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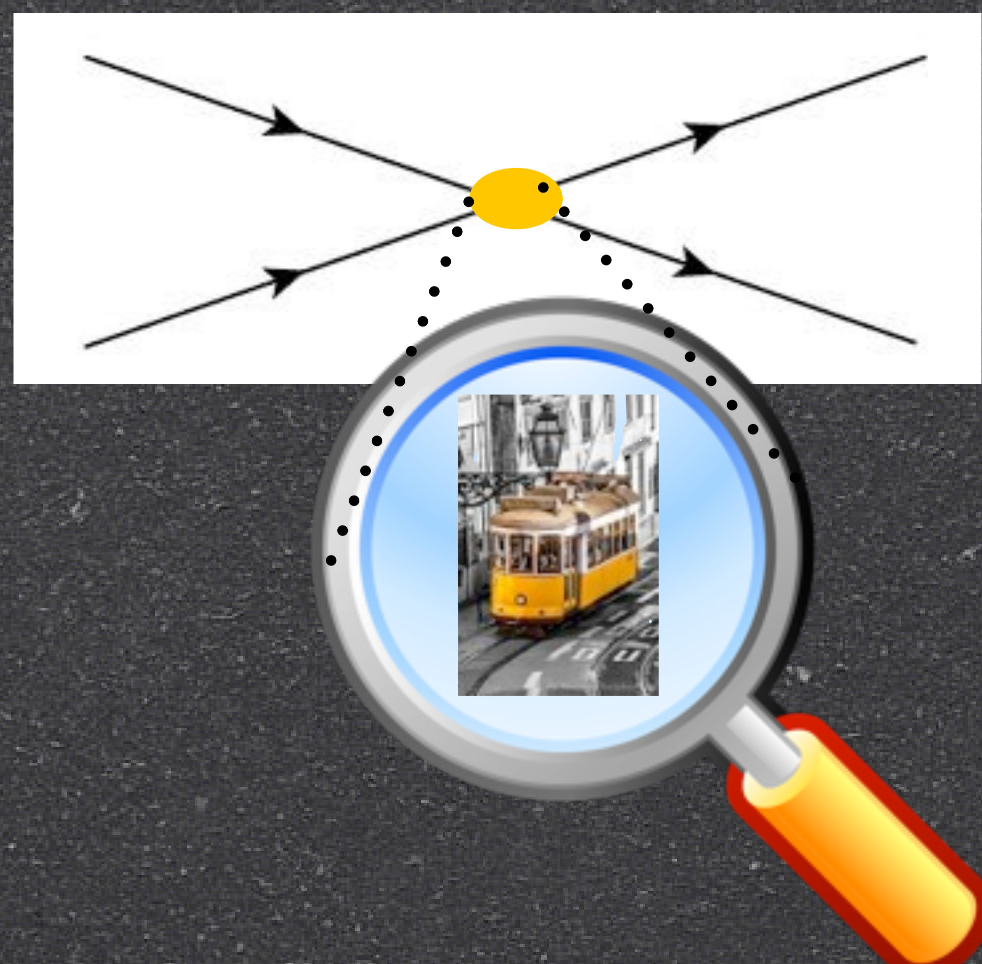
Constraints on Higgs Effective Field Theory

Lisbon Story, 7 September 2016



Based on my 1505.00046, on 1503.07872 with Aielet Efrati and Yotam Soreq, on 1411.0669 with Francesco Riva, on 1508.00581 with Martín Gonzalez-Alonso, Admir Greljo, and David Marzocca, 1511.07434 with Kin Mimouni, and some work in progress

Higgs Boson:
experimental status

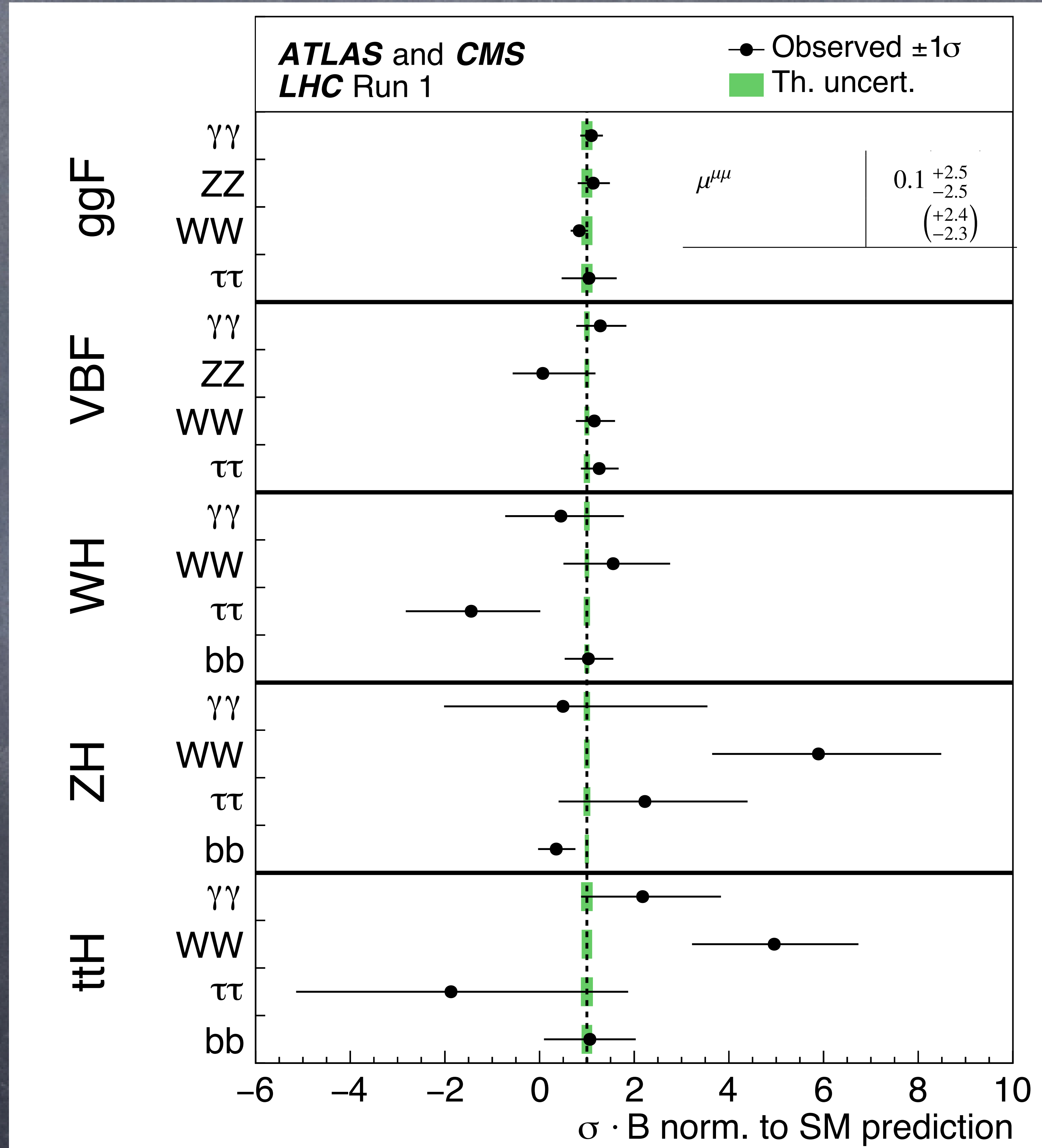
Higgs in Run-1

$$m_H = 125.09 \pm 0.21(\text{stat.}) \pm 0.11(\text{syst.})\ \text{GeV},$$

- Higgs mass very precisely measured, probably more precisely than we'll ever need
- Several decay modes observed with high significance: γγ, ZZ*, WW*, ττ. BB not too far from present sensitivity. Non-trivial constraints on μμ and Zγ modes
- Two distinct production modes observed: gluon fusion, and vector-boson fusion. VH and ttH associated production not too far from Run-1 sensitivity
- Measured rates in perfect agreement with SM predictions

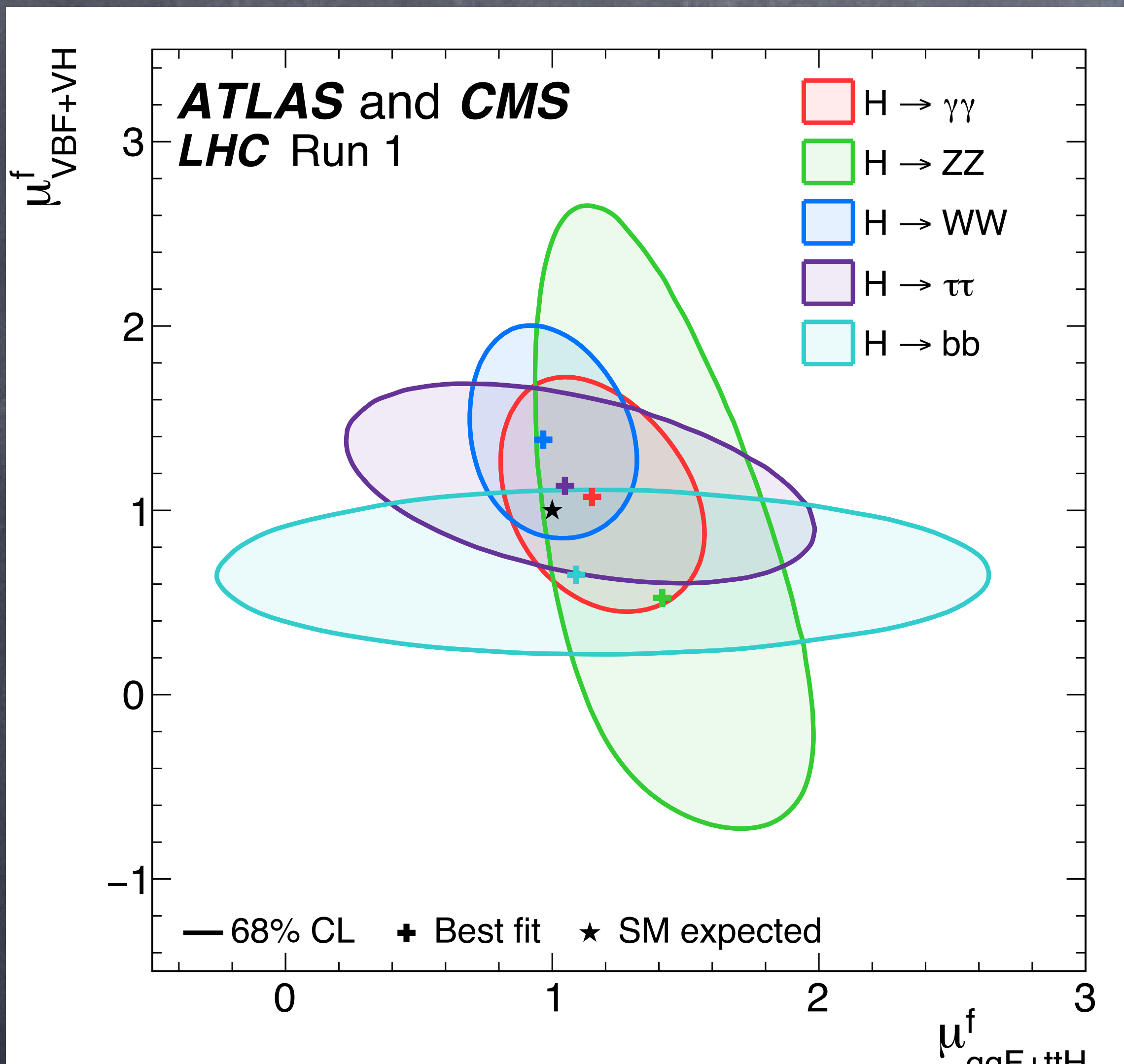
Signal strengths in Run-1

ATLAS+CMS 1606.02266



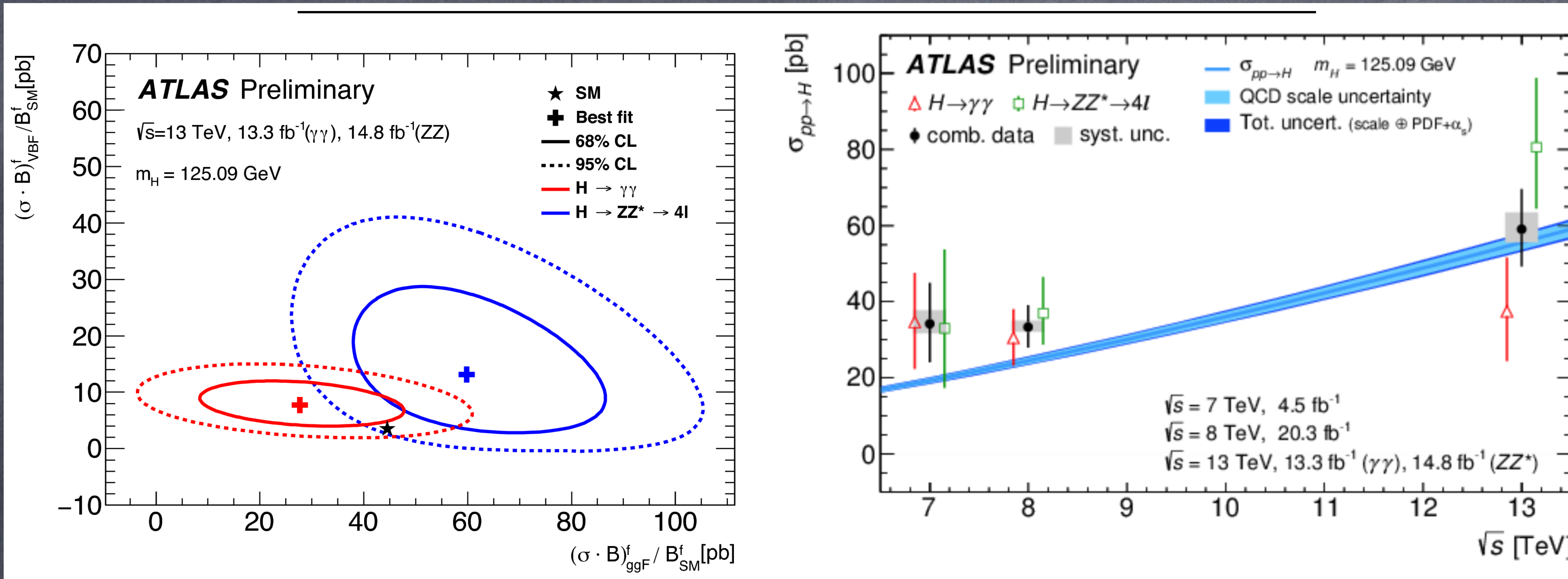
Higgs in Run-1

Non-trivial correlations between measured signal strengths of different production modes. Unfortunately, public information not enough to fully reconstruct them



Decay	Production	μ
$\gamma\gamma$	$\begin{pmatrix} \text{ggh + tth} \\ \text{VBF + Vh} \end{pmatrix}$	$\begin{pmatrix} 1.05^{+0.44}_{-0.41} \\ 1.16^{+0.27}_{-0.24} \end{pmatrix}$
	Wh	$0.5^{+1.3}_{-1.2}$
	Zh	$0.5^{+3.0}_{-2.5}$
	$t\bar{t}h$	$2.2^{+1.6}_{-1.3}$
$Z\gamma$	incl.	$2.7^{+4.5}_{-4.3}$ [1] & $-0.2^{+4.9}_{-4.9}$ [2]
ZZ^*	$\begin{pmatrix} \text{ggh + tth} \\ \text{VBF + Vh} \end{pmatrix}$	$\begin{pmatrix} 1.42^{+0.37}_{-0.33} \\ 0.47^{+1.37}_{-0.92} \end{pmatrix}$
WW^*	$\begin{pmatrix} \text{ggh + tth} \\ \text{VBF + Vh} \end{pmatrix}$	$\begin{pmatrix} 0.98^{+0.22}_{-0.20} \\ 1.38^{+0.41}_{-0.37} \end{pmatrix}$
	Wh	$1.6^{+1.2}_{-1.0}$
	Zh	$5.9^{+2.6}_{-2.2}$
	$t\bar{t}h$	$5.0^{+1.8}_{-1.7}$
$\tau^+\tau^-$	$\begin{pmatrix} \text{ggh} \\ \text{VBF} \end{pmatrix}$	$\begin{pmatrix} 1.0^{+0.6}_{-0.6} \\ 1.3^{+0.4}_{-0.4} \end{pmatrix}$
	Wh	$-1.4^{+1.4}_{-1.4}$
	Zh	$2.2^{+2.2}_{-1.8}$
	$t\bar{t}h$	$-1.9^{+3.7}_{-3.3}$
$b\bar{b}$	Wh	$1.0^{+0.5}_{-0.5}$
	Zh	$0.4^{+0.4}_{-0.4}$
	$t\bar{t}h$	$1.15^{+0.99}_{-0.94}$
$\mu^+\mu^-$	incl.	$0.1^{+2.5}_{-2.5}$

Higgs in Run-2



- For Higgs analyses, the energy gain from 8 to 13 TeV is less relevant than for heavy new physics searches: cross section increases only by factor of 2. Therefore, progress with respect to run-1 is less spectacular.
- Nevertheless, already enough data analyzed to rediscover the Higgs boson at 13 TeV, and rates are measured with similar precision as in Run-1
- So far, Higgs rediscovered in γγ and ZZ channels

Higgs in Run-2

So far...

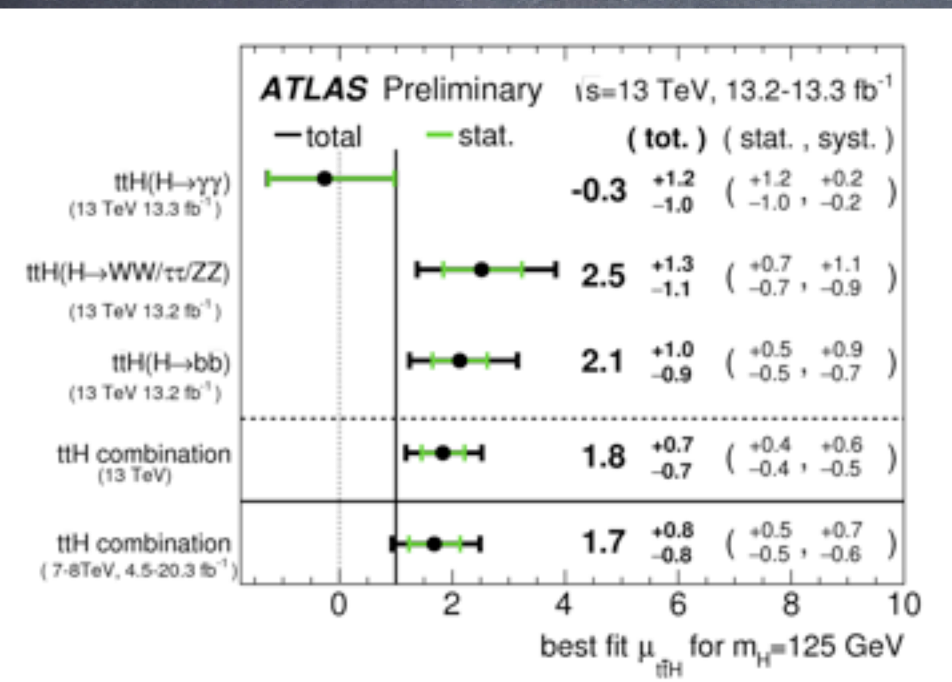
Channel	Production	μ(ATLAS)	μ(CMS)
$\gamma\gamma$	ggh	$0.59^{+0.29}_{-0.28}$	$0.77^{+0.25}_{-0.23}$
	VBF	$2.24^{+0.80}_{-0.71}$	$1.61^{+0.90}_{-0.80}$
	Vh	$0.23^{+1.27}_{-1.05}$	-
	tth	$-0.25^{+1.26}_{-0.99}$	$1.9^{+1.5}_{-1.2}$
ZZ^*	ggh	$1.37^{+0.37}_{-0.34}$	$0.96^{+0.40}_{-0.33}$
	VBF	$3.7^{+2.8}_{-2.1}$	$0.67^{+1.61}_{-0.67}$
	Vh	$0.00^{+2.54}_{-0.17}$	-
	tth	-	$8.4^{+13.1}_{-8.2}$
WW^*	inc	-	0.3 ± 0.5
$b\bar{b}$	VBF	$-3.9^{+2.8}_{-2.9}$	$-3.7^{+2.4}_{-2.5}$
	Vh	$0.21^{+0.51}_{-0.50}$	-
	tth	$2.1^{+1.0}_{-0.9}$	$-2.0^{+1.8}_{-1.8}$
multi-ℓ	cats.	$2.5^{+1.3}_{-1.1}$	$2.3^{+0.9}_{-0.8}$

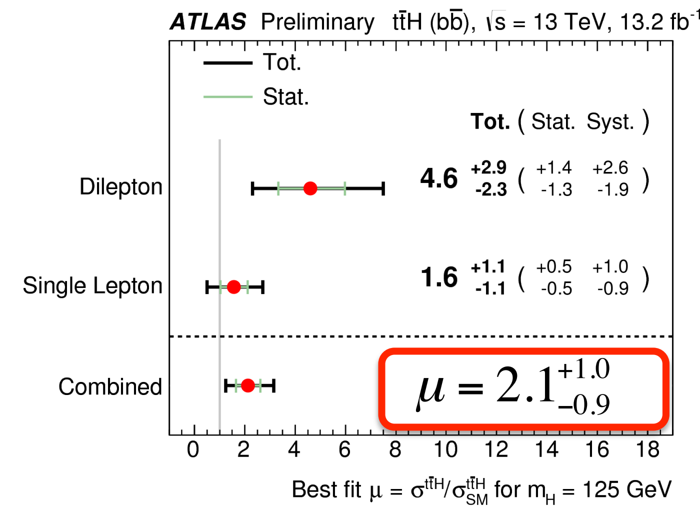
Where run-2 measurements are available, precision is comparable to run-1 results

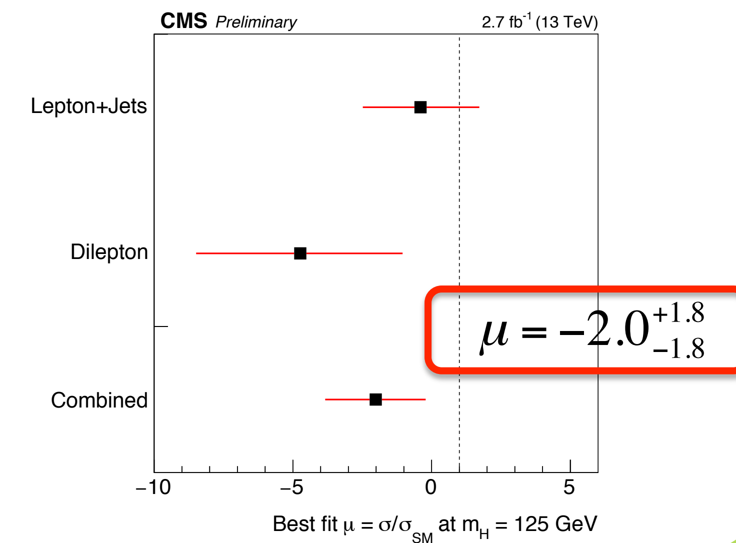
Run-1

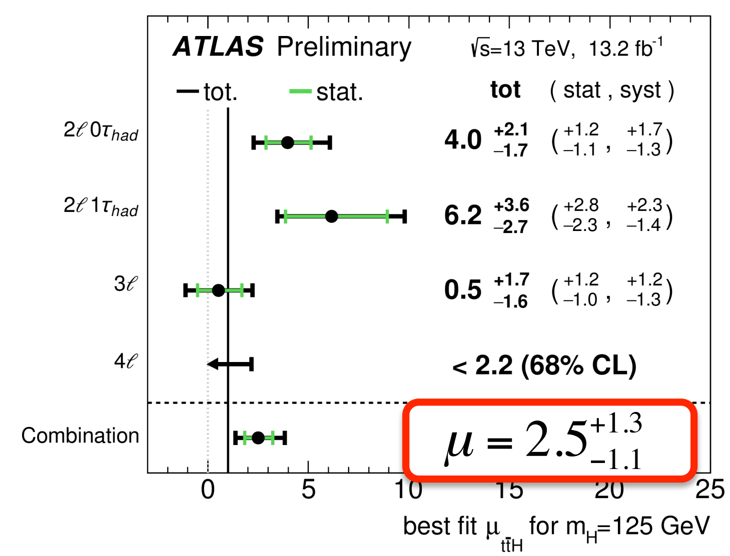
Higgs tth production

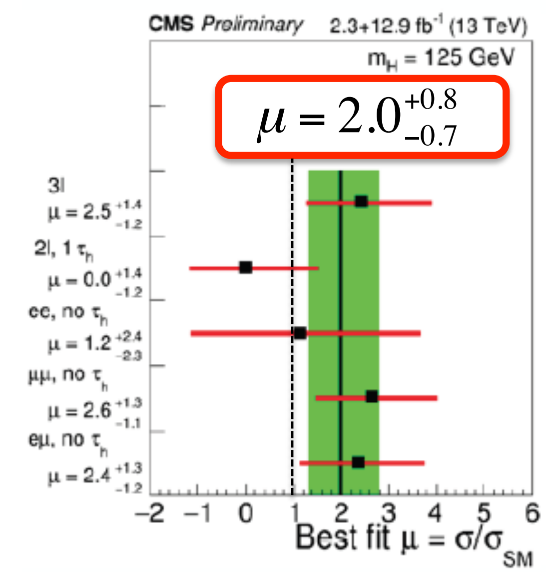
Production process	ATLAS+CMS	ATLAS	CMS
μ_{ggF}	$1.03^{+0.16}_{-0.14}$ $\binom{+0.16}{-0.14}$	$1.26^{+0.23}_{-0.20}$ $\binom{+0.21}{-0.18}$	$0.84^{+0.18}_{-0.16}$ $\binom{+0.20}{-0.17}$
μ_{VBF}	$1.18^{+0.25}_{-0.23}$ $\binom{+0.24}{-0.23}$	$1.21^{+0.33}_{-0.30}$ $\binom{+0.32}{-0.29}$	$1.14^{+0.37}_{-0.34}$ $\binom{+0.36}{-0.34}$
μ_{WH}	$0.89^{+0.40}_{-0.38}$ $\binom{+0.41}{-0.39}$	$1.25^{+0.56}_{-0.52}$ $\binom{+0.56}{-0.53}$	$0.46^{+0.57}_{-0.53}$ $\binom{+0.60}{-0.57}$
μ_{ZH}	$0.79^{+0.38}_{-0.36}$ $\binom{+0.39}{-0.36}$	$0.30^{+0.51}_{-0.45}$ $\binom{+0.55}{-0.51}$	$1.35^{+0.58}_{-0.54}$ $\binom{+0.55}{-0.51}$
μ_{ttH}	$2.3^{+0.7}_{-0.6}$ $\binom{+0.5}{-0.5}$	$1.9^{+0.8}_{-0.7}$ $\binom{+0.7}{-0.7}$	$2.9^{+1.0}_{-0.9}$ $\binom{+0.9}{-0.8}$











- For ttH, cross section increases by factor of 4 between 8 and 13 TeV LHC, so progress is faster.
- Naively combining 13 and 8 TeV results, one could claim discovery of ttH and a 2.5 sigma hint of new physics!

$$\mu_{\rm ttH} = 2.0 \pm 0.4$$

(naive!)

Effective Field Theory approach to Higgs data

Effective Theory Approach to BSM

Basic assumptions

$$H = \frac{1}{\sqrt{2}}\begin{pmatrix} \dots \\ v + h + \dots \end{pmatrix}$$

- New physics scale Λ separated from EW scale v, Λ >> v
- Linearly realized SU(3)xSU(2)xU(1) local symmetry spontaneously broken by VEV of Higgs doublet field

EFT Lagrangian beyond the SM expanded in operator dimension D

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

Appear when starting from BSM theory, and integrating out heavy particles with m≈Λ

Cutoff scale of EFT

Effective Theory Approach to BSM

Basic assumptions

- New physics scale Λ separated from EW scale v, $\Lambda >> v$
- Linearly realized SU(3)xSU(2)xU(1) local symmetry spontaneously broken by VEV of Higgs doublet field

EFT Lagrangian beyond the SM expanded in operator dimension D

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

By assumption, subleading to D=6

Lepton number or B-L violating, hence too small to probed at LHC

Generated by integrating out heavy particle with mass scale Λ
In large class of BSM models, describe leading effects of new physics on weak scale observables

EFT approach to BSM

- To understand all possible leading order deformations of Higgs couplings, we just need to know all possible D=6 operators
- First attempts to classify dimension-6 operators back in 1986

Buchmuller,Wyler pre-arxiv (1986)

- First complete and non-redundant set of operators explicitly written down only in 2010

Grządkowski et al. 1008.4884

- Operators can be traded for other operators using integration by parts, field redefinition, equations of motion, Fierz transformation, etc
- Because of that, one can choose many different bases == non-redundant sets of operators

see e.g.
Grządkowski et al. 1008.4884
Giudice et al hep-ph/0703164
Contino et al 1303.3876

Example of a basis: Warsaw Basis

Bosonic CP-even		Bosonic CP-odd	
O_H	$(H^\dagger H)^3$		
$O_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$		
O_{HD}	$\left\|H^\dagger D_\mu H\right\|^2$		
O_{HG}	$H^\dagger H\, G^a_{\mu\nu} G^a_{\mu\nu}$	$O_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}^a_{\mu\nu} G^a_{\mu\nu}$
O_{HW}	$H^\dagger H\, W^i_{\mu\nu} W^i_{\mu\nu}$	$O_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}^i_{\mu\nu} W^i_{\mu\nu}$
O_{HB}	$H^\dagger H\, B_{\mu\nu} B_{\mu\nu}$	$O_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B_{\mu\nu}$
O_{HWB}	$H^\dagger \sigma^i H\, W^i_{\mu\nu} B_{\mu\nu}$	$O_{H\widetilde{W}B}$	$H^\dagger \sigma^i H\, \widetilde{W}^i_{\mu\nu} B_{\mu\nu}$
O_W	$\epsilon^{ijk} W^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$	$O_{\widetilde{W}}$	$\epsilon^{ijk} \widetilde{W}^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$
O_G	$f^{abc} G^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$	$O_{\widetilde{G}}$	$f^{abc} \widetilde{G}^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$

Table 2.2: Bosonic $d = 6$ operators in the Warsaw basis.

Yukawa	
$[O^\dagger_{eH}]_{IJ}$	$H^\dagger H e^c_I H^\dagger \ell_J$
$[O^\dagger_{uH}]_{IJ}$	$H^\dagger H u^c_I \widetilde{H}^\dagger q_J$
$[O^\dagger_{dH}]_{IJ}$	$H^\dagger H d^c_I H^\dagger q_J$

Vertex		Dipole	
$[O^{(1)}_{H\ell}]_{IJ}$	$i\bar{\ell}_I \bar{\sigma}_\mu \ell_J H^\dagger \overleftrightarrow{D}_\mu H$	$[O^\dagger_{eW}]_{IJ}$	$e^c_I \sigma_{\mu\nu} H^\dagger \sigma^i \ell_J W^i_{\mu\nu}$
$[O^{(3)}_{H\ell}]_{IJ}$	$i\bar{\ell}_I \sigma^i \bar{\sigma}_\mu \ell_J H^\dagger \sigma^i \overleftrightarrow{D}_\mu H$	$[O^\dagger_{eB}]_{IJ}$	$e^c_I \sigma_{\mu\nu} H^\dagger \ell_J B_{\mu\nu}$
$[O_{He}]_{IJ}$	$ie^c_I \sigma_\mu \bar{e}^c_J H^\dagger \overleftrightarrow{D}_\mu H$	$[O^\dagger_{uG}]_{IJ}$	$u^c_I \sigma_{\mu\nu} T^a \widetilde{H}^\dagger q_J\, G^a_{\mu\nu}$
$[O^{(1)}_{Hq}]_{IJ}$	$i\bar{q}_I \bar{\sigma}_\mu q_J H^\dagger \overleftrightarrow{D}_\mu H$	$[O^\dagger_{uW}]_{IJ}$	$u^c_I \sigma_{\mu\nu} \widetilde{H}^\dagger \sigma^i q_J\, W^i_{\mu\nu}$
$[O^{(3)}_{Hq}]_{IJ}$	$i\bar{q}_I \sigma^i \bar{\sigma}_\mu q_J H^\dagger \sigma^i \overleftrightarrow{D}_\mu H$	$[O^\dagger_{uB}]_{IJ}$	$u^c_I \sigma_{\mu\nu} \widetilde{H}^\dagger q_J\, B_{\mu\nu}$
$[O_{Hu}]_{IJ}$	$iu^c_I \sigma_\mu \bar{u}^c_J H^\dagger \overleftrightarrow{D}_\mu H$	$[O^\dagger_{dG}]_{IJ}$	$d^c_I \sigma_{\mu\nu} T^a H^\dagger q_J\, G^a_{\mu\nu}$
$[O_{Hd}]_{IJ}$	$id^c_I \sigma_\mu \bar{d}^c_J H^\dagger \overleftrightarrow{D}_\mu H$	$[O^\dagger_{dW}]_{IJ}$	$d^c_I \sigma_{\mu\nu} \bar{H}^\dagger \sigma^i q_J\, W^i_{\mu\nu}$
$[O_{Hud}]_{IJ}$	$iu^c_I \sigma_\mu \bar{d}^c_J \tilde{H}^\dagger D_\mu H$	$[O^\dagger_{dB}]_{IJ}$	$d^c_I \sigma_{\mu\nu} H^\dagger q_J\, B_{\mu\nu}$

Grządkowski et al. 1008.4884

Assuming baryon and lepton number conservation, 59 different kinds of operators, of which 17 are complex

2499 distinct operators, including flavor structure and CP conjugates

Alonso et al 1312.2014

+4 fermion operators

Example: SILH Basis

	Bosonic CP-even		Bosonic CP-odd
O_H	$\frac{1}{2v^2}\left[\partial_\mu(H^\dagger H)\right]^2$		
O_T	$\frac{1}{2v^2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$		
O_6	$-\frac{\lambda}{v^2}(H^\dagger H)^3$		
O_g	$\frac{g_s^2}{m_W^2} H^\dagger H\, G^a_{\mu\nu}G^a_{\mu\nu}$	$\widetilde{O}_{GG}$	$\frac{g_s^2}{m_W^2} H^\dagger H\, \widetilde{G}^a_{\mu\nu}G^a_{\mu\nu}$
O_γ	$\frac{g'^2}{m_W^2} H^\dagger H\, B_{\mu\nu}B_{\mu\nu}$	$\widetilde{O}_{BB}$	$\frac{g'^2}{m_W^2} H^\dagger H\, \widetilde{B}_{\mu\nu}B_{\mu\nu}$
O_W	$\frac{ig}{2m_W^2}\left(H^\dagger \sigma^i \overleftrightarrow{D}_\mu H\right) D_\nu W^i_{\mu\nu}$		
O_B	$\frac{ig'}{2m_W^2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right) \partial_\nu B_{\mu\nu}$		
O_{HW}	$\frac{ig}{2m_W^2}\left(D_\mu H^\dagger \sigma^i D_\nu H\right) W^i_{\mu\nu}$	$\widetilde{O}_{HW}$	$\frac{ig}{2m_W^2}\left(D_\mu H^\dagger \sigma^i D_\nu H\right) \widetilde{W}^i_{\mu\nu}$
O_{HB}	$\frac{ig'}{2m_W^2}\left(D_\mu H^\dagger D_\nu H\right) B_{\mu\nu}$	$\widetilde{O}_{HB}$	$\frac{ig}{2m_W^2}\left(D_\mu H^\dagger D_\nu H\right) \widetilde{B}_{\mu\nu}$
O_{2W}	$\frac{1}{m_W^2} D_\mu W^i_{\mu\nu} D_\rho W^i_{\rho\nu}$		
O_{2B}	$\frac{1}{m_W^2} \partial_\mu B_{\mu\nu} \partial_\rho B_{\rho\nu}$		
O_{2G}	$\frac{1}{m_W^2} D_\mu G^a_{\mu\nu} D_\rho G^a_{\rho\nu}$		
O_{3W}	$\frac{g^3}{m_W^2} \epsilon^{ijk} W^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$	$\widetilde{O}_{3W}$	$\frac{g^3}{m_W^2} \epsilon^{ijk} \widetilde{W}^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$
O_{3G}	$\frac{g_s^3}{m_W^2} f^{abc} G^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$	$\widetilde{O}_{3G}$	$\frac{g_s^3}{m_W^2} f^{abc} \widetilde{G}^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$

Table 1: Bosonic D=6 operators in the SILH basis.

Giudice et al hep-ph/0703164
Contino et al 1303.3876

More bosonic operators,
at the expense of some 2-fermion
and 4-fermion operators
Total still adds up to 2499

+4 fermion operators

	Yukawa and Vertex
$[O_e]_{ij}$	$\frac{\sqrt{2m_{e_i}m_{e_j}}}{v} H^\dagger H \bar{\ell}_i H e_j$
$[O_u]_{ij}$	$\frac{\sqrt{2m_{u_i}m_{u_j}}}{v} H^\dagger H \bar{q}_i \widetilde{H} u_j$
$[O_d]_{ij}$	$\frac{\sqrt{2m_{d_i}m_{d_j}}}{v} H^\dagger H \bar{q}_i H d_j$
$[O_{H\ell}]_{ij}$	$i\bar{\ell}_i \gamma_\mu \ell_j H^\dagger \overleftrightarrow{D}_\mu H$
$[O'_{H\ell}]_{ij}$	$\frac{i}{v^2}\bar{\ell}_i \sigma^k \gamma_\mu \ell_j H^\dagger \sigma^k \overleftrightarrow{D}_\mu H$
$[O_{He}]_{ij}$	$\frac{i}{v^2}\bar{e}_i \gamma_\mu \bar{e}_j H^\dagger \overleftrightarrow{D}_\mu H$
$[O_{Hq}]_{ij}$	$\frac{i}{v^2}\bar{q}_i \gamma_\mu q_j H^\dagger \overleftrightarrow{D}_\mu H$
$[O'_{Hq}]_{ij}$	$\frac{i}{v^2}\bar{q}_i \sigma^k \gamma_\mu q_j H^\dagger \sigma^k \overleftrightarrow{D}_\mu H$
$[O_{Hu}]_{ij}$	$\frac{i}{v^2}\bar{u}_i \gamma_\mu u_j H^\dagger \overleftrightarrow{D}_\mu H$
$[O_{Hd}]_{ij}$	$\frac{i}{v^2}\bar{d}_i \gamma_\mu d_j H^\dagger \overleftrightarrow{D}_\mu H$
$[O_{Hud}]_{ij}$	$\frac{i}{v^2}\bar{u}_i \gamma_\mu d_j \tilde{H}^\dagger D_\mu H$

	Dipole
$[O_{eW}]_{ij}$	$\frac{g}{m_W^2}\frac{\sqrt{2m_{e_i}m_{e_j}}}{v}\bar{\ell}_i \sigma^k H \sigma_{\mu\nu} e_j W^k_{\mu\nu}$
$[O_{eB}]_{ij}$	$\frac{g'}{m_W^2}\frac{\sqrt{2m_{e_i}m_{e_j}}}{v}\bar{\ell}_i H \sigma_{\mu\nu} e_j B_{\mu\nu}$
$[O_{uG}]_{ij}$	$\frac{g_s}{m_W^2}\frac{\sqrt{2m_{u_i}m_{u_j}}}{v}\bar{q}_i \tilde{H} \sigma_{\mu\nu} T^a u_j G^a_{\mu\nu}$
$[O_{uW}]_{ij}$	$\frac{g}{m_W^2}\frac{\sqrt{2m_{u_i}m_{u_j}}}{v}\bar{q}_i \sigma^k \tilde{H} \sigma_{\mu\nu} u_j W^k_{\mu\nu}$
$[O_{uB}]_{ij}$	$\frac{g'}{m_W^2}\frac{\sqrt{2m_{u_i}m_{u_j}}}{v}\bar{q}_i \tilde{H} \sigma_{\mu\nu} u_j B_{\mu\nu}$
$[O_{dG}]_{ij}$	$\frac{g_s}{m_W^2}\frac{\sqrt{2m_{d_i}m_{d_j}}}{v}\bar{q}_i H \sigma_{\mu\nu} T^a d_j G^a_{\mu\nu}$
$[O_{dW}]_{ij}$	$\frac{g}{m_W^2}\frac{\sqrt{2m_{d_i}m_{d_j}}}{v}\bar{q}_i \sigma^k H \sigma_{\mu\nu} d_j W^k_{\mu\nu}$
$[O_{dB}]_{ij}$	$\frac{g'}{m_W^2}\frac{\sqrt{2m_{d_i}m_{d_j}}}{v}\bar{q}_i H \sigma_{\mu\nu} d_j B_{\mu\nu}$

Higgs couplings to matter in D=6 EFT

Higgs couplings to 2 gauge bosons:

$$
\begin{aligned}
\mathcal{L}_{\rm hvv} =& \frac{h}{v}[2(1+\delta c_w)m_W^2 W_\mu^+ W_\mu^- + (1+\delta c_z)m_Z^2 Z_\mu Z_\mu \\
&+ c_{ww}\frac{g_L^2}{2}W_{\mu\nu}^+ W_{\mu\nu}^- + \tilde{c}_{ww}\frac{g_L^2}{2}W_{\mu\nu}^+ \tilde{W}_{\mu\nu}^- + c_{w\Box}g_L^2\left(W_\mu^- \partial_\nu W_{\mu\nu}^+ + \text{h.c.}\right) \\
&+ c_{gg}\frac{g_s^2}{4}G_{\mu\nu}^a G_{\mu\nu}^a + c_{\gamma\gamma}\frac{e^2}{4}A_{\mu\nu}A_{\mu\nu} + c_{z\gamma}\frac{e g_L}{2c_\theta}Z_{\mu\nu}A_{\mu\nu} + c_{zz}\frac{g_L^2}{4c_\theta^2}Z_{\mu\nu}Z_{\mu\nu} \\
&+ c_{z\Box}g_L^2 Z_\mu \partial_\nu Z_{\mu\nu} + c_{\gamma\Box}g_L g_Y Z_\mu \partial_\nu A_{\mu\nu} \\
&+ \tilde{c}_{gg}\frac{g_s^2}{4}G_{\mu\nu}^a \tilde{G}_{\mu\nu}^a + \tilde{c}_{\gamma\gamma}\frac{e^2}{4}A_{\mu\nu}\tilde{A}_{\mu\nu} + \tilde{c}_{z\gamma}\frac{e g_L}{2c_\theta}Z_{\mu\nu}\tilde{A}_{\mu\nu} + \tilde{c}_{zz}\frac{g_L^2}{4c_\theta^2}Z_{\mu\nu}\tilde{Z}_{\mu\nu}]
\end{aligned}
$$

Higgs couplings to 2 fermions:

$$
\mathcal{L}_{\rm hff} = -\frac{h}{v}\sum_{f=u,d,e} m_f f^c (I + \delta y_f e^{i\phi_f}) f + \text{h.c.}
$$

Cubic Higgs self-interactions:

$$
\mathcal{L}_{h,\rm self} = -(\lambda + \delta\lambda_3) v h^3.
$$

Lagrangian also contains Higgs couplings to:

- 2 fermions and 1 or more gauge bosons
- 3 or 4 gauge bosons
- itself (quartic and higher)

LHCHXSWG-INT-2015-001

Higgs couplings to matter

- BSM corrections to Higgs couplings in BSMC Lagrangian can be related by linear transformation to Wilson coefficients of any basis of D=6 operators
- Unexpected dependence of fermionic operators due to rescaling of SM couplings
- Corrections to Higgs and other SM couplings are O(1/Λ^2) in EFT expansion.

Example:
Higgs couplings
expressed by
SILH Wilson coefficients

$$c_{gg} = \frac{16}{g^2}\bar{c}_g, \qquad \delta c_w = -\frac{1}{2}\bar{c}_H - \frac{1}{g^2-g'^2}\left[4g'^2(\bar{c}_W+\bar{c}_B+\bar{c}_{2B}+c_{2W}) - 2g^2\bar{c}_T + \frac{3g^2+g'^2}{2}[\bar{c}'_{H\ell}]_{22}\right]$$

$$c_{\gamma\gamma} = \frac{16}{g^2}\bar{c}_\gamma, \qquad \delta c_z = -\frac{1}{2}\bar{c}_H - \frac{3}{2}[\bar{c}'_{H\ell}]_{22},$$

$$c_{zz} = -\frac{4}{g^2+g'^2}\left[\bar{c}_{HW} + \frac{g'^2}{g^2}\bar{c}_{HB} - 4\frac{g'^2}{g^2}s_\theta^2\bar{c}_\gamma\right],$$

$$c_{z\Box} = \frac{2}{g^2}\left[\bar{c}_W + \bar{c}_{HW} + \bar{c}_{2W} + \frac{g'^2}{g^2}(\bar{c}_B + \bar{c}_{HB} + \bar{c}_{2B}) - \frac{1}{2}\bar{c}_T + \frac{1}{2}[\bar{c}'_{H\ell}]_{22}\right],$$

$$c_{z\gamma} = \frac{2}{g^2}\left(\bar{c}_{HB} - \bar{c}_{HW} - 8s_\theta^2\bar{c}_\gamma\right),$$

$$c_{\gamma\Box} = \frac{2}{g^2}\left(\bar{c}_{HW} - \bar{c}_{HB}\right) + \frac{4}{g^2-g'^2}\left[\bar{c}_W + \bar{c}_{2W} + \frac{g'^2}{g^2}(\bar{c}_B + \bar{c}_{2B}) - \frac{1}{2}\bar{c}_T + \frac{1}{2}[\bar{c}'_{H\ell}]_{22}\right],$$

$$c_{ww} = -\frac{4}{g^2}\bar{c}_{HW},$$

$$c_{w\Box} = \frac{2\bar{c}_{HW}}{g^2} + \frac{2}{g^2-g'^2}\left[\bar{c}_W + \bar{c}_{2W} + \frac{g'^2}{g^2}(\bar{c}_B + \bar{c}_{2B}) - \frac{1}{2}\bar{c}_T + \frac{1}{2}[\bar{c}'_{H\ell}]_{22}\right], \qquad (3.18)$$

$$\delta\lambda_3 = \lambda\left(\bar{c}_6 - \frac{3}{2}\bar{c}_H - \frac{1}{2}[\bar{c}'_{H\ell}]_{22}\right)$$

See
LHCHXSWG-INT-2015-001
for full dictionary and other bases

Higgs couplings to matter

- Corrections to Higgs couplings in phenomenological effective Lagrangian can be related by linear transformation to Wilson coefficients of any basis of D=6 operators
- Unexpected dependence of fermionic operators due to rescaling of SM couplings
- Corrections to Higgs and other SM couplings are O(1/Λ^2) in EFT expansion.

Grządkowski et al.
1008.4884

Example:
Higgs couplings expressed by Warsaw Wilson coefficients

$$\delta c_w = c_{H\Box} - \frac{5g_L^2 - g_Y^2}{4(g_L^2 - g_Y^2)} c_{HD} - \frac{4 g_L g_Y}{g_L^2 - g_Y^2} c_{HWB} + \frac{3g_L^2 + g_Y^2}{4(g_L^2 - g_Y^2)} \left([c_{\ell\ell}]_{1221} - 2[c_{H\ell}^{(3)}]_{11} - 2[c_{H\ell}^{(3)}]_{22} \right),$$

$$\delta c_z = c_{H\Box} - \frac{1}{4} c_{HD} + \frac{3}{4} \left([c_{\ell\ell}]_{1221} - 2[c_{H\ell}^{(3)}]_{11} - 2[c_{H\ell}^{(3)}]_{22} \right) \tag{2.35}$$

$$[\delta y_f]_{IJ} e^{i\phi_{IJ}^f} = -\frac{v}{\sqrt{2 m_{f_I} m_{f_J}}} [c_{fH}^\dagger]_{IJ} + \delta_{IJ} \left(c_{H\Box} - \frac{1}{4} c_{HD} + \frac{1}{4} [c_{\ell\ell}]_{1221} - \frac{1}{2} [c_{H\ell}^{(3)}]_{11} - \frac{1}{2} [c_{H\ell}^{(3)}]_{22} \right), \tag{2.36}$$

$$c_{z\Box} = \frac{1}{2g_L^2} \left(c_{HD} - [c_{\ell\ell}]_{1221} + 2[c_{H\ell}^{(3)}]_{11} + 2[c_{H\ell}^{(3)}]_{22} \right),$$

$$c_{\gamma\Box} = \frac{1}{g_L^2 - g_Y^2} \left(2\frac{g_L^2 + g_Y^2}{g_L g_Y} c_{HWB} + c_{HD} - [c_{\ell\ell}]_{1221} + 2[c_{H\ell}^{(3)}]_{11} + 2[c_{H\ell}^{(3)}]_{22} \right),$$

$$c_{w\Box} = \frac{1}{2(g_L^2 - g_Y^2)} \left(4\frac{g_Y}{g_L} c_{HWB} + c_{HD} - [c_{\ell\ell}]_{1221} + 2[c_{H\ell}^{(3)}]_{11} + 2[c_{H\ell}^{(3)}]_{22} \right), \quad ($$

See
LHCHXSWG-INT-2015-001
for full dictionary and other bases

Effective Lagrangian: Higgs couplings to matter

$$\mathcal{L}_{\rm hvv} = \frac{h}{v}[2(1+\delta c_w) m_W^2 W_\mu^+ W_\mu^- + (1+\delta c_z) m_Z^2 Z_\mu Z_\mu$$
$$+ c_{ww} \frac{g_L^2}{2} W_{\mu\nu}^+ W_{\mu\nu}^- + \tilde{c}_{ww} \frac{g_L^2}{2} W_{\mu\nu}^+ \tilde{W}_{\mu\nu}^- + c_{w\Box} g_L^2 \left(W_\mu^- \partial_\nu W_{\mu\nu}^+ + \text{h.c.}\right)$$
$$+ c_{gg} \frac{g_s^2}{4} G_{\mu\nu}^a G_{\mu\nu}^a + c_{\gamma\gamma} \frac{e^2}{4} A_{\mu\nu} A_{\mu\nu} + c_{z\gamma} \frac{e g_L}{2c_\theta} Z_{\mu\nu} A_{\mu\nu} + c_{zz} \frac{g_L^2}{4c_\theta^2} Z_{\mu\nu} Z_{\mu\nu}$$
$$+ c_{z\Box} g_L^2 Z_\mu \partial_\nu Z_{\mu\nu} + c_{\gamma\Box} g_L g_Y Z_\mu \partial_\nu A_{\mu\nu}$$
$$+ \tilde{c}_{gg} \frac{g_s^2}{4} G_{\mu\nu}^a \tilde{G}_{\mu\nu}^a + \tilde{c}_{\gamma\gamma} \frac{e^2}{4} A_{\mu\nu} \tilde{A}_{\mu\nu} + \tilde{c}_{z\gamma} \frac{e g_L}{2c_\theta} Z_{\mu\nu} \tilde{A}_{\mu\nu} + \tilde{c}_{zz} \frac{g_L^2}{4c_\theta^2} Z_{\mu\nu} \tilde{Z}_{\mu\nu}]$$

- D=6 EFT with linearly realized SU(3)xSU(2)xU(1) enforces relations between Higgs couplings to gauge bosons (otherwise, more parameters)
- These relations are independent in which basis of D=6 operators the Higgs couplings are calculated

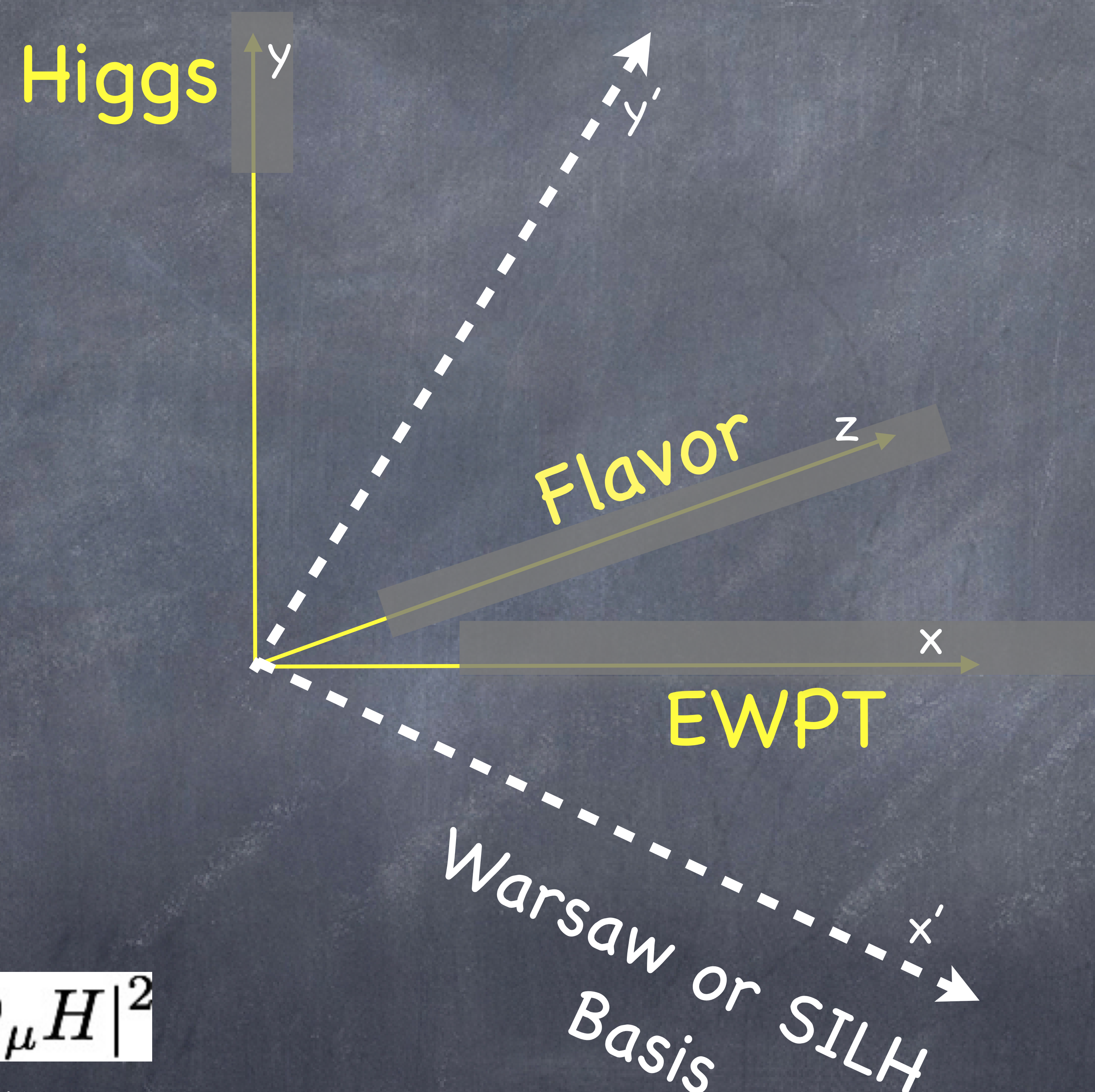
$$\delta c_w = \delta c_z + 4\delta m,$$

relative correction to W mass

$$c_{ww} = c_{zz} + 2 s_\theta^2 c_{z\gamma} + s_\theta^4 c_{\gamma\gamma},$$
$$\tilde{c}_{ww} = \tilde{c}_{zz} + 2 s_\theta^2 \tilde{c}_{z\gamma} + s_\theta^4 \tilde{c}_{\gamma\gamma},$$
$$c_{w\Box} = \frac{1}{g_L^2 - g_Y^2}\left[g_L^2 c_{z\Box} + g_Y^2 c_{zz} - e^2 s_\theta^2 c_{\gamma\gamma} - (g_L^2 - g_Y^2) s_\theta^2 c_{z\gamma}\right],$$
$$c_{\gamma\Box} = \frac{1}{g_L^2 - g_Y^2}\left[2 g_L^2 c_{z\Box} + (g_L^2 + g_Y^2) c_{zz} - e^2 c_{\gamma\gamma} - (g_L^2 - g_Y^2) c_{z\gamma}\right]$$

LHCHXSWG-INT-2015-001

Bird's eye view of EFT space



e.g.

$$O_{HD} = |H^\dagger D_\mu H|^2$$

contributes both
to Higgs couplings and
to W/Z mass difference

Higgs Basis - parameters

EFT parameters along EWPT unconstrained directions
affecting LHC Higgs observables at leading order

Higgs couplings to gauge bosons

CP even : δc_z $c_{z\Box}$ c_{zz} $c_{z\gamma}$ $c_{\gamma\gamma}$ c_{gg}

CP odd : $\tilde{c}_{zz}$ $\tilde{c}_{z\gamma}$ $\tilde{c}_{\gamma\gamma}$ $\tilde{c}_{gg}$

Higgs couplings to fermions

CP even : δy_u δy_d δy_e

CP odd : ϕ_u ϕ_d ϕ_e

Higgs couplings to itself

CP even : $\delta\lambda_3$

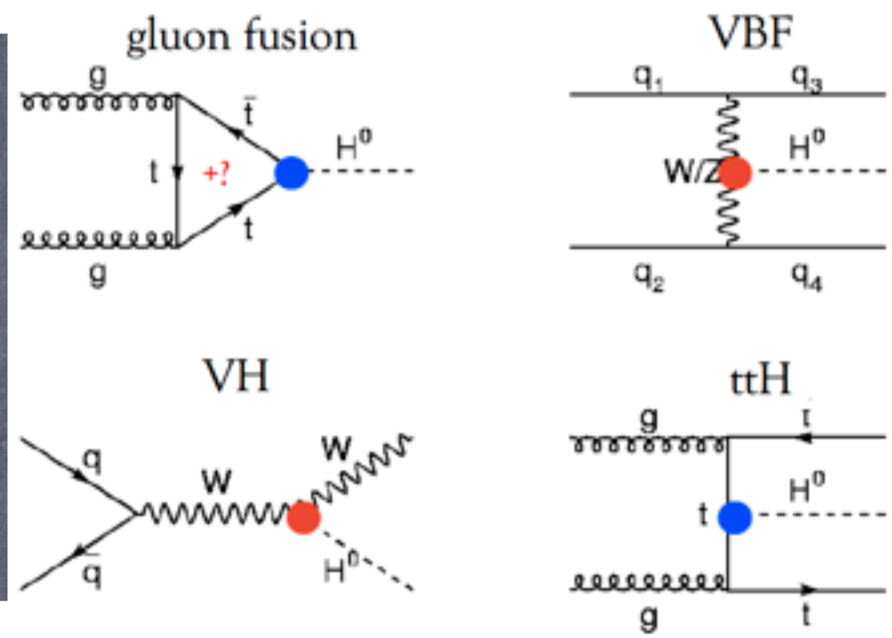
Assuming Minimal Flavor Violation, and that parameters strongly constrained at LO by EWPT can be ignored, we have 10 CP-even and 6 CP-odd parameters to be constrained by LHC Higgs analyses

Constraints on EFT parameters
from LHC Higgs data

Dependence of Higgs production on EFT parameters

$$\frac{\sigma_{ggh}}{\sigma_{ggh}^{\rm SM}} \simeq 1 + 237 c_{gg} + 2.06\delta y_u - 0.06\delta y_d.$$

$$\frac{\sigma_{VBF}}{\sigma_{VBF}^{\rm SM}} \simeq 1 + 1.49\delta c_w + 0.51\delta c_z - \begin{pmatrix} 1.08 \\ 1.11 \\ 1.23 \end{pmatrix} c_{w\Box} - 0.10 c_{ww} - \begin{pmatrix} 0.35 \\ 0.35 \\ 0.40 \end{pmatrix} c_{z\Box}$$
$$-0.04 c_{zz} - 0.10 c_{\gamma\Box} - 0.02 c_{z\gamma}$$
$$\to 1 + 2\delta c_z - 2.25 c_{z\Box} - 0.83 c_{zz} + 0.30 c_{z\gamma} + 0.12 c_{\gamma\gamma}.$$



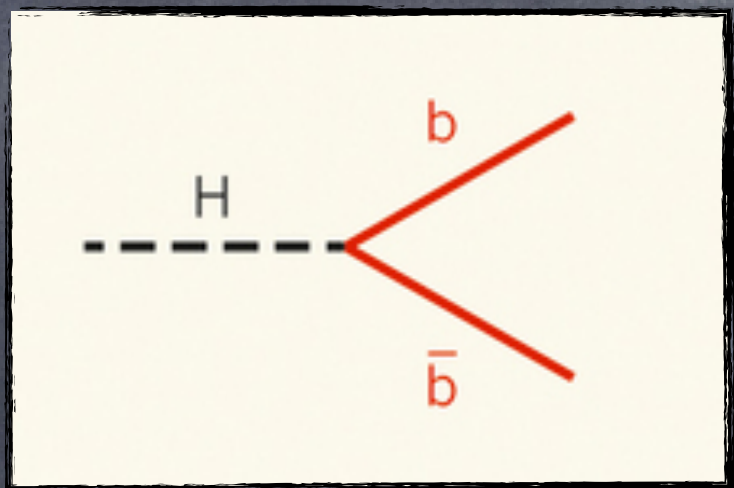
$$\frac{\sigma_{tth}}{\sigma_{tth}^{\rm SM}} \simeq 1 + 2\delta y_u.$$

$$\frac{\sigma_{Wh}}{\sigma_{Wh}^{\rm SM}} \simeq 1 + 2\delta c_w + \begin{pmatrix} 6.39 \\ 6.51 \\ 6.96 \end{pmatrix} c_{w\Box} + \begin{pmatrix} 1.49 \\ 1.49 \\ 1.50 \end{pmatrix} c_{ww}$$
$$\to 1 + 2\delta c_z + \begin{pmatrix} 9.26 \\ 9.43 \\ 10.08 \end{pmatrix} c_{z\Box} + \begin{pmatrix} 4.35 \\ 4.41 \\ 4.63 \end{pmatrix} c_{zz} - \begin{pmatrix} 0.81 \\ 0.84 \\ 0.93 \end{pmatrix} c_{z\gamma} - \begin{pmatrix} 0.43 \\ 0.44 \\ 0.48 \end{pmatrix} c_{\gamma\gamma}$$

$$\frac{\sigma_{Zh}}{\sigma_{Zh}^{\rm SM}} \simeq 1 + 2\delta c_z + \begin{pmatrix} 5.30 \\ 5.40 \\ 5.72 \end{pmatrix} c_{z\Box} + \begin{pmatrix} 1.79 \\ 1.80 \\ 1.82 \end{pmatrix} c_{zz} + \begin{pmatrix} 0.80 \\ 0.82 \\ 0.87 \end{pmatrix} c_{\gamma\Box} + \begin{pmatrix} 0.22 \\ 0.22 \\ 0.22 \end{pmatrix} c_{z\gamma},$$
$$\to 1 + 2\delta c_z + \begin{pmatrix} 7.61 \\ 7.77 \\ 8.24 \end{pmatrix} c_{z\Box} + \begin{pmatrix} 3.31 \\ 3.35 \\ 3.47 \end{pmatrix} c_{zz} - \begin{pmatrix} 0.58 \\ 0.60 \\ 0.65 \end{pmatrix} c_{z\gamma} + \begin{pmatrix} 0.27 \\ 0.28 \\ 0.30 \end{pmatrix} c_{\gamma\gamma}.$$

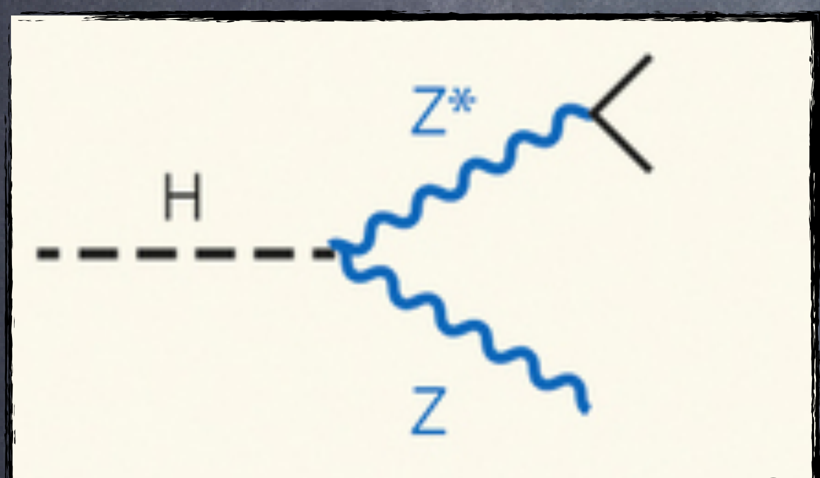
$\begin{pmatrix} 7 \\ 8 \\ 13 \end{pmatrix}$ TeV

Dependence of Higgs widths on EFT parameters



Decays to 2 fermions

$$\frac{\Gamma_{cc}}{\Gamma_{cc}^{\rm SM}} \simeq 1 + 2\delta y_u, \qquad \frac{\Gamma_{bb}}{\Gamma_{bb}^{\rm SM}} \simeq 1 + 2\delta y_d, \qquad \frac{\Gamma_{\tau\tau}}{\Gamma_{\tau\tau}^{\rm SM}} \simeq 1 + 2\delta y_e,$$

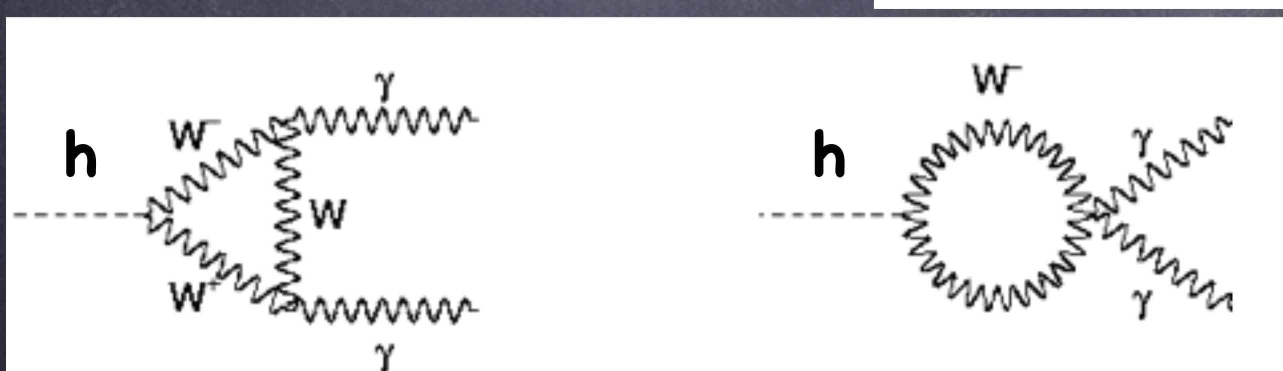


Decays to 4 fermions

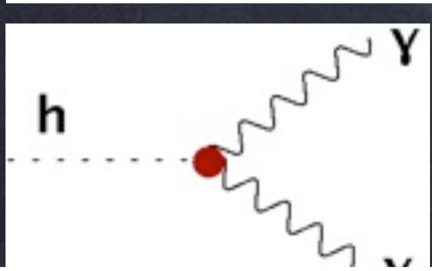
$$\begin{aligned} \frac{\Gamma_{2\ell 2\nu}}{\Gamma_{2\ell 2\nu}^{\rm SM}} &\simeq 1 + 2\delta c_w + 0.46 c_{w\Box} - 0.15 c_{ww} \\ &\to 1 + 2\delta c_z + 0.67 c_{z\Box} + 0.05 c_{zz} - 0.17 c_{z\gamma} - 0.05 c_{\gamma\gamma}. \end{aligned}$$

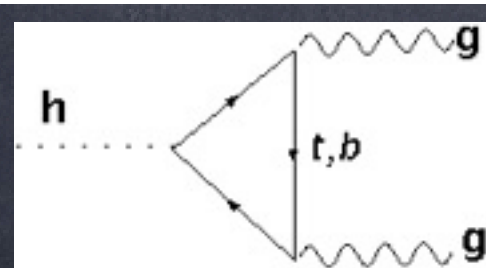
$\begin{pmatrix} \text{2e2μ} \\ \text{4e} \end{pmatrix}$

$$\begin{aligned} \frac{\bar\Gamma_{4\ell}}{\bar\Gamma_{4\ell}^{\rm SM}} &\simeq 1 + 2\delta c_z + \begin{pmatrix} 0.41 \\ 0.39 \end{pmatrix} c_{z\Box} - \begin{pmatrix} 0.15 \\ 0.14 \end{pmatrix} c_{zz} + \begin{pmatrix} 0.07 \\ 0.05 \end{pmatrix} c_{z\gamma} - \begin{pmatrix} 0.02 \\ 0.02 \end{pmatrix} c_{\gamma\Box} + \begin{pmatrix} < 0.01 \\ 0.03 \end{pmatrix} c_{\gamma\gamma} \\ &\to 1 + 2\delta c_z + \begin{pmatrix} 0.35 \\ 0.32 \end{pmatrix} c_{z\Box} - \begin{pmatrix} 0.19 \\ 0.19 \end{pmatrix} c_{zz} + \begin{pmatrix} 0.09 \\ 0.08 \end{pmatrix} c_{z\gamma} + \begin{pmatrix} 0.01 \\ 0.02 \end{pmatrix} c_{\gamma\gamma}. \end{aligned} \tag{4.13}$$



Decays to 2 gauge bosons





$$\frac{\Gamma_{VV}}{\Gamma_{VV}^{\rm SM}} \simeq \left| 1 + \frac{\hat c_{vv}}{c_{vv}^{\rm SM}} \right|^2, \qquad vv \in \{gg, \gamma\gamma, z\gamma\},$$

$$\begin{aligned} \hat c_{\gamma\gamma} &= c_{\gamma\gamma}, \qquad c_{\gamma\gamma}^{\rm SM} \simeq -8.3 \times 10^{-2}, \\ \hat c_{z\gamma} &= c_{z\gamma}, \qquad c_{z\gamma}^{\rm SM} \simeq -5.9 \times 10^{-2}, \end{aligned}$$

Higgs observables in the Higgs basis

Signal strength

$$\mu_{X;Y} = \frac{\sigma(pp \to X)}{\sigma(pp \to X)_{\rm SM}} \frac{\Gamma(h \to Y)}{\Gamma(h \to Y)_{\rm SM}} \frac{\Gamma(h \to {\rm all})_{\rm SM}}{\Gamma(h \to {\rm all})}.$$

In EFT, assuming no other degrees of freedom,
so total width is just sum of partial width into SM particle
no invisible width in this analysis

- One can express all measured signal strength in terms of the 9 EFT parameters (no meaningful constraints on Higgs self-coupling yet)

$$\delta c_z \quad c_{z\Box} \quad c_{zz} \quad c_{z\gamma} \quad c_{\gamma\gamma} \quad c_{gg} \quad \delta y_u \quad \delta y_d \quad \delta y_e$$

- Using available LHC signal strength data one can obtain simultaneous constraints on most of these parameters

Higgs constraints on EFT

Run-1 fit

	Ellipses	DC tth	DC tth+Vh
δc_z	0.01 ± 0.31	-0.12 ± 0.25	-0.13 ± 0.18
c_{zz}	0.21 ± 0.50	0.14 ± 0.76	0.76 ± 0.69
$c_{z\Box}$	-0.21 ± 0.31	-0.22 ± 0.31	-0.38 ± 0.44
$c_{\gamma\gamma}$	0.006 ± 0.015	-0.008 ± 0.014	-0.0040 ± 0.0089
$c_{z\gamma}$	-0.002 ± 0.073	-0.0025 ± 0.0625	-0.001 ± 0.054
c_{gg}	-0.0001 ± 0.0047	-0.0055 ± 0.0028	-0.0060 ± 0.0029
δy_u	0.03 ± 0.51	0.58 ± 0.35	0.62 ± 0.45
δy_d	-0.13 ± 0.53	-0.43 ± 0.32	-0.55 ± 0.27
δy_e	-0.14 ± 0.36	-0.28 ± 0.21	-0.32 ± 0.28

Flat direction

$c_{zz} \approx -2 * c_{z\Box}$

Needs more data, e.g. differential distributions in h->4f decays, or VBF/VH signal strength at different energy

- Not all parameters yet constrained enough that EFT approach is robustly valid - one flat direction among higher derivative Higgs couplings to WW and ZZ

- Results sensitive to including corrections to Higgs observables quadratic in EFT parameters which are formally O(1/Λ^4). Thus, in general, results may be sensitive to including dimension-8 operators

Higgs constraints on EFT

Run-1 fit
Run-1 fit

	Ellipses	DC tth	DC tth+Vh
δc_z	0.01 ± 0.31	-0.12 ± 0.25	-0.13 ± 0.18
c_{zz}	0.21 ± 0.50	0.14 ± 0.76	0.76 ± 0.69
$c_{z\Box}$	-0.21 ± 0.31	-0.22 ± 0.31	-0.38 ± 0.44
$c_{\gamma\gamma}$	0.006 ± 0.015	-0.008 ± 0.014	-0.0040 ± 0.0089
$c_{z\gamma}$	-0.002 ± 0.073	-0.0025 ± 0.0625	-0.001 ± 0.054
c_{gg}	-0.0001 ± 0.0047	-0.0055 ± 0.0028	-0.0060 ± 0.0029
δy_u	0.03 ± 0.51	0.58 ± 0.35	0.62 ± 0.45
δy_d	-0.13 ± 0.53	-0.43 ± 0.32	-0.55 ± 0.27
δy_e	-0.14 ± 0.36	-0.28 ± 0.21	-0.32 ± 0.28

- Some tension in the fit because of excess in tth production and deficit in bb decays.
- Effective gluon coupling tries to compensate to recover SM-like Higgs production in gluon fusion.

Higgs constraints on EFT

Run-1+2 fit

	Ellipses	DC tth	DC tth+Vh
δc_z	-0.02 ± 0.13	-0.01 ± 0.12	-0.08 ± 0.12
c_{zz}	-0.29 ± 0.38	-0.29 ± 0.38	-0.50 ± 0.33
$c_{z\Box}$	0.07 ± 0.17	0.06 ± 0.16	0.18 ± 0.12
$c_{\gamma\gamma}$	0.0007 ± 0.0089	0.0006 ± 0.0085	-0.0024 ± 0.0078
$c_{z\gamma}$	-0.011 ± 0.076	-0.011 ± 0.074	-0.010 ± 0.077
c_{gg}	-0.0037 ± 0.0010	-0.0041 ± 0.0010	-0.0040 ± 0.0009
δy_u	0.22 ± 0.16	0.26 ± 0.15	0.22 ± 0.15
δy_d	-0.38 ± 0.21	-0.39 ± 0.21	-0.47 ± 0.20
δy_e	-0.11 ± 0.13	-0.12 ± 0.13	-0.11 ± 0.13

Run-1 fit

DC tth+Vh
-0.13 ± 0.18
0.76 ± 0.69
-0.38 ± 0.44
-0.0040 ± 0.0089
-0.001 ± 0.054
-0.0060 ± 0.0029
0.62 ± 0.45
-0.55 ± 0.27
-0.32 ± 0.28

Excess in tth production and deficit in bb decays only got stronger...

SM disfavored at 99.4% confidence level (2.8 sigma)

Higgs constraints on EFT

Run-1+2 fit

	Ellipses	DC tth	DC tth+Vh
δc_z	-0.02 ± 0.13	-0.01 ± 0.12	-0.08 ± 0.12
c_{zz}	-0.29 ± 0.38	-0.29 ± 0.38	-0.50 ± 0.33
$c_{z\Box}$	0.07 ± 0.17	0.06 ± 0.16	0.18 ± 0.12
$c_{\gamma\gamma}$	0.0007 ± 0.0089	0.0006 ± 0.0085	-0.0024 ± 0.0078
$c_{z\gamma}$	-0.011 ± 0.076	-0.011 ± 0.074	-0.010 ± 0.077
c_{gg}	-0.0037 ± 0.0010	-0.0041 ± 0.0010	-0.0040 ± 0.0009
δy_u	0.22 ± 0.16	0.26 ± 0.15	0.22 ± 0.15
δy_d	-0.38 ± 0.21	-0.39 ± 0.21	-0.47 ± 0.20
δy_e	-0.11 ± 0.13	-0.12 ± 0.13	-0.11 ± 0.13

Run-1 fit

DC tth+Vh
-0.13 ± 0.18
0.76 ± 0.69
-0.38 ± 0.44
-0.0040 ± 0.0089
-0.001 ± 0.054
-0.0060 ± 0.0029
0.62 ± 0.45
-0.55 ± 0.27
-0.32 ± 0.28

- In simultaneous 9-parameter fit errors much smaller than in Run-1 alone, because of lifted degeneracies
- Flat direction of Run-1 largely lifted, because of different dependence of VBF cross section on different 2-derivative Higgs couplings

Take away

- Assuming MFV, and taking into account precision constraints on D=6 operators, allows one to describe LO EFT deformations of single Higgs signal strength LHC observables by just 9 parameters

- There are non-trivial constraints on all of these 9 parameters from run-1 Higgs data, though validity of EFT approach not robust yet in some corners of allowed parameter space

- Including Run-2 data has an important impact on Higgs EFT fit, because of lifted degeneracies in the parameter space

- Synergy of TGC and Higgs coupling measurements provides another handle to improve the fit

Effective Lagrangian: Triple Gauge Couplings

SM predicts TGCs in terms of gauge couplings
as consequence of SM gauge symmetry and renormalizability:

$$\begin{aligned}\mathcal{L}_{\rm TGC}^{\rm SM} =& ie\left[A_{\mu\nu}\, W^+_\mu W^-_\nu + \left(W^+_{\mu\nu}W^-_\mu - W^-_{\mu\nu}W^+_\mu\right) A_\nu\right] \\ &+ig_L c_\theta \left[\left(W^+_{\mu\nu}W^-_\mu - W^-_{\mu\nu}W^+_\mu\right) Z_\nu + Z_{\mu\nu}\, W^+_\mu W^-_\nu\right]\end{aligned}$$

In EFT with D=6 operators, new "anomalous" contributions to TGCs arise

$$\begin{aligned}\mathcal{L}_{\rm tgc}^{D=6} =& ie\left[\delta\kappa_\gamma A_{\mu\nu}\, W^+_\mu W^-_\nu + \tilde\kappa_\gamma \tilde A_{\mu\nu}\, W^+_\mu W^-_\nu\right] \\ &+ig_L c_\theta\left[\delta g_{1,z}\left(W^+_{\mu\nu}W^-_\mu - W^-_{\mu\nu}W^+_\mu\right) Z_\nu + \delta\kappa_z Z_{\mu\nu}\, W^+_\mu W^-_\nu + \tilde\kappa_z\, \tilde Z_{\mu\nu}\, W^+_\mu W^-_\nu\right] \\ &+i\frac{e}{m_W^2}\left[\lambda_\gamma W^+_{\mu\nu}W^-_{\nu\rho}A_{\rho\mu} + \tilde\lambda_\gamma W^+_{\mu\nu}W^-_{\nu\rho}\tilde A_{\rho\mu}\right] + i\frac{g_L c_\theta}{m_W^2}\left[\lambda_z W^+_{\mu\nu}W^-_{\nu\rho}Z_{\rho\mu} + \tilde\lambda_z W^+_{\mu\nu}W^-_{\nu\rho}\tilde Z_{\rho\mu}\right]\end{aligned}$$

These depend on previously introduced parameters
describing Higgs couplings to electroweak gauge
bosons, and on 2 new parameters

$$\delta g_{1,z} = \frac{1}{2(g_L^2 - g_Y^2)}\left[c_{\gamma\gamma}e^2 g_Y^2 + c_{z\gamma}(g_L^2 - g_Y^2)g_Y^2 - c_{zz}(g_L^2 + g_Y^2)g_Y^2 - c_{z\Box}(g_L^2 + g_Y^2)g_L^2\right]$$

$$\delta\kappa_\gamma = -\frac{g_L^2}{2}\left(c_{\gamma\gamma}\frac{e^2}{g_L^2 + g_Y^2} + c_{z\gamma}\frac{g_L^2 - g_Y^2}{g_L^2 + g_Y^2} - c_{zz}\right),$$

$$\tilde\kappa_\gamma = -\frac{g_L^2}{2}\left(\tilde c_{\gamma\gamma}\frac{e^2}{g_L^2 + g_Y^2} + \tilde c_{z\gamma}\frac{g_L^2 - g_Y^2}{g_L^2 + g_Y^2} - \tilde c_{zz}\right)$$

$$\begin{aligned}\delta\kappa_z =& \delta g_{1,z} - t_\theta^2 \delta\kappa_\gamma \\ \tilde\kappa_z =& -t_\theta^2\tilde\kappa_\gamma \\ \lambda_\gamma =& \lambda_z \\ \tilde\lambda_\gamma =& \tilde\lambda_z\end{aligned}$$