

Higgs Couplings in an Effective Theory Framework

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in collaboration with Adam Falkowski



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Based on [HBM, A. Falkowski (arXiv:1311.1113)] and [HBM (arXiv:1404.5343)]
& [HBM, A. Falkowski, *Work in preparation*]

Overview

1 Motivation

- The Standard Model
- The Higgs boson in the SM
- But what?

2 Effective Approach

- The basics & an example...
- Dimension-6 operators & Higgs \mathcal{L}_{eff}

3 Constraints on some Higgs-gauge & Yukawa operators

- Further simplifications for Higgs \mathcal{L}_{eff}
- Physical observables; Global fits
- Summary

4 Flavour-changing Higgs couplings (WIP)

- Why?
- Experimental data
- Summary: what to do

5 Conclusion

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Standard Model Particle Contents (naïve version, no Higgs)

Three Generations of Matter (Fermions)				
	I	II	III	
mass	2.4 MeV/c ²	1.27 GeV/c ²	171.2 GeV/c ²	0
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
Quarks	name	u	c	γ
	mass	2.4 MeV/c ²	1.27 GeV/c ²	0
	charge	$\frac{2}{3}$	$\frac{2}{3}$	0
	spin	$\frac{1}{2}$	$\frac{1}{2}$	1
	name	up	charm	photon
	mass	4.8 MeV/c ²	104 MeV/c ²	0
	charge	$-\frac{1}{3}$	$-\frac{1}{3}$	0
	spin	$\frac{1}{2}$	$\frac{1}{2}$	1
	name	d	s	gluon
Leptons	mass	<2.2 eV/c ²	<0.17 MeV/c ²	<15.5 MeV/c ²
	charge	0	0	0
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Gauge Bosons	mass	0.511 MeV/c ²	105.7 MeV/c ²	1.777 GeV/c ²
	charge	-1	-1	-1
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	name	e	μ	τ
Leptoquarks	mass	80.4 GeV/c ²	91.2 GeV/c ²	100 GeV/c ²
	charge	$\pm\frac{1}{2}$	0	0
	spin	1	0	0
Higgs	mass	125 GeV/c ²	125 GeV/c ²	125 GeV/c ²
	charge	0	0	0
Bosons	mass	0	0	0
	charge	0	0	0

Standard Model Lagrangian (naïve version, no Higgs)

- Symmetry gauge group: $SU(3)_C \times SU(2)_L \times U(1)_Y$.

- Lagrangian:

$$\mathcal{L}_{SM}^0 = \underbrace{-\frac{1}{4} \sum_V V_{\mu\nu}^a V^{a\mu\nu}}_{\text{Gauge kinetic + self-interaction terms}} + \underbrace{\overline{f_L}^i i \not{D} f_L^i + \overline{f_R}^i i \not{D} f_R^i}_{\text{Fermion kinetic + interaction terms}}$$

Field-strength tensor:

$$V_{\mu\nu}^a = \partial_\mu V_\nu^a - \partial_\nu V_\mu^a + \underbrace{g_V f^{abc} V_\mu^b V_\nu^c}_{\text{Only for non-abelian interactions}}$$

Covariant derivative:

$$D_\mu = \partial_\mu - i \sum_V g_V t_V^a V_\mu^a \quad ; \quad \not{D} \equiv \gamma^\mu D_\mu$$

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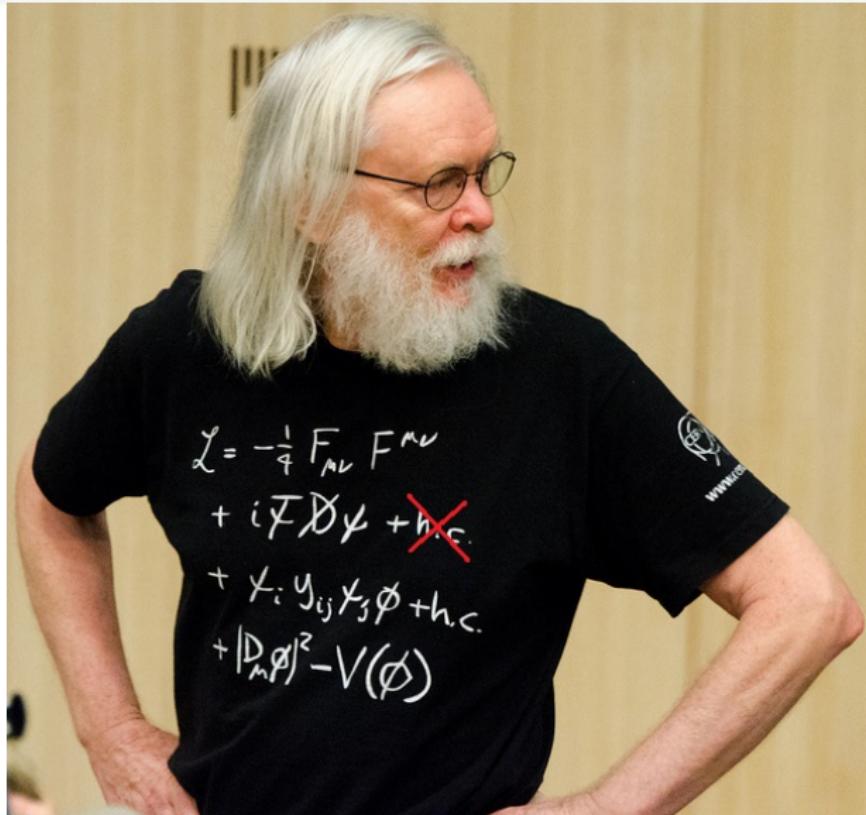
$m\bar{f}f = m\bar{f}_L f_R + m\bar{f}_R f_L$?? *Aaaaaaar* *g* *h*!

→ How can we include masses?

Standard Model Particle Contents (complete version)

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Quarks	name	u	c	t
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	spin	1/2	1/2	1/2
	name	d	s	b
		down	strange	bottom
	mass	<2.2 eV/c ²	<0.17 MeV/c ²	<15.5 MeV/c ²
	charge	0	0	0
Leptons	name	e	ν_μ	ν_τ
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Gauge Bosons	name	e	μ	τ
		electron	muon	tau
	mass	80.4 GeV/c ²	±1	1
	charge	W [±]	W-boson	

Standard Model Lagrangian (complete version)...



... that fits on a T-shirt*!
(after compression)

* notice the peculiarity!

John Ellis, 4th July 2012,
CERN Main Auditorium

Standard Model Lagrangian (complete version)

- Lagrangian:

$$\mathcal{L}_{SM} = \mathcal{L}_{SM}^0 + \underbrace{\left(Y_{ij} \overline{f_L^i} H f_R^j + \text{h.c.} \right)}_{\text{Yukawa terms}} + \underbrace{|D_\mu H|^2}_{\text{Higgs Kinetic + gauge-Higgs interaction terms}} - \underbrace{V(H)}_{\text{Higgs potential}}$$

Gauge invariance is now preserved!

- Higgs $SU(2)_L$ doublet:

$$H = (\phi^+ \quad \phi^0)^T$$

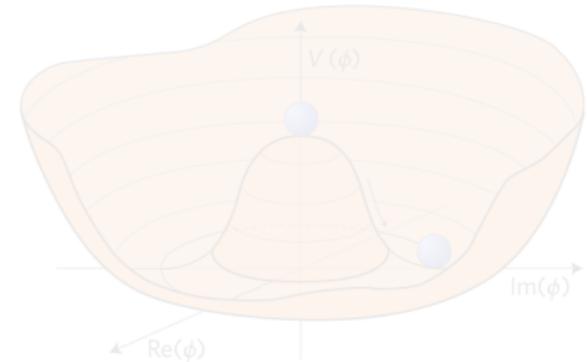
- Higgs potential:

$$V(H) = \mu_H^2 H^\dagger H + \lambda (H^\dagger H)^2$$

When $\mu_H^2 < 0$, EW symmetry breaking (EWSB) happens:

$$SU(2)_L \times U(1)_Y \rightarrow U(1)_{\text{EM}}$$

The potential acquires the famous form:



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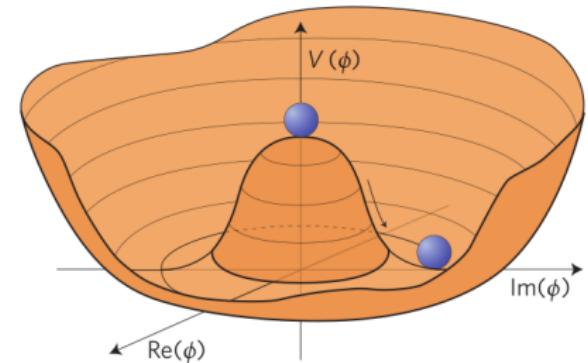
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- After EWSB, the neutral part of the Higgs doublet acquires a vacuum expectation value (vev): v . In unitary gauge:

$$H \rightarrow \frac{v}{\sqrt{2}} \begin{pmatrix} 0 ; 1 + \frac{h}{v} \end{pmatrix}^T$$

Masses and Higgs couplings in the SM (1/2)

The Higgs boson introduces masses for:

- the fermions via the Yukawa terms: $m_f = -\frac{\lambda_f v}{\sqrt{2}}$ (however, not the ν 's).
 → Need to diagonalize the Yukawas for leptons and quarks (CKM matrix appearing).
 → H actually gives mass to down-type fermions only. For up-quarks, use:

$$H^c \equiv i\sigma^2 H^* = \frac{v}{\sqrt{2}} \left(1 + \frac{h}{v} ; 0 \right)^T.$$
 The λ_f are free... so are their masses! ;
- the EW gauge bosons (sauf photon): $M_W = \frac{gv}{2}$; $M_Z = \frac{\sqrt{g^2+g'^2}}{2} v$;
- itself via its potential: $m_H = \sqrt{2}\mu_H = \sqrt{2\lambda v^2}$.
 v known via μ^- decay (G_F and M_W). But λ is free... so is the Higgs mass!

Masses and Higgs couplings in the SM (2/2)

The figure displays five Feynman diagrams illustrating Higgs boson interactions:

- Diagram 1:** Higgs boson h interacting with a fermion-antifermion pair $f\bar{f}$. The vertex is labeled $= -i \frac{m_f}{v}$.
- Diagram 2:** Higgs boson h interacting with a muon neutrino V_μ . The vertex is labeled $= 2i \frac{m_V^2}{v} g_{\mu\nu}$.
- Diagram 3:** Higgs boson h interacting with an electron neutrino V_ν . The vertex is labeled $= 2i \frac{m_V^2}{v^2} g_{\mu\nu}$.
- Diagram 4:** Higgs boson h interacting with three Higgs bosons. The vertex is labeled $= -3i \frac{m_H^2}{v}$.
- Diagram 5:** Higgs boson h interacting with four Higgs bosons. The vertex is labeled $= -6i\lambda \equiv -3i \frac{m_H^2}{v^2}$.

Some remarks...

Even if the Higgs boson solves few problems within the original SM (generation of masses for gauge bosons and fermions, and also (not discussed here) W_L - W_L scattering unitarity), there are still problems present:

- Higgs is a scalar \rightarrow its mass is not protected by any symmetry principle (like gauge invariance, ...) \rightarrow quantum corrections to its mass pushes it to very large values: "hierarchy" problem.
- Arbitrary Yukawa matrices.
- **The Higgs mechanism is ad-hoc: it was introduced by hand!**

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Other enigmas (not related *a priori* to Higgs), not explained by the SM:

- Nature of the Dark Matter; Baryogenesis (f/\bar{f} asymmetry);
- Inflation;
- ...
- and Gravity!

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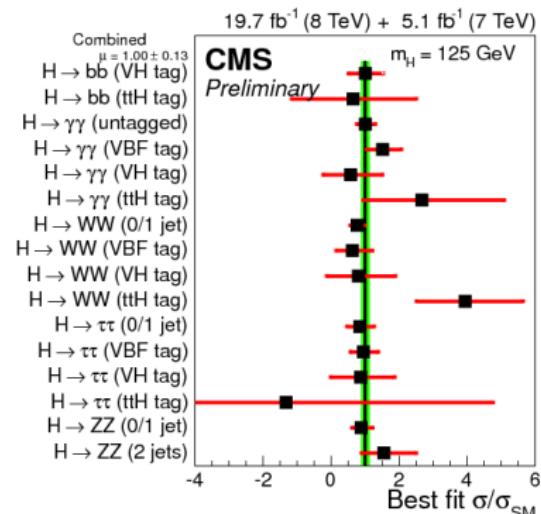
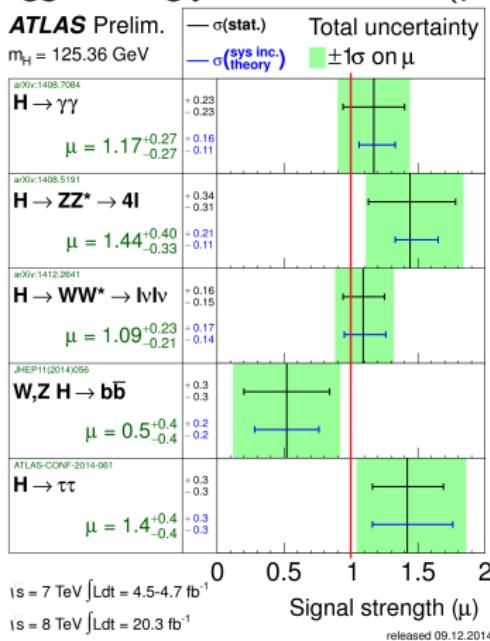
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*The SM+Higgs cannot be the ultimate theory,
we need to go beyond it.*

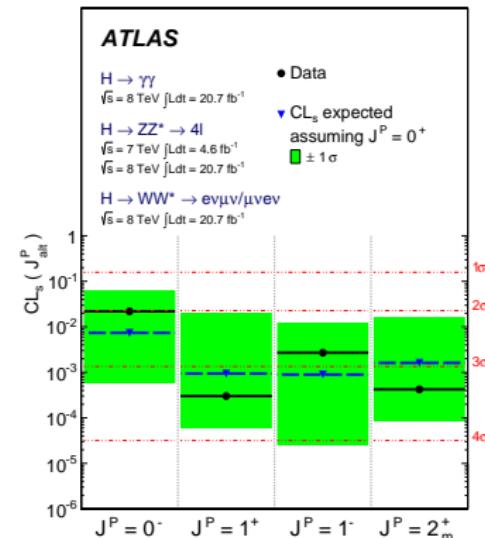
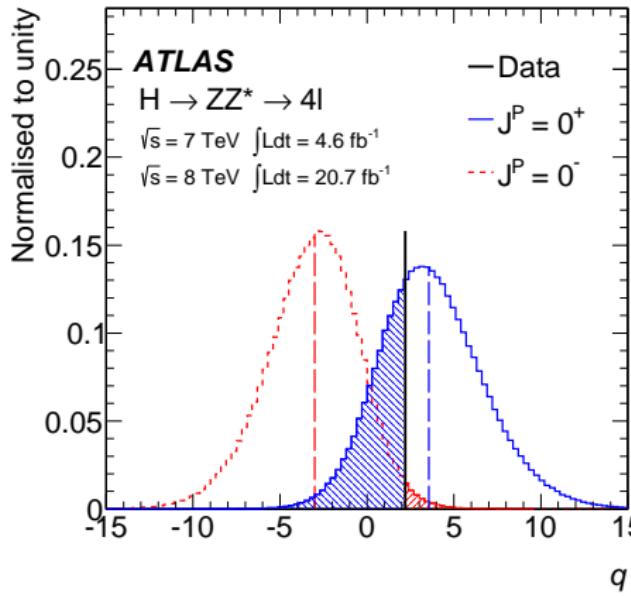
From the experimental side...

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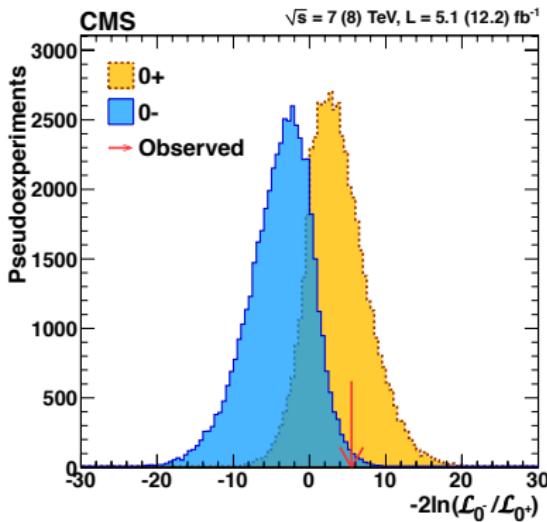
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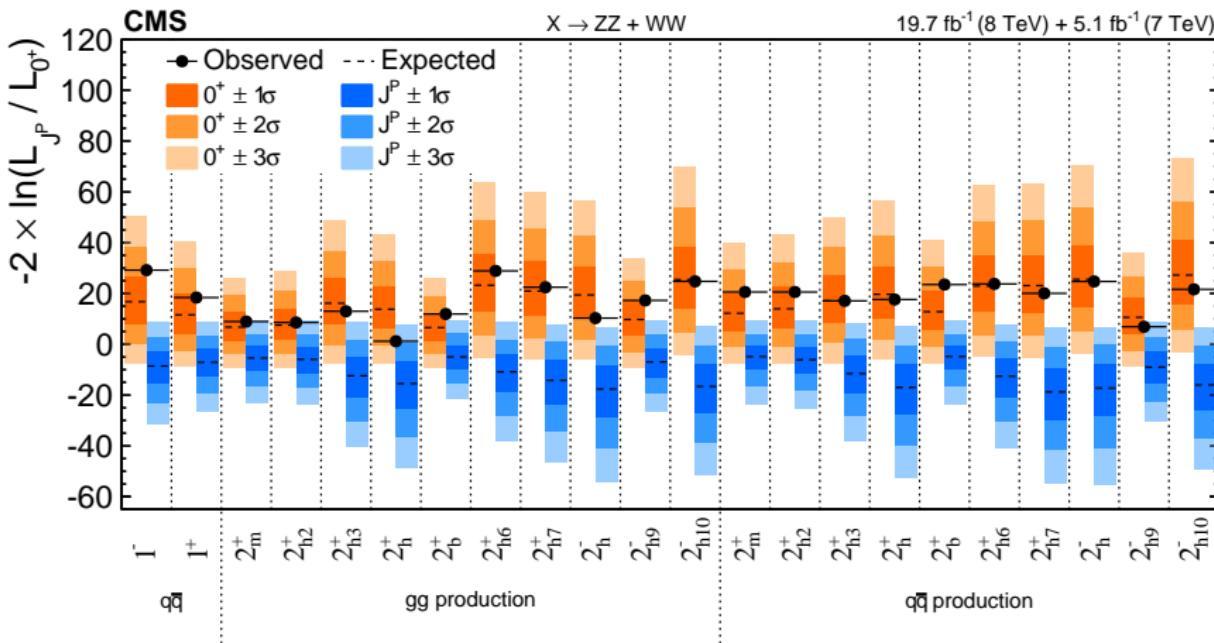
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Two possible approaches:

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

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The basics & an example...

Effective Approach – Basics

- We suppose NP heavy (high energy) degrees of freedom
 \rightarrow Separation of scales.
- 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.

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

- \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*.

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- $\mathcal{L}_{D=6}$ is the part of interest for us!

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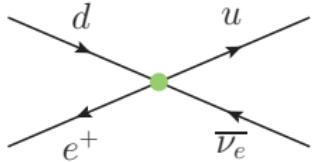
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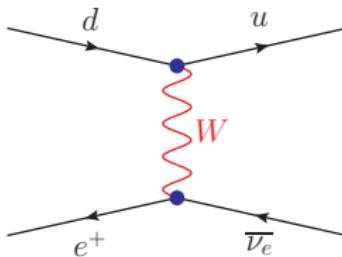
- \mathcal{L}_{SM} : the usual Standard-Model Lagrangian.
- $\mathcal{L}_{D=5}$ (Weinberg operator) gives masses to neutrinos, does not play a role in the Higgs phenomenology.
- $\mathcal{L}_{D=6}$ is the part of interest for us!
- $D > 6$ operators are neglected here as they will not be constrained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

The basics & an example...

Example: Fermi theory – β decay: $d e^+ \rightarrow u \bar{\nu}_e$



(a) Effective vertex



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

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

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

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

The basics & an example...

Non-exhaustive common usages of EFTs

- Chiral Perturbation Theory: describes low-energy pions interactions. Needed because at this scale QCD is non-perturbative.
- Heavy Quark EFT: for describing hadrons with one heavy quark (bottom or charm), and the Non-Relativistic QCD for hadrons with two heavy quarks.
- The SM is very certainly an EFT of some more fundamental UV-complete theory... Gravity too.
- Theories in condensed matter (BCS theory of superconductivity)...

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)] for 1 fermion family (many more with 3 families).
- Using EOMs to redefine operators → different choices of bases available → Need to use a convenient basis, well suited for a study in particular.

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Dimension-6 operators and Higgs \mathcal{L}_{eff} : Prerequisites

In this work several assumptions made on NP:

- Separation of scales: $m(\text{NP}) \gg m(\text{EW})$.
- We also suppose that the Higgs boson h is part of the Higgs field H that transforms 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 a vev: v .
- No violation of baryon and lepton numbers.

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- No violation of baryon and lepton numbers.

Higgs \mathcal{L}_{eff}

- SM Lagrangian (with $V(H)$ the potential seen earlier):

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

- Dimension-6 Lagrangian written in a convenient basis, we use the one of [Contino et al. (arXiv:1303.3876)]:

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

("CPC": charge-parity-conserving (CP-even); "CPV": charge-parity-violating (CP-odd))

In addition we ignore few things:

- Pure gauge self-couplings operators;
- $(H^\dagger H)^3$ 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));

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Overview

1 Motivation

- The Standard Model
- The Higgs boson in the SM
- But what?

2 Effective Approach

- The basics & an example...
- Dimension-6 operators & Higgs \mathcal{L}_{eff}

3 Constraints on some Higgs-gauge & Yukawa operators

- Further simplifications for Higgs \mathcal{L}_{eff}
- Physical observables; Global fits
- Summary

4 Flavour-changing Higgs couplings (WIP)

- Why?
- Experimental data
- Summary: what to do

5 Conclusion

Additional assumptions for the dimension-6 operators

To simplify the fit of the Higgs-gauge and Yukawa coefficients, we impose extra assumptions:

- No Flavour-Changing operators;
- No 2-fermion vertex and dipole operators, and 4-fermion operators.

We will see what happens with them in the next part...

Further simplifications for Higgs \mathcal{L}_{eff}

Higgs \mathcal{L}_{eff}

Final expression:

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

with the CP-conserving part:

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

and the CP-violating part:

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

Further simplifications for Higgs \mathcal{L}_{eff}

Higgs \mathcal{L}_{eff}

After EWSB, in unitary gauge and after canonical normalization of the Higgs kinetic term, we get: $\mathcal{L}_{eff} = \mathcal{L}_0 + \mathcal{L}_h + \dots$ with \mathcal{L}_h having the form:

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

- The c_i and \tilde{c}_i couplings are function of the barred ones (see previous slide).
 - The X_{WW} couplings can be shown to be related to the X_{ZZ} , $X_{Z\gamma}$ and $X_{\gamma\gamma}$ ones.

Further simplifications for Higgs \mathcal{L}_{eff}

Simplifications via S,T,U oblique parameters

- S,T,U parameters [Peskin, Takeuchi] parametrize potential NP contributions to radiative corrections to EW bosons propagators.
- Dimension-6 operators introduce at 1-loop **quartic, quadratic and logarithmic divergences** in S,T,U that should cancel (\rightarrow current constraints on S,T,U (GFitter)).
- A second hypothesis: **no fine-tuned cancellations** between operators of **different types** (CP-even, CP-odd and κ_i).

Removing the divergences in S,T,U requires the following constraints:

$$\kappa_i = 0$$

$$c_Z = c_W \equiv c_V (\rightarrow \bar{c}_T = 0 : \text{custodial symmetry})$$

$$c_{WW} = c_{\gamma\gamma} + \frac{c_w}{s_w} c_{Z\gamma} \quad (\text{and } \rightarrow \tilde{c}_{WW})$$

$$c_{ZZ} = c_{WW} - \frac{s_w}{c_w} c_{Z\gamma} \quad (\text{and } \rightarrow \tilde{c}_{ZZ})$$

Only logarithmic corrections remain.

Effective couplings kept

- The 1st-order Higgs Lagrangian 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:

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

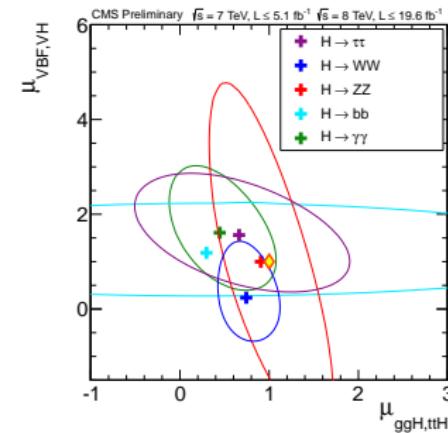
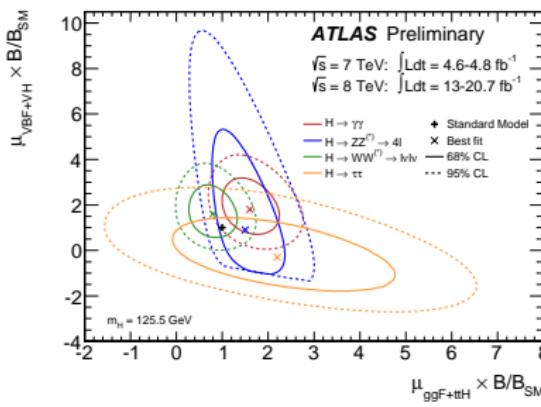
- The SM Higgs is the case where $c_V = c_{f=u,d,l} = 1$, $c_{\gamma\gamma} = c_{Z\gamma} = c_{gg} = 0$ (at tree level) and all the $\tilde{c}_i = 0$.

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

Higgs rates

- We use the relative Higgs rates (signal strength) $\hat{\mu}_{XX}^{YH} = \frac{\sigma_{YH}}{\sigma_{YH}^{SM}} \frac{\text{Br}(h \rightarrow XX)}{\text{Br}(h \rightarrow XX)_{SM}}$ given by ATLAS and CMS in various channels, with:

$$\frac{\text{Br}(h \rightarrow XX)}{\text{Br}(h \rightarrow XX)_{SM}} = \frac{\Gamma_{XX}}{\Gamma_{XX,SM}} \frac{\Gamma_{tot,SM}}{\Gamma_{tot}}$$
, 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 also [Giardino et al. (arXiv:1303.3570)]).



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:

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

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

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Relative production Xsecs

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

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

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

Principle of the fit

Minimization of:

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

The $\hat{\mu}^{th}$ are functions of the c_i and \tilde{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 (as of end of April 2014):

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

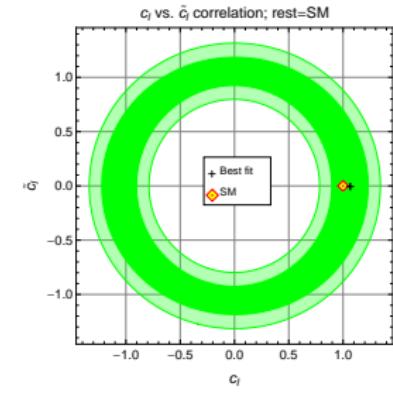
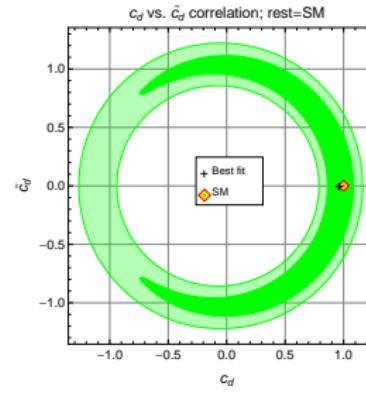
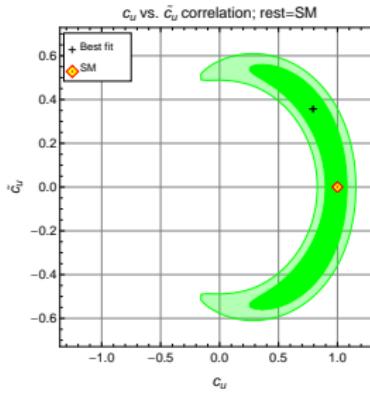
$$\tilde{c}_u = \pm(0.87_{-2.08}^{+0.33}), \quad \tilde{c}_d = -0.0035_{-0.4581}^{+0.4608}, \quad \tilde{c}_l = \pm(0.37_{-0.99}^{+0.25}), \\ \tilde{c}_{gg} = 0.0004_{-0.0040}^{+0.0038}, \quad \tilde{c}_{\gamma\gamma} = \pm(0.0033_{-0.0028}^{+0.0017}), \quad \tilde{c}_{Z\gamma} = 0.0075_{-0.0345}^{+0.0200}.$$

$\chi^2_{\text{SM}} - \chi^2_{\text{min}} = 5.3$ 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: contrary to the previous slide, here 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...

3rd-generation CP-violation constraints for t and τ [Brod et al. (arXiv:1310.1385)], supposing SM values for the other generations.

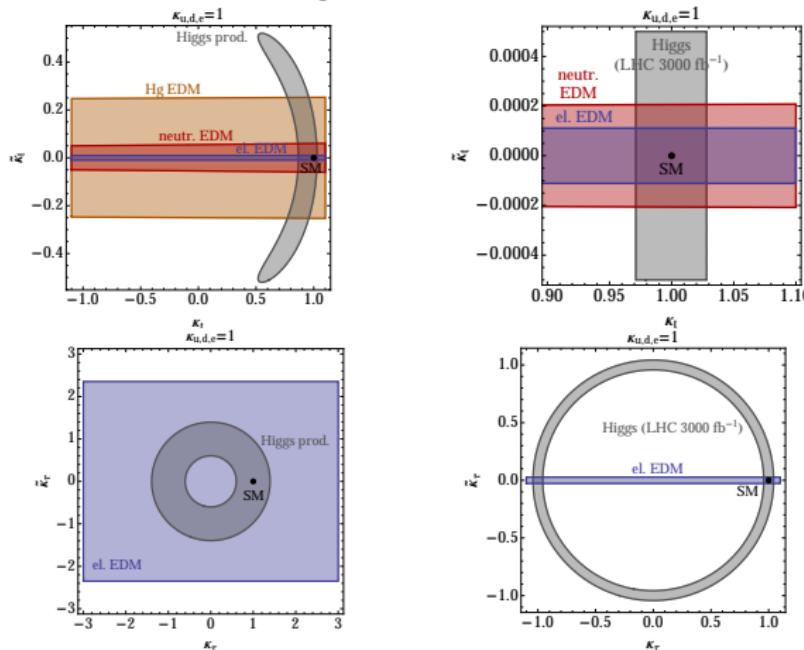


Figure: Left: Present constraints on top and tau Higgs couplings from EDMs and Higgs measurements. Right: Projected future constraints considering 14 TeV LHC at 3000 fb^{-1} and improvements of factor 90 over the current electron and 300 over the current neutron EDM limits. ($\kappa_i \equiv c_i$ and $\tilde{\kappa}_i \equiv \tilde{c}_i$).

Summary

- Reduce number of the effective couplings that are related to each other, and reduce more using EW oblique corrections arguments.
- We obtain meaningful constraints on most of the CP-even parameters, they are SM-compatible within 68% CL;
- Some CP-odd parameters are constrained, but not all. It should be noted that until now the rate measurements only constrain $|c_f|^2 + |\tilde{c}_f|^2$ or $|\widehat{c_{V_1 V_2}}|^2 + |\widehat{\tilde{c}_{V_1 V_2}}|^2 \rightarrow$ more elaborate methods needed to constrain the possible values of CP-even and CP-odd parameters! (e.g. EDMs, tensor structure of $H \rightarrow VV$, ...).

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Why looking at Flavour-changing Higgs?

- In the SM there is no flavour-changing Higgs couplings (to fermions) because you can always diagonalize the Yukawa matrices (and rotate the fermions to this mass basis) (separately for up- and down-type quarks, and leptons).
- Some dimension-6 operators can introduce flavour-violating interactions:
 - The Yukawa-like operators: $\frac{H^\dagger H}{v^2} \bar{c}_f y_f \overline{f_L} H f_R + \text{h.c.}$ (for quarks and leptons) introduce corrections to the SM Higgs couplings to fermions, such that the mass and Yukawa terms take the form:

$$\overline{f'_L}^i m_f^i f'_R{}^i + \overline{f'_L}^i \left(m_f^i \delta^{ij} + \bar{C}_f^{ij} \right) f'_R{}^j \frac{h}{v}$$

(i, j : flavour indices; f' denotes fermions after rotation to the mass basis).

The matrix \bar{C}_f^{ij} can be anything and in particular, not being diagonal and hence be a potential source for flavour violation.

- The 2-fermion vertex (e.g. $\frac{i \bar{c}_H^{ij}}{v^2} (\overline{q_L}^i \gamma^\mu q_L^j)(H^\dagger \overleftrightarrow{D}_\mu H)$) and dipole operators (e.g. $\frac{(\bar{c}_{dB} y_d)^{ij} g'}{m_W^2} (\overline{q_L}^i H \sigma^{\mu\nu} d_R^j) B_{\mu\nu}$).
- The 4-fermion operators: $(\overline{L} L)(\overline{L} L)$, $(\overline{R} R)(\overline{R} R)$, $(\overline{L} L)(\overline{R} R)$, $(\overline{L} R)(\overline{L} R)$.

In this part the operators of the previous section will be ignored, whereas we will focus now on part of those FV operators.

Direct searches

- Lepton flavour violation: $h \rightarrow \tau\mu$ by CMS: [CMS-PAS-HIG-14-005]. However, limit derived supposing that no other NP operators were present and the other diagonal Higgs couplings (for the vectors and for the other leptons and quarks) are SM-like.

Process	95% CL. upper limits on Br	Ref.
$h \rightarrow \tau\mu$	1.57×10^{-2}	[CMS-PAS-HIG-14-005]

NOTE: There are some indirect limits on $h \rightarrow \mu e$ and $h \rightarrow \tau e$ set via constraints from $\mu \rightarrow e\gamma$ and $\tau \rightarrow e\gamma$ (see 1209.1397). They are:
 $Br(h \rightarrow \mu e) \leq 1.0 \times 10^{-8}$ and $Br(h \rightarrow \tau e) \leq 2.0 \times 10^{-1}$.

- Quark flavour violation:

Process	95% CL. upper limits on Br	Ref.
$t \rightarrow q (= c + u) h$	7.9×10^{-3}	ATLAS [arXiv:1403.6293]
$t \rightarrow ch$	5.6×10^{-3}	CMS [CMS-PAS-HIG-13-034]

Indirect searches (Leptonic sector)

Process	95% CL. upper limits on Br	Ref.
$\mu \rightarrow e\gamma$	5.7×10^{-13}	MEG [arXiv:1303.0754]
$\mu \rightarrow 3e$	1.0×10^{-12}	SINDRUM [SIN-PR-87-09]
$\tau \rightarrow e\gamma$	3.3×10^{-8}	BaBar [arXiv:0908.2381]
$\tau \rightarrow \mu\gamma$	4.4×10^{-8}	BaBar [arXiv:0908.2381]
$\tau \rightarrow 3e$	2.7×10^{-8}	Belle [arXiv:1001.3221]
$\tau^- \rightarrow e^- \mu^+ \mu^-$	2.7×10^{-8}	Belle [arXiv:1001.3221]
$\tau^- \rightarrow e^+ \mu^- \mu^-$	1.7×10^{-8}	Belle [arXiv:1001.3221]
$\tau \rightarrow 3\mu$	2.1×10^{-8}	Belle [arXiv:1001.3221]
$\tau^- \rightarrow \mu^- e^+ e^-$	1.8×10^{-8}	Belle [arXiv:1001.3221]
$\tau^- \rightarrow \mu^+ e^- e^-$	1.5×10^{-8}	Belle [arXiv:1001.3221]
$Z^0 \rightarrow \mu e$	7.5×10^{-7}	ATLAS [arXiv:1408.5774]
$Z^0 \rightarrow \tau e$	9.8×10^{-6}	OPAL [CERN-PPE-95-043]
$Z^0 \rightarrow \tau \mu$	1.2×10^{-5}	DELPHI [CERN-PPE-96-129]

Indirect searches (Quark sector)

Process	95% CL. upper limits on Br	Ref.
$t \rightarrow Zu$	5.1×10^{-3} (single top)	CMS [CMS-PAS-TOP-12-021]
$t \rightarrow Zc$	11.40×10^{-2}	
$t \rightarrow Zq (= c + u)$	0.05×10^{-2}	CMS [arXiv:1312.4194]

And also, D^0 , $B_{d/s}^0$ and K^0 mesons oscillations constraints, see Table 2 of [Harnik, Kopp, Zupan ([arXiv:1209.1397](#))] and [UTfit Collab. ([arXiv:0707.0636](#))].

Indirect searches

We use the indirect upper limits from the processes listed above to obtain constraints on effective coefficients combinations, from which we can derive upper limits on NP processes.

If only vertex operators in the game:

$$Br(h \rightarrow Z\mu^\pm e^\mp) \leq (1.14 \pm 0.01) \times 10^{-10}$$

$$Br(h \rightarrow Z\tau^\pm e^\mp) \leq (1.51 \pm 0.01) \times 10^{-9}$$

$$Br(h \rightarrow Z\tau^\pm \mu^\mp) \leq (1.84 \pm 0.02) \times 10^{-9}$$

If only dipole operators in the game:

$$Br(h \rightarrow Z\mu^\pm e^\mp) \leq (1.33 \pm 0.01) \times 10^{-8}$$

$$Br(h \rightarrow Z\tau^\pm e^\mp) \leq (1.71 \pm 0.01) \times 10^{-7}$$

$$Br(h \rightarrow Z\tau^\pm \mu^\mp) \leq (2.11 \pm 0.01) \times 10^{-7}$$

Processes generated only with dipole operators:

$$Br(h \rightarrow \gamma\mu^\pm e^\mp) \leq (3.4634 \pm 0.0006) \times 10^{-39}$$

$$Br(h \rightarrow \gamma\tau^\pm e^\mp) \leq (1.7344 \pm 0.0003) \times 10^{-15}$$

$$Br(h \rightarrow \gamma\tau^\pm \mu^\mp) \leq (2.2826 \pm 0.0004) \times 10^{-15}$$

Summary

Since studying the full parameter space of dimension-6 operators would be extremely difficult, we can first restrict to the simpler case when only one dimension-6 operator is present at the time.

What needs to be done:

- Obtain the limits on each of the operators from precision tests of the SM. For quark operators, need to use RG equations for dimension-6 operators [Alonso, Jenkins, Manohar, Trott (arXiv:1308.2627, 1310.4838 and 1312.2014)] when using indirect constraints from low-energy processes to obtain bounds on the effective coefficients at high-energy.
- Obtain maximum exotic Higgs branching fraction that these limits permit.
- ...

Overview

1 Motivation

- The Standard Model
- The Higgs boson in the SM
- But what?

2 Effective Approach

- The basics & an example...
- Dimension-6 operators & Higgs \mathcal{L}_{eff}

3 Constraints on some Higgs-gauge & Yukawa operators

- Further simplifications for Higgs \mathcal{L}_{eff}
- Physical observables; Global fits
- Summary

4 Flavour-changing Higgs couplings (WIP)

- Why?
- Experimental data
- Summary: what to do

5 Conclusion

Conclusion

- We used a model-independent effective framework for parametrizing deviations of Higgs couplings to matter from their SM prediction.
- Meaningful constraints on most of the Higgs-gluon and Yukawa CP-even parameters are obtained, they are SM-compatible within 68% CL;
- Some of the Higgs-gluon and Yukawa CP-odd parameters are constrained, but not all, when using the signal strengths. More elaborate methods need to be used to constrain the possible values of CP-even and CP-odd parameters (e.g. EDMs, tensor structure of $H \rightarrow VV$, ...).
- Explore possible BSM flavour-violating Higgs couplings.
- With LHC Run 2 at 14 TeV, check in more detail how these constraints evolve, and hope for an era of Higgs precision physics!

Thank you!

Backup slides

Higgs \mathcal{L}_{eff} : Neglected parts (1/3)

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

- 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.

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Higgs \mathcal{L}_{eff} : Neglected parts (2/3)

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

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

$(H^\dagger H)^3$ 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} : Neglected parts (3/3)

CP-violating part:

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

Gauge self-couplings modifications are also ignored here.

Structure of $\mathcal{L}_{eff} = \mathcal{L}_0 + \mathcal{L}_h + \dots$ (1/2)

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

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

Structure of $\mathcal{L}_{eff} = \mathcal{L}_0 + \mathcal{L}_h + \dots$ (2/2)

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

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

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

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

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

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

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

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

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

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

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

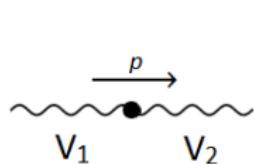
$$\kappa_{ZZ} = -2 \left(\bar{c}_{HW} + \bar{c}_W + \frac{s_w^2}{c_w^2} \bar{c}_{HB} + \frac{s_w^2}{c_w^2} \bar{c}_B \right)$$

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

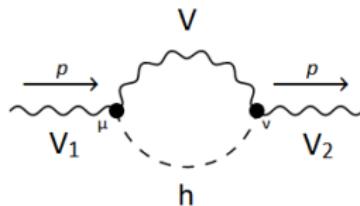
Oblique corrections – S, T, U parameters (1/2)

[Peskin, Takeuchi (Phys.Rev.D46(1992)381-409)] They parametrize potential NP contributions to radiative corrections to EW bosons propagators.

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



(a) Tree from \mathcal{L}_0



(b) Loop from \mathcal{L}_h

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

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

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

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

Oblique corrections – S,T,U parameters (2/2)

- At tree-level:

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

- Dimension-6 operators introduce at 1-loop quartic (in T only), quadratic and logarithmic divergences in S,T,U .

Current constraints on S,T,U (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 :

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

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

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

Simplifications via S,T,U oblique parameters

Removing the divergences in S,T,U requires the following constraints:

$$\begin{aligned}\kappa_i = 0 &\rightarrow \bar{c}_{HB} + \bar{c}_B = 0 = \bar{c}_{HW} + \bar{c}_W \\ c_Z = c_W \equiv c_V &\rightarrow \bar{c}_T = 0 : \text{custodial symmetry}\end{aligned}$$

and:

$$\left. \begin{aligned}c_{WW} &= c_{\gamma\gamma} + \frac{c_w}{s_w} c_{Z\gamma} & (\text{and } \rightarrow \tilde{c}_{WW}) \\ c_{ZZ} &= c_{WW} - \frac{s_w}{c_w} c_{Z\gamma} & (\text{and } \rightarrow \tilde{c}_{ZZ})\end{aligned}\right\} \rightarrow \bar{c}_{HW} + \bar{c}_{HB} = 0 = \tilde{c}_{HW} + \tilde{c}_{HB}$$

Only logarithmic corrections remain.

SM Constants values for numerical computations

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

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

¹World's average of α_S in 2012, see [\[arXiv:1210.0325\]](https://arxiv.org/abs/1210.0325).

²This is the Higgs mass combination from ATLAS and CMS as of April 2014.

Relative decay widths (1/3)

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

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

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

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

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

- $V_1 = V_2 = \gamma$:

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

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

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

Relative decay widths (2/3)

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

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

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

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

Relative decay widths (3/3)

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

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

Relative 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: $p_{TH} \geq 200$ GeV; $p_{TV} \geq 190$ GeV ("boosted" Higgs)

[LHC Higgs XSecs (arXiv:1307.1347)]

Relative production XSecs (1/2 – VH)

$$\left(\frac{\sigma}{\sigma_{SM}} \right)_{hW} \simeq c_V^2 + 24.481c_{\gamma\gamma}^2 + 79.810c_{Z\gamma}^2 - 4.610c_Vc_{\gamma\gamma} - 8.324c_Vc_{Z\gamma}$$

$$+ 88.405c_{\gamma\gamma}c_{Z\gamma}$$

$$+ 22.430\tilde{c}_{\gamma\gamma}^2 + 73.122\tilde{c}_{Z\gamma}^2 + 80.997\tilde{c}_{\gamma\gamma}\tilde{c}_{Z\gamma}$$

$$\left(\frac{\sigma}{\sigma_{SM}} \right)_{hZ} \simeq c_V^2 + 18.992c_{\gamma\gamma}^2 + 57.969c_{Z\gamma}^2 - 4.460c_Vc_{\gamma\gamma} - 6.708c_Vc_{Z\gamma}$$

$$+ 59.580c_{\gamma\gamma}c_{Z\gamma}$$

$$+ 16.546\tilde{c}_{\gamma\gamma}^2 + 50.645\tilde{c}_{Z\gamma}^2 + 51.865\tilde{c}_{\gamma\gamma}\tilde{c}_{Z\gamma}$$

Relative production XSecs (2/2 – VBF)

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

Table: 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 $\tilde{c}_{WW}\tilde{c}_{ZZ/\gamma\gamma/Z\gamma}$) 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 (Values given for the chosen cuts described before).

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](#))]: $\hat{\mu}_{\gamma\gamma}^{\text{incl.}} = 6.2^{+3.2}_{-3.2}$, $\hat{\mu}_{WW}^{\text{incl.}} = 0.9^{+0.9}_{-0.8}$, $\hat{\mu}_{bb}^{VH} = 1.62^{+0.77}_{-0.77}$, $\hat{\mu}_{\tau\tau}^{\text{incl.}} = 2.1^{+2.2}_{-2.0}$,
- 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	$1.0^{+1.9}_{-2.0}$	
	$\gamma\gamma$	$-0.2^{+2.4}_{-1.9}$	[ttH-Combi]
	$\tau\tau$	$-1.4^{+6.3}_{-5.5}$	
	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:

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

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:

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