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Where do we stand with Higgs couplings

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Project BEYONDSM

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Status report

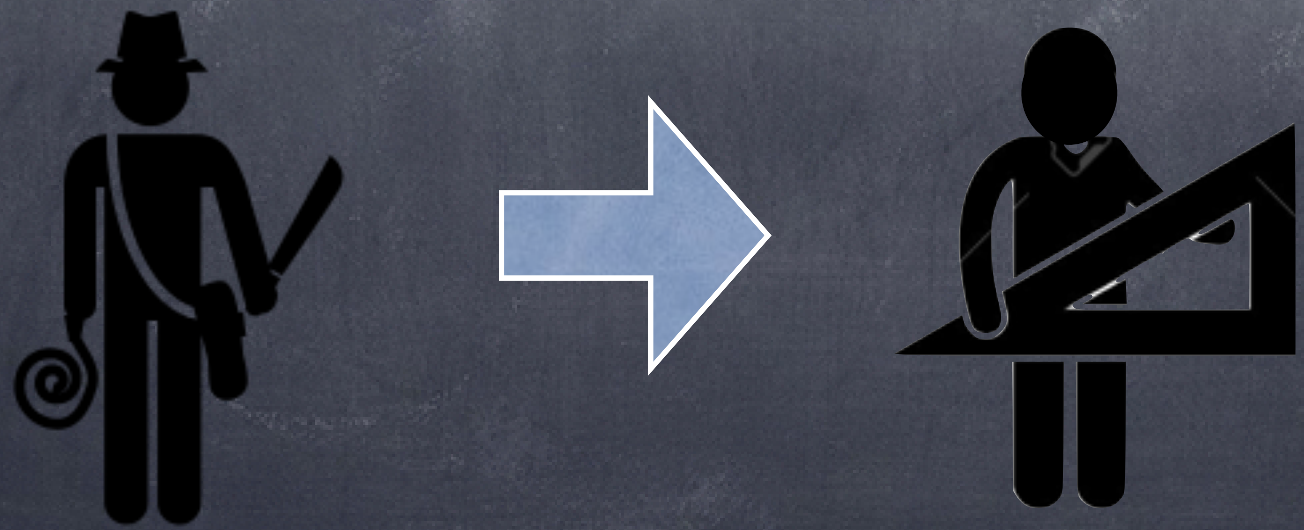
- SM has been shamelessly successful in describing all collider and low-energy experiments. Discovery of 125 GeV Higgs boson is the last piece of puzzle that falls into place. There is no more free unknown parameters in the SM

- 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



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

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

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

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

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

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

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

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

SM EFT with dimension-6 operators

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

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

Leading corrections to SM for E<<Λ

Pole observables constrain vertex and oblique corrections

Anomalous dipole moments constrain dipole operators

Off-pole scattering probes 4-fermion operators

WW/WZ production

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

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

Dipole

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

Bosonic CP-even

O_H	$(H^\dagger H)^3$		
$O_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$		
O_{HD}	$\left\vert H^\dagger D_\mu H\right\vert^2$		
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}	$H^\dagger\sigma^i H\, W^i_{\mu\nu}B_{\mu\nu}$	$O_{H\widetilde WB}$	$H^\dagger\sigma^i H\, \widetilde W^i_{\mu\nu}B_{\mu\nu}$
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	$f^{abc}G^a_{\mu\nu}G^b_{\nu\rho}G^c_{\rho\mu}$	$O_{\widetilde G}$	$f^{abc}\widetilde G^a_{\mu\nu}G^b_{\nu\rho}G^c_{\rho\mu}$

$(\bar R R)(\bar R R)$

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

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

Scope of LHC Higgs searches

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

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

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

Bosonic CP-even	
O_H	$(H^\dagger H)^3$
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O_{HD}	$\lvert H^\dagger D_\mu H\rvert^2$
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	$f^{abc}G^a_{\mu\nu}G^b_{\nu\rho}G^c_{\rho\mu}$

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

$(\bar RR)(\bar RR)$	
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}	$(u^c\sigma_\mu T^a\bar u^c)(d^c\sigma_\mu T^a\bar d^c)$

$(\bar LL)(\bar RR)$	
$O_{\ell e}$	$(\bar\ell\bar\sigma_\mu\ell)(e^c\sigma_\mu\bar e^c)$
$O_{\ell u}$	$(\bar\ell\bar\sigma_\mu\ell)(u^c\sigma_\mu\bar u^c)$
$O_{\ell d}$	$(\bar\ell\bar\sigma_\mu\ell)(d^c\sigma_\mu\bar d^c)$
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}	$(\bar q\bar\sigma_\mu T^a q)(d^c\sigma_\mu T^a\bar d^c)$

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

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

Effects of SM EFT D=6 operators on Higgs couplings

- Corrections to Higgs self-couplings
- Corrections to SM Higgs couplings to 2 SM fields and new tensor structures of these interactions
- Higgs couplings to 3 or more SM particles affecting multi-body Higgs decays

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

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

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

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

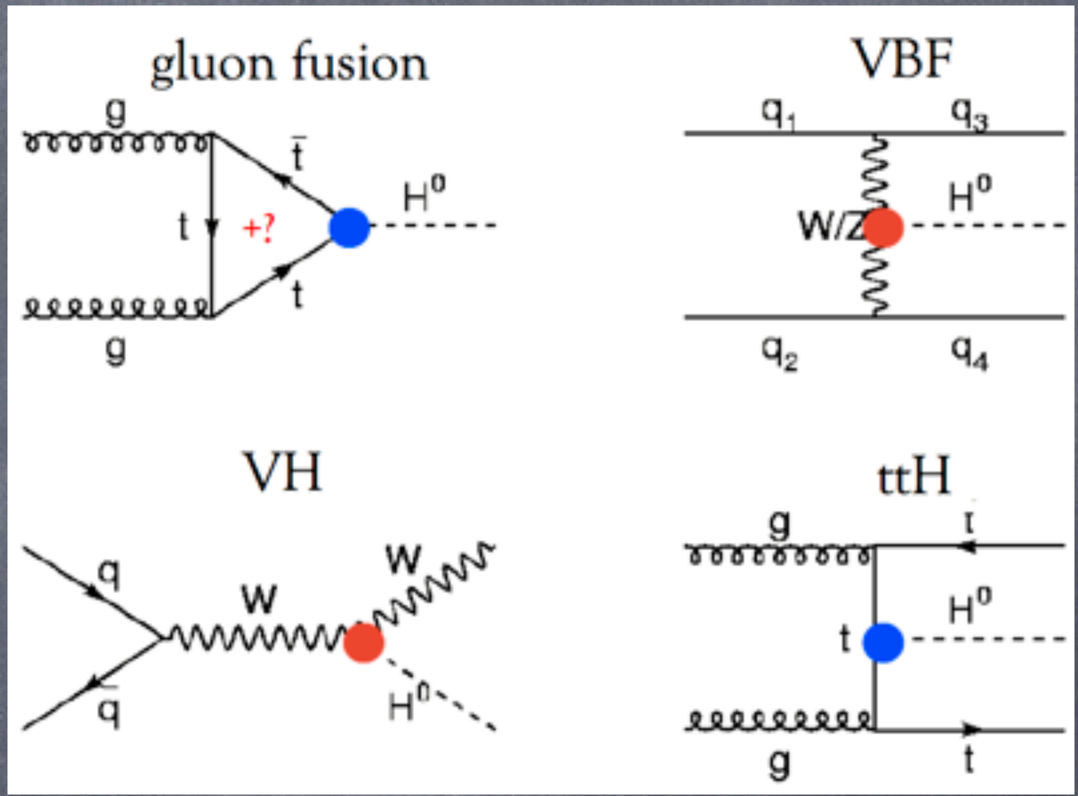
LHC Higgs signal strength so far

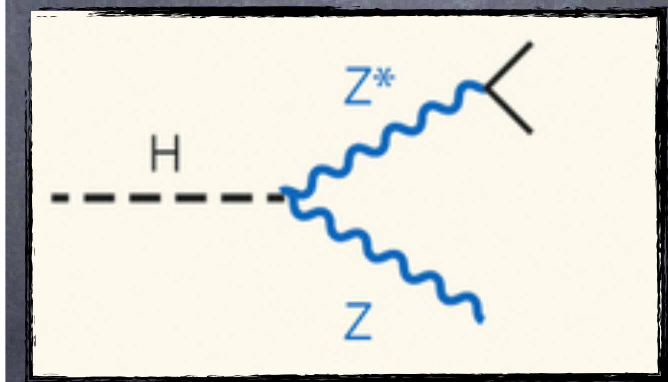
Run-1 results from ATLAS+CMS 1606.02266

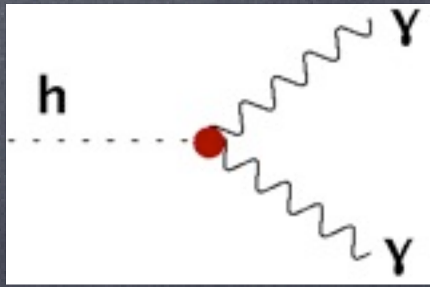
Run-2 results scavenged from various conf-notes

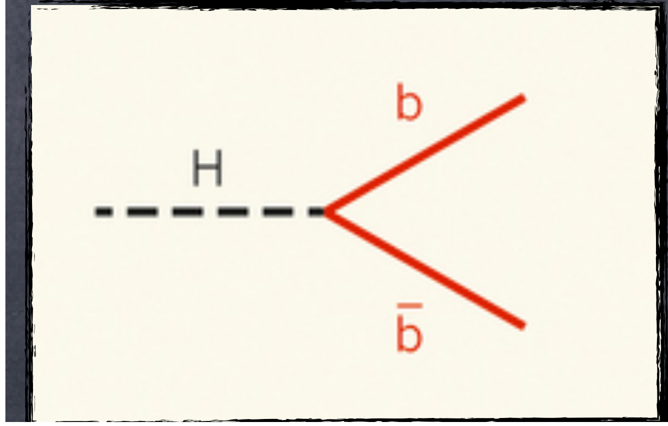
Not using any input from differential distributions here

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]	$1.5^{+0.5}_{-0.5}$ [?]









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

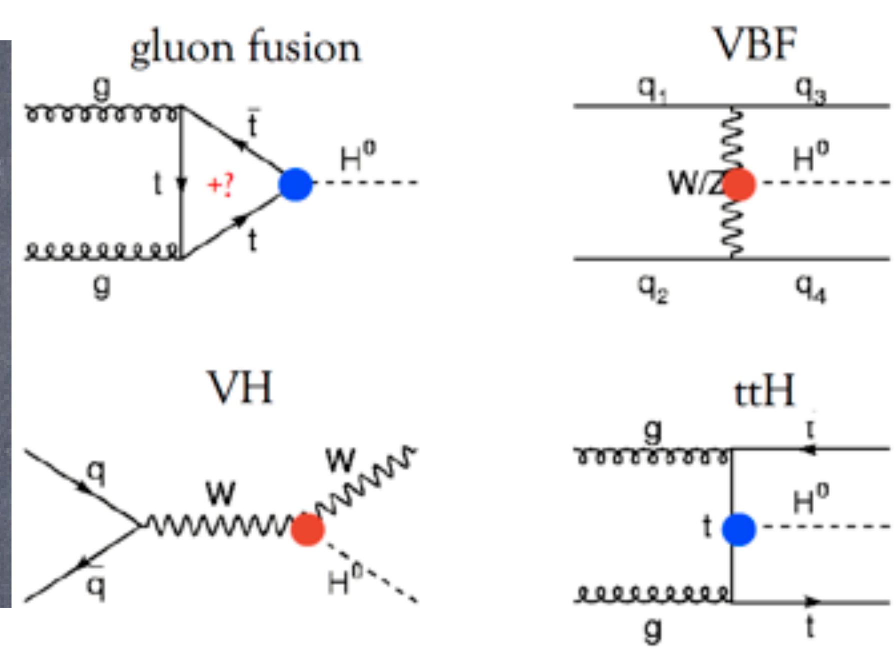
- Thus, assuming MFV couplings to fermions, only 9 EFT parameters affect Higgs signal strength measured at LHC

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

Corrections to Higgs production from dimension-6 operators

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

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

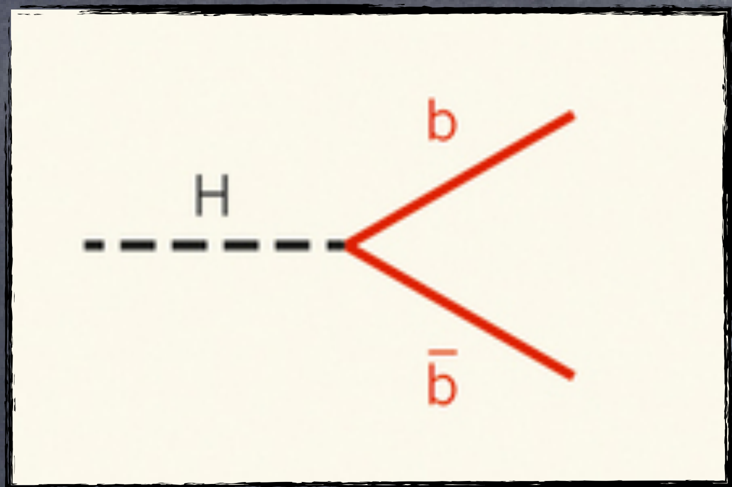


$$\frac{\sigma_{tth}}{\sigma_{tth}^{\rm SM}} \simeq 1 + 2\delta y_u.$$

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

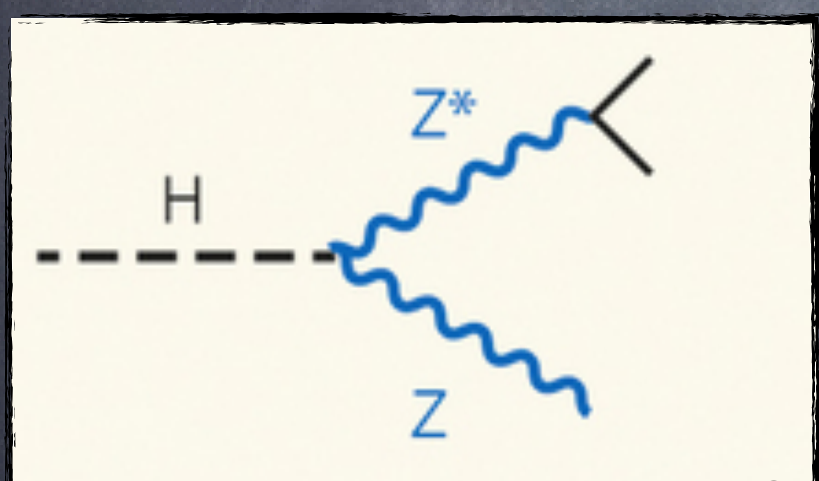
$\begin{pmatrix}7\\8\\13\end{pmatrix}$ TeV

Corrections to Higgs decays from dimension-6 operators



Decays to 2 fermions

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

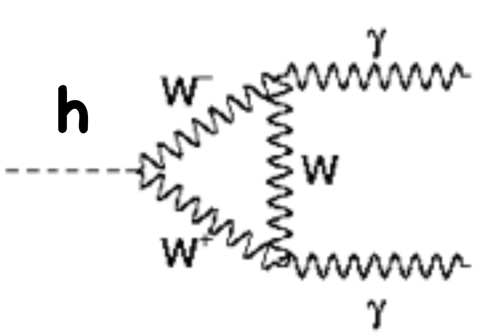


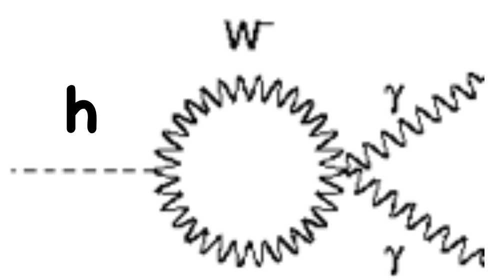
Decays to 4 fermions

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

$\begin{pmatrix} 2e2\mu \\ 4e \end{pmatrix}$

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

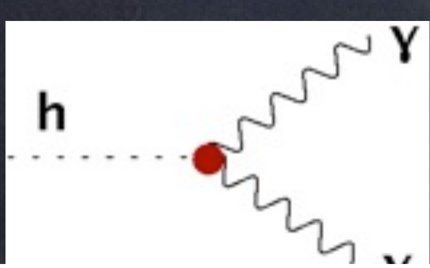


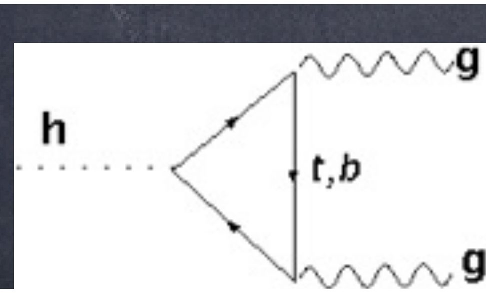


Decays to 2 gauge bosons

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

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





Global constraints on Higgs coupling in SM EFT

Combined constraints from LHC Higgs and electroweak precision constraints

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

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

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

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

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

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