Higgs decay into four charged leptons in presence of dimension-six operators

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New physics parametrization

- Precise measurements of the properties of the Higgs boson and hints of new physics (NP) beyond the standard model (BSM).
- Model independent parametrization of NP.
- $\kappa-$framework: not a gauge invariant parametrization of new physics, does not capture the kinematic effects due to NP.
- The current experimental bounds allow a deviation of 10-30% in the Higgs boson couplings to gauge bosons and fermions 1606.02266.
- Going beyond $\kappa-$framework: Phenomenological Lagrangian / anomalous vertices, pseudo observables and Effective Field Theories (EFT) 1612.00269.

NP & EFT

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{C_i}{\Lambda^{d_i-4}}\mathcal{O}^i; \ (d_i > 4) \quad (1)$$

- A set of GI independent operators of a given mass dimension form a basis.
- Unlike $\kappa-$framework, EFT gives rise to new structure to SM vertices and also introduces new LO vertices.
- Some popular choice of bases include `Warsaw, SILH` etc 1008.4884, 0703164, 1303.3876.
- The choice of the basis is usually led by the convenience of minimizing the number of parameters required to capture the BSM effects on a given class of observables.
- We study the NP effects using SMEFT in $H \to 4\ell$ decay channel.

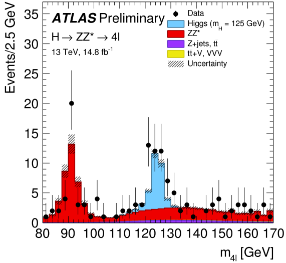
$H \to 4\ell$ decay channel

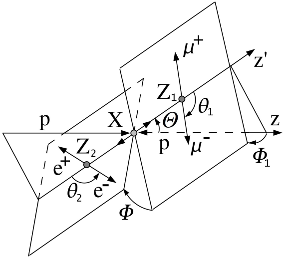
- $H \to 4\ell$ has low event rates, however, it has a very high signal-over-background ratio. It is mainly sensitive in GGF production ATLAS-CONF-2016-079,

$$\mu^{\text{CMS+ATLAS}} = 1.13^{+0.34}_{-0.31}.$$

Together with $H \to \gamma\gamma$, it has a high mass resolution,

$$m_H^{\text{CMS+ATLAS}} = 125.09 \pm 0.24 \text{ GeV}.$$





- Due to its non-trivial kinematics, it is suitable to study new physics effects 1208.4840, 1211.1959, 1310.2893, 1412.6038, 1401.2077, 1504.04018, 1507.02555.

The Higgs basis

- It is designed to parameterize new physics effects in the Higgs sector 1405.0181, 1610.07922.

- The interaction Lagrangian is constructed using mass eigenstates.

- The parameters of the Higgs basis are connected to the Wilson coefficients of dimension-six operators in a given basis via linear transformation.

- The number of independent parameters of the Higgs basis are same as the number of independent dimension-six operators.

- We consider the parts of the Higgs basis Lagrangian relevant to $H \to 4\ell$ decay.

The Higgs basis

- *HVV* coupling

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

- Only five of the six CP-even parameters are independent,

$$c_{\gamma\Box} = \frac{1}{g_2^2 - g_1^2}\left[2g_2^2 c_{Z\Box} + (g_2^2 + g_1^2)c_{ZZ} - e^2 c_{\gamma\gamma} - (g_2^2 - g_1^2)c_{Z\gamma}\right]. \tag{3}$$

The Higgs basis

- $V\ell\ell$ and $HV\ell\ell$ couplings

$$\mathcal{L}_{D=6}^{Z\ell\ell} = \sqrt{g_1^2 + g_2^2} \sum_{\ell=e,\mu} Z_\mu \left[\bar{\ell}_L \gamma^\mu \left(I_{W,\ell}^3 - s_W^2 Q_\ell + \delta g_L^{Z\ell\ell} \right) \ell_L + \right. \\ \left. + \bar{\ell}_R \gamma^\mu \left(-s_W^2 Q_\ell + \delta g_R^{Z\ell\ell} \right) \ell_R \right], \tag{4}$$

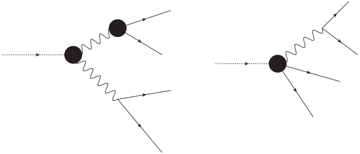
$$\mathcal{L}_{D=6}^{HZ\ell\ell} = 2\frac{\sqrt{g_1^2 + g_2^2}}{v} \sum_{\ell=e,\mu} \left[\delta g_L^{HZ\ell\ell} H Z_\mu \bar{\ell}_L \gamma^\mu \ell_L + \delta g_R^{HZ\ell\ell} H Z_\mu \bar{\ell}_R \gamma^\mu \ell_R \right]. \tag{5}$$

- In the linear EFT, the $HV\ell\ell$ coupling is not independent.

$$\delta g_L^{Z\ell\ell} = \delta g_L^{HZ\ell\ell}, \qquad \delta g_R^{Z\ell\ell} = \delta g_R^{HZ\ell\ell}. \tag{6}$$

Implementation in Hto4l event generator

- The publicly available Hto4l code, can provide precise prediction for Higgs decay into four charged leptons with NLOEW+PS accuracy 1503.07394.



- The calculation of new matrix elements for $H \rightarrow 2e2\mu$ and $H \rightarrow 4e/4\mu$ is carried out in FORM, and it is implemented in a new version of Hto4l code.
- The matrix elements are given in Higgs basis. To allow the user a flexibility in the choice of basis, the mappings from popular EFT bases like Warsaw, SILH and SILH' are also provide in the code.
- The code has a provision to include/drop the quadratic dependence on the parameters.

Partial decay width ($2e2\mu$)

- The modifications to partial decay width in presence of the parameters of the Higgs basis can be parameterized by,

$$
\begin{aligned}
R_{\rm BSM} &= \frac{\Gamma_{\rm BSM}}{\Gamma_{\rm SM}}(H \to 2e2\mu) \\
&= 1.00 + \sum_i X_i c_i + \sum_{ij} X_{ij} c_i c_j + \sum_{ij} \tilde{X}_{ij} \tilde{c}_i \tilde{c}_j. \qquad (7)
\end{aligned}
$$

where $c_i = \{\delta c_Z, c_{\gamma\gamma}, c_{Z\gamma}, c_{ZZ}, c_{Z\Box}, \delta g_L^{Z\ell\ell}, \delta g_R^{Z\ell\ell}, \delta g_L^{HZ\ell\ell}, \delta g_R^{HZ\ell\ell}\}$ and $\tilde{c}_i = \{\tilde{c}_{\gamma\gamma}, \tilde{c}_{Z\gamma}, \tilde{c}_{ZZ}\}$.

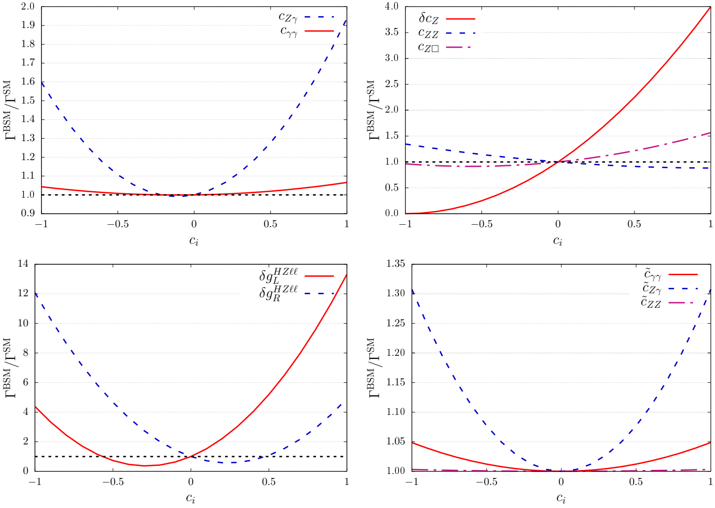
Partial decay width ($2e2\mu$)

$$X_i = \begin{pmatrix} 2.00 & 0.0115 & 0.170 & -0.232 & 0.301 & -8.77 & 7.04 & 4.47 & -3.58 \end{pmatrix},$$

$$X_{ij} = \begin{pmatrix} 1.00 & 0.0115 & 0.170 & -0.232 & 0.301 & -8.77 & 7.04 & 4.47 & -3.58 \\ 0 & 0.055 & 0.0706 & -0.0312 & -0.0448 & -0.227 & -0.179 & -0.181 & 0.174 \\ 0 & 0 & 0.768 & -0.490 & -0.702 & -3.47 & -2.80 & 2.81 & 2.740 \\ 0 & 0 & 0 & 0.114 & 0.273 & 2.23 & 0.696 & -1.55 & -0.873 \\ 0 & 0 & 0 & 0 & 0.265 & 0.566 & 3.41 & -0.974 & -2.51 \\ 0 & 0 & 0 & 0 & 0 & 25.4 & -15.4 & -25.9 & 7.85 \\ 0 & 0 & 0 & 0 & 0 & 0 & 22.0 & 7.85 & -22.4 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 7.85 & -1.58 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 7.50 \end{pmatrix},$$

$$\tilde{X}_{ij} = \begin{pmatrix} 0.0487 & -0.00745 & 0.0000910 \\ 0 & 0.308 & -0.00592 \\ 0 & 0 & 0.00317 \end{pmatrix}.$$

Partial decay width ($2e2\mu$)



Partial decay width ($2e2\mu$)

- The effect of $c_{Z\gamma}$ is larger than that of $c_{\gamma\gamma}$ due to different propagator effects. The contact interaction parameters modify decay width the most.
- The effects of c_{ZZ} and $c_{Z\Box}$ on the partial decay width are opposite in nature.
- Unlike CP-even parameters, the CP-odd ones contribute only at quadratic level ($\sim 1/\Lambda^4$).
- Some of these parameters are already constrained by the experimental data from LEP and LHC.

Partial decay width ($2e2\mu$)

- Among CP-even HVV parameters, c_{ZZ} and $c_{Z\Box}$ are least constrained 1505.00046, 1508.00581.
- In linear EFT, the parameters of contact interactions are severely constrained (at the level of 0.1%) 1503.07872.
- Since $H \to 4\ell$ decay can provide independent information on $HZ\ell\ell$ interaction, we keep them unconstrained (a departure from linear EFT).
- Current Higgs data constrains $\tilde{c}_{\gamma\gamma}$ at 1% level. The allowed values for $|\tilde{c}_{Z\gamma}|$ and $|\tilde{c}_{ZZ}|$ can be as large as 0.7 and 0.5 respectively 1612.01808.

Kinematic Distributions ($2e2\mu$)

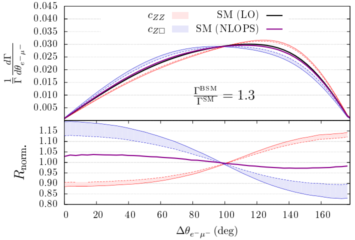
- The study of kinematic distributions can provide complementary information to the analyses of signal strengths based on total rates.
- We consider a scenario in which individual parameter leads to a deviation of 30% in partial decay width.

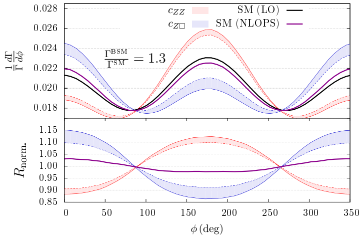
c_i	int.	quad.
c_{ZZ}	-1.29	-0.897
$c_{Z\Box}$	0.996	0.638
$\delta g_L^{HZ\ell\ell}$	0.067	0.060
$\delta g_R^{HZ\ell\ell}$	-0.084	-0.073
$\tilde{c}_{Z\gamma}$	0	±1.0

Kinematic Distributions ($2e2\mu$): CP-even

- The angular observables (ϕ and $\Delta\theta_{e^-\mu^-}$) are more sensitive to BSM kinematic effects.

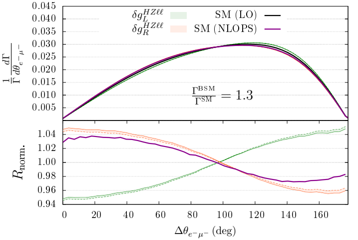
- In ϕ observable the effect of BSM is well separated from the corresponding SM prediction.

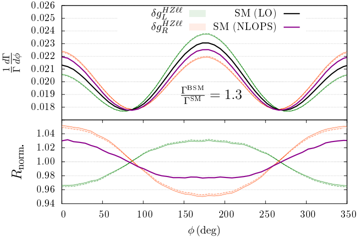




Kinematic Distributions ($2e2\mu$): CP-even

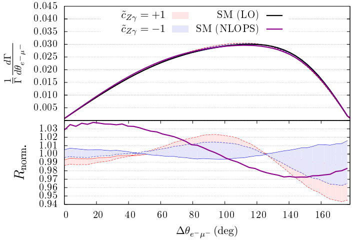
- The effects of $g_i^{HZ\ell\ell}$ (20-35%) on observables are smaller than those of c_{ZZ} and $c_{Z\square}$ (10-50%).
- The quadratic dependence is relatively larger for c_{ZZ} and $c_{Z\square}$.

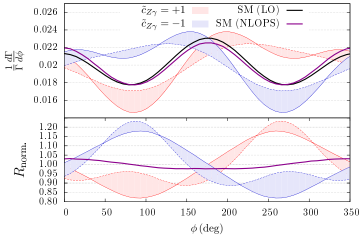




Kinematic Distributions ($2e2\mu$): CP-odd

- For CP-odd parameter $\tilde{c}_{Z\gamma}$, ϕ is the most sensitive observable.
- ϕ is CP sensitive, and unlike decay width it has a dependence on the linear term.
- It can also provide information on the sign of the parameter.





Summary and Outlook

- We have developed a new version of `Hto4l` event generator, which allows the study of $H \to 2e2\mu$ and $H \to 4e/4\mu$ decay in presence of dimension-six operators.
- The BSM matrix elements are calculated in the Higgs basis, and a mapping between the parameters of the Higgs basis and those of `Warsaw`, `SILH` and `SILH'` bases is also implemented.
- In our simplified study, we find that the angular observables like ϕ and $\Delta\theta_{e^- \mu^-}$ are quite useful in discriminating various parameters of the dimension-six operators.
- Future directions:
  -Implementation of $H \to 2\ell 2\nu$ BSM matrix elements in `Hto4l`.
  -BSM+PS predictions.
  -Phenomenological study in a more complex and realistic scenario.

Backup: Feynman Rules

$$V_{H\gamma\gamma}^{\mu_1\mu_2}(p_1, p_2) = \frac{ie^2}{v} c_{\gamma\gamma} \left[p_1^{\mu_2} p_2^{\mu_1} - (p_1 \cdot p_2)\, g^{\mu_1\mu_2}\right] + \frac{ie^2}{v} \tilde{c}_{\gamma\gamma}\ \epsilon_{\mu_1\mu_2 p_1 p_2} \tag{8}$$

$$V_{HZ\gamma}^{\mu_1\mu_2}(p_1, p_2) = \frac{ie^2}{c_W s_W v} \Big\{ c_{Z\gamma} \left[p_1^{\mu_2} p_2^{\mu_1} - (p_1 \cdot p_2)\, g^{\mu_1\mu_2}\right] - c_{\gamma\Box} \left[p_2^{\mu_1} p_2^{\mu_2} - p_2^2 g^{\mu_1\mu_2}\right] + \tilde{c}_{Z\gamma}\ \epsilon_{\mu_1\mu_2 p_1 p_2} \Big\}, \tag{9}$$

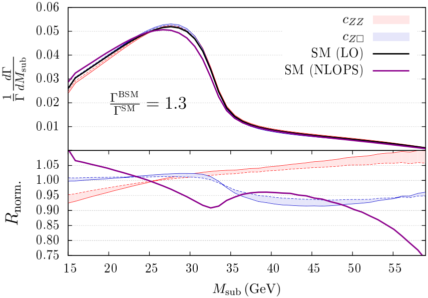
Backup: Feynman Rules

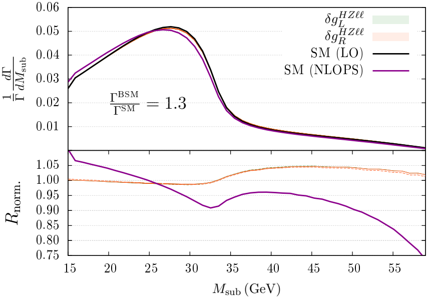
$$
\begin{aligned}
V^{\mu_1\mu_2}_{HZZ}(p_1,p_2) = &+ \frac{ieM_Z}{s_W c_W}\left(1+\delta c_Z\right) g^{\mu_1\mu_2} \\
&+ \frac{ie^2}{c_W^2 s_W^2 v} c_{ZZ}\left[p_1^{\mu_2} p_2^{\mu_1} - (p_1\cdot p_2)\, g^{\mu_1\mu_2}\right] \\
&- \frac{ie^2}{s_W^2 v} c_{Z\Box}\left[+p_1^{\mu_1} p_1^{\mu_2} + p_2^{\mu_1} p_2^{\mu_2} - \left(p_1^2+p_2^2\right) g^{\mu_1\mu_2}\right] \\
&+ \frac{ie^2}{c_W^2 s_W^2 v}\tilde{c}_{ZZ}\ \epsilon_{\mu_1\mu_2 p_1 p_2}
\end{aligned}
\tag{10}
$$

$$
V^{\mu}_{HZ\ell\bar{\ell}} = \frac{2ie}{c_W s_W v}\gamma^\mu\left(\delta g_L^{HZ\ell\ell}\omega_L + \delta g_R^{HZ\ell\ell}\omega_R\right) \tag{11}
$$

$$
V^{\mu}_{Z\ell\bar{\ell}} = \frac{ie}{c_W s_W}\gamma^\mu\left[\left(g_L^{Z\ell\ell}+\delta g_L^{Z\ell\ell}\right)\omega_L + \left(g_R^{Z\ell\ell}+\delta g_R^{Z\ell\ell}\right)\omega_R\right] \tag{12}
$$

Backup: Kinematic distributions





Backup: $H \to 4e/4\mu$

$$X_i = \begin{pmatrix} 2.00 & 0.0115 & 0.170 & -0.232 & 0.301 & -8.77 & 7.04 & 4.47 & -3.58 \end{pmatrix},$$

$$X_{ij} = \begin{pmatrix} 1.00 & 0.0115 & 0.170 & -0.232 & 0.301 & -8.77 & 7.04 & 4.47 & -3.58 \\ 0 & 0.055 & 0.0706 & -0.0312 & -0.0448 & -0.227 & -0.179 & -0.181 & 0.174 \\ 0 & 0 & 0.768 & -0.490 & -0.702 & -3.47 & -2.80 & 2.81 & 2.740 \\ 0 & 0 & 0 & 0.114 & 0.273 & 2.23 & 0.696 & -1.55 & -0.873 \\ 0 & 0 & 0 & 0 & 0.265 & 0.566 & 3.41 & -0.974 & -2.51 \\ 0 & 0 & 0 & 0 & 0 & 25.4 & -15.4 & -25.9 & 7.85 \\ 0 & 0 & 0 & 0 & 0 & 0 & 22.0 & 7.85 & -22.4 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 7.85 & -1.58 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 7.50 \end{pmatrix},$$

$$\tilde{X}_{ij} = \begin{pmatrix} 0.0487 & -0.00745 & 0.0000910 \\ 0 & 0.308 & -0.00592 \\ 0 & 0 & 0.00317 \end{pmatrix}.$$