathrm{jL}} \left(\mathrm{i}\sigma_2 \Phi_\mathrm{j}^* \right) \nu_{\mathrm{jR}} + \mathrm{h.c.} \right]$ with $y_{\nu_j} \to 0$.

$L_{jL} = (\nu_j, \ell_j)^T =$ left-handed lepton doublet of Standard Model

An on-shell renormalization of α, β

[Denner, Dittmaier, Lang 1808.03466]

Renormalization conditions:

- OS 1: α via $\frac{\mathcal{M}_{H\to\nu_1\bar{\nu}_1}}{\mathcal{M}_{h\to\nu_1\bar{\nu}_1}} \stackrel{!}{=} \frac{\mathcal{M}^0_{H\to\nu_1\bar{\nu}_1}}{\mathcal{M}^0_{h\to\nu_1\bar{\nu}_1}}$, β via $\frac{\mathcal{M}_{A^0\to\nu_1\bar{\nu}_1}}{\mathcal{M}_{h\to\nu_1\bar{\nu}_1}} \stackrel{!}{=} \frac{\mathcal{M}^0_{A^0\to\nu_1\bar{\nu}_1}}{\mathcal{M}^0_{H\to\nu_1\bar{\nu}_1}}$
- OS 2: as above but $\nu_1 \to \nu_2$
- OS 12: α via $\frac{\mathcal{M}_{H\to\nu_2\bar{\nu}_2}}{\mathcal{M}_{h\to\nu_2\bar{\nu}_2}} \stackrel{!}{=} \frac{\mathcal{M}^0_{H\to\nu_2\bar{\nu}_2}}{\mathcal{M}^0_{h\to\nu_2\bar{\nu}_2}}$,

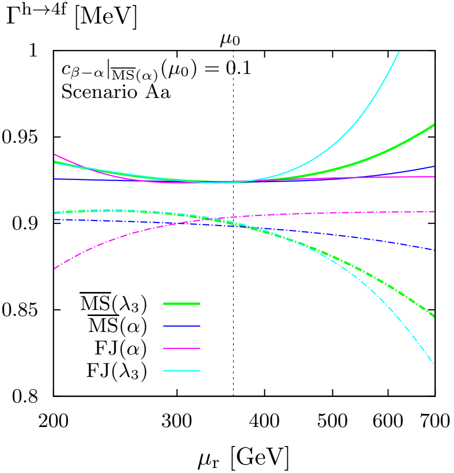
  β via

$$0 = \frac{F_0^{A^0\to\nu_1\bar{\nu}_1}}{c_\alpha F_0^{H\to\nu_1\bar{\nu}_1} - s_\alpha F_0^{h\to\nu_1\bar{\nu}_1}\, c_\beta} + \frac{F_0^{A^0\to\nu_2\bar{\nu}_2}}{s_\alpha F_0^{H\to\nu_1\bar{\nu}_1} + c_\alpha F_0^{h\to\nu_1\bar{\nu}_1}\, s_\beta}$$
$$\stackrel{!}{=} \frac{F^{A^0\to\nu_1\bar{\nu}_1}}{c_\alpha F^{H\to\nu_1\bar{\nu}_1} - s_\alpha F^{h\to\nu_1\bar{\nu}_1}\, c_\beta} + \frac{F^{A^0\to\nu_2\bar{\nu}_2}}{s_\alpha F^{H\to\nu_1\bar{\nu}_1} + c_\alpha F^{h\to\nu_1\bar{\nu}_1}\, s_\beta}$$

$$M^0_{\{h,H\}\to\nu_j\bar{\nu}_j} = [\bar{u}_\nu v_\nu]_{\{h,H\}} F^{\{h,H\}\to\nu_j\bar{\nu}_j},\ M^0_{A^0\to\nu_j\bar{\nu}_j} = [\bar{u}_\nu \mathrm{i}\gamma_5 \mathrm{v}_\nu]_{\mathrm{A}^0} \mathrm{F}^{\mathrm{A}^0\to\nu_\mathrm{j}\bar{\nu}_\mathrm{j}}$$

Again: μ_r dependence of $\Gamma(h \to 4f)$

[Altenkamp, Dittmaier, H.R. 1710.07598]



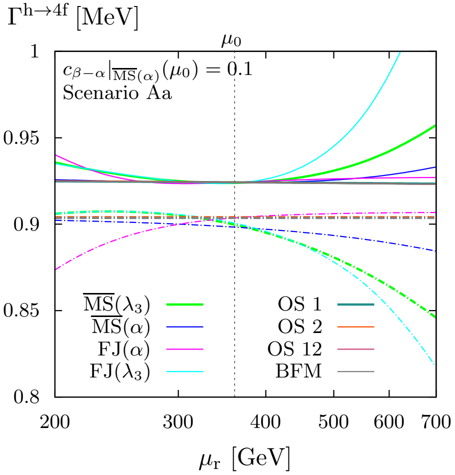
$\mu_0 = (M_h + M_H + M_{A_0} + 2M_{H^+})/5$

LO: dashed

NLO: solid

- Scheme α $\overline{\text{MS}}$ used

Again: μ_r dependence of $\Gamma(h \to 4f)$



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

LO: dashed

NLO: solid

- Scheme α $\overline{\text{MS}}$ used

  [Altenkamp, Dittmaier, H.R. 1710.07598]

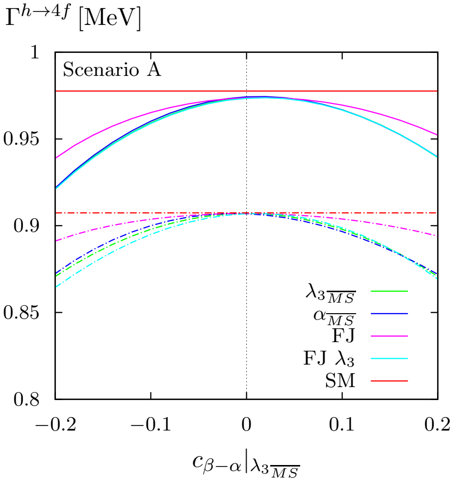
- Additional schemes included

  [Denner, Dittmaier, Lang 1808.03466]

- Good agreement at μ_0

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

[Altenkamp, Dittmaier, H.R. 1704.02645, 1710.07598]



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

leading order (LO): dashed

next-to leading order: solid

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

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

- Deviations of up to

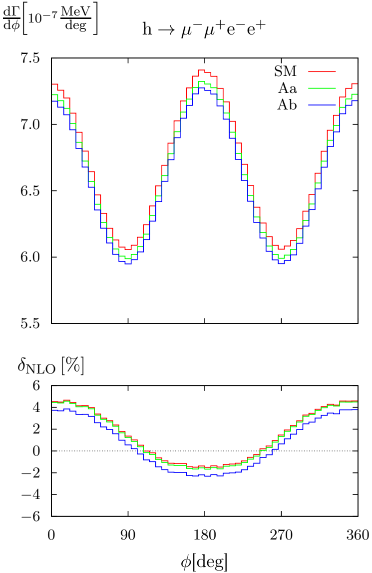
  $\sim$ 5% from the SM prediction

Partial decay widths for scenario Ab (scheme λ_3 $\overline{\text{MS}}$)

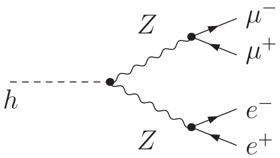
Final state	$\Gamma^{h\to4f}_{\text{NLO}}$ [MeV]	δ_{EW} [%]	δ_{QCD} [%]	$\Delta^{\text{NLO}}_{\text{SM}}$ [%]	$\Delta^{\text{LO}}_{\text{SM}}$ [%]
inclusive $h\to4f$	0.95980(7)	1.87(0)	4.97(1)	−1.82(1)	−1.00(1)
ZZ	0.105464(5)	−0.34(0)	4.90(0)	−1.75(1)	−1.00(0)
WW	0.85938(8)	2.14(0)	5.01(1)	−1.83(1)	−1.00(1)
WW/ZZ int.	−0.00504(5)	0.5(1)	10.7(8)	−2(1)	−1(1)
$\nu_e e^+ \mu^- \bar{\nu}_\mu$	0.010116(1)	2.17(1)	0.00	−1.87(1)	−1.00(1)
$\nu_e e^+ u\bar{d}$	0.031463(4)	2.16(0)	3.76(1)	−1.84(2)	−1.00(1)
$u\bar{d}s\bar{c}$	0.09770(2)	2.11(0)	7.52(1)	−1.81(2)	−1.00(1)
$\nu_e e^+ e^- \bar{\nu}_e$	0.010112(1)	2.27(1)	0.00	−1.87(1)	−1.00(1)
$u\bar{d}d\bar{u}$	0.09972(2)	1.99(0)	7.38(2)	−1.80(2)	−1.00(1)
$\nu_e\bar{\nu}_e\nu_\mu\bar{\nu}_\mu$	0.000943(0)	2.34(0)	0.00	−1.78(1)	−1.00(1)
$e^-e^+\mu^-\mu^+$	0.000237(0)	0.62(1)	0.00	−1.79(2)	−1.00(1)
$\nu_e\bar{\nu}_e\mu^-\mu^+$	0.000474(0)	1.78(1)	0.00	−1.78(2)	−1.00(1)
$\nu_e\bar{\nu}_e\nu_e\bar{\nu}_e$	0.000565(0)	2.23(0)	0.00	−1.79(2)	−1.00(1)
$e^-e^+e^-e^+$	0.000131(0)	0.45(1)	0.00	−1.78(2)	−1.00(1)
$\nu_e\bar{\nu}_e u\bar{u}$	0.001668(0)	−0.08(1)	3.76(1)	−1.76(2)	−1.00(1)
$\nu_e\bar{\nu}_e d\bar{d}$	0.002163(0)	1.02(0)	3.76(1)	−1.76(2)	−1.00(1)
$e^-e^+u\bar{u}$	0.000840(0)	−0.57(1)	3.76(1)	−1.77(2)	−1.00(1)
$e^-e^+d\bar{d}$	0.001081(0)	−0.21(1)	3.76(1)	−1.76(2)	−1.00(1)
$u\bar{u}c\bar{c}$	0.002952(0)	−2.48(1)	7.51(1)	−1.75(2)	−1.00(1)
$d\bar{d}d\bar{d}$	0.002545(1)	−1.06(0)	4.57(2)	−1.67(3)	−1.00(1)
$d\bar{d}s\bar{s}$	0.004925(1)	−1.04(0)	7.51(1)	−1.74(2)	−1.00(1)
$u\bar{u}s\bar{s}$	0.003828(1)	−1.35(1)	7.51(1)	−1.74(2)	−1.00(1)
$u\bar{u}u\bar{u}$	0.001500(0)	−2.60(1)	4.31(2)	−1.65(3)	−1.00(1)

Example distribution

[Altenkamp, Dittmaier, HR 1710.07598]



- ϕ = angle between $\mu^-\mu^+$ and e^-e^+ decay planes



- negligible shape differences between SM and 2HDM

(Scheme λ_3 $\overline{\text{MS}}$ used)

Summary

Higgs decay to four fermions:

- PROPHECY4F includes electroweak and QCD NLO corrections:

  Extended to the 2HDM (& to the singlet extension)
  available on request [Altenkamp, Boggia, Dittmaier 1801.07291]

- Different renormalization schemes available:

  $\Rightarrow$ Consistent conversion of parameters between
  the different renormalization schemes has to be performed

  $\rightarrow$ Useful for theory uncertainty estimate

  $\star$ Effects of running and conversion of parameters can be sizeable

- For $\Gamma(h \to 4f)$: Deviation from the SM about 0 to -6%
  NLO corrections contribute 1–2%.

Mixing angles and field renormalization

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

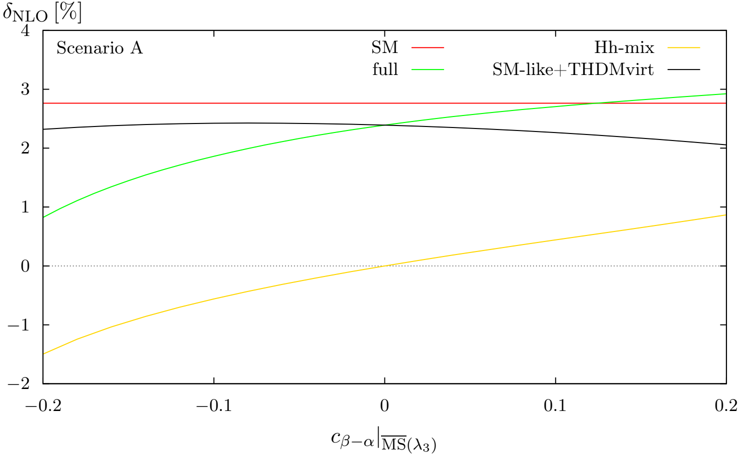
$$\begin{pmatrix} h_{1,0} \\ h_{2,0} \end{pmatrix} = \begin{pmatrix} 1+\frac{1}{2}\delta Z_{\mathrm{h_1h_1}} & \frac{1}{2}\delta Z_{\mathrm{h_1h_2}} \\ \frac{1}{2}\delta Z_{\mathrm{h_2h_1}} & 1+\frac{1}{2}\delta Z_{\mathrm{h_2h_2}} \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}, \qquad \theta_0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

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

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

Contributions to NLO corrections

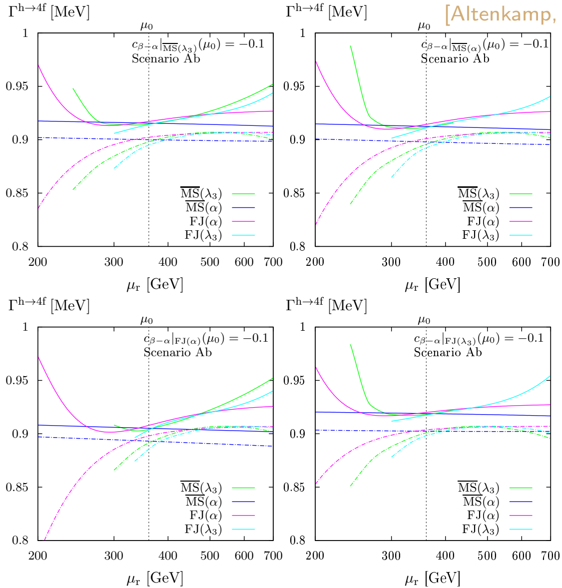
[Altenkamp, Dittmaier, HR 1710.07598]



- Higgs mixing contributions important for dependence of NLO corrections on $\cos(\beta-\alpha)$

μ_r dependence of $\Gamma(h \to 4f)$

[Altenkamp, Dittmaier, HR 1710.07598]



Now scenario Ab:

For all input schemes:

- Plateau
- Reduction of scale dependence from LO to NLO

Partial decay widths for scenario Aa (scheme λ_3 $\overline{\text{MS}}$)

Final state	$\Gamma^{h\to 4f}_{\text{NLO}}$ [MeV]	δ_{EW} [%]	δ_{QCD} [%]	$\Delta^{\text{NLO}}_{\text{SM}}$ [%]	$\Delta^{\text{LO}}_{\text{SM}}$ [%]
inclusive $h\to 4f$	0.96730(7)	2.71(0)	4.96(1)	−1.05(1)	−1.00(1)
ZZ	0.106126(6)	0.34(0)	4.88(0)	−1.13(1)	−1.00(0)
WW	0.86630(8)	3.00(0)	5.01(1)	−1.04(1)	−1.00(1)
WW/ZZ int.	−0.00513(5)	1.3(2)	12.0(8)	−1(1)	−1(1)
$\nu_e e^+ \mu^- \bar{\nu}_\mu$	0.010201(1)	3.03(0)	0.00	−1.04(1)	−1.00(1)
$\nu_e e^+ u \bar{d}$	0.031719(4)	3.02(0)	3.76(1)	−1.04(2)	−1.00(1)
$u \bar{d} s \bar{c}$	0.09847(2)	2.97(0)	7.52(1)	−1.04(2)	−1.00(1)
$\nu_e e^+ e^- \bar{\nu}_e$	0.010197(1)	3.12(0)	0.00	−1.04(1)	−1.00(1)
$u \bar{d} d \bar{u}$	0.10048(2)	2.85(0)	7.35(2)	−1.06(3)	−1.00(1)
$\nu_e \bar{\nu}_e \nu_\mu \bar{\nu}_\mu$	0.000949(0)	3.01(0)	0.00	−1.14(1)	−1.00(1)
$e^- e^+ \mu^- \mu^+$	0.000239(0)	1.30(1)	0.00	−1.13(2)	−1.00(1)
$\nu_e \bar{\nu}_e \mu^- \mu^+$	0.000477(0)	2.45(1)	0.00	−1.13(2)	−1.00(1)
$\nu_e \bar{\nu}_e \nu_e \bar{\nu}_e$	0.000569(0)	2.90(0)	0.00	−1.14(2)	−1.00(1)
$e^- e^+ e^- e^+$	0.000132(0)	1.12(1)	0.00	−1.12(2)	−1.00(1)
$\nu_e \bar{\nu}_e u \bar{u}$	0.001679(0)	0.60(1)	3.76(1)	−1.12(2)	−1.00(1)
$\nu_e \bar{\nu}_e d \bar{d}$	0.002177(1)	1.69(0)	3.76(1)	−1.12(2)	−1.00(1)
$e^- e^+ u \bar{u}$	0.000845(0)	0.11(1)	3.76(1)	−1.12(2)	−1.00(1)
$e^- e^+ d \bar{d}$	0.001088(0)	0.47(1)	3.76(1)	−1.12(2)	−1.00(1)
$u \bar{u} c \bar{c}$	0.002971(0)	−1.80(1)	7.51(1)	−1.11(2)	−1.00(1)
$d \bar{d} d \bar{d}$	0.002556(1)	−0.38(0)	4.38(2)	−1.21(3)	−1.00(1)
$d \bar{d} s \bar{s}$	0.004956(1)	−0.36(0)	7.51(1)	−1.12(2)	−1.00(1)
$u \bar{u} s \bar{s}$	0.003852(1)	−0.66(1)	7.51(1)	−1.11(2)	−1.00(1)
$u \bar{u} u \bar{u}$	0.001506(0)	−1.92(1)	4.06(3)	−1.24(4)	−1.00(1)