Higgs boson decay into four leptons in the presence of dimension–6 operators

Based on 1703.06667

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Introduction

The EFT framework

If the scale of New Physics Λ is **much heavier** than the energy scales probed by LHC, low energy effects of heavy degrees of freedom can be adequately described by an **EFT Lagrangian**.

$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda}\sum_i c_i^{(5)}\mathcal{O}_i^{(5)} + \frac{1}{\Lambda^2}\sum_i c_i^{(6)}\mathcal{O}_i^{(6)} + \cdots$$

Departures from the SM are parametrized by **Wilson coefficients of $D = 6$ operators**

The $H \to 4\ell$ channel

Due to its **clean signature** and **non-trivial kinematics**, the Higgs decay into four leptons is an important channel for the study of NP and it has been considered in a number of works:

- Effective couplings: [Stolarski and Vega Morales, 2012] [Chen at al. 2013] [Chen and Vega Morales 2014] [Chen et al. 2015]
- Pseudo-observables: [Gonzales-Alonzo et al. 2015] [Bordone et al. 2015]
- EFT: [Beneke et al. 2014]

`Hto4l`: an event generator for Higgs decay into four leptons

`http://www.pv.infn.it/hepcomplex/hto4l.html`

- `Hto4l` is an event generator for the SM Higgs decay into 4 charged leptons up to NLOPS electroweak accuracy [SB, Carloni Calame, Montagna, Nicrosini, Piccinini, 2015]
- It can be used in association with **any event generator which provides events for the Higgs production**
- The last version of `Hto4l` allows for the event generation in presence of $D = 6$ operators. **Three possible bases: Warsaw, SILH and Higgs** [SB, Carloni Calame, Montagna, Nicrosini, Piccinini, Shivaji, arXiv:1703.06667]

Computational details

The EFT Lagrangian

The **mass-eigenstate** effective Lagrangian is:

$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}^{D=6}_{HVV} + \mathcal{L}^{D=6}_{Z\ell\ell} + \mathcal{L}^{D=6}_{HZ\ell\ell}$$

The master formula for the $H \to 4\ell$ width is:

$$\Gamma^{D=6}_{\mathrm{LO}}(H \to 4\ell) = \frac{1}{2M_H} \int \left\{ \left|\mathcal{M}_{\mathrm{SM}}\right|^2 + 2\mathrm{Re}\left(\mathcal{M}_{D=6}\,\mathcal{M}^{*}_{\mathrm{SM}}\right) + \left|\mathcal{M}_{D=6}\right|^2 \right\} \mathrm{d}\Phi_4$$

$\mathcal{M}_{D=6}$ is computed in the Higgs basis
[Handbook of LHC Higgs Cross Sections 4]

The Higgs basis

- The basis is spanned by particular combinations of $D = 6$ operators
- Each combination maps to an interaction term of the mass-eigenstate Lagrangian
- We do not rely on the mapping (from Warsaw/SILH -> Higgs) provided in the original work on Higgs basis.
- We developed a mapping independent from the Higgs basis assumptions
  1. Problems with gauge invariance [Burgess et al. 2010] [Passarino and Trott, 2016] [Brivio and Trott, 2017]
  2. The original mapping is defined in the $\alpha-$scheme, while we work in the G_μ-scheme

Bosonic operators

$$\mathcal{L}_{D=6}^{HVV} = \frac{H}{v}\Big[(1+\delta c_Z)\frac{1}{4}(g_1^2+g_2^2)v^2 Z_\mu Z^\mu +$$
$$+ c_{\gamma\gamma}\frac{e^2}{4}A_{\mu\nu}A^{\mu\nu} + c_{Z\gamma}\frac{e\sqrt{g_1^2+g_2^2}}{2}Z_{\mu\nu}A^{\mu\nu} + c_{ZZ}\frac{g_1^2+g_2^2}{4}Z_{\mu\nu}Z^{\mu\nu} +$$
$$+ c_{Z\Box}g_2^2 Z_\mu \partial_\nu Z^{\mu\nu} + c_{\gamma\Box}g_1 g_2 Z_\mu \partial_\nu A^{\mu\nu} +$$
$$+ \tilde{c}_{\gamma\gamma}\frac{e^2}{4}A_{\mu\nu}\tilde{A}^{\mu\nu} + \tilde{c}_{Z\gamma}\frac{e\sqrt{g_1^2+g_2^2}}{2}Z_{\mu\nu}\tilde{A}^{\mu\nu} + \tilde{c}_{ZZ}\frac{g_1^2+g_2^2}{4}Z_{\mu\nu}\tilde{Z}^{\mu\nu} \Big]$$

Only **five** parameters are independent

$$c_{\gamma\Box} = \frac{1}{g_2^2-g_1^2}\left[2g_2^2 c_{Z\Box} + (g_2^2+g_1^2)c_{ZZ} - e^2 c_{\gamma\gamma} - (g_2^2-g_1^2)c_{Z\gamma}\right]$$

Semi-fermionic operators

Anomalous contributions to $Z\ell\ell$ vertex:

$$\mathcal{L}_{D=6}^{HZ\ell\ell} = 2\frac{\sqrt{g_1^2+g_2^2}}{v}\sum_{\ell=e,\mu}\left[\delta g_L^{HZ\ell\ell} H Z_\mu \bar{\ell}_L \gamma^\mu \ell_L + \delta g_R^{HZ\ell\ell} H Z_\mu \bar{\ell}_R \gamma^\mu \ell_R\right]$$

Contact interactions:

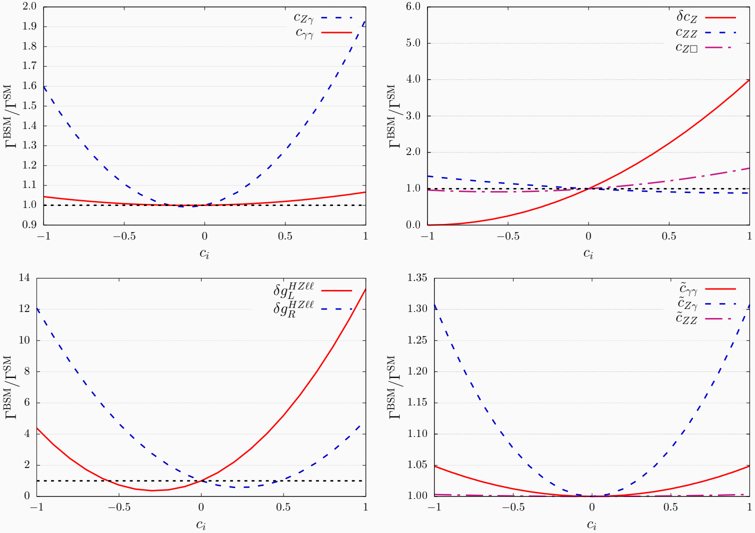
$$\mathcal{L}_{D=6}^{HZ\ell\ell} = 2\frac{\sqrt{g_1^2+g_2^2}}{v}\sum_{\ell=e,\mu}\left[\delta g_L^{HZ\ell\ell} H Z_\mu \bar{\ell}_L \gamma^\mu \ell_L + \delta g_R^{HZ\ell\ell} H Z_\mu \bar{\ell}_R \gamma^\mu \ell_R\right].$$

In the Higgs basis these coefficients are set to be the same

$$\delta g_L^{Z\ell\ell} = \delta g_L^{HZ\ell\ell} \qquad \delta g_R^{Z\ell\ell} = \delta g_R^{HZ\ell\ell}$$

Numerical results

$H \to 2e2\mu$ integrated partial width



Quadratic effects included!

Present constraints

- $c_{\gamma\gamma}$ and $c_{Z\gamma}$ are constrained at the 10^{-3} and 10^{-2} level.
- δc_Z, c_{ZZ} and $c_{Z\Box}$ are loosely constrained.
- An approximate degeneracy, which corresponds to a strong correlation, is found between c_{ZZ} and $c_{Z\Box}$
- Complementary information coming from kinematic observables can be helpful to constrain these coefficients

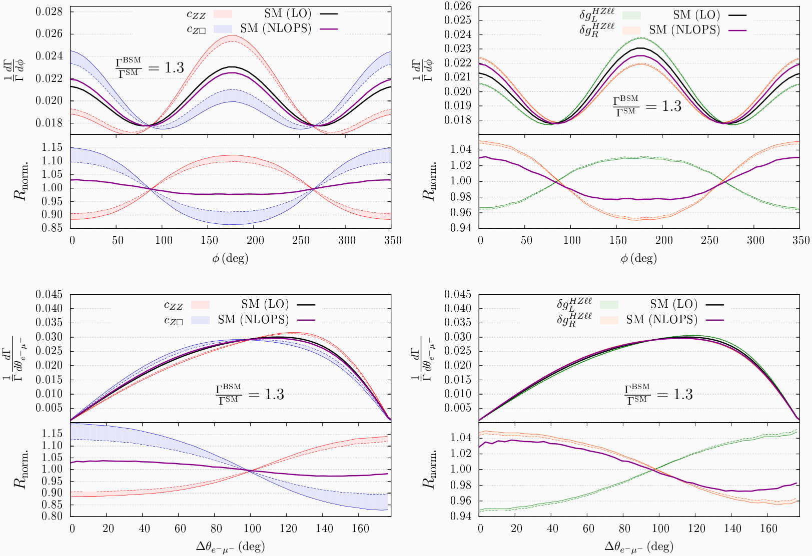
Kinematic distributions

We consider a scenario in which an individual parameter leads to a deviation of 30% in partial decay width.

c_i	int.	quad.
c_{ZZ}	-1.29	-0.897
$c_{Z\Box}$	0.996	0.638
$\delta g_L^{HZ\ell\ell}$	0.067	0.060
$\delta g_R^{HZ\ell\ell}$	-0.084	-0.073

$$H \to 2e2\mu$$

Kinematic distributions

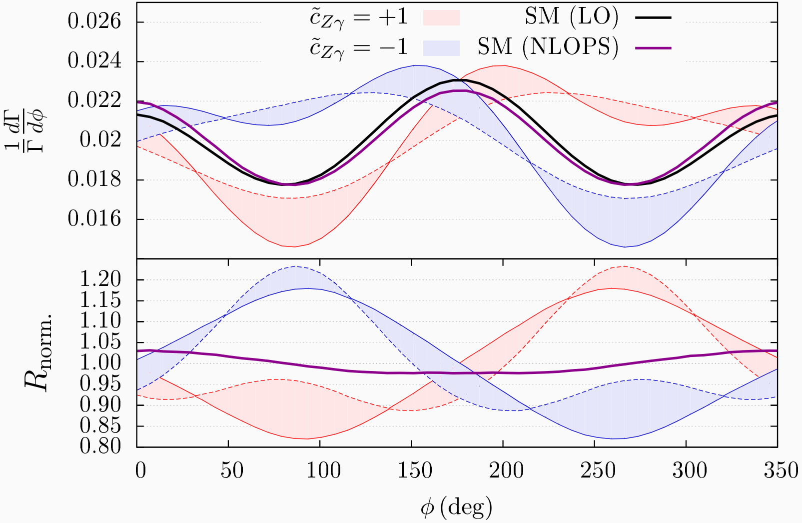


Summary and outlook

- We have developed a new version of `Hto4l` event generator for the study of $H \to 2e2\mu$ and $H \to 4e/4\mu$ in presence of $D = 6$ operators
- The BSM matrix elements are calculated in the Higgs basis. A mapping from the Warsaw and SILH bases to the Higgs basis is allowed
- Angular variables turn out to be quite useful in discriminating various parameters of the dimension-six operators
- Phenomenological study in a more complex and realistic scenario (e.g. in the HL-LHC context) are necessary to explore the potential of differential distributions can improve the constraints on Wilson coefficients

Backup slides

CP-odd



$\tilde{c}_{Z\gamma} = +1$
$\tilde{c}_{Z\gamma} = -1$
SM (LO)
SM (NLOPS)
0.026
0.024
0.022
0.02
0.018
0.016
$\frac{1}{\Gamma}\frac{d\Gamma}{d\phi}$
1.20
1.15
1.10
1.05
1.00
0.95
0.90
0.85
0.80
$R_{\text{norm.}}$
0
50
100
150
200
250
300
350
$\phi\,(\text{deg})$

From Warsaw to Higgs basis

$$
\begin{aligned}
c_{\gamma\gamma} &= 4v^2\Big(\frac{C_{HB}}{g_1^2} + \frac{C_{HW}}{g_2^2} - \frac{C_{HWB}}{g_1 g_2}\Big)\\
\tilde{c}_{\gamma\gamma} &= 4v^2\Big(\frac{C_{H\tilde{B}}}{g_1^2} + \frac{C_{H\tilde{W}}}{g_2^2} - \frac{C_{H\tilde{W}B}}{g_1 g_2}\Big)\\
c_{Z\gamma} &= 2v^2\frac{g_1^2+g_2^2}{g_1 g_2}\Big(\frac{2}{g_1 g_2}(C_{HW} - C_{HB}) - (\frac{1}{g_1^2} - \frac{1}{g_2^2})C_{HWB}\Big)\\
\tilde{c}_{Z\gamma} &= 2v^2\frac{g_1^2+g_2^2}{g_1 g_2}\Big(\frac{2}{g_1 g_2}(C_{H\tilde{W}} - C_{H\tilde{B}}) - (\frac{1}{g_1^2} - \frac{1}{g_2^2})C_{H\tilde{W}B}\Big)\\
c_{\gamma\Box} &= 0\\
\delta c_Z &= v^2\Big(C_{H\Box} + \frac{3}{4}C_{HD} + 2\frac{g_1 g_2}{g_1^2+g_2^2}C_{HWB}\Big)\\
c_{ZZ} &= 4v^2\frac{1}{(g_1^2+g_2^2)^2}\Big(g_1^2 C_{HB} + g_2^2 C_{HW} + g_1 g_2 C_{HWB}\Big)
\end{aligned}
$$

From Warsaw to Higgs basis

$$
\begin{aligned}
c_{Z\Box} &= 0 \\
\delta g_L^{HZ\ell\ell} &= -\frac{v^2}{2}\left(C_{H\ell}^{(1)} + C_{H\ell}^{(3)}\right) \\
\delta g_R^{HZ\ell\ell} &= -\frac{v^2}{2} C_{He} \\
\delta g_L^{Z\ell\ell} &= \frac{v^2}{2}\left(- C_{H\ell}^{(1)} - C_{H\ell}^{(3)} + \frac{g_1 g_2}{(g_1^2 + g_2^2)^2}(g_2^2 - g_1^2) C_{HWB}\right) \\
\delta g_R^{Z\ell\ell} &= \frac{v^2}{2}\left(- C_{He} + \frac{g_1 g_2}{(g_1^2 + g_2^2)^2}(2 g_2^2) C_{HWB}\right)
\end{aligned}
$$

From Warsaw to Higgs basis

The corrections to weak boson masse are given by,

$$\begin{aligned}\delta m_W^2 &= 0,\\ \delta m_Z^2 &= \frac{1}{4}(g_1^2+g_2^2)v^4\left(\frac{C_{HD}}{2}+2\frac{g_1 g_2}{g_1^2+g_2^2}C_{HWB}\right).\end{aligned}$$

In addition, s_W and e have a modified dependence on g_1 and g_2 given by,

$$\begin{aligned}s_W^2 &= \frac{g_1^2}{g_1^2+g_2^2}\left(1-\frac{g_2}{g_1}\frac{g_1^2-g_2^2}{g_1^2+g_2^2}v^2 C_{HWB}\right)\\ e &= \frac{g_1 g_2}{\sqrt{g_1^2+g_2^2}}\left(1-\frac{g_1 g_2}{g_1^2+g_2^2}v^2 C_{HWB}\right).\end{aligned}$$

The G_μ-scheme

In the input parameter scheme $\{G_F, M_Z, M_W\}$, the parameters in the Feynman rules of the Warsaw basis are given by,

$$
\begin{aligned}
v^2 &= v_{\rm SM}^2\Big(1+\frac{1}{\sqrt{2}G_F}(2C_{H\ell}^{(3)}-C_{\ell\ell})\Big)\\
g_1 &= g_1^{\rm SM}\Big(1-\frac{1}{2\sqrt{2}G_F}(2C_{H\ell}^{(3)}-C_{\ell\ell})-\frac{\delta m_Z^2}{2(M_Z^2-M_W^2)}\Big)\\
g_2 &= g_2^{\rm SM}\Big(1-\frac{1}{2\sqrt{2}G_F}(2C_{H\ell}^{(3)}-C_{\ell\ell})\Big)
\end{aligned}
$$

where,

$$
v_{\rm SM}^2 = \frac{1}{\sqrt{2}G_F} \tag{1}
$$

$$
g_1^{\rm SM} = 2(2)^{(1/4)}\sqrt{G_F(M_Z^2-M_W^2)} \tag{2}
$$

$$
g_2^{\rm SM} = 2(2)^{(1/4)}M_W\sqrt{G_F} \tag{3}
$$