Probing the Higgs trilinear self-coupling via single Higgs production and precision physics

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M. Fedele, P.P. Giardino, G.D JHEP 1704 (2017) 155
Outline

• Status of the Higgs sector of the SM

• Getting information on the trilinear Higgs self-coupling looking at loop effects in:
  i) single Higgs production and decay processes
  ii) Precision Observables

• Perspective for the future

• Conclusions
Present view: the Standard Model

Strong, electromagnetic and weak interactions (not gravity) are described with very good accuracy by a remarkably simple renormalizable theory:

\[
\mathcal{L}_{SM} = -\frac{1}{4} F^{a\mu\nu} F_{a\mu\nu} + i \bar{\psi} D^\nu \psi + (\lambda_{ij} \bar{\psi}_i \psi_j \phi + h.c) + |D^\mu \phi|^2 - V(\phi) + \bar{N}_i N \lambda_{ij} M_{ij} N_j
\]

- Gauge: Experimentally tested with high accuracy (room for NP?)
- Flavor: exp. tested with accuracy (room for NP?)
- EWSB: we just started (room for NP)

Symmetry principle
Gauge + flavor symmetry

\[SU(3)_c \times SU(2)_W \times U(1)_Y\]
local symmetry

- Principle of minimality

\[\nu\text{-mass (Majorana)}\]
**Gauge sector well tested (W and Z physics)**

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \alpha_{\text{had}}^{(5)}(m_Z)$</td>
<td>$0.02750 \pm 0.00033$</td>
</tr>
<tr>
<td>$m_Z$ [GeV]</td>
<td>$91.1875 \pm 0.0021$</td>
</tr>
<tr>
<td>$\Gamma_Z$ [GeV]</td>
<td>$2.4952 \pm 0.0023$</td>
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<tr>
<td>$\sigma_{\text{had}}^{0}$ [nb]</td>
<td>$41.540 \pm 0.037$</td>
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<tr>
<td>$R_t$</td>
<td>$20.767 \pm 0.025$</td>
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<tr>
<td>$A_{\text{fb}}^{0,l}$</td>
<td>$0.01714 \pm 0.00095$</td>
</tr>
<tr>
<td>$A_t(P_T)$</td>
<td>$0.1465 \pm 0.0032$</td>
</tr>
<tr>
<td>$R_b$</td>
<td>$0.21629 \pm 0.00066$</td>
</tr>
<tr>
<td>$R_c$</td>
<td>$0.1721 \pm 0.0030$</td>
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<tr>
<td>$A_{\text{fb}}^{0,b}$</td>
<td>$0.0992 \pm 0.0016$</td>
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<tr>
<td>$A_{\text{fb}}^{0,c}$</td>
<td>$0.0707 \pm 0.0035$</td>
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<tr>
<td>$A_{b}$</td>
<td>$0.923 \pm 0.020$</td>
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<tr>
<td>$A_{c}$</td>
<td>$0.670 \pm 0.027$</td>
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<td>$A_t(SLD)$</td>
<td>$0.1513 \pm 0.0021$</td>
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<tr>
<td>$\sin^2 \theta_{\text{eff}}^{\text{lept}}(Q_{\text{fb}})$</td>
<td>$0.2324 \pm 0.0012$</td>
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<tr>
<td>$m_W$ [GeV]</td>
<td>$80.385 \pm 0.015$</td>
</tr>
<tr>
<td>$\Gamma_W$ [GeV]</td>
<td>$2.085 \pm 0.042$</td>
</tr>
<tr>
<td>$m_t$ [GeV]</td>
<td>$173.20 \pm 0.90$</td>
</tr>
</tbody>
</table>

March 2012

**Precision ~ 5-1 \cdot 10^{-3}**

$M_W = 80.385 \pm 0.015$ GeV (w.a.)

$M_W = 80.370 \pm 0.019$ GeV (ATLAS, 16)

$M_W = 80.357 \pm 0.010$ GeV (SM)
Higgs sector, what we know

EWSB is achieved in the SM via the Higgs mechanism realized in the most economical and simple way, i.e. with the introduction of a single elementary SU(2)_L scalar doublet with a $\Phi^4$ potential

$$\mathcal{L}_{Higgs} = (\lambda_{ij} \bar{\psi}_i \psi_j \phi + h.c) + |D^\mu \phi|^2 - V(\phi)$$

EWSB: $m_f, h\bar{f}f$  $m_{w,z}, HVV, HHVV$  $m_H, HHH, HHHH,...$

The ground state of the potential known since long time

$$G_\mu = \frac{1}{2v^2} \quad v = \langle \phi^\dagger \phi \rangle^{1/2} \sim 246 \text{ GeV}$$

$$V^{SM}(\phi) = -m^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$
Testing $\mathcal{L}_{\text{Higgs}} : m_H$

4th July 2012
Testing $\mathcal{L}_{Higgs} : (\lambda_{ij} \bar{\psi}_i \psi_j \phi + h.c) + |D^{\mu} \phi|^2$

HVV (Hff) couplings

\[
\mu_i = \frac{\sigma_i}{(\sigma_i)_{SM}} \quad \mu_f = \frac{B_f}{(B_f)_{SM}} \quad \mu_f = \mu_i \times \mu_f
\]
HVV, Hff couplings perspectives

Run I

HL-LHC: 14 TeV 3/ab int. luminosity

<table>
<thead>
<tr>
<th>Process</th>
<th>Combination</th>
<th>Theory</th>
<th>Experimental</th>
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<tbody>
<tr>
<td>$ggF$</td>
<td>0.07</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>VBF</td>
<td>0.22</td>
<td>0.16</td>
<td>0.15</td>
</tr>
<tr>
<td>$H \to \gamma\gamma$</td>
<td>$t\bar{t}H$</td>
<td>0.17</td>
<td>0.12</td>
</tr>
<tr>
<td>$WH$</td>
<td>0.19</td>
<td>0.08</td>
<td>0.17</td>
</tr>
<tr>
<td>$ZH$</td>
<td>0.28</td>
<td>0.07</td>
<td>0.27</td>
</tr>
<tr>
<td>$\gamma\gamma$</td>
<td>$ggF$</td>
<td>0.06</td>
<td>0.05</td>
</tr>
<tr>
<td>$VBF$</td>
<td>0.17</td>
<td>0.10</td>
<td>0.14</td>
</tr>
<tr>
<td>$H \to ZZ$</td>
<td>$t\bar{t}H$</td>
<td>0.20</td>
<td>0.12</td>
</tr>
<tr>
<td>$WH$</td>
<td>0.16</td>
<td>0.06</td>
<td>0.15</td>
</tr>
<tr>
<td>$ZH$</td>
<td>0.21</td>
<td>0.08</td>
<td>0.20</td>
</tr>
<tr>
<td>$H \to WW$</td>
<td>$ggF$</td>
<td>0.07</td>
<td>0.05</td>
</tr>
<tr>
<td>$VBF$</td>
<td>0.15</td>
<td>0.12</td>
<td>0.09</td>
</tr>
<tr>
<td>$H \to Z\gamma$</td>
<td>incl.</td>
<td>0.30</td>
<td>0.13</td>
</tr>
<tr>
<td>$H \to bb$</td>
<td>$WH$</td>
<td>0.37</td>
<td>0.09</td>
</tr>
<tr>
<td>$ZH$</td>
<td>0.14</td>
<td>0.05</td>
<td>0.13</td>
</tr>
<tr>
<td>$H \to \tau^+\tau^-$</td>
<td>$VBF$</td>
<td>0.19</td>
<td>0.12</td>
</tr>
</tbody>
</table>

Estimated relative uncertainties

Di Vita et al. (17) arXiv 1704.01953
Testing \( \mathcal{L}_{\text{Higgs}} : \quad V(H) = \frac{m_H^2}{2} H^2 + \lambda_3 v H^3 + \frac{\lambda_4}{4} H^4 + \ldots \)

The shape of \( V(H) \): Higgs self couplings

n-Higgs production probes (n+1)-Higgs self-coupling

In the SM at tree-level only \( \lambda_3 \) and \( \lambda_4 \) fixed by:

\[
\lambda_3 = \lambda_4 = \lambda = \frac{m_H^2}{(2v^2)} \quad v = \left( \sqrt{2} G_F \right)^{-1/2}
\]

\( \lambda_3 \): double Higgs production

destructive interference, small cross section

\[
\sigma(pp \rightarrow HH)_{\text{SM}} \sim 35 \text{ fb}
\]

4 particles in the final state

\( \lambda_4 \): triple Higgs production

\[
\sigma(pp \rightarrow HHH)_{\text{SM}} \sim 0.1 \text{ fb}
\]

\( \kappa_{gg} = 1, \kappa_t = 1 \)
\( \lambda_3 \) status: “best” channels \( gg \rightarrow HH \rightarrow bb\gamma\gamma, \; gg \rightarrow HH \rightarrow bb\tau\tau \)

\[
\lambda_3 = \kappa_\lambda \lambda_3^{SM} = \kappa_\lambda \frac{G_\mu}{\sqrt{2}m_H^2}
\]

\[
\kappa_{gg} = 1, \; \kappa_t = 1
\]

\[\sigma(gg \rightarrow HH) \sim 70 \sigma^{SM}(gg \rightarrow HH) \; \kappa_\lambda = [-17.5, 22.5]\]

\( \lambda_3 \) perspective:

HL-LHC, 3000 fb\(^{-1}\), \( \langle \mu \rangle = 200 \)
No systematic

\[
\kappa_\lambda = [-0.8, 7.7]
\]
Present status:

- SM has been extremely successful in describing all low and high-energy results. The Higgs mass value prediction is the last success of an impressive series, $M_W, m_t, m_H$

- We know that physics beyond the SM must exist (neutrino masses, dark matter, barion asymmetry)

- We do not know at which energy scale New Physics should appear and LHC is pushing the scale higher up. Long standing theoretical argument (naturalness) are “suffering”.

- Models addressing the naturalness problems, like supersymmetry, makes predictions for the $\sim 1$ TeV scale, but can survive LHC because they are constructed to enforce the decoupling. “They cannot be ruled out, they can be only be abandoned”.

- Many New Physics models can be constructed and, a part theoretical argument, there is no way to prefer one with respect to another.

Outcome

Use a “model independent” approach to NP in which the SM is the starting point “Standard Model Effective Field Theory Approach” (SM EFT)
SM EFT Approach

**Basic assumption:** Sizable gap between the mass scale of NP ($\Lambda$) and the Energy scale ($E$) presently probed $\Lambda >> E$. Deviations from the SM results are expressed in powers of $E/\Lambda$.

**Framework employed:** Effective Field Theory in which the SM Lagrangian is augmented by higher dimensional operators, constructed used only SM fields, that respect the $SU(3)_C \times SU(2)_L \times U(1)_Y$ symmetry

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \frac{1}{\Lambda} \mathcal{L}^{D=5} + \frac{1}{\Lambda^2} \mathcal{L}^{D=6} + \frac{1}{\Lambda^3} \mathcal{L}^{D=7} + \frac{1}{\Lambda^4} \mathcal{L}^{D=8}$$

Lepton number or B-L violating

Very constrained

Starting point is generally OK, but for $V(H)$

$$\mathcal{L}_{EFT} = \cdots - m^2 \left( \frac{H + v}{\sqrt{2}} \right)^2 + \lambda \left( \frac{H + v}{\sqrt{2}} \right)^4 + \frac{c_6}{\Lambda^2} \left( \frac{H + v}{\sqrt{2}} \right)^6 + \cdots$$

$$\kappa \lambda = 1 + c_6 \frac{2v^2}{m_H^2} \frac{v^2}{\Lambda^2} \sim \mathcal{O}(\pm 5)$$

We are far from probing this case
Remark: we can envisage a scenario such that at the end of the HL-LHC program the couplings of the Higgs to gauge fields and fermions will be known $O(\leq 10\%)$ while $\lambda_3$ will be known $O(1)$

**QUESTION**

Can we use alternative information with respect to double Higgs production in order to constraint $\lambda_3$ today? (Obviously some assumptions are needed)
Notice: \[
\frac{\sigma(pp \rightarrow H)_{SM}}{\sigma(pp \rightarrow HH)_{SM}} = \frac{50 \, pb}{\sim 35 \, fb} \sim \frac{1}{1400} \sim \mathcal{O}\left(\frac{\alpha}{4\pi}\right)
\]

Idea

Constrain \(\lambda_3\) via loop effects:

Exploit the dependence of single Higgs (total and differential) cross sections and decay rates upon the trilinear Higgs self coupling at NLO EW

See also: M. McCullough (13) \((e^+e^- \rightarrow ZH)\); M. Gorbahn, U. Haisch (16) \((gg \rightarrow H, H \rightarrow \gamma\gamma)\); W. Bizon, M. Gorbahn, U. Haisch, G. Zanderighi (1610.05771), (WH, ZH, VBF)

Use the sensitivity of precision observables to \(\lambda_3\) at NNLO EW

See also: Kribs et al. (1702.07678)
Working assumption: only the Higgs self-couplings are modified or, equivalently, any modification of the Higgs coupling to fermion and bosons is much smaller.

Not the most general assumption, but can be relaxed in the future when information on the other Higgs couplings will become more accurate.

It is the best we can do today.

Related problems:

- How I identify the contribution proportional to $\lambda_3$? What about $\lambda_4$, $\lambda_5$ etc.?

- If I “deform” $\lambda_3^{SM} \rightarrow \lambda_3 = \kappa \lambda \lambda_3^{SM}$ the theory become not renormalizable. I expect a dependence on $\Lambda$, the scale of NP.

- I expect to be able to probe large values of $\kappa \lambda$. My scenario is not a standard EFT. Does it have a limit to an EFT?
Identifying $\lambda_3$ contributions

In the SM in an $R_\xi$ gauge not only the $HHH$ vertex is proportional to $\lambda_3$ but also the vertices with unphysical scalars $H\phi^+\phi^-, H\phi_2\phi_2$.

Identification of the $\lambda_3$ is not straightforward.

Solution: Go to the Unitary gauge
Gauge-dependent result? See later

$\lambda_4, \lambda_5$ ..... 

At the level of (N)NLO EW corrections, i.e.:

1-loop corrections for $\sigma_{VBF}$, $\sigma_{VH}$, $\sigma_{t\bar{t}H}$, $\Gamma_{VV}$, $\Gamma_{f\bar{f}}$

2-loop corrections for: $\sigma_{gg}$, $\Gamma_{gg}$, $\Gamma_{\gamma\gamma}$, $M_W$, $\sin^2\theta_{\text{eff}}$

the Higgs quartic self interaction enters only through the Higgs mass correction diagram

Canceled by the Higgs mass counterterm
No dependence on $\lambda_4$

At the (N)NLO level $\lambda_5, \lambda_6$ .... interactions do not contribute
The unitary gauge is a tricky gauge: one is interchanging

\[ \lim_{\xi \to \infty} \int d^n k \longrightarrow \int d^n k \lim_{\xi \to \infty} \]

Vector boson propagator:

\[ \frac{-i}{k^2 - M_V^2 + i\epsilon} \left[ g^{\mu\nu} + (\xi - 1) \frac{k^\mu k^\nu}{k^2 - \xi M_V^2} \right] \longrightarrow -i \frac{g^{\mu\nu} - k^\mu k^\nu / M_V^2}{k^2 - M_V^2 + i\epsilon} \]

Ghost, unphysical scalar propagator:

\[ \frac{-i}{k^2 - \xi M_V^2 + i\epsilon} \longrightarrow 0 \]

No ghosts, no unphysical in an UG calculation

However, in \( R_\xi \), in principle, there can be residues from the \( \xi \) in the denominators from the propagators and the one in the numerators from vertices of higgses with ghosts

\[ \lim_{\xi \to \infty} \int d^n k \frac{\xi^2}{(k^2 - \xi m_W^2)^2} = \int d^n k \frac{1}{m_W^4} = 0 \]
Although our theory is not renormalizable the result for $\kappa_\lambda$ at the level of (N)NLO EW corrections is finite, i.e. it does not depend on $\Lambda$

Reason: the “Born” results do not depend upon $\lambda_3$. Renormalization of $\lambda_3$ is not needed

What about $\lambda_3$? In UG is not there; you are trading a coupling for a kinematical mass

NLO $\lambda_3$-dependent diagram:

Finite after Higgs mass renormalization
What is my scenario?

My scenario is described by the SM Lagrangian with a modified scalar potential:

\[ V^{NP} = \sum_{n=1}^{N} c_{2n} (\Phi^\dagger \Phi)^n \quad \Phi = \left( \frac{\phi^+}{\sqrt{2}} v + H + i\phi_2 \right) \]

\[ m_H^2 = v^2 \sum_{n=1}^{N} c_{2n} n(n-1) \left( \frac{v^2}{2} \right)^{n-2} \]

\[ V_{4\phi}^{NP} = \frac{m_H^2}{2v^2} \left[ \phi^+ \phi^- (\phi^+ \phi^- + \phi_2^2) + \frac{1}{4} \phi_2^4 \right] + \left( \frac{m_H^2}{2v^2} + d\lambda_4 \right) \frac{1}{4} H^4 \]

\[ + \left( \frac{m_H^2}{2v^2} + 3d\lambda_3 \right) H^2 \left[ \phi^+ \phi^- + \frac{1}{2} \phi_2^2 \right] + \left( \frac{m_H^2}{2v} + v d\lambda_3 \right) H^3 \]

Few couplings modified with respect to the SM and there are correlations

\[ d\lambda_3 = \frac{1}{3} \sum_{n=3}^{N} c_{2n} n(n-1)(n-2) \left( \frac{v^2}{2} \right)^{n-2} \]

\[ d\lambda_4 = \frac{2}{3} \sum_{n=3}^{N} c_{2n} n^2(n-1)(n-2) \left( \frac{v^2}{2} \right)^{n-2} \]

N unspecified. \( C_{2n} \) arbitrary

Limit to EFT:
\( N=3,4.. \quad c_{2n+2} \sim c_{2n}/\Lambda^2 \)
Diagrams that in $R_\xi$ can give additional contributions with respect to the UG result

Insertion of:

\[
\begin{align*}
\phi_1 \quad & \quad \phi_1 \\
\phi_2 & = \phi_1 \quad \phi_1 + \phi_1 \\
\phi_1 & \quad \phi_1 \\
\phi_1 & \quad \phi_1
\end{align*}
\]

\begin{align*}
\phi_1 \quad & \quad \phi_1 \\
\phi_2 & = \phi_2 \quad \phi_2 \\
\phi_1 & \quad \phi_2 \\
\phi_1 & \quad \phi_2
\end{align*}

\begin{align*}
\phi_1 \quad & \quad \phi_1 \\
\phi_1 & \quad \phi_1 \\
\phi_1 & \quad \phi_1
\end{align*}

\begin{align*}
\phi_1 \quad & \quad \phi_1 \\
\phi_1 & \quad \phi_1 \\
\phi_1 & \quad \phi_1
\end{align*}

\begin{align*}
\phi_1 & \quad \phi_1 \\
\phi_1 & \quad \phi_1 \\
\phi_1 & \quad \phi_1
\end{align*}

\begin{align*}
\phi_1 & \quad \phi_1 \\
\phi_1 & \quad \phi_1 \\
\phi_1 & \quad \phi_1
\end{align*}

All these contributions are canceled by the mass renormalization counterterms

\[
\delta m_\phi^2 = \delta m_V^2 + \delta T
\]

Tadpole contribution
What is my scenario?

- I am dealing with “large” couplings, but they cannot be too large otherwise I have problem with perturbativity.

- Although I find a finite result at the (N)NLO level my theory is not renormalizable. \( \Lambda \)-dependent contributions will appear in higher order of perturbation theory.

- To estimate the cutoff scale of this scenario one can look at

\[ V_L V_L \rightarrow V_L V_L H^n \]

\[ \Lambda \lessapprox \frac{4\pi v}{\sqrt{|\kappa_\lambda - 1|}} \sqrt{\frac{32\pi}{15}} \frac{v}{m_H} \rightarrow \Lambda \lessapprox 3 \text{ TeV}, \ |\kappa_\lambda| \lessapprox 20 \]

A. Falkowski, R. Rattazzi in preparation
Single Higgs processes
Master Formula

\[ \Sigma_{NLO} = Z_H \Sigma_{LO} \left( 1 + \kappa \lambda \right) C_1 \]

dressed with QCD

\[ C_1^\Gamma = \frac{\int d\Phi \, 2\Re (M_0^* M_1)}{\int d\Phi \, |M_0|^2} \]

process dependent

\[ C_1^\sigma = \frac{\sum_{i,j} \int dx_1 dx_2 f_i(x_1) f_j(x_2) \, 2\Re (M_{0,ij}^* M_{1,ij}^1) \, d\Phi}{\sum_{i,j} \int dx_1 dx_2 f_i(x_1) f_j(x_2) \, |M_{0,ij}^1|^2 \, d\Phi} \]
Master Formula

\[ \Sigma_{NLO} = Z_H \Sigma_{LO} \left( 1 + \kappa_\lambda C_1 \right) \]

\[ \delta \Sigma \equiv \frac{\Sigma_{NLO} - \Sigma_{NLO}^{SM}}{\Sigma_{LO}} = (\kappa_\lambda^2 - 1) C_2 + (\kappa_\lambda - 1) C_1 \]

\[ Z_H = \frac{1}{1 - \kappa_\lambda^2 \delta Z_H} \]

Resummation requires \(|\kappa_\lambda| \lesssim 25\)

\[ \delta Z_H = -\frac{9}{16} \frac{G_\mu m_H^2}{\sqrt{2} \pi^2} \left( \frac{2\pi}{3\sqrt{3}} - 1 \right) \]
Results: total cross sections

\[ \delta \sigma = (\kappa^2 - 1)C_2 + (\kappa - 1)C_1 \]

\[
C_2 = -9.14 \cdot 10^{-4}, \quad \kappa_\lambda = \pm 20
\]

\[
C_2 = -1.53 \cdot 10^{-3}, \quad \kappa_\lambda = \pm 1
\]

Largest effects in t\bar{t}H and VH

<table>
<thead>
<tr>
<th>$C_1^\sigma$ [%]</th>
<th>ggF</th>
<th>VBF</th>
<th>WH</th>
<th>ZH</th>
<th>t\bar{t}H</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 TeV</td>
<td>0.66</td>
<td>0.65</td>
<td>1.05</td>
<td>1.22</td>
<td>3.78</td>
</tr>
<tr>
<td>13 TeV</td>
<td>0.66</td>
<td>0.64</td>
<td>1.03</td>
<td>1.19</td>
<td>3.51</td>
</tr>
</tbody>
</table>

Only t\bar{t}H receive sizable positive corrections
Results: differential cross sections

Kinematical dependence of the $C_1$ coefficient.

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

Table 1: $C_1^\sigma$ at 13 TeV obtained by imposing the cut $p_T(H) < p_T,_{cut}$, for several values of $p_T,_{cut}$. In parentheses the fraction of events left after the quoted cut is applied.

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

Table 1: $C_1^\sigma$ at 13 TeV obtained by imposing the cut $m_{tot} < K \cdot m_{thr}$, for several values of $K$. In parentheses the fraction of even ts left after the quoted cut is applied.
Results: decay rates

\[ C_1^{\Gamma} [\%] \]
<table>
<thead>
<tr>
<th>on-shell H</th>
<th>$\gamma\gamma$</th>
<th>ZZ</th>
<th>WW</th>
<th>$f\bar{f}$</th>
<th>gg</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.49</td>
<td>0.83</td>
<td>0.73</td>
<td>0</td>
<td>0.66</td>
<td></td>
</tr>
</tbody>
</table>

\[ C_1^{\Gamma_{tot}} \equiv \sum_j \text{BR}^{SM}(j)C_1^{\Gamma}(j) = 2.3 \cdot 10^{-3} \]

\[ \delta\text{BR}_{\lambda_3}(i) = \frac{(\kappa_\lambda - 1)(C_1^{\Gamma}(i) - C_1^{\Gamma_{tot}})}{1 + (\kappa_\lambda - 1)C_1^{\Gamma_{tot}}} \]

Much milder dependence on $\kappa_\lambda$ in the BR because no $C_2$ contribution
Constraints on $\lambda_3$ from 8 TeV data

Using signal strength results from the combination of ATLAS and CMS we can make a one-parameter fit to estimate the limit that can be set on $\kappa_\lambda$

$$\chi^2(\kappa_\lambda) \equiv \sum_{\bar{\mu}_i^f \in \{\bar{\mu}_i^f\}} \frac{(\mu_i^f(\kappa_\lambda) - \bar{\mu}_i^f)^2}{(\Delta_i^f(\kappa_\lambda))^2}$$

$$\mu_i^f(\kappa_\lambda) = \mu_i(\kappa_\lambda) \times \mu^f(\kappa_\lambda)$$
$$\mu_i(\kappa_\lambda) = 1 + \delta \sigma_{\lambda_3}(i)$$
$$\mu^f(\kappa_\lambda) = 1 + \delta \text{BR}_{\lambda_3}(f)$$

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

$p$-value($\kappa_\lambda$) = 1 - $F_{\chi^2(n)}(\chi^2(\kappa_\lambda))$

$p > 0.05 \quad \kappa_\lambda > -14.3$
Precision Observables
\( \lambda_3 \)-dependent contributions in \( m_W \) and \( \sin^2 \theta_{\text{eff}}^{\text{lep}} \)

\( m_W \) and the effective sine are obtained from \( \alpha, G_\mu \) and \( m_z \) via

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

\[
\sin^2 \theta_{\text{eff}}^{\text{lep}} \sim \frac{1}{2} \left\{ 1 - \left[ 1 - \frac{4\hat{A}^2}{m_Z^2 \hat{\rho}} (1 + \Delta \hat{\rho}_W) \right]^{1/2} \right\}
\]

\( \hat{\rho} = \frac{1}{1 - Y_{\overline{MS}}} \)

\( \hat{A} = \frac{\pi \hat{\alpha}(m_Z)/(\sqrt{2}G_\mu)^{1/2}}{1 - \Delta \hat{\alpha}(m_Z)} \)

\( \hat{\alpha}(m_Z) = \frac{\alpha}{1 - \Delta \hat{\alpha}(m_Z)} \)

\( G_\mu = \frac{\pi \hat{\alpha}(m_Z)}{2m_W^2 \hat{s}^2} (1 + \Delta \hat{\rho}_W) \)

\( \hat{s} = \frac{1}{1 - Y_{\overline{MS}}} \)

\( \Delta \hat{\rho}_W^{(2)} = \text{Re} \frac{A_{ww}^{(2)}(m_W^2)}{m_W^2} - \frac{A_{ww}^{(2)}(0)}{m_W^2} + \ldots \)

\( Y_{\overline{MS}}^{(2)} = \text{Re} \left[ \frac{A_{ww}^{(2)}(m_W^2)}{m_W^2} - \frac{A_{zz}^{(2)}(m_Z^2)}{m_Z^2} \right] + \ldots \)

\( \sim k_\lambda \)

\( \sim k_\lambda^2 \)
Constraints on $\lambda_3$ from P.O. and 8 TeV data

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

<table>
<thead>
<tr>
<th></th>
<th>$C_1$</th>
<th>$C_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_W$</td>
<td>$6.27 \times 10^{-6}$</td>
<td>$-1.72 \times 10^{-6}$</td>
</tr>
<tr>
<td>$\sin^2 \theta_{\text{eff}}$</td>
<td>$-1.56 \times 10^{-5}$</td>
<td>$4.55 \times 10^{-6}$</td>
</tr>
</tbody>
</table>

P.O. + ggF + VBF

$\kappa_\lambda^{\text{best}} = 0.5$, $\kappa_\lambda^{1\sigma} = [-4.7, 8.9]$, $\kappa_\lambda^{2\sigma} = [-8.2, 13.7]$  
$p > 0.05$ $\kappa_\lambda > -13.3$, $\kappa_\lambda < 20$

ggF + VBF

$\kappa_\lambda^{\text{best}} = -0.24$, $\kappa_\lambda^{1\sigma} = [-5.6, 11.2]$, $\kappa_\lambda^{2\sigma} = [-9.4, 17.0]$  
$p > 0.05$ $\kappa_\lambda > -14.3$
Perspectives for the future
Exercise: \( \mu_i^f = 1 \rightarrow \kappa_{\chi}^{\text{best}} = 1 \)  central values are SM

Relative uncertainties as estimated in \textit{Peskin arXiv: 1312.4974}

### CMS-II (300 fb\(^{-1}\))

- \( \kappa_{\chi}^{1\sigma} = [-1.8, 7.3] \)
- \( \kappa_{\chi}^{2\sigma} = [-3.5, 9.6] \)
- \( \kappa_{\chi}^{p>0.05} = [-6.7, 13.8] \)

### CMS-HL-II (3000 fb\(^{-1}\))

- \( \kappa_{\chi}^{1\sigma} = [-0.7, 4.2] \)
- \( \kappa_{\chi}^{2\sigma} = [-2.0, 6.8] \)
- \( \kappa_{\chi}^{p>0.05} = [-4.1, 9.8] \)
Conclusions

- The shape of the Higgs potential is presently very poorly known and the bounds on the trilinear self-couplings from double Higgs production do not allow to test weakly coupled models.

- I presented the idea of using the sensitivity to the Higgs trilinear coupling of single Higgs processes and precision observables in order to gather information on the Higgs potential.

- These kind of studies can be competitive and complementary to the direct double Higgs measurements.

- Our studies rely on some assumptions (some of which are in common with the double Higgs analyses) that can be in the future progressively relaxed.