Higgs self coupling determination from single Higgs production and decay

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Based on 1607.04251 and its extension(ongoing...)

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Higgs potential and new physics

- Higgs potential & EWSB in the SM,

$$V^{\rm SM}(\Phi) = -\mu^2(\Phi^\dagger\Phi)^2 + \lambda(\Phi^\dagger\Phi)^4 \quad (1)$$

$$\Rightarrow V(H) = \frac{m_H^2}{2}H^2 + \lambda_3 v H^3 + \lambda_4 H^4. \quad (2)$$

The mass and the self-couplings of the Higgs boson depend only on λ and $v = (\sqrt{2}G_\mu)^{-1/2}$,

$$m_H^2 = 2\lambda v^2;\ \lambda_3^{\rm SM} = \lambda;\ \lambda_4^{\rm SM} = \lambda/4. \quad (3)$$

- $m_H = 125$ GeV and $v \sim 246$ GeV, $\Rightarrow \lambda \simeq 0.13$.

Higgs potential and new physics

- Presence of new physics at higher energy scales can contribute to the Higgs potential and modify the Higgs self couplings. Therefore, an independent determination of λ_3 and λ_4 is crucial.

- Deviations in Higgs self-couplings due to new physics,

$$\lambda_3 = \kappa_\lambda \lambda_3^{\rm SM}, \ \lambda_4 = \kappa_4 \lambda_4^{\rm SM}. \tag{4}$$

The Higgs mass and vev remain unchanged. In general, κ_λ and κ_4 are independent.

Contribution from Higher dim. operators: an example

- Dim-6:

$$V^6(\Phi) = V^{\rm SM}(\Phi) + \frac{C_6}{v^2}(\Phi^\dagger\Phi)^3 \quad (5)$$

$$\Rightarrow \kappa_\lambda = 1 + 2c_6\frac{v^2}{m_H^2},\ \kappa_4 = 1 + 12c_6\frac{v^2}{m_H^2} \quad (6)$$

The trilinear and the quartic Higgs self-couplings are still correlated ($\kappa_4 = 6\kappa_\lambda$).

- Dim-8:

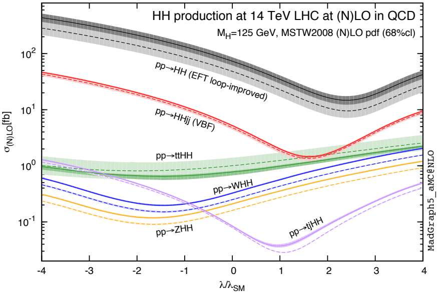
$$V^8(\Phi) = V^{\rm SM}(\Phi) + \frac{C_6}{v^2}(\Phi^\dagger\Phi)^3 + \frac{C_8}{v^4}(\Phi^\dagger\Phi)^4 \quad (7)$$

$$\Rightarrow \kappa_\lambda = 1 + (2c_6 + 4c_8)\frac{v^2}{m_H^2},\ \kappa_4 = 1 + (12c_6 + 32c_8)\frac{v^2}{m_H^2} \quad (8)$$

The trilinear and the quartic Higgs self-couplings are no more correlated.

Direct determination of Higgs self couplings

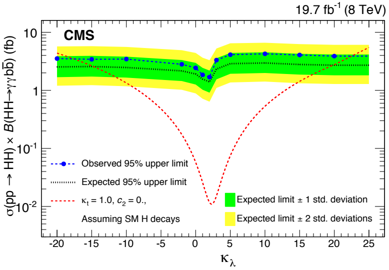
- Information on λ_3 and λ_4 can be extracted by studying multi-Higgs production processes.
- Higgs pair production is the standard channel for λ_3 measurement. Its SM cross section at 13 TeV LHC is about 35 fb. (Compare it with the single Higgs production cross section: ~ 50 pb.) Frederix et al. '14:



Direct determination of Higgs self couplings

- Current experimental bounds on κ_λ are very weak. CMS in $2\gamma 2b$ final state with 8 TeV and 19.7 fb^{-1} data (1603.06896) excludes κ_λ in the range,

$$\kappa_\lambda < -17.5 \text{ and } \kappa_\lambda > 22.5$$



Direct determination of Higgs self couplings

- The ATLAS data at 13 TeV in $4b$ final state and with 13.3 fb^{-1} excludes (ATLAS-CONF-2016-049),

$$\kappa_\lambda < -8 \text{ and } \kappa_\lambda >\sim 12$$

- Future prospects at HL-LHC with 3000 fb^{-1} data, (ATL-PHYS-PUB-2014-019,2015-046)

$$\kappa_\lambda < -1.3 \text{ and } \kappa_\lambda > 8.7 \; (2\gamma 2b)$$
$$\kappa_\lambda < -4 \text{ and } \kappa_\lambda > 12 \; (2\tau 2b)$$

- No realistic hope of measuring λ_4 in $gg \to HHH$ production channel at the LHC due to a very small cross section: ~ 0.1 fb at 13 TeV.

Indirect determination of λ_3

- $\mathcal{O}(\lambda)$ corrections to single Higgs production and decay processes
  Matthew McCullough: 1312.3322, Chen Shen, Shou-hua Zhu: 1504.05626 ($e^+e^- \to ZH$)
  Martin Gorbahn, Ulrich Haisch: 1607.03773 ($gg \to H, H \to \gamma\gamma$)
  Giuseppe Degrassi, Pier Paolo Giardino, Fabio Maltoni, Davide Pagani: 1607.04251 (Relevant Higgs production and decay modes)
  Wojciech Bizon, Martin Gorbahn, Ulrich Haisch, Giulia Zanderighi: 1610.05771 (VH, VBF)
- $\mathcal{O}(\lambda)$ corrections in electroweak precision observables
  Giuseppe Degrassi, Marco Fedele, Pier Paolo Giardino: 1702.01737
  Graham D. Kribs, Andreas Maier, Heidi Rzehak, Michael Spannowsky, Philip Waite: 1702.07678

Indirect determination of λ_3 (1607.04251)

- Master formula

$$\Sigma_{\rm NLO} = Z_H \Sigma_{\rm LO}(1+\kappa_\lambda C_1); \; Z_H = \frac{1}{(1-\kappa_\lambda^2 \delta Z_H)} \quad (9)$$

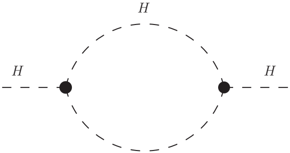
$$\delta\Sigma_{\lambda_3} = \frac{\Sigma_{\rm NLO} - \Sigma_{\rm NLO}^{\rm SM}}{\Sigma_{\rm LO}} = (\kappa_\lambda - 1)C_1 + (\kappa_\lambda^2 - 1)C_2 + \mathcal{O}(\kappa_\lambda^3 \alpha^2) \quad (10)$$

$\mathcal{O}(\kappa_\lambda^3 \alpha^2) \simeq \kappa_\lambda^3 C_1 \delta Z_H < 10\% \Rightarrow |\kappa_\lambda| \lesssim 20.$

- C_2, which arises from the wave function renormalization, is universal.

$$C_2 = \frac{\delta Z_H}{(1-\kappa_\lambda^2 \delta Z_H)}; \; \delta Z_H = -\frac{9}{16}\frac{G_\mu m_H^2}{\sqrt{2}\pi^2}\left(\frac{2\pi}{3\sqrt{3}} - 1\right) \quad (11)$$

Indirect determination of λ_3 (1607.04251)



- The process-independent factor C_2 can range from $C_2 = -1.536 \cdot 10^{-3}$ for $\kappa_\lambda = 1$ up to $C_2 = -9.514 \cdot 10^{-4}$ for $\kappa_\lambda = \pm 20$.

- C_1 is process dependent and can have kinematic dependence. It arises from the interference between LO amplitude and $\mathcal{O}(\lambda)$ virtual corrections.

Indirect determination of λ_3 (1607.04251)

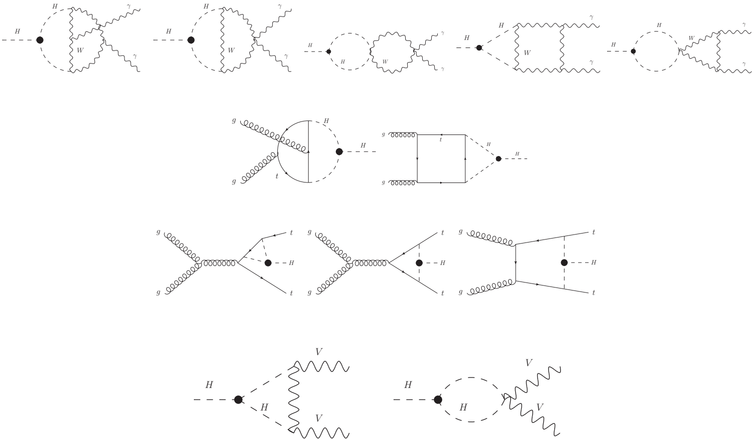


Figure: Diagrams contributing to $\mathcal{O}(\lambda)$ virtual corrections to single Higgs production and decay channels.

Indirect determination of λ_3 (1607.04251)

- C_1 for decay modes:

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

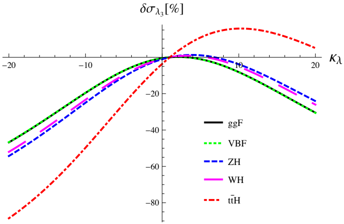
- C_1 for production modes:

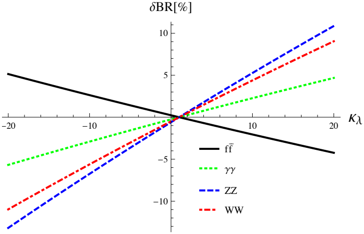
C_1^σ [%]	ggF	VBF	WH	ZH	ttH
7 TeV	0.66	0.65	1.06	1.23	3.87
8 TeV	0.66	0.65	1.05	1.22	3.78
13 TeV	0.66	0.64	1.03	1.19	3.51
14 TeV	0.66	0.64	1.03	1.18	3.47

Indirect determination of λ_3 (1607.04251)

Modifications in production cross sections and BRs:

Except *ttH*, for all other production channels large corrections are mostly -ve and for large $|\kappa_\lambda|$.

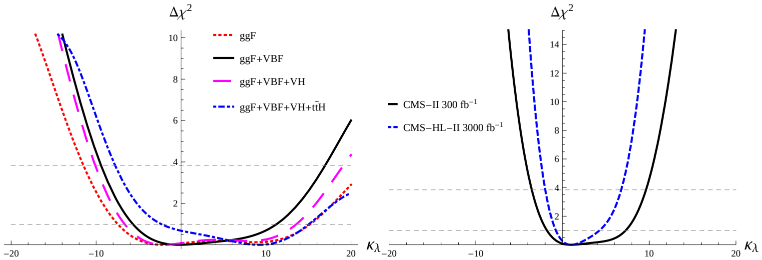




Corrections to BRs are much smaller, however, around SM predictions, the decay modes are more sensitive to κ_λ than the production modes.

Indirect determination of λ_3 (1607.04251)

$\chi^2(\kappa_\lambda)$ fit: present and future



The most stringent bound comes using *ggF* + *VBF* 8 TeV data,

$$\kappa_\lambda^{\rm best} = -0.24,\ \kappa_\lambda^{1\sigma} = [-5.6, 11.2],\ \kappa_\lambda^{2\sigma} = [-9.4, 17.0].$$

Indirect determination of λ_3: kinematic dependence

- $\mathcal{O}(\lambda)$ corrections have non-trivial dependence on external momenta, e.g., for the *VVH* vertex the correction is

$$i\mathcal{V}^{\mu_1\mu_2}_{VVH} = \frac{i\lambda}{16\pi^2}\frac{M_V^2}{v}[(-6B_0 - 24M_V^2 C_0 + 24C_{00})g^{\mu_1\mu_2} - 24p_1^{\mu_2}p_2^{\mu_1}C_{12}]. \quad (12)$$

- We calculate C_1 for kinematic distributions. Here we consider, Production (*VH*, *VBF* and *ttH* at 13 TeV) & Decay ($H \to 4l$).

- The $\mathcal{O}(\lambda)$ corrections for the production channels are computed via reweighting in MG5@MC_NLO. The results for $H \to 4l$ are obtained using the publicly available Hto4l code (1503.07394).

Preliminary results: ZH

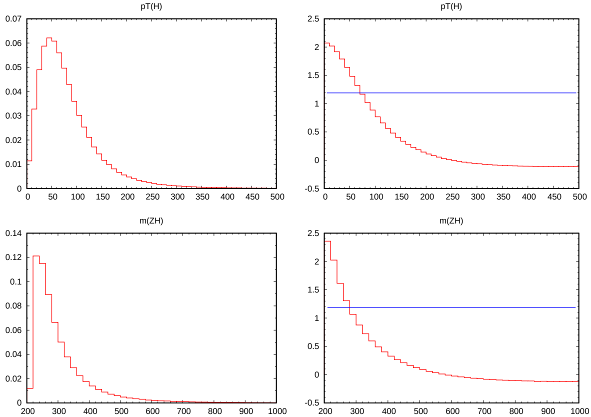
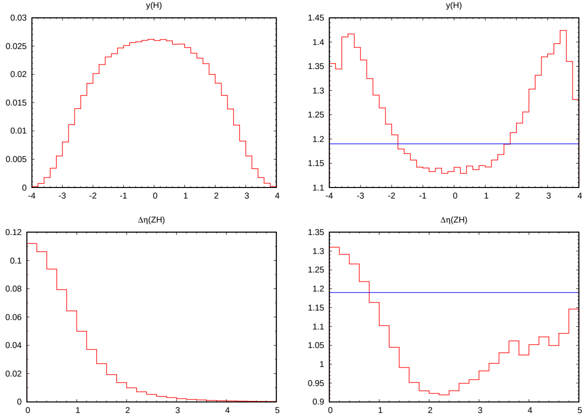


Figure: LO distribution (left). Differential $C_1(\%)$ (right). Blue line: $C_1(\%)$ for total rate.

Preliminary results: ZH



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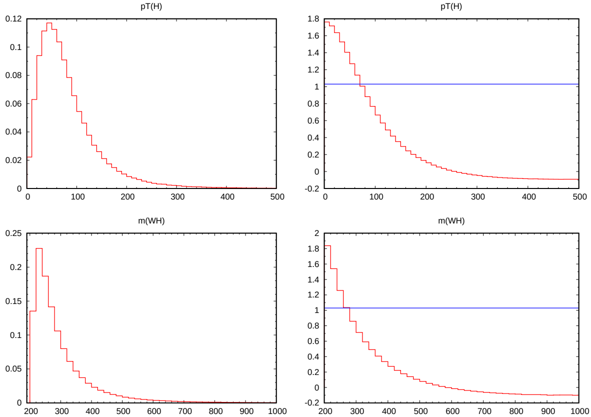

Figure: LO distribution (left). Differential $C_1(\%)$ (right). Blue line: $C_1(\%)$ for total rate.

Preliminary results: *WH*

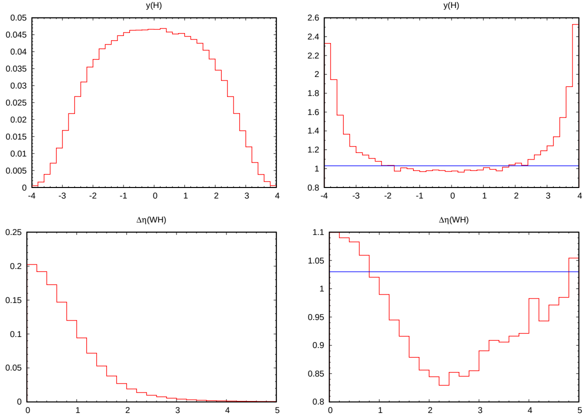

Figure: LO distribution (left). Differential $C_1(\%)$ (right). Blue line: $C_1(\%)$ for total rate.

Preliminary results: *VBF*

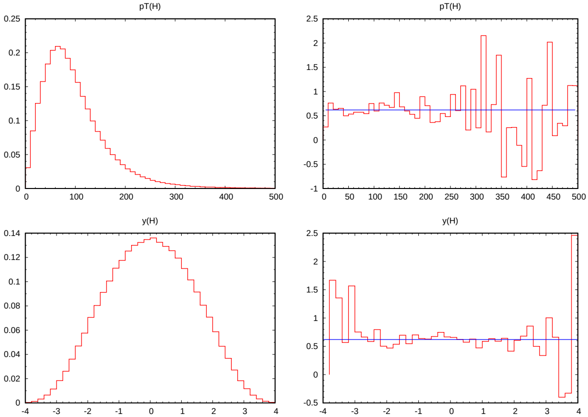

Figure: LO distribution (left). Differential $C_1(\%)$ (right). Blue line: $C_1(\%)$ for total rate.

Preliminary results: *ttH*

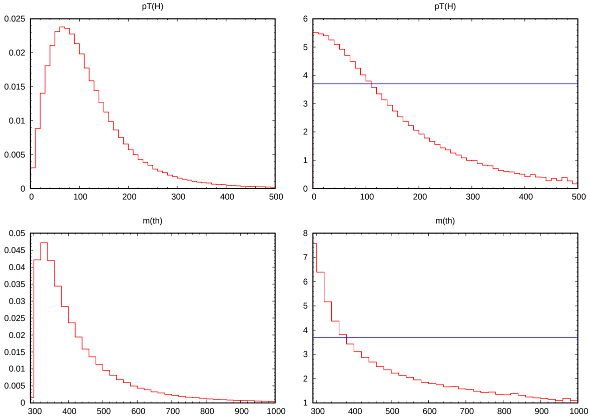

Figure: LO distribution (left). Differential $C_1(\%)$ (right). Blue line: $C_1(\%)$ for total rate.

Preliminary results: ttH

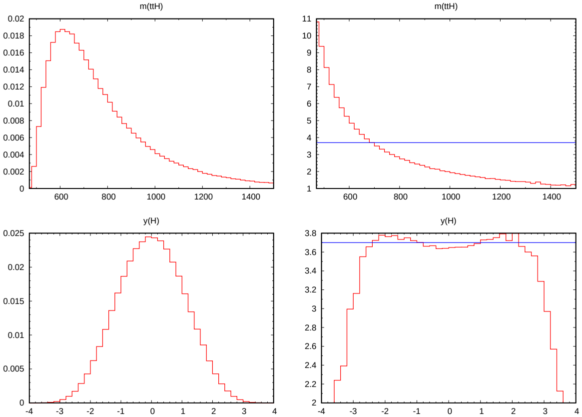

Figure: LO distribution (left). Differential $C_1(\%)$ (right). Blue line: $C_1(\%)$ for total rate.

Preliminary results: ttH

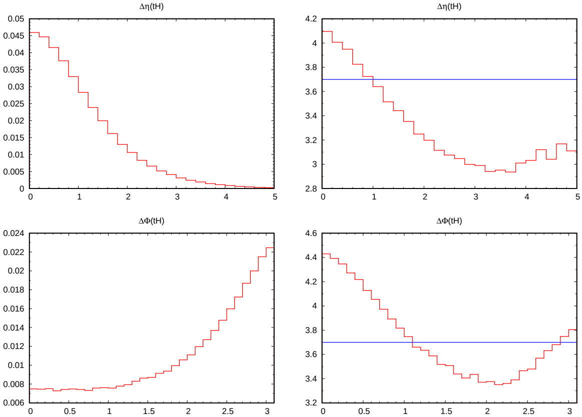

Figure: LO distribution (left). Differential $C_1(\%)$ (right). Blue line: $C_1(\%)$ for total rate.

Preliminary results: $H4l$ ($e^+e^-\mu^+\mu^-$)

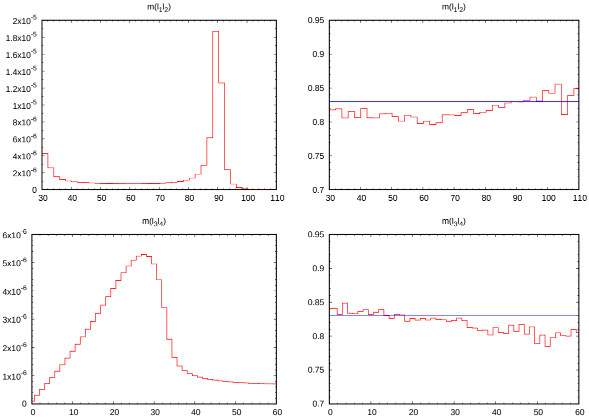

Figure: LO distribution (left). Differential $C_1(\%)$ (right). Blue line: $C_1(\%)$ for total rate.

Summary

- The indirect determination of Higgs self couplings via EW corrections to Higgs production and decay channels can complement its direct determination via multi-Higgs production at the LHC.

- The study of differential distributions which get affected in a non-trivial way can help in lifting the degeneracy due to modifications in other couplings and improve the bounds on Higgs self couplings (Work in progress...).

Backup

$C_1^\sigma[\%]$	25 GeV	50 GeV	100 GeV	200 GeV	500 GeV
WH	1.71 (0.11)	1.56 (0.34)	1.29 (0.72)	1.09 (0.94)	1.03 (0.99)
ZH	2.00 (0.10)	1.83 (0.33)	1.50 (0.71)	1.26 (0.94)	1.19 (0.99)
$t\bar{t}H$	5.44 (0.04)	5.14 (0.17)	4.66 (0.48)	3.95 (0.84)	3.54 (0.99)

Table: C_1^σ at 13 TeV obtained by imposing the cut $p_T(H) < p_{T,\mathrm{cut}}$, for several values of $p_{T,\mathrm{cut}}$. In parentheses the fraction of events left after the quoted cut is applied.

$C_1^\sigma[\%]$	1.1	1.2	1.5	2	3
WH	1.78 (0.17)	1.60 (0.36)	1.32 (0.70)	1.15 (0.89)	1.06 (0.97)
ZH	2.08 (0.19)	1.86 (0.38)	1.51 (0.72)	1.31 (0.90)	1.22 (0.98)
$t\bar{t}H$	8.57 (0.02)	7.02 (0.10)	5.11 (0.43)	4.12 (0.76)	3.64 (0.94)

Table: C_1^σ at 13 TeV obtained by imposing the cut $m_{\mathrm{tot}} < K \cdot m_{\mathrm{thr}}$, for several values of K. In parentheses the fraction of events left after the quoted cut is

Backup

Future projections: $\kappa_\lambda^{\rm best} = 1$

$$
\begin{aligned}
\kappa_\lambda^{1\sigma} &= [-1.8, 7.3],\ \kappa_\lambda^{2\sigma} = [-3.5, 9.6]\ ({\rm CMS}, 300{\rm fb}^{-1}) \\
\kappa_\lambda^{1\sigma} &= [-0.7, 4.2],\ \kappa_\lambda^{2\sigma} = [-2.0, 6.8]\ ({\rm CMS}, 3000{\rm fb}^{-1})
\end{aligned}
$$