Status of theory Computations

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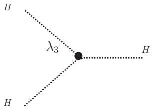
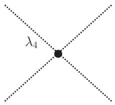
SM Higgs potential & New Physics

Higgs potential & EWSB in the SM,

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

$$\text{EWSB} \Rightarrow V(H) = \frac{1}{2}m_H^2 H^2 + \lambda_3 v H^3 + \frac{1}{4}\lambda_4 H^4.$$





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.

New Physics Parametrization

Model independent parametrization of new physics such that Higgs mass (m_H) and vev (v) remain unchanged,

$$\lambda_3 = \kappa_3 \lambda_3^{\rm SM},\ \lambda_4 = \kappa_4 \lambda_4^{\rm SM}.$$

In an EFT these deviations can be captured by higher dim operators.

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

$$\Rightarrow \kappa_3 = 1 + (2C_6 + 4C_8)\frac{v^2}{m_H^2},\ \kappa_4 = 1 + (12C_6 + 32C_8)\frac{v^2}{m_H^2}$$

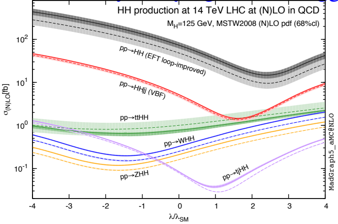
@ dim-6 : there is a one-to-one correspondence between κ_3 and C_6

The dim-6 operator $\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi)$ also affects λ_3 and other Higgs couplings.

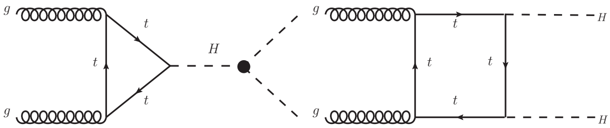
Disclaimer : κ_t is equivalent to EFT in single Higgs but not in double Higgs.

Direct determination of λ_3

Information on λ_3 can be extracted by studying double Higgs production processes.



[Frederix et al. 1408.6542]



Numerous pheno studies :

Baur et al. '03. Baglio et al.; Papaefstathiou et al. '12. Barger et al.; Yao '13. de Lima et al.; Englert et al.; Liu and Zhang; Wardrope et al. '14. Azatov et al.; Behr et al.; Cao et al.; Dolan et al.; Lu et al. '15.

Very challenging due to small cross section of HH processes.

Need to wait for high-lumi run of the LHC ?

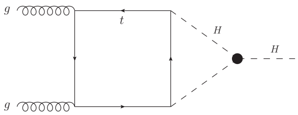
Indirect determination of λ_3

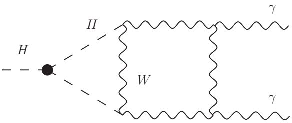
A complementary strategy of probing λ_3 in single Higgs processes via quantum effects (NLO EW)

Proposed for the first time by *McCullough* *1312.3322* in ZH production at e^+e^- collider.

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

λ_3 in single Higgs : Calculation

Degrassi, Giardino, Maltoni, Pagani '16; Maltoni, Pagani, AS, Zhao '17

Master formula: *Anomalous trilinear coupling* ($\kappa_3 = \lambda_3/\lambda_3^{\rm SM}$)

$$\Sigma_{\rm NLO}^{\rm BSM} = Z_H^{\rm BSM}[\Sigma_{\rm LO}(1 + \kappa_3 C_1 + \delta Z_H + \delta_{\rm EW}|_{\lambda_3=0})]$$

$$\delta_{\rm EW}|_{\lambda_3=0} = K_{\rm EW} - 1 - C_1 - \delta Z_H$$

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

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

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. For event-by-event calculation of C_1

$$C_1(\{p_i\}) \equiv \frac{2\mathcal{R}(\mathcal{M}^{0*}\mathcal{M}^1_{\lambda_3^{\rm SM}})}{|\mathcal{M}^0|^2}$$

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

$\delta_{\rm EW}|_{\lambda_3=0}$ includes contribution from virtual W, Z and γ as well as real emissions.

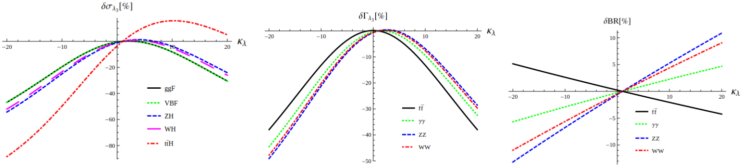
C_1 for cross section and decay

Degrassi, Giardino, Maltoni, Pagani '16; Maltoni, Pagani, AS, Zhao '17

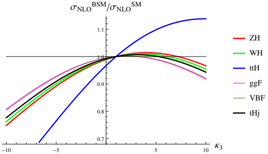
Channels	ggF	VBF	ZH	WH	$t\bar{t}H$	tHj	$H \to 4\ell$
$C_1(\%)$	0.66	0.63	1.19	1.03	3.52	0.91	0.82

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

$$\delta\Sigma_{\kappa_3} = \frac{\Sigma_{\lambda_3}^{\rm BSM} - \Sigma_{\lambda_3}^{\rm SM}}{\Sigma_{\rm LO}} = (Z_H^{\rm BSM} - 1)(1 + \delta Z_H) + (Z_H^{\rm BSM}\kappa_3 - 1)C_1,$$



The impact of full NLO EW corrections : more important for production channels



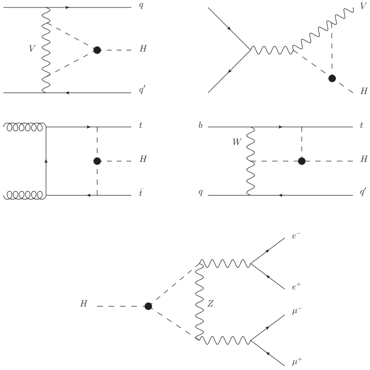
Channels	ggF	VBF	ZH	WH	ttH	tHj
$K_{\rm EW}$	1.049	0.932	0.947	0.93	1.014	0.95

The full EW effect at inclusive level in signal strength is neglegible.

Calculation of Differential C_1

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

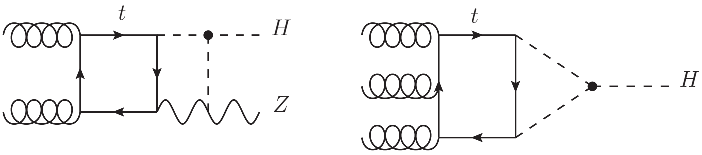


Relevant for processes with non-trivial final state kinematics
Production: VBF, VH, ttH and tHj; Decay: $H \to 4\ell$

Calculation of Differential C_1

Although C_1 for ggF is small at inclusive level, the process gives dominant contribution to single H production.

Differential C_1 not available for ggF channel. For that one needs to compute λ_3 induced effect in gg $\rightarrow$ H + j, H + Z processes. Very challenging calculations.

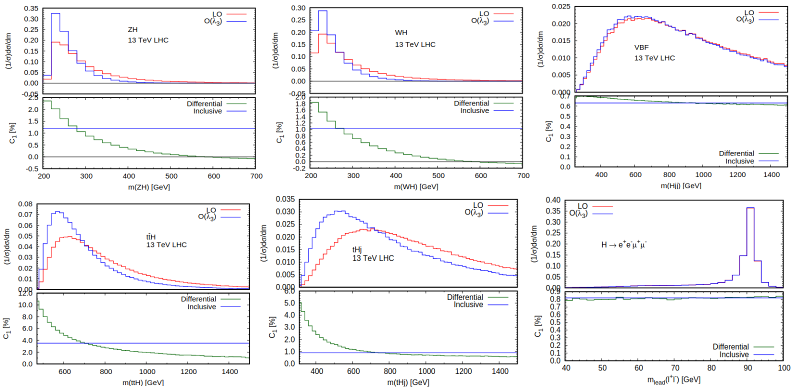


Calculation of relevant two-loop H + j amplitude available in heavy top quark limit (valid for $p_T(H) << m_t$); *Gorbahn, Haisch 1902.05480*

Like for $gg \rightarrow H$, C_1 may not be large for $gg \rightarrow H + j$ and kinematic dependence is expected to be small.

Inclusive vs Differential

C_1 peaks in the threshold region due to Sommerfeld enhancement in VH, ttH and tHj. The kinematic dependence of C_1 is most significant in ttH. C_1 is small and flat for VBF and Hto4ℓ.



Since VBF events include VH configurations, they can be combined to have an effective C_1

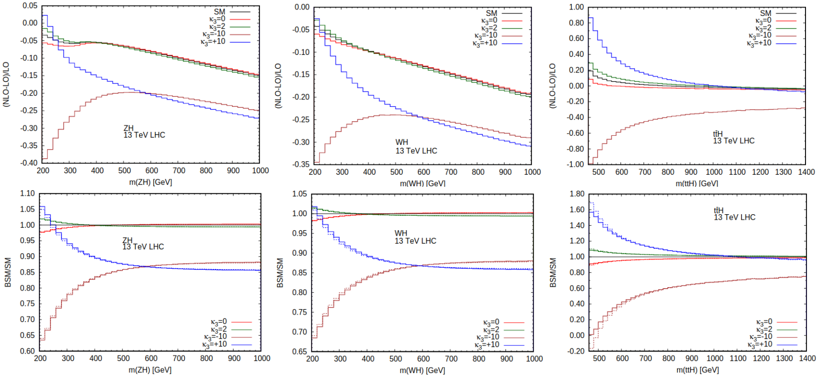
Running scale over fixed scale should be preferred if bin size is not small.

Impact of NLO EW corrections

NLO EW corrections (except for ggF) can be computed using `MadGraph5_aMC@NLO`

In the SM, the EW corrections are large in the boosted regime.

$K_{\mathrm{EW}} - 1$ vs Signal Strength (with & without full NLO EW)



Shape in the threshold region is affected by C_1, Z_H^{BSM} responsible for overall shift.

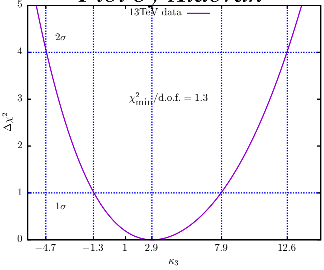
Like in the inclusive case, the EW effects do not alter the signal strength significantly for small values of κ_3.

The global fit based on signal strength will not be affected by the NLO EW corrections.

Extra Slides

Current and future reach at the LHC

Plot by Xiaoran



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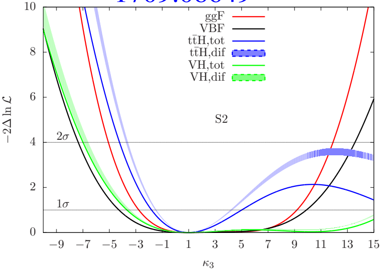

13 TeV:

$$-4.7 < \kappa_3 < 12.6$$

HL-LHC:

$$-2 \lesssim \kappa_3 \lesssim 8$$