

Uncovering new physics with precision

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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 in the universe
 - ...
 - 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

Two main approaches

Specific extensions of
the Standard Model

- Lagrangian respecting specific symmetries and particle content
- light particles depend on model

Effective field theory

- add higher-dimensional operators to Lagrangian
e.g. $\frac{\bar{c}_6 \lambda_{\text{SM}}}{v^2} (\Phi^\dagger \Phi)^3$
- no new “light” particles

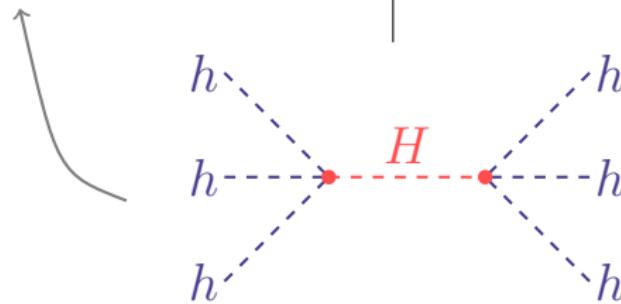
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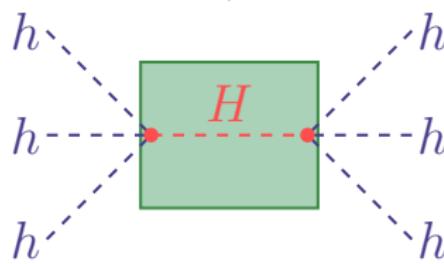
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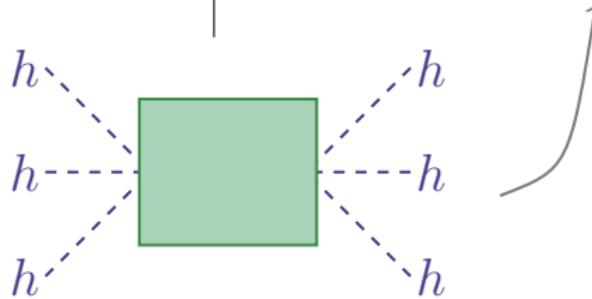
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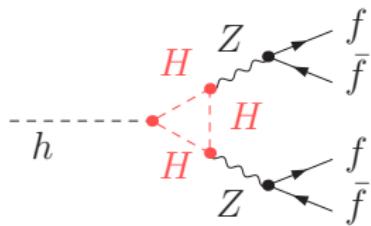
- Lagrangian respecting specific symmetries and particle content
 - light particles depend on model
 - very specific assumptions
- Coupling/decay example:
Higgs boson → 4 fermions

Effective field theory

- add higher-dimensional operators to Lagrangian
e.g. $\frac{c_6 \lambda_{\text{SM}}}{v^2} (\Phi^\dagger \Phi)^3$
 - no new “light” particles
 - many new parameters
- Coupling example:
triple Higgs coupling

Example: 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?

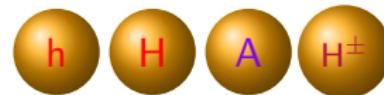


Two-Higgs-Doublet Model

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)



- Embedded in other, more “complete” theories,
e.g. supersymmetric extensions such as the MSSM

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 $\Phi_1 \rightarrow -\Phi_1$ for $m_{12}^2 = 0$ (softly broken by $m_{12}^2 \neq 0$)

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

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

Two-Higgs-Doublet Model

Higgs potential:

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- CP conserving
 - invariant under $\Phi_1 \rightarrow -\Phi_1$ for $m_{12}^2 = 0$ (softly broken by $m_{12}^2 \neq 0$)
 - m_{11}^2, m_{22}^2 fixed by minimum condition
 $m_{12}^2, \lambda_1, \dots, \lambda_5$ free parameters
- ⇒ enough free parameters to define all Higgs masses independently
- ⇒ 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:

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

Input parameters

Originally:

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

Chosen:

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

on-shell

Renormalization

On-shell renormalization:

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

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

→ no mixing of external on-shell fields

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

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

- $\tan \beta$
 - λ_3 or α
 - λ_5
- $\left. \right\} \rightarrow \text{renormalization-scale dependent parameter}$

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
→ no need to renormalize mixing angles

But: If original parameters replaced by mixing angles

→ 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

→ potentially gauge-dependent terms enter relations
between renormalized parameters and observables

- b) Vanishing bare tadpoles: $t_{S,0} = 0$ [Fleischer, Jegerlehner 80; Actis, Ferroglio, 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

→ relation between renormalized parameters and
observables are gauge independent

Four possibilities for λ_3/α and β

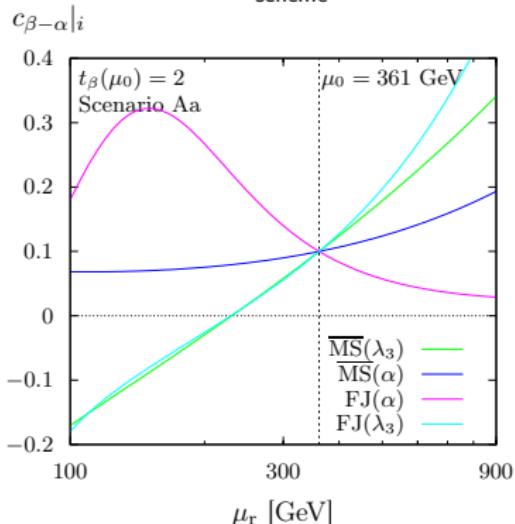
- Scheme $\lambda_3_{\overline{\text{MS}}}$: see [Altenkamp, Dittmaier, H.R. 1704.02645]
 $\lambda_3 \overline{\text{MS}}, \tan \beta \overline{\text{MS}}$
tadpole scheme: $t_S = 0$
- Scheme $\alpha_{\overline{\text{MS}}}$:
 α instead of λ_3 : $\alpha \overline{\text{MS}}, \tan \beta \overline{\text{MS}}$
tadpole scheme: $t_S = 0$
- Scheme FJ:
 $\alpha \overline{\text{MS}}, \tan \beta \overline{\text{MS}}$
tadpole scheme: $t_{S,0} = 0$ see also [Krause, Mühlleitner, Lorenz, Santos, Ziesche 1605.04853; Denner, Jenniches, Lang, Sturm 1607.07352]
- Scheme FJ λ_3 :
 $\lambda_3 \overline{\text{MS}}, \tan \beta \overline{\text{MS}}$
tadpole scheme: $t_{S,0} = 0$

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

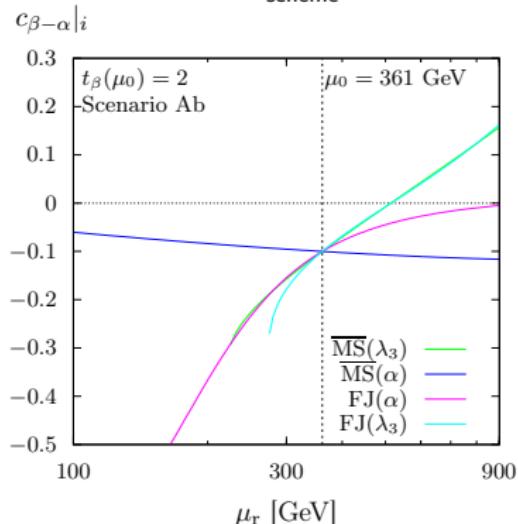
[Altenkamp, Dittmaier, H.R. 1704.02645, 1710.07598]

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

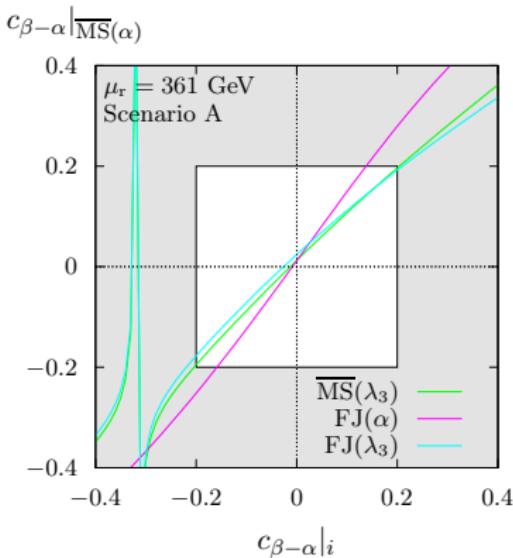
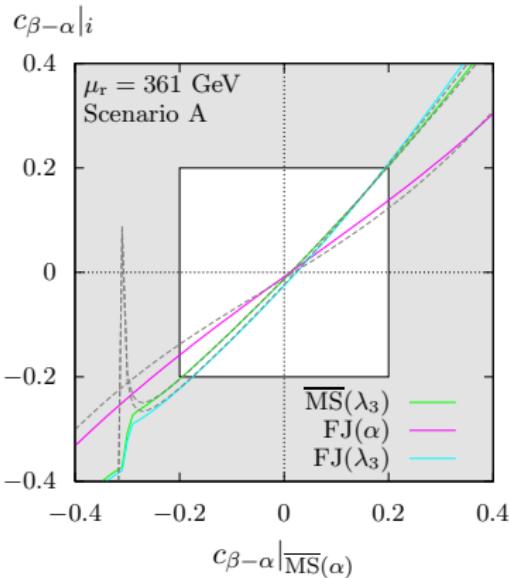


⇒ sizeable running effects

Conversion of parameters

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

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

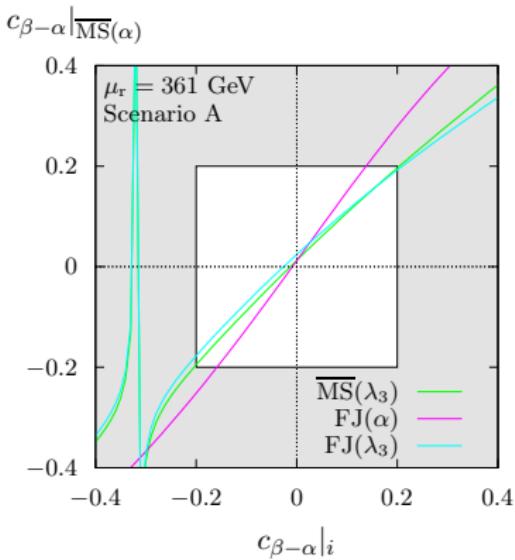
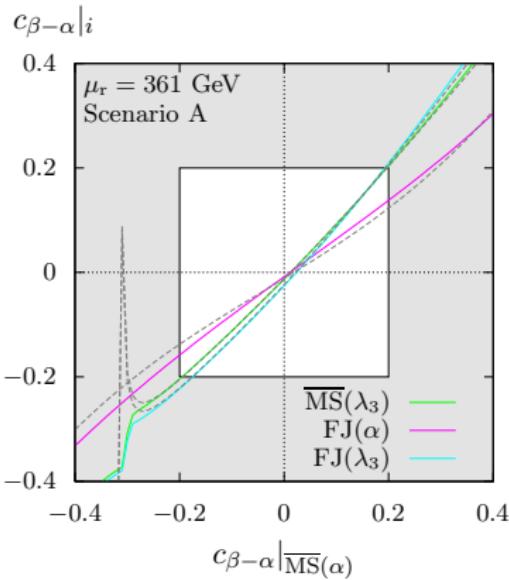


- Scenarios depend on the chosen renormalization scheme.

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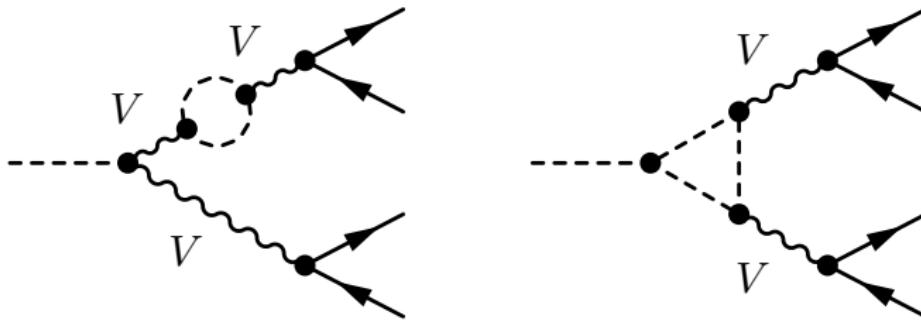
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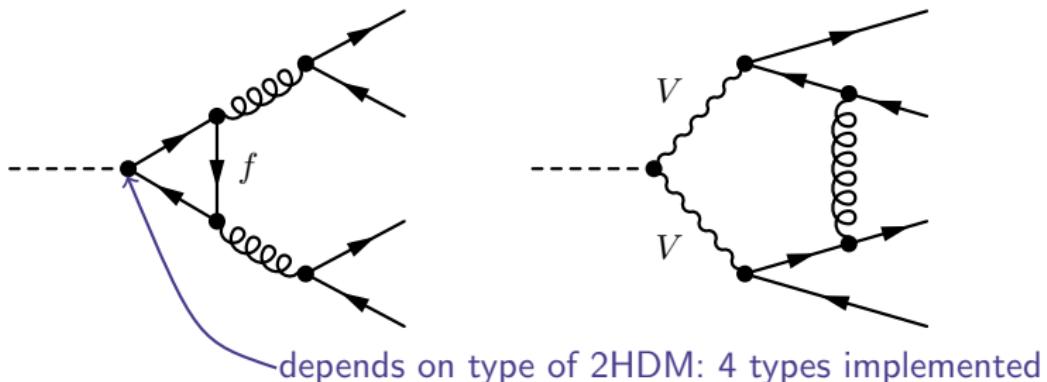
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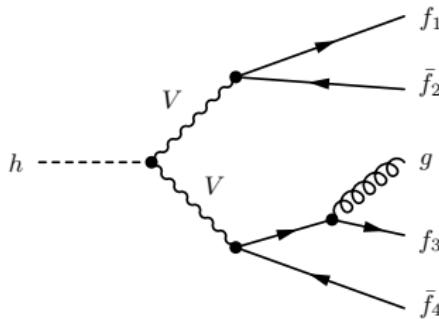
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virtual **QCD** diagrams: obtained by proper rescaling of Higgs couplings
- real diagrams: obtained by rescaling of Higgs coupling $g_{hVV} = \sin(\beta - \alpha) g_{hVV}^{\text{SM}}$



Implementation in PROPHECY4F

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Proper description of the Higgs decay into 4 fermions

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

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- evaluation of loop integrals with **Collier** [Denner, Dittmaier, Hofer 1604.06792]

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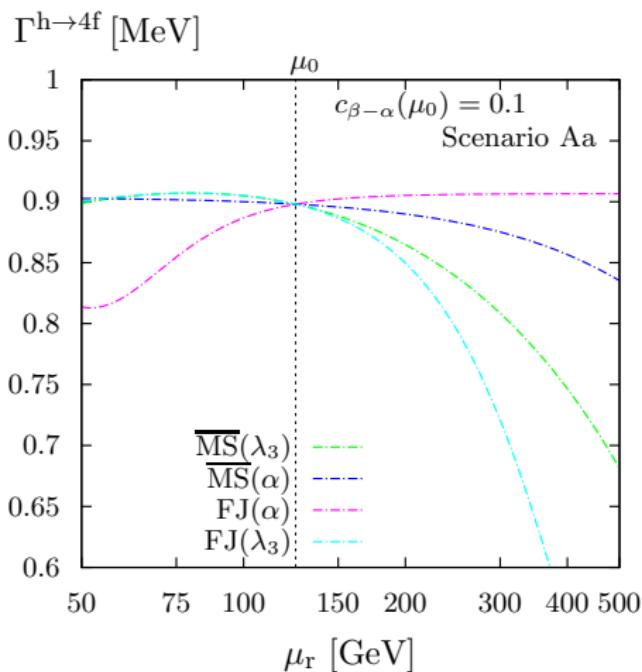
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- infrared divergences treated with dipole subtraction
[Catani, Seymour hep-ph/9605323; Dittmaier hep-ph/9904440]

μ_r dependence of $\Gamma(h \rightarrow 4f)$

[Altenkamp, Dittmaier, H.R. 1704.02645]



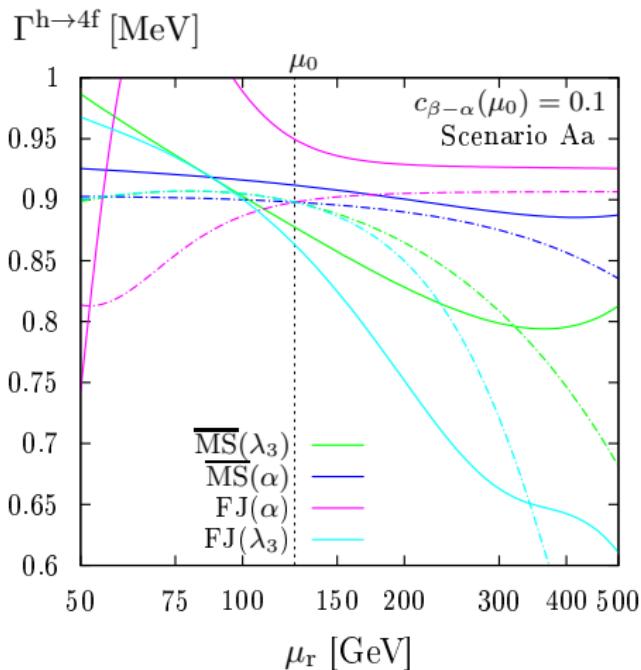
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leading order (LO): dashed

- No conversion:
scenario interpreted as given
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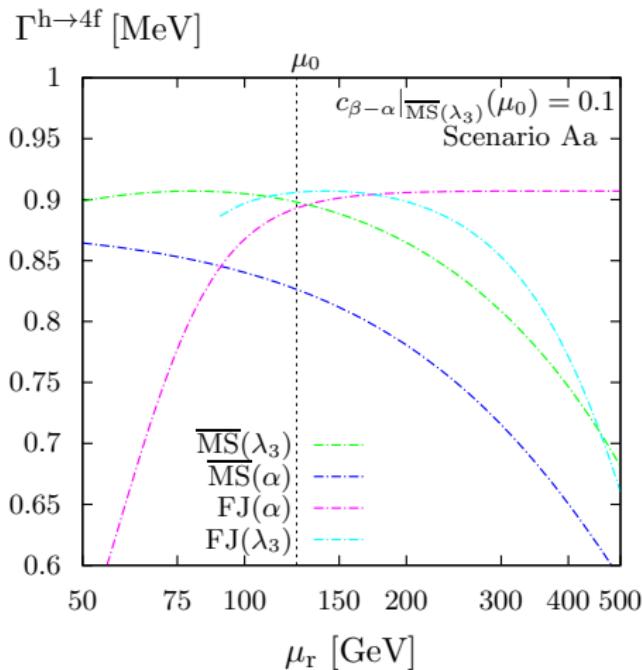
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next-to LO (NLO) electroweak (EW):
solid

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- No clear plateau around
 $\mu_r = \mu_0$ at NLO

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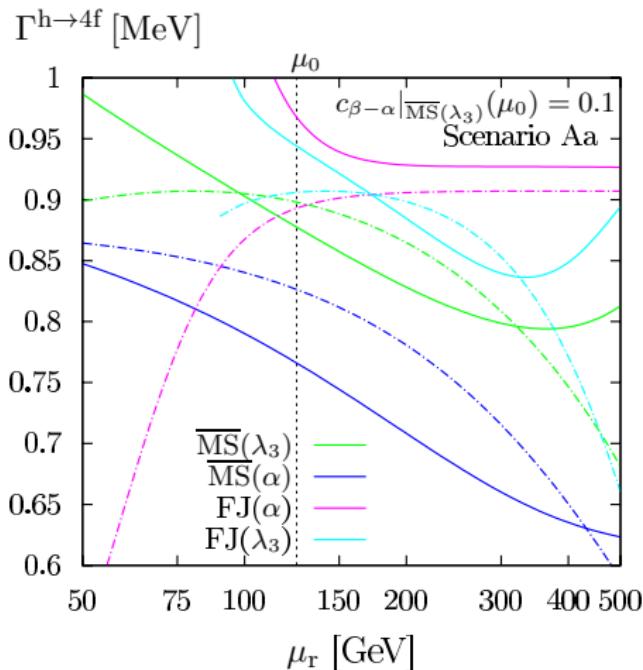
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LO: dashed

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

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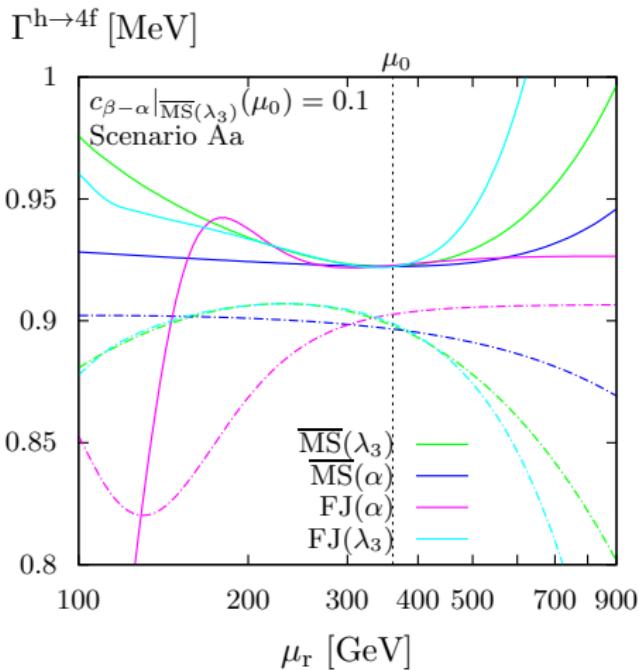
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NLO EW: solid

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

An on-shell renormalization of α_s , β

[Denner, Dittmaier, Lang 1808.03466]

Idea:

- Use ratio of matrix elements, e.g. $\frac{\mathcal{M}_{H \rightarrow ZZ}}{\mathcal{M}_{h \rightarrow ZZ}}$
 - Ensure: Matrix elements evaluated at phase-space points in physical region:
 - ▶ problematic for $\frac{\mathcal{M}_{H \rightarrow ZZ}}{\mathcal{M}_{h \rightarrow ZZ}}$ if h is SM like
 - ▶ introduce new fields and decouple them:
 - ★ two right-handed fermion singlets ν_{1R}, ν_{2R}
 - ★ additional Z_2 symmetry: $\nu_{1R} \rightarrow -\nu_{1R}, \nu_{2R} \rightarrow \nu_{2R}$
- $\Rightarrow \nu_{jR}$ couples only to Φ_j

$$\mathcal{L}_{\nu_R} = \sum_{j=1}^2 i \bar{\nu}_{jR} \partial \nu_{jR} - [y_{\nu_j} \bar{L}_{jL} (i \sigma_2 \Phi_j^*) \nu_{jR} + \text{h.c.}] \text{ with } y_{\nu_j} \rightarrow 0.$$

$L_{jL} = (\nu_j, \ell_j)^T$ = 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 $\frac{\mathcal{M}_{H \rightarrow \nu_1 \bar{\nu}_1}}{\mathcal{M}_{h \rightarrow \nu_1 \bar{\nu}_1}} \stackrel{!}{=} \frac{\mathcal{M}_{H \rightarrow \nu_1 \bar{\nu}_1}^0}{\mathcal{M}_{h \rightarrow \nu_1 \bar{\nu}_1}^0}$, β via $\frac{\mathcal{M}_{A^0 \rightarrow \nu_1 \bar{\nu}_1}}{\mathcal{M}_{H \rightarrow \nu_1 \bar{\nu}_1}} \stackrel{!}{=} \frac{\mathcal{M}_{A^0 \rightarrow \nu_1 \bar{\nu}_1}^0}{\mathcal{M}_{H \rightarrow \nu_1 \bar{\nu}_1}^0}$

- OS 2: as above but $\nu_1 \rightarrow \nu_2$

- OS 12: α via $\frac{\mathcal{M}_{H \rightarrow \nu_2 \bar{\nu}_2}}{\mathcal{M}_{h \rightarrow \nu_2 \bar{\nu}_2}} \stackrel{!}{=} \frac{\mathcal{M}_{H \rightarrow \nu_2 \bar{\nu}_2}^0}{\mathcal{M}_{h \rightarrow \nu_2 \bar{\nu}_2}^0}$,

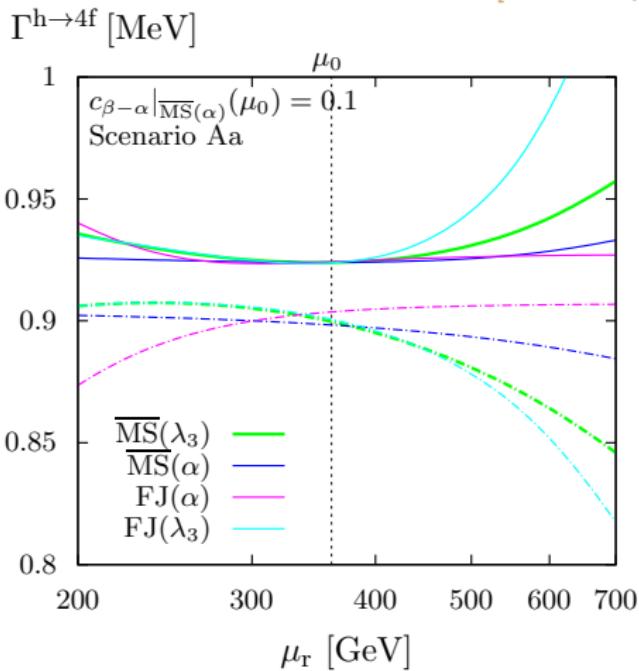
β via

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

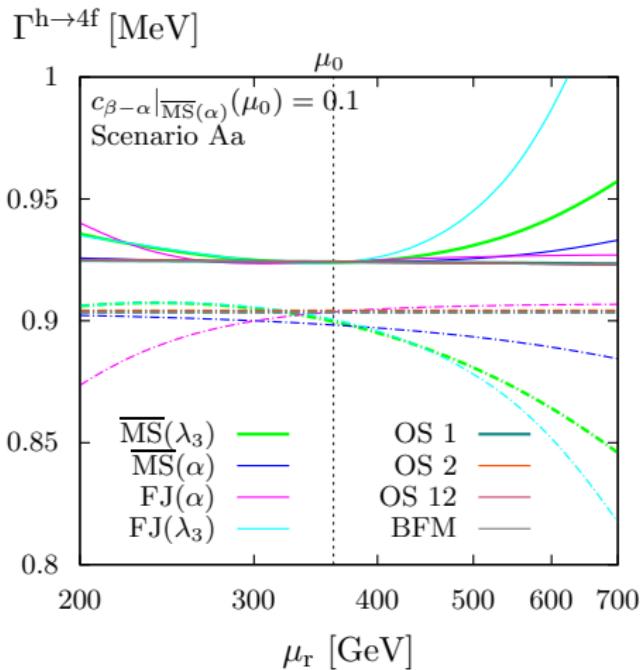
$$M_{\{h,H\} \rightarrow \nu_i \bar{\nu}_j}^0 = [\bar{u}_\nu v_\nu]_{\{h,H\}} F^{\{h,H\} \rightarrow \nu_j \bar{\nu}_j}, M_{A^0 \rightarrow \nu_i \bar{\nu}_j}^0 = [\bar{u}_\nu i \gamma_5 v_\nu]_{A^0} F^{A^0 \rightarrow \nu_j \bar{\nu}_j}$$

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

[Altenkamp, Dittmaier, H.R. 1710.07598]



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



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

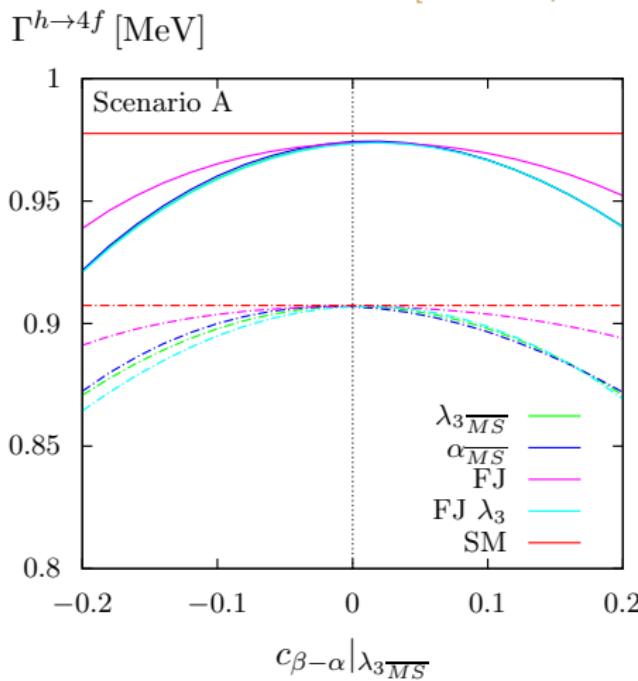
LO: dashed

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 $\Gamma(h \rightarrow 4f)$

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



leading order (LO): dashed
next-to leading order: solid

- Scheme $\lambda_3 \overline{MS}$ used:
 $\Gamma_{2HDM, LO}|_{\lambda_3, \overline{MS}} = \sin^2(\beta - \alpha) \Gamma_{SM, LO}^{h \rightarrow 4f}$
- Deviations of up to
 $\sim 5\%$ from the SM prediction

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

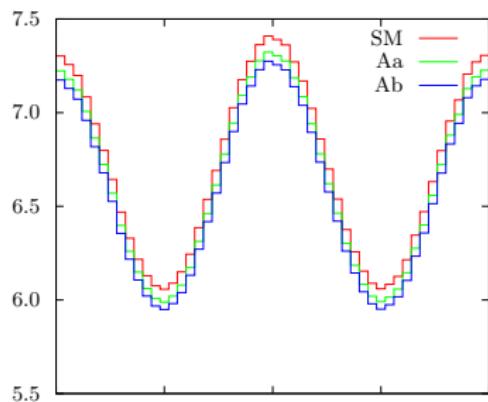
Partial decay widths for scenario Ab (scheme λ_3 MS)

Final state	$\Gamma_{\text{NLO}}^{\text{h} \rightarrow 4f}$ [MeV]	δ_{EW} [%]	δ_{QCD} [%]	$\Delta_{\text{SM}}^{\text{NLO}}$ [%]	$\Delta_{\text{SM}}^{\text{LO}}$ [%]
inclusive $\text{h} \rightarrow 4f$	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)

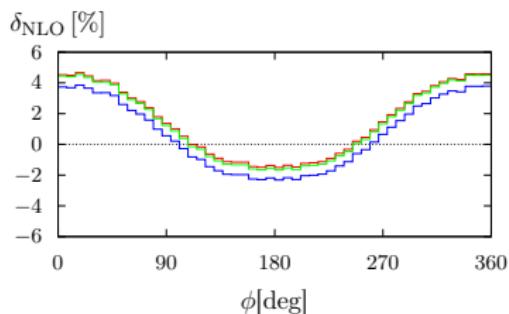
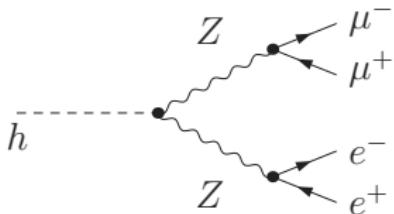
Example distribution

$$\frac{d\Gamma}{d\phi} \left[10^{-7} \frac{\text{MeV}}{\text{deg}} \right] \quad h \rightarrow \mu^-\mu^+e^-e^+$$

[Altenkamp, Dittmaier, HR 1710.07598]



- $\phi = \text{angle between } \mu^-\mu^+ \text{ and } e^-e^+ \text{ decay planes}$



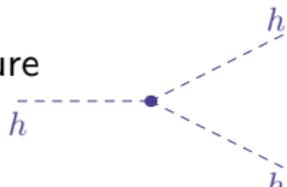
- negligible shape differences between SM and 2HDM

(Scheme $\lambda_3 \overline{\text{MS}}$ used)

Example: Triple Higgs coupling

Higgs self couplings:

- Quartic Higgs coupling near to impossible to measure
- Triple Higgs coupling hard to measure:



Deviation κ_λ defined via Higgs potential $V = \dots + \kappa_\lambda \lambda_{\text{SM}} v h^3 + \dots$

- ★ Direct measurement via Higgs-pair production:

Run 1: $-14.5 \leq \kappa_\lambda \leq 19.1$ [ATLAS, 1509.04670];

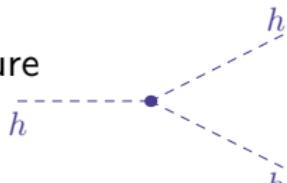
Gorbahn, Haisch, 1607.03773]

Run 2: $-8.4 \leq \kappa_\lambda \leq 13.4$ [ATLAS-CONF-2016-049; Bizon, Gorbahn,
Haisch, Zanderighi, 1610.05771]

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- ★ Constraints from single Higgs measurements:

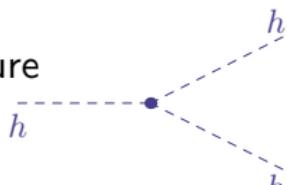
Combined: $-9.4 \leq \kappa_\lambda \leq 17.0$ [Degrassi, Giardino, Maltoni, Pagani,
1607.04251]

(see also [[Di Vita, Grojean, Panico, Riembau, Vantalona, 1704.01953;
Maltoni, Pagani, Shivaji, Zhao, 1709.08649]])

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(see also [[Di Vita, Grojean, Panico, Riembau, Vantalona, 1704.01953;
Maltoni, Pagani, Shivaji, Zhao, 1709.08649]])

⇒ Constraints from precision observables?

S and T parameter

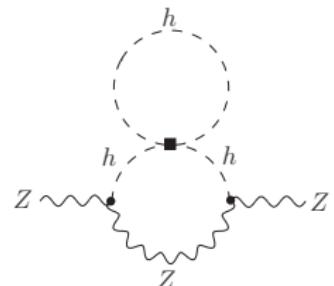
S and T parameter:

- Convenient parameterization of new physics contributions to electroweak quantum corrections

- Assumptions:

- ★ No additional electroweak gauge bosons
 - ★ Couplings to light fermions:
Correction due to new physics suppressed
 - ★ New physics scale large compare to the electroweak scale

- Simple relation to observables such as the W and the Z mass

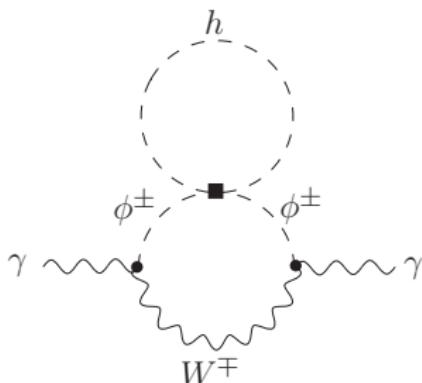
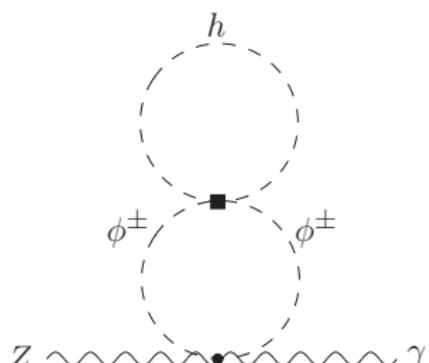
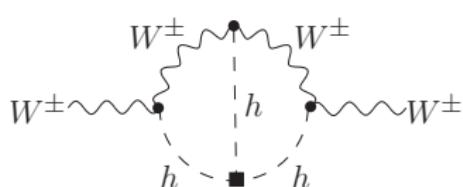
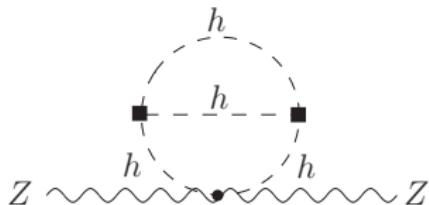


c_6 contributions to S and T

Higgs potential:

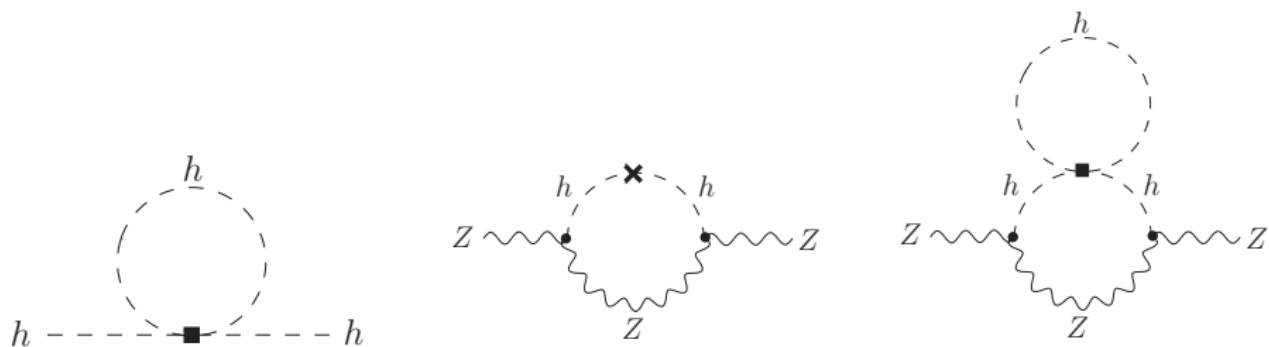
[Kribs, Maier, H.R., Spannowsky, Waite, 1702.07678]

$$V(H) = \mu^2 H^\dagger H + \lambda (H^\dagger H)^2 + \frac{\bar{c}_6 \lambda_{\text{SM}}}{v^2} (H^\dagger H)^3 + \sum_{n>3} \frac{\bar{c}_{2n} \lambda_{\text{SM}}}{v^{2n-4}} (H^\dagger H)^n ,$$



Just a κ_λ deviation

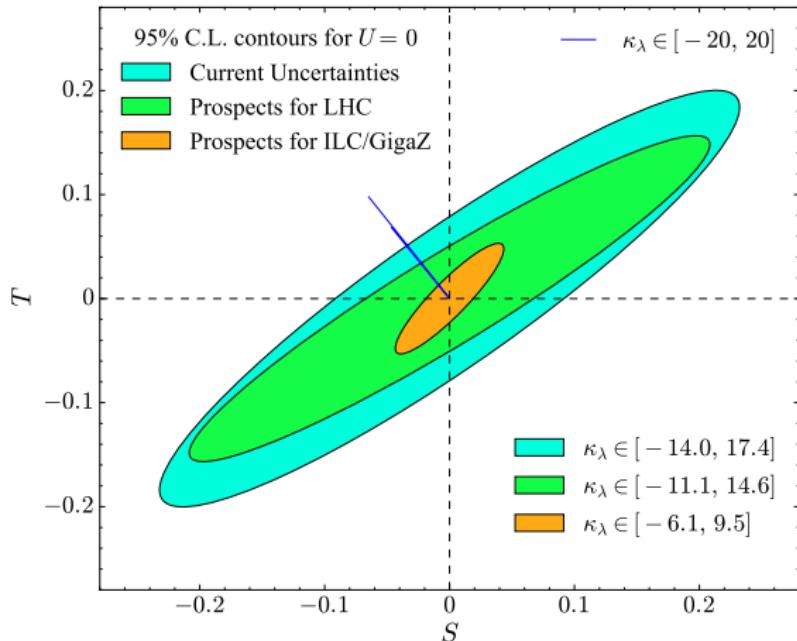
[Kribs, Maier, H.R., Spannowsky, Waite, 1702.07678]



⇒ quartic contribution cancels due to on-shell mass renormalization

Constraints from S and T

[Kribs, Maier, H.R., Spannowsky, Waite, 1702.07678]



$\Rightarrow -14.0 \leq \kappa_\lambda \leq 17.4$ (compatible with [Degrassi, Fedele, Giardino, 1702.01737])

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

► Constraints of triple Higgs coupling from S and T parameter:

- compatible and complementary: $-14.0 \leq \kappa_\lambda \leq 17.4$

Mixing angles and field renormalization

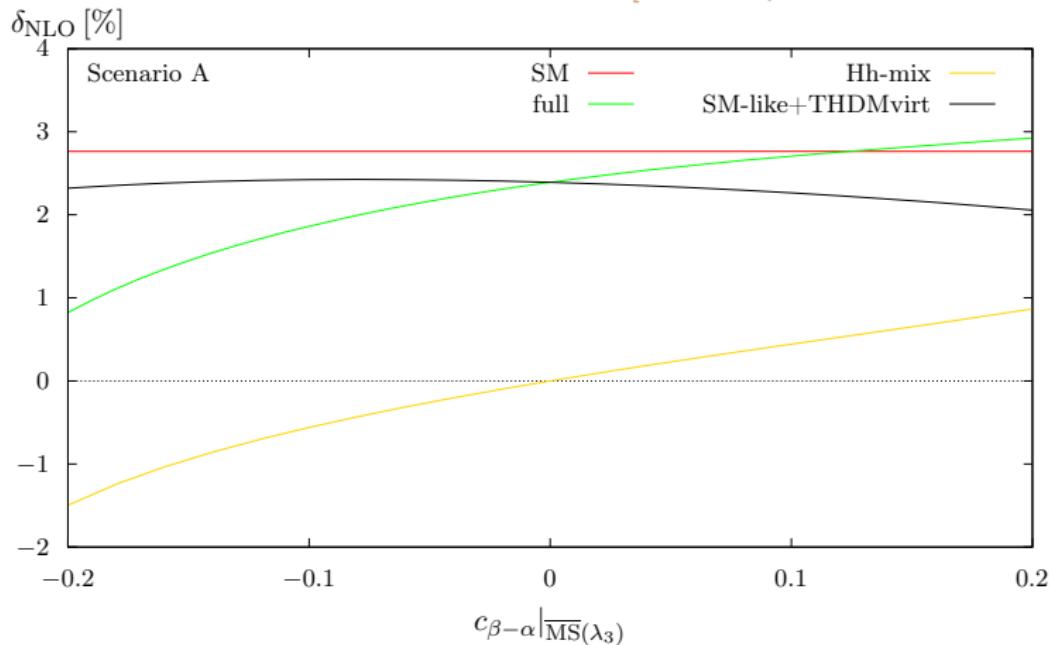
$$\begin{pmatrix} \varphi_{1,0} \\ \varphi_{2,0} \end{pmatrix} = \mathbf{R}_\varphi(\theta_0) \begin{pmatrix} h_{1,0} \\ h_{2,0} \end{pmatrix} = \begin{pmatrix} c_{\theta,0} & -s_{\theta,0} \\ s_{\theta,0} & c_{\theta,0} \end{pmatrix} \begin{pmatrix} h_{1,0} \\ h_{2,0} \end{pmatrix},$$

$$\begin{pmatrix} h_{1,0} \\ h_{2,0} \end{pmatrix} = \begin{pmatrix} 1 + \frac{1}{2}\delta Z_{h_1 h_1} & \frac{1}{2}\delta Z_{h_1 h_2} \\ \frac{1}{2}\delta Z_{h_2 h_1} & 1 + \frac{1}{2}\delta Z_{h_2 h_2} \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}, \quad \theta_0 = \theta + \delta\theta.$$

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

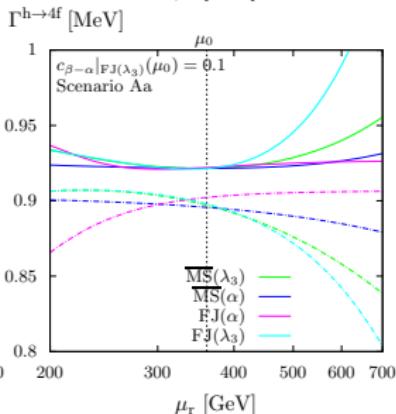
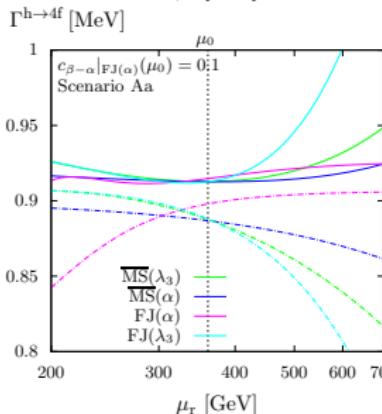
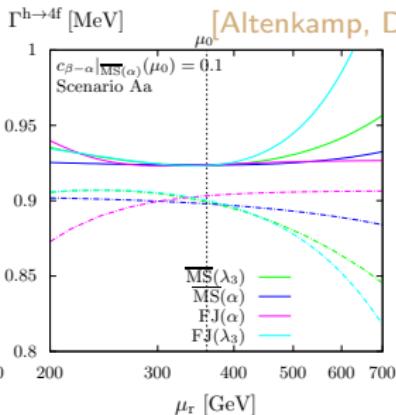
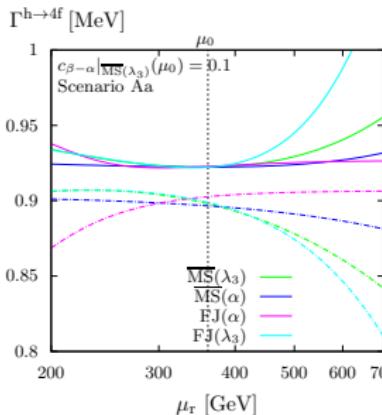
Contributions to NLO corrections

[Altenkamp, Dittmaier, HR 1710.07598]



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

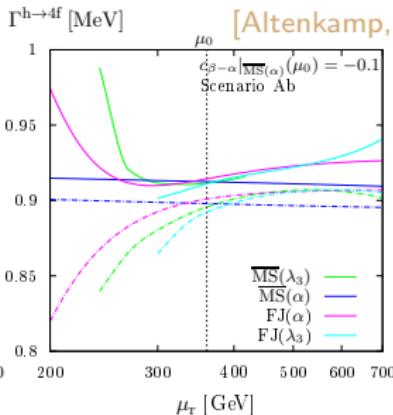
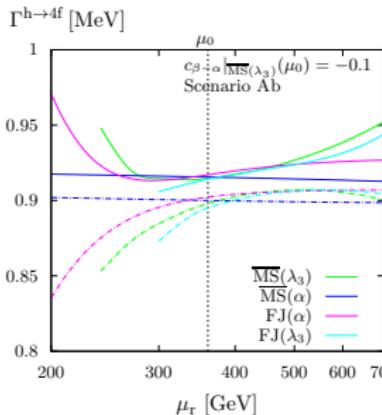
μ_r dependence of $\Gamma(h \rightarrow 4f)$



For all input schemes:

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

μ_r dependence of $\Gamma(h \rightarrow 4f)$



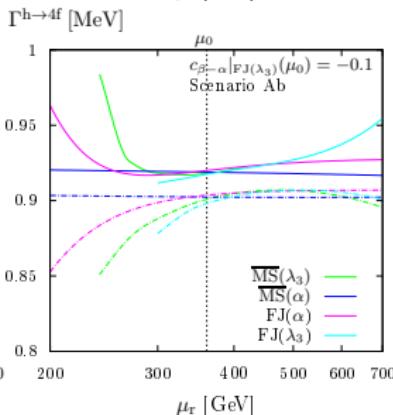
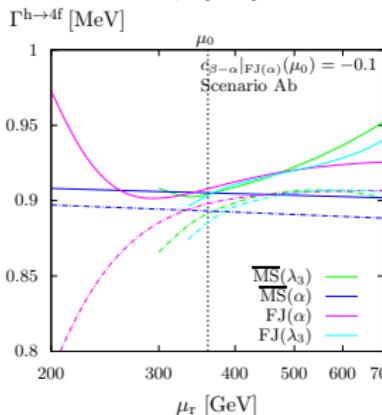
[Altenkamp, Dittmaier, HR 1710.07598]

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 MS)

Final state	$\Gamma_{\text{NLO}}^{\text{h} \rightarrow 4f}$ [MeV]	δ_{EW} [%]	δ_{QCD} [%]	$\Delta_{\text{SM}}^{\text{NLO}}$ [%]	$\Delta_{\text{SM}}^{\text{LO}}$ [%]
inclusive $\text{h} \rightarrow 4f$	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)