Probing Higgs self-couplings at Future Colliders

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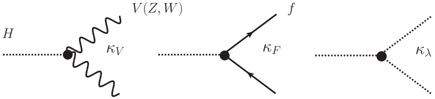
Higgs couplings in the SM

The SM Higgs sector is governed by the following Lagrangian,

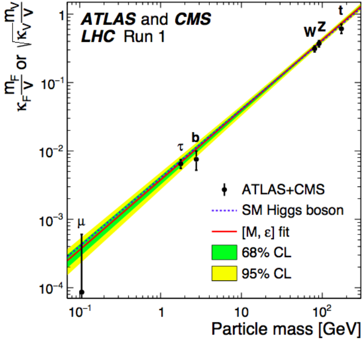
$$\mathcal{L}_{\rm Higgs} = |D_\mu \Phi|^2 - \sum_f y_f \bar{L}_f \Phi R_f - V(\Phi)$$



- 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 ?*

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

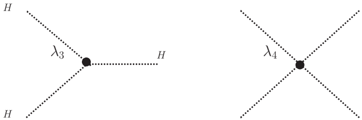
κ_λ : practically unconstrained!



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 $v = (\sqrt{2}G_\mu)^{-1/2}$,

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

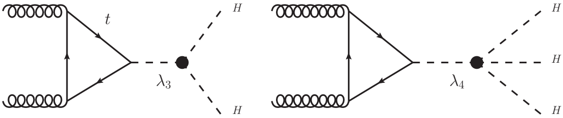
$$m_H = 125 \text{ GeV and } v \sim 246 \text{ GeV}, \Rightarrow \boxed{\lambda \simeq 0.13}.$$

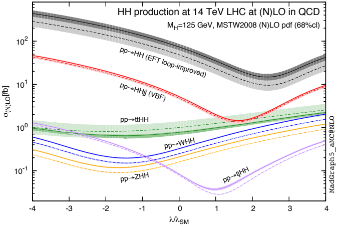
Presence of new physics at higher energy scales can contribute to the Higgs potential and modify the Higgs self-couplings.

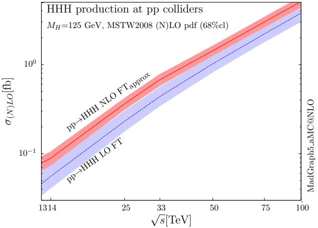
Independent measurements of λ_3 and λ_4 are crucial.

Direct determination of Higgs self-couplings

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







[Frederix et al. '14, 1408.6542]

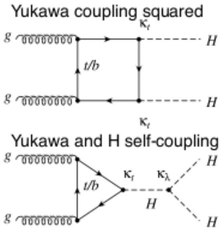
Very challenging due to small cross sections: ∼33 fb (HH), ∼ 0.1 fb (HHH)

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

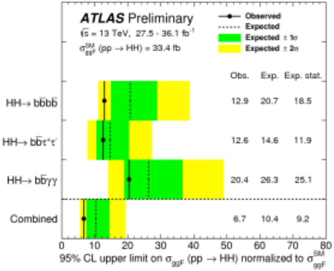
Current experimental sensitivity

Di-Higgs production

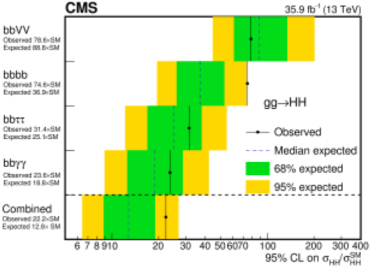
- ATLAS: μ<6.7 (exp 10.4) @95% CL
- CMS: μ<22 (exp 13) @95% C.L.
- Limits at 95% CL on self-coupling scale factor κ_λ:
  - ATLAS: $-5.0<\kappa_\lambda<12.1$
  - CMS: $-11.8<\kappa_\lambda<18.8$



ATLAS-CONF-2018-043



CMS-PAS-HIG-17-030



26 November 2018 Stefano Rosati - Higgs Couplings 2018 24

Future Projections

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

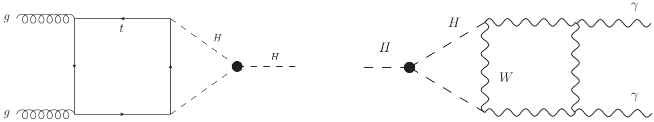
$$\kappa_3 < -0.8 \text{ and } \kappa_3 >\sim 7.7$$

Bounds are sensitive to κ_t value.

Are there alternative methods of probing λ_3 and λ_4?

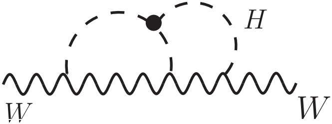
Indirect determination of λ_3

- $\lambda-$dependent corrections to single Higgs processes



> 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

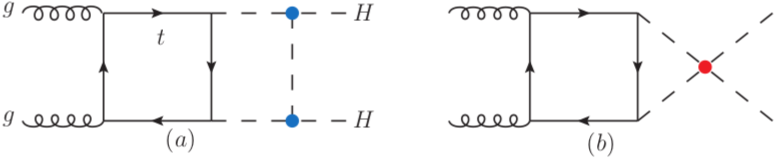
- $\lambda-$dependent corrections in electroweak precision observables



> Degrassi, Fedele, Giardino: 1702.01737
> Kribs, Maier, Rzehak, Spannowsky, Waite: 1702.07678

Indirect determination of λ_4

[1810.04665,1811.12366]



NP parametrization

$$V^{\rm NP}(\Phi) \equiv \sum_{n=3}^{\infty} \frac{c_{2n}}{\Lambda^{2n-4}} \left(\Phi^\dagger \Phi - \frac{1}{2} v^2\right)^n .$$

$$V(H) = \frac{1}{2} m_H^2 H^2 + \lambda_3 v H^3 + \frac{1}{4} \lambda_4 H^4 + \lambda_5 \frac{H^5}{v} + O(H^6),$$

$$\kappa_3 \equiv \frac{\lambda_3}{\lambda_3^{\rm SM}} = 1 + \frac{c_6 v^2}{\lambda \Lambda^2} \equiv 1 + \bar{c}_6,$$

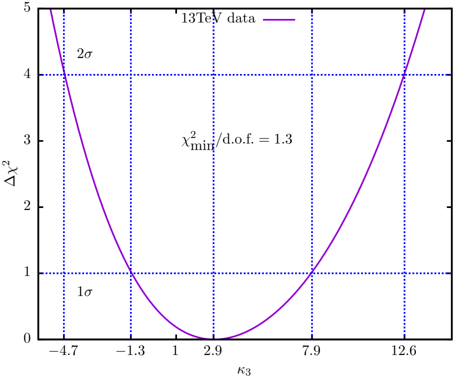
$$\kappa_4 \equiv \frac{\lambda_4}{\lambda_4^{\rm SM}} = 1 + \frac{6 c_6 v^2}{\lambda \Lambda^2} + \frac{4 c_8 v^4}{\lambda \Lambda^4} \equiv 1 + 6\bar{c}_6 + \bar{c}_8 .$$

Single Higgs

Current reach at the LHC

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) $\Rightarrow$

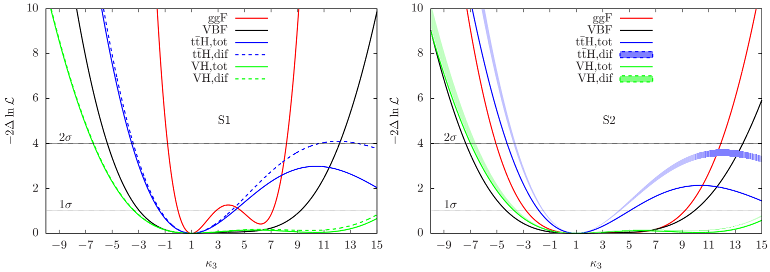
$$-9.4 < \kappa_3 < 17$$



(*Plot by Xiaoran*)

Future projections (1P): constraints on κ_3 ($\kappa_t = \kappa_V = 1$)

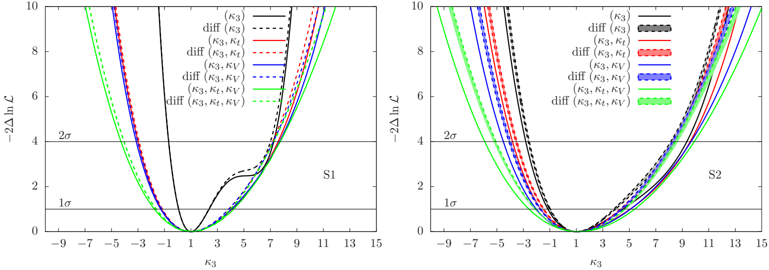
ATLAS-HL: S1 (stat.), S2 (stat. + sys. + th.) *Different production channels*



- In S1 the fit is dominated by the *gg*F-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.

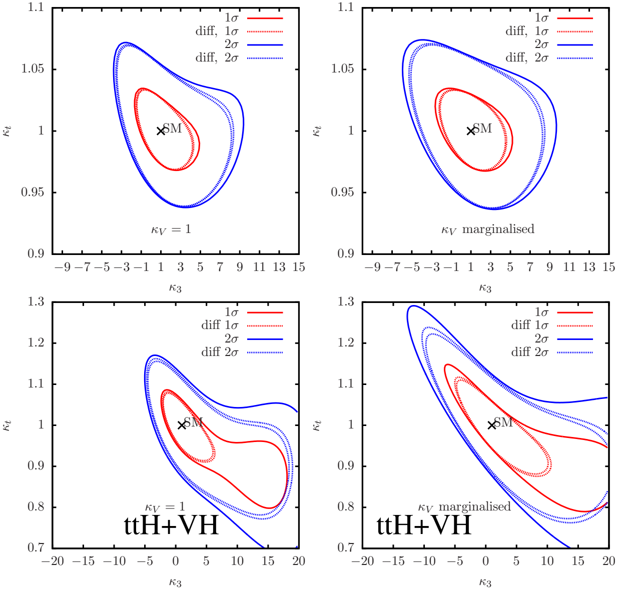
Future projections(1P): constraints on κ_3 in presence of $\kappa_t,\ \kappa_V$

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

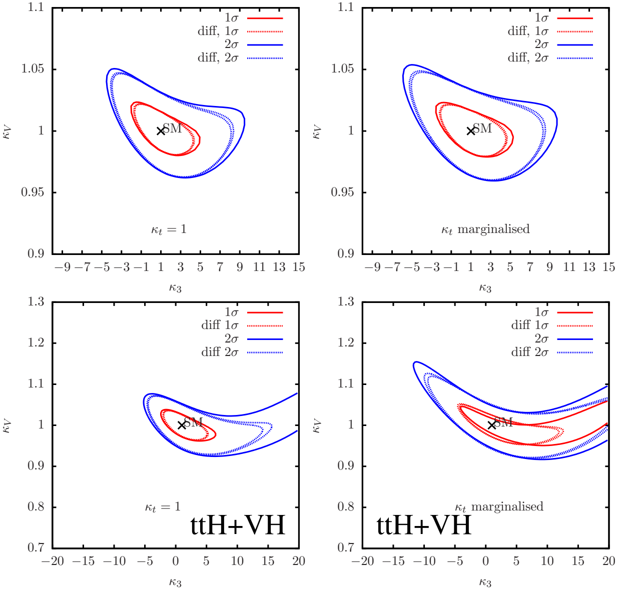


- Inclusion of more parameters to the fit relaxes the constraints especially in the region $\kappa_3 < 1$.
- Due to κ_t dependence of the gluon fusion channel, the constraints in presence of κ_t are stronger than those in presence of κ_V .
- Differential information from VH and ttH do improve the bounds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

Future projections (2P): constraints on κ_3 and κ_t in S2

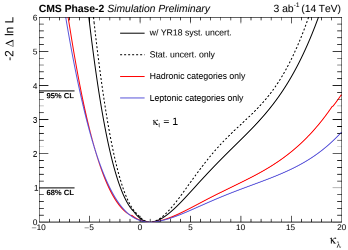


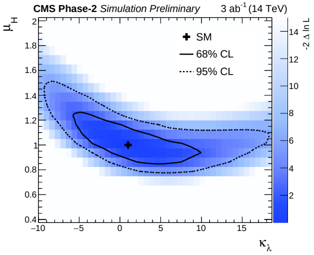
Future projections (2P): constraints on κ_3 and κ_V in S2



CMS Projections: HL-LHC

tH + ttH



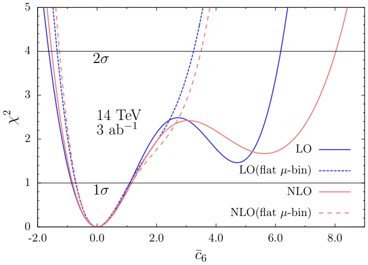


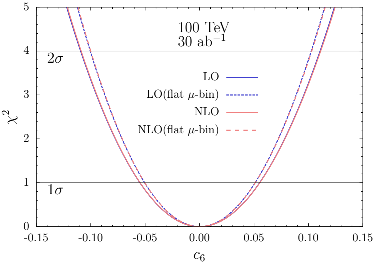
[CMS-PAS-FTR-18-020]

Double Higgs

Constraints at HL-LHC and at 100 TeV: 1P

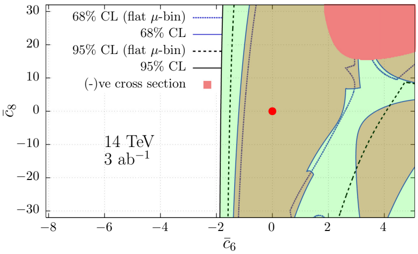
$$
\begin{aligned}
\sigma_{\rm NLO}^{\rm pheno} &= \sigma_{\rm LO} + \Delta\sigma_{\bar{c}_6} + \Delta\sigma_{\bar{c}_8}\ , \\
\sigma_{\rm LO} &= \sigma_0 + \sigma_1\,\bar{c}_6 + \sigma_2\,\bar{c}_6^2\,, \\
\Delta\sigma_{\bar{c}_6} &= \bar{c}_6^2\left[\sigma_{30}\,\bar{c}_6 + \sigma_{40}\,\bar{c}_6^2\right] + \tilde{\sigma}_{20}\,\bar{c}_6^2\,, \\
\Delta\sigma_{\bar{c}_8} &= \bar{c}_8\left[\sigma_{01} + \sigma_{11}\,\bar{c}_6 + \sigma_{21}\,\bar{c}_6^2\right],
\end{aligned}
$$

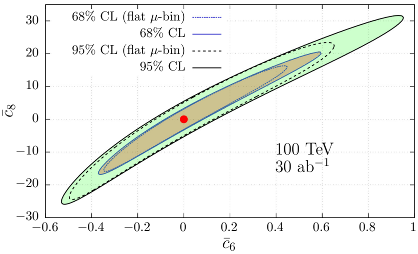




[1811.12366] (See also [1810.04665])

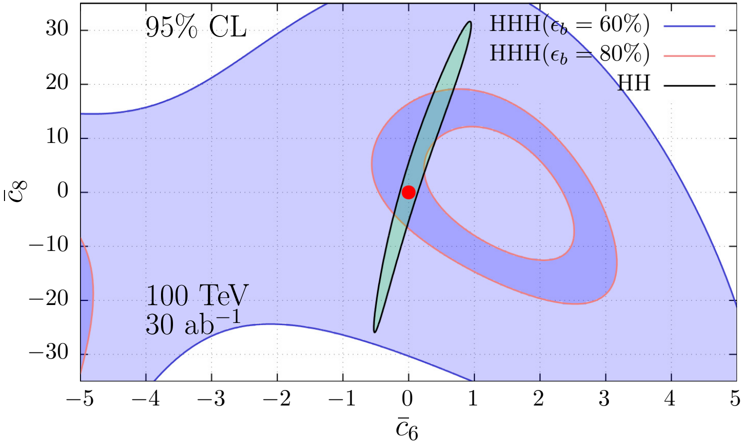
Constraints at HL-LHC and at 100 TeV: 2P





[1811.12366]

Constraints at 100 TeV: *HH* vs *HHH*



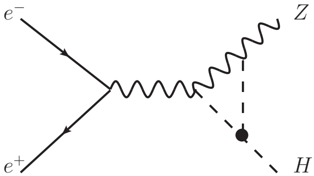
[1811.12366]

Prospects at e^+e^- colliders

Indirect determination of λ_3

We can be sensitive to λ_3 in higher order EW corrections in observables of interest: McCullough: 1312.3322.

$$e^+e^- \to Z + H$$



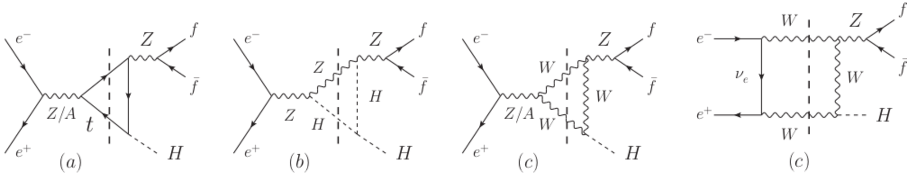
For $\sqrt{s} = 240$ GeV and $\mathcal{L} = 10$ ab^{-1}, $\kappa_3 \sim 28\%$.
(See also [1711.03978,1802.07616,1805.03417])

Direct determination of λ_3

$$e^+e^- \to Z(\to \ell^+\ell^-) + H$$

$$\frac{d^3\sigma}{d\cos\Theta\, d\cos\theta\, d\phi} \to \underbrace{F_1(1+\cos^2\theta) + F_2(1-3\cos^2\theta) + F_3\sin 2\theta\cos\phi + F_4\sin^2\theta\cos 2\phi}_{\text{T-even}}$$

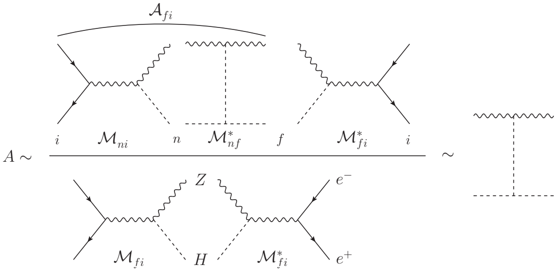
$$+ \underbrace{F_5\cos\theta + F_6\sin\theta\cos\phi}_{\text{T-even}} \underbrace{- F_7\sin\theta\sin\phi - F_8\sin 2\theta\sin\phi - F_9\sin^2\theta\sin 2\phi}_{\text{T-odd}},$$



[1812.01576]

T-odd Asymmetries

$$A_7 \equiv \frac{\sum_\tau \xi(\tau)\left(\int_0^1 - \int_{-1}^0\right) d\cos\Theta F_7(\tau, \cos\Theta)}{\sum_\tau \xi(\tau) \int_{-1}^1 d\cos\Theta F_1(\tau, \cos\Theta)},$$

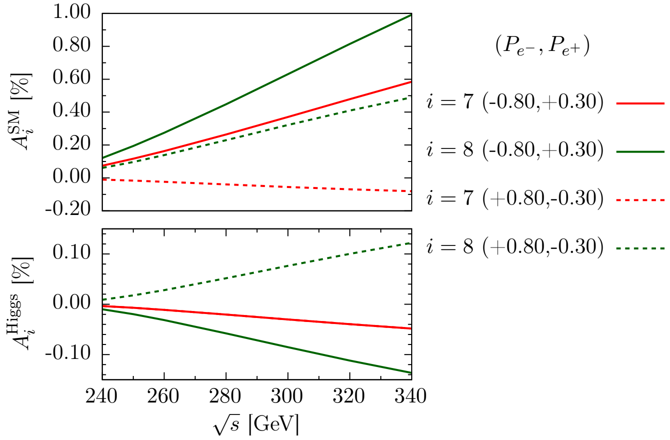


$$\lambda_3 = \lambda_3^{\mathrm{SM}}(1 + \delta_h)$$

[1812.01576]

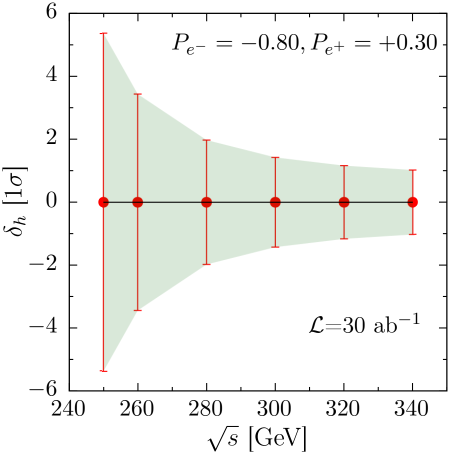
SM and BSM asymmetries

$$A_i^{\mathrm{SM}} = A_i^{\mathrm{Higgs}} + A_i^{\mathrm{Gauge}};\ A_i^{\mathrm{BSM}} = \delta_h \times A_i^{\mathrm{Higgs}} + A_i^{\mathrm{SM}}$$



[1812.01576]

Direct constraint on trilinear from the T-odd asymmetries



[1812.01576]

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 and future colliders.
- A number of studies have shown the complementarity between direct and indirect approaches to probe Higgs self-couplings.
- Efforts are needed to improve the reach by including all the relevant higher order corrections in single and double Higgs production processes.

Thank You.