A global view on the Higgs self coupling

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DESY - IFAE

Based on:
Motivation

\[ V_{SM} = \frac{1}{2} m_h^2 + \lambda_3^{SM} h^3 + \lambda_4^{SM} h^4 \]

\[ \lambda_3^{SM} = \frac{m_h^2}{2v} \quad \lambda_4^{SM} = \frac{m_h^2}{8v^2} \]

Standard model Higgs potential depends on only 2 parameters and is indirectly precisely measured.

Direct measurements of \( h^3 \) and \( h^4 \) are challenging but an important consistency check.
- Stability of EW vacuum
- Baryogenesis through first order phase transition?

\( h^3 \) challenging to measure at LHC \quad \text{\( h^4 \)} out of reach of LHC
Motivation

Standard model Higgs potential depends on only 2 parameters and is indirectly precisely measured.

Direct measurements of $h^3$ and $h^4$ are challenging but an important consistency check.
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$h^3$ challenging to measure at LHC

$h^4$ out of reach of LHC
Double Higgs production

Small production cross section:

\[ \frac{\sigma(pp \to hh)}{\sigma(pp \to h)} \sim 10^{-3} \]

Negative interference decrease cross section:

Most promising channel is a trade off between cleanness and statistic:

\[ \text{Br}(h \to b\bar{b}) \times \text{Br}(h \to \gamma\gamma) \sim 60\% \times 0.1\% \]

HL-LHC @ 3 ab\(^{-1}\), 95\% CL \( \kappa_\lambda \in [-0.8, 7.7] \) \( \text{ATL-PHYS_PUB_2017-001} \)

Idea, since the bounds are so loose and trilinear enter at NLO in single Higgs process

Can single Higgs process help?

McCullough, 1312.3322
Gorbahn, Haisch 1607.03773
Degrassi, et al. 1607.04251
Bizon, et al. 1610.05771
The trilinear coupling enter at loop level in single Higgs observables

Only $\kappa_\lambda$ deviate from SM:
(68% CL at 3ab$^{-1}$)

$\kappa_\lambda \in [-0.7, 4.2]$

Compared to another double Higgs expected bound in $HH \to b\bar{b}\gamma\gamma$

Dim. 6 EFT

$\kappa_\lambda \in [0, 2.8] \cup [4.5, 6.1]$

Degrassi, et al. 1607.04251

Azatov et al. 1502.00539
The trilinear coupling enter at loop level in single Higgs observables.

Compared to an other double Higgs expected bound in $\text{HH} \to b\bar{b}\gamma\gamma$

Dim. 6 EFT

$k_\lambda \in [0, 2.8] \cup [4.5, 6.1]$
Other deviations?

Setting on one anomalous coupling at a time is a strong assumption.

Versus

Is it possible to disentangle the different contributions?
The setup

Parametrization of dominating BSM effects in Higgs physics using dimension 6 Lagrangian in the "Higgs basis"

Assuming flavour universality and no CP violating operator

8 (+2) Independent operators that affect Higgs physics at leading order and have not been tested in existing precision measurements

6 parameters controlling deformations of the couplings to the SM gauge bosons

\[ \delta c_z, \ c_{zz}, \ c_{z\Box}, \ \hat{c}_{z\gamma}, \ \hat{c}_{\gamma\gamma}, \ \hat{c}_{gg}, \]

3 related to the deformations of the fermion Yukawa's

\[ \delta y_t, \ \delta y_d, \ \delta y_\tau, \]

1 distortion to the Higgs trilinear self-coupling

\[ \kappa \chi. \] Today’s focus
Inclusive observables at 8 TeV

We have 10 quantities receiving modifications from 9+1 parameters. So, we should be able to constrain them by looking at the signal strengths.

This is not possible.

Only 9 Independent signal strength combinations (at the linear level)

\[ \mu \approx 1 + \delta \sigma + \delta \text{BR} \]

Shift in production can be compensated by opposite shift in decay

\[ \delta \sigma = -\delta \text{BR} \]

Diaconu @ Planck ’17
Effect of the flat direction

Single Higgs without NLO effect validity

Incl. single Higgs data

Only valid for reasonable value of the trilinear coupling
**Effect of the flat direction**

Single Higgs without NLO effect validity

Incl. single Higgs data

Only valid for reasonable value of the trilinear coupling

Valid in a SILH model

\[
\delta c_Z \sim \frac{v^2}{f^2}
\]

\[
\delta \kappa_\lambda \equiv \kappa_\lambda - 1 \sim \frac{v^2}{f^2},
\]

\[
\delta c_Z \sim \delta \kappa_\lambda
\]

with \( f \sim \frac{m^*}{g^*} \)

Hard to have model with large deviation only in \( \delta \kappa \)

Counter example:

**Higgs portal**

This is true for a broad class of model
Anomalous TGCs

At dimension 6, the aTGCs can be written in terms of the Higgs basis parameters

\[
\delta g_{1,z} = \frac{1}{2(g - g')} \left[ c_{\gamma\gamma} e^2 g' + c_{z\gamma} \left( g^2 - g'^2 \right) g'^2 - c_{zz} \left( g^2 + g'^2 \right) g'^2 \right],
\]

\[
\delta \kappa_{\gamma} = -\frac{g^2}{2} \left( c_{\gamma\gamma} \frac{e^2}{g^2 + g'^2} + c_{z\gamma} \frac{g^2 - g'^2}{g^2 + g'^2} - c_{zz} \right).
\]

\[
H \rightarrow Z\gamma
\]

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<th>Combination</th>
<th>Theory</th>
<th>Experimental</th>
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+ Updated ggF uncertainties
The flat direction

Value of all the couplings in function of $\delta \kappa_{\lambda}$ such that All the $\delta \mu=0$

Higgs couplings variation along the flat direction
The flat direction

Value of all the couplings in function of $\delta k_\lambda$ such that All the $\delta \mu = 0$

Higgs couplings variation along the flat direction

Main components of the flat direction
What we constrained

Value of all the couplings in function of $\delta k_\lambda$ such that All the $\delta \mu = 0$

Higgs couplings variation along the flat direction

Constrained TGC

Constrained H-$\rightarrow$Z$\gamma$

Constrained TGC

Main components of the flat direction

$\delta y_t$

$\delta y_b$

$\delta y_\tau$
Not enough constraints

Need to work harder
Differential Observables

**Rough** analysis looking at the prospects of differential observables

Cross section in each bin in terms of the EFT parameters computed using MadGraph.

Dependence on Higgs trilinear computed in Degrassi, et al. 1607.04251

Restore some power to the method, may be seen as complement to double Higgs

Maybe other differential observable can be more powerful

68% CL, 3ab\(^{-1}\)

\[ \kappa \lambda \in [-3.4, 6.4] \]
Adding double Higgs

H & HH all diff.

For all the results, see ArXiv:1704.01953

68% CL, 3ab⁻¹  \( \kappa_\lambda \in [0.12, 2.24] \)

Enough constraint on \( \kappa_\lambda \) to solve the flat direction issue in single Higgs only fit.

Single Higgs help lifting this minimum (More clear for Inclusive double Higgs)

Gaussian approx.

\[
\begin{pmatrix}
\hat{c}_{gg} \\
\hat{c}_{zz} \\
\hat{c}_{z\square} \\
\hat{c}_{z\gamma} \\
\hat{c}_{\gamma\gamma} \\
\hat{\delta}_{yt} \\
\hat{\delta}_{yb} \\
\hat{\delta}_{y_t} \\
\hat{\delta}_{\kappa_\lambda}
\end{pmatrix} = \pm \begin{pmatrix}
0.06 \\
0.04 \\
0.04 \\
0.02 \\
0.09 \\
0.03 \\
0.06 \\
0.07 \\
1.0
\end{pmatrix}
\]
Conclusion

- At the inclusive level the trilinear corrections to single Higgs observables introduce a flat direction in the global fit.

- This flat direction degrades the precision achievable on the wilson coefficients. Some control on the trilinear is needed to solve this issue.

- Double Higgs is still the best way to extract Higgs trilinear and to restore the control over single Higgs fit.

- Most promising way to remove the flat direction without using double Higgs is to use differential distribution. More work in this direction is needed.

Work in progress

- Lepton colliders will give us more precision and observables to constraint the single Higgs. (N. Craig, S. Di Vita, G. Durieux, C. Grojean, Z. Liu, G. Panico, M. Riembau, T. Vantalon)

More results in ArXiv:1704.01953
Thank you
Some lepton collider results

$\Delta \chi^2$ vs. $\delta \kappa_\lambda$, profiling over other parameters

- HL-LHC + CEPC 240GeV(5/ab) + 350GeV(1.5/ab)
- HL-LHC + CEPC 240GeV(5/ab) + 350GeV(200/fb)
- HL-LHC only

range given by different assumptions on TGC measurements ($e^+e^-\rightarrow WW$)

Preliminary
Our parametrisation:

Parametrization of dominating BSM effects in Higgs couplings:

\[ \mathcal{L}^{\text{NP}} \supset \frac{h}{v} \left[ \delta c_w \frac{g^2 v^2}{2} W^+ W^- \mu + \delta c_z \frac{(g^2 + g'^2) v^2}{4} Z_\mu Z^\mu ight] 
+ c_{ww} \frac{g^2}{2} W^+ W - \mu \nu + c_{w} \square g^2 \left( W^+_\mu \partial_\nu W^+_{\mu \nu} + \text{h.c.} \right) 
+ \hat{c}_{\gamma \gamma} \frac{e^2}{4\pi^2} A_{\mu \nu} A^{\mu \nu} + c_{z} \square g^2 Z_\mu \partial_\nu Z^\mu + c_{\gamma \square} g g' Z_\mu \partial_\nu A^{\mu \nu} 
+ c_{zz} \frac{g^2 + g'^2}{4} Z_{\mu \nu} Z^{\mu \nu} + \hat{c}_{z \gamma} \frac{e \sqrt{g^2 + g'^2}}{2\pi^2} Z_{\mu \nu} A^{\mu \nu} \right] 
+ \frac{g_s^2}{48\pi^2} \left( \hat{c}_{gg} \frac{h}{v} + \hat{c}_{gg}^{(2)} \frac{h^2}{2v^2} \right) G_{\mu \nu} G^{\mu \nu} 
- \sum_f m_f \left[ \delta y_f \frac{h}{v} + \delta y_f^{(2)} \frac{h^2}{2v^2} \right] \bar{f}_R f_L + \text{h.c.} \]

\[ + (\kappa_\lambda - 1) \lambda_{SM} v h^3 \quad \text{Only enter at loop level in single Higgs observable} \]
A counter example

May not be valid for Higgs portal

\[ \mathcal{L} \supset \theta g_* m_* H^\dagger H \varphi - \frac{m_*^4}{g_*^2} V(g_* \varphi / m_*) \]

Will generate:

\[ \delta c_z \sim \theta^2 g_*^2 \frac{v^2}{m_3^2} \]
\[ \delta \kappa_\lambda \sim \theta^3 g_*^4 \frac{1}{\lambda_{3}^{SM}} \frac{v^2}{m^2} \]

With a typical tuning of \( \Delta \sim \frac{\theta^2 g_*^2}{\lambda_3^{SM}} \)

Perturbative expansion \( \varepsilon \equiv \frac{\theta g_*^2 v^2}{m_*^2} \ll 1 \)

\( \theta \simeq 1, \ g_* \simeq 3 \) and \( m_* \simeq 2.5 \) TeV

\( \varepsilon \simeq 0.1, \ 1/\Delta \simeq 1.5\% \)

Hard to have model with large deviation only in \( \delta \kappa \)

Single Higgs fit valid for most model
Robustness of the analysis

Sensibility to single Higgs uncertainties