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 $\Lambda$ 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.

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

Departures from the SM are parametrized by Wilson coefficients of $\mathcal{D} = 6$ operators
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 et 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 mass-eigenstate effective Lagrangian is:

\[ \mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{HVV}}^{D=6} + \mathcal{L}_{Z\ell\ell}^{D=6} + \mathcal{L}_{HZ\ell\ell}^{D=6} \]

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

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

$\mathcal{M}_{D=6}$ 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 $G_\mu$-scheme
\[ \mathcal{L}_{D=6}^{HHV} = \frac{H}{V} \left[ (1 + \delta c_Z) \frac{1}{4} (g_1^2 + g_2^2) v^2 Z_\mu Z^\mu + ight. \\
+ c_{\gamma\gamma} \frac{e^2}{4} A_{\mu\nu} A^{\mu\nu} + c_{Z\gamma} \frac{e \sqrt{g_1^2 + g_2^2}}{2} Z_{\mu\nu} A^{\mu\nu} + c_{ZZ} \frac{g_1^2 + g_2^2}{4} Z_{\mu\nu} Z^{\mu\nu} + \\
+ c_{Z\Box} g_2 Z_\mu \partial_\nu Z^{\mu\nu} + c_{\gamma\Box} g_1 g_2 Z_\mu \partial_\nu A^{\mu\nu} + \\
\left. + \tilde{c}_{\gamma\gamma} \frac{e^2}{4} A_{\mu\nu} \tilde{A}^{\mu\nu} + \tilde{c}_{Z\gamma} \frac{e \sqrt{g_1^2 + g_2^2}}{2} Z_{\mu\nu} \tilde{A}^{\mu\nu} + \tilde{c}_{ZZ} \frac{g_1^2 + g_2^2}{4} Z_{\mu\nu} \tilde{Z}^{\mu\nu} \right] \\
\]

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:

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

Contact interactions:

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

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

$$\delta g_{L}^{Z\ell\ell} = \delta g_{L}^{Hz\ell\ell}, \quad \delta g_{R}^{Z\ell\ell} = \delta g_{R}^{Hz\ell\ell}.$$
Numerical results
$H \rightarrow 2e2\mu$ 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.
- $\delta c_z$, $c_{ZZ}$ 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.
We consider a scenario in which an individual parameter leads to a deviation of 30% in partial decay width.

<table>
<thead>
<tr>
<th>$c_i$</th>
<th>int.</th>
<th>quad.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_{ZZ}$</td>
<td>-1.29</td>
<td>-0.897</td>
</tr>
<tr>
<td>$c_{Z\Box}$</td>
<td>0.996</td>
<td>0.638</td>
</tr>
<tr>
<td>$\delta g_L^{HZ\ell\ell}$</td>
<td>0.067</td>
<td>0.060</td>
</tr>
<tr>
<td>$\delta g_R^{HZ\ell\ell}$</td>
<td>-0.084</td>
<td>-0.073</td>
</tr>
</tbody>
</table>

$H \rightarrow 2e2\mu$
Kinematic distributions

\[ \Gamma_{BSM} / \Gamma_{SM} = 1.3 \]

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Summary and outlook

• We have developed a new version of Hto4l event generator for the study of $H \rightarrow 2e2\mu$ and $H \rightarrow 4e/4\mu$ 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
The diagram shows the dependence of $1/d\Gamma/\partial\phi$ and $R_{\text{norm.}}$ on $\phi$ in degrees for different values of $\tilde{c}_{Z\gamma}$.

For $\tilde{c}_{Z\gamma} = +1$, the SM (LO) curve is shown in black, and for $\tilde{c}_{Z\gamma} = -1$, the SM (NLOPS) curve is shown in purple.

The horizontal axis represents $\phi$ in degrees, ranging from 0 to 350 degrees.

The vertical axis on the left shows $1/d\Gamma/\partial\phi$, ranging from 0.016 to 0.026.

The vertical axis on the right shows $R_{\text{norm.}}$, ranging from 0.80 to 1.20.

The data points are spread across the graph, indicating variations in the CP-odd parameters with respect to $\phi$. The graph visually highlights the differences between the SM (LO) and SM (NLOPS) predictions for both positive and negative values of $\tilde{c}_{Z\gamma}$. 

The graph is labeled with the text "CP-odd" at the top, indicating the focus on CP-odd effects.
\[ c_{\gamma\gamma} = 4v^2 \left( \frac{C_{HB}}{g_1^2} + \frac{C_{HW}}{g_2^2} - \frac{C_{HWB}}{g_1 g_2} \right) \]

\[ \tilde{c}_{\gamma\gamma} = 4v^2 \left( \frac{C_{H\tilde{B}}}{g_1^2} + \frac{C_{H\tilde{W}}}{g_2^2} - \frac{C_{H\tilde{WB}}}{g_1 g_2} \right) \]

\[ c_{Z\gamma} = 2v^2 \frac{g_1^2 + g_2^2}{g_1 g_2} \left( \frac{2}{g_1 g_2} (C_{HW} - C_{HB}) - \left( \frac{1}{g_1^2} - \frac{1}{g_2^2} \right) C_{HWB} \right) \]

\[ \tilde{c}_{Z\gamma} = 2v^2 \frac{g_1^2 + g_2^2}{g_1 g_2} \left( \frac{2}{g_1 g_2} (C_{H\tilde{W}} - C_{H\tilde{B}}) - \left( \frac{1}{g_1^2} - \frac{1}{g_2^2} \right) C_{H\tilde{WB}} \right) \]

\[ c_{\gamma\Box} = 0 \]

\[ \delta c_Z = v^2 \left( C_{H\Box} + \frac{3}{4} C_{HD} + 2 \frac{g_1 g_2}{g_1^2 + g_2^2} C_{HWB} \right) \]

\[ c_{ZZ} = 4v^2 \frac{1}{(g_1^2 + g_2^2)^2} \left( g_1^2 C_{HB} + g_2^2 C_{HW} + g_1 g_2 C_{HWB} \right) \]
\[ c_{Z\Box} = 0 \]
\[ \delta g_{L}^{HZ\ell\ell} = -\frac{v^2}{2} \left( C_{H\ell}^{(1)} + C_{H\ell}^{(3)} \right) \]
\[ \delta g_{R}^{HZ\ell\ell} = -\frac{v^2}{2} C_{He} \]
\[ \delta g_{L}^{Z\ell\ell} = \frac{v^2}{2} \left( -C_{H\ell}^{(1)} - C_{H\ell}^{(3)} + \frac{g_1 g_2}{(g_1^2 + g_2^2)^2} (g_2^2 - g_1^2) C_{HWB} \right) \]
\[ \delta g_{R}^{Z\ell\ell} = \frac{v^2}{2} \left( -C_{He} + \frac{g_1 g_2}{(g_1^2 + g_2^2)^2} (2g_2^2) C_{HWB} \right) \]
The corrections to weak boson masses are given by,

\[
\delta m_W^2 = 0,
\]
\[
\delta m_Z^2 = \frac{1}{4} (g_1^2 + g_2^2) v^4 \left( \frac{C_{HD}}{2} + 2 \frac{g_1 g_2}{g_1^2 + g_2^2} C_{HWB} \right).
\]

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

\[
s_W^2 = \frac{g_1^2}{g_1^2 + g_2^2} \left( 1 - \frac{g_2^2}{g_1^2 + g_2^2} v^2 C_{HWB} \right)
\]
\[
e = \frac{g_1 g_2}{\sqrt{g_1^2 + g_2^2}} \left( 1 - \frac{g_1 g_2}{g_1^2 + g_2^2} v^2 C_{HWB} \right).
\]
The $G_\mu$-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,

\[
\begin{align*}
\nu^2 &= \nu_{SM}^2 \left(1 + \frac{1}{\sqrt{2}G_F} \left(2C_{H\ell}^{(3)} - C_{\ell\ell}\right)\right) \\
g_1 &= g_{1SM} \left(1 - \frac{1}{2\sqrt{2}G_F} \left(2C_{H\ell}^{(3)} - C_{\ell\ell}\right) - \frac{\delta m_{Z}^2}{2(M_Z^2 - M_W^2)}\right) \\
g_2 &= g_{2SM} \left(1 - \frac{1}{2\sqrt{2}G_F} \left(2C_{H\ell}^{(3)} - C_{\ell\ell}\right)\right)
\end{align*}
\]

where,

\[
\begin{align*}
\nu_{SM}^2 &= \frac{1}{\sqrt{2}G_F} \quad (1) \\
g_{1SM} &= 2(2)^{(1/4)} \sqrt{G_F(M_Z^2 - M_W^2)} \quad (2) \\
g_{2SM} &= 2(2)^{(1/4)} M_W \sqrt{G_F} \quad (3)
\end{align*}
\]