Adam Falkowski

Where do we stand with Higgs couplings

Paris, 21 April 2017

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Status report

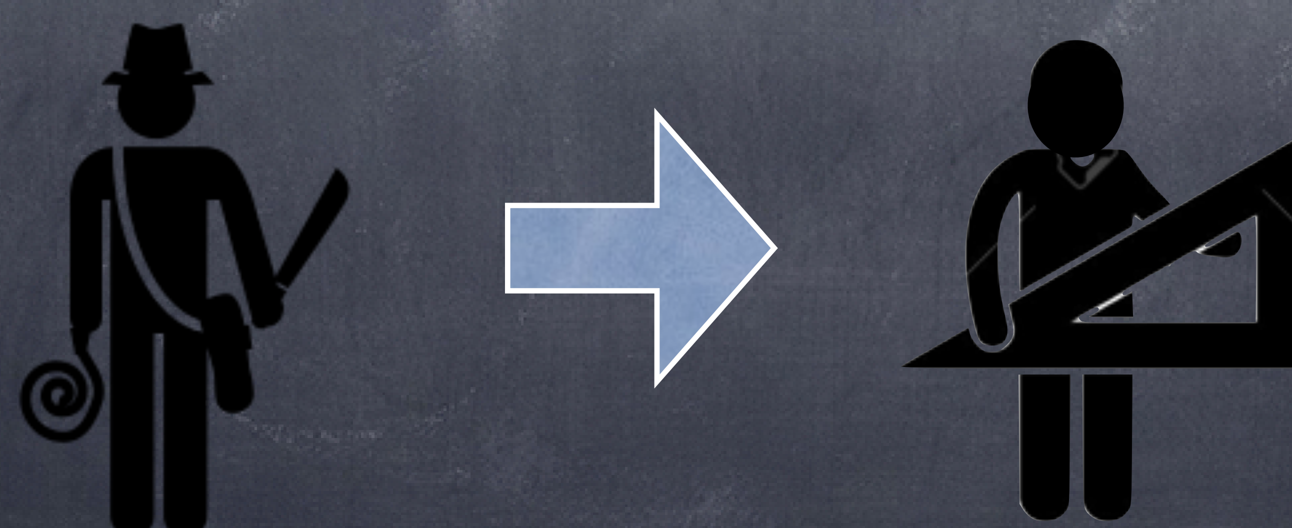
- SM has been shamelessly successful in describing all collider and low-energy experiments. Discovery of 125 GeV Higgs boson is the last piece of puzzle that falls into place. There is no more free unknown parameters in the SM

- We know physics beyond SM exists (neutrino masses, dark matter, inflation, baryon asymmetry). There are also some theoretical hints for new physics (strong CP problem, flavor hierarchies, gauge coupling unifications). Unfortunately, none of these issues points unambiguously to a concrete mass scale where new physics addressing the above mentioned problems should become manifest...

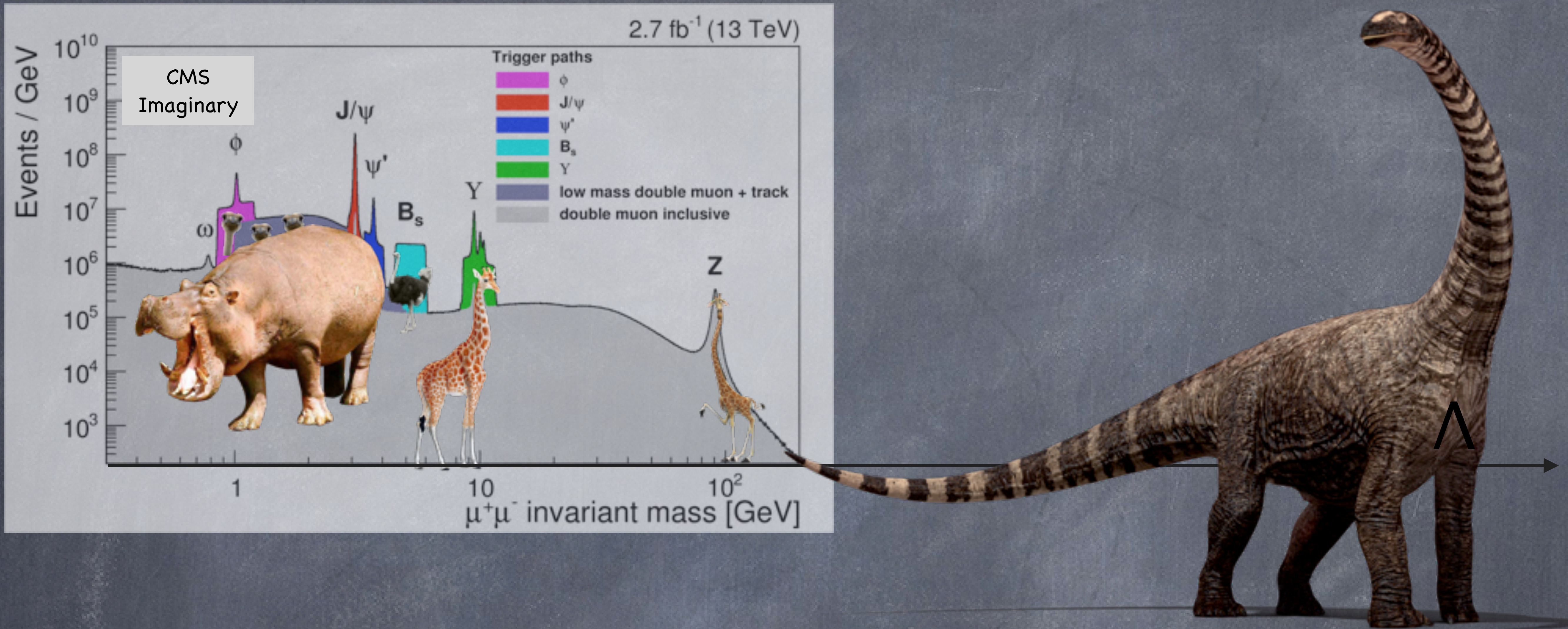
- In the past, the concept of naturalness was used as a guiding principle. Models addressing naturalness problem (supersymmetry, composite Higgs, ...) make very definite predictions about new particles and interactions that should become visible below 1 TeV energy scale. But all realistic models addressing naturalness have certain tensions and involve baroque theoretical constructions, which casts serious doubts on whether they are relevant in our reality

Lord Kelvin's nightmare

- It is likely that for some time (maybe a few decades, maybe longer) we won't be able to directly produce on-shell particles from beyond the SM
- However, quantum mechanics comes to a rescue as all existing particle are continuously produced and annihilated off-shell, and this way they may the affect the properties and interactions of the known SM particles
- Therefore, in the near future of particle physics should be focused on precision measurements
- For this we need a versatile and general formalism, which can accommodate many different ways new physics may show up in experiment and indicate promising research directions



Fantastic Beasts and Where To Find Them



x) It looks more and more likely that new degrees of freedom beyond the SM may not be directly available at the LHC or even at future colliders

x) However, even if it is not possible to see the head, it may be possible to see the tail...

Formalisms for precision measurements

3 formalisms in use

- SM EFT, effective theory for the SM degrees of freedom where the electroweak symmetry is realized as a linear transformation of the SM fields
- HEFT, effective theory for the SM degrees of freedom where electroweak symmetry is realized non-linearly
- Ad-hoc modifiers for SM couplings

+

SM EFT

- Assume that the SM degrees of freedom is all there is at the weak scale. But we treat the SM as an effective theory, and call it the SM EFT
- In the SM EFT, the SM Lagrangian is treated as the lowest order approximation of the dynamics. Effects of heavy particles are encoded in new contact interactions of the SM fields in the Lagrangian
- The SM EFT Lagrangian can be defined as an expansion in the inverse mass scale of heavy particles, which coincides with the expansion in operator dimensions
- Under certain (mild) assumptions, the SM EFT framework allows one to describe effects of new physics beyond the SM in a model independent way

SM EFT Approach to BSM

Basic assumptions

- Much as in SM, relativistic QFT with linearly realized SU(3)xSU(2)xU(1) local symmetry spontaneously broken by VEV of Higgs doublet field

$$H \to LH, \qquad L \in SU(2)_L$$

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

- SM EFT Lagrangian expanded in inverse powers of Λ, equivalently in operator dimension D

$$v \ll \Lambda \ll \Lambda_L$$

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

Lepton number or B-L violating,
hence too small to probed at present
and near-future colliders

By assumption,
subleading
to D=6

Generated by integrating out
heavy particles with mass scale Λ
In large class of BSM models that conserve B-L,
D=6 operators capture leading effects of new physics
on collider observables at E << Λ

Buchmuller,Wyler
(1986)

Warsaw basis for B-conserving D=6 operators

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	$f^{abc} G^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$	$O_{\widetilde{G}}$	$f^{abc} \widetilde{G}^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$

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

$[O^{(1)}_{H\ell}]_{IJ}$	$i\bar{\ell}_I \bar{\sigma}_\mu \ell_J H^\dagger \overleftrightarrow{D}_\mu H$
$[O^{(3)}_{H\ell}]_{IJ}$	$i\bar{\ell}_I \sigma^i \bar{\sigma}_\mu \ell_J H^\dagger \sigma^i \overleftrightarrow{D}_\mu H$
$[O_{He}]_{IJ}$	$ie^c_I \sigma_\mu \bar{e}^c_J H^\dagger \overleftrightarrow{D}_\mu H$
$[O^{(1)}_{Hq}]_{IJ}$	$i\bar{q}_I \bar{\sigma}_\mu q_J H^\dagger \overleftrightarrow{D}_\mu H$
$[O^{(3)}_{Hq}]_{IJ}$	$i\bar{q}_I \sigma^i \bar{\sigma}_\mu q_J H^\dagger \sigma^i \overleftrightarrow{D}_\mu H$
$[O_{Hu}]_{IJ}$	$iu^c_I \sigma_\mu \bar{u}^c_J H^\dagger \overleftrightarrow{D}_\mu H$
$[O_{Hd}]_{IJ}$	$id^c_I \sigma_\mu \bar{d}^c_J H^\dagger \overleftrightarrow{D}_\mu H$
$[O_{Hud}]_{IJ}$	$iu^c_I \sigma_\mu \bar{d}^c_J \tilde{H}^\dagger D_\mu H$

Dipole

$[O^\dagger_{eW}]_{IJ}$	$e^c_I \sigma_{\mu\nu} H^\dagger \sigma^i \ell_J W^i_{\mu\nu}$
$[O^\dagger_{eB}]_{IJ}$	$e^c_I \sigma_{\mu\nu} H^\dagger \ell_J B_{\mu\nu}$
$[O^\dagger_{uG}]_{IJ}$	$u^c_I \sigma_{\mu\nu} T^a \widetilde{H}^\dagger q_J\, G^a_{\mu\nu}$
$[O^\dagger_{uW}]_{IJ}$	$u^c_I \sigma_{\mu\nu} \widetilde{H}^\dagger \sigma^i q_J\, W^i_{\mu\nu}$
$[O^\dagger_{uB}]_{IJ}$	$u^c_I \sigma_{\mu\nu} \widetilde{H}^\dagger q_J\, B_{\mu\nu}$
$[O^\dagger_{dG}]_{IJ}$	$d^c_I \sigma_{\mu\nu} T^a H^\dagger q_J\, G^a_{\mu\nu}$
$[O^\dagger_{dW}]_{IJ}$	$d^c_I \sigma_{\mu\nu} \bar{H}^\dagger \sigma^i q_J\, W^i_{\mu\nu}$
$[O^\dagger_{dB}]_{IJ}$	$d^c_I \sigma_{\mu\nu} H^\dagger q_J\, B_{\mu\nu}$

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

$(\bar{R}R)(\bar{R}R)$

O_{ee}	$\eta(e^c\sigma_\mu \bar{e}^c)(e^c\sigma_\mu \bar{e}^c)$
O_{uu}	$\eta(u^c\sigma_\mu \bar{u}^c)(u^c\sigma_\mu \bar{u}^c)$
O_{dd}	$\eta(d^c\sigma_\mu \bar{d}^c)(d^c\sigma_\mu \bar{d}^c)$
O_{eu}	$(e^c\sigma_\mu \bar{e}^c)(u^c\sigma_\mu \bar{u}^c)$
O_{ed}	$(e^c\sigma_\mu \bar{e}^c)(d^c\sigma_\mu \bar{d}^c)$
O_{ud}	$(u^c\sigma_\mu \bar{u}^c)(d^c\sigma_\mu \bar{d}^c)$
O'_{ud}	$(u^c\sigma_\mu T^a \bar{u}^c)(d^c\sigma_\mu T^a \bar{d}^c)$

$(\bar{L}L)(\bar{R}R)$

$O_{\ell e}$	$(\bar{\ell}\bar{\sigma}_\mu \ell)(e^c\sigma_\mu \bar{e}^c)$
$O_{\ell u}$	$(\bar{\ell}\bar{\sigma}_\mu \ell)(u^c\sigma_\mu \bar{u}^c)$
$O_{\ell d}$	$(\bar{\ell}\bar{\sigma}_\mu \ell)(d^c\sigma_\mu \bar{d}^c)$
O_{eq}	$(e^c\sigma_\mu \bar{e}^c)(\bar{q}\bar{\sigma}_\mu q)$
O_{qu}	$(\bar{q}\bar{\sigma}_\mu q)(u^c\sigma_\mu \bar{u}^c)$
O'_{qu}	$(\bar{q}\bar{\sigma}_\mu T^a q)(u^c\sigma_\mu T^a \bar{u}^c)$
O_{qd}	$(\bar{q}\bar{\sigma}_\mu q)(d^c\sigma_\mu \bar{d}^c)$
O'_{qd}	$(\bar{q}\bar{\sigma}_\mu T^a q)(d^c\sigma_\mu T^a \bar{d}^c)$

$(\bar{L}L)(\bar{L}L)$

$O_{\ell\ell}$	$\eta(\bar{\ell}\bar{\sigma}_\mu \ell)(\bar{\ell}\bar{\sigma}_\mu \ell)$
O_{qq}	$\eta(\bar{q}\bar{\sigma}_\mu q)(\bar{q}\bar{\sigma}_\mu q)$
O'_{qq}	$\eta(\bar{q}\bar{\sigma}_\mu \sigma^i q)(\bar{q}\bar{\sigma}_\mu \sigma^i q)$
$O_{\ell q}$	$(\bar{\ell}\bar{\sigma}_\mu \ell)(\bar{q}\bar{\sigma}_\mu q)$
$O'_{\ell q}$	$(\bar{\ell}\bar{\sigma}_\mu \sigma^i \ell)(\bar{q}\bar{\sigma}_\mu \sigma^i q)$

$(\bar{L}R)(\bar{L}R)$

O_{quqd}	$(u^c q^j)\epsilon_{jk}(d^c q^k)$
O'_{quqd}	$(u^c T^a q^j)\epsilon_{jk}(d^c T^a q^k)$
$O_{\ell equ}$	$(e^c \ell^j)\epsilon_{jk}(u^c q^k)$
$O'_{\ell equ}$	$(e^c \bar{\sigma}_{\mu\nu} \ell^j)\epsilon_{jk}(u^c \bar{\sigma}^{\mu\nu} q^k)$
$O_{\ell edq}$	$(\bar{\ell}\bar{e}^c)(d^c q)$

Grządkowski et al.
1008.4884

Advantages of SM EFT

- Framework general enough to describe leading effects of a large class (though not all!) of BSM scenarios
- Theoretical correlations between signal and background and different signal channels taken into account
- Very easy to recast SM EFT results as constraints on specific BSM models
- SM EFT is consistent QFT, so that calculations and predictions can be systematically improved (higher-loops, higher order terms in EFT expansion if needed). In particular, SM EFT is renormalizable at each order in $1/\Lambda$ expansion
- Some tools to assess validity of $1/\Lambda$ expansion

HEFT

- Alternative formalism inspired by low-energy QCD description of pions and kaons
- No linear electroweak symmetry realized in Lagrangian -> replaced by non-linear version
- Expansion in operator dimensions replaced by derivative expansion

$$H = \frac{1}{\sqrt{2}}\begin{pmatrix} \dots \\ v + \cancel{h(x)} + \dots \end{pmatrix} \longrightarrow h(x)$$

$$\cancel{\Lambda} \longrightarrow 4\pi v$$

HEFT

for review see e.g.
LHCHXSWG 1610.07922

Introduce triplet of Goldstone field φ via unitary matrix U

$$U = \exp(2i\varphi^a T^a/v)$$

Transformation of U under SU(2)LxU(1) implies electroweak symmetry is realized non-linearly on φ

$$U \to g_L U g_Y^\dagger, \qquad h \to h$$

Higgs boson is perfect singlet under electroweak symmetry

$$\begin{aligned}\mathcal{L}_2 = &-\frac{1}{2}\langle G_{\mu\nu}G^{\mu\nu}\rangle - \frac{1}{2}\langle W_{\mu\nu}W^{\mu\nu}\rangle - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \sum_{\psi=q_L,l_L,u_R,d_R,e_R} \bar\psi i \not{D}\psi \\ &+\frac{v^2}{4}\langle D_\mu U^\dagger D^\mu U\rangle\,(1+F_U(h)) + \frac{1}{2}\partial_\mu h \partial^\mu h - V(h) \\ &-v\left[\bar q_L\left(Y_u + \sum_{n=1}^\infty Y_u^{(n)}\left(\frac{h}{v}\right)^n\right) U P_+ q_R + \bar q_L \left(Y_d + \sum_{n=1}^\infty Y_d^{(n)}\left(\frac{h}{v}\right)^n\right) U P_- q_R \right.\\ &\left.+\bar l_L\left(Y_e + \sum_{n=1}^\infty Y_e^{(n)}\left(\frac{h}{v}\right)^n\right) U P_- l_R + \text{h.c.}\right]\end{aligned}$$

Lowest order Lagrangian supplemented by higher-derivative terms

$$\begin{aligned}\mathcal{L}_4 = &\, a_1 g' g\langle U T_3 B_{\mu\nu} U^\dagger W^{\mu\nu}\rangle + i a_2 g'\langle U T_3 B_{\mu\nu} U^\dagger [V^\mu, V^\nu]\rangle - i a_3 g\langle W_{\mu\nu}[V^\mu, V^\nu]\rangle \\ &+a_4\langle V_\mu V_\nu\rangle\langle V^\mu V^\nu\rangle + a_5\langle V_\mu V^\mu\rangle\langle V_\nu V^\nu\rangle + \frac{e^2}{16\pi^2} c_{\gamma\gamma}\frac{h}{v}F_{\mu\nu}F^{\mu\nu} + \frac{g^{hh}}{v^4}(\partial_\mu h \partial^\mu h)^2 \\ &+\frac{d^{hh}}{v^2}(\partial_\mu h \partial^\mu h)\langle D_\nu U^\dagger D^\nu U\rangle + \frac{e^{hh}}{v^2}(\partial_\mu h \partial^\nu h)\langle D^\mu U^\dagger D_\nu U\rangle + \ldots\end{aligned}$$

$$D_\mu U = \partial_\mu U + i g W_\mu U - i g' B_\mu U T_3$$

$$F_U(h) = \sum_{n=1}^\infty f_{U,n}\left(\frac{h}{v}\right)^n, \qquad V(h) = v^4 \sum_{n=2}^\infty f_{V,n}\left(\frac{h}{v}\right)^n$$

Advantages of HEFT

- More general than SM EFT, so more flexible to describe BSM models
- HEFT is consistent QFT, so that calculations and predictions can be systematically improved (higher-loops, higher order terms in EFT expansion if needed). In particular, HEFT is renormalizable at each order in loop expansion

However

- The non-linear Lagrangian becomes strongly coupled at the scale $4\pi v \sim 3$ TeV, where amplitudes lose perturbative unitarity. This is true even for very small deformations from the SM, due to multi-Higgs production processes quickly growing with energy
- The non-linear formalism is relevant probably only for BSM theories with new particles whose masses vanish in the limit on no electroweak symmetry breaking

Coupling modifiers

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

$$\mathcal{L}_{\rm SM} = D_\mu H^\dagger D_\mu H + m_H^2 H^\dagger H - \lambda (H^\dagger H)^2 - (H^\dagger f_c Y_f F + {\rm h.c}) + \dots$$

Couplings to EW gauge bosons

Self-Couplings

Couplings to fermions

$$\mathcal{L}_{\rm SM} \supset \frac{h}{v}\left[2 m_W^2 W_\mu^+ W_\mu^- + m_Z^2 Z_\mu Z_\mu - \frac{m_h^2}{2} h^2 - (m_f f_c f + {\rm h.c.})\right]$$

Assume only new physics only modifies coupling strength of interactions already present in SM Lagrangian

$$\mathcal{L}_{\rm eff} \supset \frac{h}{v}\left[2 \kappa_W m_W^2 W_\mu^+ W_\mu^- + \kappa_Z m_Z^2 Z_\mu Z_\mu - \frac{m_h^2}{2} \kappa_h h^2 - (\kappa_f m_f f_c f + {\rm h.c.})\right]$$

Note that this makes sense only at tree level, as loops will always generate counterterms for interactions that go beyond the SM Lagrangian

Similarly as for HEFT, amplitudes hit strong coupling around the scale 4πv~3 TeV, even for very small deformations of the couplings from the SM value

Higgs Couplings in effective theories

Effects of SM EFT D=6 operators on Higgs couplings

$$\mathcal{L} \supset \frac{m_h^2}{2v}(1+\delta\lambda_3)\,h^3$$

- Corrections to Higgs self-couplings

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

- Corrections to SM Higgs couplings to 2 SM fields and new tensor structures of these interactions

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

- Higgs couplings to 3 or more SM particles affecting multi-body Higgs decays

$$\begin{aligned}\mathcal{L}_{h,\rm EFT} \supset& \frac{h}{v}\sqrt{g_L^2+g_Y^2}\left[\delta g_L^{Ze} Z_\mu \bar{e}_L\gamma_\mu e_L + \delta g_R^{Ze} Z_\mu \bar{e}_R \gamma_\mu e_R + \ldots\right] \\ &+ \frac{h}{v^2}\left[(d_{Ae}A_{\mu\nu}\bar{e}_L\sigma_{\mu\nu}e_R + \text{h.c.}) + (d_{Ze}Z_{\mu\nu}\bar{e}_L\sigma_{\mu\nu}e_R + \text{h.c.}) + \ldots\right]\end{aligned}$$

Higgs couplings to pairs of SM fields in SM EFT

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.

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

relative correction to W mass

$$c_{ww} = c_{zz} + 2 s_\theta^2 c_{z\gamma} + s_\theta^4 c_{\gamma\gamma},$$

$$\tilde{c}_{ww} = \tilde{c}_{zz} + 2 s_\theta^2 \tilde{c}_{z\gamma} + s_\theta^4 \tilde{c}_{\gamma\gamma},$$

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

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

$$\begin{aligned}
\delta c_w &= c_{H\Box} - \frac{5g_L^2 - g_Y^2}{4(g_L^2 - g_Y^2)} c_{HD} - \frac{4 g_L g_Y}{g_L^2 - g_Y^2} c_{HWB} + \frac{3g_L^2 + g_Y^2}{4(g_L^2 - g_Y^2)}\left([c_{\ell\ell}]_{1221} - 2[c^{(3)}_{H\ell}]_{11} - 2[c^{(3)}_{H\ell}]_{22}\right),\\
\delta c_z &= c_{H\Box} - \frac{1}{4} c_{HD} + \frac{3}{4}\left([c_{\ell\ell}]_{1221} - 2[c^{(3)}_{H\ell}]_{11} - 2[c^{(3)}_{H\ell}]_{22}\right),
\end{aligned} \tag{2.38}$$

$$[\delta y_f]_{IJ} e^{i\phi^f_{IJ}} = -\frac{v}{\sqrt{2 m_{f_I} m_{f_J}}}[c^\dagger_{fH}]_{IJ} + \delta_{IJ}\left(c_{H\Box} - \frac{1}{4} c_{HD} + \frac{1}{4}[c_{\ell\ell}]_{1221} - \frac{1}{2}[c^{(3)}_{H\ell}]_{11} - \frac{1}{2}[c^{(3)}_{H\ell}]_{22}\right), \tag{2.39}$$

$$\begin{aligned}
c_{gg} &= \frac{4}{g_s^2} c_{HG},\\
c_{ww} &= \frac{4}{g_L^2} c_{HW},\\
c_{\gamma\gamma} &= 4\left(\frac{1}{g_L^2} c_{HW} + \frac{1}{g_Y^2} c_{HB} - \frac{1}{g_L g_Y} c_{HWB}\right),\\
c_{zz} &= 4\frac{g_L^2 c_{HW} + g_Y^2 c_{HB} + g_L g_Y c_{HWB}}{(g_L^2 + g_Y^2)^2},\\
c_{z\gamma} &= \frac{4 c_{HW} - 4 c_{HB} - 2\frac{g_L^2 - g_Y^2}{g_L g_Y} c_{HWB}}{g_L^2 + g_Y^2},
\end{aligned}$$

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$$\begin{aligned}
\tilde{c}_{gg} &= \frac{4}{g_s^2} c_{H\tilde{G}},\\
\tilde{c}_{\gamma\gamma} &= 4\left(\frac{1}{g_L^2} c_{H\tilde{W}} + \frac{1}{g_Y^2} c_{H\tilde{B}} - \frac{1}{g_L g_Y} c_{H\tilde{W}B}\right),\\
\tilde{c}_{zz} &= 4\frac{g_L^2 c_{H\tilde{W}} + g_Y^2 c_{H\tilde{B}} + g_L g_Y c_{H\tilde{W}B}}{(g_L^2 + g_Y^2)^2},\\
\tilde{c}_{z\gamma} &= \frac{4 c_{H\tilde{W}} - 4 c_{H\tilde{B}} - 2\frac{g_L^2 - g_Y^2}{g_L g_Y} c_{H\tilde{W}B}}{g_L^2 + g_Y^2},
\end{aligned}$$

(

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

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Important: correlations between different parameters describing deviations from SM

Correlations between higher order Higgs couplings and vertex corrections in SM EFT

- In SM EFT Higher-point Higgs vertices with gauge bosons and fermions are correlated with gauge boson couplings to fermions

- Thus, they are related to precisely measured observables at LEP and low-energy experiments

$$\mathcal{L}_{\rm EFT} \supset \sqrt{g_L^2+g_Y^2}\left[\left(1+\delta g_L^{Ze}\right) Z_\mu \bar{e}_L \gamma_\mu e_L + \left(1+\delta g_R^{Ze}\right) Z_\mu \bar{e}_R \gamma_\mu e_R + \ldots\right] + \frac{1}{v}\left[\left(d_{Ae} A_{\mu\nu} \bar{e}_L \sigma_{\mu\nu} e_R + {\rm h.c.}\right) + \left(d_{Ze} Z_{\mu\nu} \bar{e}_L \sigma_{\mu\nu} e_R + {\rm h.c.}\right) + \ldots\right]$$

$$\mathcal{L}_{h,\rm EFT} \supset \frac{h}{v}\sqrt{g_L^2+g_Y^2}\left[\delta g_L^{Ze} Z_\mu \bar{e}_L \gamma_\mu e_L + \delta g_R^{Ze} Z_\mu \bar{e}_R \gamma_\mu e_R + \ldots\right] + \frac{h}{v^2}\left[\left(d_{Ae} A_{\mu\nu} \bar{e}_L \sigma_{\mu\nu} e_R + {\rm h.c.}\right) + \left(d_{Ze} Z_{\mu\nu} \bar{e}_L \sigma_{\mu\nu} e_R + {\rm h.c.}\right) + \ldots\right]$$

All in all, vertex- and dipole-type interactions of Higgs with 2 fermions and 1 gauge field can be neglected in the LHC context, given constraints from other precision experiments (and assuming MFV)

LHCHXSWG
1610.07922

Higgs couplings in HEFT

$$\mathcal{L}_{\rm EFT} \supset \sqrt{g_L^2+g_Y^2}\left[\left(1+\delta g_L^{Ze}\right) Z_\mu \bar{e}_L \gamma_\mu e_L + \left(1+\delta g_R^{Ze}\right) Z_\mu \bar{e}_R \gamma_\mu e_R + \dots\right] + \frac{1}{v}\left[\left(d_{Ae} A_{\mu\nu} \bar{e}_L \sigma_{\mu\nu} e_R + \text{h.c.}\right) + \left(d_{Ze} Z_{\mu\nu} \bar{e}_L \sigma_{\mu\nu} e_R + \text{h.c.}\right) + \dots\right]$$

All the same couplings as in SM EFT do arise

$$\mathcal{L}_{h,\rm EFT} \supset \frac{h}{v}\sqrt{g_L^2+g_Y^2}\left[\delta \tilde{g}_L^{Ze} Z_\mu \bar{e}_L \gamma_\mu e_L + \delta \tilde{g}_R^{Ze} Z_\mu \bar{e}_R \gamma_\mu e_R + \dots\right] + \frac{h}{v^2}\left[\left(\tilde{d}_{Ae} A_{\mu\nu} \bar{e}_L \sigma_{\mu\nu} e_R + \text{h.c.}\right) + \left(\tilde{d}_{Ze} Z_{\mu\nu} \bar{e}_L \sigma_{\mu\nu} e_R + \text{h.c.}\right) + \dots\right]$$

However, no correlation between Higgs and non-Higgs couplings!

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

Also, no correlation between couplings to WW and to ZZ/Zγ/γγ, unless custodial symmetry imposed

Testing the correlations may be one day the best means of differentiating between the SM EFT and HEFT descriptions

Expansion parameter for Higgs couplings

SM EFT

free O(1) parameter

$$\mathcal{L}_{\rm EFT} \supset m_W^2 W_\mu^+ W_\mu^- + 2\frac{h}{v} m_W^2 W_\mu^+ W_\mu^- \left(1 + c\frac{g_*^2 v^2}{\Lambda^2}\right)$$

HEFT

free O(1) parameter

$$\mathcal{L}_{\rm EFT} \supset m_W^2 W_\mu^+ W_\mu^- + c\frac{h}{v} m_W^2 W_\mu^+ W_\mu^-$$

- In SM EFT there is order parameter Λ that controls deviations of Higgs boson couplings from SM predictions. As long as $\Lambda/g^* \gg v$, the couplings should be close to SM values, as measured by LHC experiments.
- In HEFT there is no order parameter that controls deviations of Higgs boson couplings from SM predictions. The experimental proximity of Higgs boson couplings to SM values must be considered accidental in the HEFT framework

LHC Higgs vs other precision measurements

LHC Higgs new physics reach

Example (always arise for composite Higgs)

$$\mathcal{L} \supset \frac{c_{H\Box}(H^\dagger H)\Box(H^\dagger H)}{\Lambda^2}$$
$$= -\frac{c_{H\Box}\partial_\mu(H^\dagger H)\partial_\mu(H^\dagger H)}{\Lambda^2}$$
$$= -\frac{c_{H\Box}\partial_\mu(v+h)^2\partial_\mu(v+h)^2}{4\Lambda^2}$$
$$= -\frac{c_{H\Box}v^2}{\Lambda^2}\partial_\mu h\partial_\mu h + \ldots$$

This operator modifies Higgs boson kinetic term. To retrieve canonical normalization we need to rescale:

$$h \to h\left(1 + \frac{v^2}{\Lambda^2}c_{H\Box}\right)$$

$$\frac{1}{2}(\partial_\mu h)^2 \to \frac{1}{2}(\partial_\mu h)^2\left(1 + \frac{2v^2}{\Lambda^2}c_{H\Box}\right)$$

Note that everything that is order 1/Λ^4 has to be consistently ignored in my calculation, otherwise I need to also take into account dimension-8 operator

LHC Higgs new physics reach

$$h \to h\left(1 + \frac{v^2}{\Lambda^2} c_{H\Box}\right)$$

But then *all* Higgs boson couplings present in SM are universally rescaled

$$\frac{h}{v}\left[2m_W^2 W_\mu^+ W_\mu^- + m_Z^2 Z_\mu Z_\mu\right]$$
$$\to \frac{h}{v}\left(1 + \frac{c_{H\Box} v^2}{\Lambda^2}\right)\left[2m_W^2 W_\mu^+ W_\mu^- + m_Z^2 Z_\mu Z_\mu\right]$$

$$\frac{h}{v}\sum_f m_f \bar{f} f$$
$$\to \frac{h}{v}\left(1 + \frac{c_{H\Box} v^2}{\Lambda^2}\right)\sum_f m_f \bar{f} f$$

Bound on Wilson coefficient $c_{H\Box}$ from Higgs signal strength measurements at LHC

$$\mu = 1.09 \pm 0.11$$

ATLAS + CMS
1606.02266

$$\frac{2v^2 c_{H\Box}}{\Lambda^2} = 0.09 \pm 0.11$$

or

$$-0.06 < \frac{v^2 c_{H\Box}}{\Lambda^2} < 0.15 \qquad @\ 95\%\ \text{CL}$$

Assuming this is leading dimension-6 operator

$$c_{H\Box} \sim g_*^2$$

$$\frac{\Lambda}{g_*} \gtrsim 1\ \text{TeV}$$

For negative sign

weakly coupled

$$\Lambda \gtrsim 1\ \text{TeV} \qquad g_* \sim 1$$
$$\Lambda \gtrsim 10\ \text{TeV} \qquad g_* \sim 4\pi$$

strongly coupled

Precision measurements new physics reach

LHC Higgs precision measurements are typically irrelevant to constraint BSM physics that violates approximate symmetries of the SM

E.g. for baryon-number violating new physics we can probe dimension-6 operator suppressed by up to 10^16 GeV

$$
\begin{aligned}
O_{duq} &= (d^c u^c)(\bar{Q}\bar{\ell}) \\
O_{qqu} &= (qq)(\bar{u}^c \bar{e}^c) \\
O_{qqq} &= (qq)(q\ell) \\
O_{duu} &= (d^c u^c)(u^c e^c)
\end{aligned}
$$

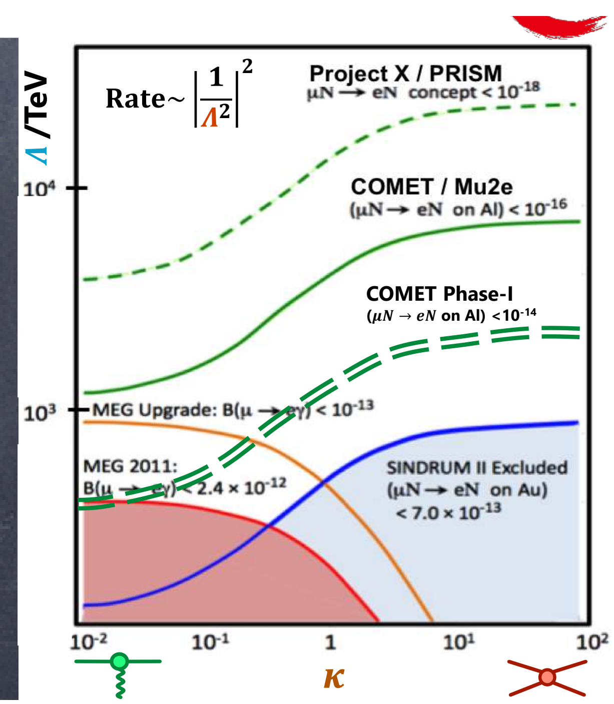
$$
\begin{aligned}
\mathcal{M}(p \to e^+\pi^0) &\sim \frac{1}{\Lambda_B^2} \\
\Gamma(p \to e^+\pi^0) &\sim \frac{m_p^5}{8\pi\Lambda_B^4} \\
\tau(p \to e^+\pi^0) &\sim \frac{8\pi\Lambda_B^4}{m_p^5} \\
&\sim 10^{34}\text{years}\left(\frac{\Lambda_B}{10^{16}\text{GeV}}\right)^4
\end{aligned}
$$

E.g. for flavor violating new physics we can probe dimension-6 operators suppressed up 100 TeV-100 PeV

Operator	Bound on Λ [TeV] ($C=1$) Re	Im	Bound on C ($\Lambda = 1$ TeV) Re	Im	Observables
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ϵ_K
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ϵ_K
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{b}_L\gamma^\mu d_L)^2$	6.6×10^2	9.3×10^2	2.3×10^{-6}	1.1×10^{-6}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	2.5×10^3	3.6×10^3	3.9×10^{-7}	1.9×10^{-7}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_L\gamma^\mu s_L)^2$	1.4×10^2	2.5×10^2	5.0×10^{-5}	1.7×10^{-5}	Δm_{B_s}; $S_{\psi\phi}$
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	4.8×10^2	8.3×10^2	8.8×10^{-6}	2.9×10^{-6}	Δm_{B_s}; $S_{\psi\phi}$

Isidori 1302.0661

Also lepton-flavor violating or flavor conserving CP-violating operators are probed up to 100 TeV



Friday, April 21, 17

SM EFT with dimension-6 operators

$$\mathcal{L}_{\mathrm{SM\ EFT}} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda_L}\mathcal{L}^{D=5} + \frac{1}{\Lambda^2}\mathcal{L}^{D=6} + \frac{1}{\Lambda_L^3}\cancel{\mathcal{L}}^{D=7} + \frac{1}{\Lambda^4}\cancel{\mathcal{L}}^{D=8} + \ldots$$

$$v \ll \Lambda \ll \Lambda_L$$

Leading corrections
to SM for E<<Λ

Pole observables
constrain vertex
and oblique
corrections

Off-pole observables probe
4-fermion operators

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

$[O^{(1)}_{H\ell}]_{IJ}$	$i\bar{\ell}_I\bar{\sigma}_\mu \ell_J H^\dagger \overleftrightarrow{D}_\mu H$
$[O^{(3)}_{H\ell}]_{IJ}$	$i\bar{\ell}_I\sigma^i\bar{\sigma}_\mu \ell_J H^\dagger \sigma^i\overleftrightarrow{D}_\mu H$
$[O_{He}]_{IJ}$	$ie^c_I\sigma_\mu\bar{e}^c_J H^\dagger \overleftrightarrow{D}_\mu H$
$[O^{(1)}_{Hq}]_{IJ}$	$i\bar{q}_I\bar{\sigma}_\mu q_J H^\dagger \overleftrightarrow{D}_\mu H$
$[O^{(3)}_{Hq}]_{IJ}$	$i\bar{q}_I\sigma^i\bar{\sigma}_\mu q_J H^\dagger \sigma^i\overleftrightarrow{D}_\mu H$
$[O_{Hu}]_{IJ}$	$iu^c_I\sigma_\mu\bar{u}^c_J H^\dagger \overleftrightarrow{D}_\mu H$
$[O_{Hd}]_{IJ}$	$id^c_I\sigma_\mu\bar{d}^c_J H^\dagger \overleftrightarrow{D}_\mu H$
$[O_{Hud}]_{IJ}$	$iu^c_I\sigma_\mu\bar{d}^c_J \tilde{H}^\dagger D_\mu H$

Dipole

$[O^\dagger_{eW}]_{IJ}$	$e^c_I\sigma_{\mu\nu}H^\dagger\sigma^i\ell_J W^i_{\mu\nu}$
$[O^\dagger_{eB}]_{IJ}$	$e^c_I\sigma_{\mu\nu}H^\dagger\ell_J B_{\mu\nu}$
$[O^\dagger_{uG}]_{IJ}$	$u^c_I\sigma_{\mu\nu}T^a\widetilde{H}^\dagger q_J\, G^a_{\mu\nu}$
$[O^\dagger_{uW}]_{IJ}$	$u^c_I\sigma_{\mu\nu}\widetilde{H}^\dagger\sigma^i q_J\, W^i_{\mu\nu}$
$[O^\dagger_{uB}]_{IJ}$	$u^c_I\sigma_{\mu\nu}\widetilde{H}^\dagger q_J\, B_{\mu\nu}$
$[O^\dagger_{dG}]_{IJ}$	$d^c_I\sigma_{\mu\nu}T^a H^\dagger q_J\, G^a_{\mu\nu}$
$[O^\dagger_{dW}]_{IJ}$	$d^c_I\sigma_{\mu\nu}\bar{H}^\dagger\sigma^i q_J\, W^i_{\mu\nu}$
$[O^\dagger_{dB}]_{IJ}$	$d^c_I\sigma_{\mu\nu}H^\dagger q_J\, B_{\mu\nu}$

Table 2.3: Two-fermion D=6 operators in the Warsaw basis. The flavor indices are denoted by I, J. For complex operators (O_{Hud} and all Yukawa and dipole operators) the corresponding complex conjugate operator is implicitly included.

$(\bar{R}R)(\bar{R}R)$

O_{ee}	$\eta(e^c\sigma_\mu\bar{e}^c)(e^c\sigma_\mu\bar{e}^c)$
O_{uu}	$\eta(u^c\sigma_\mu\bar{u}^c)(u^c\sigma_\mu\bar{u}^c)$
O_{dd}	$\eta(d^c\sigma_\mu\bar{d}^c)(d^c\sigma_\mu\bar{d}^c)$
O_{eu}	$(e^c\sigma_\mu\bar{e}^c)(u^c\sigma_\mu\bar{u}^c)$
O_{ed}	$(e^c\sigma_\mu\bar{e}^c)(d^c\sigma_\mu\bar{d}^c)$
O_{ud}	$(u^c\sigma_\mu\bar{u}^c)(d^c\sigma_\mu\bar{d}^c)$
O'_{ud}	$(u^c\sigma_\mu T^a\bar{u}^c)(d^c\sigma_\mu T^a\bar{d}^c)$

$(\bar{L}L)(\bar{R}R)$

$O_{\ell e}$	$(\bar{\ell}\bar{\sigma}_\mu\ell)(e^c\sigma_\mu\bar{e}^c)$
$O_{\ell u}$	$(\bar{\ell}\bar{\sigma}_\mu\ell)(u^c\sigma_\mu\bar{u}^c)$
$O_{\ell d}$	$(\bar{\ell}\bar{\sigma}_\mu\ell)(d^c\sigma_\mu\bar{d}^c)$
O_{eq}	$(e^c\sigma_\mu\bar{e}^c)(\bar{q}\bar{\sigma}_\mu q)$
O_{qu}	$(\bar{q}\bar{\sigma}_\mu q)(u^c\sigma_\mu\bar{u}^c)$
O'_{qu}	$(\bar{q}\bar{\sigma}_\mu T^a q)(u^c\sigma_\mu T^a\bar{u}^c)$
O_{qd}	$(\bar{q}\bar{\sigma}_\mu q)(d^c\sigma_\mu\bar{d}^c)$
O'_{qd}	$(\bar{q}\bar{\sigma}_\mu T^a q)(d^c\sigma_\mu T^a\bar{d}^c)$

$(\bar{L}L)(\bar{L}L)$

$O_{\ell\ell}$	$\eta(\bar{\ell}\bar{\sigma}_\mu\ell)(\bar{\ell}\bar{\sigma}_\mu\ell)$
O_{qq}	$\eta(\bar{q}\bar{\sigma}_\mu q)(\bar{q}\bar{\sigma}_\mu q)$
O'_{qq}	$\eta(\bar{q}\bar{\sigma}_\mu\sigma^i q)(\bar{q}\bar{\sigma}_\mu\sigma^i q)$
$O_{\ell q}$	$(\bar{\ell}\bar{\sigma}_\mu\ell)(\bar{q}\bar{\sigma}_\mu q)$
$O'_{\ell q}$	$(\bar{\ell}\bar{\sigma}_\mu\sigma^i\ell)(\bar{q}\bar{\sigma}_\mu\sigma^i q)$

$(\bar{L}R)(\bar{L}R)$

O_{quqd}	$(u^c q^j)\epsilon_{jk}(d^c q^k)$
O'_{quqd}	$(u^c T^a q^j)\epsilon_{jk}(d^c T^a q^k)$
$O_{\ell equ}$	$(e^c\ell^j)\epsilon_{jk}(u^c q^k)$
$O'_{\ell equ}$	$(e^c\bar{\sigma}_{\mu\nu}\ell^j)\epsilon_{jk}(u^c\bar{\sigma}^{\mu\nu}q^k)$
$O_{\ell edq}$	$(\bar{\ell}\bar{e}^c)(d^c q)$

Bosonic CP-even

O_H	$(H^\dagger H)^3$
$O_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
O_{HD}	$\left\lvert H^\dagger D_\mu H\right\rvert^2$
O_{HG}	$H^\dagger H\, G^a_{\mu\nu}G^a_{\mu\nu}$
O_{HW}	$H^\dagger H\, W^i_{\mu\nu}W^i_{\mu\nu}$
O_{HB}	$H^\dagger H\, B_{\mu\nu}B_{\mu\nu}$
O_{HWB}	$H^\dagger\sigma^i H\, W^i_{\mu\nu}B_{\mu\nu}$
O_W	$\epsilon^{ijk}W^i_{\mu\nu}W^j_{\nu\rho}W^k_{\rho\mu}$
O_G	$f^{abc}G^a_{\mu\nu}G^b_{\nu\rho}G^c_{\rho\mu}$

$O_{H\widetilde{G}}$	$H^\dagger H\,\widetilde{G}^a_{\mu\nu}G^a_{\mu\nu}$
$O_{H\widetilde{W}}$	$H^\dagger H\,\widetilde{W}^i_{\mu\nu}W^i_{\mu\nu}$
$O_{H\widetilde{B}}$	$H^\dagger H\,\widetilde{B}_{\mu\nu}B_{\mu\nu}$
$O_{H\widetilde{W}B}$	$H^\dagger\sigma^i H\,\widetilde{W}^i_{\mu\nu}B_{\mu\nu}$
$O_{\widetilde{W}}$	$\epsilon^{ijk}\widetilde{W}^i_{\mu\nu}W^j_{\nu\rho}W^k_{\rho\mu}$
$O_{\widetilde{G}}$	$f^{abc}\widetilde{G}^a_{\mu\nu}G^b_{\nu\rho}G^c_{\rho\mu}$

Off-Pole constraints on 4-fermion operators

$(ee)(qq)$

	$[c^{(3)}_{\ell q}]_{1111}$	$[c_{\ell q}]_{1111}$	$[c_{\ell u}]_{1111}$	$[c_{\ell d}]_{1111}$	$[c_{eq}]_{1111}$	$[c_{eu}]_{1111}$	$[c_{ed}]_{1111}$
LEP-2	3.5 ± 2.2	-42 ± 28	-21 ± 14	42 ± 28	-18 ± 11	-9.0 ± 5.7	18 ± 11
APV	27 ± 19	1.6 ± 1.1	3.4 ± 2.3	3.0 ± 2.0	-1.6 ± 1.1	-3.4 ± 2.3	-3.0 ± 2.0
QWEAK	7.0 ± 12	-2.3 ± 4.0	-3.5 ± 6.0	-7 ± 12	2.3 ± 4.0	3.5 ± 6.0	7 ± 12
PVDIS	-8 ± 12	24 ± 35	38 ± 48	-77 ± 96	-77 ± 96	-12 ± 17	24 ± 35
SAMPLE	-8 ± 45	x	-17 ± 90	17 ± 90	x	-17 ± 90	17 ± 90
CHARM	-80 ± 180	700 ± 1800	370 ± 880	-700 ± 1800	x	x	x
LEF	0.38 ± 0.28	x	x	x	x	x	x

Constraints on c v^2/Λ^2 in units of 10^-3

$(\mu\mu)(qq)$

	$[c^{(3)}_{\ell q}]_{2211}$	$[c_{\ell q}]_{2211}$	$[c_{\ell u}]_{2211}$	$[c_{\ell d}]_{2211}$	$[c_{eq}]_{2211}$	$[c_{eu}]_{2211}$	$[c_{ed}]_{2211}$
PDG ν_μ	20 ± 15	4 ± 21	18 ± 19	-20 ± 37	x	x	x
SPS	0 ± 1000	0 ± 3000	0 ± 1500	0 ± 3000	40 ± 390	-20 ± 190	40 ± 390
LEF	-0.4 ± 1.2	x	x	x	x	x	x

$$\begin{pmatrix} [c_{\ell equ}]_{1111} \\ [c_{\ell edq}]_{1111} \\ [c^{(3)}_{\ell equ}]_{1111} \\ [c_{\ell equ}]_{2211} \\ [c_{\ell edq}]_{2211} \end{pmatrix} = \begin{pmatrix} (-1.3 \pm 4.9) \cdot 10^{-7} \\ (1.3 \pm 4.9) \cdot 10^{-7} \\ (-0.2 \pm 1.6) \cdot 10^{-3} \\ (0.3 \pm 1.0) \cdot 10^{-4} \\ (-0.3 \pm 1.0) \cdot 10^{-4} \end{pmatrix}$$

AA, Gonzalez-Alonso, Mimouni
to appear

Off-Pole constraints on 4-lepton observables

Preliminary

$$
\begin{pmatrix}
\delta g_L^{We} \\ \delta g_L^{W\mu} \\ \delta g_L^{W\tau} \\ \delta g_L^{Ze} \\ \delta g_L^{Z\mu} \\ \delta g_L^{Z\tau} \\ \delta g_R^{Ze} \\ \delta g_R^{Z\mu} \\ \delta g_R^{Z\tau} \\ \delta g_L^{Zu} \\ \delta g_L^{Zc} \\ \delta g_L^{Zt} \\ \delta g_R^{Zu} \\ \delta g_R^{Zc} \\ \delta g_L^{Zd} \\ \delta g_L^{Zs} \\ \delta g_L^{Zb} \\ \delta g_R^{Zd} \\ \delta g_R^{Zs} \\ \delta g_R^{Zb} \\ \delta g_R^{Wq_1} \\ [c_{\ell\ell}]_{1111} \\ [c_{\ell e}]_{1111} \\ [c_{ee}]_{1111} \\ [c_{\ell\ell}]_{1221} \\ [c_{\ell\ell}]_{1122} \\ [c_{\ell e}]_{1122} \\ [c_{\ell e}]_{2211} \\ [c_{ee}]_{1122} \\ [c_{\ell\ell}]_{1331} \\ [c_{\ell\ell}]_{1133} \\ [c_{\ell e}]_{1133} \\ [c_{\ell e}]_{3311} \\ [c_{ee}]_{1133} \\ [c_{\ell\ell}]_{2332}
\end{pmatrix}
=
\begin{pmatrix}
-1.00 \pm 0.64 \\ -1.36 \pm 0.59 \\ 1.95 \pm 0.79 \\ -0.023 \pm 0.028 \\ 0.01 \pm 0.12 \\ 0.018 \pm 0.059 \\ -0.033 \pm 0.027 \\ 0.00 \pm 0.14 \\ 0.042 \pm 0.062 \\ -0.8 \pm 3.1 \\ -0.15 \pm 0.36 \\ -0.3 \pm 3.8 \\ 1.4 \pm 5.1 \\ -0.35 \pm 0.53 \\ -0.9 \pm 4.4 \\ 0.9 \pm 2.8 \\ 0.33 \pm 0.17 \\ 3 \pm 16 \\ 3.4 \pm 4.9 \\ 2.30 \pm 0.88 \\ -1.3 \pm 1.7 \\ 1.01 \pm 0.38 \\ -0.22 \pm 0.22 \\ 0.20 \pm 0.38 \\ -4.8 \pm 1.6 \\ 1.5 \pm 2.1 \\ 1.5 \pm 2.2 \\ -1.4 \pm 2.2 \\ 3.4 \pm 2.6 \\ 1.5 \pm 1.3 \\ 0 \pm 11 \\ -2.3 \pm 7.2 \\ 1.7 \pm 7.2 \\ -1 \pm 12 \\ 3.0 \pm 2.3
\end{pmatrix}
\times 10^{-2},
$$

$$
\begin{pmatrix}
[c_{\ell q}^{(3)}]_{1111} \\ [\hat{c}_{eq}]_{1111} \\ [\hat{c}_{\ell u}]_{1111} \\ [\hat{c}_{\ell d}]_{1111} \\ [\hat{c}_{eu}]_{1111} \\ [\hat{c}_{ed}]_{1111} \\ [\hat{c}_{\ell q}^{(3)}]_{1122} \\ [c_{\ell u}]_{1122} \\ [\hat{c}_{\ell d}]_{1122} \\ [c_{eq}]_{1122} \\ [c_{eu}]_{1122} \\ [\hat{c}_{ed}]_{1122} \\ [\hat{c}_{\ell q}^{(3)}]_{1133} \\ [c_{\ell d}]_{1133} \\ [c_{eq}]_{1133} \\ [c_{ed}]_{1133} \\ [c_{\ell q}^{(3)}]_{2211} \\ [c_{\ell q}]_{2211} \\ [c_{\ell u}]_{2211} \\ [c_{\ell d}]_{2211} \\ [\hat{c}_{eq}]_{2211} \\ [c_{\ell equ}]_{1111} \\ [c_{\ell edq}]_{1111} \\ [c_{\ell equ}^{(3)}]_{1111} \\ [\hat{c}_{\ell equ}]_{2211}
\end{pmatrix}
=
\begin{pmatrix}
-2.2 \pm 3.2 \\ 110 \pm 180 \\ -5 \pm 11 \\ -5 \pm 23 \\ -1 \pm 12 \\ -4 \pm 21 \\ -61 \pm 32 \\ 2.4 \pm 8.0 \\ -310 \pm 130 \\ -21 \pm 28 \\ -87 \pm 46 \\ 270 \pm 140 \\ -8.6 \pm 8.0 \\ -1.4 \pm 10 \\ -3.2 \pm 5.1 \\ 18 \pm 20 \\ -1.2 \pm 3.9 \\ 1.3 \pm 7.6 \\ 15 \pm 12 \\ 25 \pm 34 \\ 4 \pm 41 \\ -0.14 \pm 0.13 \\ -0.14 \pm 0.13 \\ -0.02 \pm 0.16 \\ -0.05 \pm 0.29
\end{pmatrix}
\times 10^{-2}.
$$

AA, Gonzalez-Alonso, Mimouni
to appear

- Full correlation matrix also calculated
- Typical constraints for vertex corrections are at 0.1% level, although some directions in parameter space less constrained
- Typical constraints for 4-fermion operators are at 1% level, though again some less constrained directions
- Chirality violating 2L2Q operators more stringently constrained

Scope of LHC Higgs searches

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

$$v \ll \Lambda \ll \Lambda_L$$

Leading corrections
to SM for E<<Λ

Certain dimension-6 operators can be probed **exclusively** by Higgs processes

Only certain linear combinations of operators are probed by pole observables, and Higgs data are need to resolve degeneracies

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

$[O^{(1)}_{H\ell}]_{IJ}$	$i\bar{\ell}_I\bar{\sigma}_\mu\ell_J H^\dagger \overleftrightarrow{D}_\mu H$
$[O^{(3)}_{H\ell}]_{IJ}$	$i\bar{\ell}_I\sigma^i\bar{\sigma}_\mu\ell_J H^\dagger \sigma^i\overleftrightarrow{D}_\mu H$
$[O_{He}]_{IJ}$	$ie^c_I\sigma_\mu\bar{e}^c_J H^\dagger \overleftrightarrow{D}_\mu H$
$[O^{(1)}_{Hq}]_{IJ}$	$i\bar{q}_I\bar{\sigma}_\mu q_J H^\dagger \overleftrightarrow{D}_\mu H$
$[O^{(3)}_{Hq}]_{IJ}$	$i\bar{q}_I\sigma^i\bar{\sigma}_\mu q_J H^\dagger \sigma^i\overleftrightarrow{D}_\mu H$
$[O_{Hu}]_{IJ}$	$iu^c_I\sigma_\mu\bar{u}^c_J H^\dagger \overleftrightarrow{D}_\mu H$
$[O_{Hd}]_{IJ}$	$id^c_I\sigma_\mu\bar{d}^c_J H^\dagger \overleftrightarrow{D}_\mu H$
$[O_{Hud}]_{IJ}$	$iu^c_I\sigma_\mu\bar{d}^c_J \tilde{H}^\dagger D_\mu H$

Dipole

$[O^\dagger_{eW}]_{IJ}$	$e^c_I\sigma_{\mu\nu}H^\dagger\sigma^i\ell_J W^i_{\mu\nu}$
$[O^\dagger_{eB}]_{IJ}$	$e^c_I\sigma_{\mu\nu}H^\dagger\ell_J B_{\mu\nu}$
$[O^\dagger_{uG}]_{IJ}$	$u^c_I\sigma_{\mu\nu}T^a\widetilde{H}^\dagger q_J\, G^a_{\mu\nu}$
$[O^\dagger_{uW}]_{IJ}$	$u^c_I\sigma_{\mu\nu}\widetilde{H}^\dagger\sigma^i q_J\, W^i_{\mu\nu}$
$[O^\dagger_{uB}]_{IJ}$	$u^c_I\sigma_{\mu\nu}\widetilde{H}^\dagger q_J\, B_{\mu\nu}$
$[O^\dagger_{dG}]_{IJ}$	$d^c_I\sigma_{\mu\nu}T^a H^\dagger q_J\, G^a_{\mu\nu}$
$[O^\dagger_{dW}]_{IJ}$	$d^c_I\sigma_{\mu\nu}\bar{H}^\dagger\sigma^i q_J\, W^i_{\mu\nu}$
$[O^\dagger_{dB}]_{IJ}$	$d^c_I\sigma_{\mu\nu}H^\dagger q_J\, B_{\mu\nu}$

Table 2.3: Two-fermion D=6 operators in the Warsaw basis. The flavor indices are denoted by I, J. For complex operators (O_{Hud} and all Yukawa and dipole operators) the corresponding complex conjugate operator is implicitly included.

$(\bar{R}R)(\bar{R}R)$

O_{ee}	$\eta(e^c\sigma_\mu\bar{e}^c)(e^c\sigma_\mu\bar{e}^c)$
O_{uu}	$\eta(u^c\sigma_\mu\bar{u}^c)(u^c\sigma_\mu\bar{u}^c)$
O_{dd}	$\eta(d^c\sigma_\mu\bar{d}^c)(d^c\sigma_\mu\bar{d}^c)$
O_{eu}	$(e^c\sigma_\mu\bar{e}^c)(u^c\sigma_\mu\bar{u}^c)$
O_{ed}	$(e^c\sigma_\mu\bar{e}^c)(d^c\sigma_\mu\bar{d}^c)$
O_{ud}	$(u^c\sigma_\mu\bar{u}^c)(d^c\sigma_\mu\bar{d}^c)$
O'_{ud}	$(u^c\sigma_\mu T^a\bar{u}^c)(d^c\sigma_\mu T^a\bar{d}^c)$

$(\bar{L}L)(\bar{R}R)$

$O_{\ell e}$	$(\bar{\ell}\bar{\sigma}_\mu\ell)(e^c\sigma_\mu\bar{e}^c)$
$O_{\ell u}$	$(\bar{\ell}\bar{\sigma}_\mu\ell)(u^c\sigma_\mu\bar{u}^c)$
$O_{\ell d}$	$(\bar{\ell}\bar{\sigma}_\mu\ell)(d^c\sigma_\mu\bar{d}^c)$
O_{eq}	$(e^c\sigma_\mu\bar{e}^c)(\bar{q}\bar{\sigma}_\mu q)$
O_{qu}	$(\bar{q}\bar{\sigma}_\mu q)(u^c\sigma_\mu\bar{u}^c)$
O'_{qu}	$(\bar{q}\bar{\sigma}_\mu T^a q)(u^c\sigma_\mu T^a\bar{u}^c)$
O_{qd}	$(\bar{q}\bar{\sigma}_\mu q)(d^c\sigma_\mu\bar{d}^c)$
O'_{qd}	$(\bar{q}\bar{\sigma}_\mu T^a q)(d^c\sigma_\mu T^a\bar{d}^c)$

$(\bar{L}L)(\bar{L}L)$

$O_{\ell\ell}$	$\eta(\bar{\ell}\bar{\sigma}_\mu\ell)(\bar{\ell}\bar{\sigma}_\mu\ell)$
O_{qq}	$\eta(\bar{q}\bar{\sigma}_\mu q)(\bar{q}\bar{\sigma}_\mu q)$
O'_{qq}	$\eta(\bar{q}\bar{\sigma}_\mu\sigma^i q)(\bar{q}\bar{\sigma}_\mu\sigma^i q)$
$O_{\ell q}$	$(\bar{\ell}\bar{\sigma}_\mu\ell)(\bar{q}\bar{\sigma}_\mu q)$
$O'_{\ell q}$	$(\bar{\ell}\bar{\sigma}_\mu\sigma^i\ell)(\bar{q}\bar{\sigma}_\mu\sigma^i q)$

$(\bar{L}R)(\bar{L}R)$

O_{quqd}	$(u^c q^j)\epsilon_{jk}(d^c q^k)$
O'_{quqd}	$(u^c T^a q^j)\epsilon_{jk}(d^c T^a q^k)$
$O_{\ell equ}$	$(e^c\ell^j)\epsilon_{jk}(u^c q^k)$
$O'_{\ell equ}$	$(e^c\bar{\sigma}_{\mu\nu}\ell^j)\epsilon_{jk}(u^c\bar{\sigma}^{\mu\nu}q^k)$
$O_{\ell edq}$	$(\bar{\ell}\bar{e}^c)(d^c q)$

Bosonic CP-even

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_{HW}	$H^\dagger H\, W^i_{\mu\nu}W^i_{\mu\nu}$
O_{HB}	$H^\dagger H\, B_{\mu\nu}B_{\mu\nu}$
O_{HWB}	$H^\dagger\sigma^i H\, W^i_{\mu\nu}B_{\mu\nu}$
O_W	$\epsilon^{ijk}W^i_{\mu\nu}W^j_{\nu\rho}W^k_{\rho\mu}$
O_G	$f^{abc}G^a_{\mu\nu}G^b_{\nu\rho}G^c_{\rho\mu}$

$O_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}^a_{\mu\nu}G^a_{\mu\nu}$
$O_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}^i_{\mu\nu}W^i_{\mu\nu}$
$O_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu}B_{\mu\nu}$
$O_{H\widetilde{W}B}$	$H^\dagger\sigma^i H\, \widetilde{W}^i_{\mu\nu}B_{\mu\nu}$
$O_{\widetilde{W}}$	$\epsilon^{ijk}\widetilde{W}^i_{\mu\nu}W^j_{\nu\rho}W^k_{\rho\mu}$
$O_{\widetilde{G}}$	$f^{abc}\widetilde{G}^a_{\mu\nu}G^b_{\nu\rho}G^c_{\rho\mu}$

Scope of LHC Higgs searches

- Accuracy of LHC Higgs measurements is inferior, compared e.g. to that of LEP-1 Z-pole observables, so for generic new physics scenarios they will not provide the strongest constraints

- However, the value of Higgs observables is that they give access to some completely unexplored directions in the parameter space of SM EFT

- One can concisely characterize these unconstrained directions that should be explored at the LHC

- There do exist (not fine-tuned) new physics scenarios where only the operators along these particular directions are generated with sizable coefficients in the low-energy effective theory

Higgs Basis - parameters

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

Higgs couplings to gauge bosons

$$\text{CP even}: \quad \delta c_z \quad c_{z\Box} \quad c_{zz} \quad c_{z\gamma} \quad c_{\gamma\gamma} \quad c_{gg}$$

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

Higgs couplings to fermions

$$\text{CP even}: \quad \delta y_u \quad \delta y_d \quad \delta y_e$$

$$\text{CP odd}: \quad \phi_u \quad \phi_d \quad \phi_e$$

Higgs couplings to itself

$$\text{CP even}: \quad \delta\lambda_3$$

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

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

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

Update on LHC Higgs constraints on SM EFT

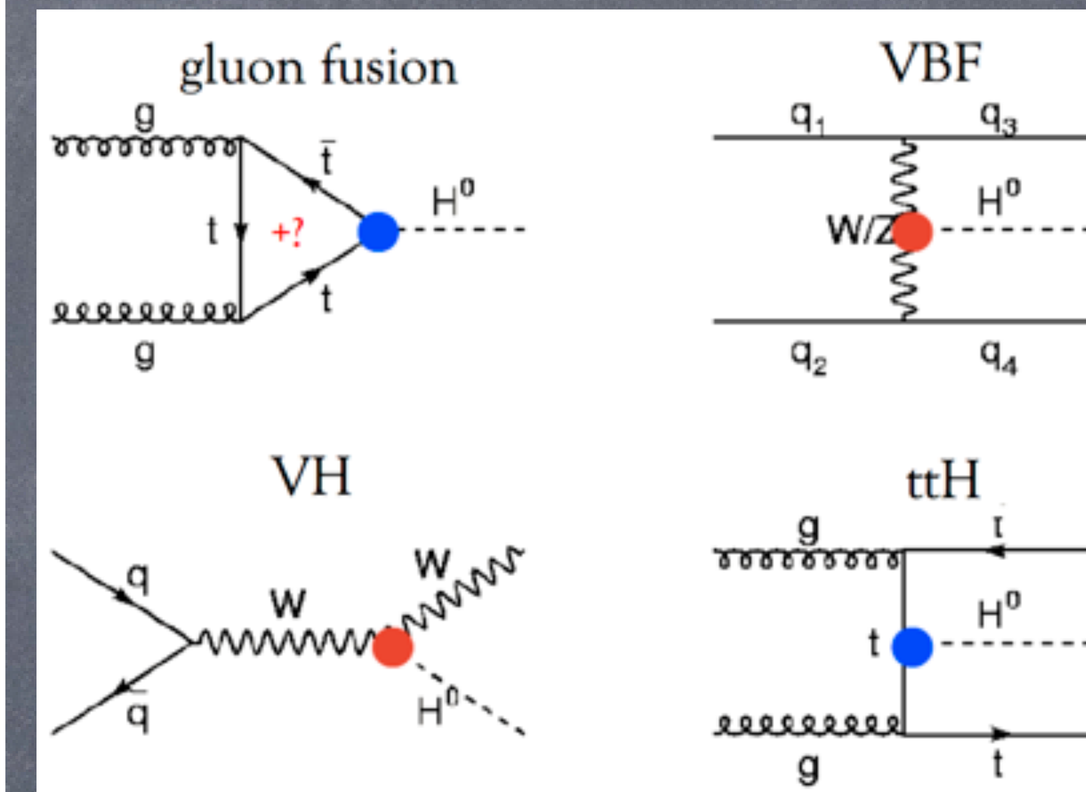
LHC Higgs signal strength so far

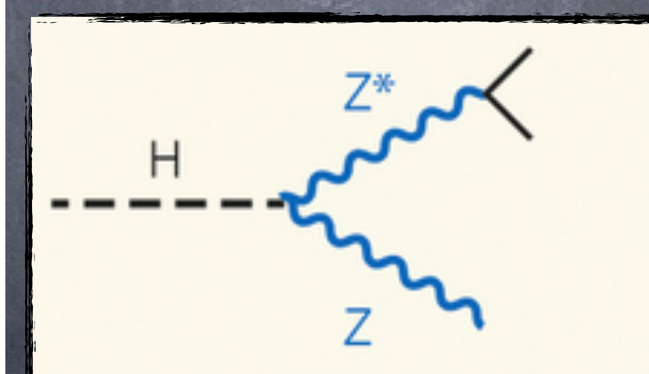
Channel	Production	Run-1	ATLAS Run-2	CMS Run-2
$\gamma\gamma$	ggh	$1.10^{+0.23}_{-0.22}$	$0.62^{+0.30}_{-0.29}$ [106]	$0.77^{+0.25}_{-0.23}$ [107]
	VBF	$1.3^{+0.5}_{-0.5}$	$2.25^{+0.75}_{-0.75}$ [106]	$1.61^{+0.90}_{-0.80}$ [107]
	Wh	$0.5^{+1.3}_{-1.2}$	-	-
	Zh	$0.5^{+3.0}_{-2.5}$	-	-
	Vh	-	$0.30^{+1.21}_{-1.12}$ [106]	-
	$t\bar{t}h$	$2.2^{+1.6}_{-1.3}$	$-0.22^{+1.26}_{-0.99}$ [106]	$1.9^{+1.5}_{-1.2}$ [107]
$Z\gamma$	incl.	$1.4^{+3.3}_{-3.2}$	-	-
ZZ^*	ggh	$1.13^{+0.34}_{-0.31}$	$1.34^{+0.39}_{-0.33}$ [106]	$0.96^{+0.40}_{-0.33}$ [108]
	VBF	$0.1^{+1.1}_{-0.6}$	$3.8^{+2.8}_{-2.2}$ [106]	$0.67^{+1.61}_{-0.67}$ [108]
	cats.	-	-	$1.05^{+0.19}_{-0.17}$ [?]
WW^*	ggh	$0.84^{+0.17}_{-0.17}$	-	-
	VBF	$1.2^{+0.4}_{-0.4}$	$1.7^{+1.1}_{-0.9}$ [109]	-
	Wh	$1.6^{+1.2}_{-1.0}$	$3.2^{+4.4}_{-4.2}$ [109]	-
	Zh	$5.9^{+2.6}_{-2.2}$	-	-
	$t\bar{t}h$	$5.0^{+1.8}_{-1.7}$	-	-
	incl.	-	-	0.3 ± 0.5 [110]
$\tau^+\tau^-$	ggh	$1.0^{+0.6}_{-0.6}$	-	-
	VBF	$1.3^{+0.4}_{-0.4}$	-	-
	Wh	$-1.4^{+1.4}_{-1.4}$	-	-
	Zh	$2.2^{+2.2}_{-1.8}$	-	
	$t\bar{t}h$	$-1.9^{+3.7}_{-3.3}$	-	$0.72^{+0.62}_{-0.53}$ [?]
$b\bar{b}$	VBF	-	$-3.9^{+2.8}_{-2.9}$ [111]	$-3.7^{+2.4}_{-2.5}$ [112]
	Wh	$1.0^{+0.5}_{-0.5}$	-	-
	Zh	$0.4^{+0.4}_{-0.4}$	-	-
	Vh	-	$0.21^{+0.51}_{-0.50}$ [113]	-
	$t\bar{t}h$	$1.15^{+0.99}_{-0.94}$	$2.1^{+1.0}_{-0.9}$ [114]	$-0.19^{+0.80}_{-0.81}$ [115]
$\mu^+\mu^-$	incl.	$0.1^{+2.5}_{-2.5}$	$-0.1^{+1.5}_{-1.5}$ [?]	
multi-ℓ	cats.	-	$2.5^{+1.3}_{-1.1}$ [117]	$1.5^{+0.5}_{-0.5}$ [?]

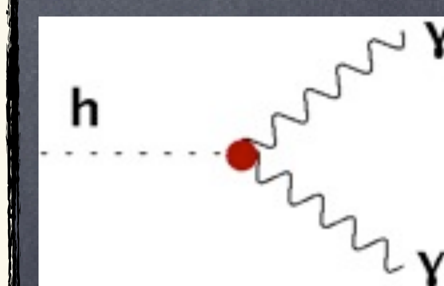
Run-1 results from ATLAS+CMS 1606.02266

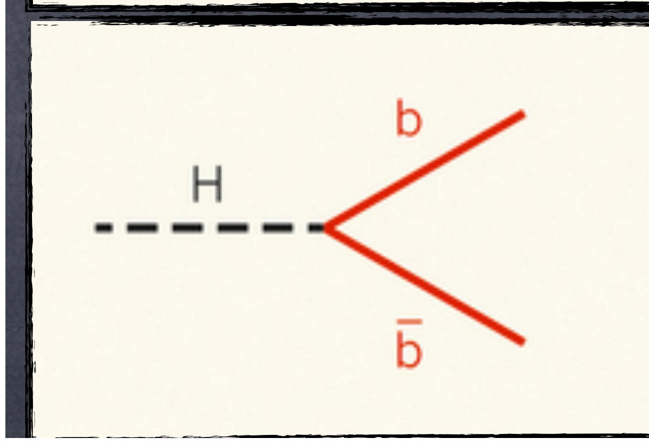
Run-2 results scavenged from various conf-notes

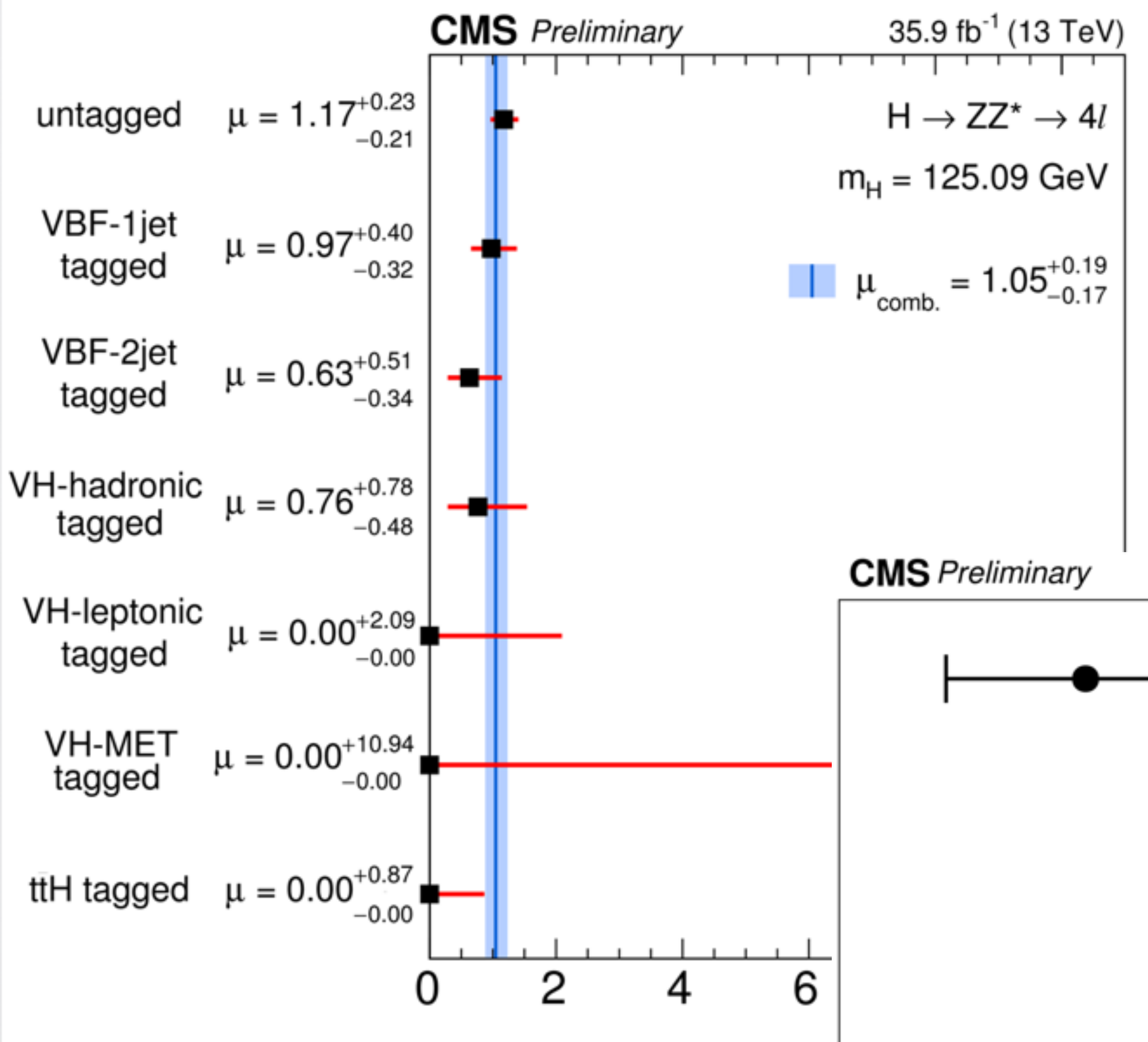
Not using any input from differential distributions here

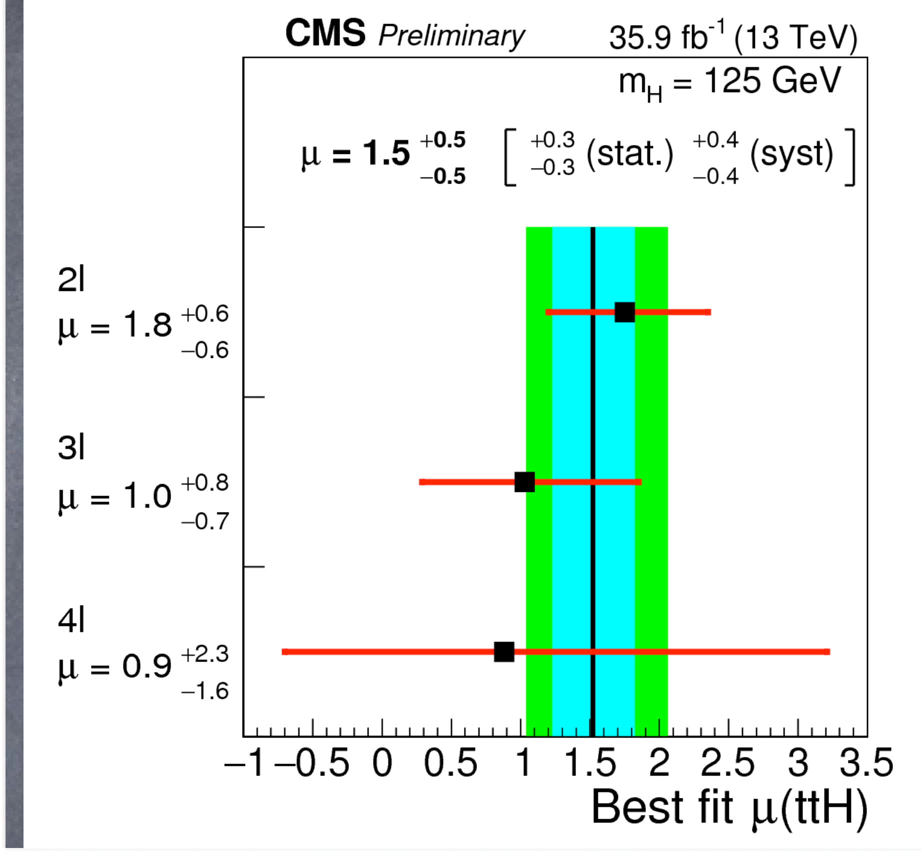


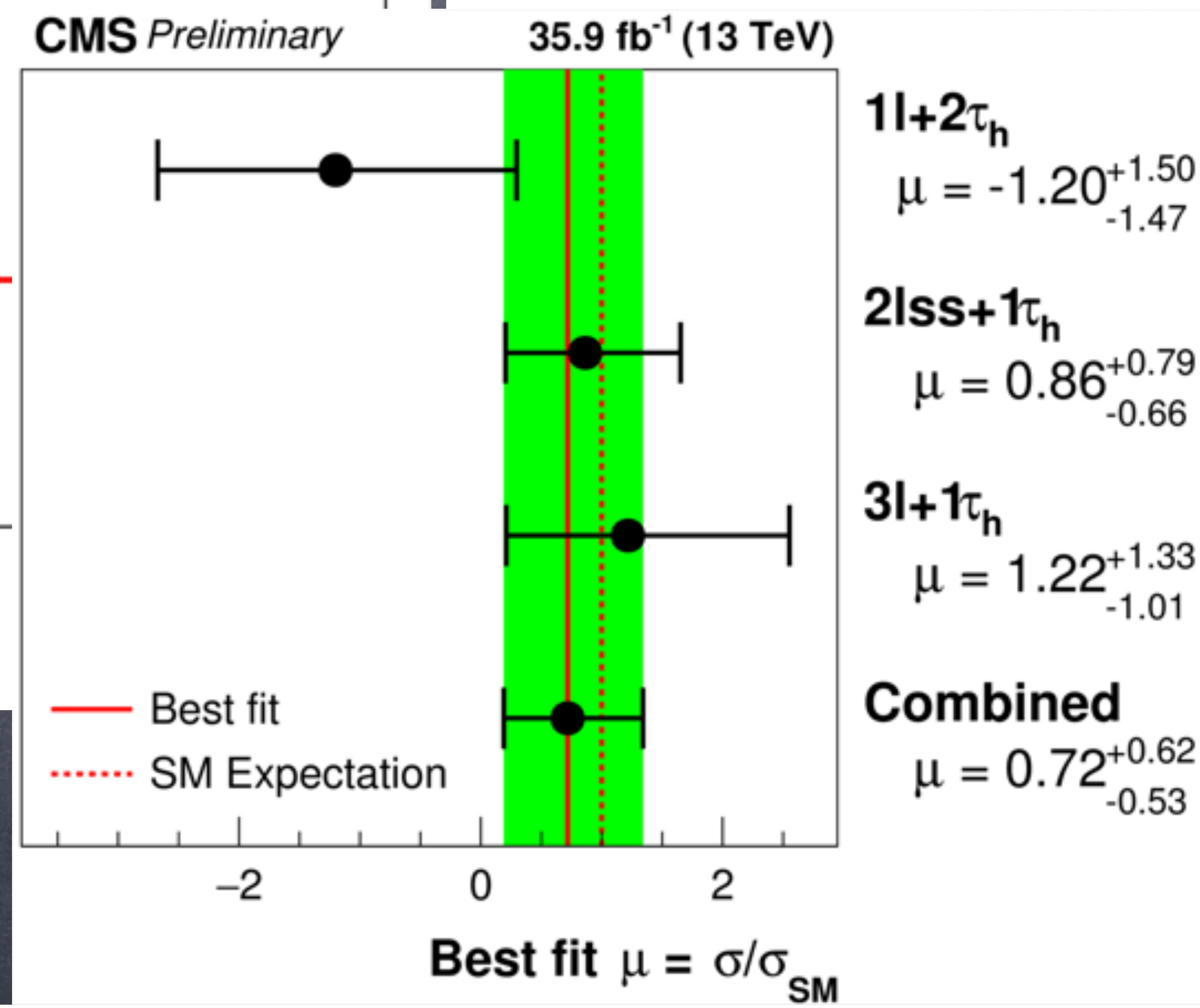







CMS Preliminary
35.9 fb^{-1} (13 TeV)
$H \to ZZ^* \to 4l$
m_H = 125.09 GeV
$\mu_{comb.} = 1.05^{+0.19}_{-0.17}$
untagged $\mu = 1.17^{+0.23}_{-0.21}$
VBF-1jet tagged $\mu = 0.97^{+0.40}_{-0.32}$
VBF-2jet tagged $\mu = 0.63^{+0.51}_{-0.34}$
VH-hadronic tagged $\mu = 0.76^{+0.78}_{-0.48}$
VH-leptonic tagged $\mu = 0.00^{+2.09}_{-0.00}$
VH-MET tagged $\mu = 0.00^{+10.94}_{-0.00}$
ttH tagged $\mu = 0.00^{+0.87}_{-0.00}$
0
2
4
6


CMS Preliminary
35.9 fb^{-1} (13 TeV)
m_H = 125 GeV
$\mu = \mathbf{1.5}^{+0.5}_{-0.5}$ $\left[{}^{+0.3}_{-0.3} \text{(stat.)} {}^{+0.4}_{-0.4} \text{(syst)} \right]$
2l $\mu = 1.8^{+0.6}_{-0.6}$
3l $\mu = 1.0^{+0.8}_{-0.7}$
4l $\mu = 0.9^{+2.3}_{-1.6}$
−1 −0.5 0 0.5 1 1.5 2 2.5 3 3.5
Best fit μ(ttH)


CMS Preliminary
35.9 fb^{-1} (13 TeV)
$1l+2\tau_h$ $\mu = -1.20^{+1.50}_{-1.47}$
$2lss+1\tau_h$ $\mu = 0.86^{+0.79}_{-0.66}$
$3l+1\tau_h$ $\mu = 1.22^{+1.33}_{-1.01}$
Combined $\mu = 0.72^{+0.62}_{-0.53}$
Best fit
SM Expectation
−2
0
2
Best fit $\mu = \sigma/\sigma_{SM}$

tth status

	ATLAS Run 2	CMS Run 2	
bb	$2.1^{+1.0}_{-0.9}$	$-0.2^{+0.8}_{-0.8}$	*PAS HIG 16-038*
multilep	$2.5^{+1.3}_{-1.1}$	$1.5^{+0.5}_{-0.5}$	*PAS HIG 17-004 **(35.9 fb^{-1})***
γγ	$-0.3^{+1.2}_{-1.0}$	$1.9^{+1.5}_{-1.2}$	*PAS HIG 16-020*
4ℓ		$0.0^{*}\,{}^{+1.2*}_{-0.0*}$	*PAS HIG 16-041 **(35.9 fb^{-1})***
comb.	$1.8^{+0.7}_{-0.7}$ *ATLAS-CONF-2016-068*		
Run1 comb. *JHEP 08(2016) 045*		$2.3^{+1.2}_{-1.0}$	

(*) $-2\Delta\ln L = 1$ interval with $\mu \geq 0$ constraint

AA's naive combination

$$\mu_{\mathrm{tth}} = 1.26 \pm 0.26$$

Slide from G. Petrucciani's talk in Moriond'17

Effects of dimension-6 operators on triple gauge couplings (TGCs)

In SM, cubic (and quartic) gauge interactions completely fixed, once gauge couplings known

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

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

Relations between anomalous TGCs and Wilson coefficients in Warsaw basis

$$
\begin{aligned}
\delta g_{1,z} &= -\frac{g_L^2+g_Y^2}{4(g_L^2-g_Y^2)}\left(4\frac{g_Y}{g_L}c_{HWB} + c_{HD} + 2[c^{(3)}_{H\ell}]_{11} + 2[c^{(3)}_{H\ell}]_{22} - [c_{\ell\ell}]_{1221}\right), \\
\delta\kappa_\gamma &= \frac{g_L}{g_Y}c_{HWB}, \\
\delta\kappa_z &= -\frac{g_L^2+g_Y^2}{4(g_L^2-g_Y^2)}\left(8\frac{g_L g_Y}{g_L^2+g_Y^2}c_{HWB} + c_{HD} + 2[c^{(3)}_{H\ell}]_{11} + 2[c^{(3)}_{H\ell}]_{22} - [c_{\ell\ell}]_{1221}\right), \\
\lambda_z = \lambda_\gamma &= -\frac{3}{2}g_L c_W, \\
\tilde{\kappa}_\gamma &= \frac{g_L}{g_Y}c_{H\tilde{W}B}, \qquad \tilde{\kappa}_z = -\frac{g_Y}{g_L}c_{H\tilde{W}B}, \\
\tilde{\lambda}_z = \tilde{\lambda}_\gamma &= -\frac{3}{2}g_L c_{\tilde{W}}.
\end{aligned}
$$

TGC - Higgs Synergy

TGC

$\mathrm{CP\ even}: \quad \delta\kappa_\gamma \quad \delta g_{1,z} \quad \lambda_z$

$\mathrm{CP\ odd}: \quad \tilde{\kappa}_\gamma \quad \tilde{\lambda}_z$

$\Longleftrightarrow$

Higgs

$\mathrm{CP\ even}: \quad \delta c_z \quad c_{z\Box} \quad c_{zz} \quad c_{z\gamma} \quad c_{\gamma\gamma}$

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

Linearly realized SU(3)xSU(2)xU(1) local symmetry in Lagrangian with operators up to D=6 implies that aTGC and Higgs couplings to EW gauge bosons are related:

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

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

$$\tilde{\kappa}_\gamma = -\frac{g_L^2}{2}\left(\tilde{c}_{\gamma\gamma}\frac{e^2}{g_L^2+g_Y^2} + \tilde{c}_{z\gamma}\frac{g_L^2-g_Y^2}{g_L^2+g_Y^2} - \tilde{c}_{zz}\right),$$

- Therefore constraints on δg1z and δκγ imply constraints on Higgs couplings to electroweak gauge bosons, and vice-versa
- In fact, TGCs probe directions in EFT parameter space that are weakly constrained by Higgs searches. Therefore, important to combine Higgs and TGC data!
- That is possible provided both aTGCs and Higgs couplings are constrained in a general consistent, multi-dimensional fit, and the correlation matrix is given!

D=6 EFT parameters probed by LHC Higgs searches

- Combinations of EFT parameters constrained by precision tests much better than at O(10%) are not relevant at the LHC, given current precision
- Assuming MFV, one can identify 16 combinations of EFT parameters that are weakly or not at all constrained by precision tests, and which affect LHC Higgs observables at leading order. These correspond to 16 Higgs basis parameters in previous slide.
- Higgs signal strength observables at $O(1/\Lambda^2)$ are only sensitive to CP-even parameters (CP-odd ones enter only quadratically and are ignored - one needs to study differential distributions to access those at $O(1/\Lambda^2)$).
- Currently not much experimental sensitivity to modifications of Higgs cubic self-interactions, thus parameter $\delta\lambda_3$ cannot be reasonably constrained

Di Vita et al 1704.01953

- Thus, assuming MFV couplings to fermions, only 9 EFT parameters affect Higgs signal strength measured at LHC

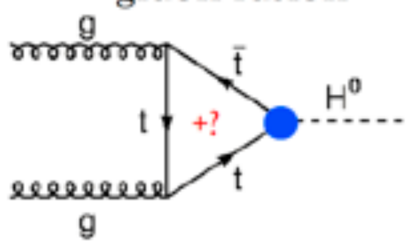
$$\delta c_z \quad c_{z\Box} \quad c_{zz} \quad c_{z\gamma} \quad c_{\gamma\gamma} \quad c_{gg} \quad \delta y_u \quad \delta y_d \quad \delta y_e$$

Corrections to Higgs production from dimension-6 operators

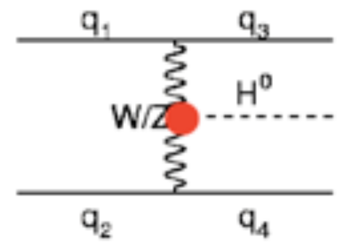
$$\frac{\sigma_{ggh}}{\sigma_{ggh}^{\rm SM}} \simeq 1 + 237 c_{gg} + 2.06\delta y_u - 0.06\delta y_d.$$

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

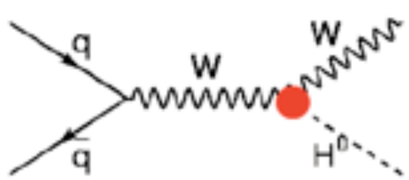
gluon fusion



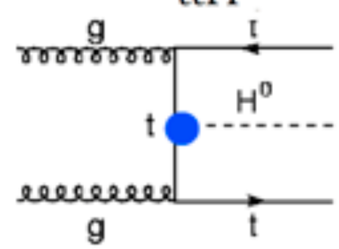
VBF



VH



ttH

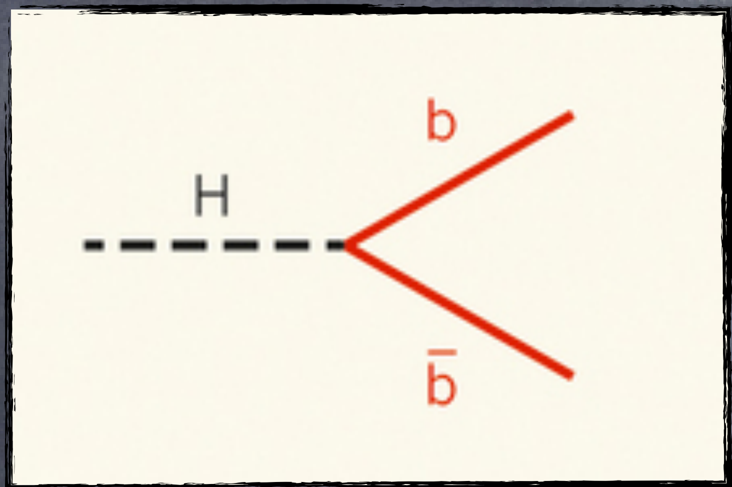


$$\frac{\sigma_{tth}}{\sigma_{tth}^{\rm SM}} \simeq 1 + 2\delta y_u.$$

$$\begin{aligned}\frac{\sigma_{Wh}}{\sigma_{Wh}^{\rm SM}} &\simeq 1 + 2\delta c_w + \begin{pmatrix}6.39\\6.51\\6.96\end{pmatrix} c_{w\Box} + \begin{pmatrix}1.49\\1.49\\1.50\end{pmatrix} c_{ww}\\ &\to 1 + 2\delta c_z + \begin{pmatrix}9.26\\9.43\\10.08\end{pmatrix} c_{z\Box} + \begin{pmatrix}4.35\\4.41\\4.63\end{pmatrix} c_{zz} - \begin{pmatrix}0.81\\0.84\\0.93\end{pmatrix} c_{z\gamma} - \begin{pmatrix}0.43\\0.44\\0.48\end{pmatrix} c_{\gamma\gamma}\\ \frac{\sigma_{Zh}}{\sigma_{Zh}^{\rm SM}} &\simeq 1 + 2\delta c_z + \begin{pmatrix}5.30\\5.40\\5.72\end{pmatrix} c_{z\Box} + \begin{pmatrix}1.79\\1.80\\1.82\end{pmatrix} c_{zz} + \begin{pmatrix}0.80\\0.82\\0.87\end{pmatrix} c_{\gamma\Box} + \begin{pmatrix}0.22\\0.22\\0.22\end{pmatrix} c_{z\gamma},\\ &\to 1 + 2\delta c_z + \begin{pmatrix}7.61\\7.77\\8.24\end{pmatrix} c_{z\Box} + \begin{pmatrix}3.31\\3.35\\3.47\end{pmatrix} c_{zz} - \begin{pmatrix}0.58\\0.60\\0.65\end{pmatrix} c_{z\gamma} + \begin{pmatrix}0.27\\0.28\\0.30\end{pmatrix} c_{\gamma\gamma}.\end{aligned}$$

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

Corrections to Higgs decays from dimension-6 operators

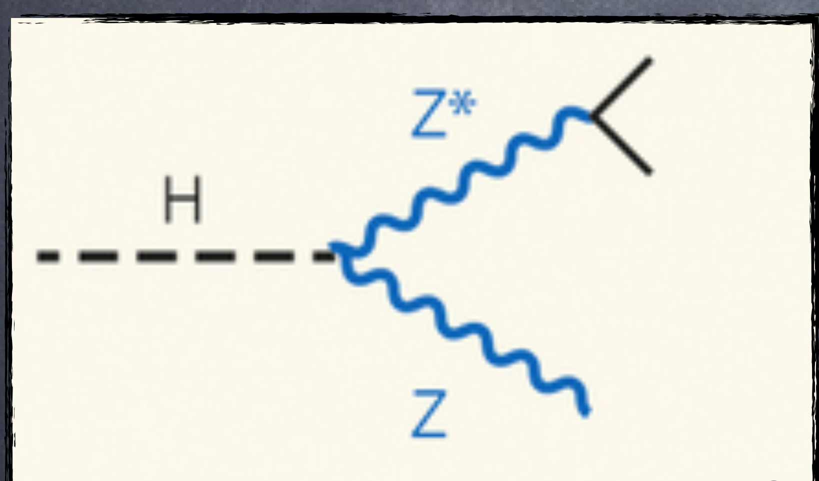


Decays to 2 fermions

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

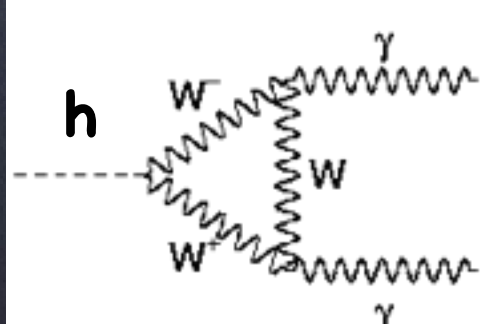
Decays to 4 fermions

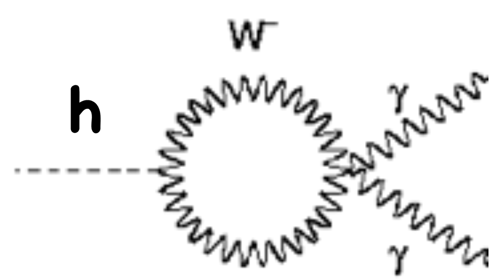
$$\begin{aligned}\frac{\Gamma_{2\ell 2\nu}}{\Gamma_{2\ell 2\nu}^{\mathrm{SM}}} &\simeq 1 + 2\delta c_w + 0.46 c_{w\Box} - 0.15 c_{ww} \\ &\to 1 + 2\delta c_z + 0.67 c_{z\Box} + 0.05 c_{zz} - 0.17 c_{z\gamma} - 0.05 c_{\gamma\gamma}.\end{aligned}$$



$\left(\begin{array}{c} \text{2e2μ} \\ \text{4e} \end{array}\right)$

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

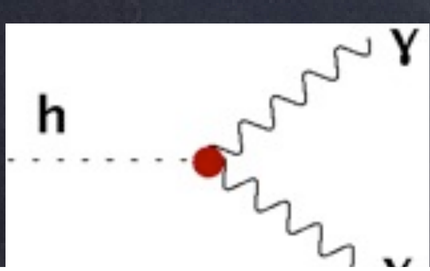


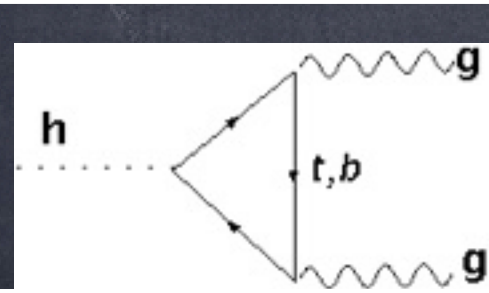


Decays to 2 gauge bosons

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

$$\begin{aligned}\hat{c}_{\gamma\gamma} &\approx c_{\gamma\gamma} - 0.11\delta c_z + 0.02\delta y_u, & c_{\gamma\gamma}^{\mathrm{SM}} &\simeq -8.3 \times 10^{-2}, \\ \hat{c}_{z\gamma} &\approx c_{z\gamma} - 0.06\delta c_z + 0.003\delta y_u, & c_{z\gamma}^{\mathrm{SM}} &\simeq -5.9 \times 10^{-2},\end{aligned}$$





Global constraints on Higgs coupling in SM EFT

Combined constraints from LHC Higgs and electroweak precision constraints

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

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

$$\mathcal{L}_{\rm tgc} = ie\left[\left(W_{\mu\nu}^+ W_\mu^- - W_{\mu\nu}^- W_\mu^+\right) A_\nu + (1+\delta\kappa_\gamma) A_{\mu\nu} W_\mu^+ W_\nu^- + \tilde{\kappa}_\gamma \tilde{A}_{\mu\nu} W_\mu^+ W_\nu^-\right]$$
$$+ i g_L c_\theta \left[(1+\delta g_{1,z})\left(W_{\mu\nu}^+ W_\mu^- - W_{\mu\nu}^- W_\mu^+\right) Z_\nu + (1+\delta\kappa_z) Z_{\mu\nu} W_\mu^+ W_\nu^- + \tilde{\kappa}_z \tilde{Z}_{\mu\nu} W_\mu^+ W_\nu^-\right]$$
$$+ i\frac{e}{m_W^2}\lambda_\gamma W_{\mu\nu}^+ W_{\nu\rho}^- A_{\rho\mu} + i\frac{g_L c_\theta}{m_W^2}\lambda_z W_{\mu\nu}^+ W_{\nu\rho}^- Z_{\rho\mu} + i\frac{e}{m_W^2}\tilde{\lambda}_\gamma W_{\mu\nu}^+ W_{\nu\rho}^- \tilde{A}_{\rho\mu} + i\frac{g_L c_\theta}{m_W^2}\tilde{\lambda}_z W_{\mu\nu}^+ W_{\nu\rho}^- \tilde{Z}_{\rho\mu}$$

$$\begin{pmatrix} \delta c_z \\ c_{zz} \\ c_{z\Box} \\ c_{\gamma\gamma} \\ c_{z\gamma} \\ c_{gg} \\ \delta y_u \\ \delta y_d \\ \delta y_e \\ \lambda_z \end{pmatrix} = \begin{pmatrix} -0.07 \pm 0.09 \\ 0.11 \pm 0.29 \\ -0.06 \pm 0.13 \\ 0.0024 \pm 0.0071 \\ -0.019 \pm 0.060 \\ -0.0017 \pm 0.0009 \\ -0.02 \pm 0.13 \\ -0.40 \pm 0.19 \\ -0.18 \pm 0.14 \\ -0.058 \pm 0.043 \end{pmatrix},$$

Correlation matrix available

- Overall SM is very good (too good?) fit, no evidence or even hint of D=6 operators
- Some tension in global fit due to deficit in the bb decay, but mostly gone after Moriond
- Decrease in bb needs to be compensated by negative contributions to Higgs-gluon couplings, to avoid overshooting γγ, WW, and ZZ channels

What's in store

- More Higgs signal strength results coming. Especially WW and bb measurements should have important impact on the fits
- ATLAS + CMS combination with correlations
- Additional constraints from Higgs differential distributions that should help disentangle different tensor structures of Higgs coupling to VV and access CP violating operators
- Constraints from high-energy tails of differential distributions where higher energy of the LHC trumps its inferior accuracy

LHC vs low-energy

One-by-one constraints of LLQQ operators in units of 0.1%

$(ee)(qq)$

	$[c^{(3)}_{\ell q}]_{1111}$	$[c_{\ell q}]_{1111}$	$[c_{\ell u}]_{1111}$	$[c_{\ell d}]_{1111}$	$[c_{eq}]_{1111}$	$[c_{eu}]_{1111}$	$[c_{ed}]_{1111}$
LE	0.45 ± 0.28	1.6 ± 1.0	2.8 ± 2.1	3.6 ± 2.0	-1.8 ± 1.1	-4.0 ± 2.0	-2.7 ± 2.0
ATLAS ($\sqrt{s} \leq 1.5$ TeV)	$-0.65^{+0.60}_{-0.67}$	$2.3^{+1.9}_{-2.2}$	$2.6^{+2.3}_{-2.6}$	$-1.4^{+2.9}_{-2.8}$	$1.3^{+1.7}_{-1.9}$	$1.5^{+2.4}_{-1.4}$	$-2.7^{+3.2}_{-2.8}$
ATLAS ($\sqrt{s} \leq 1$ TeV)	$-0.78^{+0.81}_{-0.89}$	3.2 ± 3.4	3.8 ± 4.1	-1.9 ± 4.2	1.9 ± 2.8	$1.7^{+9.1}_{-1.8}$	-3.8 ± 4.7

$(\mu\mu)(qq)$

	$[c^{(3)}_{\ell q}]_{2211}$	$[c_{\ell q}]_{2211}$	$[c_{\ell u}]_{2211}$	$[c_{\ell d}]_{2211}$	$[c_{eq}]_{2211}$	$[c_{eu}]_{2211}$	$[c_{ed}]_{2211}$
LE	-0.2 ± 1.2	4 ± 21	18 ± 19	-20 ± 37	40 ± 390	-20 ± 190	40 ± 390
ATLAS ($\sqrt{s} \leq 1.5$ TeV)	$-1.35^{+0.56}_{-0.63}$	1.8 ± 1.1	2.0 ± 1.3	-1.0 ± 1.6	1.02 ± 0.99	$2.8^{+1.7}_{-1.3}$	-2.0 ± 1.8
ATLAS ($\sqrt{s} \leq 1$ TeV)	$-0.72^{+0.76}_{-0.83}$	3.2 ± 3.4	3.8 ± 4.1	-1.9 ± 4.2	1.9 ± 2.7	$1.6^{+2.4}_{-1.7}$	-3.8 ± 4.7

CV

	$[c_{\ell equ}]_{1111}$	$[c_{\ell edq}]_{1111}$	$[c^{(3)}_{\ell equ}]_{1111}$	$[c_{\ell equ}]_{2211}$	$[c_{\ell edq}]_{2211}$	$[c^{(3)}_{\ell equ}]_{2211}$
LE	-0.00013 ± 0.00049	0.00013 ± 0.00049	-0.2 ± 1.6	0.03 ± 0.10	-0.03 ± 0.10	x
ATLAS ($\sqrt{s} \leq 1.5$ TeV)	0 ± 1.7	0 ± 2.3	0 ± 0.8	0 ± 0.98	0 ± 1.3	0 ± 0.45
ATLAS ($\sqrt{s} \leq 1$ TeV)	0 ± 2.6	0 ± 3.3	0 ± 1.2	0 ± 2.5	0 ± 3.2	0 ± 1.2

Take Away

- Several theoretical frameworks to describe possible deformations of Higgs coupling from SM predictions, among which SM EFT is preferred by most theorists

- Accuracy of LHC Higgs measurements is rather unimpressive as only dimension-6 operators suppressed by scales smaller than ~1 TeV can be probed. Still, for strongly coupled UV completions this gives access to new physics at ~10 TeV, beyond the direct reach of the LHC

- The importance of Higgs observables is that they constraint certain linear combinations of dimension-6 operators that cannot be accessed by any other means

- One should stress the importance of global fits, where all (unconstrained) dimension-6 operators are assumed to be present, as only these lead to model-independent and convention-independent constraints that can be applied to a large class of BSM scenarios

- Current theory-level analyses meaningfully probe 9 of these linear combinations. No serious hints for the presence of any of these operators exist in the latest data, with previous hints driven by tth and h->bb going away