EFT analysis of the double Higgs production in gluon fusion

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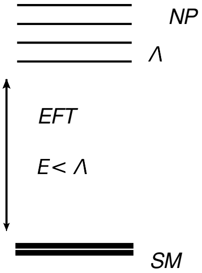
AA, R.Contino, G.Panico, M.Son arXiv: 1502.00539

When can we use EFT analysis ?

- If new physics states are heavier than the SM states as well as the typical mass scale of the process $\Lambda > E$.
- We can integrate these states out and parametrize their effects in terms of the higher dimensional operators.
- The effects of new physics will appear as a corrections in the $\left(\frac{E}{\Lambda}\right)$ series.



Operators important for the Higgs pair production in gluon fusion

- Assuming that the Higgs boson is neutral under $U(1)_{em}$ the most generic lagrangian parametrizing the Higgs pair production in gluon fusion is

$$\mathcal{L}^{n.l.} = -m_t \bar{t} t \left(c_t \frac{h}{v} + c_{2t} \frac{h^2}{v^2} \right) - c_3 \frac{m_h^2}{2v} h^3 + \frac{g_s^2}{4\pi^2} \left(c_g \frac{h}{v} + c_{2g} \frac{h^2}{2v^2} \right) G_{\mu\nu}^2$$

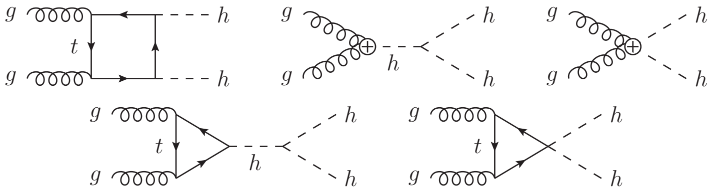
  where we have kept only the terms with up to two derivatives.

- Terms with the higher number of derivatives should appear as a corrections in $\left(\frac{E}{\Lambda}\right)$ series.

Low et al; Goertz et al,1205.5444 ,1405.7040,1410.3471

Double Higgs production in gluon fusion

$$\mathcal{L}^{n.l.} = -m_t \bar{t} t \left(c_t \frac{h}{v} + c_{2t} \frac{h^2}{v^2} \right) - c_3 \frac{m_h^2}{2v} h^3 + \frac{g_s^2}{4\pi^2} \left(c_g \frac{h}{v} + c_{2g} \frac{h^2}{2v^2} \right) G_{\mu\nu}^2$$



c_t, c_g will be constrained also by the single Higgs measurements

c_{2t}, c_{2g}, c_3 can constrained only by the double Higgs measurements

Linear vs non-linear lagrangian

- The constraints from EWPT from LEP and single Higgs measurements at LHC 7+8 TeV indicate strongly that the Higgs boson comes as a part of the electroweak doublet.
- Assuming the doublet structure and keeping only the dim 6 operators the relevant lagrangian for the Higgs interactions becomes

$$\Delta\mathcal{L}^{lin.} = \frac{\bar{c}_u}{v^2} y_t \left(HH^\dagger \bar{q}_L H^c t_R + h.c.\right) - \frac{\bar{c}_6}{v^2}\frac{m_h^2}{2v^2}\left(H^\dagger H\right)^3 + \bar{c}_g \frac{g_s^2}{m_w^2} H^\dagger H G_{\mu\nu}^2$$

$$\mathcal{L}^{n.l.} = -m_t \bar{t} t \left(c_t \frac{h}{v} + c_{2t}\frac{h^2}{v^2}\right) - c_3 \frac{m_h^2}{2v} h^3 + \frac{g_s^2}{4\pi^2}\left(c_g \frac{h}{v} + c_{2g}\frac{h^2}{2v^2}\right) G_{\mu\nu}^2$$

$$c_t = 1 - \bar{c}_u,\ \ c_{2t} = -\frac{3}{2}\bar{c}_u,\ \ c_g = c_{2g} = \bar{c}_g \left(\frac{4\pi}{\alpha_2}\right)$$

$$c_3 = 1 - \bar{c}_6$$

The doublet structure of the Higgs interactions fixes the relations between $tth(ggh)$ and $tthh(gghh)$ interactions

EFT limitations

- We must be in the regime when the effects of the dimension (> 6) operators are not important
- Linear lagrangian shows what are the range of the Wilson coefficients

$$\mathcal{L}_y = y_t \bar{q}_L H^c t_R \left(1 + \frac{\bar{c}_u H^\dagger H}{v^2} + \sum_n c_{n,m} \left(\frac{\partial}{v}\right)^m \left(\frac{H^\dagger H}{v^2}\right)^n\right)$$

- we can estimate the size of $c_n \sim \left(\frac{v^2 g_*^2}{\Lambda^2}\right)^n \left(\frac{v}{\Lambda}\right)^m$
- Expansion is valid if only $\frac{v^2 g_*^2}{\Lambda^2} \ll 1$ where g_* and Λ are the coupling constant and the mass scale of the new resonances.

Dimension-8 vs dimension-6 operators

$$O_6 = \bar{c}_g \frac{g_s^2}{m_w^2} H^\dagger H G_{\mu\nu}^2, \quad O_8 = \bar{c}_{D0} \frac{g_s^2}{m_w^4} G_{\mu\nu}^2 |D_\sigma H|^2$$

- keeping only the largest terms growing with energy

$$A \sim \frac{\alpha}{4\pi} \left[y_t^2 + g_6^2(E) + g_8^2(E) + \ldots \right]$$

$$g_6^2(E) \sim \bar{c}_g \frac{4\pi}{\alpha_2} \frac{E^2}{v^2}, \quad g_8^2 \sim \bar{c}_{D0} \frac{4\pi}{\alpha_2} \frac{E^4}{m_W^2 v^2}$$

- We can estimate this contributions to be

$$g_6^2(E) \sim \frac{g_*^2 E^2}{\Lambda^2}, \quad g_8^2(E) \sim \frac{g_*^2 E^4}{\Lambda^4}$$

Dimension-8 vs dimension-6 operators

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- keeping only the terms fastest growing with energy

$$A \sim \frac{\alpha}{4\pi} \left[y_t^2 + g_6^2(E) + g_8^2(E) + \ldots \right]$$

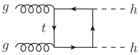
$$g_6^2(E) \sim \bar{c}_g \frac{4\pi}{\alpha_2} \frac{E^2}{v^2}, \quad g_8^2 \sim \bar{c}_{D0} \frac{4\pi}{\alpha_2} \frac{E^4}{m_W^2 v^2}$$

- We can estimate this contributions to be

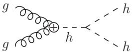
$$g_6^2(E) \sim \frac{g_*^2 E^2}{\Lambda^2} \left(\frac{\lambda^2}{g_*^2} \right), \quad g_8^2(E) \sim \frac{g_*^2 E^4}{\Lambda^4}$$

In Composite PNGB higgs models dimension 6 operators have an additional suppression $\Rightarrow$ thus there will be energy region where the contribution of the dim-8 will larger than dim 6, $E \gtrsim \Lambda \left(\frac{\lambda}{g_*} \right)$ and comparable to SM $E \gtrsim \Lambda / \sqrt{g_*}$ and at the same time within validity of EFT $E < \Lambda$

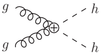
Choosing the better strategy in extracting the Higgs couplings

- 

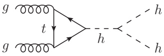
, $\mathcal{A}_{\square} \sim c_t^2 \frac{\alpha_s}{4\pi} y_t^2$

- 

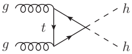
, $\mathcal{A}_3 \sim c_g c_3 \frac{\alpha_s}{4\pi} \frac{m_h^2}{v^2}$

- 

, $\mathcal{A}_4 \sim c_{2g} \frac{\alpha_s}{4\pi} \frac{\hat{s}}{v^2}$

- 

, $\mathcal{A}_{\triangle} \sim c_t c_3 \frac{\alpha_s}{4\pi} y_t^2 \frac{m_h^2}{\hat{s}} \left(\log \frac{m_t^2}{\hat{s}} + i\pi\right)^2$

- 

, $\mathcal{A}_{\triangle nl} \sim c_{t2} \frac{\alpha_s}{4\pi} y_t^2 \left(\log \frac{m_t^2}{\hat{s}} + i\pi\right)^2$

Different contributions scale differently with the center of mass energy $\sqrt{s}$, exclusive measurements will have better sensitivities on the Higgs couplings

Angular distributions

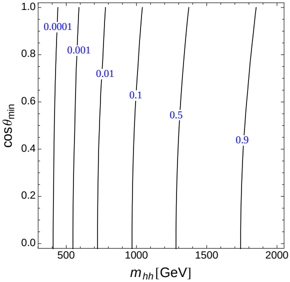
$$A(g(p_a)g(p_b) \to h(p_c)h(p_d)) = (P_0^{\mu\nu} M_0 + P_2^{\mu\nu} M_2)\, \epsilon^\mu(p_a)\epsilon^\nu(p_b)$$

$M_{0,2}$ are the contributions mediating $J_Z = 0, J_z = \pm 2$ transitions

- In the SM we are dominated by the M_0 contribution
- NP contributions coming from Dim-6 operators contribute only to M_0
- Dim-8 operators can contribute to the M_2

$$\boxed{\left(\eta^{\mu\nu}\partial_\rho h^\dagger \partial^\rho h - 4\,\partial^\mu h \partial^\nu h\right) G^a_{\mu\alpha} G^{a\,\alpha}_\nu}$$

$$c_{dim-8} \sim \frac{g_*^2}{\Lambda^4}$$



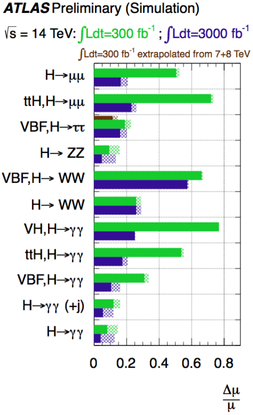
$$\Lambda = 1.9\,TeV,\, g_* = 3$$

Simulation details

- Signal yield as a function of c_i was simulated by the dedicated code, which was tested against hpair.
- We have decided to study only $bb\gamma\gamma$ final state due to cleaner signal and smaller background
- In order to take into account NLO and NNLO QCD corrections to the Higgs production we use the k-factor calculated in the infinite top mass limit $k_{14} = 2.27$ *(1309.6594)*
- We bin our events in center of mass energy $\sqrt{s}$
- And for every bin after application of the selection cuts we extract the Higgs pair production cross section as a polinomial in c_i couplings.

$$\sigma = \sigma_{SM}\Big[A_1\, c_t^4 + A_2 c_{2t}^2 + A_3\, c_t^2 c_3^2 + A_4\, c_g^2 c_3^2 + A_5\, c_{2g}^2 + A_6\, c_{2t} c_t^2$$
$$+A_7\, c_t^3 c_3 + A_8\, c_{2t} c_t\, c_3 + A_9\, c_{2t} c_g c_3 + A_{10}\, c_{2t} c_{2g} + A_{11}\, c_t^2 c_g c_3$$
$$+A_{12}\, c_t^2 c_{2g} + A_{13}\, c_t c_3^2 c_g + A_{14}\, c_t c_3 c_{2g} + A_{15}\, c_g c_3 c_{2g}\Big]$$

Combining single and double Higgs measurements



- The bounds from single and double Higgs measurements are correlated
- In order to estimate the strength of the combined constraints we have constructed the approximate "likelihood" based on the ATLAS high luminosity studies of the Higgs interaction measurements

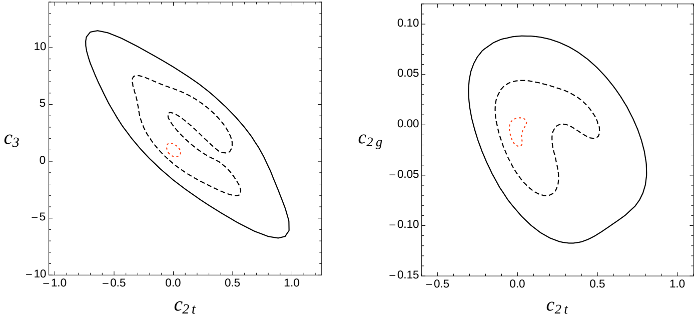
Simulation details, yields for 14 TeV LHC 3 ab−1

- Most of the Higgses are produced at threshold. We use the traditional cut based analysis to differentiate the background from the signal.

$m_{hh}^{\rm reco}$ [GeV]	250 – 400	400 – 550	550 – 700	700 – 850	850 – 1000	1000–
hh	2.14	6.34	2.86	0.99	0.33	0.17
$\gamma\gamma b\bar{b}$	7.69	10.1	3.35	1.38	1.18	0.59
$\gamma\gamma jj$	0.66	0.95	0.31	0.16	0.08	0.045
$t\bar{t}h$	3.33	4.53	1.41	0.41	0.16	0.043
$b\bar{b}h$	0.20	0.16	0.03	0.0054	0.0022	0.00054
Zh	0.13	0.19	0.067	0.021	0.009	0.0009

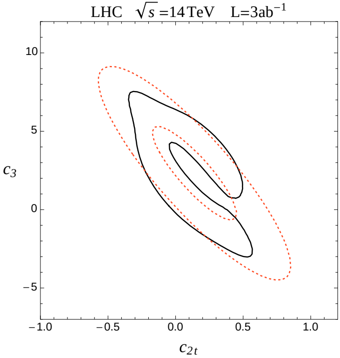
Results

In order to understand the HL-LHC prospects on measuring the various Higgs couplings we wanted to combine the information from the double and single Higgs production measurements. In order to derive approximate the LHC sensibility on the Higgs couplings we have used the ATLAS projections for the HL-LHC.



Results: inclusive vs exclusive

Binning in m_{hh} improves the sensibility. However at 14 TeV we are dominated by the low energy bins, thus the improvement is not so big.



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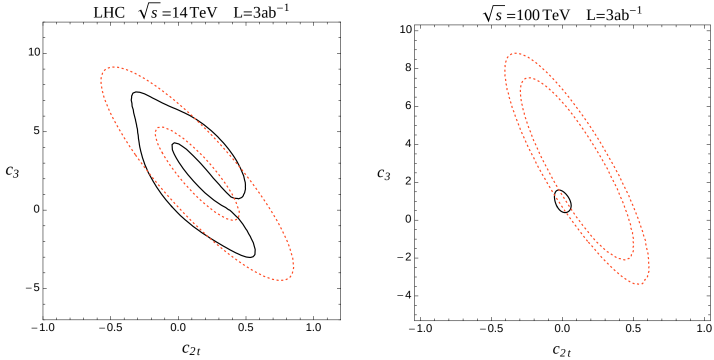
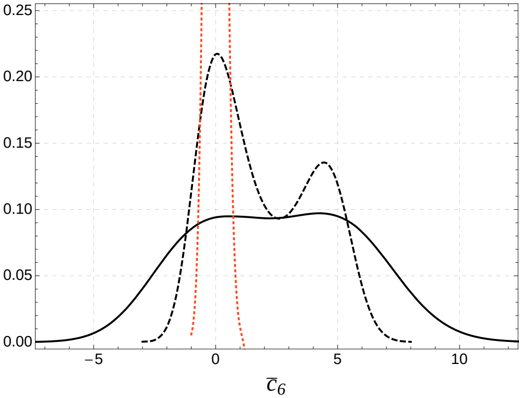


Results



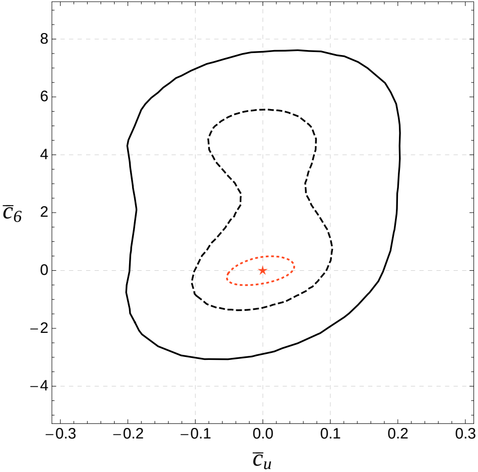
$$c_3 = 1 - \bar{c}_6$$

68% credibility intervals are

LHC	HL-LHC	FCC
$[-1.2, 6.1]$	$[-1.0, 1.8] \cup [3.5, 5.1]$	$[-0.33, 0.29]$

Interpreting LHC results

LHC	HL-LHC
$[-1.2, 6.1]$	$[-1.0, 1.8] \cup [3.5, 5.1]$



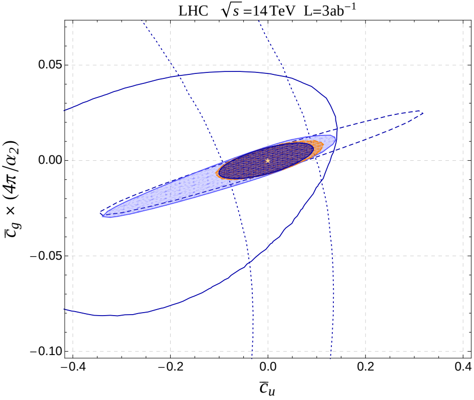
- LHC is sensitive to the order one deviations in the trilinear Higgs coupling
- In this regime the EFT is probably not valid, unless the BSM model has some strong dynamics coupled through the Higgs portal.

Results

- The single Higgs production in gluon fusion is proportional to

$$-m_t c_t \frac{h}{v} + \frac{g_s^2}{4\pi^2} c_g \frac{h}{v} \Rightarrow$$
$$\sigma \propto |c_t + 12 c_g|^2$$
$$\sigma \propto |1 - \bar{c}_u + 12\left(\frac{4\pi}{\alpha_2}\bar{c}_g\right)|^2$$

- We have large degeneracy in the Higgs couplings in $\bar{c}_u, \bar{c}_g$ space which is broken only by the tth and $h \to \gamma\gamma$ measurements.
- The double Higgs production can break this degeneracy due to the different scaling of the cross section with $\bar{c}_u, \bar{c}_g$



Summary

- If there is a mass gap between the new physics and the SM states EFT presents a coherent framework for analysing the Higgs interactions.
- The double Higgs production in gluon fusion is sensitive to the $HH^\dagger G_{\mu\nu}^2$, $\bar{t}tH(H^\dagger H)$, $(H^\dagger H)^3$ operators, which modify not only the trilinear coupling, but also the interactions between the Higgs boson and the top quark and gluons.
  - In order to extract the Wilson coefficients the combination with single Higgs production measurements is essential.
  - Studying energy distributions is very important in constraining the EFT operators.
- It looks like HL-LHC can determine the trilinear coupling with order one uncertainty.

14 TeV selection cuts, double Higgs production

- photon isolation: $p_T(\gamma) > 25\text{GeV}$, $|\eta(\gamma)| < 2.5$, $\epsilon_\gamma = 0.8$
- 2 b-taggged jets: $p_T(j) > 25$ GeV $|\eta(j)| < 2.5$, $\epsilon_b = 0.7, \quad \epsilon_{j\to b} = 0.01$
- $\Delta R(b,b) < 2$, $\Delta R(\gamma,\gamma) < 2$,$\Delta R(b,\gamma) > 1.5$
- $105 < m_{bb}^{rec} < 145$, $120 < m_{\gamma\gamma}^{rec} < 130$ GeV