Single Higgs production at LHC as a probe for an anomalous Higgs self coupling

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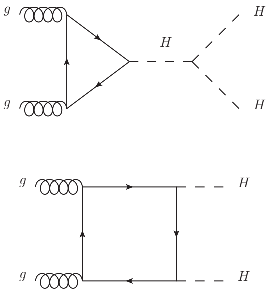
Based mainly on: G. Degrassi, PPG, F. Maltoni, D. Pagani arXiv:1607.04251

and G. Degrassi, M. Fedele, PPG arXiv:1702.01737

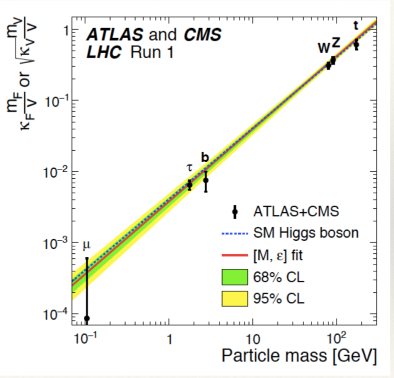
Outline

$$V(h) = \frac{1}{2} M_h^2 h^2 + \frac{M_h^2}{2v} h^3 + \frac{M_h^2}{8v^2} h^4$$



A Standard Higgs

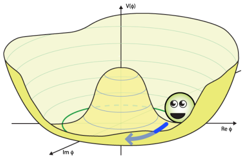
JHEP 1608 (2016) 045



- The Higgs still appears to be quite "Standard".
- The couplings with the vector bosons are compatible with the SM within a $\sim 10\%$ uncertainty,
- for the couplings to fermions the compatibility is within $\sim 15-20\%$ uncertainty.

But the situation with the Higgs self couplings is quite different.

The SM Higgs Potential



quantumdiaries.com

$$V(\phi) = -\mu^2(\phi^\dagger\phi) + \lambda(\phi^\dagger\phi)^2$$
$$V(h) = \frac{1}{2}M_h^2 h^2 + \frac{M_h^2}{2v}h^3 + \frac{M_h^2}{8v^2}h^4$$

- The self couplings are fixed once the Higgs mass and the vev are known.
- Trilinear coupling can be investigated at LHC from Higgs Pair Production.
- The quartic coupling will not be measured at LHC (or at ILC/CLIC).

Outline

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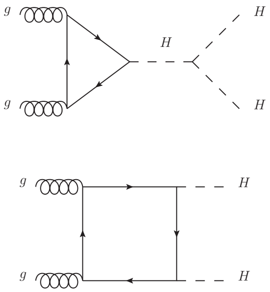
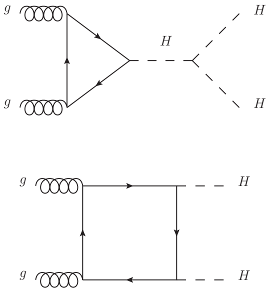


Higgs pair production



One vs. Two at 13 TeV

$gg \to H \sim 40$ pb
$gg \to HH \sim 30$ fb

Very small Cross Section.

- Heavier final state.
- Additional weak coupling.
- Destructive interference.

Higgs pair production

The situation might change if we assume

$$V_{H^3} = \lambda_3 v H^3 \equiv \kappa_\lambda \lambda_3^{\rm SM} v H^3.$$

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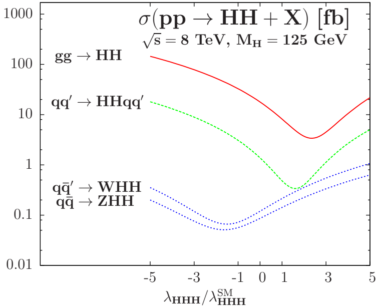

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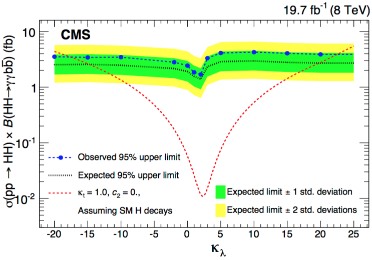
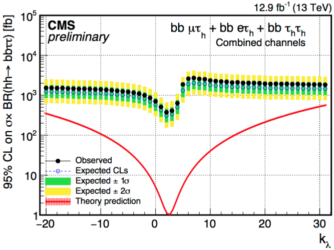
Bounds on the anomalous trilinear



arxiv:1603.06896



PAS-HIG-16-028

Assuming no change in the other Higgs couplings at 8 TeV,

ATLAS and CMS constraints λ_3 in the region $\mathcal{O}(\pm(15-20)\lambda_3^{\mathrm{SM}})$

arXiv:1509.0467; arXiv:1506.0028; arXiv:1603.0689; ATLAS-CONF-2016-049

At 3000 fb^{-1} λ_3 is constraint in the region $(-1.3, 8.7)\lambda_3^{\mathrm{SM}}$

ATL-PHYS-PUB-2014-019; ATL-PHYS-PUB-2015-046

Outline

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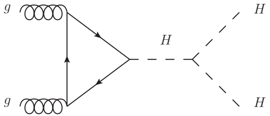
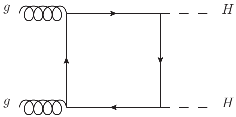




The dimension 6 operator

$$V^{\mathrm{dim}-6}(\Phi) = V^{\mathrm{SM}}(\Phi) + \frac{c6}{v^2}(\Phi^\dagger\Phi)^3, \text{ with } \Phi = \frac{1}{\sqrt{2}}\begin{pmatrix}\phi^+ \\ v + H + i\phi^0\end{pmatrix}$$

From the conditions $\left|\frac{dV^{\mathrm{dim}-6}(\Phi)}{d\Phi}\right|_{|\Phi|=v/\sqrt{2}} = 0,$

$$\kappa_\lambda = 1 + \frac{2c_6 v^2}{m_H^2}$$

We need to impose that $\Phi = \frac{v}{\sqrt{2}}$ is still a global minimum.

$$V^{\mathrm{dim}-6}(v/\sqrt{2}) = \frac{c_6 v^4 - m_H^2 v^2}{8} < 0 = V^{\mathrm{dim}-6}(0) \rightarrow \kappa_\lambda < 3$$

C. Grojean, G. Servant and J. D. Wells; Phys. Rev. D71 (2005) 036001

P. Huang, A. Joglekar, B. Li and C. E. M. Wagner; Phys. Rev. D93 (2016) 055049

EFT vs. κ_λ

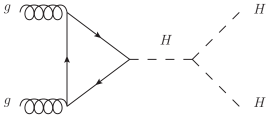
$\kappa_\lambda < 3$ is not very interesting for present phenomenology
More in general one can write $V^{NP} = \sum_{n=1}^{N} c_{2n}(\Phi^\dagger \Phi)^n$.
We ask the series to be convergent but we do not impose other conditions on c_{2n}.
Expanding up to ϕ^4 ($\xi = \phi^+\phi^- + \frac{1}{2}\phi_2^2$)

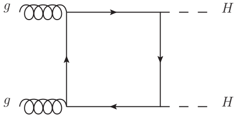
$$V_{4\phi}^{NP} = \frac{m_H^2}{2v^2}\,\xi^2 + \left(\frac{m_H^2}{2v^2} + d\lambda_4\right)\frac{1}{4}\,\phi_1^4 + \left(\frac{m_H^2}{2v^2} + 3\,d\lambda_3\right)\,\xi\,\phi_1^2 + \left(\frac{m_H^2}{2v} + d\lambda_3\right)\phi_1^3 + \frac{m_H^2}{v}\,\xi\,\phi_1 + \frac{1}{2}m_H^2\,\phi_1^2\,.$$

$V_{4\phi}^{NP}$ gives the same results of the anomalous coupling, since contributions due to $d\lambda_4$ are zero at the order of our calculations.

Outline

$$V(h) = \frac{1}{2}M_h^2 h^2 + \frac{M_h^2}{2v}h^3 + \frac{M_h^2}{8v^2}h^4$$

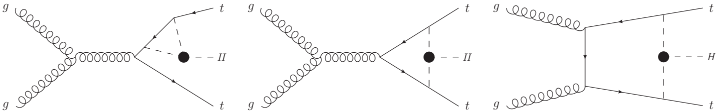




Single Higgs at NLO

The trilinear appears at NLO in Single Higgs processes.

Due to the presence of different Loop structures these contributions cannot be captured by a local rescaling.



For similar ideas: M. McCullough Phys. Rev. D90 (2014), no. 1 015001,

M. Gorbahn and U. Haisch, arXiv:1607.03773 [hep-ph]

Calculation

Processes at NLO

$$\Sigma_{NLO} = Z_H \Sigma_{LO}(1 + \kappa_\lambda C_1)$$

- Σ_{LO} contains QCD corrections.
- C_1 depends on the process.
- Z_H is Higgs wave function renormalization,
- $Z_H = \frac{1}{1-\kappa_\lambda^2 \delta Z_H}$

The range of validity of our calculation is $|\kappa_\lambda| \lesssim 20$

In general an Observable O can be written as

$$O = O^{\mathrm{SM}}[1 + (\kappa_\lambda - 1)C_1 + (\kappa_\lambda^2 - 1)C_2]$$

Calculation

In general an observable O can be written as

$$O = O^{\mathrm{SM}}[1 + (\kappa_\lambda - 1)C_1 + (\kappa_\lambda^2 - 1)C_2]$$

C_1 depend on the specific observable, $\sqrt{s}$, p_t cuts...

$$C_1 = \frac{\int 2\Re(\mathcal{M}^{0*}\mathcal{M}^1_{\lambda_3^{\mathrm{SM}}})}{\int |\mathcal{M}^0|^2}$$

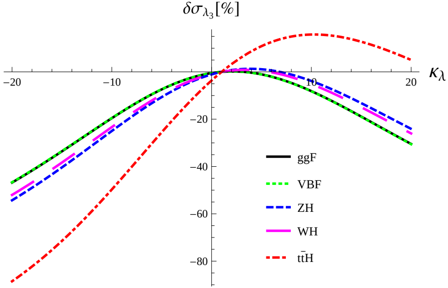
Amplitudes generated by FeynArts, computed by FormCalc interfaced to Loop-Tools, checked with FeynCalc.

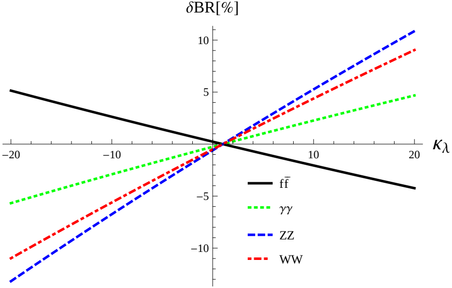
C_2 is calculated from δZ_H and does not depend on the observable.

C_1 coefficients

C_1^σ[%]	ggF	VBF	WH	ZH	$t\bar{t}H$
8 TeV	0.66	0.65	1.05	1.22	3.78
14 TeV	0.66	0.64	1.03	1.18	3.47

C_1^Γ[%]	$\gamma\gamma$	ZZ	WW	$f\bar{f}$	gg
on-shell H	0.49	0.83	0.73	0	0.66





Differential Information

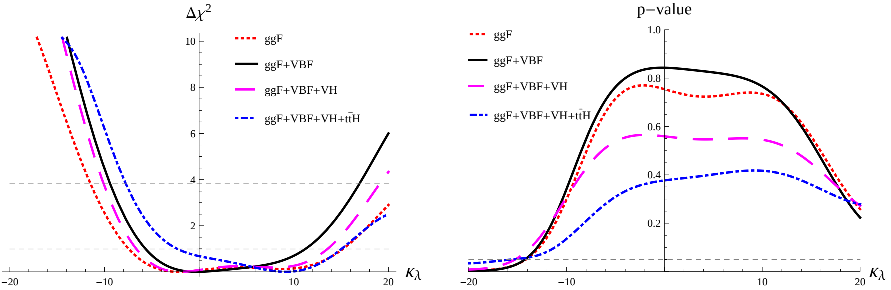
Further information can be in principle obtained from the kinematical dependence of the C_1 coefficients.

C_1^σ[%]	25 GeV	50 GeV	100 GeV	200 GeV	500 GeV
WH	1.71	1.56	1.29	1.09	1.03
ZH	2.00	1.83	1.50	1.26	1.19
$t\bar{t}H$	5.44	5.14	4.66	3.95	3.54

Table: C_1^σ at 13 TeV obtained by imposing the cut $p_T(H) < p_{T,\mathrm{cut}}$, for several values of $p_{T,\mathrm{cut}}$.

Present

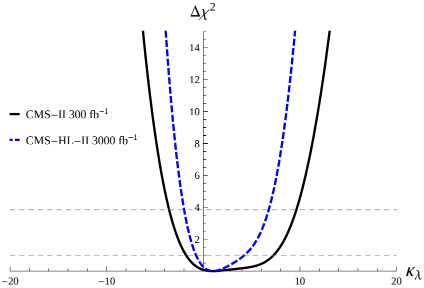
Fit on different "scenarios". Data from ATLAS-CMS 8 TeV data combination [JHEP 1608 (2016) 045]

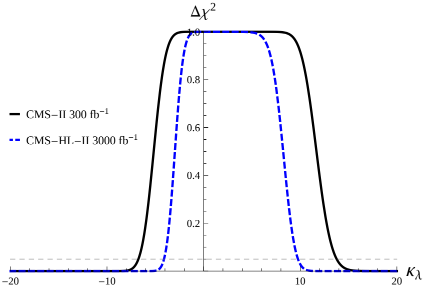


- For ggF+VBF: $\kappa_\lambda^{\text{best}} = -0.24$, $\kappa_\lambda^{1\sigma} = [-5.7, 11.2]$, $\kappa_\lambda^{2\sigma} = [-9.4, 17.0]$.
- Requiring $p > 0.05$, we exclude at more than 2σ $\kappa_\lambda < -14.3$

Future

Using the uncertainties presented in arXiv:1312.4974, and assuming that LHC will measure SM, we can estimate the future capabilities of LHC.

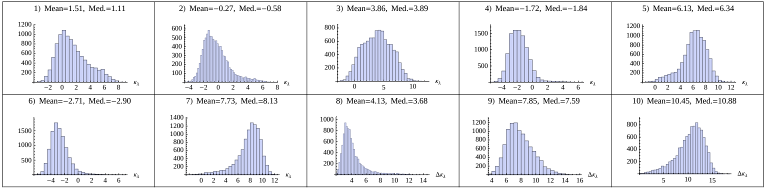




For CMS-HL-II 3000 fb^{-1}: $\kappa_\lambda^{1\sigma} = [-0.8, 4.2]$, $\kappa_\lambda^{2\sigma} = [-2.0, 6.8]$, $\kappa_\lambda^{p>0.05} = [-4.1, 9.8]$.

Future

A more reliable approach is to consider central values compatible with SM.
We produce a collection of pseudo-measurements randomly generated with a gaussian distribution around the SM.



1) best values, 2) 1σ region lower limit, 3) 1σ region upper limit, 4) 2σ region lower limit, 5) 2σ region upper limit, 6) $p > 0.05$ region lower limit, 7) $p > 0.05$ region upper limit, 8) 1σ region width, 9) 2σ region width, 10) $p > 0.05$ region width.

$$\kappa_\lambda^{p>0.05} = [-2.8, 7.9]$$

For ATLAS 3000 fb^{-1} $\kappa_\lambda^{p>0.05} = [-1.3, 8.7]$

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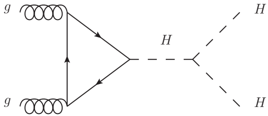
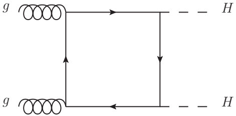




λ_3-dependent contributions in m_W and $\sin^2\theta_{\rm eff}^{\rm lep}$

Precision physics can also give informations on the trilinear. [1]
The theoretical predictions of m_W and $\sin^2\theta_{\rm eff}^{\rm lep}$ can be expressed in terms of physical quantities:

$$m_W^2 = \frac{\hat{\rho}\, m_Z^2}{2}\left\{1+\left[1-\frac{4\hat{A}^2}{m_Z^2\hat{\rho}}(1+\Delta\hat{r}_W)\right]^{1/2}\right\}$$

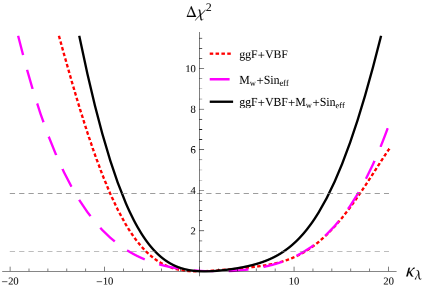
with $\hat{A} = (\pi\hat{\alpha}(m_Z)/(\sqrt{2}G_\mu))^{1/2}$.
$\hat{\rho}$ and $\Delta\hat{r}_W$ are related to the Peskin-Takeuchi parameters T and S.

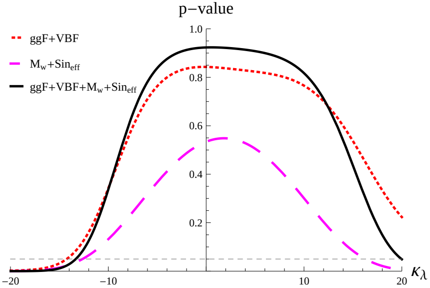
$$O = O^{\rm SM}[1+(\kappa_\lambda-1)C_1+(\kappa_\lambda^2-1)C_2]$$

[1] see also Kribs , Maier, Rzehak, Spannowsky, Waite arXiv:1702.07678

Results

	C_1	C_2
m_W	6.27×10^{-6}	-1.72×10^{-6}
$\sin^2 \theta_{\rm eff}^{\rm lep}$	-1.56×10^{-5}	4.55×10^{-6}





- $\kappa_\lambda^{\rm best} = 0.5$, $\kappa_\lambda^{1\sigma} = [-4.7, 8.9]$, $\kappa_\lambda^{2\sigma} = [-8.2, 13.7]$.
- Requiring $p > 0.05$ we exclude at more than 2σ $\kappa_\lambda < -13.3$ and $\kappa_\lambda > 20.0$

FAQ

- In our fit we variate only the trilinear coupling. Is this a necessity? (e.g. arXiv: 1704.01953).
- We can have $k_\lambda \simeq 20$. Is this allowed by unitarity conditions? (Falkowski and Rattazzi private note: theory with only self-coupling modifications valid up to few TeV for $k_\lambda \lesssim 10$)
- Are there concrete models with k_λ so large? (arXiv: 1704.02311, arXiv: 1704.01953).

Conclusions

- No direct measurement of the Higgs self couplings. In particular of the trilinear.
- The Higgs trilinear coupling can be investigated from single Higgs processes.
- Compared to Higgs pair production, the bounds obtained are competitive and complementary.
- Precision physics can help further constraints the allowed region.