The inclusive Higgs width in the SMEFT

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in collaboration with M. Trott and T. Corbett
to appear very soon!

The Niels Bohr International Academy

The SMEFT

SMEFT = Effective Field Theory with **SM fields + symmetries**

a Taylor expansion in canonical dimensions $(v, E/\Lambda)$:

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \frac{1}{\Lambda^3}\mathcal{L}_7 + \frac{1}{\Lambda^4}\mathcal{L}_8 + \dots$$

$\mathcal{L}_n = \sum_i C_i \mathcal{O}_i^{d=n}$

C_i free parameters (Wilson coefficients)

$\mathcal{O}_i$ invariant operators that form a complete basis

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$\mathcal{L}_n = \sum_i C_i \mathcal{O}_i^{d=n}$

C_i free parameters (Wilson coefficients)

$\mathcal{O}_i$ invariant operators that form a complete basis

---

- describes impact of any UV
  - nearly decoupled: $\Lambda \gg v, E$
  - converges to SM in the limit $E \ll \Lambda$
- not just a parameterization but a consistent QFT → loops, RGE etc.

The SMEFT for LHC experiments

lack of direct discoveries so far → systematic **indirect searches** needed

SMEFT is the best tool for this!

see talk by J. de Blas

- reasonably **model-independent**
- **complete & well-defined.** → long-term, extensible analysis plan
  → combination with other experiments

significant developments happened in the last 5 - 10 yrs.

- main focus $\mathcal{L}_6$: leading effects @LHC
- theory improvements
- tools for phenomenology

bottom-up approach: constraining (measuring!) as many parameters as possible, minimizing UV assumptions

- requires a global analysis: EW + Higgs + top + . . .

see talk by A. Biekötter

- minimum bias setup, flavor symmetric → 20-30 params relevant @LHC

The Higgs width

a crucial observable for the Higgs sector

SM: $$\Gamma_H \simeq 4\ \text{MeV} \quad \rightarrow \quad \frac{\Gamma_H}{m_H} \simeq 3 \cdot 10^{-5} \ll 1$$

$\Rightarrow$ Higgs measurements can be factored into

$$\sigma(i \to H) \times Br(H \to f)$$

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SMEFT: probe separately production and decay ☞

$$Br(H \rightarrow f) = \frac{\Gamma(H \rightarrow f)}{\Gamma_H^{\text{tot}}}$$

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SMEFT: probe separately production and decay 👍

$$Br_{\mathrm{SMEFT}}(H \to f) = \left[\frac{\Gamma(H \to f)}{\Gamma_H^{\mathrm{tot}}}\right]_{\mathrm{SM}} \left[1 + \frac{\delta\Gamma(H \to f)}{\Gamma_{\mathrm{SM}}(H \to f)} - \frac{\delta\Gamma_H^{\mathrm{tot}}}{\Gamma_{H,\mathrm{SM}}^{\mathrm{tot}}}\right]$$

- both $\delta\Gamma(H \to f)$ and $\delta\Gamma_H^{\mathrm{tot}}$ need to be determined
- $\delta\Gamma_H^{\mathrm{tot}}$ enters all processes $\rightarrow$ **strong impact** on global SMEFT analyses!

The Higgs width in the SMEFT - preliminaries

Focus on the leading contributions:

- LO in the EFT: up to SM - $\mathcal{L}_6$ **interference**.

$$\Gamma_H = \Gamma_{H,\mathrm{SM}}\left[1+\frac{\delta\Gamma_H}{\Gamma_{H,\mathrm{SM}}}\right] \qquad \frac{\delta\Gamma_H}{\Gamma_{H,\mathrm{SM}}} = \sum_i a_i \bar{C}_i = \sum_i a_i\left(C_i \frac{v^2}{\Lambda^2}\right)$$

- **tree level**.

  SM couplings $H\gamma\gamma$, $HZ\gamma$, Hgg included as effective vertices for $H\to f\bar{f}\gamma\ /\ \gamma\gamma\ /\ gg$.
  Neglected in other channels.

- up to **4-body** decays.

Conventions and assumptions:

- Warsaw basis — Grzadkowski,Iskrzynski,Misiak,Rosiek 1008.4884
- **U(3)^5 flavor symmetry** $\to g_{Hff}\sim y_f$ also in the SMEFT
- **inclusive** calculation, not differential $\to$ CP odd terms do not contribute
- EW input scheme: $\{m_Z, m_W, G_F\}$ $\to \delta m_W, \delta m_Z = 0$, $\delta e \neq 0$ ⇝ **backup**

The Higgs width in the SMEFT

leading channels:

$$H \to \bar{f}f$$

$$H \to gg$$

$$H \to \gamma\gamma$$

$$H \to \bar{f}f\gamma$$

$$H \to 4f$$

- $\Gamma(H \to 4f), \Gamma(H \to \gamma\gamma), \Gamma(H \to \bar{b}b)$ most relevant ones individually
- all need to be calculated for $\delta\Gamma_H^{\rm tot} \to Br$

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$H \to \bar{f}f\gamma$

$H \to 4f$

$$\frac{\Gamma(H\to\bar{f}f)}{\Gamma_{SM}(H\to\bar{f}f)} \simeq 1 + 2\delta g_{Hff}$$

$$\delta g_{Hff} = \bar{C}_{H\Box} - \frac{\bar{C}_{HD}}{4} - \bar{C}_{Hl}^{(3)} + \frac{\bar{C}'_{ll}}{2} - \frac{5}{2}\bar{C}_{fH}$$

Alonso, Jenkins, Manohar, Trott 1312.2014

- renorm. of the H field
- contrib. to μ decay $\to G_F \to v$
- direct $\mathcal{O}_{fH}$ contribution $\quad (-\frac{3}{2}\bar{C}_{fH})$
  $+$
  contrib. to $m_f \to y_f \quad (-\bar{C}_{fH})$

- $\Gamma(H\to 4f), \Gamma(H\to\gamma\gamma), \Gamma(H\to\bar{b}b)$ most relevant ones individually
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The Higgs width in the SMEFT

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$H \to \bar{f} f$

$H \to gg$

$H \to \gamma\gamma$

$H \to \bar{f} f \gamma$

$H \to 4f$

$$\frac{\Gamma(h \to gg)}{\Gamma^{SM}(h \to gg)} \simeq 1 + \frac{16\pi^2}{g_s^2 I^g} \bar{C}_{HG}, \qquad I^g \simeq 0.375$$

Manohar,Wise 0601212

- $\Gamma(H \to 4f), \Gamma(H \to \gamma\gamma), \Gamma(H \to \bar{b}b)$ most relevant ones individually
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The Higgs width in the SMEFT

leading channels:

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$H \to gg$

$H \to \gamma\gamma$

$H \to \bar{f}f\gamma$

$H \to 4f$

$$\frac{\Gamma(h\to\gamma\gamma)}{\Gamma^{SM}(h\to\gamma\gamma)} \simeq 1 + \frac{16\pi^2}{e^2 I^\gamma}\mathscr{C}_{\gamma\gamma}, \qquad I^\gamma \simeq -1.65$$

$$\mathscr{C}_{\gamma\gamma} = s_\theta^2\,\bar{C}_{HW} + c_\theta^2\,\bar{C}_{HB} - s_\theta c_\theta\,\bar{C}_{HWB}$$

Bergström,Hulth Nucl.Phys.B259(1985)137
Manohar,Wise 0601212

- $\Gamma(H\to 4f), \Gamma(H\to\gamma\gamma), \Gamma(H\to\bar{b}b)$ most relevant ones individually
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The Higgs width in the SMEFT

leading channels:

$H \to \bar{f} f$

⟶ $H \to gg$

⟶ $H \to \gamma\gamma$

⟶ $H \to \bar{f} f \gamma$

$H \to 4f$

$$\frac{\Gamma(h \to \gamma\gamma)}{\Gamma^{SM}(h \to \gamma\gamma)} \simeq 1 - \frac{16\pi^2}{e^2 I^\gamma} \mathscr{C}_{\gamma\gamma}, \qquad I^\gamma \simeq -1.65$$

$$\mathscr{C}_{\gamma\gamma} = s_\theta^2 \bar{C}_{HW} + c_\theta^2 \bar{C}_{HB} - s_\theta c_\theta \bar{C}_{HWB}$$

Bergström,Hulth Nucl.Phys.B259(1985)137
Manohar,Wise 0601212

loop-factor enhancement
in the relative correction:

tree-level SMEFT vs loop SM

- $\Gamma(H \to 4f), \Gamma(H \to \gamma\gamma), \Gamma(H \to \bar{b}b)$ most relevant ones individually
- all need to be calculated for $\delta\Gamma_H^{\rm tot} \to Br$

The Higgs width in the SMEFT

leading channels:

$H \to \bar{f}f$

$H \to gg$

$H \to \gamma\gamma$

$H \to \bar{f}f\gamma$

$H \to 4f$

available as $H \to ZZ^*$, $H \to WW^*$ $\times Br(Z, W)$ relying on narrow width approx. for Z, W.

good in SM but **not sufficient** in the SMEFT!

main reason: tree $\gamma\gamma, Z\gamma$ mediated diagrams

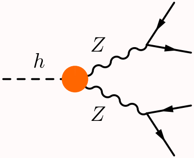
also missing:

- CC - NC interference
- crossed-current interference in ZZ diagrams
- $\delta\Gamma_V$, δm_V^2 corrections for off-shell boson

- $\Gamma(H \to 4f), \Gamma(H \to \gamma\gamma), \Gamma(H \to \bar{b}b)$ most relevant ones individually
- all need to be calculated for $\delta\Gamma_H^{\rm tot} \to Br$

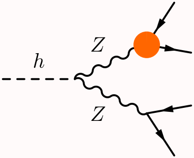
H $\rightarrow$ 4f in the SMEFT

① corrections to SM diagrams

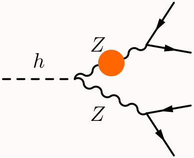


$\propto g_{\mu\nu}$ (SM-like)

$\propto g_{\mu\nu} p \cdot q - p_\nu q_\mu$



$\delta g_L, \delta g_R$



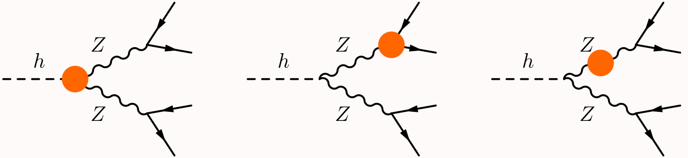
$$\frac{-i m_Z \delta\Gamma_Z + (2m_Z - i\Gamma_Z)\delta m_Z}{p^2 - m_Z^2 + i\Gamma_Z m_Z}$$

$\uparrow$

hard to extract from MC simulation!
full treatment requires analytic calculation

H → 4f in the SMEFT

① corrections to SM diagrams



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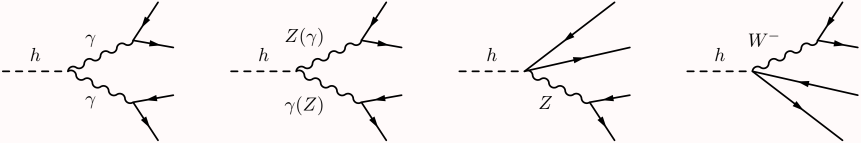
$\delta g_L, \delta g_R$

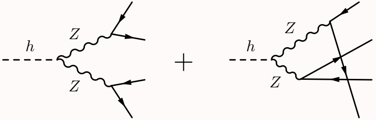
$$\frac{-i m_Z \delta\Gamma_Z + (2m_Z - i\Gamma_Z)\delta m_Z}{p^2 - m_Z^2 + i\Gamma_Z m_Z}$$

② genuine SMEFT diagrams

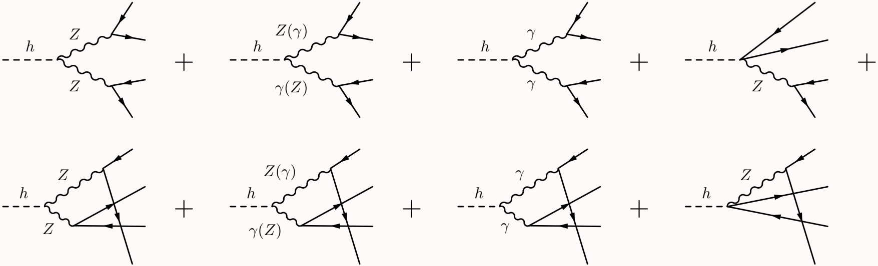


$$h \to e^+ e^- e^+ e^-$$

SM

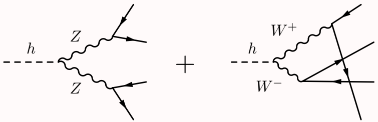


interfering with

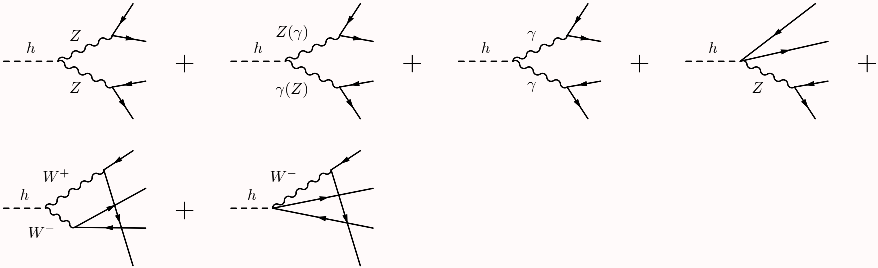


$h \to \bar{u}\, u\, \bar{d}\, d$

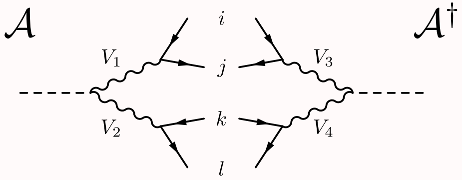
SM



interfering with



fully analytical treatment. automated with general decomposition:



$$\mathcal{A}\mathcal{A}^\dagger \sim g_{HV_1V_2}\, g_{HV_3V_4} \sum_n \mathcal{T}^{(n)}$$

$$\mathcal{T}^{(n)} = \mathcal{K}^{(n)}\left(g_{L,R}^{ij,V_1}, g_{L,R}^{ij,V_3}, g_{L,R}^{kl,V_2}, g_{L,R}^{kl,V_4}\right)\mathcal{F}^{(n)}_{V_1V_2V_3V_4}(p_a, m_a)\,, \quad a = \{i,j,k,l\}$$

- for $m_i, m_j, m_k, m_l = 0$ there are only 8 independent $\mathcal{F}_{V_1V_2V_3V_4}$
- $\mathcal{F}$ computed for every $\{V\}$ set.
  numerical integration of phase space: `Vegas` in `Mathematica`.
  cross-check: 2 independent parameterizations of phase sp., `RAMBO`.

$H \to$ 4f - results

Example: $H \to e^+ e^- \mu^+ \mu^-$ $\qquad m_i, m_j, m_k, m_l = 0$

$$\frac{\delta\Gamma(H \to e^+ e^- \mu^+ \mu^-)}{\Gamma_{\rm SM}(H \to e^+ e^- \mu^+ \mu^-)} = \sum_i a_i \bar{C}_i$$

	$\bar{C}_{HW}$	$\bar{C}_{HB}$	$\bar{C}_{HWB}$	$\bar{C}_{H\Box}$	$\bar{C}_{HD}$	$\bar{C}_{Hl}^{(1)}$	$\bar{C}_{Hl}^{(3)}$	$\bar{C}_{He}$	$\bar{C}_{Hq}^{(1)}$	$\bar{C}_{Hq}^{(3)}$	$\bar{C}_{Hu}$	$\bar{C}_{Hd}$	$\bar{C}'_{ll}$
Z	-0.78	-0.22	0.30	2	0.17	4.38	-1.62	-3.52					3.
A	1.04	-1.08	-0.68										
E						-2.23	-2.23	1.80					
G			-0.38		0.06	0.15	1.14	0.15	-0.39	-1.34	-0.20	0.15	-0.83
tot	0.26	-1.30	-0.76	2.	0.23	2.30	-2.71	-1.58	-0.39	-1.34	-0.20	0.15	2.17

Z	corrections to SM diagram
A	γ diagrams
E	contact diagrams ($HZee$)
G	$\delta\Gamma_Z^{\rm tot}/\Gamma_{Z,SM}$ on + off-shell Z

H → 4f - results

Example: $H \to e^+ e^- \mu^+ \mu^-$ $m_i, m_j, m_k, m_l = 0$

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Impact of previously neglected contributions

(1) photon-mediated diagrams

$\mathcal{O}(1-250)\%$ effect

	with γ			without γ		
	$\bar{C}_{HW}$	$\bar{C}_{HB}$	$\bar{C}_{HWB}$	$\bar{C}_{HW}$	$\bar{C}_{HB}$	$\bar{C}_{HWB}$
$h \to e^+e^-\mu^+\mu^-$	0.26	-1.30	-0.38	-0.77	-0.22	0.30
$h \to \bar{u}u\bar{c}c$	1.45	-2.63	-0.29	-0.77	-0.22	1.33
$h \to e^+e^-\bar{d}d$	0.50	-1.55	-0.37	-0.77	-0.22	0.47
$h \to e^+e^-e^+e^-$	0.02	-2.28	0.27	-0.76	-0.21	0.44
$h \to \bar{u}u\bar{u}u$	1.39	-2.72	-0.14	-0.76	-0.21	1.19
$h \to e^+e^-\bar{\nu}_e\nu_e$	-1.49	0.01	-0.06	-1.48	-0.007	-0.07

Impact of previously neglected contributions

(2) $Z-W$ interference terms

$\mathcal{O}(1-200)\%$ effect

$\delta\Gamma(H\to e^+e^-\bar\nu_e\nu_e)/\Gamma_{\rm SM}$ omitting γ and $\delta\Gamma_Z,\delta\Gamma_W$ contrib.

	$\bar C_{HW}$	$\bar C_{HB}$	$\bar C_{HWB}$	$\bar C_{H\Box}$	$\bar C_{HD}$	$\bar C_{Hl}^{(1)}$	$\bar C_{Hl}^{(3)}$	$\bar C_{He}$	$\bar C_{Hq}^{(1)}$	$\bar C_{Hq}^{(3)}$	$\bar C_{Hu}$	$\bar C_{Hd}$	$\bar C'_{ll}$
full	-1.49	-0.007	-0.07	2.	-0.55	-0.008	-3.74	-0.04	0	0	0	0	3.
NW	-1.46	-0.01	-0.003	2.	-0.49	0.004	-3.77	-0.04	0.	0.	0.	0.	3.

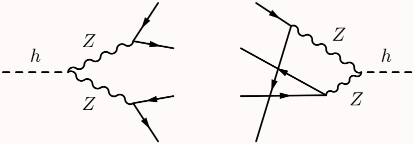
full	$\lvert\mathcal{A}_{ZZ}\rvert^2+\lvert\mathcal{A}_{WW}\rvert^2+2{\rm Re}\mathcal{A}_{ZZ}\mathcal{A}_{WW}^\dagger$
NW	$\lvert\mathcal{A}_{ZZ}\rvert^2+\lvert\mathcal{A}_{WW}\rvert^2$

breadown of the full case:

	$\bar C_{HW}$	$\bar C_{HB}$	$\bar C_{HWB}$	$\bar C_{H\Box}$	$\bar C_{HD}$	$\bar C_{Hl}^{(1)}$	$\bar C_{Hl}^{(3)}$	$\bar C_{He}$	$\bar C_{Hq}^{(1)}$	$\bar C_{Hq}^{(3)}$	$\bar C_{Hu}$	$\bar C_{Hd}$	$\bar C'_{ll}$
ZZ	-0.04	-0.01	-0.003	0.09	-0.008	0.004	-0.19	-0.04	0	0	0	0	0.14
WW	-1.49	0	0	2.0	-0.50	0	-3.77	0	0	0	0	0	3.00
WZ	0.04	0.004	-0.06	-0.10	-0.04	-0.01	0.21	0	0	0	0	0	-0.14
tot	-1.49	-0.007	-0.07	2.	-0.55	-0.008	-3.74	-0.04	0	0	0	0	3.

(3) NC crossed - interference terms

$\mathcal{O}(\text{few} - 40)\%$ effect



$\delta\Gamma(H \to e^+e^-e^+e^-)/\Gamma_{\rm SM}$ incl. only ZZ and $HZee$ diagrams

	$\bar{C}_{HW}$	$\bar{C}_{HB}$	$\bar{C}_{HWB}$	$\bar{C}_{H\square}$	$\bar{C}_{HD}$	$\bar{C}_{Hl}^{(1)}$	$\bar{C}_{Hl}^{(3)}$	$\bar{C}_{He}$	$\bar{C}_{Hq}^{(1)}$	$\bar{C}_{Hq}^{(3)}$	$\bar{C}_{Hu}$	$\bar{C}_{Hd}$	$\bar{C}'_{ll}$
full	-0.75	-0.22	0.43	2.	0.28	2.09	-3.91	-1.64	0	0	0	0	3.
NW	-0.78	-0.221	0.30	2.	0.17	2.15	-3.85	-1.73	0.	0.	0.	0.	3.

full: $|\mathcal{A}_{ijkl}|^2 + |\mathcal{A}_{ilkj}|^2 + 2\mathrm{Re}\mathcal{A}_{ijkl}\mathcal{A}^\dagger_{ilkj}$
NW: $|\mathcal{A}_{ijkl}|^2 + |\mathcal{A}_{ilkj}|^2$

Impact of previously neglected contributions

(4) $\delta\Gamma_V$, δm_V from off-shell boson

$\mathcal{O}$(few)% effect

narrow width approx.:

$$\frac{\delta\Gamma(H\to VV^*\to 4f)}{\Gamma_{SM}(H\to VV^*\to 4f)} = -\frac{\delta\Gamma_V}{\Gamma_{V,SM}} + \dots$$

full calculation:

$$\begin{array}{l|l}
h\to e^+e^-\mu^+\mu^- & -0.820 \quad \delta\Gamma_Z/\Gamma_{Z,SM} \\
h\to e^+e^-e^+e^- & -0.748 \quad \delta\Gamma_Z/\Gamma_{Z,SM} \\
h\to e^+\nu_e\bar\nu_\mu\mu^- & -0.915 \quad \delta\Gamma_W/\Gamma_{W,SM} \\
h\to e^+\nu_e\bar\nu_e e^- & -0.914 \quad \delta\Gamma_W/\Gamma_{W,SM} \;-\; 0.038 \quad \delta\Gamma_Z/\Gamma_{Z,SM}
\end{array}$$

H → 4f summary

- we did a **fully analytic** calculation, with numerical integration of phase space
- also generated all channels with `MG5_aMC@NLO` using the `SMEFTsim` package → agreement to 1% or better ✓

  Brivio,Jiang,Trott 1709.06492
- analytic treatment has a few advantages:
  - allows to separate contributions
  - easier to linearize in $\delta\Gamma_V, \delta m_V$
  - more stable for the massless fermions case with γ diagrams
  - calculation can be **automated** in a dedicated package → much faster than MC generation
- some previously neglected contributions turn out to be relevant:

  γ diagrams and $Z - W$ interference

The total Higgs width in the SMEFT

putting together all the main contributions* we obtain

$$\Gamma_H^{\rm tot} = \Gamma_{H,SM}^{\rm tot}\left[1 + \frac{\delta\Gamma_H^{\rm tot}}{\Gamma_{H,SM}^{\rm tot}}\right]$$

$$\Gamma_{H,SM}^{\rm tot} = 5.98 \text{ MeV}$$

$$\begin{aligned}\frac{\delta\Gamma_H^{\rm tot}}{\Gamma_{H,SM}^{\rm tot}} =& -1.43\,\bar{C}_{dH} - 0.13\,\bar{C}_{uH} - 0.09\,\bar{C}_{eH}\\ &+ 22.24\,\bar{C}_{HG} - 0.80\,\bar{C}_{HW} - 1.05\,\bar{C}_{HB} + 0.85\,\bar{C}_{HWB} + 1.92\,\bar{C}_{H\Box} - 0.47\,\bar{C}_{HD}\\ &- 0.004\,\bar{C}_{Hl}^{(1)} - 2.18\,\bar{C}_{Hl}^{(3)} + 0.001\,\bar{C}_{He} + 0.003\,\bar{C}_{Hq}^{(1)} + 0.019\,\bar{C}_{Hq}^{(3)}\\ &+ 0.00004\,\bar{C}_{Hu} - 0.0005\,\bar{C}_{Hd} + 1.10\,\bar{C}'_{ll}\end{aligned}$$

*$gg + \gamma\gamma + \bar{b}b + \bar{c}c + \tau^+\tau^- + 4f + \bar{f}f\gamma$

PRELIMINARY

Conclusions

- the inclusive Higgs width is a crucial observable for the Higgs sector
- improved calculation of $H \to 4f,\ H \to \bar{f} f \gamma$
  without relying on the narrow width approx. for Z, W
  $\to$ important for LHC measurements
- joined all the main channels into $\delta\Gamma_H^{\text{tot}}$
- the complete analysis will appear very soon!
  with an automated package that gives $\text{Br}_{H\to X}(C_i)$
- Br's and Γ_H^{tot} are computed **once and for all!**
  $\to$ can be used directly without further MC generation
- possible refinements:
  $\{\alpha_{em}, m_Z, G_F\}$ input scheme
  full massive fermions treatment
  phase space integration with cuts
  ...

Backup slides

The Warsaw basis

Grzadkowski,Iskrzynski,Misiak,Rosiek 1008.4884

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\,\varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\,\varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde W B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

The Warsaw basis

Grzadkowski,Iskrzynski,Misiak,Rosiek 1008.4884

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$		

Shifts from input parameters

SM case.

Parameters in the canonically normalized Lagrangian : $\bar{v}, \bar{g}_1, \bar{g}_2, s_{\bar{\theta}}$

The values can be inferred from the measurements e.g. of $\{\alpha_{\rm em}, m_Z, G_f\}$:

$$\alpha_{\rm em} = \frac{\bar{g}_1 \bar{g}_2}{\bar{g}_1^2 + \bar{g}_2^2} \qquad m_Z = \frac{\bar{g}_2 \bar{v}}{2 c_{\bar{\theta}}} \qquad G_f = \frac{1}{\sqrt{2}\bar{v}^2}$$

$$\rightarrow$$

$$\hat{v}^2 = \frac{1}{\sqrt{2} G_f}$$

$$\sin\hat{\theta}^2 = \frac{1}{2}\left(1 - \sqrt{1 - \frac{4\pi\alpha_{\rm em}}{\sqrt{2} G_f m_Z^2}}\right)$$

$$\hat{g}_1 = \frac{\sqrt{4\pi\alpha_{\rm em}}}{\cos\hat{\theta}}$$

$$\hat{g}_2 = \frac{\sqrt{4\pi\alpha_{\rm em}}}{\sin\hat{\theta}}$$

in the SM at tree-level $\bar{\kappa} = \hat{\kappa}$

Shifts from input parameters

SMEFT case.

Parameters in the canonically normalized Lagrangian : $\bar{v}, \bar{g}_1, \bar{g}_2, s_{\bar{\theta}}$

The values can be inferred from the measurements e.g. of $\{\alpha_{\rm em}, m_Z, G_f\}$:

$$\alpha_{\rm em} = \frac{\bar{g}_1\bar{g}_2}{\bar{g}_1^2+\bar{g}_2^2}\left[1+\bar{v}^2 C_{HWB}\frac{\bar{g}_2^3/\bar{g}_1}{\bar{g}_1^2+\bar{g}_2^2}\right]$$

$$m_Z = \frac{\bar{g}_2\bar{v}}{2c_{\bar{\theta}}} + \delta m_Z(C_i) \qquad \rightarrow$$

$$G_f = \frac{1}{\sqrt{2}\bar{v}^2} + \delta G_f(C_i)$$

$$\hat{v}^2 = \frac{1}{\sqrt{2}G_f}$$

$$\sin\hat{\theta}^2 = \frac{1}{2}\left(1-\sqrt{1-\frac{4\pi\alpha_{\rm em}}{\sqrt{2}G_f m_Z^2}}\right)$$

$$\hat{g}_1 = \frac{\sqrt{4\pi\alpha_{\rm em}}}{\cos\hat{\theta}}$$

$$\hat{g}_2 = \frac{\sqrt{4\pi\alpha_{\rm em}}}{\sin\hat{\theta}}$$

in the SM at tree-level $\bar{\kappa} = \hat{\kappa}$

in the SMEFT $\bar{\kappa} = \hat{\kappa} + \delta\kappa(C_i)$

Shifts from input parameters

To have numerical predictions it is necessary to replace $\bar{\kappa} \to \hat{\kappa} + \delta\kappa(C_i)$ for all the parameters in the Lagrangian.

$\{\alpha_{\rm em}, m_Z, G_f\}$ scheme

$$\delta m_Z^2 = m_Z^2 \hat{v}^2 \left(\frac{c_{HD}}{2} + 2 c_{\hat\theta} s_{\hat\theta} c_{HWB}\right)$$

$$\delta G_f = \frac{\hat{v}^2}{\sqrt{2}} \left((c_{Hl}^{(3)})_{11} + (c_{Hl}^{(3)})_{22} - (c_{ll})_{1221}\right)$$

$$\delta g_1 = \frac{s_{\hat\theta}^2}{2(1-2s_{\hat\theta}^2)} \left(\sqrt{2}\delta G_f + \delta m_Z^2/m_Z^2 + 2\frac{c_{\hat\theta}^3}{s_{\hat\theta}} c_{HWB} \hat{v}^2\right)$$

$$\delta g_2 = -\frac{c_{\hat\theta}^2}{2(1-2s_{\hat\theta}^2)} \left(\sqrt{2}\delta G_f + \delta m_Z^2/m_Z^2 + 2\frac{s_{\hat\theta}^3}{c_{\hat\theta}} c_{HWB} \hat{v}^2\right)$$

$$\delta s_\theta^2 = 2 c_{\hat\theta}^2 s_{\hat\theta}^2 (\delta g_1 - \delta g_2) + c_{\hat\theta} s_{\hat\theta} (1 - 2 s_{\hat\theta}^2) c_{HWB} \hat{v}^2$$

$$\delta m_h^2 = m_h^2 \hat{v}^2 \left(2 c_{H\Box} - \frac{c_{HD}}{2} - \frac{3 c_H}{2 lam}\right)$$

Shifts from input parameters

To have numerical predictions it is necessary to replace $\bar{\kappa} \to \hat{\kappa} + \delta\kappa(C_i)$ for all the parameters in the Lagrangian.

$\{m_W, m_Z, G_f\}$ scheme

$$\delta m_Z^2 = m_Z^2 \hat{v}^2 \left(\frac{c_{HD}}{2} + 2 c_{\hat{\theta}} s_{\hat{\theta}} c_{HWB}\right)$$

$$\delta G_f = \frac{\hat{v}^2}{\sqrt{2}} \left((c_{Hl}^{(3)})_{11} + (c_{Hl}^{(3)})_{22} - (c_{ll})_{1221}\right)$$

$$\delta g_1 = -\frac{1}{2} \left(\sqrt{2}\delta G_f + \frac{1}{s_{\hat{\theta}}^2} \frac{\delta m_Z^2}{m_Z^2}\right)$$

$$\delta g_2 = -\frac{1}{\sqrt{2}} \delta G_f$$

$$\delta s_\theta^2 = 2 c_{\hat{\theta}}^2 s_{\hat{\theta}}^2 (\delta g_1 - \delta g_2) + c_{\hat{\theta}} s_{\hat{\theta}} (1 - 2 s_{\hat{\theta}}^2) c_{HWB} \hat{v}^2$$

$$\delta m_h^2 = m_h^2 \hat{v}^2 \left(2 c_{H\Box} - \frac{c_{HD}}{2} - \frac{3 c_H}{2 lam}\right)$$

The SMEFTsim package

an **UFO & FeynRules model** with*:

Brivio,Jiang,Trott 1709.06492
feynrules.irmp.ucl.ac.be/wiki/SMEFT

1. the complete B-conserving Warsaw basis for 3 generations, including all complex phases and ~~CP~~ terms

2. automatic field redefinitions to have **canonical kinetic terms**

⇝ **backup**

3. automatic **parameter shifts** due to the choice of an input parameters set

Main scope:

estimate **tree-level** $|\mathcal{A}_{\mathbf{SM}}\mathcal{A}^*_{\mathbf{d=6}}|$ **interference** terms → theo. accuracy $\gtrsim 1\%$

* at the moment only LO, unitary gauge implementation

The SMEFTsim package

6 different implementations available

Brivio,Jiang,Trott 1709.06492

③ flavor structures: general; $U(3)^5$ symmetric; linear MFV

×

② input schemes: $\hat{\alpha}_{\rm em}, \hat{m}_Z, \hat{G}_f$; $\hat{m}_W, \hat{m}_Z, \hat{G}_f$

feynrules.irmp.ucl.ac.be/wiki/SMEFT

wiki: SMEFT

Standard Model Effective Field Theory -- The SMEFTsim package

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Pre-exported UFO files (include restriction cards)

	Set A		Set B	
	α scheme	m_W scheme	α scheme	m_W scheme
Flavor general SMEFT	SMEFTsim_A_general_alphaScheme_UFO.tar.gz	SMEFTsim_A_general_MwScheme_UFO.tar.gz	SMEFT_alpha_UFO.zip	SMEFT_mW_UFO.zip
MFV SMEFT	SMEFTsim_A_MFV_alphaScheme_UFO.tar.gz	SMEFTsim_A_MFV_MwScheme_UFO.tar.gz	SMEFT_alpha_MFV_UFO.zip	SMEFT_mW_MFV_UFO.zip
$U(3)^5$ SMEFT	SMEFTsim_A_U35_alphaScheme_UFO.tar.gz	SMEFTsim_A_U35_MwScheme_UFO.tar.gz	SMEFT_alpha_FLU_UFO.zip	SMEFT_mW_FLU_UFO.zip