Constraints on Higgs couplings via an Effective Theory Framework

Hermès Bélusca–Maïto
hermes.belusca@th.u-psud.fr

in collaboration with Adam Falkowski

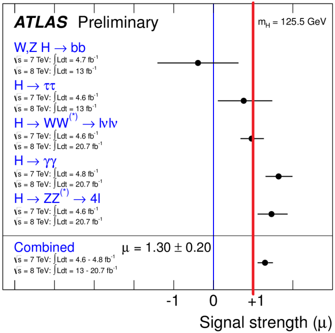
Laboratoire de Physique Théorique, Université Paris-Sud XI, Orsay, France

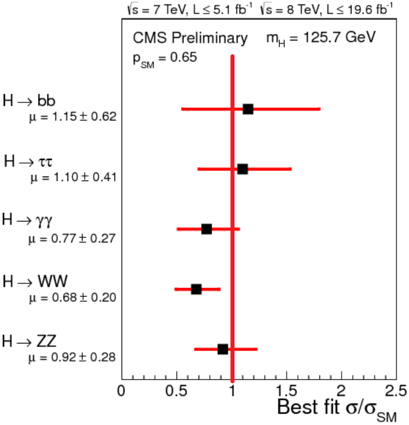
Cargèse International School, 15th July 2014

[HBM, Adam Falkowski (arXiv:1311.1113)] and [HBM (arXiv:1404.5343)]

Motivation

- No new physics (NP) signs seen at LHC so far. Higgs strongly looks SM-like (production and decay rates, spin-parity).





Motivation

- No new physics (NP) signs seen at LHC so far. Higgs strongly looks SM-like (production and decay rates, spin-parity).
- Fundamental nature of EWSB? Properties? Check for possible tiny departures of Higgs couplings from predicted SM values.

Motivation

- No new physics (NP) signs seen at LHC so far. Higgs strongly looks SM-like (production and decay rates, spin-parity).

- Fundamental nature of EWSB? Properties? Check for possible tiny departures of Higgs couplings from predicted SM values.

$\rightarrow$ *What can we learn from current LHC data?*

Motivation

- No new physics (NP) signs seen at LHC so far. Higgs strongly looks SM-like (production and decay rates, spin-parity).
- Fundamental nature of EWSB? Properties? Check for possible tiny departures of Higgs couplings from predicted SM values.

$\rightarrow$ *What can we learn from current LHC data?*

Two possible approaches:

- use concrete BSM models to interpret Higgs data, or...
- ... use an effective model-independent approach (continuous deformation of the SM) $\rightarrow$ Effective Lagrangian. We need $m(NP) \gg m(EW)$.

Motivation

- No new physics (NP) signs seen at LHC so far. Higgs strongly looks SM-like (production and decay rates, spin-parity).
- Fundamental nature of EWSB? Properties? Check for possible tiny departures of Higgs couplings from predicted SM values.

$\rightarrow$ *What can we learn from current LHC data?*

Two possible approaches:

- use concrete BSM models to interpret Higgs data, or...
- ... use an effective model-independent approach (continuous deformation of the SM) $\rightarrow$ Effective Lagrangian. We need $m(NP) \gg m(EW)$.

Additional assumptions for Higgs $\mathcal{L}_{eff}$

In this work several assumptions made on NP:

- No violation of baryon and lepton numbers. No FCNC.

- We also suppose that the Higgs boson h is part of the Higgs field H that trasforms as $(\mathbf{1}, \mathbf{2})_{1/2}$ representation of the Standard Model $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge group and acquires an expectation value v.

Additional assumptions for Higgs $\mathcal{L}_{eff}$

In this work several assumptions made on NP:

- No violation of baryon and lepton numbers. No FCNC.
- We also suppose that the Higgs boson h is part of the Higgs field H that trasforms as $(\mathbf{1},\mathbf{2})_{1/2}$ representation of the Standard Model $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge group and acquires an expectation value v.

Higgs $\mathcal{L}_{eff}$

- SM Lagrangian:

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

- and the dimension-6 Lagrangian ([Grzadkowski et al. (arXiv:1008.4884)], choice of basis from [Contino et al. (arXiv:1303.3876)]):

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

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

$$\mathcal{L}_{CPC} = \Delta\mathcal{L}_{SILH} + \cancel{\Delta\mathcal{L}_{Fv}} + \cancel{\Delta\mathcal{L}_{Fd}} + \cancel{\Delta\mathcal{L}_{4F} + \Delta\mathcal{L}_{Gauge}}$$

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

[Contino et al. (arXiv:1303.3876)]

Higgs $\mathcal{L}_{eff}$

Strongly-Interacting Light Higgs [Giudice et al. (arXiv:hep-ph/0703164)]:

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

$\bar{c}_6$ 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)).

Higgs $\mathcal{L}_{eff}$

CP-violating part:

$$\mathcal{L}_{CPV} = \frac{i\widetilde{c}_{HW}\ g}{m_W^2}(D^\mu H)^\dagger \sigma^i (D^\nu H)\widetilde{W}^i_{\mu\nu} + \frac{i\widetilde{c}_{HB}\ g'}{m_W^2}(D^\mu H)^\dagger (D^\nu H)\widetilde{B}_{\mu\nu}$$
$$+ \frac{\widetilde{c}_\gamma\ g'^2}{m_W^2}(H^\dagger H) B_{\mu\nu}\widetilde{B}^{\mu\nu} + \frac{\widetilde{c}_g\ g_S^2}{m_W^2}(H^\dagger H) G^a_{\mu\nu}\widetilde{G}^{a\mu\nu}$$
$$+ \frac{\widetilde{c}_{3W}\ g^3}{m_W^2}\epsilon^{ijk} W^{i\nu}_\mu W^{j\rho}_\nu \widetilde{W}^{k\mu}_\rho + \frac{\widetilde{c}_{3G}\ g_S^3}{m_W^2} f^{abc} G^{a\nu}_\mu G^{b\rho}_\nu \widetilde{G}^{c\mu}_\rho$$

Gauge self-couplings modifications are also ignored here.

Higgs $\mathcal{L}_{eff}$

Final expression:

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

with the CP-conserving part:

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

and the CP-violating part:

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

Higgs $\mathcal{L}_{eff}$

In unitary gauge, after expansion of the Higgs field around its vev. and canonical normalization of the Higgs kinetic term: $\mathcal{L}_{eff} = \mathcal{L}_0 + \mathcal{L}_h + \cdots$:

$$\begin{aligned}\mathcal{L}_h = \frac{h}{v}\Big[& 2c_W m_W^2 W_\mu^\dagger W^\mu + c_Z m_Z^2 Z_\mu Z^\mu - \sum_{f=u,d,l} m_f \bar{f}\,(c_f + \imath\gamma_5\,\tilde{c}_f)\,f \\ & - \frac{1}{2}c_{WW} W_{\mu\nu}^\dagger W^{\mu\nu} - \frac{1}{4}c_{ZZ} Z_{\mu\nu} Z^{\mu\nu} - \frac{1}{4}c_{\gamma\gamma}\gamma_{\mu\nu}\gamma^{\mu\nu} - \frac{1}{2}c_{Z\gamma}\gamma_{\mu\nu}Z^{\mu\nu} + \frac{1}{4}c_{gg} G_{\mu\nu}^a G^{a\mu\nu} \\ & - \frac{1}{2}\tilde{c}_{WW} W_{\mu\nu}^\dagger \widetilde{W}^{\mu\nu} - \frac{1}{4}\tilde{c}_{ZZ} Z_{\mu\nu} \widetilde{Z}^{\mu\nu} - \frac{1}{4}\tilde{c}_{\gamma\gamma}\gamma_{\mu\nu}\widetilde{\gamma}^{\mu\nu} - \frac{1}{2}\tilde{c}_{Z\gamma}\gamma_{\mu\nu}\widetilde{Z}^{\mu\nu} + \frac{1}{4}\tilde{c}_{gg} G_{\mu\nu}^a \widetilde{G}^{a\mu\nu} \\ & - (\kappa_{WW} W^\mu D^\nu W_{\mu\nu}^\dagger + \text{h.c.}) - \kappa_{ZZ} Z^\mu \partial^\nu Z_{\mu\nu} - \kappa_{Z\gamma} Z^\mu \partial^\nu \gamma_{\mu\nu} \Big]\end{aligned}$$

The c_i and $\tilde{c}_i$ parameters are function of the SILH ones.

Simplifications via S, T, U oblique parameters

Dimension-6 operators introduce at 1-loop quartic (in T only), quadratic and logarithmic divergences in S, T, U that should cancel ($\rightarrow$ current constraints on the oblique parameters (GFitter)).
A second hypothesis: no fine-tuned cancellations between operators of different types (CP-even, CP-odd and κ_i).
Removing the quadratic divergences in S, T, U requires the following constraints:

$$\kappa_i = 0 \rightarrow \bar{c}_{HB} + \bar{c}_B = 0 = \bar{c}_{HW} + \bar{c}_W$$
$$c_Z = c_W \equiv c_V \rightarrow \bar{c}_T = 0$$

and:

$$\left.\begin{array}{r} c_{WW} = c_{\gamma\gamma} + \dfrac{c_w}{s_w} c_{Z\gamma} \quad (\text{and} \rightarrow \widetilde{c}_{WW}) \\ c_{ZZ} = c_{WW} - \dfrac{s_w}{c_w} c_{Z\gamma} \quad (\text{and} \rightarrow \widetilde{c}_{ZZ}) \end{array}\right\} \rightarrow \bar{c}_{HW} + \bar{c}_{HB} = 0 = \widetilde{c}_{HW} + \widetilde{c}_{HB}$$

Only logarithmic corrections remain.

Effective couplings kept

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

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

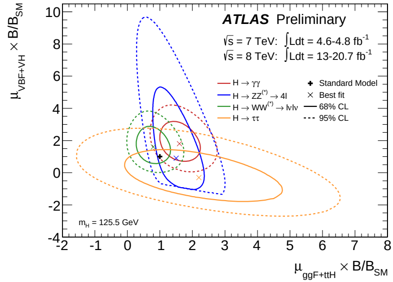
  and 6 independent parameters in the CP-odd sector:

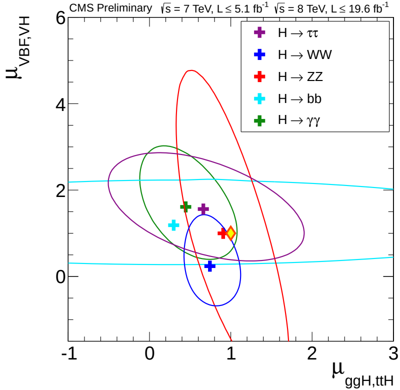
$$\widetilde{c}_u\,,\quad \widetilde{c}_d\,,\quad \widetilde{c}_l\,,\quad \widetilde{c}_{\gamma\gamma}\,,\quad \widetilde{c}_{Z\gamma}\,,\quad \widetilde{c}_{gg}\,.$$

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

Higgs rates

- ATLAS and CMS give the relative Higgs rates (signal strength) $\hat{\mu}^{YH}_{XX} = \frac{\sigma_{YH}}{\sigma^{SM}_{YH}} \frac{\mathrm{Br}(h\to XX)}{\mathrm{Br}(h\to XX)_{SM}}$ in various channels, with: $\frac{\mathrm{Br}(h\to XX)}{\mathrm{Br}(h\to XX)_{SM}} = \frac{\Gamma_{XX}}{\Gamma_{XX,SM}} \frac{\Gamma_{tot,SM}}{\Gamma_{tot}}$, where Γ_{tot} is the sum of all the partial widths.
- We use the given $\hat{\mu}$ values or the 2-dimensional (2D) likelihood functions in $\hat{\mu}_{ggH+ttH}$–$\hat{\mu}_{VBF+VH}$ plane, or exploit their given upper bounds on rates at 95% CL (see [Giardino et al. (arXiv:1303.3570)]).





Relative decay widths

Tree-level Higgs-decay:

$$\left(\frac{\Gamma}{\Gamma_{SM}}\right)_{h\to f\bar{f}} \simeq |c_f|^2 + |\widetilde{c}_f|^2 \quad \text{(light fermions)}$$

$$\left(\frac{\Gamma}{\Gamma_{SM}}\right)_{ZZ^*\to 4l} \text{ and } \left(\frac{\Gamma}{\Gamma_{SM}}\right)_{WW^*\to 2l2\nu}$$

1-loop (SM) + tree-level (effective) generated:
$(V_1 = V_2 = g)$; $(V_1 = V_2 = \gamma)$; $(V_1 = Z, V_2 = \gamma)$

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

Relative decay widths

Tree-level Higgs-decay:

$$\left(\frac{\Gamma}{\Gamma_{SM}}\right)_{h\to f\bar{f}} \simeq |c_f|^2 + |\tilde{c}_f|^2 \quad \text{(light fermions)}$$

$$\left(\frac{\Gamma}{\Gamma_{SM}}\right)_{ZZ^*\to 4l} \text{ and } \left(\frac{\Gamma}{\Gamma_{SM}}\right)_{WW^*\to 2l2\nu}$$

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

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

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

Relative production XSecs

Selection cuts efficiencies taken into account in the relative Xsecs, defined as:

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

Higgs associated production: $\left(\frac{\sigma}{\sigma_{SM}}\right)_{hW/Z}$; Vector boson fusion: $\left(\frac{\sigma}{\sigma_{SM}}\right)_{VBF}$.

Principle

Minimization of:

$$\chi^2(c_i, \widetilde{c}_i) = \chi^2_{EWPT}(\{c_i\}) + \sum \chi^2_{1D}(\hat{\mu}^{th}, \hat{\mu}^{exp} \pm \delta\mu) + \sum \chi^2_{2D}(\hat{\mu}^{th}_{ggH+ttH}, \hat{\mu}^{th}_{VBF+VH}) + \cdots$$

The $\hat{\mu}^{th}$ are functions of the c_i and $\widetilde{c}_i$. SM ggH production uncertainty is taken as a nuisance parameter.

CP-even and odd parameters

Central values and 68% CL intervals for the parameters:

$$c_V = 1.04 \pm 0.03, \quad c_u = 1.31^{+0.10}_{-0.34}, \quad c_d = 0.92^{+0.22}_{-0.13}, \quad c_l = 1.09^{+0.13}_{-0.11},$$
$$c_{gg} = -0.0016^{+0.0021}_{-0.0022}, \quad c_{\gamma\gamma} = 0.0009^{+0.0008}_{-0.0010}, \quad c_{Z\gamma} = -0.0006^{+0.0183}_{-0.0240}.$$

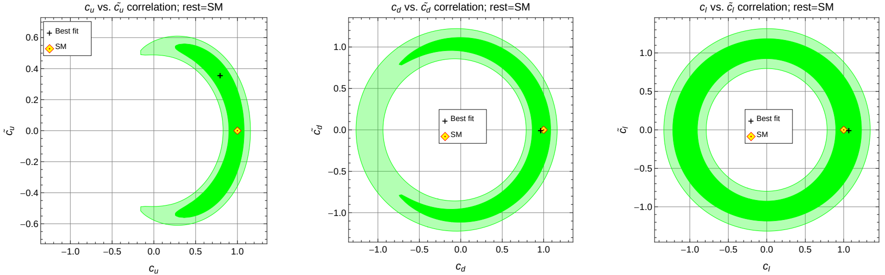
$$\widetilde{c}_u = \pm(0.87^{+0.33}_{-2.08}), \quad \widetilde{c}_d = -0.0035^{+0.4608}_{-0.4581}, \quad \widetilde{c}_l = \pm(0.37^{+0.25}_{-0.99}),$$
$$\widetilde{c}_{gg} = 0.0004^{+0.0038}_{-0.0040}, \quad \widetilde{c}_{\gamma\gamma} = \pm(0.0033^{+0.0017}_{-0.0028}), \quad \widetilde{c}_{Z\gamma} = 0.0075^{+0.0200}_{-0.0345}.$$

$\chi^2_{\mathrm{SM}} - \chi^2_{\mathrm{min}} = 5.3$ meaning SM gives a perfect fit to the Higgs and EW precision data.

However...

... some CP-odd couplings are not constrained by their sign: data actually constrain the sum of the squares of CP-even and CP-odd couplings.

(Pictures – hypotheses: the other parameters take their SM values. Dark green: 68% CL; light green: 95% CL).



Can be greatly improved by using EDMs and LHC High lumi [Brod et al. (arXiv:1310.1385)]; tensor structures [Chen et al. (arXiv:1405.6723)], etc...

Summary

- We used a model-independent effective framework for parametrizing deviations of Higgs couplings to matter from their SM prediction.

- Some of the effective couplings are in fact related to each other, and we further reduce their number arguing about EW oblique corrections.

- We obtain meaningful constraints on most of the CP-even parameters;

- Some CP-odd parameters are constrained, but not all. It should be noted that until now the rate measurements only constrain $|c_f|^2 + |\widetilde{c}_f|^2$ or $\left|\widehat{c_{V_1 V_2}}\right|^2 + \left|\widehat{\widetilde{c}_{V_1 V_2}}\right|^2$ → more elaborate methods needed to constrain the possible values of CP-even and CP-odd parameters! (e.g. EDMs, tensor structure of $H \to VV$, ...).

Thank you!

Backup slides

Effective Approach – Basics

- We suppose NP at high energy scale $\rightarrow$ new heavy degrees of freedom.
- At lower energies, NP effect is to modify interactions of SM fields (modify SM predictions).
- Formally: NP fields are integrated out, generation of (non-renormalisable) dim. ≥ 5 effective operators.

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{d \geq 5} \frac{\mathcal{C}^{(d)}}{\Lambda^{d-4}} \mathcal{O}^{(d)} (\{\text{SM fields}\})$$

- $\mathcal{L}_{SM}$: the usual Standard-Model Lagrangian.
- Λ: energy scale of NP;
  $\mathcal{C}^{(d)}$: dimensionless effective coupling ("Wilson coefficient");
  $\mathcal{O}^{(d)}$: effective operator, *function of SM fields only*.

Effective Approach – Basics

- We suppose NP at high energy scale $\rightarrow$ new heavy degrees of freedom.
- At lower energies, NP effect is to modify interactions of SM fields (modify SM predictions).
- Formally: NP fields are integrated out, generation of (non-renormalisable) dim. ≥ 5 effective operators.

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

- $\mathcal{L}_{SM}$: the usual Standard-Model Lagrangian.
- $\mathcal{L}_{D=5}$ (Weinberg operator) gives masses to neutrinos, do not play a role in the Higgs phenomenology.

Effective Approach – Basics

- We suppose NP at high energy scale $\rightarrow$ new heavy degrees of freedom.
- At lower energies, NP effect is to modify interactions of SM fields (modify SM predictions).
- Formally: NP fields are integrated out, generation of (non-renormalisable) dim. ≥ 5 effective operators.

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

- $\mathcal{L}_{SM}$: the usual Standard-Model Lagrangian.
- $\mathcal{L}_{D=5}$ (Weinberg operator) gives masses to neutrinos, do not play a role in the Higgs phenomenology.
- $\mathcal{L}_{D=6}$ is the part of interest for us!

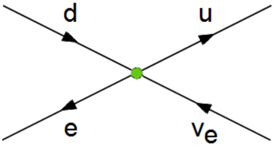
Effective Approach – Basics

- We suppose NP at high energy scale $\rightarrow$ new heavy degrees of freedom.
- At lower energies, NP effect is to modify interactions of SM fields (modify SM predictions).
- Formally: NP fields are integrated out, generation of (non-renormalisable) dim. ≥ 5 effective operators.

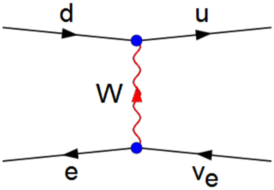
$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \mathcal{L}_{D=5} + \mathcal{L}_{D=6} + \ldots$$

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

Example: Fermi theory – β decay: $d\ e^+ \to u\ \overline{\nu_e}$



(a) Effective vertex



(b) Exchange of W, + propag./vertex rad. corr.

$$(a) : \frac{G_F}{\sqrt{2}} \overline{u}\gamma_\mu(1-\gamma_5)d \times \overline{e}\gamma^\mu(1-\gamma_5)\nu_e \,, \quad \frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2} \text{ i.e. } [G_F] = -2$$

$$(b) : \frac{g}{\sqrt{2}} \overline{u}\gamma^\mu \frac{1-\gamma_5}{2} d \times \frac{g_{\mu\nu} - \frac{p_\mu p_\nu}{M_W^2}}{p^2 - M_W^2} \times \frac{g}{\sqrt{2}} \overline{e}\gamma^\nu \frac{1-\gamma_5}{2} \nu_e \,, \quad [g^2] = 0$$

The W and corrections are "integrated-out" in the effective vertex.

Dimension-6 operators (history)

- Original list by [Buchmüller et al. (Nucl.Phys.B268(1986)621), . . .], supposing no baryon + lepton numbers violation, 80 operators 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)].

Dimension-6 operators (history)

- Original list by [Buchmüller et al. (Nucl.Phys.B268(1986)621), ...], supposing no baryon + lepton numbers violation, 80 operators 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)].

Dimension-6 operators (history)

- Original list by [Buchmüller et al. (Nucl.Phys.B268(1986)621), . . .], supposing no baryon + lepton numbers violation, 80 operators 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)].

Neglected piceces of Higgs $\mathcal{L}_{eff}$

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

- 2-fermion vertex operators $\Delta\mathcal{L}_{F_1}$; couplings of fermions to SM gauge bosons modified; strong constraints from EW measurements $\rightarrow$ Higgs phenomenology not really affected.
- 2-fermion dipole operators $\Delta\mathcal{L}_{F_2}$; contributes to electric dipole moments and anomalous magnetic moments; strong constraints from EW measurements; contribute to 3-body Higgs decay $\rightarrow$ very suppressed.
- $\Delta\mathcal{L}_{4F}$ (4-fermion operators) and $\Delta\mathcal{L}_{Gauge}$ (pure-gauge operators) are ignored because they do not affect Higgs phenomenology.
  $\Delta\mathcal{L}_{Gauge}$ modifies only triple and quadruple gauge couplings.

Neglected piceces of Higgs $\mathcal{L}_{eff}$

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

- 2-fermion vertex operators $\Delta\mathcal{L}_{F_1}$; couplings of fermions to SM gauge bosons modified; strong constraints from EW measurements $\rightarrow$ Higgs phenomenology not really affected.

- 2-fermion dipole operators $\Delta\mathcal{L}_{F_2}$; contributes to electric dipole moments and anomalous magnetic moments; strong constraints from EW measurements; contribute to 3-body Higgs decay $\rightarrow$ very suppressed.

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

Neglected piececes of Higgs $\mathcal{L}_{eff}$

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

- 2-fermion vertex operators $\Delta\mathcal{L}_{F_1}$; couplings of fermions to SM gauge bosons modified; strong constraints from EW measurements $\rightarrow$ Higgs phenomenology not really affected.

- 2-fermion dipole operators $\Delta\mathcal{L}_{F_2}$; contributes to electric dipole moments and anomalous magnetic moments; strong constraints from EW measurements; contribute to 3-body Higgs decay $\rightarrow$ very suppressed.

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

$\mathcal{L}_{eff} = \mathcal{L}_0 + \mathcal{L}_h + \cdots$

$$\mathcal{L}_0 = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}Z_{\mu\nu}Z^{\mu\nu} - \frac{1}{4}W^+_{\mu\nu}W^{-\mu\nu} - \frac{1}{4}G^a_{\mu\nu}G^{a\mu\nu} + \overline{f_L}^i \imath \not{D}\, f^i_L + \overline{f_R}^i \imath \not{D}\, f^i_R$$
$$+ \frac{m_W^2}{2}W^+_\mu W^{-\mu} + \frac{m_Z^2}{2}(1-\bar{c}_T)Z_\mu Z^\mu - \sum_{f=u,d,l} m_f \bar{f} f$$
$$+ 2\bar{c}_\gamma \tan^2\theta_W \left(s_w^2 Z_{\mu\nu}Z^{\mu\nu} + c_w^2 \gamma_{\mu\nu}\gamma^{\mu\nu} - 2 s_w c_w Z_{\mu\nu}\gamma^{\mu\nu}\right) + 2\bar{c}_g \frac{g_S^2}{g^2} G_{\mu\nu}G^{\mu\nu} + \text{CP-Odd}$$
$$+ \bar{c}_B Z^\mu \partial^\nu \left(\tan^2\theta_W Z_{\mu\nu} - \tan\theta_W \gamma_{\mu\nu}\right) + \text{CP-Odd}$$
$$+ \bar{c}_W \left(\tan\theta_W Z^\mu \partial^\nu \gamma_{\mu\nu} + Z^\mu \partial^\nu Z_{\mu\nu} + W^\mu D^\nu W^\dagger_{\mu\nu} + \text{h.c.}\right) + \text{CP-Odd}$$
$$+ \bar{c}_{HB} \times \text{3-boson} + \bar{c}_{HW} \times \text{3-boson} + \text{CP-Odd}$$

$$\mathcal{L}_h = \frac{h}{v}\Big[2c_W m_W^2 W^\dagger_\mu W^\mu + c_Z m_Z^2 Z_\mu Z^\mu - \sum_{f=u,d,l} m_f \bar{f}\,(c_f + \imath\gamma_5\, \tilde{c}_f)\, f$$
$$- \frac{1}{2}c_{WW} W^\dagger_{\mu\nu}W^{\mu\nu} - \frac{1}{4}c_{ZZ} Z_{\mu\nu}Z^{\mu\nu} - \frac{1}{4}c_{\gamma\gamma}\gamma_{\mu\nu}\gamma^{\mu\nu} - \frac{1}{2}c_{Z\gamma}\gamma_{\mu\nu}Z^{\mu\nu} + \frac{1}{4}c_{gg} G^a_{\mu\nu}G^{a\mu\nu}$$
$$- \frac{1}{2}\tilde{c}_{WW} W^\dagger_{\mu\nu}\widetilde{W}^{\mu\nu} - \frac{1}{4}\tilde{c}_{ZZ} Z_{\mu\nu}\widetilde{Z}^{\mu\nu} - \frac{1}{4}\tilde{c}_{\gamma\gamma}\gamma_{\mu\nu}\widetilde{\gamma}^{\mu\nu} - \frac{1}{2}\tilde{c}_{Z\gamma}\gamma_{\mu\nu}\widetilde{Z}^{\mu\nu} + \frac{1}{4}\tilde{c}_{gg} G^a_{\mu\nu}\widetilde{G}^{a\mu\nu}$$
$$- \left(\kappa_{WW} W^\mu D^\nu W^\dagger_{\mu\nu} + \text{h.c.}\right) - \kappa_{ZZ} Z^\mu \partial^\nu Z_{\mu\nu} - \kappa_{Z\gamma} Z^\mu \partial^\nu \gamma_{\mu\nu} \Big]$$

Not all of these parameters are independent. Indeed, it is a consequence of the SILH Lagrangian that:

$$
\begin{aligned}
c_{WW} &= c_w^2 c_{ZZ} + 2 c_w s_w c_{Z\gamma} + s_w^2 c_{\gamma\gamma} \\
\widetilde{c}_{WW} &= c_w^2 \widetilde{c}_{ZZ} + 2 c_w s_w \widetilde{c}_{Z\gamma} + s_w^2 \widetilde{c}_{\gamma\gamma} \\
\kappa_{WW} &= c_w^2 \kappa_{ZZ} + c_w s_w \kappa_{Z\gamma}
\end{aligned}
$$

SILH $\to \mathcal{L}_{eff}$ dictionary

$$c_W = 1 - \frac{\bar{c}_H}{2} \quad ; \quad c_Z = 1 - \frac{\bar{c}_H}{2} - 2\bar{c}_T$$

$$c_f = 1 - \frac{\bar{c}_H}{2} + \mathrm{Re}(\bar{c}_f) \quad ; \quad \widetilde{c}_f = \mathrm{Im}(\bar{c}_f) \quad \text{where} \quad f = u, d, l$$

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

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

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

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

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

$$\kappa_{Z\gamma} = -2\frac{s_w}{c_w}\left(\bar{c}_{HW} + \bar{c}_W - \bar{c}_{HB} - \bar{c}_B\right)$$

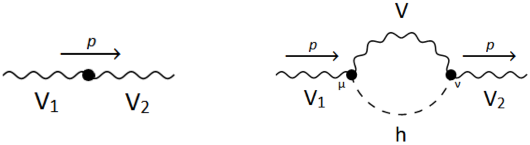
$$\kappa_{ZZ} = -2\left(\bar{c}_{HW} + \bar{c}_W + \frac{s_w^2}{c_w^2}\bar{c}_{HB} + \frac{s_w^2}{c_w^2}\bar{c}_B\right)$$

$$\kappa_{WW} = -2\left(\bar{c}_{HW} + \bar{c}_W\right)$$

Oblique corrections – S, T, U parameters

[Peskin, Takeuchi (Phys.Rev.D46(1992)381-409)]

$V_i = W^{\pm}, Z, \gamma$.



(a) Tree from $\mathcal{L}_0$ (b) Loop from $\mathcal{L}_h$

$$\Pi_{\mu\nu}(p^2) = g_{\mu\nu}\left(\Pi_{V_1V_2}(p^2) = \Pi^{(0)}_{V_1V_2}(0) + p^2\Pi^{(2)}_{V_1V_2}(0) + (p^2)^2\Pi^{(4)}_{V_1V_2}(0) + \cdots\right) + p_\mu p_\nu(\cdots)$$

$$\alpha S = -4 s_w c_w \delta\Pi^{(2)}_{3B} = 4 s_w^2 c_w^2 \left(\delta\Pi^{(2)}_{ZZ} - \delta\Pi^{(2)}_{\gamma\gamma} - \frac{c_w^2 - s_w^2}{s_w c_w}\delta\Pi^{(2)}_{Z\gamma}\right)$$

$$\alpha T = \frac{\delta\Pi^{(0)}_{11} - \delta\Pi^{(0)}_{33}}{m_W^2} = \frac{\delta\Pi^{(0)}_{WW}}{m_W^2} - \frac{c_w^2\delta\Pi^{(0)}_{ZZ}}{m_W^2} = \frac{\delta\Pi^{(0)}_{WW}}{m_W^2} - \frac{\delta\Pi^{(0)}_{ZZ}}{m_Z^2}$$

$$\alpha U = 4 s_w^2\left(\delta\Pi^{(2)}_{11} - \delta\Pi^{(2)}_{33}\right) = 4 s_w^2\left(\delta\Pi^{(2)}_{WW} - c_w^2\delta\Pi^{(2)}_{ZZ} - s_w^2\delta\Pi^{(2)}_{\gamma\gamma} - 2 c_w s_w \delta\Pi^{(2)}_{Z\gamma}\right)$$

Oblique corrections – S, T, U parameters

- At tree-level:

$$\alpha S = 2s_w^2\left(\bar{c}_B + \bar{c}_W\right)\,, \quad \alpha T = \bar{c}_T\,, \quad \alpha U = 0$$

- At 1-loop, the dimension-6 operators introduce quartic (in T only), quadratic and logarithmic divergences in S, T, U.
  Current constraints on the oblique parameters (GFitter) → divergences should cancel.
  A second hypothesis: no fine-tuned cancellations between operators of different types (CP-even, CP-odd and κ_i).

  After cancellation of the quartic divergence in T:

$$S, T, U = \frac{\Lambda^2 - m_H^2 \ln \widetilde{\Lambda}^2}{16\pi^2 v^2}\mathcal{P}(c_i, \widetilde{c}_i, \kappa_{ZZ}) + \mathcal{O}\left(\ln \widetilde{\Lambda}^2\right)$$

  where $\mathcal{P}$ is a multinom of degree 2.

Oblique corrections – S, T, U parameters

- At tree-level:

$$\alpha S = 2s_w^2\left(\bar{c}_B + \bar{c}_W\right)\,, \quad \alpha T = \bar{c}_T\,, \quad \alpha U = 0$$

- At 1-loop, the dimension-6 operators introduce quartic (in T only), quadratic and logarithmic divergences in S, T, U.
  Current constraints on the oblique parameters (GFitter) → divergences should cancel.
  A second hypothesis: no fine-tuned cancellations between operators of different types (CP-even, CP-odd and κ_i).

  After cancellation of the quartic divergence in T:

$$S,\, T,\, U = \frac{\Lambda^2 - m_H^2 \ln \widetilde{\Lambda}^2}{16\pi^2 v^2}\mathcal{P}(c_i, \widetilde{c}_i, \kappa_{ZZ}) + \mathcal{O}\left(\ln \widetilde{\Lambda}^2\right)$$

  where $\mathcal{P}$ is a multinom of degree 2.

Relative decay widths (1/3)

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

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

$$\begin{aligned}
\widehat{c_{gg}} &\simeq c_{gg} + 10^{-2} 1.298 c_t - 10^{-3}(0.765 - 1.077\imath) c_b \\
\widehat{\tilde{c}_{gg}} &\simeq \tilde{c}_{gg} - 10^{-2} 1.975 \tilde{c}_t + 10^{-3}(0.875 - 1.084\imath) \tilde{c}_b \\
\left|\widehat{c_{gg,SM}}\right| &\simeq 0.0123
\end{aligned}$$

- $\underline{V_1 = V_2 = \gamma}$:

$$\begin{aligned}
\widehat{c_{\gamma\gamma}} \simeq\ & c_{\gamma\gamma} + 10^{-2}(1.050 c_V - 0.231 c_t) + 10^{-5}(3.399 - 4.786\imath) c_b \\
& + 10^{-5}(2.934 - 2.674\imath) c_\tau \\
\widehat{\tilde{c}_{\gamma\gamma}} \simeq\ & \tilde{c}_{\gamma\gamma} + 10^{-3} 3.509 \tilde{c}_t - 10^{-5}(3.887 - 4.813\imath) \tilde{c}_b \\
& - 10^{-5}(3.136 - 2.676\imath) \tilde{c}_\tau \\
\left|\widehat{c_{\gamma\gamma,SM}}\right| \simeq\ & 0.0083
\end{aligned}$$

Relative decay widths (2/3)

- $\underline{V_1 = Z, V_2 = \gamma}$:

$$\begin{aligned}
\widehat{c_{Z\gamma}} &\simeq c_{Z\gamma} + 10^{-2}(1.507 c_V - 0.0784 c_t) + 10^{-5}(2.063 - 1.210\imath) c_b \\
&\quad + 10^{-7}(3.570 - 1.535\imath) c_\tau \\
\widehat{\widetilde{c}_{Z\gamma}} &\simeq \widetilde{c}_{Z\gamma} + 10^{-3} 1.190 \widetilde{c}_t - 10^{-5}(2.414 - 1.213\imath) \widetilde{c}_b \\
&\quad - 10^{-7}(4.008 - 1.536\imath) \widetilde{c}_\tau \\
\left|\widehat{c_{Z\gamma,SM}}\right| &\simeq 0.0143
\end{aligned}$$

Relative decay widths (3/3)

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

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

Relative 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: $\left(\frac{\sigma}{\sigma_{SM}}\right)_{hW/Z}$; Vector boson fusion: $\left(\frac{\sigma}{\sigma_{SM}}\right)_{VBF}$.

Coefficients depend on set of cuts ($\approx\rightarrow$ efficiencies):

- VBF – 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]

- VBF – 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)

  [LHC Higgs XSecs (arXiv:1307.1347)]

Relative production XSecs (1/2 – VH)

$$\left(\frac{\sigma}{\sigma_{SM}}\right)_{hW} \simeq c_V^2 + 24.481c_{\gamma\gamma}^2 + 79.810c_{Z\gamma}^2 - 4.610c_V c_{\gamma\gamma} - 8.324c_V c_{Z\gamma}$$
$$+ 88.405c_{\gamma\gamma}c_{Z\gamma}$$
$$+ 22.430\widetilde{c}_{\gamma\gamma}^2 + 73.122\widetilde{c}_{Z\gamma}^2 + 80.997\widetilde{c}_{\gamma\gamma}\widetilde{c}_{Z\gamma}$$

$$\left(\frac{\sigma}{\sigma_{SM}}\right)_{hZ} \simeq c_V^2 + 18.992c_{\gamma\gamma}^2 + 57.969c_{Z\gamma}^2 - 4.460c_V c_{\gamma\gamma} - 6.708c_V c_{Z\gamma}$$
$$+ 59.580c_{\gamma\gamma}c_{Z\gamma}$$
$$+ 16.546\widetilde{c}_{\gamma\gamma}^2 + 50.645\widetilde{c}_{Z\gamma}^2 + 51.865\widetilde{c}_{\gamma\gamma}\widetilde{c}_{Z\gamma}$$

Relative production XSecs (2/2 – VBF)

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

Table: Table of coefficients α_i and β_i for the VBF relative cross-section. For each coefficient, two values are given, the first one corresponds to a fit where cross-terms $c_{WW} c_{ZZ/\gamma\gamma/Z\gamma}$ (and $\widetilde{c}_{WW} \widetilde{c}_{ZZ/\gamma\gamma/Z\gamma}$) were kept, whereas the parenthesized one corresponds to a fit where those cross-terms were removed, because they are approximately two order of magnitude less (in pink: chosen cuts).

Cut	α_1	α_2	α_3	α_4	α_5	β_1	β_2	β_3
ATLAS	1.483 (1.490)	3.065 (3.086)	0.327 (0.328)	0.569 (0.570)	3.329 (3.352)	1.367 (1.370)	2.765 (2.777)	3.004 (3.017)
CMS	1.281 (1.284)	2.419 (2.429)	0.270 (0.270)	0.465 (0.466)	2.635 (2.645)	1.210 (1.212)	2.243 (2.255)	2.451 (2.460)

Experimental data (1/2)

- Combined Tevatron measurements [CDF & DØ (arXiv:1303.6346)]: $\hat{\mu}^{\text{incl.}}_{\gamma\gamma} = 6.2^{+3.2}_{-3.2}$, $\hat{\mu}^{\text{incl.}}_{WW} = 0.9^{+0.9}_{-0.8}$, $\hat{\mu}^{VH}_{bb} = 1.62^{+0.77}_{-0.77}$, $\hat{\mu}^{\text{incl.}}_{\tau\tau} = 2.1^{+2.2}_{-2.0}$,
- ATLAS and CMS data:

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]
	$\tau\tau$	$1.36^{+0.43}_{-0.38}$	[ATLAS-CONF-2013-108]
VH	bb	$0.2^{+0.7}_{-0.6}$	[ATLAS-CONF-2013-079]
ttH	bb	1.7 ± 1.4	[ATLAS-CONF-2014-011]
	$\gamma\gamma$	-1.39 ± 3.18	[ATLAS-CONF-2013-080]
inclusive	$Z\gamma$	2.18 ± 4.57	[arXiv:1402.3051]
	$\mu\mu$	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	$0.92^{+0.25}_{-0.22}$	[arXiv:1312.5353]
	WW	$0.72^{+0.20}_{-0.18}$	[arXiv:1312.1129]
	$\tau\tau$	$0.97^{+0.27}_{-0.25}$	[arXiv:1401.5041]
VH	bb	1.0 ± 0.5	[arXiv:1310.3687]
VBF	bb	0.7 ± 1.4	[CMS-PAS-HIG-13-011]
ttH	bb	$1.0^{+1.9}_{-2.0}$	[ttH-Combi]
	$\gamma\gamma$	$-0.2^{+2.4}_{-1.9}$	
	$\tau\tau$	$-1.4^{+6.3}_{-5.5}$	
	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]

Experimental data (2/2)

- EW precision measurements from LEP, SLC and Tevatron collected in Table 1 of [Falkowski et al. (arXiv:1303.1812)] using a cut-off scale $\Lambda = 3$ TeV for the logarithmically divergent corrections from the Higgs loops to the EW precision observables.

The χ^2_{EWPT} function can be approximated around its best-fit point $(c_V^0, c_{\gamma\gamma}^0, c_{Z\gamma}^0)$ by the following quadratic form:

$$\chi^2_{EWPT}(\{c_i\}) = 193.005 + \sum_{i,j=V,\gamma\gamma,Z\gamma} (c_i - c_i^0)(\sigma^2)^{-1}_{ij}(c_j - c_j^0)$$

where $(\sigma^2)_{ij} = \sigma_i \rho_{ij} \sigma_j$; its minimum point and the corresponding standard deviations for each component being:

$$c_V^0 = 1.082, \quad c_{\gamma\gamma}^0 = 0.096, \quad c_{Z\gamma}^0 = -0.036,$$
$$\sigma_V = 0.066, \quad \sigma_{\gamma\gamma} = 0.653, \quad \sigma_{Z\gamma} = 0.915$$

and the correlation matrix in the $\{c_V, c_{\gamma\gamma}, c_{Z\gamma}\}$ basis:

$$\rho = \begin{pmatrix} 1 & 0.275 & -0.138 \\ 0.275 & 1 & -0.989 \\ -0.138 & -0.989 & 1 \end{pmatrix}.$$

SM Constants values for the fit

We use the following values for the SM constants (from PDG 2012):

$$G_F = 1.166\,37 \times 10^{-5}\,\text{GeV}^{-2}, \quad \alpha_{EW}(m_Z) = 7.8186 \times 10^{-3},$$
$$\alpha_S(m_Z) \overset{1}{=} 0.1184, \quad m_Z = 91.1876\,\text{GeV}, \quad m_h = 125.6\,\text{GeV}$$

[1] World's average of α_S in 2012, see [arXiv:1210.0325].

2D Likelihoods (1/5)

2D likelihoods functions, defined in the $\hat{\mu}_{ggH+ttH}$–$\hat{\mu}_{VBF+VH}$ plane:

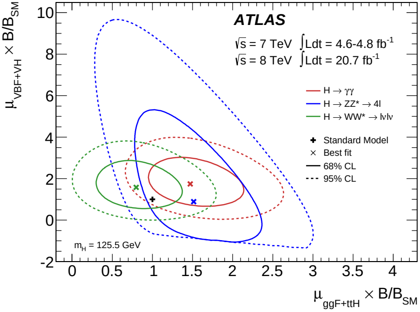
- are given in numerical data form for a limited range of signal strengths: ATLAS $H \to \gamma\gamma$, ZZ and WW (see main slides). For them: polynomial interpolation of order 1 in the range of signal strengths of interest. Or...
- ... only their 95% CL or 68% CL contours are given: ATLAS $H \to \tau\tau$, and CMS $H \to \gamma\gamma$, ZZ, WW and $\tau\tau$. For them: reconstruction of an approximate 2D likelihood function.

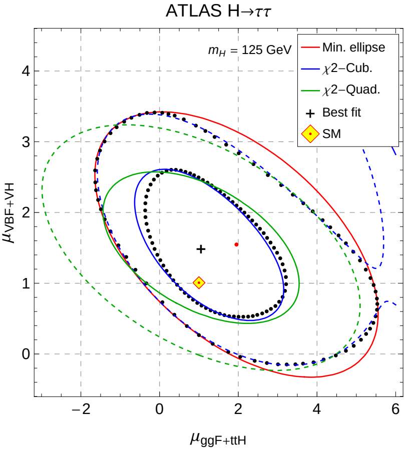
In the following pictures: continuous lines = 68% CL; dashed lines = 95% CL.

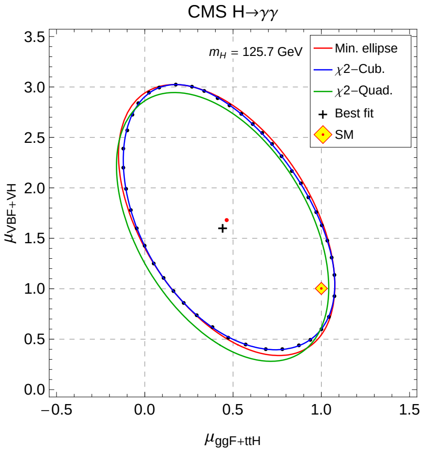
2D Likelihoods (2/5 – Reconstruction)

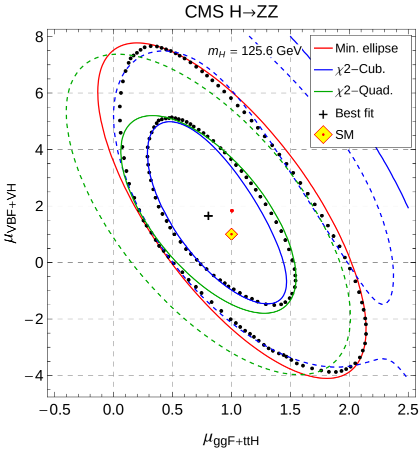
- Quadratic-cubic 2D likelihood fitted polynom inside the enclosed region of a given (closed) 95% CL contour, such that its section corresponding to 95% CL passes through almost all of the points of this contour.
- 95% CL contour approximated by its minimal enclosing ellipse: construction based on the original Welzl's algorithm "Smallest Enclosing Disks (Balls and Ellipsoids)" (improved version used, due to Gärtner et al. "Exact Primitives for Smallest Enclosing Ellipses"; C implementation by P.Sakov).
- 2D quadratic polynom computed such that its minimum coincides with the best-fit point for the given contour, and its section at 95% CL is precisely the computed minimal enclosing ellipse.
- Reconstructed 2D likelihood function is piecewise: the first part is the fitted quadratic-cubic 2D likelihood polynom in the region $\leq$ 95% CL; the second part is made of all the points in the region between this contour and the minimal enclosing ellipse and are set to 95% CL. The third part consists of the fitted 2D quadratic polynom in the region $\geq$ 95% CL. This construction provides us a satisfactory description for the approximate 2D likelihood function continued to the whole $\hat{\mu}_{ggH+ttH}$–$\hat{\mu}_{VBF+VH}$ plane and continuous everywhere, such that it takes the correlations between those rates into account.

2D Likelihoods (3/5 – ATLAS)






CMS H→γγ
m_H = 125.7 GeV
Min. ellipse
χ2–Cub.
χ2–Quad.
Best fit
SM
$\mu_{\mathrm{VBF+VH}}$
$\mu_{\mathrm{ggF+ttH}}$
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
0.0
0.5
1.0
1.5


CMS H→ZZ
m_H = 125.6 GeV
Min. ellipse
χ2–Cub.
χ2–Quad.
Best fit
SM
$\mu_{\mathrm{VBF+VH}}$
$\mu_{\mathrm{ggF+ttH}}$
8
6
4
2
0
−2
−4
−0.5
0.0
0.5
1.0
1.5
2.0
2.5

2D Likelihoods (5/5 – CMS)