Decays of (more or less) exotic Higgs bosons

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Status

- Discovery of a Higgs boson
- Many searches for new particles

  → Many exclusion limits
- Open questions:
  - Dark matter
  - Matter-antimatter asymmetry
  - ...

  → Models addressing these questions often require an extended Higgs sector

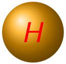
⇒ ⋆ Study properties of discovered Higgs boson
⋆ Continue searching, also for additional Higgs bosons

→ Need precise theory predictions

Higgs sectors

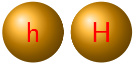
- Standard Model:

  1 CP-even Higgs boson



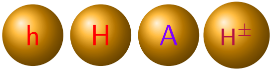
- Singlet extension:

  2 CP-even Higgs bosons



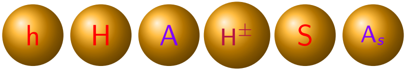
- Two-Higgs-Doublet Model (2HDM):

  2 CP-even, 1 CP-odd,
  1 charged Higgs bosons



- Singlet-extended 2HDM:

  3 CP-even, 2 CP-odd,
  1 charged Higgs bosons



- Further extensions, e.g. Higgs triplet with doubly charged Higgs boson

→ One Standard Model (like) Higgs boson + possibly "exotic" Higgs bosons

Higgs sectors

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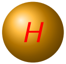

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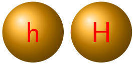
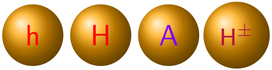


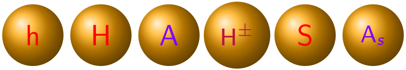
- Two-Higgs-Doublet Model (2HDM):

  MSSM 2 CP-even, 1 CP-odd,
  1 charged Higgs bosons



- Singlet-extended 2HDM:

  NMSSM 3 CP-even, 2 CP-odd,
  1 charged Higgs bosons



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Higgs decays: Partial decay widths

Many tools include QCD corrections:

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Partly included in spectrum generators:

- SOFTSUSY (MSSM, NMSSM) [Allanach, Cridge 1703.09717]
- SPheno (MSSM — but extendable using Sarah [Staub 1309.7223])
  [Porod hep-ph/0301101; Porod, Staub 1104.1573]
- FeynHiggs (MSSM Higgs spectrum generator
  — partly complete one-loop decays)
  [Bahl, Hahn, Heinemeyer, Hollik, Paßehr, H.R., Weiglein]
- NMSSMTOOLS with NMHDECAY (NMSSM)
  [Ellwanger, Gunion, Hugonie hep-ph/0406215]
- NMSSMCALC (NMSSM Higgs spectrum generator)
  [Baglio, Gröber, Mühlleitner, Nhung, H.R., Spira, Streicher, Walz 1312.4788]

decays based on HDECAY [1003.1643]

Higgs decays: Partial decay widths

Many tools include QCD corrections:

HDECAY family: [Djouadi, Kalinowski, (Mühlleitner,) Spira hep-ph/9704448, 1003.1643]

Partial decay widths and branching ratios for different models

- MSSM: HDECAY: "mother" program
- sHDECAY: singlet extension
  (different types, also for CP-violation)
  [Costa, Mühlleitner, Sampaio, Santos 1512.05355]
- C2HDECAY: 2HDM extension (also for CP-violation)
  [Fontes, Mühlleitner, Romão, Santos, Silva, Wittbrodt 1711.09419]
- N2HDECY: Singlet extended 2HDM
  [Mühlleitner, Sampaio, Santos, Wittbrodt 1612.01309]
- eHDECAY: minimal composite Higgs models
  (partly also electroweak corrections)
  [Contino, Ghezzi, Grojean, Mühlleitner, Spira 1403.3381]

Higgs decays: Partial decay widths

Many tools include QCD corrections:

For distributions:

- MadGraph5_aMC@NLO
  [Alwall, Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Shao, Stelzer, Torrielli, Zaro 1405.0301]
- combining amplitude generator and event generator tools (e.g. SHERPA or Herwig++ with OpenLoops)
  [SHERPA: Bothmann, Hoeche, Krauss, Kuttimalai, Schoenherr, Schumann, Siegert, Thompson, Winter, Zapp;
  Herwig++: Bellm, Gieseke, Grellscheid, Kirchgaeßer, Loshaj, Nail, Papaefstathiou, Plätzer , Podskubka, Rauch, Reuschle, Richardson, Schichtel, Seymour, Siòdmok, Webster;
  OpenLoops: Cascioli, Lindert, Maierhöfer, Pozzorini]

Including electroweak (EW) corrections

Full one-loop corrections using a $\overline{\text{DR}}$ scheme:

- HFOLD [Eberl, Frisch, Hlucha 1012.5025]
- SARAH [Goodsell, Lieber, Staub 1703.09237]

Problem with $\overline{\text{DR}}$ scheme:

LSZ theorem requires on-shell properties for external particles

$\rightarrow$ shift from $\overline{\text{DR}}$ mass to on-shell mass mixes orders

$\rightarrow$ use as many on-shell conditions as possible

for example for the MSSM [Heinemeyer, Schappacher 1503.02996]

for the NMSSM [Domingo, Heinemeyer, Paßehr, Weiglein 1807.06322]

$\rightarrow$ see talk by Sven Heinemeyer

More general tool: RECOLA2 for processes incl. EW corrections

[Denner, Lang, Uccirati 1705.06053]

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)
- 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 $m_{12}^2 = 0$ (we use $m_{12} \neq 0$)

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 $m_{12}^2 = 0$ (we use $m_{12} \neq 0$)
- 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: m_{11}^2 m_{22}^2 m_{12}^2 λ_1 λ_2 λ_4

vacuum expectation values: v_1 v_2

gauge couplings: g g'

parameters of Higgs potential: λ_3 λ_5

Chosen:

tadpole parameters: t_h t_H — Minimum condition

Higgs masses: M_h M_H M_A M_{H^+}

gauge-boson masses: M_W M_Z

electric charge: e

(M_h … e: on-shell)

$\tan\beta$ $\left(= \frac{v_2}{v_1}\right)$ λ_3/α (mixing angle) λ_5/m_{12}^2 — $\overline{\text{MS}}$

Renormalization

see also [Santos, Barroso 97; Kanemura, Okada, Senaha, Yuan hep-ph/0408364; Lopez-Val, Sola 0908.2898; Degrande 1406.3030]

On-shell renormalization: [Krause, Mühlleitner, Lorenz, Santos, Ziesche 1605.04853; Denner, Jenniches, Lang, Sturm 1607.07352; Krause, Mühlleitner, Santos, Ziesche 1609.04185; Altenkamp, Dittmaier, H.R. 1704.02645]

- 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 or m_{12}^2 or M_{ab}^2

} $\rightarrow$ 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

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

Tadpole renormalization

Two variants:

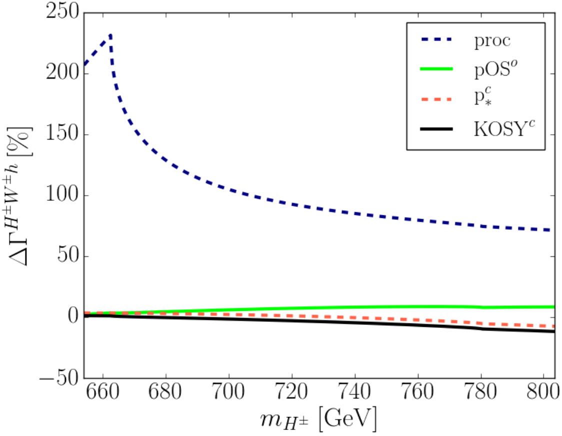
a) Vanishing renormalized tadpoles: $t_{S,0} = \overbrace{t_S}^{=0} + \delta t_S$

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

$H^+ \to hW^+$ in 2HDM



- complete EW contributions
- different renormalization schemes:
  - ⋆ only $t_S = 0$ for KOSY otherwise $t_{S,0} = 0$
  - ⋆ α, β renormalized
  - ⋆ pinch technique for pOS, $p^\star$
- no parameter conversion taken into account

[Krause, Lorenz, Mühlleitner, Santos, Ziesche 1608.01880]

Four possibilities for λ_3/α and β

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

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

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

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

- Scheme FJ:

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

- Scheme FJ λ_3:

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

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

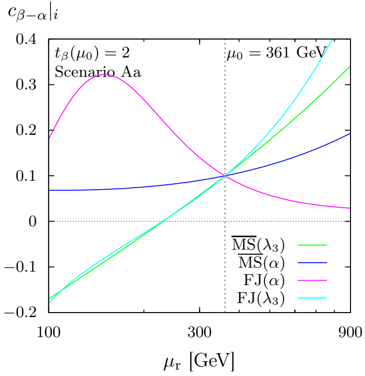
Running of $\cos(\beta - \alpha)$ in different schemes

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

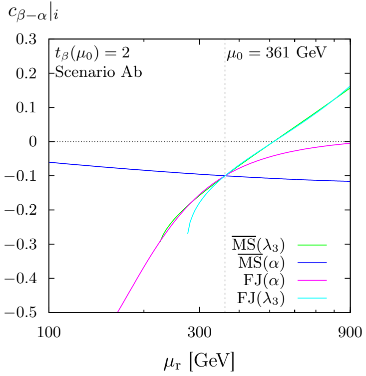
Scenario A: $M_h = 125$ GeV, $M_H = 300$ GeV, $M_{A_0} = M_{H^+} = 460$ GeV, $\lambda_5 = -1.9$, $\tan\beta = 2$

$\mu_0 = M_h + M_H + M_A + 2M_{H^+}$ for 2HDM type 1, see [Haber , Stål, 1507.04281]

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



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

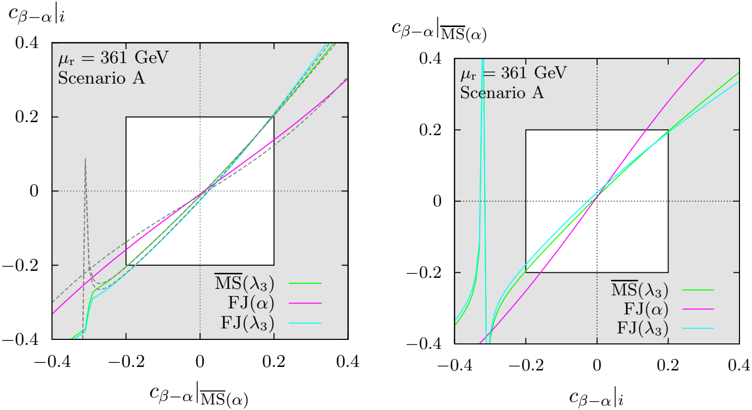


$\Rightarrow$ sizeable running effects

Conversion of parameters

[Altenkamp, Dittmaier, 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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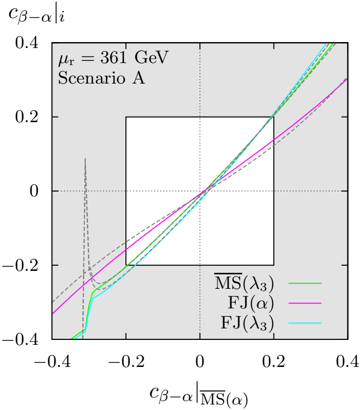

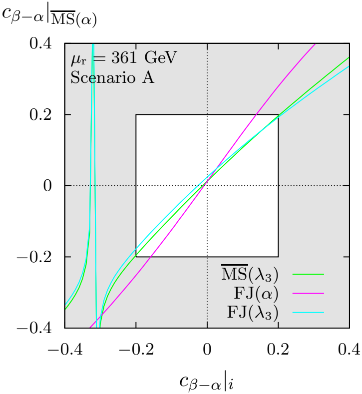

- Peak region: λ_3 is a bad input parameter if $\cos(2\alpha) \approx 0$,
  (to avoid the issue: choose different λ_i).

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]

$\rightarrow$ use the functionality of PROPHECY4F for 2HDM

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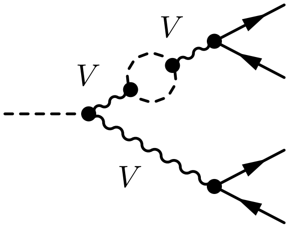

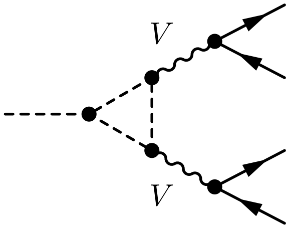

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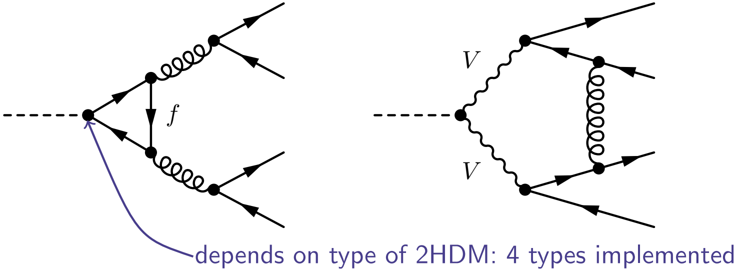

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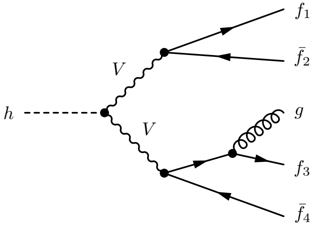

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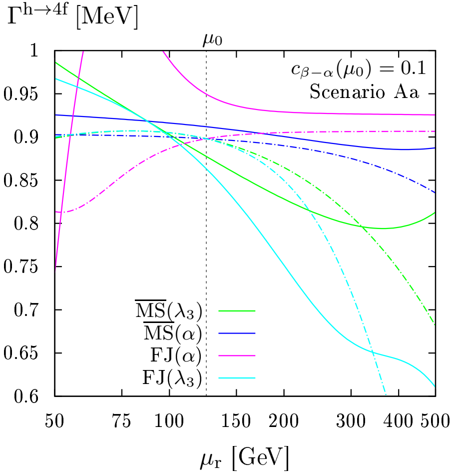
- infrared divergences treated with dipole subtraction [Catani, Seymour hep-ph/9605323; Dittmaier hep-ph/9904440]

μ_r dependence of $\Gamma(h \to 4f)$



[Altenkamp, Dittmaier, H.R. 1704.02645]

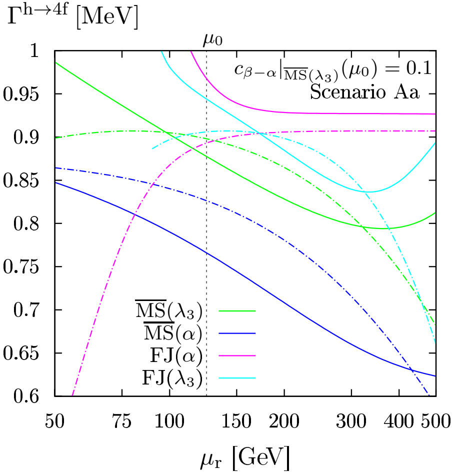
"naive" scale: $\mu_0 = M_h$

LO: dashed

NLO EW: solid

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

μ_r dependence of $\Gamma(h \to 4f)$



[Altenkamp, Dittmaier, H.R. 1704.02645]

"naive" scale: $\mu_0 = M_h$

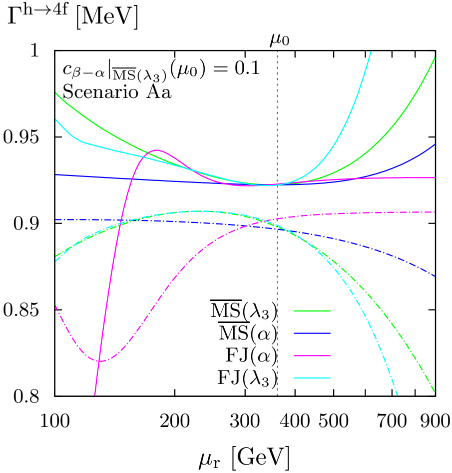
LO: dashed

NLO EW: solid

- Scheme λ_3 $\overline{\text{MS}}$ used
- With conversion:
  Sizeable effects already at LO
- No clear plateau around
  $\mu_r = \mu_0$ at NLO

μ_r dependence of $\Gamma(h \to 4f)$

[Altenkamp, Dittmaier, H.R. 1704.02645]



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

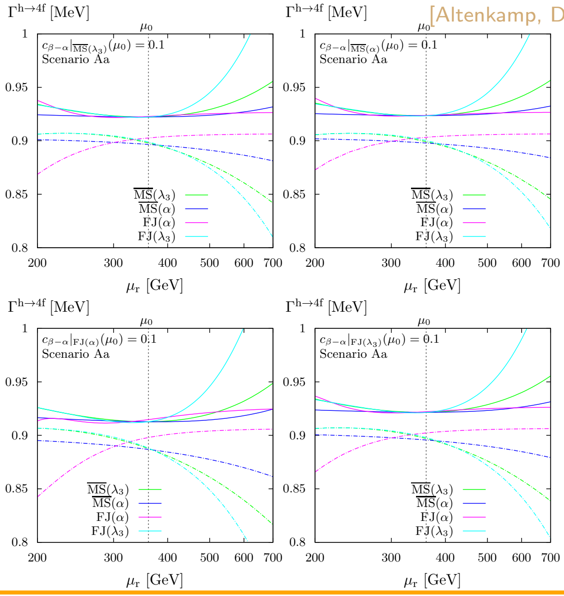
LO: dashed

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

μ_r dependence of $\Gamma(h \to 4f)$

[Altenkamp, Dittmaier, H.R. 1710.07598]

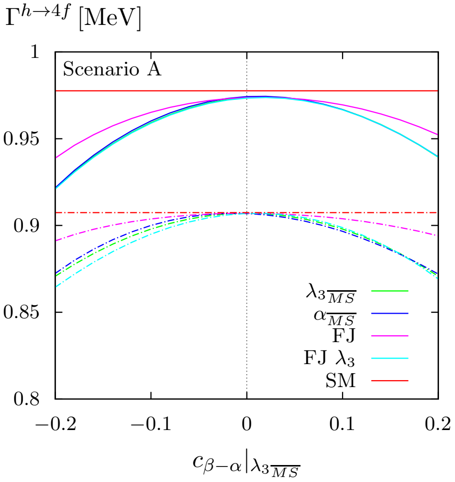


For all input schemes:

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

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

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



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

LO: dashed

NLO: solid

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

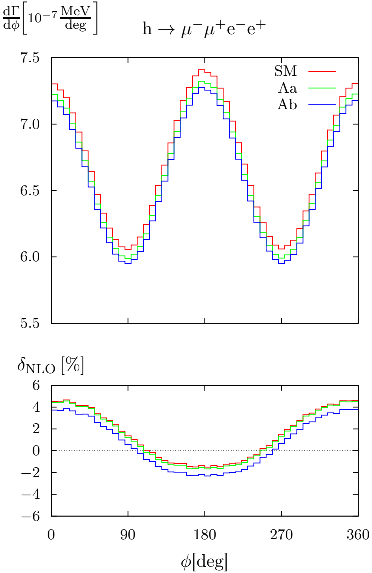
$\Gamma^{h\to 4f}_{\text{2HDM, LO}}\big|_{\lambda_3,\overline{\text{MS}}} = s^2_{\beta-\alpha}\Gamma^{h\to 4f}_{\text{SM, LO}}$

Partial decay widths for scenario Ab (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 $h\to 4f$	0.95980(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, H.R. 1710.07598]



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

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

Summary

- A variety of tools for BSM models available including at least:
  - ⋆ partly QCD corrections
  - ⋆ partial decay widths (often no distributions)
- Complete NLO predictions including electroweak corrections are becoming available:

  Different renormalization schemes available:

  ⇒ Consistent conversion of parameters between
  the different renormalization schemes has to be performed

  → Useful for theory uncertainty estimate

  ⋆ 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%.
- PROPHECY4F: Extended to the 2HDM (& to the singlet extension) available on request [Altenkamp, Boggia, Dittmaier 1801.07291]

Mixing angles and field renormalization

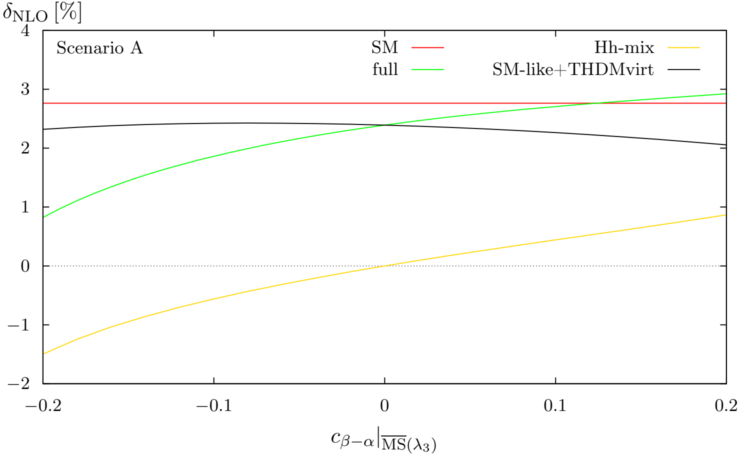
$$\begin{pmatrix}\varphi_{1,0}\\ \varphi_{2,0}\end{pmatrix} = \mathbf{R}_\varphi(\theta_0)\begin{pmatrix}h_{1,0}\\ h_{2,0}\end{pmatrix} = \begin{pmatrix}c_{\theta,0} & -s_{\theta,0}\\ s_{\theta,0} & c_{\theta,0}\end{pmatrix}\begin{pmatrix}h_{1,0}\\ h_{2,0}\end{pmatrix},$$

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

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

Contributions to NLO corrections

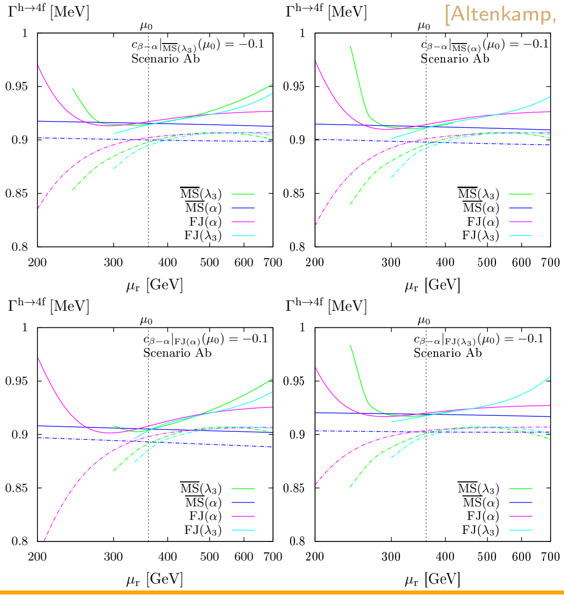
[Altenkamp, Dittmaier, HR 1710.07598]



- 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:

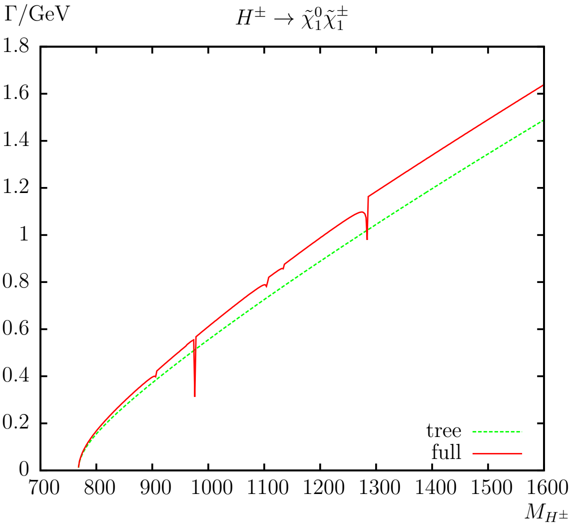
For all input schemes:

- 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)

Recent work in MSSM: $H^+ \to \chi^0\chi^+$



[Heinemeyer, Schappacher, arXiv:1503.02996]

- complete EW contributions
- dips = threshold effects
- compare also to HFOLD

  [Eberl, Frisch, Hlucha, arXiv:1012.5025]