Indirect Probes of the Higgs Trilinear Coupling

Martin Gorbahn
University of Liverpool

HEFT 2017
Lumley Castle
May 22

Content

- Higgs Potential and trilinear Higgs coupling
- Double Higgs production
- Two-loop anomalous dimensions
- Finite matching corrections

Based on:
1610.05771 [Bizoń, MG, Haisch, Zanderighi],
1607.03773 [MG, Haisch]
also:
1607.04251 [Degrassi, Giardino, Maltoni, Pagani]
and Electroweak: 1702.0767 and 1702.01737

Standard Model Higgs Potential

$$\mathcal{L}_H^{(4)} = |D_\mu H|^2 - V(H), \quad \text{where} \quad H = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\,\phi^+ \\ v + h + i\phi^0 \end{pmatrix}$$

and

$$\begin{aligned} V(H) &= -\mu^2 H^\dagger H + \lambda_2 (H^\dagger H)^2 \\ &\to \frac{M_h^2}{2} h^2 + \lambda v\, h^3 + \frac{\lambda}{4} h^4 \end{aligned}$$

In the SM

$$\lambda = \frac{M_h^2}{2v^2} \simeq 0.13$$

The trilinear / cubic and quartic couplings can be modified in beyond the SM physics.

Simple modification of the trilinear coupling

Add a higher dimension operator to modify the trilinear coupling in a gauge invariant way:

$$\mathcal{L}_H = \mathcal{L}_H^{(4)} + \frac{c_6}{v^2} O_6 = \mathcal{L}_H^{(4)} + \frac{c_6}{v^2} \left\{ -\lambda (H^\dagger H)^3 \right\}$$

then we have

$$V(h) = \frac{M_h^2}{2} h^2 + (1 + c_6) \lambda v h^3 + (1 + 6c_6) \frac{\kappa}{4} h^4$$

Still: $\lambda = \frac{M_h^2}{2v^2}$, *but* $\lambda_2 = (1 - \frac{3}{2} c_6) \lambda$ *and* $\mu^2 = (1 - \frac{3}{4} c_6) M_h^2$

Other operators that affect the h^3 coupling

- At $d = 6$ the only other operator that can modify the trilinear coupling is

$$O_H = \frac{1}{2}\,\partial_\mu\left(H^\dagger H\right)\partial^\mu\left(H^\dagger H\right).$$

$$(1+c_6)\lambda v\,h^3 \to (1+c_6+\frac{3}{2}c_H)\lambda v\,h^3\,.$$

But c_H rescales all other Higgs processes and is more tightly constrained.

- At $d = 8$ we would have for $O_8 = -\lambda(H^\dagger H)^4$:

$$(1+c_6+2c_8+\frac{3}{2}c_H)\lambda v\,h^3$$

Single vs Double Higgs production at LHC

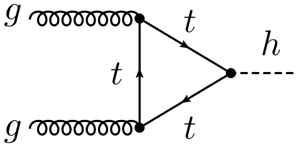
The single Higgs production is a factor 1300 larger

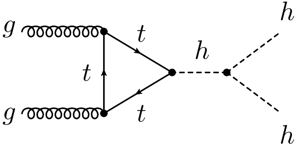
$$\sigma(pp \to h)_{SM} = \mathcal{O}(45pb)$$

than the double Higgs production

$$\sigma(pp \to hh)_{SM} = \mathcal{O}(35fb)$$

in the SM at the LHC



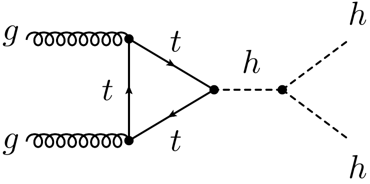


$\sigma(pp \to hh)_{SM}^{14TeV}$ NNLO M_H^2/m_t^2 expansion [de Florian, et. al. '13]
New NLO exact calculation [Borowka, et. al. '16]

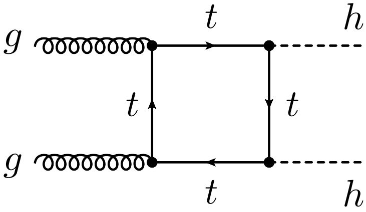
Trilinear Coupling in $pp \to hh$

Two contributions for double Higgs production:

Trilinear contribution



Background from box



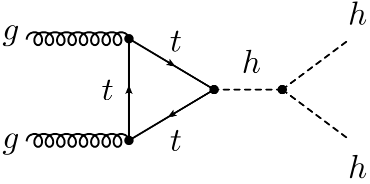
Large top mass limit gives:

$$\mathcal{L}_{eff}^{h\,top} = \frac{\alpha_s}{\pi} G^a_{\mu\nu} G^{a\,\mu\nu} \left\{ \frac{h}{v} \frac{1}{12} \left(1 + \frac{11\alpha_s}{4\pi}\right) - \frac{h^2}{v^2} \frac{1}{24} \left(1 + \frac{11\alpha_s}{4\pi}\right) \right\}$$

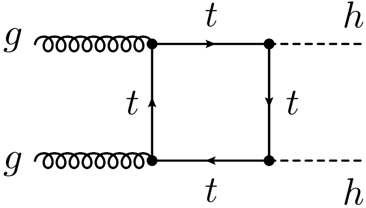
Where there is a negative interference between the contribution.

Interference in $pp \to hh$

Trilinear contribution



Background from box



$$\frac{\sigma_{c6}(pp \to hh)}{\sigma_{SM}(pp \to hh)} \simeq 2.2 - 1.53\,(c_6 + 1)\; + \;0.33\,(c_6+1)^2$$

using HPAIR [Grober, Mühlleitner, Spira, Streicher]

Excluding double Higgs production up to the SM rate:

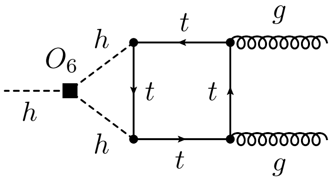
$$\sigma_{exp} \leqslant \sigma_{SM} \quad \to \quad c_6 \in [\,0\,,\,2.7\,]$$

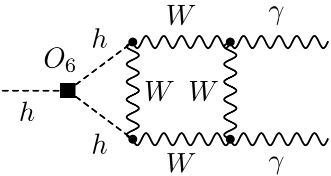
From $\sigma^{combined,8TeV}_{ATLAS}(pp \to 2h \to 2b\bar{b}) \to c_6 \in [-9.5, 12.3]$

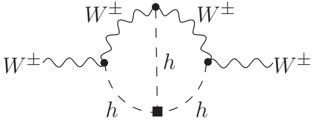
What other constraints for c_6 are there?

Modified loop corrections

- Higgs production
  - 2loops: $pp \to h$
  - 1loop: VBF, hV
- Higgs decay
  - 2loops: $h \to \gamma\gamma$
  - 1loop: $h \to \bar{f}f$
  - 1loop: $h \to VV$
- Electroweak precision
  - Z-Penguin at 2loops?
  - Oblique Parameters

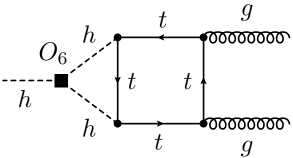






$gg \to h$

- Maintain gauge invariance: Use effective theory.
- O_6 might e.g. mix into $O_{GG} \propto H^\dagger H \, G^a_{\mu\nu} G^{a,\mu\nu}$.
- Renormalise O_6 before finite $\langle h | O_6 | gg \rangle$ calculation.



For $d = 6$ Higgs effective theory

$$\mathcal{L}_{\text{eff}} = \mathcal{L}^{(4)} + \sum_i c_i O_i \quad \text{renormalise} \quad c_i O_i \to \sum_j c_i Z_{ij} Z_{\psi_j} Q_j$$

$$\text{and} \quad \mu \frac{d}{d\mu} \vec{c} = \hat{\gamma} \vec{c}, \quad \text{where} \quad \hat{\gamma} = \hat{\gamma}(\alpha, Z_{ij}, \beta)$$

List of Operators

$$O_6 = -\lambda \left(H^\dagger H\right)^3 \qquad O_H = \frac{1}{2}\,\partial_\mu \left(H^\dagger H\right) \partial^\mu \left(H^\dagger H\right)$$

$$O_T = \frac{1}{2}\left(H^\dagger \overset{\leftrightarrow}{D}_\mu H\right)\left(H^\dagger \overset{\leftrightarrow}{D}{}^\mu H\right) \qquad O_W = \frac{4i}{g}\left(H^\dagger \tau^i \overset{\leftrightarrow}{D}_\mu H\right) D_\nu W^{i,\mu\nu}$$

$$O_B = \frac{2ig'}{g^2}\left(H^\dagger \overset{\leftrightarrow}{D}_\mu H\right) D_\nu B^{\mu\nu} \qquad O_{HW} = \frac{8i}{g}\left(D_\mu H^\dagger \tau^i D_\nu H\right) W^{i,\mu\nu}$$

$$O_{HB} = \frac{4ig'}{g^2}\left(D_\mu H^\dagger D_\nu H\right) B^{\mu\nu} \qquad O_{GG} = \frac{2g_s}{g^2} H^\dagger H\, G^a_{\mu\nu} G^{a,\mu\nu}$$

$$O_{BB} = \frac{2g'}{g^2} H^\dagger H\, B_{\mu\nu} B^{\mu\nu} \qquad O_f = -Y_f\, H^\dagger H\, \bar{Q}_L u_R \overset{(\sim)}{H}$$

Calculation of the 2-loop mixing

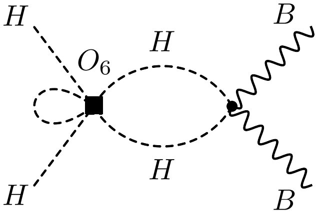
- Use unbroken theory, i.e. $SU(3) \otimes SU(2) \otimes U(1)$ invariant
- Consider $\langle H^\dagger H | O_6 | H^\dagger H \rangle$, $\langle B_\mu B_\nu | O_6 | H^\dagger H \rangle$, $\langle B_\mu W^a_\nu | O_6 | H^\dagger H \rangle$, $\langle W^a_\mu W^b_\nu | O_6 | H^\dagger H \rangle$ and $\langle \bar{f} f | O_6 | H^{(\dagger)} H^\dagger H \rangle$ Green's functions.
- Extract UV pole of diagrams using infrared rearrangement.

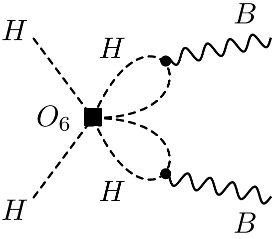
$$\frac{1}{(k+p)^2 - m^2} = \frac{1}{k^2 - M^2} - \frac{p^2 + 2k \cdot p - m^2 + M^2}{k^2 - M^2} \frac{1}{(k+p)^2 - m^2}$$

- M regularises spurious IR-divergences of naive Taylor expansion in external momentum p.

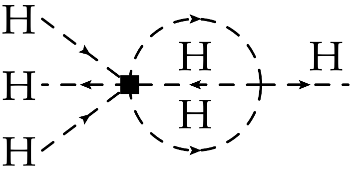
(Non-)vanishing Diagrams

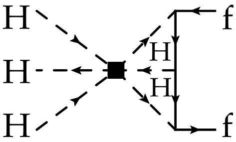
Mixing into $H^\dagger H B_{\mu\nu} B^{\mu\nu}, \ldots$ vanishes at two loops:





But there are non-vanishing contributions:





Equations of Motions:

Computing $\langle H^\dagger H O_6 H^\dagger H \rangle_{(2)}$ and collect all $\mathcal{O}(p^2)$ divergent terms

$\to$ mixing into Q_{eom}

$$
\begin{aligned}
O_{eom} = H^\dagger H \Big[& H^\dagger \left[D_\mu D^\mu H \right] + \left[D_\mu \left(D^\mu H \right)^\dagger \right] H \\
& - m_h^2 \left(1 - \frac{3\bar{c}_6}{4} \right) H^\dagger H + 4\lambda \left(1 - \frac{3\bar{c}_6}{2} \right) \left(H^\dagger H \right)^2 \\
& + \left(Y_u \, \bar{Q}_L u_R \, \tilde{H} + Y_d \, \bar{Q}_L d_R \, H + Y_\ell \, \bar{L}_L \ell_R \, H + \text{h.c.} \right) \Big]
\end{aligned}
$$

$\to$ results in mixing of O_6 into O_f, O_6, O_H, O_4.

2-loop Anomalous Dimensions

- Only non-vanishing off-diagonal mixing

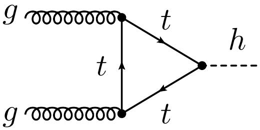
$$\gamma_{H6} = \frac{1}{16\pi^4}\, 12\,\lambda^2\,, \qquad \gamma_{f6} = -\frac{1}{16\pi^4}\left(\lambda^2 + 3\,Y_f Y_f^\dagger\right)\,,$$

- These operators mix into other operators.
- At three-loop O_6 would mix into most operators.
- The two-loop $gg \to h$ and $h \to \gamma\gamma$ matrix elements will be free of operator mixing UV poles.

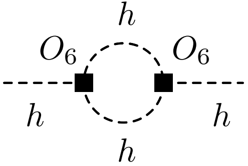
$gg \to h$ Matching onto $hG^a_{\mu\nu}G^{a\,\mu\nu}$

Corrections to SM one-loop triangle

$$c_g = \frac{\alpha_s}{\pi}\left(c_g^{(0)} + \frac{\lambda}{(4\pi)^2}\, c_g^{(1)}\right)$$



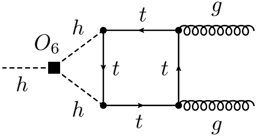
come from the wave-function plus



$$Z_h^{(1)} = \left(9 - 2\sqrt{3}\pi\right)\bar{c}_6\,(\bar{c}_6 + 2)$$

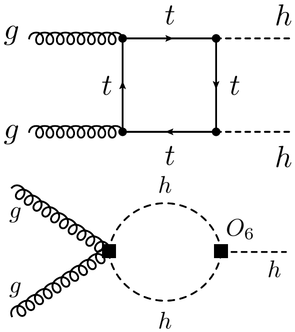
two-loop $M_H/(2m_t)$ expanded diagram:

$$c_g^{(1)} = -\frac{1}{12}\left(\frac{1}{4} + 3\ln\frac{\mu_w^2}{m_t^2}\right)\bar{c}_6 + \frac{Z_h^{(1)}}{2}\, c_g^{(0)}$$



$h \to gg$ Finite Results

- The $hhG_{\mu\nu}G^{\mu\nu}$ contributes via an higgs-loop matrix element.
- This cancels the $\log \mu_W$ dependence in the Wilson coefficient.



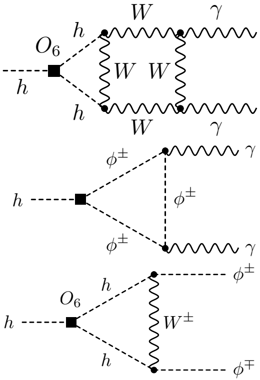
$$\Delta\Gamma_g = \frac{\Delta\Gamma_{h\to gg}}{\Gamma_{SM}} = \frac{\lambda\bar{c}_6}{(4\pi)^2}\left(\frac{23}{12} - \frac{\pi}{\sqrt{3}} - 3\log\frac{M_h^2}{m_t^2} - 9(c_6+2)B_0'\right)$$

Here the wave-function renormalisation gives the dominant contribution.

$h \to \hat{\gamma}\hat{\gamma}$ matching onto $h\hat{F}_{\mu\nu}F^{\mu\nu}$

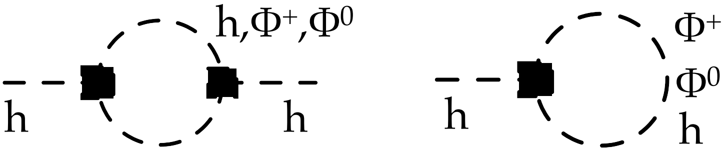
- Real cuts: $h \to AA$ – expand in $M_H/(2M_W)$.

- Only few diagrams @LO in $\frac{M_H}{2M_W}$.
- Expansion $\to$ off-shell $\langle\gamma\gamma|O_6|h\rangle$.
- Use background field: $\langle\hat{\gamma}\hat{\gamma}|O_6|h\rangle$
- UV divergent diagram $h\phi^+\phi^-$ sub-divergence.



Electroweak Renormalisation

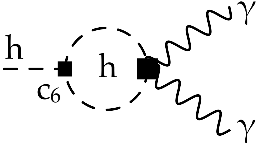
- $\lambda(H^\dagger H)^3$ renormalises Higgs Potential
- On-shell renormalisation for v and M_H
- $\delta Z_{h\phi^+\phi^-} \approx \left(\frac{\delta M_H^2}{M_H^2} + \frac{e}{2s_w}\frac{\delta t}{M_W M_H^2}\right)$
- Determine c.t. from tadpole and higgs self-energy



- Cancels the UV divergence and part of the log μ_W terms

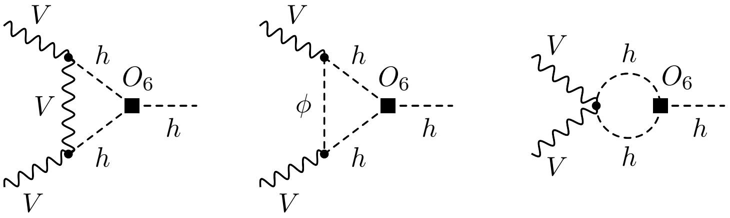
Finite corrections $gg \to h$ and $h \to \gamma\gamma$

- Include $hhF_{\mu\nu}F^{\mu\nu}$ contribution via higgs-loop matrix eleent.
- Cancels remaining scale dependence.



$$
\begin{aligned}
\Delta_g &= \frac{\lambda \bar{c}_6}{(4\pi)^2} \left(8.42 - 9 m_h^2 \left(\bar{c}_6 + 2\right) B_0'\right) \\
\Delta_\gamma &= \frac{\lambda \bar{c}_6}{(4\pi)^2} \left(-3.70 - 9 m_h^2 \left(\bar{c}_6 + 2\right) B_0'\right) .
\end{aligned}
$$

Corrections to the VVh Vertex



Vertex $V(q_1)V(q_2) \to h$-on-shell gives two form factors:

$$\Gamma_V^{\mu\nu}(q_1, q_2) = 2m_V^2/v\Big[g^{\mu\nu}\ \big(1 + \mathcal{F}_1(q_1^2, q_2^2)\big) + q_1^\nu q_2^\mu\ \mathcal{F}_2(q_1^2, q_2^2)\Big]$$

Can be computed using FormCalc or by hand.

$$\mathcal{F}_1(q_1^2, q_2^2) = \frac{\lambda\,\bar{c}_6}{(4\pi)^2}\left(-3B_0 - 12\left(m_V^2\,C_0 - C_{00}\right) - \frac{9\,m_h^2}{2}\left(\bar{c}_6 + 2\right)B_0'\right)$$

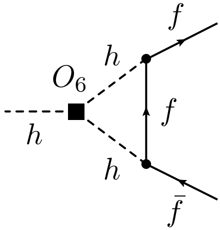
$$\mathcal{F}_2(q_1^2, q_2^2) = \frac{\lambda\,\bar{c}_6}{(4\pi)^2}\,12\left(C_1 + C_{11} + C_{12}\right).$$

Where the B_0' comes again from the wave-function renormalisation.

Corrections to the $h\bar{f}f$ Vertex

Higgs couplings to fermions

- Vertex diagram m_f^2 suppressed
- Universal wave-function renormalisation



$$\Gamma_f = 2\frac{m_f}{v}\left[1+\frac{\lambda\,\bar{c}_6}{(4\pi)^2}\,\mathrm{Re}\left(-6\,m_f^2\,(C_0 - C_1 - C_2) - \frac{9}{2}\,m_h^2\,(\bar{c}_6 + 2)\,B_0'\right)\right]$$

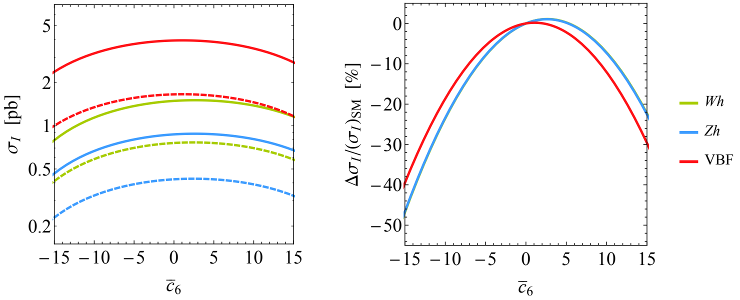
gives

$$\Delta\Gamma\ (h \to f\bar{f}) = \frac{N_c^f G_F m_h m_f^2}{4\sqrt{2}\pi}\left(1 - \frac{4m_f^2}{m_h^2}\right)^{3/2} \times$$

$$\times\frac{\lambda\bar{c}_6}{(4\pi)^2}\,\mathrm{Re}\left(-12 m_f^2\,(C_0 - C_1 - C_2) - 9 m_h^2\,(\bar{c}_6 + 2)\,B_0'\right)$$

Vh & VBF cross sections

[Bizoń, MG, Haisch, Zanderighi]



dashed line: $\sqrt{s} = 8 TeV$, solid line $\sqrt{s} = 13 TeV$

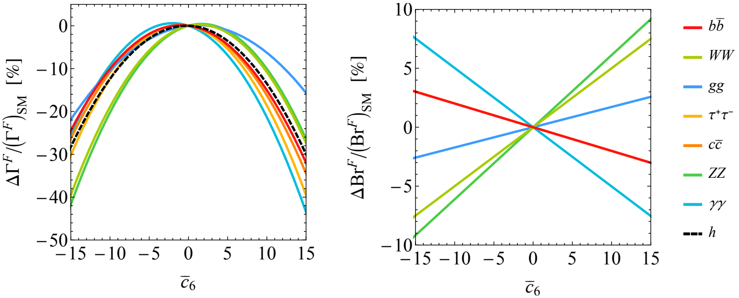
$$\sigma_{Wh}^{13\,\text{TeV}} = (\sigma_{Wh}^{13\,\text{TeV}})_{\text{SM}} \left(1 + 8.2 \cdot 10^{-3}\, \bar{c}_6 - 1.5 \cdot 10^{-3}\, \bar{c}_6^2\right)$$
$$\sigma_{Zh}^{13\,\text{TeV}} = (\sigma_{Zh}^{13\,\text{TeV}})_{\text{SM}} \left(1 + 8.0 \cdot 10^{-3}\, \bar{c}_6 - 1.5 \cdot 10^{-3}\, \bar{c}_6^2\right)$$
$$\sigma_{\text{VBF}}^{13\,\text{TeV}} = (\sigma_{\text{VBF}}^{13\,\text{TeV}})_{\text{SM}} \left(1 + 3.3 \cdot 10^{-3}\, \bar{c}_6 - 1.5 \cdot 10^{-3}\, \bar{c}_6^2\right)$$

see also [Degrassi et. al. '16]

Higgs width and branching fractions

Define the ratio of the cross section times branching fraction as signal strength $\mu_I^F = (\sigma_I \mathrm{Br}^F)/(\sigma_{I\,\mathrm{SM}} \mathrm{Br}^F_{\mathrm{SM}})$
Compute branching fraction, where the universal wave-function factor drops out.

[Bizoń, MG, Haisch, Zanderighi]



see also [Degrassi et. al. ’16]

Constraints from *Vh* and *VBF*

Compare the signal strength

$$\mu_I^F = \frac{\sigma_I \mathrm{Br}^F}{\sigma_{I\,\mathrm{SM}} \mathrm{Br}^F_{\mathrm{SM}}}$$

with LHC Run I [ATLAS-CONF-2015-044] has:

$$\mu_V^{b\bar{b}} = 0.65^{+0.30}_{-0.29}\,, \qquad \mu_V^{WW} = 1.38^{+0.41}_{-0.37}\,,$$
$$\mu_V^{\tau^+\tau^-} = 1.12^{+0.37}_{-0.35}\,, \qquad \mu_V^{ZZ} = 0.48^{+1.37}_{-0.91}\,, \qquad \mu_V^{\gamma\gamma} = 1.05^{+0.44}_{-0.41}\,,$$

This results in:

$$c_6 \in [-13.6, 16.9]\,, \quad \text{(LHC Run I)}$$

HL-LHC

$$\Delta\mu^{b\bar{b}}_{Wh} = \pm 37\%\,, \quad \Delta\mu^{\gamma\gamma}_{Wh} = \pm 19\%\,,$$

$$\Delta\mu^{b\bar{b}}_{Zh} = \pm 14\%\,, \quad \Delta\mu^{\gamma\gamma}_{Zh} = \pm 28\%\,, \quad \Delta\mu^{ZZ}_{Vh} = \pm 13\%\,,$$

$$\Delta\mu^{WW}_{\mathrm{VBF}} = \pm 15\%\,, \quad \Delta\mu^{\tau^+\tau^-}_{\mathrm{VBF}} = \pm 19\%\,, \quad \Delta\mu^{ZZ}_{\mathrm{VBF}} = \pm 21\%\,, \quad \Delta\mu^{\gamma\gamma}_{\mathrm{VBF}} = \pm 22\%\,,$$

HL-LHC [ATL-PHYS-PUB-2014-016] gives:
$c_6 \in [-7.0, 10.9]$

$$\Delta\mu^{b\bar{b}}_{Wh} = \pm 36\%\,, \quad \Delta\mu^{\gamma\gamma}_{Wh} = \pm 17\%\,,$$

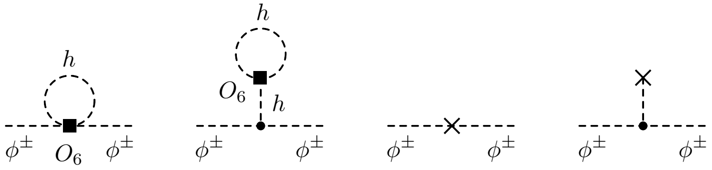
$$\Delta\mu^{b\bar{b}}_{Zh} = \pm 13\%\,, \quad \Delta\mu^{\gamma\gamma}_{Zh} = \pm 27\%\,, \quad \Delta\mu^{ZZ}_{Vh} = \pm 12\%\,,$$

$$\Delta\mu^{WW}_{\mathrm{VBF}} = \pm 9\%\,, \quad \Delta\mu^{\tau^+\tau^-}_{\mathrm{VBF}} = \pm 15\%\,, \quad \Delta\mu^{ZZ}_{\mathrm{VBF}} = \pm 16\%\,, \quad \Delta\mu^{\gamma\gamma}_{\mathrm{VBF}} = \pm 15\%\,.$$

HL-LHC without theory uncertainties: $c_6 \in [-6.2, 9.6]$

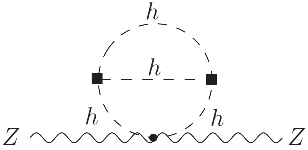
Electroweak Precision Observables

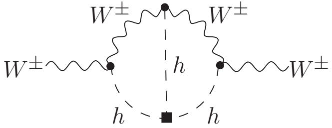
Naively O_6 might also affect electroweak precision observables such as $Z \to \bar{b}b$ or $B_s \to \bar{\mu}\mu$.
Yet all contributions cancel

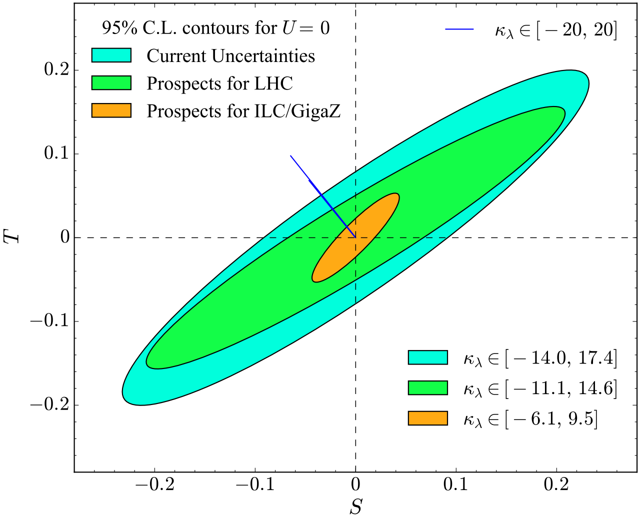


But contributions to M_W and M_Z mass present.
Calculation either modified h^3 or effective theory yield:

[Degrassi, Fedele, Giardino ’17], [Kribs, et. al. ’17]







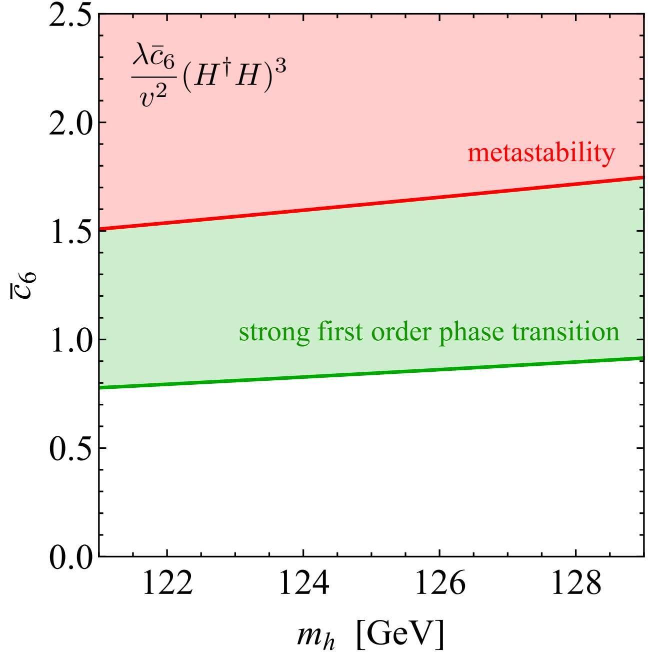
Plot from [1702.07678] [Kribs, et. al. '17]

Conclusions

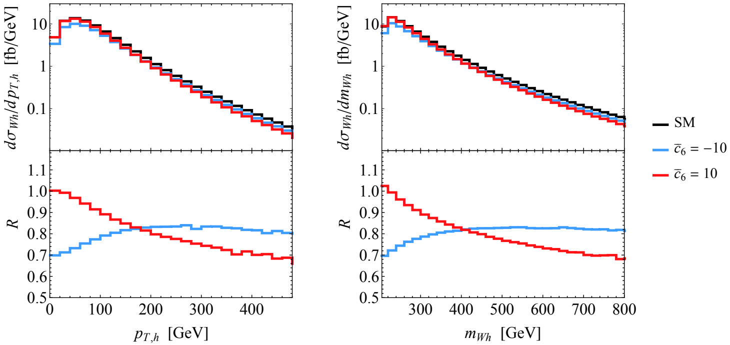
- While it is hard to generate large deviations for the trilinear coupling in a concrete model, it is still important to test the symmetry breaking mechanism.
- LHC Run I+II: single Higgs production and decay constrain the trilinear Higgs coupling at the same level as double Higgs production.
- HL-LHC: Double Higgs production might put stronger constraints, but indirect constraints will give complementary information.

Backup

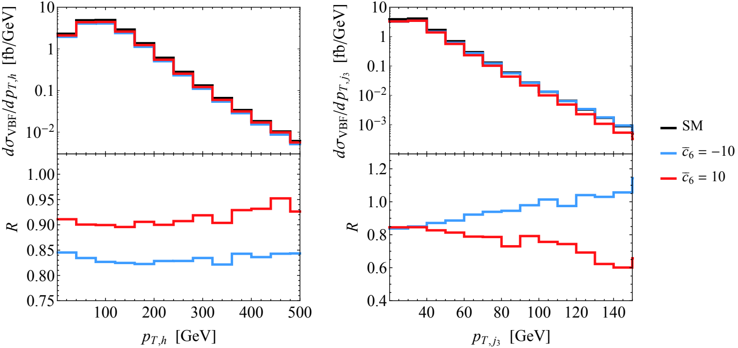
First Order Transition and Vacuum Stability



Wh distibutions



VBF distribution



Matching onto the Higgs Effective Theory

- EFT useful for model independent analysis
- But there might not be a model that maps onto the EFT
- Match benchmark models

THDM

Transform in the unbroken phase to the Higgs basis.

$$\langle H_1 \rangle = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} \quad \text{and} \quad \langle H_2 \rangle = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$

E.g. the THDM in the unbroken phase and Higgs basis:

$$\begin{aligned} V_{\text{tree}}(H_1, H_2) = \tilde{\mu}_1^2 |H_1|^2 + \tilde{\mu}_2^2 |H_2|^2 - \tilde{\mu}^2 \left[H_1^\dagger H_2 + \text{H.c.} \right] + \frac{\tilde{\lambda}_1}{2} |H_1|^4 \\ + \frac{\tilde{\lambda}_2}{2} |H_2|^4 + \tilde{\lambda}_3 |H_1|^2 |H_2|^2 + \tilde{\lambda}_4 \left| H_1^\dagger H_2 \right|^2 + \frac{\tilde{\lambda}_5}{2} \left[\left(H_1^\dagger H_2 \right)^2 + \text{H.c.} \right] \\ + \tilde{\lambda}_6 \left[|H_1|^2 H_1^\dagger H_2 + \text{H.c.} \right] + \tilde{\lambda}_7 \left[|H_2|^2 H_1^\dagger H_2 + \text{H.c.} \right] \end{aligned}$$

H_1 it then the standard model Higgs field that carries the vev, while H_2 will be integrated out.

Results for the 2HDM

$$\bar{c}_H = -\left[-4\tilde{\lambda}_3\tilde{\lambda}_4 + \tilde{\lambda}_4^2 + \tilde{\lambda}_5^2 - 4\tilde{\lambda}_3^2\right] \frac{v^2}{192\,\pi^2\,\tilde{\mu}_2^2}$$

$$\bar{c}_6 = -\left(\tilde{\lambda}_4^2 + \tilde{\lambda}_5^2\right) \frac{v^2}{192\,\pi^2\,\tilde{\mu}_2^2}$$

$$\bar{c}_T = (\tilde{\lambda}_4^2 - \tilde{\lambda}_5^2) \frac{v^2}{192\,\pi^2\,\tilde{\mu}_2^2}$$

$$\bar{c}_\gamma = \frac{m_W^2\,\tilde{\lambda}_3}{256\,\pi^2\,\tilde{\mu}_2^2}$$

$$\bar{c}_W = -\bar{c}_{HW} = \frac{m_W^2\,(2\,\tilde{\lambda}_3 + \tilde{\lambda}_4)}{192\,\pi^2\,\tilde{\mu}_2^2} = \frac{8}{3}\,\bar{c}_\gamma + \frac{m_W^2\,\tilde{\lambda}_4}{192\,\pi^2\,\tilde{\mu}_2^2}$$

$$\bar{c}_B = -\bar{c}_{HB} = \frac{m_W^2\,(-2\,\tilde{\lambda}_3 + \tilde{\lambda}_4)}{192\,\pi^2\,\tilde{\mu}_2^2} = -\frac{8}{3}\,\bar{c}_\gamma + \frac{m_W^2\,\tilde{\lambda}_4}{192\,\pi^2\,\tilde{\mu}_2^2}$$

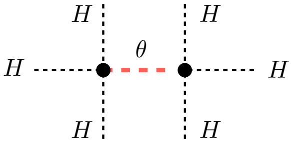
Compare different Models

	$\bar{c}_H$	$\bar{c}_6$	$\bar{c}_T$	$\bar{c}_W$	$\bar{c}_B$	$\bar{c}_{HW}$	$\bar{c}_{HB}$	$\bar{c}_{3W}$	$\bar{c}_\gamma$	$\bar{c}_g$
Higgs Portal (G)	L	L	X	X	X	X	X	X	X	X
Higgs Portal (Spontaneous $\not{G}$)	T	L	RG	RG	RG	X	X	X	X	X
Higgs Portal (Explicit $\not{G}$)	T	T	RG	RG	RG	X	X	X	X	X
2HDM Benchmark A ($c_{\beta-\alpha} = 0$)	L	L	L	L	L	L	L	L	L	X
2HDM Benchmark B ($c_{\beta-\alpha} \neq 0$)	T	T	L	L	L	L	L	L	L	X
Radion/Dilaton	T	T	RG	T	T	T	T	L	T	T

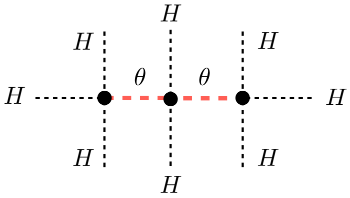
- Typically it is not easy to generate c_6 but no other coefficient.
- Yet all other coefficients are more tightly constrained.

Is there a model that generates only c_6?

- consider a quartuplet $\theta(1,4)_{1/2}$
- $\mathcal{L}_{int} = \lambda_1 H^\dagger \sigma H \tilde{H} + \lambda_2 \theta^2 H^\dagger H$



$$\longrightarrow \quad \frac{|\lambda_1|^2}{M_\theta^2} (H^\dagger H)^3$$



$$\longrightarrow \quad \frac{|\lambda_1|^2 \lambda_2}{M_\theta^4} (H^\dagger H)^4$$

- we generate only c_6 and c_8 – ($O_8 = -\lambda (H^\dagger H)^4$)