



Effective Lagrangian and Constraints on Higgs couplings

Hermès BÉLUSCA-MAÏTO
in collaboration with Adam Falkowski (LPT Orsay)

Laboratoire de Physique Théorique, Université Paris-Sud XI, ORSAY, France

hermes.belusca@th.u-psud.fr

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[HBM, Adam Falkowski ([arXiv:1311.1113](https://arxiv.org/abs/1311.1113))] & a work in preparation

Overview

1 Introduction

2 Effective Lagrangian

3 Link with observables

4 Global fits

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1 Introduction

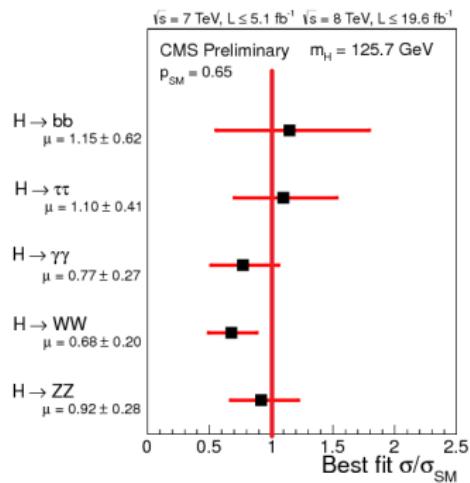
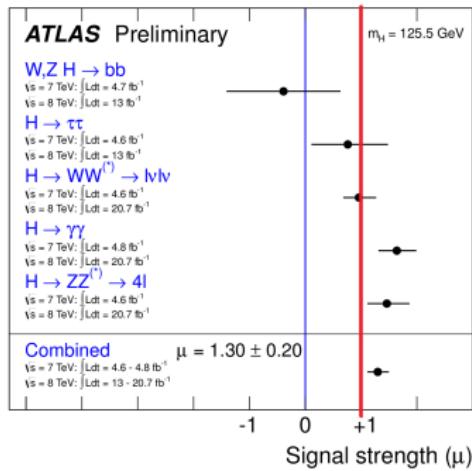
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- Use concrete BSM models to interpret Higgs data (and obtain constraints for these models), or
- Use an effective model-independent approach, consisting on a continuous deformation of the SM \rightarrow effective Lagrangian approach.

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Assumptions for \mathcal{L}_{eff}

Several assumptions made on new physics:

- $m(\text{NP}) \gg m(\text{EW}) \rightarrow$ NP fields can be integrated out.
- We assume no violation of baryon and lepton numbers. No FCNC.
- We also suppose here that the Higgs boson h is part of the Higgs field H that transforms as $(1, 2)_{1/2}$ representation of the Standard Model $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge group and acquires an expectation value v .

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Effective Lagrangian expanded as:

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{SM} + \mathcal{L}_{D=5} + \mathcal{L}_{D=6} + \dots$$

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- $\mathcal{L}_{D=5}$ (Weinberg's operator) gives masses to neutrinos, do not play a role in the Higgs phenomenology.
- $D > 6$ operators are neglected here as they will not be constrained (given current experimental precision).
- $\mathcal{L}_{D=6}$ is the part of interest for us!

Dimension-6 operators

- Original list by [Buchmüller et al. ([Nucl.Phys.B268\(1986\)621](#)), ...], supposing no baryon + lepton numbers violation, 80 operators were obtained but many of them redundant (via EOMs).
- Complete list of 59 operators by [[Grzadkowski et al. \(arXiv:1008.4884\)](#)].
- Using EOMs to redefine operators → different choices of bases available → use a convenient one: we take the one of [Contino et al. ([arXiv:1303.3876](#))].

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Lagrangian (cont.)

Standard Model Lagrangian:

$$\mathcal{L}_{SM} \supset |D_\mu H|^2 - V(H) - \left(y_{ij} H \overline{\psi_L^i} \psi_R^j + \text{h.c.} \right) + \dots$$
$$V(H) = \mu^2 H^\dagger H + \lambda (H^\dagger H)^2$$

and the dimension-6 Lagrangian:

$$\mathcal{L}_{D=6} = \mathcal{L}_{CPC} + \mathcal{L}_{CPV}$$

with the charge-parity-conserving (CP-even) part being:

$$\mathcal{L}_{CPC} = \Delta \mathcal{L}_{SILH} + \Delta \mathcal{L}_{F_1} + \Delta \mathcal{L}_{F_2} + \Delta \mathcal{L}_{4F} + \Delta \mathcal{L}_{Gauge}$$

and \mathcal{L}_{CPV} is the CP-violating part.

[Contino et al. (arXiv:1303.3876)]

Dimension-6 operators (cont.)

2-fermion vertex operators

$$\begin{aligned}\Delta\mathcal{L}_{F_1} = & \frac{i\bar{c}_{Hq}}{v^2}(\overline{q_L}\gamma^\mu q_L)\left(H^\dagger\overleftrightarrow{D}_\mu H\right) + \frac{i\bar{c}'_{Hq}}{v^2}(\overline{q_L}\gamma^\mu\sigma^i q_L)\left(H^\dagger\sigma^i\overleftrightarrow{D}_\mu H\right) \\ & + \frac{i\bar{c}_{Hu}}{v^2}(\overline{u_R}\gamma^\mu u_R)\left(H^\dagger\overleftrightarrow{D}_\mu H\right) + \frac{i\bar{c}_{Hd}}{v^2}(\overline{d_R}\gamma^\mu d_R)\left(H^\dagger\overleftrightarrow{D}_\mu H\right) \\ & + \left[\frac{i\bar{c}_{Hud}}{v^2}(\overline{u_R}\gamma^\mu d_R)\left(H^{c\dagger}\overleftrightarrow{D}_\mu H\right) + \text{h.c.}\right] \\ & + \frac{i\bar{c}_{HL}}{v^2}(\overline{L_L}\gamma^\mu L_L)\left(H^\dagger\overleftrightarrow{D}_\mu H\right) + \frac{i\bar{c}'_{HL}}{v^2}(\overline{L_L}\gamma^\mu\sigma^i L_L)\left(H^\dagger\sigma^i\overleftrightarrow{D}_\mu H\right) \\ & + \frac{i\bar{c}_{HI}}{v^2}(\overline{I_R}\gamma^\mu I_R)\left(H^\dagger\overleftrightarrow{D}_\mu H\right)\end{aligned}$$

Couplings of fermions to SM gauge bosons modified; strong constraints from EW measurements → Higgs phenomenology not really affected.

Dimension-6 operators (cont.)

2-fermion dipole operators; contributes to electric dipole moments and anomalous magnetic moments; strong constraints from EW measurements; contribute to 3-body Higgs decay → very suppressed.

$$\begin{aligned}\Delta\mathcal{L}_{F_2} = & \frac{\bar{c}_{uB}}{m_W^2} \frac{g'}{y_u} \overline{q_L} H^c \sigma^{\mu\nu} u_R B_{\mu\nu} + \frac{\bar{c}_{uW}}{m_W^2} \frac{g}{y_u} \overline{q_L} \sigma^i H^c \sigma^{\mu\nu} u_R W_{\mu\nu}^i \\ & + \frac{\bar{c}_{uG}}{m_W^2} \frac{g_S}{y_u} \overline{q_L} H^c \sigma^{\mu\nu} \lambda^a u_R G_{\mu\nu}^a \\ & + \frac{\bar{c}_{dB}}{m_W^2} \frac{g'}{y_d} \overline{q_L} H \sigma^{\mu\nu} d_R B_{\mu\nu} + \frac{\bar{c}_{dW}}{m_W^2} \frac{g}{y_d} \overline{q_L} \sigma^i H \sigma^{\mu\nu} d_R W_{\mu\nu}^i \\ & + \frac{\bar{c}_{dG}}{m_W^2} \frac{g_S}{y_d} \overline{q_L} H \sigma^{\mu\nu} \lambda^a d_R G_{\mu\nu}^a \\ & + \frac{\bar{c}_{lB}}{m_W^2} \frac{g'}{y_l} \overline{l_L} H \sigma^{\mu\nu} l_R B_{\mu\nu} + \frac{\bar{c}_{lW}}{m_W^2} \frac{g}{y_l} \overline{l_L} \sigma^i H \sigma^{\mu\nu} l_R W_{\mu\nu}^i + \text{h.c.}\end{aligned}$$

$\Delta\mathcal{L}_{4F}$ (4-fermion operators) and $\Delta\mathcal{L}_{\text{Gauge}}$ (pure-gauge operators) are ignored because they do not affect Higgs phenomenology.
 $\Delta\mathcal{L}_{\text{Gauge}}$ modifies only triple and quadruple gauge couplings.

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Dimension-6 operators (cont.)

Strongly-Interacting Light Higgs

$$\begin{aligned}\Delta\mathcal{L}_{SILH} = & \frac{\bar{c}_H}{2v^2}\partial^\mu(H^\dagger H)\partial_\mu(H^\dagger H) + \frac{\bar{c}_T}{2v^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D_\mu} H\right) \\ & - \frac{\bar{c}_6}{v^2} \cancel{\lambda} \cancel{(H^\dagger H)^3} \\ & + \frac{H^\dagger H}{v^2} (\bar{c}_u y_u \overline{q_L} H^c u_R + \bar{c}_d y_d \overline{q_L} H d_R + \bar{c}_l y_l \overline{L_L} H l_R + \text{h.c.}) \\ & + \frac{i\bar{c}_W g}{2m_W^2} \left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right) (D^\nu W_{\mu\nu})^i + \frac{i\bar{c}_B g'}{2m_W^2} \left(H^\dagger \overleftrightarrow{D^\mu} H\right) (\partial^\nu B_{\mu\nu}) \\ & + \frac{i\bar{c}_{HW} g}{m_W^2} (D^\mu H)^\dagger \sigma^i (D^\nu H) W_{\mu\nu}^i + \frac{i\bar{c}_{HB} g'}{m_W^2} (D^\mu H)^\dagger (D^\nu H) B_{\mu\nu} \\ & + \frac{\bar{c}_\gamma g'^2}{m_W^2} (H^\dagger H) B_{\mu\nu} B^{\mu\nu} + \frac{\bar{c}_g g_S^2}{m_W^2} (H^\dagger H) G_{\mu\nu}^a G^{a\mu\nu}\end{aligned}$$

\bar{c}_6 term ignored because it modifies Higgs self-couplings only and current precision is not enough (some prospects for LHC upgrade: [arXiv:1206.5001, arXiv:1301.3492] (LHC 14TeV), [arXiv:1212.5581] (LHC high lumi)).

Dimension-6 operators (cont.)

CP-violating part

$$\begin{aligned}\mathcal{L}_{CPV} = & \frac{i\tilde{c}_{HW} g}{m_W^2} (D^\mu H)^\dagger \sigma^i (D^\nu H) \widetilde{W}_{\mu\nu}^i + \frac{i\tilde{c}_{HB} g'}{m_W^2} (D^\mu H)^\dagger (D^\nu H) \widetilde{B}_{\mu\nu} \\ & + \frac{\tilde{c}_\gamma g'^2}{m_W^2} (H^\dagger H) B_{\mu\nu} \widetilde{B}^{\mu\nu} + \frac{\tilde{c}_g g_S^2}{m_W^2} (H^\dagger H) G_{\mu\nu}^a \widetilde{G}^{a\mu\nu} \\ & + \cancel{\frac{\tilde{c}_{3W} g^3}{m_W^2} \epsilon^{ijk} W_\mu^{i\nu} W_\nu^{j\rho} \widetilde{W}_\rho^{k\mu}} + \cancel{\frac{\tilde{c}_{3G} g_S^3}{m_W^2} f^{abc} G_\mu^{a\nu} G_\nu^{b\rho} \widetilde{G}_\rho^{c\mu}} \\ & + \frac{H^\dagger H}{v^2} (\tilde{c}_u y_u \overline{q_L} \gamma_5 H^c u_R + \tilde{c}_d y_d \overline{q_L} \gamma_5 H d_R + \tilde{c}_l y_l \overline{L_L} \gamma_5 H l_R + \text{h.c.})\end{aligned}$$

Gauge self-couplings modifications are also ignored here.

Effective Lagrangian

Final expression:

$$\mathcal{L}_{D=6} = \mathcal{L}_{CPC} + \mathcal{L}_{CPV}$$

with the CP-conserving part:

$$\begin{aligned}\mathcal{L}_{CPC} = & \frac{\bar{c}_H}{2v^2} \partial^\mu (H^\dagger H) \partial_\mu (H^\dagger H) + \frac{\bar{c}_T}{2v^2} \left(H^\dagger \overleftrightarrow{D^\mu} H \right) \left(H^\dagger \overleftrightarrow{D_\mu} H \right) \\ & + \frac{H^\dagger H}{v^2} \left(\bar{c}_u y_u \overline{q_L} H^c u_R + \bar{c}_d y_d \overline{q_L} H d_R + \bar{c}_l y_l \overline{L_L} H l_R + \text{h.c.} \right) \\ & + \frac{i\bar{c}_W g}{2m_W^2} \left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H \right) (D^\nu W_{\mu\nu})^i + \frac{i\bar{c}_B g'}{2m_W^2} \left(H^\dagger \overleftrightarrow{D^\mu} H \right) (\partial^\nu B_{\mu\nu}) \\ & + \frac{i\bar{c}_{HW} g}{m_W^2} (D^\mu H)^\dagger \sigma^i (D^\nu H) W_{\mu\nu}^i + \frac{i\bar{c}_{HB} g'}{m_W^2} (D^\mu H)^\dagger (D^\nu H) B_{\mu\nu} \\ & + \frac{\bar{c}_\gamma g'^2}{m_W^2} (H^\dagger H) B_{\mu\nu} B^{\mu\nu} + \frac{\bar{c}_g g_S^2}{m_W^2} (H^\dagger H) G_{\mu\nu}^a G^{a\mu\nu}\end{aligned}$$

and the CP-violating part:

$$\begin{aligned}\mathcal{L}_{CPV} = & \frac{i\widetilde{c}_{HW} g}{m_W^2} (D^\mu H)^\dagger \sigma^i (D^\nu H) \widetilde{W}_{\mu\nu}^i + \frac{i\widetilde{c}_{HB} g'}{m_W^2} (D^\mu H)^\dagger (D^\nu H) \widetilde{B}_{\mu\nu} \\ & + \frac{\widetilde{c}_\gamma g'^2}{m_W^2} (H^\dagger H) B_{\mu\nu} \widetilde{B}^{\mu\nu} + \frac{\widetilde{c}_g g_S^2}{m_W^2} (H^\dagger H) G_{\mu\nu}^a \widetilde{G}^{a\mu\nu}\end{aligned}$$

Effective Lagrangian (cont.)

In unitary gauge, after expansion of the Higgs field around its vev. and canonical normalization of the Higgs kinetic term, and keeping terms linear in h (see also Marco Zaro's talk):

$$\mathcal{L}_{SM} + \mathcal{L}_{D=6} \supset \frac{h}{v} \left[\begin{array}{l} 2c_W m_W^2 W_\mu^\dagger W^\mu + c_Z m_Z^2 Z_\mu Z^\mu - \sum_{\substack{\text{up-type fermions} \\ f = \\ \text{down-type} \\ e, \mu, \tau}} m_f \bar{f} (c_f + i \tilde{c}_f \gamma_5) f \\ - \frac{1}{2} c_{WW} W_{\mu\nu}^\dagger W^{\mu\nu} - \frac{1}{4} c_{ZZ} Z_{\mu\nu} Z^{\mu\nu} - \frac{1}{4} c_{\gamma\gamma} \gamma_{\mu\nu} \gamma^{\mu\nu} - \frac{1}{2} c_{Z\gamma} \gamma_{\mu\nu} Z^{\mu\nu} + \frac{1}{4} c_{gg} G_{\mu\nu}^a G^{a\mu\nu} \\ - \frac{1}{2} \tilde{c}_{WW} W_{\mu\nu}^\dagger \widetilde{W}^{\mu\nu} - \frac{1}{4} \tilde{c}_{ZZ} Z_{\mu\nu} \widetilde{Z}^{\mu\nu} - \frac{1}{4} \tilde{c}_{\gamma\gamma} \gamma_{\mu\nu} \widetilde{\gamma}^{\mu\nu} - \frac{1}{2} \tilde{c}_{Z\gamma} \gamma_{\mu\nu} \widetilde{Z}^{\mu\nu} + \frac{1}{4} \tilde{c}_{gg} G_{\mu\nu}^a \widetilde{G}^{a\mu\nu} \\ - \kappa_{Z\gamma} (\partial^\nu \gamma_{\mu\nu}) Z^\mu - \kappa_{ZZ} (\partial^\nu Z_{\mu\nu}) Z^\mu - (\kappa_{WW} (D^\nu W_{\mu\nu}^\dagger) W^\mu + \text{h.c.}) \end{array} \right]$$

The c_i and \tilde{c}_i parameters are function of the SILH ones. Not all of these parameters are independent. Indeed, it is a consequence of the SILH Lagrangian that:

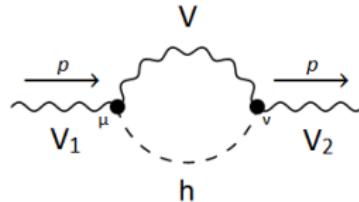
$$c_{WW} = c_w^2 c_{ZZ} + 2c_w s_w c_{Z\gamma} + s_w^2 c_{\gamma\gamma}$$

$$\tilde{c}_{WW} = c_w^2 \tilde{c}_{ZZ} + 2c_w s_w \tilde{c}_{Z\gamma} + s_w^2 \tilde{c}_{\gamma\gamma}$$

$$\kappa_{WW} = c_w^2 \kappa_{ZZ} + c_w s_w \kappa_{Z\gamma}$$

S,T,U oblique corrections

[Peskin, Takeuchi (Phys.Rev.D46(1992)381-409)]. $V_i = W^\pm, Z, \gamma$.



$$\Pi_{\mu\nu}(p^2) = g_{\mu\nu} \left(\Pi_{V_1 V_2}(p^2) = \Pi_{V_1 V_2}^{(0)}(0) + p^2 \Pi_{V_1 V_2}^{(2)}(0) + (p^2)^2 \Pi_{V_1 V_2}^{(4)}(0) + \dots \right) + p_\mu p_\nu (\dots)$$

$$\alpha S = 4 s_w^2 c_w^2 \left(\delta \Pi_{ZZ}^{(2)} - \delta \Pi_{\gamma\gamma}^{(2)} - \frac{c_w^2 - s_w^2}{s_w c_w} \delta \Pi_{Z\gamma}^{(2)} \right)$$

$$\alpha T = \frac{\delta \Pi_{WW}^{(0)}}{m_W^2} - \frac{c_w^2 \delta \Pi_{ZZ}^{(0)}}{m_W^2} = \frac{\delta \Pi_{WW}^{(0)}}{m_W^2} - \frac{\delta \Pi_{ZZ}^{(0)}}{m_Z^2}$$

$$\alpha U = 4 s_w^2 \left(\delta \Pi_{WW}^{(2)} - c_w^2 \delta \Pi_{ZZ}^{(2)} - s_w^2 \delta \Pi_{\gamma\gamma}^{(2)} - 2 c_w s_w \delta \Pi_{Z\gamma}^{(2)} \right)$$

(sometimes completed with αV , αW , αX and αY from [Barbieri et al. (arXiv:hep-ph/0405040)]).

S,T,U oblique corrections (cont.)

- The dimension-6 operators introduce quartic (in T only), quadratic and logarithmic divergences in S, T and U (*full expressions big enough not to be put here!*).
- To remove the (quartic and) quadratic divergences, we must impose constraints. We can do:

$$c_Z = c_W \equiv c_V$$

$$c_{ZZ} = c_{\gamma\gamma} + \frac{c_w^2 - s_w^2}{s_w c_w} c_{Z\gamma} \quad \text{and same for } \tilde{c}_{ZZ}$$

$$c_{WW} = c_{\gamma\gamma} + \frac{c_w}{s_w} c_{Z\gamma} \quad \text{and same for } \tilde{c}_{WW}$$

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$$\kappa_i = 0$$

Effective parameters kept

The Higgs couplings therefore depend on 7 independent parameters in the CP-even sector:

$$c_V, \quad c_u, \quad c_d, \quad c_l, \quad c_{gg}, \quad c_{\gamma\gamma}, \quad c_{Z\gamma}$$

and 6 independent parameters in the CP-odd sector:

$$\tilde{c}_u, \quad \tilde{c}_d, \quad \tilde{c}_l, \quad \tilde{c}_{gg}, \quad \tilde{c}_{\gamma\gamma}, \quad \tilde{c}_{Z\gamma}.$$

The SM Higgs is the case where $c_V = c_{f=u,d,l} = 1$, $c_{gg} = c_{\gamma\gamma} = c_{Z\gamma} = 0$ and all the $\tilde{c}_i = 0$.

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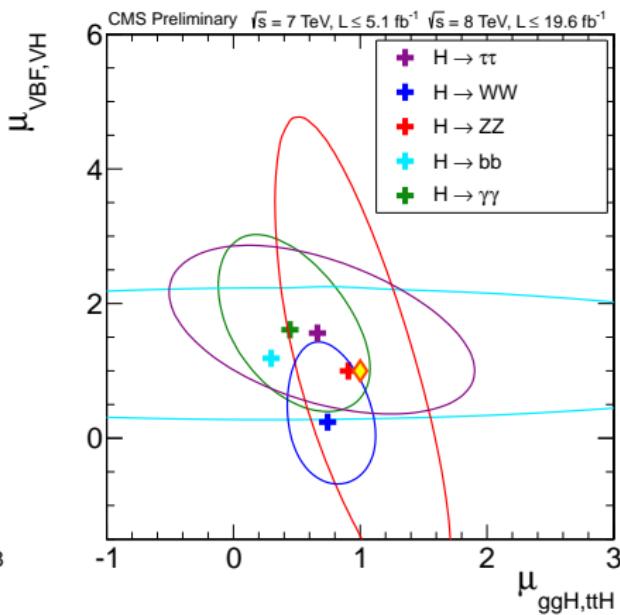
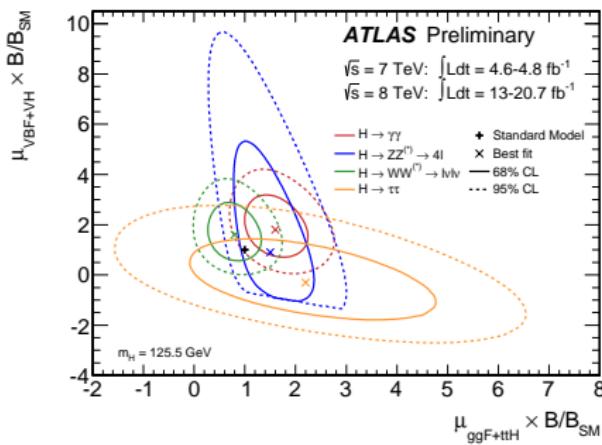
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Higgs rates

ATLAS and CMS give the relative Higgs rates (signal strength)

$\hat{\mu}_{XX}^{YH} = \frac{\sigma_{YH}}{\sigma_{YH}^{SM}} \frac{\text{Br}(h \rightarrow XX)}{\text{Br}(h \rightarrow XX)_{SM}}$ in various channels (we use them or the 2-dimensional (2D) likelihood functions).



Relative decay widths

Tree-level Higgs-decay:

$$\left(\frac{\Gamma}{\Gamma_{SM}} \right)_{h \rightarrow f\bar{f}} \simeq |c_f|^2 + |\tilde{c}_f|^2 \quad (\text{light fermions})$$
$$\left(\frac{\Gamma}{\Gamma_{SM}} \right)_{ZZ^* \rightarrow 4l} \text{ and } \left(\frac{\Gamma}{\Gamma_{SM}} \right)_{WW^* \rightarrow 2l2\nu}$$

1-loop (SM) + tree-level (effective) generated:

$(V_1 = V_2 = g)$; $(V_1 = V_2 = \gamma)$; $(V_1 = Z, V_2 = \gamma)$

$$\left(\frac{\Gamma}{\Gamma_{SM}} \right)_{h \rightarrow V_1 V_2} \simeq \frac{\widehat{|c_{V_1 V_2}|^2} + \widehat{|\tilde{c}_{V_1 V_2}|^2}}{\widehat{|c_{V_1 V_2, SM}|^2}}$$

Rates measurements constrain only the sum of the squares...

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$$\left(\frac{\Gamma}{\Gamma_{SM}} \right)_{h \rightarrow f\bar{f}} \simeq |c_f|^2 + |\tilde{c}_f|^2 \quad (\text{light fermions})$$
$$\left(\frac{\Gamma}{\Gamma_{SM}} \right)_{ZZ^* \rightarrow 4l} \text{ and } \left(\frac{\Gamma}{\Gamma_{SM}} \right)_{WW^* \rightarrow 2l2\nu}$$

1-loop (SM) + tree-level (effective) generated:

$(V_1 = V_2 = g)$; $(V_1 = V_2 = \gamma)$; $(V_1 = Z, V_2 = \gamma)$

$$\left(\frac{\Gamma}{\Gamma_{SM}} \right)_{h \rightarrow V_1 V_2} \simeq \frac{\widehat{|c_{V_1 V_2}|^2} + \widehat{|\tilde{c}_{V_1 V_2}|^2}}{\widehat{|c_{V_1 V_2, SM}|^2}}$$

Rates measurements constrain only the sum of the squares...

Relative production XSecs

Many events generated with MadEvents at $\sqrt{s} = 8$ TeV to simulate the production of Higgs via pp collisions for a set of values of c_i and \tilde{c}_i couplings, then we perform a fit on a multinom of the form:

$$\left(\frac{\sigma}{\sigma_{SM}} \right) \simeq c_V^2 + \alpha_1 c_{\gamma\gamma}^2 + \alpha_2 c_{Z\gamma}^2 + \alpha_3 c_V c_{\gamma\gamma} + \alpha_4 c_V c_{Z\gamma} + \alpha_5 c_{\gamma\gamma} c_{Z\gamma} \\ + \beta_1 \tilde{c}_{\gamma\gamma}^2 + \beta_2 \tilde{c}_{Z\gamma}^2 + \beta_3 \tilde{c}_{\gamma\gamma} \tilde{c}_{Z\gamma}$$

- Higgs associated production with W or Z: $\left(\frac{\sigma}{\sigma_{SM}} \right)_{hW}$
- Vector boson fusion: $\left(\frac{\sigma}{\sigma_{SM}} \right)_{VBF}$

They also depend on the cuts chosen by the experiments for their analyses!

- ATLAS: $p_T \geq 25$ GeV and $|\eta| \leq 2.4$; $p_T \geq 30$ GeV and $2.4 \leq |\eta| \leq 4.5$; $m_{jj} \geq 500$ GeV; $|\Delta\eta_{jj}| \geq 2.8$; $\Delta R_{jj} = 0.4$
[ATLAS-CONF-2013-030, ATLAS-CONF-2013-067]
- CMS: $p_T \geq 30$ GeV; $|\eta| \leq 4.7$; $m_{jj} \geq 650$ GeV; $|\Delta\eta_{jj}| \geq 3.5$; $\Delta R_{jj} = 0.5$
[CMS-PAS-HIG-13-007]

VH: $p_{T H} \geq 200$ GeV; $p_{T V} \geq 190$ GeV ("boosted" Higgs)

[Handbook of LHC Higgs cross sections (arXiv:1307.1347)]

Overview

1 Introduction

2 Effective Lagrangian

3 Link with observables

4 Global fits

Experimental data

- Combined Tevatron measurements [Aaltonen et al. (arXiv:1303.6346)]:
 $\hat{\mu}_{\gamma\gamma}^{\text{incl.}} = 6.2^{+3.2}_{-3.2}$, $\hat{\mu}_{WW}^{\text{incl.}} = 0.9^{+0.9}_{-0.8}$, $\hat{\mu}_{bb}^{VH} = 1.62^{+0.77}_{-0.77}$, $\hat{\mu}_{\tau\tau}^{\text{incl.}} = 2.1^{+2.2}_{-2.0}$,
- EW precision measurements from LEP, SLC and Tevatron collected in Table 1 of [Falkowski et al. (arXiv:1303.1812)].

ATLAS			
Production	Decay	$\hat{\mu}$	Ref.
2D	$\gamma\gamma$	$1.55^{+0.33}_{-0.29}$	[arXiv:1307.1427]
	ZZ	$1.41^{+0.42}_{-0.33}$	[arXiv:1307.1427]
	WW	$0.98^{+0.33}_{-0.26}$	[arXiv:1307.1427]
	$\tau\tau$	$1.4^{+0.5}_{-0.4}$	[ATLAS-CONF-2013-108]
VH	bb	$0.2^{+0.7}_{-0.6}$	[ATLAS-CONF-2013-079]
ttH	bb	2.69 ± 5.53	[ATLAS-CONF-2012-135]
	$\gamma\gamma$	-1.39 ± 3.18	[ATLAS-CONF-2013-080]
inclusive	$Z\gamma$	2.96 ± 6.69	[ATLAS-CONF-2013-009]
	$\mu\mu$	1.75 ± 4.26	[ATLAS-CONF-2013-010]

CMS			
Production	Decay	$\hat{\mu}$	Ref.
2D	$\gamma\gamma$	$0.77^{+0.29}_{-0.26}$	[CMS-PAS-HIG-13-001]
	ZZ	$0.92^{+0.29}_{-0.24}$	[CMS-PAS-HIG-13-005]
	WW	$0.68^{+0.21}_{-0.19}$	[CMS-PAS-HIG-13-005]
	$\tau\tau$	$1.11^{+0.43}_{-0.41}$	[CMS-PAS-HIG-13-005]
VH	bb	1.00 ± 0.49	[arXiv:1310.3687]
VBF	bb	0.7 ± 1.4	[CMS-PAS-HIG-13-011]
ttH	bb	$1.0^{+1.9}_{-2.0}$	[ttH-Combi]
	$\gamma\gamma$	$-0.2^{+2.4}_{-1.9}$	[ttH-Combi]
	$\tau\tau$	$-1.4^{+6.3}_{-5.5}$	[ttH-Combi]
	multi- ℓ	$3.7^{+1.6}_{-1.4}$	[CMS-PAS-HIG-13-020]
inclusive	$Z\gamma$	-0.21 ± 4.86	[arXiv:1307.5515]
	$\mu\mu$	$2.9^{+2.8}_{-2.7}$	[CMS-PAS-HIG-13-007]

Cut-off scale $\Lambda = 3$ TeV for the logarithmically divergent corrections from the Higgs loops to the EW precision observables.

CP-even parameters

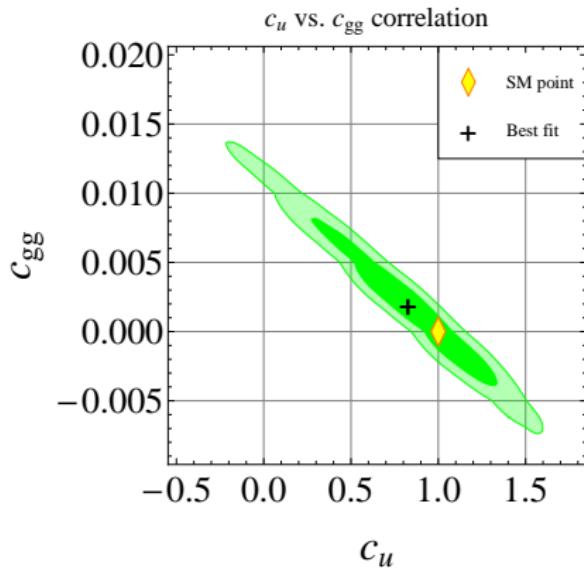
Central values and 68% CL intervals for the parameters:

$$c_V = 1.04^{+0.02}_{-0.02}, \quad c_u = 1.30^{+0.10}_{-0.30}, \quad c_d = 0.93^{+0.18}_{-0.15}, \quad c_l = 1.16^{+0.17}_{-0.15},$$

$$c_{gg} = -0.0016^{+0.0022}_{-0.0037}, \quad c_{\gamma\gamma} = 0.00059^{+0.00078}_{-0.00078}, \quad c_{Z\gamma} = -0.001^{+0.020}_{-0.039}.$$

$\chi^2_{\text{SM}} - \chi^2_{\min} = 5.0$ meaning SM gives a perfect fit to the Higgs and EW precision data.

$c_{gg} + 0.013c_u$ from ggH;
lifted by ttH.

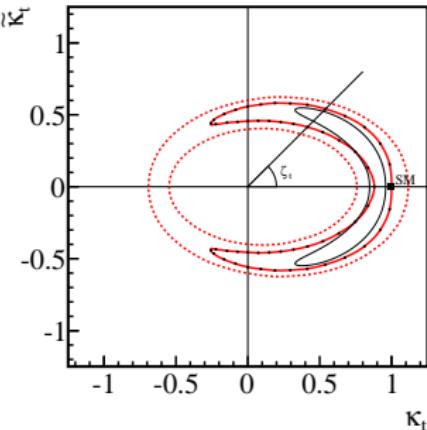


CP-odd parameters

Central values and 68% CL intervals for the parameters:

$$\begin{aligned}\tilde{c}_u &= \pm(0.80^{+0.44}_{-2.04}), & \tilde{c}_d &= 0.004^{+0.433}_{-0.427}, & \tilde{c}_l &= \pm(0.53^{+0.24}_{-1.30}), \\ \tilde{c}_{gg} &= 0.019^{+0.007}_{-0.013}, & \tilde{c}_{\gamma\gamma} &= (0.0028^{+0.0015}_{-0.0079}, -0.0035^{+0.0079}_{-0.0016}), \\ \tilde{c}_{Z\gamma} &= 0.004^{+0.024}_{-0.031}.\end{aligned}$$

Some of the fermionic odd couplings are not constrained by their sign
(data actually constrain the sum of the squares of the CP-even and
CP-odd couplings) [J.Ellis et al. (1312.5736)]:



Conclusion

- We used an effective framework to obtain constraints on Higgs couplings to matter.
- Good constraints on most of the CP-even parameters,
- Correct constraints on some CP-odd parameters, but not all. It should be noted that until now the rate measurements only constrain $|c_f|^2 + |\tilde{c}_f|^2$ or $|\widehat{c_{V_1 V_2}}|^2 + \left| \widehat{\tilde{c}_{V_1 V_2}} \right|^2$ → more elaborate methods needed to constrain the possible values of CP-even and CP-odd parameters!
(e.g. EDM [Brod et al. (arXiv:1310.1385)], tensor structure of $H \rightarrow VV$ (Cédric Delaunay's talk)).

Backup

$$c_W = 1 - \frac{\bar{c}_H}{2}$$

$$c_Z = c_W - 2\bar{c}_T$$

$$c_f = c_W + \Re \bar{c}_f \quad ; \quad \tilde{c}_f = \Im \tilde{c}_f \quad \text{where} \quad f = u, c, t; d, s, b; e, \mu, \tau$$

$$c_{WW} = 4\bar{c}_{HW} \quad \text{and same for } \tilde{c}_{WW}$$

$$c_{ZZ} = c_{WW} + 4 \left(\frac{s_w^2}{c_w^2} \bar{c}_{HB} - 4 \frac{s_w^4}{c_w^2} \bar{c}_\gamma \right) \quad \text{and same for } \tilde{c}_{ZZ}$$

$$c_{\gamma\gamma} = -16s_w^2 \bar{c}_\gamma \quad \text{and same for } \tilde{c}_{\gamma\gamma}$$

$$c_{Z\gamma} = 2 \frac{s_w}{c_w} (\bar{c}_{HW} - \bar{c}_{HB} + 8s_w^2 \bar{c}_\gamma) \quad \text{and same for } \tilde{c}_{Z\gamma}$$

$$c_{gg} = 16 \frac{g_S^2}{g^2} \bar{c}_g \quad \text{and same for } \tilde{c}_{gg}$$

Relative decay widths (1/3)

$$\left(\frac{\Gamma}{\Gamma_{SM}}\right)_{ZZ^* \rightarrow 4l} \simeq c_V^2 + 0.022c_{\gamma\gamma}^2 + 0.035c_{Z\gamma}^2 + 0.253c_Vc_{\gamma\gamma} \\ + 0.316c_Vc_{Z\gamma} + 0.056c_{\gamma\gamma}c_{Z\gamma} \\ + 0.009\tilde{c}_{\gamma\gamma}^2 + 0.014\tilde{c}_{Z\gamma}^2 + 0.023\tilde{c}_{\gamma\gamma}\tilde{c}_{Z\gamma}$$

$$\left(\frac{\Gamma}{\Gamma_{SM}}\right)_{WW^* \rightarrow 2l2\nu} \simeq c_V^2 + 0.051c_{\gamma\gamma}^2 + 0.166c_{Z\gamma}^2 + 0.380c_Vc_{\gamma\gamma} \\ + 0.687c_Vc_{Z\gamma} + 0.184c_{\gamma\gamma}c_{Z\gamma} \\ + 0.021\tilde{c}_{\gamma\gamma}^2 + 0.069\tilde{c}_{Z\gamma}^2 + 0.076\tilde{c}_{\gamma\gamma}\tilde{c}_{Z\gamma}$$

Relative decay widths (2/3)

For $\left(\frac{\Gamma}{\Gamma_{SM}}\right)_{h \rightarrow V_1 V_2}$:

- $V_1 = V_2 = g$ (which gives also $\frac{\sigma_{ggh}}{\sigma_{ggh,SM}}$):

$$\widehat{c_{gg}} \simeq c_{gg} + 10^{-2} 1.298 c_t - 10^{-3} (0.765 - 1.077i) c_b$$

$$\widetilde{c_{gg}} \simeq \widetilde{c}_{gg} - 10^{-2} 1.975 \widetilde{c}_t + 10^{-3} (0.875 - 1.084i) \widetilde{c}_b$$

$$|\widehat{c_{gg,SM}}| \simeq 0.0123$$

- $V_1 = V_2 = \gamma$:

$$\begin{aligned}\widehat{c_{\gamma\gamma}} &\simeq c_{\gamma\gamma} + 10^{-2} (1.050 c_V - 0.231 c_t) + 10^{-5} (3.399 - 4.786i) c_b \\ &\quad + 10^{-5} (2.934 - 2.674i) c_\tau\end{aligned}$$

$$\begin{aligned}\widetilde{c_{\gamma\gamma}} &\simeq \widetilde{c}_{\gamma\gamma} + 10^{-3} 3.509 \widetilde{c}_t - 10^{-5} (3.887 - 4.813i) \widetilde{c}_b \\ &\quad - 10^{-5} (3.136 - 2.676i) \widetilde{c}_\tau\end{aligned}$$

$$|\widehat{c_{\gamma\gamma,SM}}| \simeq 0.0083$$

Relative decay widths (3/3)

- $V_1 = Z, V_2 = \gamma$:

$$\widehat{c_{Z\gamma}} \simeq c_{Z\gamma} + 10^{-2}(1.507c_V - 0.0784c_t) + 10^{-5}(2.063 - 1.210i)c_b \\ + 10^{-7}(3.570 - 1.535i)c_\tau$$

$$\widehat{\tilde{c}_{Z\gamma}} \simeq \tilde{c}_{Z\gamma} + 10^{-3}1.190\tilde{c}_t - 10^{-5}(2.414 - 1.213i)\tilde{c}_b \\ - 10^{-7}(4.008 - 1.536i)\tilde{c}_\tau$$

$$|\widehat{c_{Z\gamma,SM}}| \simeq 0.0143$$