Trilinear Higgs self-coupling determination from single-Higgs differential measurements

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Double Higgs Production at Colliders Workshop
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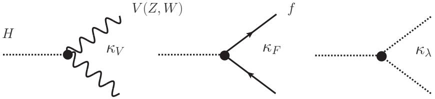
Higgs couplings in the SM

The SM Higgs sector is governed by the following Lagrangian,

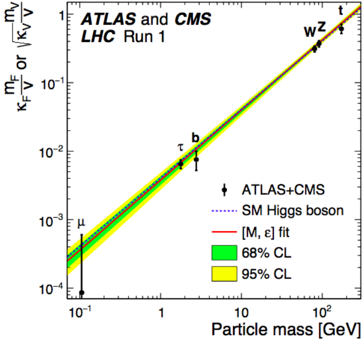
$$\mathcal{L}_{\text{Higgs}} = |D_\mu\Phi|^2 - \sum_f y_f \bar{L}_f \Phi R_f - V(\Phi)$$



- EWSB ⇒ Higgs couplings with gauge bosons (κ_V), with fermions (κ_F) and Higgs self-couplings (κ_λ)
- *How precisely do we know these couplings ?*

$$\kappa_V \sim 10\%,\ \kappa_F^\star \sim 10-20\%,$$

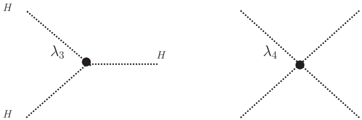
κ_λ : practically unconstrained!



SM Higgs potential & New Physics

Higgs potential & EWSB in the SM,

$$\begin{aligned} V^{SM}(\Phi) &= -\mu^2(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2 \\ \text{EWSB} \Rightarrow V(H) &= \frac{1}{2}m_H^2 H^2 + \lambda_3 v H^3 + \frac{1}{4}\lambda_4 H^4. \end{aligned}$$



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

$$m_H^2 = 2\lambda v^2; \ \lambda_3^{SM} = \lambda_4^{SM} = \lambda.$$

$$m_H = 125 \text{ GeV and } v \sim 246 \text{ GeV}, \Rightarrow \boxed{\lambda \simeq 0.13}.$$

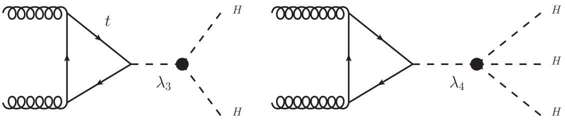
Presence of new physics at higher energy scales can contribute to the Higgs potential and modify the Higgs self-couplings.

Independent measurements of λ_3 and λ_4 are crucial.

Direct determination of Higgs self-couplings

$$\boxed{\lambda_3 = \kappa_3 \lambda_3^{\text{SM}},\ \lambda_4 = \kappa_4 \lambda_4^{\text{SM}}}$$

Information on λ_3 and λ_4 can be extracted by studying multi-Higgs production processes.

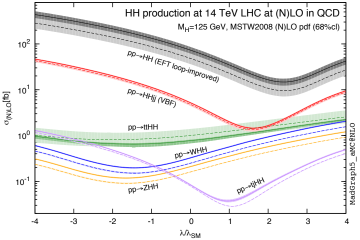


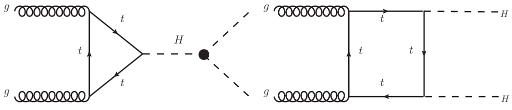
Trilinear Higgs self-coupling (λ_3) in this talk.

Direct determination of λ_3

Double Higgs production: pp → HH, HHjj, HHV, $t\bar{t}$HH

Frederix et al. '14:





Higgs pair production ($gg \to HH$) is the standard channel for probing λ_3.

Its SM cross section (no decays) at 13 TeV LHC is about 33 fb.

Compare it with the single Higgs production ($gg \to H$) cross section: $\sim$ 50 pb

Direct determination of λ_3

Current experimental bounds on κ_3 via double Higgs production are quite weak and future prospects are not very promising.

- CMS (13 TeV, 36 fb^{-1}, $2b2\gamma$) (CMS-PAS-HIG-17-008).

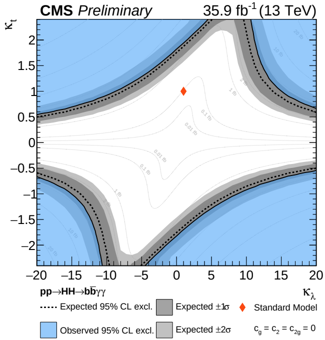
$$\kappa_3 < -9 \text{ and } \kappa_3 >\sim 15$$

- ATLAS (13 TeV, 36.1 fb^{-1}, $4b$) (1804.06174),

$$\kappa_3 < -5 \text{ and } \kappa_3 >\sim 8$$

- ATLAS (HL-LHC, $2b2\gamma$) (ATL-PHYS-PUB-2017-001),

$$\kappa_3 < -0.8 \text{ and } \kappa_3 >\sim 7.7$$

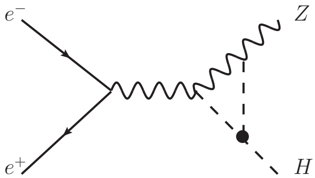


Bounds are sensitive to κ_t value.

Are there alternative methods of probing λ_3 ?

Indirect determination of λ_3

We can be sensitive to λ_3 in higher order EW corrections in observables of interest: McCullough: 1312.3322.
For $\sqrt{s} = 240$ GeV and $\mathcal{L} = 10$ ab^{-1}, $\kappa_3 \sim 28\%$.



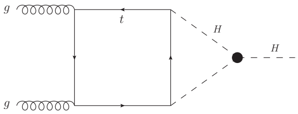
What about extending this idea to single Higgs processes at the LHC ?

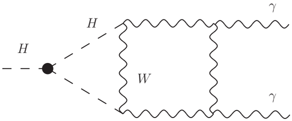
Indirect determination of λ_3

- λ−dependent corrections to single Higgs processes

Production	Loops
ggF	2
VBF, VH	1
ttH, tHj	1

Decay	Loops
$\gamma\gamma$, gg	2
ZZ,WW	1
fermions	1

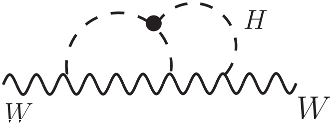




> Gorbahn, Haisch: 1607.03773
> Degrassi, Giardino, Maltoni, Pagani: 1607.04251
> Bizon, Gorbahn, Haisch, Zanderighi: 1610.05771
> Di Vita, Grojean, Panico, Riembau, Vantalon: 1704.01953
> Maltoni, Pagani, AS, Zhao: 1709.08649

Indirect determination of λ_3

- λ−dependent corrections in electroweak precision observables
  > Degrassi, Fedele, Giardino: 1702.01737
  > Kribs, Maier, Rzehak, Spannowsky, Waite: 1702.07678



- These studies have confirmed that indirect bounds on λ_3 can be competitive with the direct ones. A one parameter fit using 8 TeV LHC data (1607.04251) $\Rightarrow$

$$\boxed{-9.4 < \kappa_3 < 17}$$

Expected sensitivity at HL-LHC ?

λ_3 in single Higgs processes: Framework

- Master formula: *Anomalous trilinear coupling*

$$\boxed{\Sigma_{\rm NLO}^{\rm BSM} = Z_H^{\rm BSM}[\Sigma_{\rm LO}(1 + \kappa_3 C_1 + \delta Z_H) + \Delta_{\rm NLO}^{\rm SM}]}$$

$$Z_H^{\rm BSM} = \frac{1}{1-(\kappa_3^2-1)\delta Z_H}, \quad \delta Z_H = -1.536 \times 10^{-3}$$

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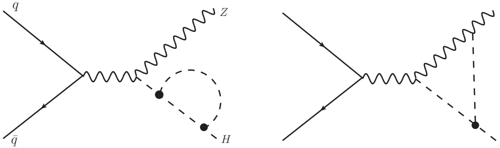
- $Z_H^{\rm BSM}$ arises from wave function renormalization and it is *universal* to all processes.



- $\Sigma_{\rm LO}$ includes any factorizable higher order correction like QCD.

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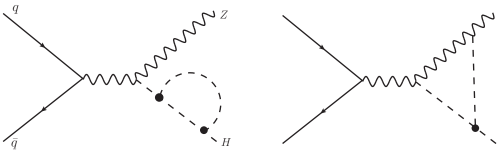
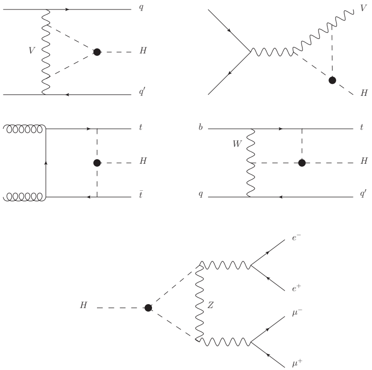


- $\Sigma_{\rm LO}$ includes any factorizable higher order correction like QCD.
- C_1 arises from the interference between LO amplitude and λ_3-dependent virtual corrections. It is finite, *process dependent* and can have non-trivial kinematic dependence.
- $\Delta_{\rm NLO}^{\rm SM}$ includes contribution from virtual W, Z and γ as well as real emissions.

MC Tools

- Two MC public codes to calculate C_1 at differential level:
  1. `trilinear-FF` 2. `trilinear-RW` (Recommended)

  https://cp3.irmp.ucl.ac.be/projects/madgraph/wiki/HiggsSelfCoupling



- Relevant for processes with non-trivial final state kinematics
  Production: VBF, VH, ttH and tHj; Decay: $H \to 4\ell$

C_1: Inclusive vs Differential

Channels	ggF	VBF	ZH	WH	$t\bar{t}H$	tHj	$H \to 4\ell$
$C_1(\%)$	0.66	0.63	1.19	1.03	3.52	0.91	0.82

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

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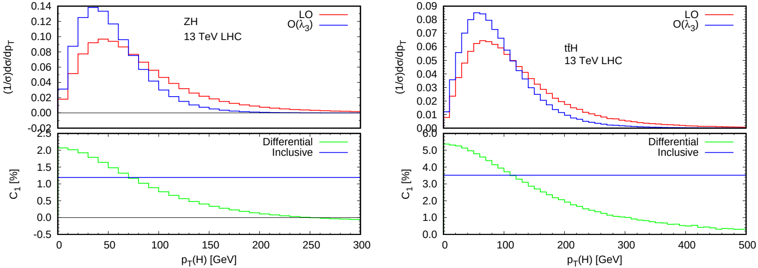
(1607.04251,1709.08649)



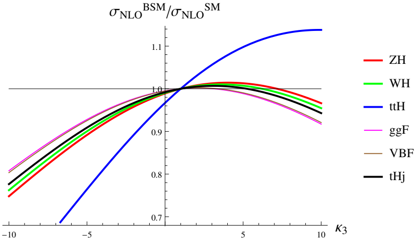
Differential C_1 for ggF: *not available*

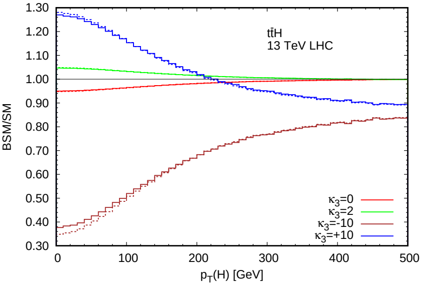
Differential C_1 for VBF, $H \to 4\ell$: *not important*

Impact of additional EW corrections in observables: Inclusive vs Differential

The EW corrections are known to be more important in production channel.

$$\mu_i = \frac{\sigma_{\text{NLO}}^{\text{BSM}}}{\sigma_{\text{NLO}}^{\text{SM}}} = Z_H^{\text{BSM}}\left[1 + \frac{1}{K_{\text{NLO}}^{\text{SM}}}(\kappa_3 - 1)C_1\right]$$





No numerical impact on the fit.

log-likelihood analysis

- The signal strength: $\mu_i^f = \mu_i \times \mu^f$

$$\mu_i = \frac{\sigma_i^{\rm BSM}}{\sigma_i^{\rm SM}} = (k_i^2 - 1) + Z_H^{\rm NP}\left[1 + \frac{1}{K(i)_{\rm NLO}^{\rm SM}}(\kappa_3 - 1)C_1\right]$$

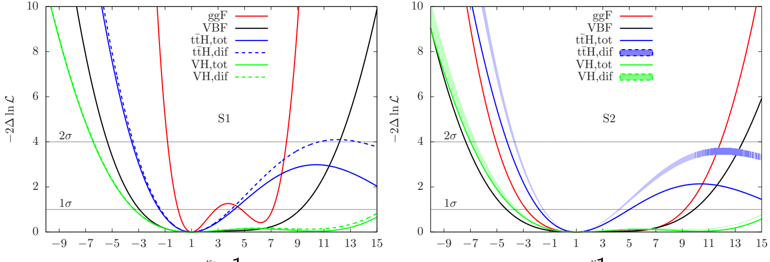
$$\mu_f = \frac{{\rm BR}^{\rm BSM}(f)}{{\rm BR}^{\rm SM}(f)} \approx \frac{k_f^2 + (\kappa_3 - 1)C_1^f}{\sum_j {\rm BR}^{\rm SM}(j)[k_j^2 + (\kappa_3 - 1)C_1^j]}$$

Parameters: $\kappa_3, \kappa_t, \kappa_V$

- Future prospects: ATLAS-HL with 3000 fb^{-1}
(ATL-PHYS-PUB-2013-014,-2014-012)
Two scenarios: S1: stat. and S2: stat. + sys. + th.

Global analysis(1P): constraints on κ_3 ($\kappa_t = \kappa_V = 1$)

ATLAS-HL: S1 (stat.), S2 (stat. + sys. + th.) *Different production channels*

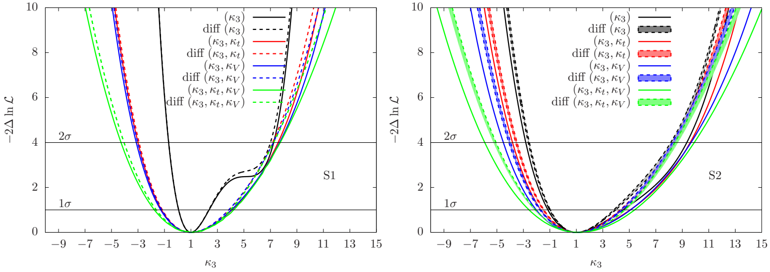


$$\mu_i = Z_H^{\mathrm{BSM}}\left[1 + \frac{1}{K_{\mathrm{NLO}}^{\mathrm{SM}}}(\kappa_3 - 1)C_1\right];\ Z_H^{\mathrm{BSM}} = \frac{1}{1-(\kappa_3^2-1)\delta Z_H}$$

- In S1 the fit is dominated by the ggF-like channel. In S2 the $t\bar{t}H$-like channel provides best constraints for $\kappa_3 < 1$.
- Improvements in bounds due to the use of differential information in $t\bar{t}H$ are more visible in S2.
- Differential information in ggF (*not yet available*) would be useful.

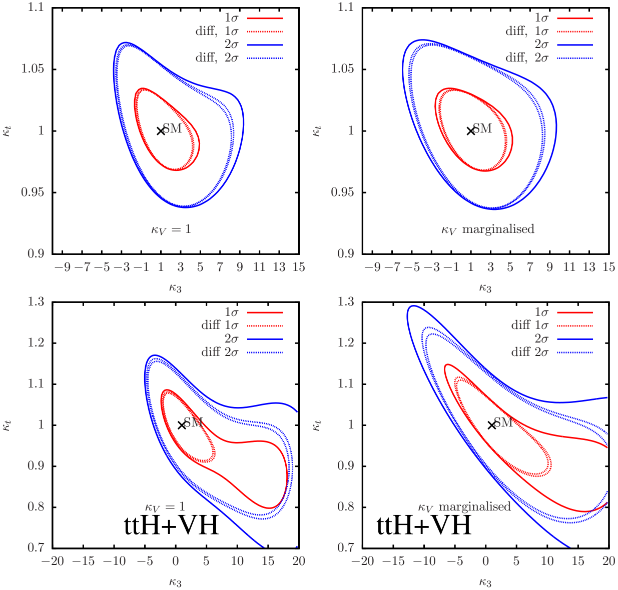
Global analysis(1P): constraints on κ_3 in presence of κ_t, κ_V

ATLAS-HL: S1 (stat.), S2 (stat. + sys. + th.) *All production channels*

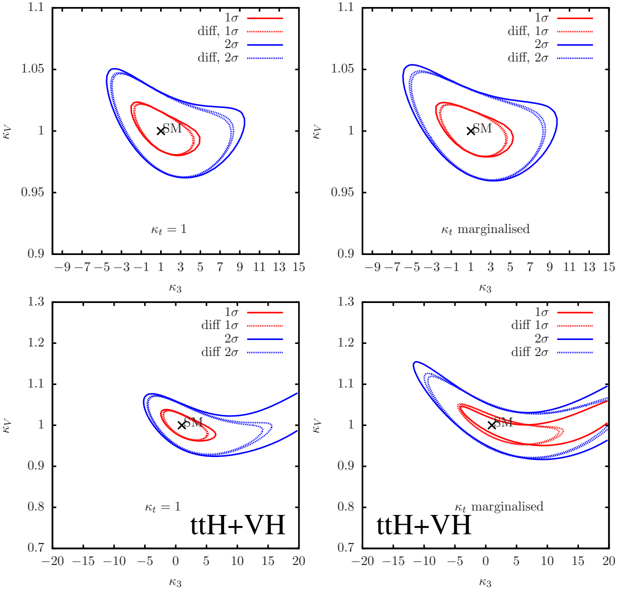


- Inclusion of more parameters to the fit relaxes the constraints especially in the region $\kappa_3 < 1$.
- Due to κ_t dependence of the gluon fusion channel, the constraints in presence of κ_t are stronger than those in presence of κ_V .
- Differential information from VH and ttH do improve the bounds in S2.

Global analysis(2P): constraints on κ_3 and κ_t



Global analysis(2P): constraints on κ_3 and κ_V



Summary and outlook

- Among all the couplings of the Higgs boson, the Higgs self-couplings are poorly known.
- Alternative approaches are being actively sought-for to constrain them using precisely measured observables at the LHC.
- We have studied the role of differential distributions in the determination of trilinear via single-Higgs production and decays measurements.
- Our study illustrates the complementarity of precision measurements in single Higgs with double Higgs production and motivates a more detailed experimental analyses at the HL & HE-LHC.
- Efforts are needed to improve the reach by including relevant higher order corrections in single and double Higgs production processes.

Thank You.

—— Extra Slides ——

Contribution from Higher dim. operators: an example

- Dim-6:

$$V^6(\Phi) = V^{\rm SM}(\Phi) + \frac{c_6}{v^2}(\Phi^\dagger\Phi)^3 \quad (1)$$

$$\Rightarrow \kappa_3 = 1 + 2c_6\frac{v^2}{m_H^2},\ \kappa_4 = 1 + 12c_6\frac{v^2}{m_H^2} \quad (2)$$

The trilinear and the quartic Higgs self-couplings are still correlated ($\kappa_4 = 6\kappa_3$).

- Dim-8:

$$V^8(\Phi) = V^{\rm SM}(\Phi) + \frac{c_6}{v^2}(\Phi^\dagger\Phi)^3 + \frac{c_8}{v^4}(\Phi^\dagger\Phi)^4 \quad (3)$$

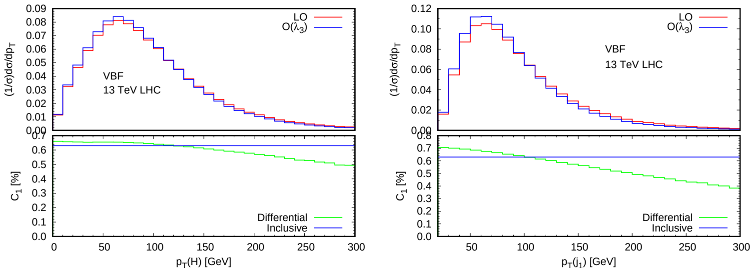
$$\Rightarrow \kappa_3 = 1 + (2c_6 + 4c_8)\frac{v^2}{m_H^2},\ \kappa_4 = 1 + (12c_6 + 32c_8)\frac{v^2}{m_H^2} \quad (4)$$

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

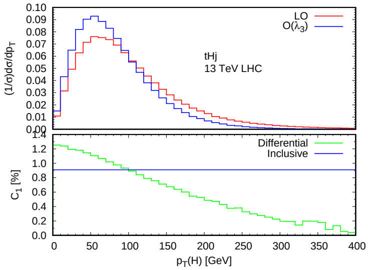
C_1 for distributions: VBF

- C_1 itself as well as the differential effects are rather small due to the fact that in VBF the vector bosons are off shell and there is no enhancement at the threshold.

$$p_T^j > 20 \text{ GeV}, \; |y_j| < 5, \; |y_{j_i} - y_{j_2}| > 3, \; M_{jj} > 130 \text{ GeV}. \qquad (5)$$

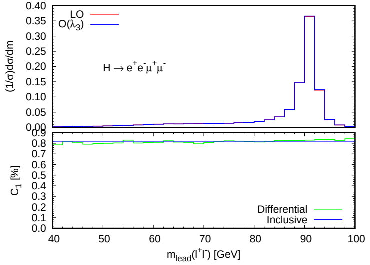


C_1 for distributions: tHj(calculated first time)

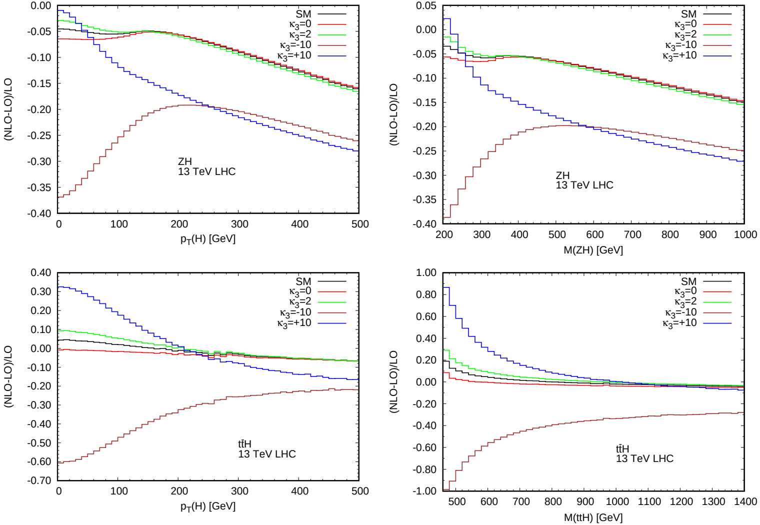


C_1 for distributions: $H \to 4\ell$

- The Higgs decay into four charged leptons is the only Higgs decay channel with nontrivial final state kinematics.
- C_1 has almost no kinematic dependence for any of the relevant observables.



NLO EW corrections in presence of κ_3



Differential C_1: 27 TeV Results

$p_T(H)$[GeV]	0-25	25-50	50-100	100-200	200-500	500+
VBF	0.653	0.649	0.646	0.616	0.517	0.294
ZH	2.00	1.74	1.21	0.503	0	-0.104
WH	1.70	1.49	1.04	0.437	0.006	-0.085
$t\bar{t}H$	5.00	4.78	4.14	2.86	1.23	0.224
tHj	1.06	1.03	0.911	0.686	0.328	0.017

Table: differential C_1(%) for single Higgs production processes at 27 TeV in different $p_T(H)$ bins.