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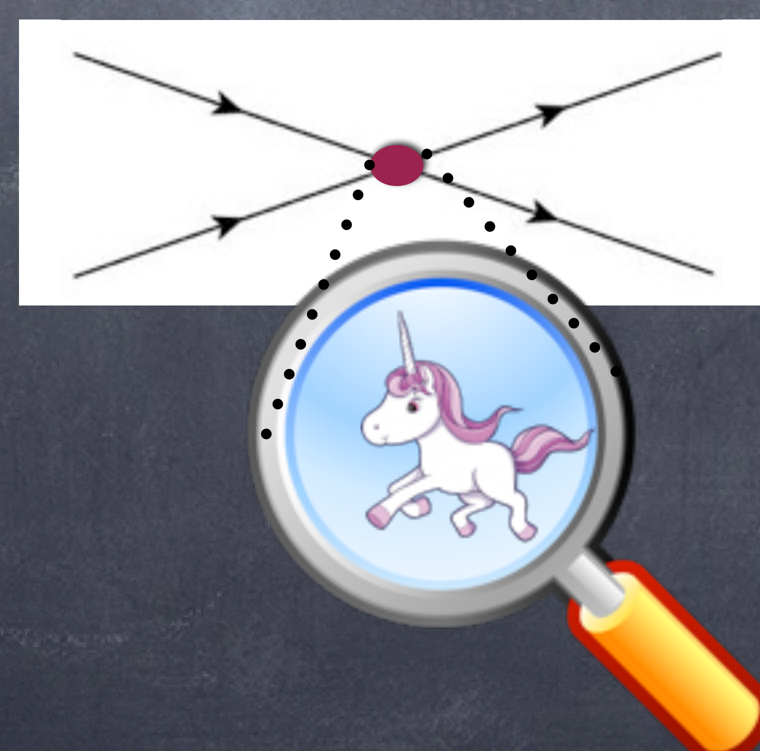
Effective field theory, precision measurements, and LHC Higgs

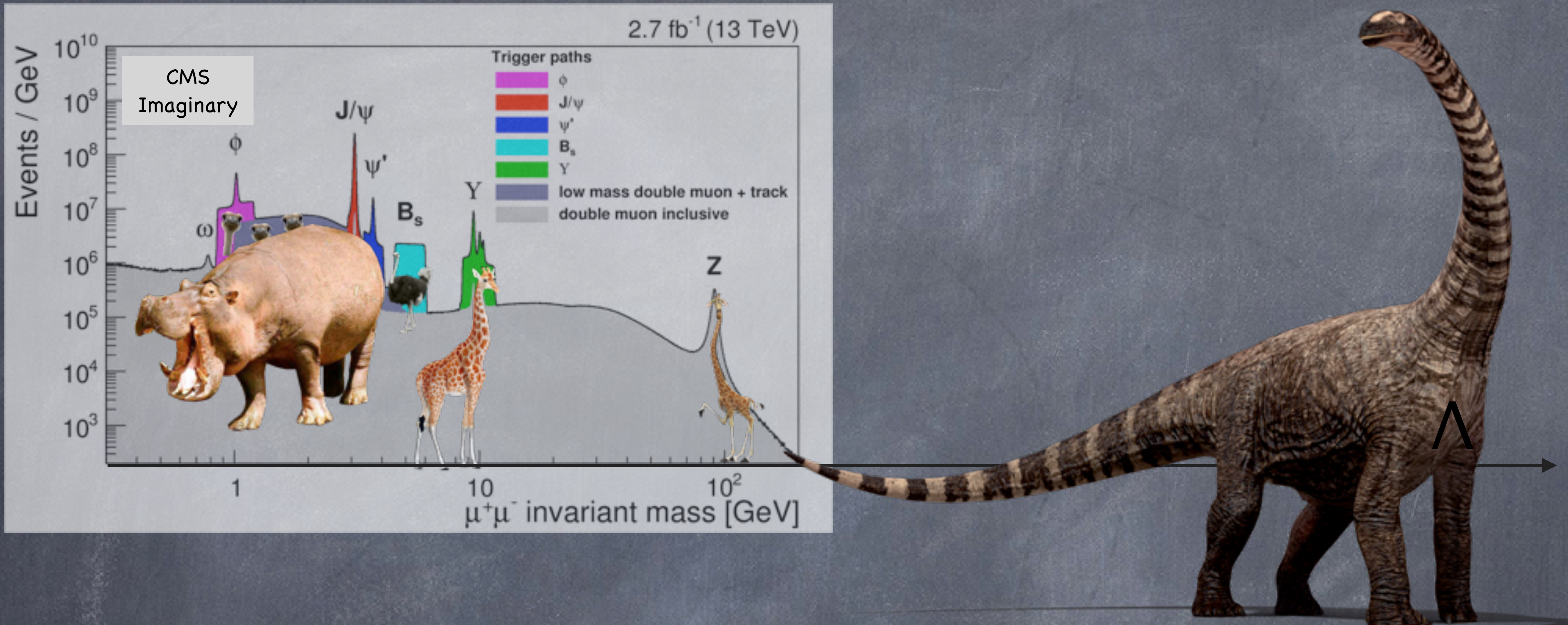
Roma, 10 April 2017



Status report

- SM has been shamelessly successful in describing all collider and low-energy experiments. Discovery of 125 GeV Higgs boson is last piece of puzzle that falls into place. No more free parameters in 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, naturalness problem)
- Models addressing naturalness problem (supersymmetry, composite Higgs, ...) make very definite predictions about new particles and interactions that should become visible around 1 TeV energy scale. But there isn't one model or class of models that is strongly preferred, and all existing models addressing naturalness have certain tensions that cast doubt on whether they really describe nature
- We need to keep open mind on many possible forms of new physics that may show up in experiment. This requires model independent approach to complete other model-dependent searches

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...

SM EFT

- Assume that the SM degrees of freedom is all there is at the weak scale. But we treat the SM as an EFT, 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

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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

- Mass scale Λ of new particles separated from characteristic energy scale E of experiment, $\Lambda \gg E$, such that experimental observables can be expanded in powers of E/Λ

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

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

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

Generated by integrating out heavy particle with mass scale Λ
In large class of BSM models, describe leading effects of new physics on collider observables at $E \ll \Lambda$

By assumption, subleading to D=6

Buchmuller,Wyler (1986)

Warsaw basis for B-conserving D=6 operators

Grządkowski et al. 1008.4884

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.

Warsaw basis for B-conserving D=6 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.

Warsaw basis for B-conserving D=6 operators

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

Table 2.4: Four-fermion D=6 operators in the Warsaw basis. Flavor indices are suppressed here to reduce the clutter. The factor η is equal to 1/2 when all flavor indices are equal (e.g. in $[O_{ee}]_{1111}$), and $\eta = 1$ otherwise. For each complex operator the complex conjugate should be included.

Advantages of SM EFT

- Framework general enough to describe leading effects of a large class (though not all!) of BSM scenarios
- Very easy to recast SM EFT results as constraints on specific BSM models
- Theoretical correlations between signal and background and different signal channels taken into account
- 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

In the rest of this talk...

- I will discuss experimental constraints on dimension-6 operators

- The goal is to obtain a likelihood function for all Wilson coefficients of dimension-6 operators that includes correlations

- Ideally, we want to be totally agnostic, and allow all independent dimension-6 operators to be simultaneously present. Also, results are basis-independent only if all non-redundant operators are taken into account

- Different BSM theories correspond to different patterns of dimension-6 operators. Identifying that pattern, we can get some idea about the shape of the theory that completes the SM at high energies

Based on

AA,Riva 1411.0669

Efrati,AA,Soreq 1503.07782

AA,Mimouni 1511.07434

AA,Mimouni, Gonzalez-Alonso to appear

Pioneered by

Han, Skiba hep-ph/0412166

See also e.g.

de Blas et al 1608.01509

Berthier Trott 1508.05060

Corbett et al 1505.05516

Ellis et al 1410.7703

Operators to Observables

Two kinds of effects

New interactions not present in SM Lagrangian

Simple, just plug in mass eigenstates into D=6 operators

Corrections to SM couplings

Several subtleties, careful treatment required

e.g.

$$\frac{c_{HB}}{\Lambda^2} H^\dagger H B_{\mu\nu} B_{\mu\nu}$$

$$\frac{c_{HB} v^2}{\Lambda^2} \left(\frac{h}{v} + \frac{h^2}{2v^2}\right) \left(c_\theta^2 A_{\mu\nu} A_{\mu\nu} + s_\theta^2 Z_{\mu\nu} Z_{\mu\nu} - 2 c_\theta s_\theta A_{\mu\nu} Z_{\mu\nu}\right)$$

Operators to Observables

More non-trivial effects D=6 operators

- Change normalization of kinetic terms

$$\frac{c_{HG}}{v^2} O_{HG} = \frac{c_{HG}}{v^2} H^\dagger H G^a_{\mu\nu} G_{\mu\nu}$$
$$\to \frac{c_{HG}}{2} G^a_{\mu\nu} G_{\mu\nu}$$

- Affect relations between couplings and input observables

e.g.

$$\frac{c_T}{v^2} O_T = \frac{c_T}{v^2} (H^\dagger \overleftrightarrow{D}_\mu H)^2$$
$$\to - c_T \frac{(g_L^2 + g_Y^2) v^2}{4} Z_\mu Z_\mu$$
$$\Rightarrow m_Z^2 = \frac{(g_L^2 + g_Y^2) v^2}{4} (1 - 2c_T)$$

- Introduce non-standard higher-derivative kinetic terms

e.g.

$$\frac{c_{2W}}{v^2} O_{2W} = \frac{c_{2W}}{v^2} (D_\nu W^i_{\mu\nu})^2$$
$$\to \frac{c_{2W}}{v^2} W^i_\mu \Box^2 W^i_\mu$$
$$\Rightarrow \langle W^+ W^- \rangle = \frac{i}{p^2 - m_W^2 - c_{2W} \frac{p^4}{v^2}}$$

- Introduce kinetic mixing between photon and Z boson

$$\frac{c_{WB}}{v^2} O_{WB} = \frac{c_{WB}}{v^2} g_L g_Y H^\dagger \sigma^i H W^i_{\mu\nu} B_{\mu\nu}$$

e.g.

$$\to - c_{WB} \frac{g_L g_Y}{2} W^3_{\mu\nu} B_{\mu\nu}$$

SM input parameters

- In SM, the values of SU(2)xU(1) couplings gL, gY, and the Higgs vacuum expectation value v are a-priori free parameters.

- To assign numerical values, we need to express 3 precisely measured observables in terms of these parameters. The common choice is GF (extracted from muon decay rate), α(0) (extracted from Thomson scattering), and mZ (measured at LEP-1).

- At tree-level there is a simple relation between these 3 parameters and 3 observables. Of course, one needs to also take into account loop corrections, which introduce dependence on top mass, Higgs mass and strong coupling.

- Dimension-6 operators will disturb these relations already at tree level. Thus, in SM EFT with dimension-6 operators the meaning of gL, gY, v is different, which affects predictions for all SM observables.

$$m_Z = \frac{\sqrt{g_L^2 + g_Y^2}\,v}{2}$$

$$\alpha \equiv \frac{e^2}{4\pi} = \frac{g_L^2 g_Y^2}{4\pi(g_L^2 + g_Y^2)}$$

$$\tau_\mu = \frac{384\pi^3 v^4}{m_\mu^5}$$

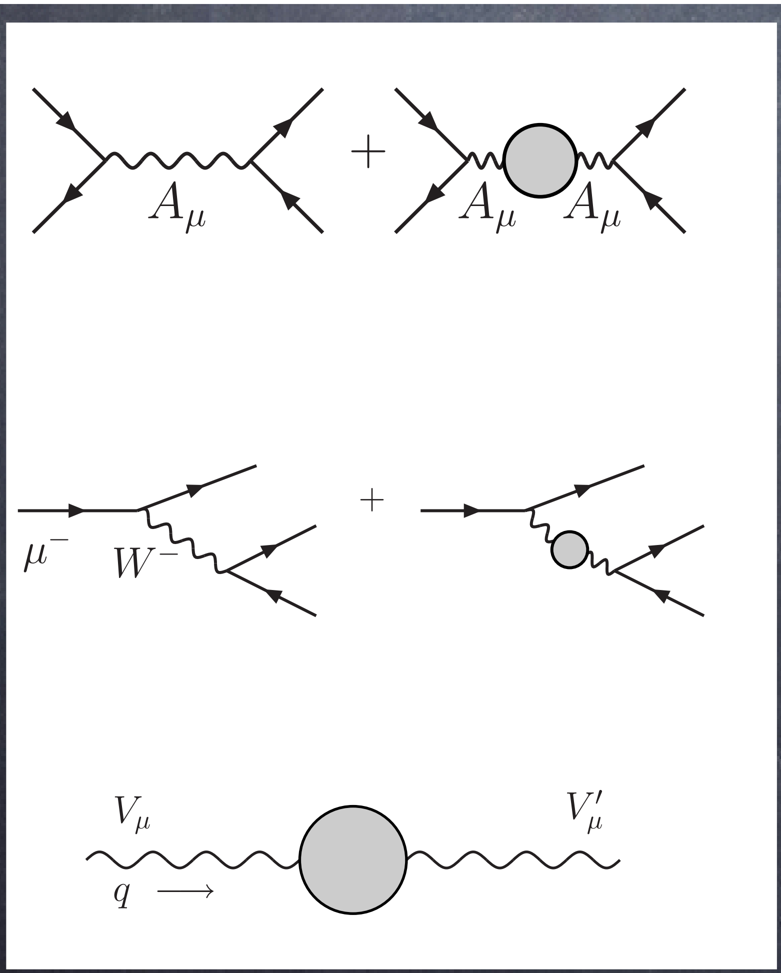
SM input parameters

General deformations of SM EW Lagrangian include oblique and vertex corrections

$$\eta_{\mu\nu}\left(\Pi_{WW}(p^2)W^+_\mu W^-_\mu + \frac{1}{2}\Pi_{ZZ}(p^2)Z_\mu Z_\mu + \frac{1}{2}\Pi_{\gamma\gamma}(p^2)A_\mu A_\mu + \Pi_{Z\gamma}(p^2)Z_\mu A_\mu\right) + p_\mu p_\nu(\dots)$$

$$\begin{aligned}\mathcal{L} \supset\ & \frac{g_{L,0}g_{Y,0}}{\sqrt{g_{L,0}^2+g_{Y,0}^2}}A_\mu \sum_f Q_f(\bar{e}_I\bar{\sigma}_\mu e_I + e_I^c\sigma_\mu\bar{e}_I^c) \\ + & \left[\frac{[g_L^{We}]_{IJ}}{\sqrt{2}}W^+_\mu\bar{\nu}_I\bar{\sigma}_\mu e_J + W^+_\mu\frac{[g_L^{Wq}]_{IJ}}{\sqrt{2}}\bar{u}_I\bar{\sigma}_\mu d_J + \frac{[g_R^{Wq}]_{IJ}}{\sqrt{2}}\, W^+_\mu u_I^c\sigma_\mu\bar{d}_J^c + \mathrm{h.c.}\right] \\ + & Z_\mu \sum_{f=u,d,e,\nu}[g_L^{Zf}]_{IJ}\bar{f}_I\bar{\sigma}_\mu f_J + Z_\mu\sum_{f=u,d,e}[g_R^{Zf}]_{IJ}f_I^c\sigma_\mu\bar{f}_J^c.\end{aligned}$$

$$\begin{aligned}[g_L^{We}]_{IJ} &= g_{L,0}\left(\delta_{IJ} + [\delta g_L^{We}]_{IJ}\right), \\ [g_L^{Wq}]_{IJ} &= g_{L,0}\left([V]_{IJ,0} + [\delta g_L^{Wq}]_{IJ}\right), \\ [g_R^{Wq}]_{IJ} &= [\delta g_R^{Wq}]_{IJ} \\ [g^{Zf}]_{IJ} &= \sqrt{g_{L,0}^2+g_{Y,0}^2}\left(T_3^f - Q_f\frac{g_{Y,0}^2}{g_{L,0}^2+g_{Y,0}^2} + [\delta g^{Zf}]_{IJ}\right)\end{aligned}$$



Then input observables are modified as

$$\begin{aligned}2\sqrt{2}G_F &= \frac{g_L^{We}g_L^{W\mu}}{2\Pi_{WW}(0)} - [c_{\ell\ell}]_{1221} - 2[c_{\ell\ell}^{(3)}]_{1122}, \\ \alpha(0) &= \frac{g_{L,0}^2 g_{Y,0}^2}{4\pi(g_{L,0}^2+g_{Y,0}^2)}\frac{-1}{\Pi'_{\gamma\gamma}(0)}, \\ m_Z^2(m_Z) &= \Pi_{ZZ}(m_Z^2).\end{aligned}$$

Valid in general for SM EFT or for SM loop corrections

SM input parameters

For small deformations we approximate

$$2\sqrt{2}G_F \approx \frac{2}{v_0^2}\left(1-\frac{\delta\Pi_{WW}(0)}{m_W^2}+\delta g_L^{We}+\delta g_L^{W\mu}-\frac{1}{2}[c_{\ell\ell}]_{1221}-[c^{(3)}_{\ell\ell}]_{1122}\right)$$

$$\alpha(0) = \frac{g_{L,0}^2 g_{Y,0}^2}{4\pi(g_{L,0}^2+g_{Y,0}^2)}\left(1+\delta\Pi'_{\gamma\gamma}(0)\right),$$

$$m_Z^2(m_Z) = \frac{(g_{L,0}^2+g_{Y,0}^2)v_0^2}{4}+\delta\Pi_{ZZ}(m_Z^2).$$

We can then absorb new physics corrections into redefined parameters gL, gY, v

$$v_0 = v(1+\delta v), \qquad g_{L,0} = g_L(1+\delta g_L), \qquad g_{Y,0} = g_Y(1+\delta g_Y),$$

$$\delta v = \frac{1}{2}\left(-\frac{\delta\Pi_{WW}(0)}{m_W^2}+\delta g_L^{We}+\delta g_L^{W\mu}-\frac{1}{2}[c_{\ell\ell}]_{1221}-[c^{(3)}_{\ell\ell}]_{1122}\right),$$

$$\delta g_L = \frac{g_L^2}{4(g_L^2-g_Y^2)v^2}\left[-\frac{2\delta\Pi_{ZZ}(m_Z^2)}{m_Z^2}+\frac{2\delta\Pi_{WW}(0)}{m_W^2}+\frac{2g_Y^2\delta\Pi'_{\gamma\gamma}(0)}{g_L^2}\right.$$
$$\left.+[c_{\ell\ell}]_{1221}+2[c^{(3)}_{\ell\ell}]_{1122}-2\delta g_L^{We}-2\delta g_L^{W\mu}\right],$$

$$\delta g_Y = \frac{g_Y^2}{4(g_L^2-g_Y^2)v^2}\left[\frac{2\delta\Pi_{ZZ}(m_Z^2)}{m_Z^2}-\frac{2\delta\Pi_{WW}(0)}{m_W^2}-\frac{2g_L^2\delta\Pi'_{\gamma\gamma}(0)}{g_Y^2}\right.$$
$$\left.-[c_{\ell\ell}]_{1221}-2[c^{(3)}_{\ell\ell}]_{1122}+2\delta g_L^{We}+2\delta g_L^{W\mu}\right].$$

Redefined gL, gY, v are connected the same way to the input observables as in the SM

$$m_Z = \frac{\sqrt{g_L^2+g_Y^2}\,v}{2}$$

$$\alpha \equiv \frac{e^2}{4\pi} = \frac{g_L^2 g_Y^2}{4\pi(g_L^2+g_Y^2)}$$

$$\tau_\mu = \frac{384\pi^3 v^4}{m_\mu^5}$$

Tree-level renormalization in SM EFT

LHCHXSWG
1610.07922
Chapter II.3 of HDR

Rescaling of fields and couplings at order 1/Λ^2

$$G^a_\mu \to (1+\delta_G)G^a_\mu, \quad A_\mu \to A_\mu(1+\delta_{AA}) + \delta_{AZ} Z_\mu, \quad Z_\mu \to Z_\mu(1+\delta_{ZZ}), \quad W^\pm_\mu \to W^\pm_\mu (1+\delta_W),$$
$$g_s \to g_s(1+\delta g_s), \quad g_L \to g_L(1+\delta g_L), \quad g_Y \to g_Y(1+\delta g_Y), \quad v \to v(1+\delta v),$$
$$h \to (1+\delta_{h1})h + \delta_{h2}h^2 + \delta_{h3}h^3, \quad \lambda \to \lambda(1+\delta\lambda). \tag{2.20}$$

Conceptually, similar to renormalization of couplings and fields to absorb effects of loop corrections in SM

$$\begin{aligned}
\delta_G &= c_{HG},\\
\delta_W &= c_{HW},\\
\delta_{ZZ} &= s_\theta^2 c_{HB} + c_\theta^2 c_{HW} + c_\theta s_\theta c_{HWB},\\
\delta_{AZ} &= 2c_\theta s_\theta (c_{HW} - c_{HB}) - (c_\theta^2 - s_\theta^2) c_{HWB},\\
\delta_{AA} &= c_\theta^2 c_{HB} + s_\theta^2 c_{HW} - c_\theta s_\theta c_{HWB},\\
\delta v &= \frac{1}{4}\left(2[c^{(3)}_{H\ell}]_{22} + 2[c^{(3)}_{H\ell}]_{22} - [c_{\ell\ell}]_{1221}\right),\\
\delta g_s &= -c_{HG},\\
\delta g_L &= -\frac{g_L^2}{4(g_L^2-g_Y^2)}\left[c_{HD} + 4\left(1-\frac{g_Y^2}{g_L^2}\right)c_{HW} + 4\frac{g_Y}{g_L}c_{HWB} + 2[c^{(3)}_{H\ell}]_{22} + 2[c^{(3)}_{H\ell}]_{22} - [c_{\ell\ell}]_{1221}\right],\\
\delta g_Y &= \frac{g_Y^2}{4(g_L^2-g_Y^2)}\left[c_{HD} + 4\left(1-\frac{g_L^2}{g_Y^2}\right)c_{HB} + 4\frac{g_L}{g_Y}c_{HWB} + 2[c^{(3)}_{H\ell}]_{22} + 2[c^{(3)}_{H\ell}]_{22} - [c_{\ell\ell}]_{1221}\right],\\
\delta\lambda &= \frac{3}{2\lambda}c_H + \frac{1}{2}c_{HD} - 2c_{H\Box} - [c^{(3)}_{H\ell}]_{22} - [c^{(3)}_{H\ell}]_{22} + \frac{1}{2}[c_{\ell\ell}]_{1221},\\
\delta_{h_1} &= c_{H\Box} - \frac{1}{4}c_{HD}, \qquad \delta_{h_2} = \delta_{h_1}, \qquad \delta_{h_3} = \frac{\delta_{h_1}}{3}.
\end{aligned} \tag{2.27}$$

!

From this moment on scale Λ absorbed into Wilson coefficients

$$c_i \frac{v^2}{\Lambda^2} \to c_i$$

such that Wilson coefficients should be considered of order 1/Λ^2

see HDR at https://sites.google.com/site/webpageofadamfalkowski/professional

Tree-level renormalization

Using freedom to redefine fields and couplings, at order 1/Λ^2 one can:

- make all kinetic terms standard and canonically normalized
- ensure same tree level relations between SM parameters gs, gL, gY, v and input observables mZ, GF, α, αs
- impose certain convenient convention choices (e.g. lack of derivative Higgs boson self-interactions)

$$\mathcal{L}_{\rm kinetic} = -\frac{1}{2}W^+_{\mu\nu}W^-_{\mu\nu} - \frac{1}{4}Z_{\mu\nu}Z_{\mu\nu} - \frac{1}{4}A_{\mu\nu}A_{\mu\nu} - \frac{1}{4}G^a_{\mu\nu}G^a_{\mu\nu} + \frac{g_L^2 v^2}{4}(1+\delta m)^2 W^+_\mu W^-_\mu + \frac{(g_L^2+g_Y^2)v^2}{8}Z_\mu Z_\mu + \frac{1}{2}\partial_\mu h \partial_\mu h - \lambda v^2 h^2$$

$$\mathcal{L}_{vff} \subset eA_\mu \sum_{f\in u,d,e} Q_f\left(\bar f \bar\sigma_\mu f + f^c \sigma_\mu \bar f^c\right) + g_s G^a_\mu \sum_{f\in u,d}\left(\bar f \bar\sigma_\mu T^a f + f^c\sigma_\mu T^a \bar f^c\right),$$

$$m_Z = \frac{\sqrt{g_L^2+g_Y^2}\,v}{2}$$

$$\alpha \equiv \frac{e^2}{4\pi} = \frac{g_L^2 g_Y^2}{4\pi(g_L^2+g_Y^2)}$$

$$\tau_\mu = \frac{384\pi^3 v^4}{m_\mu^5}$$

Once tree-level renormalization is performed, effects of dimension-6 operators are visible more intuitively

Observable effects of D=6 operators

- Corrections to SM Z and W boson couplings to fermions (so-called vertex corrections)

$$\mathcal{L}_{vff} = \frac{g_L}{\sqrt{2}}\left(W^+_\mu \bar{u}\bar{\sigma}_\mu (V_{\rm CKM} + \delta g_L^{Wq}) d + W^+_\mu u^c \sigma_\mu \delta g_R^{Wq} \bar{d}^c + W^+_\mu \bar{\nu}\bar{\sigma}_\mu (I + \delta g_L^{W\ell}) e + \text{h.c.}\right)$$
$$+ \sqrt{g_L^2 + g_Y^2} Z_\mu \left[\sum_{f \in u,d,e,\nu} \bar{f}\bar{\sigma}_\mu (T^3_f - s^2_\theta Q_f + \delta g_L^{Zf}) f + \sum_{f^c \in u^c, d^c, e^c} f^c \sigma_\mu (-s^2_\theta Q_f + \delta g_R^{Zf}) \bar{f}^c\right]$$

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

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

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

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

- Corrections to triple and quartic gauge couplings and new tensor structures of these interactions

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

- Contact 4-fermion interactions

One flavor $(I = 1\ldots3)$	Two flavors $(I < J = 1\ldots3)$
$[O_{\ell\ell}]_{IIII} = \frac{1}{2}(\bar{\ell}_I\bar{\sigma}_\mu\ell_I)(\bar{\ell}_I\bar{\sigma}_\mu\ell_I)$	$[O_{\ell\ell}]_{IIJJ} = (\bar{\ell}_I\bar{\sigma}_\mu\ell_I)(\bar{\ell}_J\bar{\sigma}_\mu\ell_J)$
	$[O_{\ell\ell}]_{IJJI} = (\bar{\ell}_I\bar{\sigma}_\mu\ell_J)(\bar{\ell}_J\bar{\sigma}_\mu\ell_I)$
$[O_{\ell e}]_{IIII} = (\bar{\ell}_I\bar{\sigma}_\mu\ell_I)(e^c_I\sigma_\mu\bar{e}^c_I)$	$[O_{\ell e}]_{IIJJ} = (\bar{\ell}_I\bar{\sigma}_\mu\ell_I)(e^c_J\sigma_\mu\bar{e}^c_J)$
	$[O_{\ell e}]_{JJII} = (\bar{\ell}_J\bar{\sigma}_\mu\ell_J)(e^c_I\sigma_\mu\bar{e}^c_I)$
	$[O_{\ell e}]_{IJJI} = (\bar{\ell}_I\bar{\sigma}_\mu\ell_J)(e^c_J\sigma_\mu\bar{e}^c_I)$
$[O_{ee}]_{IIII} = \frac{1}{2}(e^c_I\sigma_\mu\bar{e}^c_I)(e^c_I\sigma_\mu\bar{e}^c_I)$	$[O_{ee}]_{IIJJ} = (e^c_I\sigma_\mu\bar{e}^c_I)(e^c_J\sigma_\mu\bar{e}^c_J)$

- … and much more

Important: correlations between different parameters describing deviations from SM

Constraints from pole precision observables

Z-pole observables

Observable	Experimental value	Ref.	SM prediction	Definition
Γ_Z [GeV]	2.4952 ± 0.0023	[21]	2.4950	$\sum_f \Gamma(Z \to f\bar{f})$
$\sigma_{\rm had}$ [nb]	41.541 ± 0.037	[21]	41.484	$\frac{12\pi}{m_Z^2}\frac{\Gamma(Z\to e^+e^-)\Gamma(Z\to q\bar{q})}{\Gamma_Z^2}$
R_e	20.804 ± 0.050	[21]	20.743	$\frac{\sum_q \Gamma(Z\to q\bar{q})}{\Gamma(Z\to e^+e^-)}$
R_μ	20.785 ± 0.033	[21]	20.743	$\frac{\sum_q \Gamma(Z\to q\bar{q})}{\Gamma(Z\to \mu^+\mu^-)}$
R_τ	20.764 ± 0.045	[21]	20.743	$\frac{\sum_q \Gamma(Z\to q\bar{q})}{\Gamma(Z\to \tau^+\tau^-)}$
$A_{\rm FB}^{0,e}$	0.0145 ± 0.0025	[21]	0.0163	$\frac{3}{4}A_e^2$
$A_{\rm FB}^{0,\mu}$	0.0169 ± 0.0013	[21]	0.0163	$\frac{3}{4}A_e A_\mu$
$A_{\rm FB}^{0,\tau}$	0.0188 ± 0.0017	[21]	0.0163	$\frac{3}{4}A_e A_\tau$
R_b	0.21629 ± 0.00066	[21]	0.21578	$\frac{\Gamma(Z\to b\bar{b})}{\sum_q \Gamma(Z\to q\bar{q})}$
R_c	0.1721 ± 0.0030	[21]	0.17226	$\frac{\Gamma(Z\to c\bar{c})}{\sum_q \Gamma(Z\to q\bar{q})}$
$A_b^{\rm FB}$	0.0992 ± 0.0016	[21]	0.1032	$\frac{3}{4}A_e A_b$
$A_c^{\rm FB}$	0.0707 ± 0.0035	[21]	0.0738	$\frac{3}{4}A_e A_c$
A_e	0.1516 ± 0.0021	[21]	0.1472	$\frac{\Gamma(Z\to e_L^+e_L^-)-\Gamma(Z\to e_R^+e_R^-)}{\Gamma(Z\to e^+e^-)}$
A_μ	0.142 ± 0.015	[21]	0.1472	$\frac{\Gamma(Z\to \mu_L^+\mu_L^-)-\Gamma(Z\to e_\mu^+\mu_R^-)}{\Gamma(Z\to \mu^+\mu^-)}$
A_τ	0.136 ± 0.015	[21]	0.1472	$\frac{\Gamma(Z\to \tau_L^+\tau_L^-)-\Gamma(Z\to \tau_R^+\tau_R^-)}{\Gamma(Z\to \tau^+\tau^-)}$
A_b	0.923 ± 0.020	[21]	0.935	$\frac{\Gamma(Z\to b_L\bar{b}_L)-\Gamma(Z\to b_R\bar{b}_R)}{\Gamma(Z\to b\bar{b})}$
A_c	0.670 ± 0.027	[21]	0.668	$\frac{\Gamma(Z\to c_L\bar{c}_L)-\Gamma(Z\to c_R\bar{c}_R)}{\Gamma(Z\to c\bar{c})}$
A_s	0.895 ± 0.091	[22]	0.935	$\frac{\Gamma(Z\to s_L\bar{s}_L)-\Gamma(Z\to s_R\bar{s}_R)}{\Gamma(Z\to s\bar{s})}$
R_{uc}	0.166 ± 0.009	[23]	0.1724	$\frac{\Gamma(Z\to u\bar{u})+\Gamma(Z\to c\bar{c})}{2\sum_q \Gamma(Z\to q\bar{q})}$

Table 1: **Z boson pole observables**. The experimental errors of the observables between the double lines are correlated, which is taken into account in the fit. The results for $A_{e,\mu,\tau}$ listed above come from the combination of leptonic polarization and left-right asymmetry measurements at the SLD; we also include the results $A_\tau = 0.1439 \pm 0.0043$, $A_e = 0.1498 \pm 0.0049$ from tau polarization measurements at LEP-1 [21]. For the theoretical predictions we use the best fit SM values from GFitter [20]. We also include the model-independent measurement of on-shell Z boson couplings to light quarks in D0 [26].

W-pole observables

Observable	Experimental value	Ref.	SM prediction	Definition
m_W [GeV]	80.385 ± 0.015	[27]	80.364	$\frac{g_L v}{2}(1+\delta m)$
Γ_W [GeV]	2.085 ± 0.042	[23]	2.091	$\sum_f \Gamma(W \to f f')$
$\mathrm{Br}(W \to e\nu)$	0.1071 ± 0.0016	[28]	0.1083	$\frac{\Gamma(W\to e\nu)}{\sum_f \Gamma(W\to f f')}$
$\mathrm{Br}(W \to \mu\nu)$	0.1063 ± 0.0015	[28]	0.1083	$\frac{\Gamma(W\to \mu\nu)}{\sum_f \Gamma(W\to f f')}$
$\mathrm{Br}(W \to \tau\nu)$	0.1138 ± 0.0021	[28]	0.1083	$\frac{\Gamma(W\to \tau\nu)}{\sum_f \Gamma(W\to f f')}$
R_{Wc}	0.49 ± 0.04	[23]	0.50	$\frac{\Gamma(W\to cs)}{\Gamma(W\to ud)+\Gamma(W\to cs)}$
R_σ	0.998 ± 0.041	[29]	1.000	$g_L^{Wq_3}/g_{L,\mathrm{SM}}^{Wq_3}$

Table 2: **W-boson pole observables**. Measurements of the 3 leptonic branching fractions are correlated. For the theoretical predictions of m_W and Γ_W, we use the best fit SM values from GFitter [20], while for the leptonic branching fractions we take the value quoted in [28].

On-shell Z decays: nuts and bolts

Lowest order:

$$\Gamma(Z \to f\bar{f}) = \frac{N_f m_Z}{24\pi} g_{fZ}^2 \qquad g_{fZ} = \sqrt{g_L^2 + g_Y^2}\,(T_f^3 - s_\theta^2 Q_f)$$

$$\Gamma(W \to f\bar{f}') = \frac{N_f m_W}{48\pi} g_{fW,L}^2 \qquad g_{fW,L} = g_L$$

w/ new physics:

$$\Gamma(Z \to f\bar{f}) = \frac{N_f m_Z}{24\pi} {g_{fZ;\text{eff}}}^2 \quad \Gamma(W \to f\bar{f}') = \frac{N_f m_W}{48\pi} {g_{fW,L;\text{eff}}}^2$$

$$g_{fW,L;\text{eff}} = \frac{g_{L0}}{\sqrt{1 - \delta\Pi'_{WW}(m_W^2)}}\left(1 + \delta g_L^{Wf}\right)$$

$$g_{fZ;\text{eff}} = \frac{\sqrt{g_{L0}^2 + g_{Y0}^2}}{\sqrt{1 - \delta\Pi'_{ZZ}(m_Z^2)}}\left(T_f^3 - s_{\text{eff}}^2 Q_f + \delta g^{Zf}\right)$$

$$s_{\text{eff}}^2 = \frac{g_{Y0}^2}{g_{L0}^2 + g_{Y0}^2}\left(1 - \frac{g_L}{g_Y}\frac{\delta\Pi_{\gamma Z}(m_Z^2)}{m_Z^2}\right)$$

- Including leading order new physics corrections amount to replacing W/Z couplings to fermions by effective couplings, which encode the effect of vertex and oblique corrections

$$\delta m = \frac{\delta g_L^{We} + \delta g_L^{W\mu}}{2} - \frac{[c_{\ell\ell}]_{1221}}{4}.$$

- For observables with Z/W bosons on-shell, interference between SM amplitudes and 4-fermion operators is suppressed by Γ/m and can be neglected

- In my conventions, mass eigenstate Lagrangian does not have oblique corrections (except for W mass correction) thus δg directly constrained

$$g_{fW,L;eff} = g_L\left(1 + \delta g_L^{Wf}\right)$$

$$g_{fZ;eff} = \sqrt{g_L^2 + g_Y^2}\,\left(T_f^3 - s_\theta^2 Q_f + \delta g^{Zf}\right)$$

Effects of dimension-6 operators on gauge coupling strength to fermions

$$\mathcal{L} \supset \frac{g_L g_Y}{\sqrt{g_L^2 + g_Y^2}} Q_f A_\mu \bar{f} \gamma_\mu f + g_s G_\mu^a \bar{q} \gamma_\mu T^a q$$

- After tree-level renormalization, by construction, photon and gluon couplings the same as in SM
- Oblique corrections are redefined away, except for correction to W mass
- Only W and Z couplings are affected
- Effects of dimension-6 operators are parametrized by set of vertex corrections

$$\mathcal{L}_{vff} = \frac{g_L}{\sqrt{2}} \left(W_\mu^+ \bar{u} \bar{\sigma}_\mu (V_{\rm CKM} + \delta g_L^{Wq}) d + W_\mu^+ u^c \sigma_\mu \delta g_R^{Wq} \bar{d}^c + W_\mu^+ \bar{\nu} \bar{\sigma}_\mu (I + \delta g_L^{W\ell}) e + \text{h.c.} \right)$$
$$+ \sqrt{g_L^2 + g_Y^2} Z_\mu \left[\sum_{f \in u,d,e,\nu} \bar{f} \bar{\sigma}_\mu (T_f^3 - s_\theta^2 Q_f + \delta g_L^{Zf}) f + \sum_{f^c \in u^c, d^c, e^c} f^c \sigma_\mu (-s_\theta^2 Q_f + \delta g_R^{Zf}) \bar{f}^c \right]$$

Z and W couplings to fermions

$$\mathcal{L}_{vff} = \frac{g_L}{\sqrt{2}} \left(W^+_\mu \bar{u}\bar{\sigma}_\mu (V_{\rm CKM} + \delta g_L^{Wq}) d + W^+_\mu u^c \sigma_\mu \delta g_R^{Wq} \bar{d}^c + W^+_\mu \bar{\nu}\bar{\sigma}_\mu (I + \delta g_L^{W\ell}) e + \text{h.c.} \right)$$
$$+ \sqrt{g_L^2 + g_Y^2} Z_\mu \left[\sum_{f \in u,d,e,\nu} \bar{f}\bar{\sigma}_\mu (T^3_f - s_\theta^2 Q_f + \delta g_L^{Zf}) f + \sum_{f^c \in u^c, d^c, e^c} f^c \sigma_\mu (-s_\theta^2 Q_f + \delta g_R^{Zf}) \bar{f}^c \right]$$

$$\begin{aligned}
\delta g_L^{W\ell} &= c_{H\ell}^{(3)} + f(1/2,0) - f(-1/2,-1), \\
\delta g_L^{Z\nu} &= \frac{1}{2} c_{H\ell}^{(3)} - \frac{1}{2} c_{H\ell}^{(1)} + f(1/2,0), \\
\delta g_L^{Ze} &= -\frac{1}{2} c_{H\ell}^{(3)} - \frac{1}{2} c_{H\ell}^{(1)} + f(-1/2,-1), \\
\delta g_R^{Ze} &= -\frac{1}{2} c_{He} + f(0,-1),
\end{aligned}$$

- Observation: vertex corrections are not all independent. Corrections to W vertices are determined by corrections to Z vertices

$$\begin{aligned}
\delta g_L^{Z\nu} &= \delta g_L^{Ze} + \delta g_L^{W\ell} \\
\delta g_L^{Wq} &= \delta g_L^{Zu} V_{\rm CKM} - V_{\rm CKM} \delta g_L^{Zd}
\end{aligned}$$

$$\begin{aligned}
\delta g_L^{Wq} &= \left(c_{Hq}^{(3)} + f(1/2,2/3) - f(-1/2,-1/3) \right) V_{\rm CKM}, \\
\delta g_R^{Wq} &= -\frac{1}{2} c_{Hud}, \\
\delta g_L^{Zu} &= \frac{1}{2} c_{Hq}^{(3)} - \frac{1}{2} c_{Hq}^{(1)} + f(1/2,2/3), \\
\delta g_L^{Zd} &= -\frac{1}{2} V_{\rm CKM}^\dagger c_{Hq}^{(3)} V_{\rm CKM} - \frac{1}{2} V_{\rm CKM}^\dagger c_{Hq}^{(1)} V_{\rm CKM} + f(-1/2,-1/3), \\
\delta g_R^{Zu} &= -\frac{1}{2} c_{Hu} + f(0,2/3), \\
\delta g_R^{Zd} &= -\frac{1}{2} c_{Hd} + f(0,-1/3),
\end{aligned}$$

$$\begin{aligned}
f(T^3,Q) &= -I_3 Q \frac{g_L g_Y}{g_L^2 - g_Y^2} c_{HWB} \qquad (2 \\
&+ I_3 \left(\frac{1}{4} [c_{\ell\ell}]_{1221} - \frac{1}{2} [c_{H\ell}^{(3)}]_{11} - \frac{1}{2} [c_{H\ell}^{(3)}]_{22} - \frac{1}{4} c_{HD} \right) \left(T^3 + Q \frac{g_Y^2}{g_L^2 - g_Y^2} \right)
\end{aligned}$$

- Vertex corrections, when expressed by Wilson coefficients in Warsaw basis, somewhat counterintuitively, depend also on some bosonic and 4-fermion operators

Analysis Assumptions

- Working at order $1/\Lambda^2$ in EFT expansion. Taking into account corrections from D=6 operators, and neglecting D=8 and higher operators. (Only taking into account corrections to observables that are linear in D=6 Wilson coefficients, that is to say, only interference terms between SM and new physics. Quadratic corrections are formally of order $1/\Lambda^4$, much as D=8 operators that are neglected.)

- Working at tree-level in EFT parameters (SM predictions taken at NLO or NNLO, but only interference of tree-level BSM corrections with tree-level SM amplitude taken into account)

- Allowing all dimension-6 operators to be present simultaneously with arbitrary coefficients (within EFT validity range). Constraints are obtained on all parameters affecting precision observables at tree level, and correlations matrix is computed.

- Dimension-6 operators are allowed with arbitrary flavor structure (my analysis targets only flavor-diagonal operators, but it's independent of the value of flavor-off-diagonal Wilson coefficients)

- Goal: give you full likelihood in D=6 space, that can be reused for any specific model predicting any particular patter of D=6 operators

Pole constraints - Results

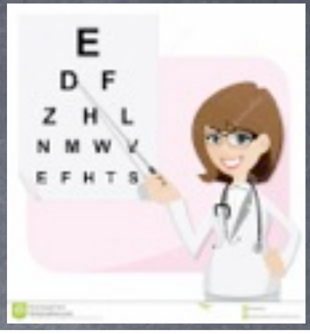
Efrati,AA,Soreq
1503.07872

All diagonal vertex corrections except for δgWqR and δgZtR simultaneously constrained in a completely model-independent way

$$\begin{pmatrix} [c_{\ell\ell}]_{1221} \\ \delta g_L^{We} \\ \delta g_L^{W\mu} \\ \delta g_L^{W\tau} \\ \delta g_L^{Ze} \\ \delta g_L^{Z\mu} \\ \delta g_L^{Z\tau} \\ \delta g_R^{Ze} \\ \delta g_R^{Z\mu} \\ \delta g_R^{Z\tau} \\ \delta g_L^{Zu} \\ \delta g_L^{Zc} \\ \delta g_L^{Zt} \\ \delta g_R^{Zu} \\ \delta g_R^{Zc} \\ \delta g_L^{Zd} \\ \delta g_L^{Zs} \\ \delta g_L^{Zb} \\ \delta g_R^{Zd} \\ \delta g_R^{Zs} \\ \delta g_R^{Zb} \end{pmatrix} = \begin{pmatrix} -4.8 \pm 1.6 \\ -1.01 \pm 0.64 \\ -1.36 \pm 0.59 \\ 1.83 \pm 0.79 \\ -0.023 \pm 0.028 \\ 0.01 \pm 0.12 \\ 0.018 \pm 0.059 \\ -0.033 \pm 0.027 \\ 0.00 \pm 0.14 \\ 0.042 \pm 0.062 \\ -0.8 \pm 3.1 \\ -0.15 \pm 0.36 \\ -0.3 \pm 3.8 \\ 1.3 \pm 5.1 \\ -0.35 \pm 0.53 \\ -1.0 \pm 4.4 \\ 0.9 \pm 2.8 \\ 0.33 \pm 0.17 \\ 3 \pm 16 \\ 3.4 \pm 4.9 \\ 2.31 \pm 0.88 \end{pmatrix} \times 10^{-2}$$

- Z coupling to charged leptons constrained at 0.1% level
- W couplings to leptons constrained at 1% level
- Some couplings to quarks (bottom, charm) also constrained at 1% level
- Some couplings very weakly constrained in a model-independent way, in particular Z couplings to light quarks (though some combinations strongly constrained)

Pole constraints - correlations



- Full correlation matrix is also derived
- From that, one can reproduce complete likelihood function in the space of vertex corrections
- Given dictionary from vertex corrections to Warsaw or SILH, results can be easily recast as constraint on Wilson coefficients in those bases (but then there will be flat directions!)
- Similarly, results can be easily recast for particular BSM models in which vertex and mass corrections are functions of (fewer) model parameters

$$\begin{pmatrix}
1. & 0.7 & 0.6 & -0.9 & -0.2 & -0.1 & 0. & 0.1 & -0.1 & -0.1 & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & -0.1 & -0.1 & 0. \\
0.7 & 1. & -0.1 & -0.6 & -0.1 & 0. & 0. & 0.1 & -0.1 & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. \\
0.6 & -0.1 & 1. & -0.6 & -0.1 & 0. & 0. & 0.1 & -0.1 & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & -0.1 & 0. & 0. \\
-0.9 & -0.6 & -0.6 & 1. & -0.1 & 0. & 0. & 0.1 & -0.1 & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. \\
-0.2 & -0.1 & -0.1 & -0.1 & 1. & -0.1 & -0.1 & 0.1 & 0. & 0. & 0. & 0.1 & 0. & 0. & 0.1 & 0. & 0. & -0.4 & 0. & 0. & -0.3 \\
-0.1 & 0. & 0. & 0. & -0.1 & 1. & 0.1 & 0. & 0.9 & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0.1 & 0. & 0. & 0. \\
0. & 0. & 0. & 0. & -0.1 & 0.1 & 1. & 0. & 0. & 0.4 & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0.1 & 0. & 0. & 0. \\
0.1 & 0.1 & 0.1 & 0.1 & 0.1 & 0. & 0. & 1. & -0.1 & 0. & 0. & 0.1 & 0. & 0. & 0.1 & 0. & 0. & -0.3 & 0. & 0. & -0.4 \\
-0.1 & -0.1 & -0.1 & -0.1 & 0. & 0.9 & 0. & -0.1 & 1. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. \\
-0.1 & 0. & 0. & 0. & 0. & 0. & 0.4 & 0. & 0. & 1. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. \\
0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 1. & -0.1 & 0. & 0.7 & 0.1 & 0.8 & -0.1 & 0. & 0.8 & -0.1 & 0. \\
0. & 0. & 0. & 0. & 0.1 & 0. & 0. & 0.1 & 0. & 0. & -0.1 & 1. & 0. & 0. & 0.3 & 0. & 0.1 & -0.1 & 0. & 0. & -0.1 \\
0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 1. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. \\
0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0.7 & 0. & 0. & 1. & 0. & 0.7 & -0.2 & 0. & 0.9 & -0.2 & 0. \\
0. & 0. & 0. & 0. & 0.1 & 0. & 0. & 0.1 & 0. & 0. & 0.1 & 0.3 & 0. & 0. & 1. & 0. & 0. & -0.2 & 0.1 & 0. & -0.1 \\
0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0.8 & 0. & 0. & 0.7 & 0. & 1. & -0.6 & 0. & 0.7 & 0. & 0. \\
0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & -0.1 & 0.1 & 0. & -0.2 & 0. & -0.6 & 1. & 0. & 0. & 0. & 0. \\
0. & 0. & 0. & 0. & -0.4 & 0.1 & 0.1 & -0.3 & 0. & 0. & 0. & -0.1 & 0. & 0. & -0.2 & 0. & 0. & 1. & 0. & 0. & 0.9 \\
-0.1 & 0. & -0.1 & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0.8 & 0. & 0. & 0.9 & 0.1 & 0.7 & 0. & 0. & 1. & -0.3 & 0. \\
-0.1 & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & -0.1 & 0. & 0. & -0.2 & 0. & 0. & 0. & 0. & -0.3 & 1. & 0. \\
0. & 0. & 0. & 0. & -0.3 & 0. & 0. & -0.4 & 0. & 0. & 0. & -0.1 & 0. & 0. & -0.1 & 0. & 0. & 0.9 & 0. & 0. & 1.
\end{pmatrix}$$

$$\chi^2_{\rm pole} = \sum_{ij} (\delta g_i - \delta g_i^0) \Delta^{-1}_{ij} (\delta g_j - \delta g_j^0),$$

$$\Delta_{ij} = \delta g_i^{\rm err} \rho_{ij} \delta g_j^{\rm err}$$

Correlation Matrix

1σ Errors

Central Values

SM EFT with dimension-6 operators

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

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

Leading corrections to SM for E<<Λ

Subleading effects ignored

Pole observables constraint vertex corrections

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

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.

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

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

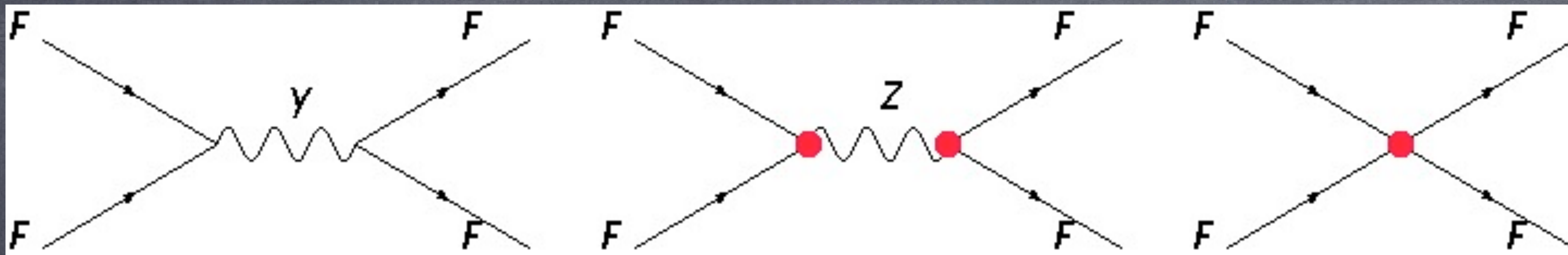
$(\bar{L}R)(\bar{L}R)$	
O_{quqd}	$(u^c q^j)\epsilon_{jk}(d^c q^k)$
O'_{quqd}	$(u^c T^a q^j)\epsilon_{jk}(d^c T^a q^k)$
$O_{\ell equ}$	$(e^c\ell^j)\epsilon_{jk}(u^c q^k)$
$O'_{\ell equ}$	$(e^c\bar{\sigma}_{\mu\nu}\ell^j)\epsilon_{jk}(u^c\bar{\sigma}^{\mu\nu}q^k)$
$O_{\ell edq}$	$(\bar{\ell}\bar{e}^c)(d^c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

Off-pole precision observables

Beyond pole measurements

- So far only vertex corrections are constrained, because pole observables are not sensitive to anything else (once oblique corrections redefined away)
- To probe 4-fermion operators one needs to venture into off-pole observables
- Three main groups: 1) Very low-energy scattering of neutrinos, electrons, etc. on various targets, 2) Off-pole fermion pair production in e+e- colliders, 3) Off-pole fermion pair production in hadron colliders
- I only consider 1) and 2) here, but 3) also important, especially for LLQQ operators

Off-pole probes of 4-fermion operators



4-fermion couplings extracted from total cross section and FB asymmetry (or full differential distribution) in e+e- → FF process in e+e- colliders

$$\begin{aligned}\delta\sigma_q &= \frac{1}{8\pi s}\left[-e^2(g_L^2+g_Y^2)\frac{s}{s-m_Z^2}\left(\delta A_{Fq}+\delta A_{Bq}\right)+(g_L^2+g_Y^2)^2\frac{s^2}{(s-m_Z^2)^2}\left(\delta B_{Fq}+\delta B_{Bq}\right)\right]\\ &+\frac{1}{8\pi v^2}(g_L^2+g_Y^2)\frac{s}{s-M_Z^2}\left(\hat{g}_L^{Ze}\hat{g}_L^{Zq}c_{LL}+\hat{g}_L^{Ze}\hat{g}_R^{Zq}c_{LR}+\hat{g}_R^{Ze}\hat{g}_L^{Zq}c_{RL}+\hat{g}_R^{Ze}\hat{g}_R^{Zq}c_{RR}\right)\\ &-\frac{1}{8\pi v^2}e^2Q_q\left(c_{LL}+c_{LR}+c_{RL}+c_{RR}\right), \qquad (3.19)\end{aligned}$$

$$\begin{aligned}\delta\sigma_q^{\rm FB} &= \frac{3}{32\pi s}\left[-e^2(g_L^2+g_Y^2)\frac{s}{s-M_Z^2}\left(\delta A_{Fq}-\delta A_{Bq}\right)+(g_L^2+g_Y^2)^2\frac{s^2}{(s-M_Z^2)^2}\left(\delta B_{Fq}-\delta B_{Bq}\right)\right]\\ &+\frac{3}{32\pi v^2}(g_L^2+g_Y^2)\frac{s}{s-M_Z^2}\left(\hat{g}_L^{Ze}\hat{g}_L^{Zq}c_{LL}+\hat{g}_R^{Ze}\hat{g}_R^{Zq}c_{RR}-\hat{g}_L^{Ze}\hat{g}_R^{Zq}c_{LR}-\hat{g}_R^{Ze}\hat{g}_L^{Zq}c_{RL}\right)\\ &-\frac{3}{32\pi v^2}e^2Q_q\left(c_{LL}+c_{RR}-c_{LR}-c_{RL}\right), \qquad (3.20)\end{aligned}$$

Note that relative effect of 4-fermion couplings grows with increasing collision energy
Energy can trump accuracy in this case

Low-energy off-pole precision measurements

Class	Observable	Exp. value	Ref. & Comments	SM value
$\nu_e \nu_e q q$	$R_{\nu_e \bar{\nu}_e}$	0.41(14)	CHARM [10]	0.33
$\nu_\mu \nu_\mu q q$	$(g_L^{\nu_\mu})^2$	0.3005(28)	PDG [7], $\rho \approx 1$	0.3034
	$(g_R^{\nu_\mu})^2$	0.0329(30)		0.0302
	$\theta_L^{\nu_\mu}$	2.500(35)		2.4631
	$\theta_R^{\nu_\mu}$	$4.56^{+0.42}_{-0.27}$		5.1765
PV low-E $eeqq$	$g_{AV}^{eu} + 2 g_{AV}^{ed}$	0.489(5)	PDG [7], $\rho \neq 1$	0.4951
	$2 g_{AV}^{eu} - g_{AV}^{ed}$	−0.708(16)		−0.7192
	$2 g_{VA}^{eu} - g_{VA}^{ed}$	−0.144(68)		−0.0949
	$g_{VA}^{eu} - g_{VA}^{ed}$	−0.042(57) −0.120(74)	SAMPLE [25]	−0.0627
PV low-E $\mu\mu qq$	$b_{\text{SPS}}(\lambda = 0.81)$	$-1.47(42) \cdot 10^{-4}$	BCDMS [26]	$-1.56 \cdot 10^{-4}$
	$b_{\text{SPS}}(\lambda = 0.66)$	$-1.74(81) \cdot 10^{-4}$		$-1.57 \cdot 10^{-4}$
$d(s) \to u \ell \nu$	$\epsilon_i^{d_j \ell}$	Eq. (3.17)	Ref. [8]	0
$e^+ e^- \to q \bar{q}$	$\sigma(q\bar{q})$	$f(\sqrt{s})$	LEPEWWG [27], $\rho \neq 1$	$f(\sqrt{s})$
	σ_c, σ_b		LEPEWWG [34], VENUS [29], TOPAZ [30]	
	A_{FB}^{cc}, A_{FB}^{bb}			
$\nu_\mu \nu_\mu e e$	$g_{LV}^{\nu_\mu e}$	−0.040(15)	PDG [7], $\rho \neq 1$	−0.0396
	$g_{LA}^{\nu_\mu e}$	−0.507(14)		−0.5064
$e^- e^- \to e^- e^-$	g_{AV}^{ee}	0.0190(27)	PDG [7]	0.0225
$\tau \to \ell \nu \nu$	$G_{\tau e}^2 / G_F^2$	1.0029(46)	PDG [7], PSI [35], $\rho \approx 1$	1
	$G_{\tau \mu}^2 / G_F^2$	0.981(18)		1
	Michel η	−0.0021(71)		0
	Michel β'/A	−0.0013(36)		0
$e^+ e^- \to \ell^+ \ell^-$	$\frac{d\sigma(ee)}{d\cos\theta}$	$f(\sqrt{s})$	LEPEWWG [27], $\rho \approx 1$	$f(\sqrt{s})$
	σ_μ, σ_τ		LEPEWWG [34], VENUS [33]	
	$A_{FB}^{\mu}, A_{FB}^{\tau}$			

Off-pole probes of 4-fermion operators

- Neutrino scattering on lepton or nucleon targets

$$\delta g_V = \delta g_L^{Ze} + \delta g_R^{Ze} + \frac{3g_Y^2 - g_L^2}{g_L^2 + g_Y^2}\left(\delta g_L^{Z\mu} + \delta g_L^{W\mu}\right) - \frac{[c_{\ell\ell}]_{1122} + [c_{\ell e}]_{2211}}{2},$$

$$\delta g_A = \delta g_L^{Ze} - \delta g_R^{Ze} - \left(\delta g_L^{Z\mu} + \delta g_L^{W\mu}\right) - \frac{[c_{\ell\ell}]_{1122} - [c_{\ell e}]_{2211}}{2}.$$

- Parity violating electron scattering on muons

$$\delta s_\theta^2 = 2(g_{R,SM}^{Ze}\delta g_R^{Ze} - g_{L,SM}^{Ze}\delta g_L^{Ze}) - \frac{1}{4}([c_{ee}]_{1111} - [c_{\ell\ell}]_{1111})$$

- Atomic parity violation
- Parity violating electron scattering on nucleons

$$g_{AV}^{e_J u} = -\frac{1}{2} + \frac{4}{3}s_\theta^2 - \left(\delta g_L^{Zu} + \delta g_R^{Zu}\right) + \frac{3 - 8s_\theta^2}{3}\left(\delta g_L^{Ze_J} - \delta g_R^{Ze_J}\right) + \frac{1}{2}\left[c_{lq}' - c_{lq} - c_{lu} + c_{eq} + c_{eu}\right]_{JJ11},$$

$$g_{AV}^{e_J d} = \frac{1}{2} - \frac{2}{3}s_\theta^2 - \left(\delta g_L^{Zd} + \delta g_R^{Zd}\right) - \frac{3 - 4s_\theta^2}{3}\left(\delta g_L^{Ze_J} - \delta g_R^{Ze_J}\right) + \frac{1}{2}\left[-c_{lq}' - c_{lq} - c_{ld} + c_{eq} + c_{ed}\right]_{JJ11},$$

$$g_{VA}^{e_J u} = -\frac{1}{2} + 2s_\theta^2 - \left(1 - 4s_\theta^2\right)\left(\delta g_L^{Zu} - \delta g_R^{Zu}\right) + \left(\delta g_L^{Ze_J} + \delta g_R^{Ze_J}\right) + \frac{1}{2}\left[c_{lq}' - c_{lq} + c_{lu} - c_{eq} + c_{eu}\right]_{JJ11},$$

$$g_{VA}^{e_J d} = \frac{1}{2} - 2s_\theta^2 - \left(1 - 4s_\theta^2\right)\left(\delta g_L^{Zd} - \delta g_R^{Zd}\right) - \left(\delta g_L^{Ze_J} + \delta g_R^{Ze_J}\right) + \frac{1}{2}\left[-c_{lq}' - c_{lq} + c_{ld} - c_{eq} + c_{ed}\right]_{JJ11},$$

- Muon and tau decay rates and differential distributions

$$A_e \equiv \frac{G_{\tau e}^2}{G_F^2} = 1 + 2\delta g_L^{W\tau} + 2\delta g_L^{We} - 4\delta m - [c_{\ell\ell}]_{1331},$$

$$A_\mu \equiv \frac{G_{\tau\mu}^2}{G_F^2} = 1 + 2\delta g_L^{W\tau} + 2\delta g_L^{W\mu} - 4\delta m - [c_{\ell\ell}]_{2332},$$

$$\eta = \frac{\mathrm{Re}[c_{\ell e}]_{1221}}{2}, \qquad \beta'/A = -\frac{\mathrm{Im}[c_{\ell e}]_{1221}}{4}.$$

Gonzalez-Alonso, Camalich 1605.07114

- Decays of pions, kaons, hyperons

Off-Pole constraints on 4-fermion operators

One flavor $(I = 1 \ldots 3)$	Two flavors $(I < J = 1 \ldots 3)$
$[O_{\ell\ell}]_{IIII} = \frac{1}{2}(\bar{\ell}_I \bar{\sigma}_\mu \ell_I)(\bar{\ell}_I \bar{\sigma}_\mu \ell_I)$	$[O_{\ell\ell}]_{IIJJ} = (\bar{\ell}_I \bar{\sigma}_\mu \ell_I)(\bar{\ell}_J \bar{\sigma}_\mu \ell_J)$
	$[O_{\ell\ell}]_{IJJI} = (\bar{\ell}_I \bar{\sigma}_\mu \ell_J)(\bar{\ell}_J \bar{\sigma}_\mu \ell_I)$
$[O_{\ell e}]_{IIII} = (\bar{\ell}_I \bar{\sigma}_\mu \ell_I)(e^c_I \sigma_\mu \bar{e}^c_I)$	$[O_{\ell e}]_{IIJJ} = (\bar{\ell}_I \bar{\sigma}_\mu \ell_I)(e^c_J \sigma_\mu \bar{e}^c_J)$
	$[O_{\ell e}]_{JJII} = (\bar{\ell}_J \bar{\sigma}_\mu \ell_J)(e^c_I \sigma_\mu \bar{e}^c_I)$
	$[O_{\ell e}]_{IJJI} = (\bar{\ell}_I \bar{\sigma}_\mu \ell_J)(e^c_J \sigma_\mu \bar{e}^c_I)$
$[O_{ee}]_{IIII} = \frac{1}{2}(e^c_I \sigma_\mu \bar{e}^c_I)(e^c_I \sigma_\mu \bar{e}^c_I)$	$[O_{ee}]_{IIJJ} = (e^c_I \sigma_\mu \bar{e}^c_I)(e^c_J \sigma_\mu \bar{e}^c_J)$

Chirality conserving $(I, J = 1, 2, 3)$	Chirality violating $(I, J = 1, 2, 3)$
$[O_{\ell q}]_{IIJJ} = (\bar{\ell}_I \bar{\sigma}_\mu \ell_I)(\bar{q}_J \bar{\sigma}_\mu q_J)$	$[O_{\ell equ}]_{IIJJ} = (\bar{\ell}^j_I \bar{e}^c_I)\epsilon_{jk}(\bar{q}^k_J \bar{u}^c_J)$
$[O^{(3)}_{\ell q}]_{IIJJ} = (\bar{\ell}_I \bar{\sigma}_\mu \sigma^i \ell_I)(\bar{q}_J \bar{\sigma}_\mu \sigma^i q_J)$	$[O^{(3)}_{\ell equ}]_{IIJJ} = (\bar{\ell}^j_I \sigma_{\mu\nu} \bar{e}^c_I)\epsilon_{jk}(\bar{q}^k_J \sigma_{\mu\nu} \bar{u}^c_J)$
$[O_{\ell u}]_{IIJJ} = (\bar{\ell}_I \bar{\sigma}_\mu \ell_I)(u^c_J \bar{\sigma}_\mu \bar{u}^c_J)$	$[O_{\ell edq}]_{IIJJ} = (\bar{\ell}^j_I \bar{e}^c_I)(d^c_J q^j_J)$
$[O_{\ell d}]_{IIJJ} = (\bar{\ell}_I \bar{\sigma}_\mu \ell_I)(d^c_J \bar{\sigma}_\mu \bar{d}^c_J)$	
$[O_{eq}]_{IIJJ} = (e^c_I \bar{\sigma}_\mu \bar{e}^c_I)(\bar{q}_J \bar{\sigma}_\mu q_J)$	
$[O_{eu}]_{IIJJ} = (e^c_I \bar{\sigma}_\mu \bar{e}^c_I)(u^c_J \bar{\sigma}_\mu \bar{u}^c_J)$	
$[O_{ed}]_{IIJJ} = (e^c_I \bar{\sigma}_\mu \bar{e}^c_I)(d^c_J \bar{\sigma}_\mu \bar{d}^c_J)$	

- Targeting 40 linear combinations QQLL and LLLL 4-fermion operators
- All relevant observables depend also on leptonic vertex corrections, so combination with previous pole constraints is necessary

AA,Mimouni
1511.07434

AA, Gonzalez-Alonso, Mimouni
to appear

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

$(\mu\mu)(qq)$

	$[c^{(3)}_{\ell q}]_{2211}$	$[c_{\ell q}]_{2211}$	$[c_{\ell u}]_{2211}$	$[c_{\ell d}]_{2211}$	$[c_{eq}]_{2211}$	$[c_{eu}]_{2211}$	$[c_{ed}]_{2211}$
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

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

Off-Pole constraints on 4-lepton observables

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

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

Preliminary

- Full correlation matrix also calculated
- Little change for vertex corrections, since pole observables are more precise
- Typical constraints for 4-lepton operators are at 1% level

LHC vs low-energy

$(ee)(qq)$

	$[c_{\ell q}^{(3)}]_{1111}$	$[c_{\ell q}]_{1111}$	$[c_{\ell u}]_{1111}$	$[c_{\ell d}]_{1111}$	$[c_{eq}]_{1111}$	$[c_{eu}]_{1111}$	$[c_{ed}]_{1111}$
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

$(\mu\mu)(qq)$

	$[c_{\ell q}^{(3)}]_{2211}$	$[c_{\ell q}]_{2211}$	$[c_{\ell u}]_{2211}$	$[c_{\ell d}]_{2211}$	$[c_{eq}]_{2211}$	$[c_{eu}]_{2211}$	$[c_{ed}]_{2211}$
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

	$[c_{\ell equ}]_{1111}$	$[c_{\ell edq}]_{1111}$	$[c_{\ell equ}^{(3)}]_{1111}$	$[c_{\ell equ}]_{2211}$	$[c_{\ell edq}]_{2211}$	$[c_{\ell equ}^{(3)}]_{2211}$
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

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

Subleading effects ignored

Pole observables constraint vertex 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	$f^{abc} G^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$

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

Pole constraints - universal theories

Oblique corrections: $\delta\mathcal{M}(V_{1,\mu}\to V_{2,\nu}) = \eta_{\mu\nu}\left(\delta\Pi^{(0)}_{V_1V_2} + \delta\Pi^{(2)}_{V_1V_2}p^2 + \delta\Pi^{(4)}_{V_1V_2}p^4 + \dots\right) + p_\mu p_\nu(\dots)$

$$\alpha S = -4\frac{g_L g_Y}{g_L^2+g_Y^2}\delta\Pi^{(2)}_{3B}$$
$$\alpha T = \frac{\delta\Pi^{(0)}_{11} - \delta\Pi^{(0)}_{33}}{m_W^2}$$
$$\alpha U = \frac{4g_Y^2}{g_L^2+g_Y^2}\left(\delta\Pi^{(2)}_{11} - \delta\Pi^{(2)}_{33}\right)$$

$$\alpha V = m_W^2\left(\delta\Pi^{(4)}_{11} - \delta\Pi^{(4)}_{33}\right)$$
$$\alpha W = -m_W^2\delta\Pi^{(4)}_{33}$$
$$\alpha X = -m_W^2\delta\Pi^{(4)}_{3B}$$
$$\alpha Y = -m_W^2\delta\Pi^{(4)}_{BB}$$

Peskin Takeuchi pre-arxiv

Barbieri et al hep-ph/0405040

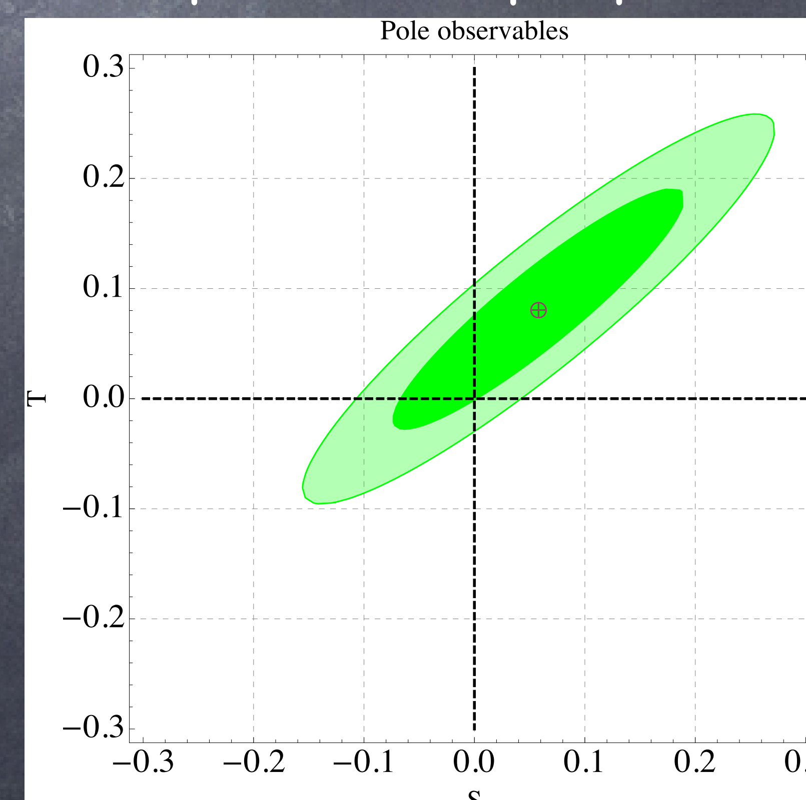
Wells Zhang 1510.08462

Equivalent to restricted form of flavor-diagonal vertex corrections, 4-fermion operators and W-mass corrections:

$$[\delta g^{Zf}]_{ij} = \delta_{ij}\alpha\left\{T^3_f\frac{T - W - \frac{g_Y^2}{g_L^2}Y}{2} + Q_f\frac{2g_Y^2 T - (g_L^2+g_Y^2)S + 2g_Y^2 W + \frac{2g_Y^2(2g_L^2-g_Y^2)}{g_L^2}Y}{4(g_L^2-g_Y^2)}\right\}$$
$$\delta m = \frac{\alpha}{4(g_L^2-g_Y^2)}\left[2g_L^2 T - (g_L^2+g_Y^2)S + 2g_Y^2 W + 2g_Y^2 Y\right]$$

$$[c_{\ell\ell}]_{IIJJ} = \alpha\left[W - \frac{g_Y^2}{g_L^2}Y\right] \qquad [c_{\ell\ell}]_{IJJI} = -2\alpha W, \qquad I<J$$
$$[c_{\ell\ell}]_{IIII} = -\alpha\left[W + \frac{g_Y^2}{g_L^2}Y\right]$$
$$[c_{\ell e}]_{IIJJ} = -\frac{2g_Y^2}{g_L^2}\alpha Y \qquad [c_{ee}]_{IIJJ} = -\frac{4g_Y^2}{g_L^2}\alpha Y$$

Same likelihood for pole observables can be used to constrain up to 3 oblique params



LHC Higgs constraints

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

Subleading effects ignored

LHC Higgs and TGC data extend the net to bosonic and Yukawa operators

Pole observables constraint vertex corrections

Off-pole observables probe 4-fermion operators

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

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

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.

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

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

$(\bar RR)(\bar RR)$	
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 dimension-6 operators on Higgs coupling strength to matter

- Shift the SM Higgs couplings to matter
- Introduce new 2-derivative couplings to gauge bosons that are not present in the SM at tree level
- Introduce CP violating couplings to fermions and gauge bosons
- In SM EFT with dimension-6 operators one finds correlations relations between different Higgs couplings to gauge bosons

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

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

Higgs couplings to pairs of SM fields

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.

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

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

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

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

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

relative correction to W mass

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

Correlations between higher order Higgs couplings and vertex corrections

- 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

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

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

TGC - Higgs Synergy

TGC	
CP even :	$\delta\kappa_\gamma \quad \delta g_{1,z} \quad \lambda_z$
CP odd :	$\tilde{\kappa}_\gamma \quad \tilde{\lambda}_z$

⟷

Higgs	
CP even :	$\delta c_z \quad c_{z\Box} \quad c_{zz} \quad c_{z\gamma} \quad c_{\gamma\gamma}$
CP odd :	$\tilde{c}_{zz} \quad \tilde{c}_{z\gamma} \quad \tilde{c}_{\gamma\gamma}$

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

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

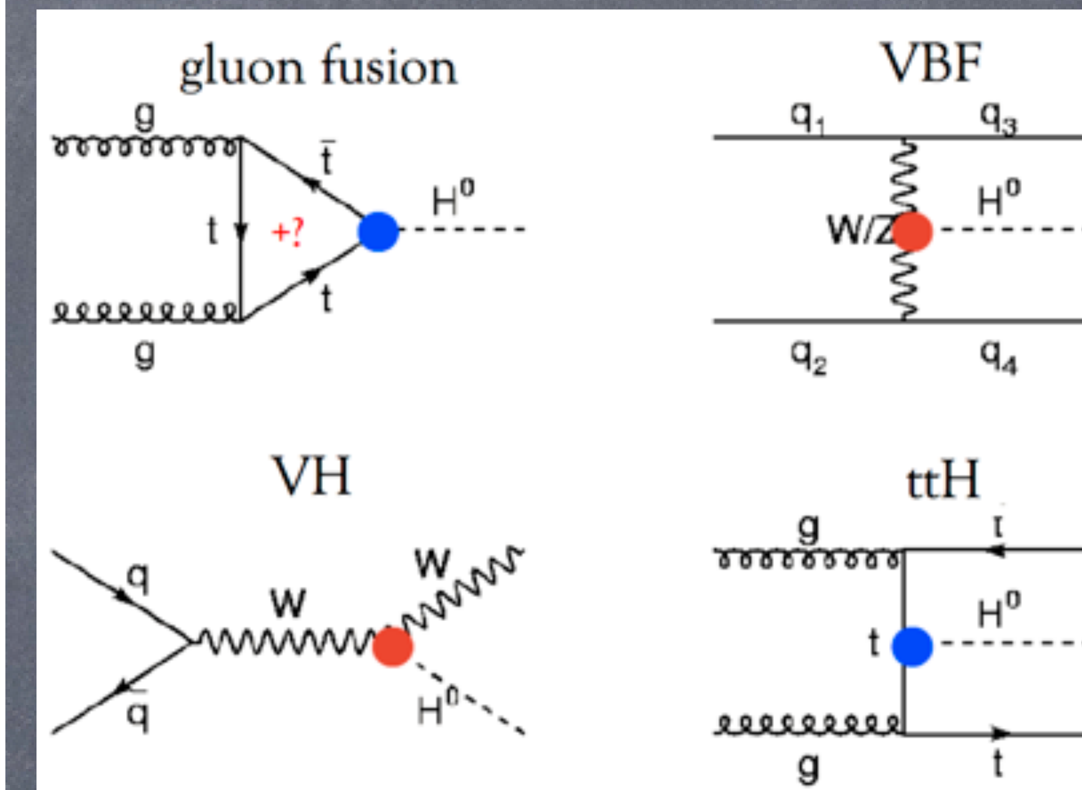
LHC Higgs signal strength so far

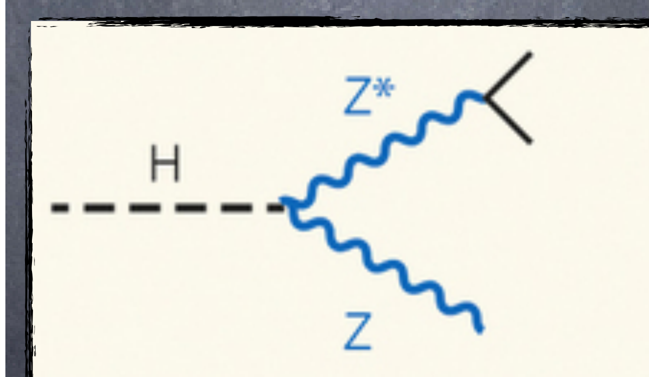
Run-1 results from ATLAS+CMS 1606.02266

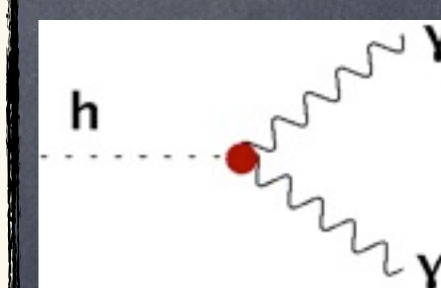
Run-2 results scavenged from various conf-notes

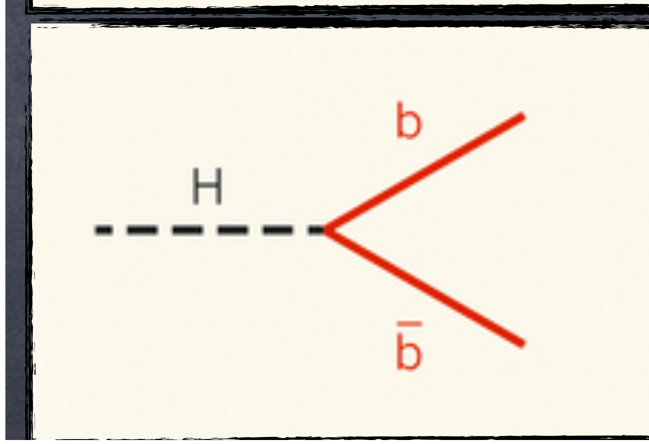
Not using any input from differential distributions here

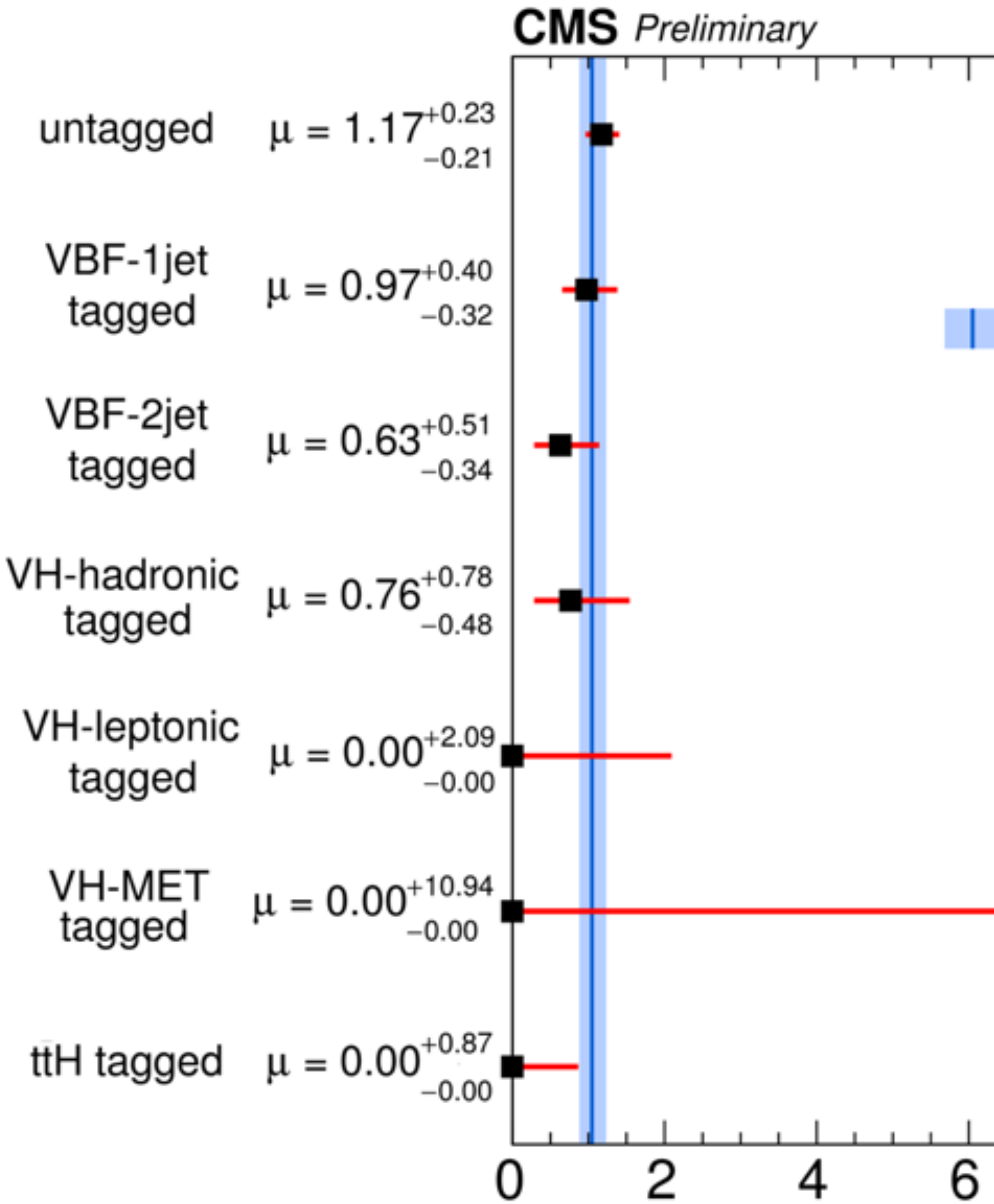
Channel	Production	Run-1	ATLAS Run-2	CMS Run-2
$\gamma\gamma$	ggh	$1.10^{+0.23}_{-0.22}$	$0.62^{+0.30}_{-0.29}$ [106]	$0.77^{+0.25}_{-0.23}$ [107]
	VBF	$1.3^{+0.5}_{-0.5}$	$2.25^{+0.75}_{-0.75}$ [106]	$1.61^{+0.90}_{-0.80}$ [107]
	Wh	$0.5^{+1.3}_{-1.2}$	-	-
	Zh	$0.5^{+3.0}_{-2.5}$	-	-
	Vh	-	$0.30^{+1.21}_{-1.12}$ [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]	$1.5^{+0.5}_{-0.5}$ [?]

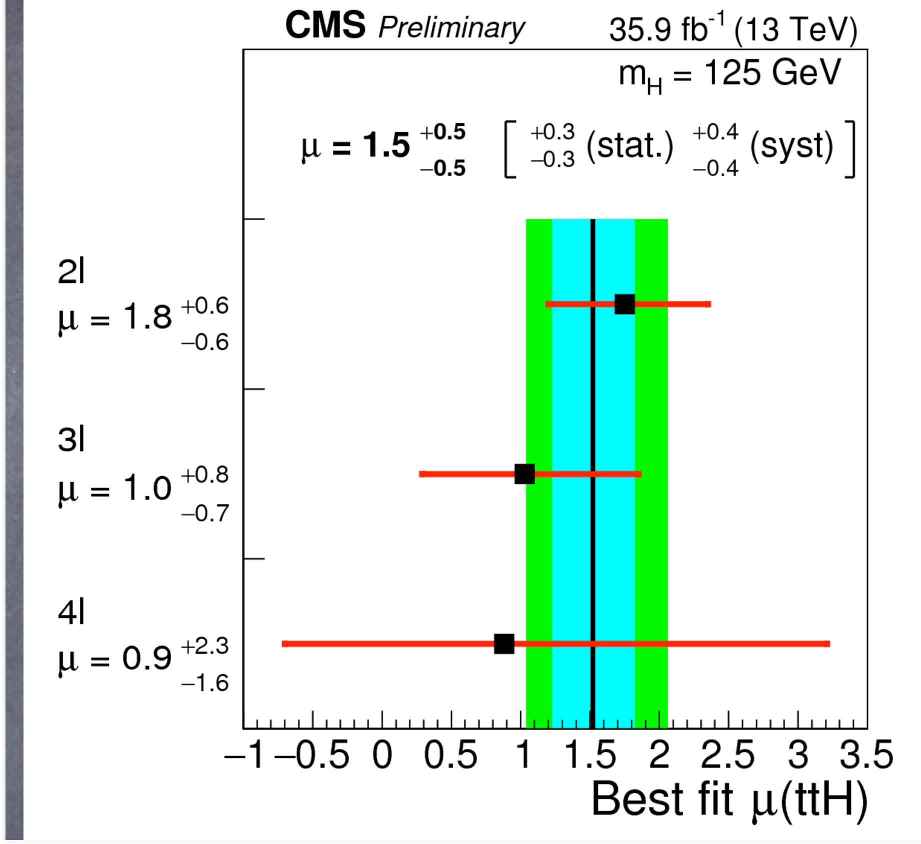


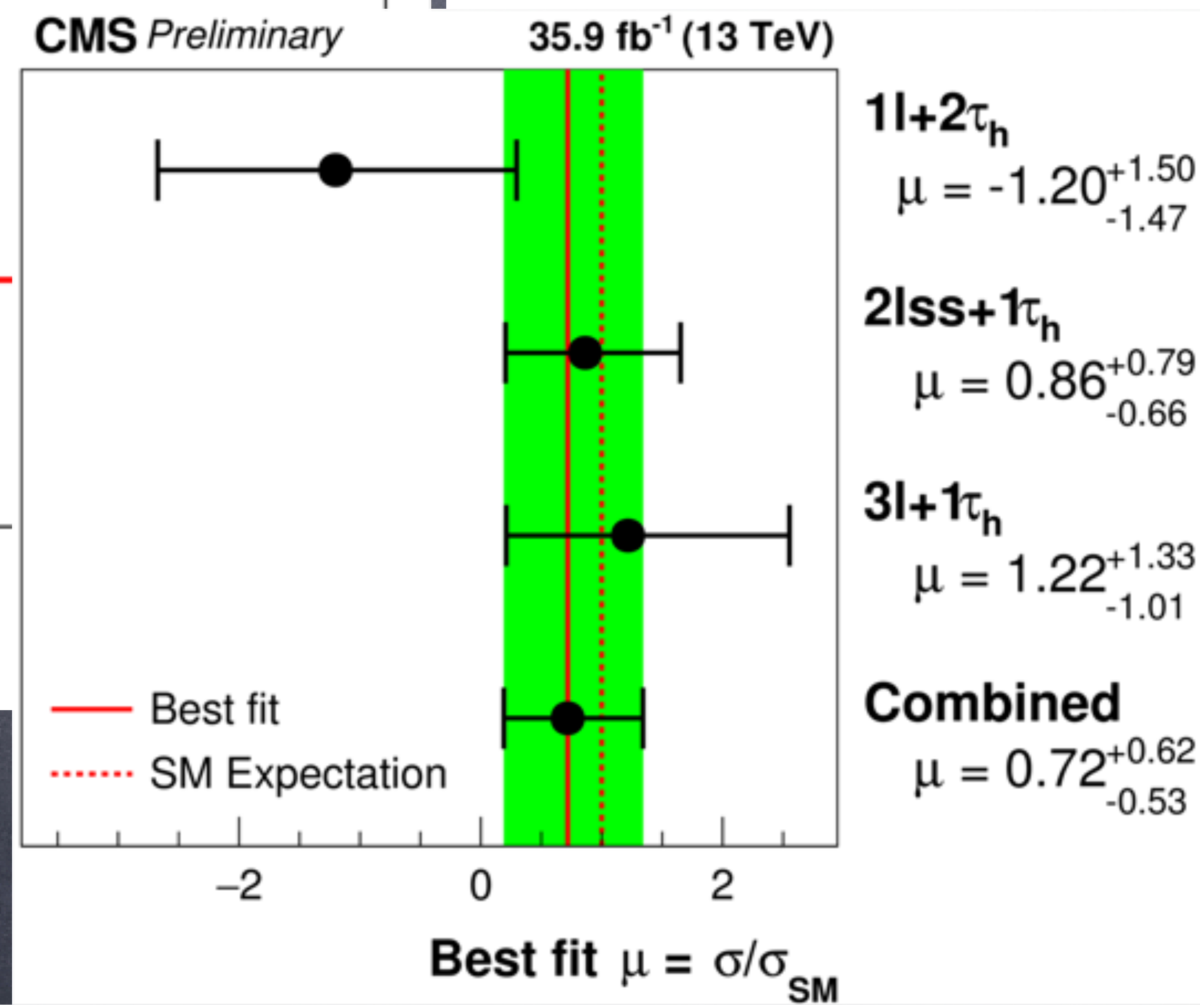







CMS Preliminary
35.9 fb-1 (13 TeV)
H → ZZ* → 4l
mH = 125.09 GeV
μcomb. = 1.05 +0.19 −0.17
untagged μ = 1.17 +0.23 −0.21
VBF-1jet tagged μ = 0.97 +0.40 −0.32
VBF-2jet tagged μ = 0.63 +0.51 −0.34
VH-hadronic tagged μ = 0.76 +0.78 −0.48
VH-leptonic tagged μ = 0.00 +2.09 −0.00
VH-MET tagged μ = 0.00 +10.94 −0.00
ttH tagged μ = 0.00 +0.87 −0.00
0
2
4
6


CMS Preliminary
35.9 fb-1 (13 TeV)
mH = 125 GeV
μ = 1.5 +0.5 −0.5 [+0.3 −0.3 (stat.) +0.4 −0.4 (syst)]
2l μ = 1.8 +0.6 −0.6
3l μ = 1.0 +0.8 −0.7
4l μ = 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+2τh μ = -1.20 +1.50 -1.47
2lss+1τh μ = 0.86 +0.79 -0.66
3l+1τh μ = 1.22 +1.33 -1.01
Combined μ = 0.72 +0.62 -0.53
Best fit
SM Expectation
−2
0
2
Best fit μ = σ/σSM

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

(*) −2ΔlnL = 1 interval with μ ≥ 0 constraint

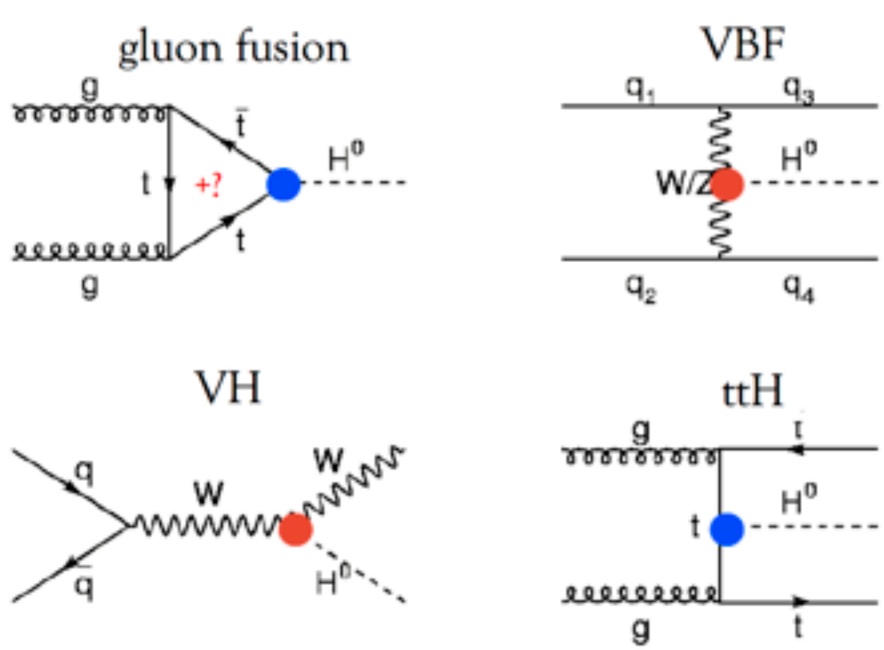
Run1 comb. *JHEP 08(2016) 045*	2.3	+1.2 −1.0	AA's naive combination $\mu_{\rm tth} = 1.26 \pm 0.26$

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

Corrections to Higgs production from dimension-6 operators

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

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



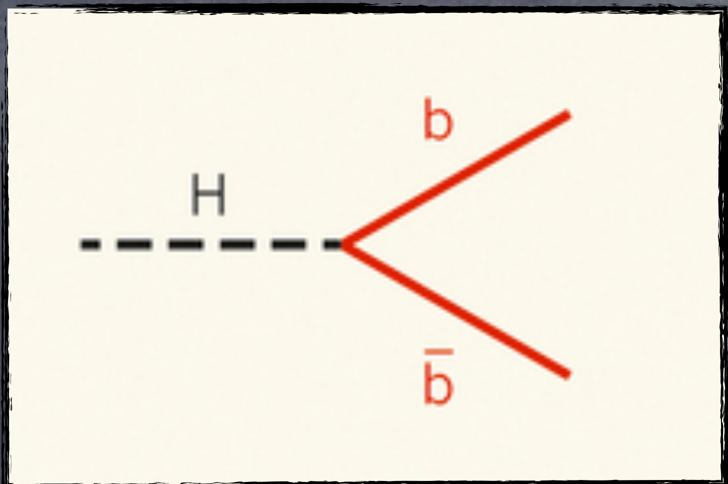
$$\frac{\sigma_{tth}}{\sigma_{tth}^{SM}} \simeq 1 + 2\delta y_u.$$

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

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

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

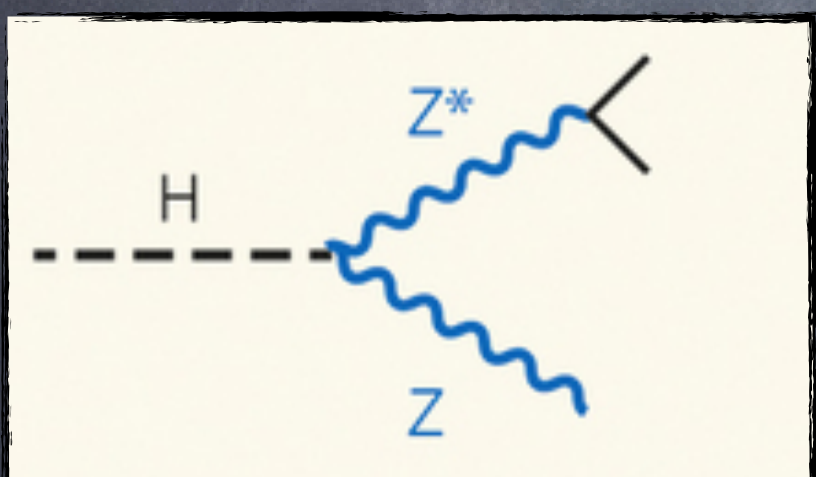
Corrections to Higgs decays from dimension-6 operators



Decays to 2 fermions

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

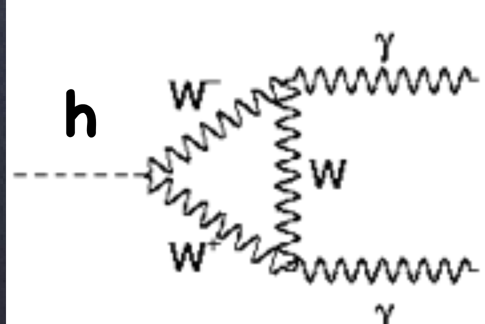
Decays to 4 fermions

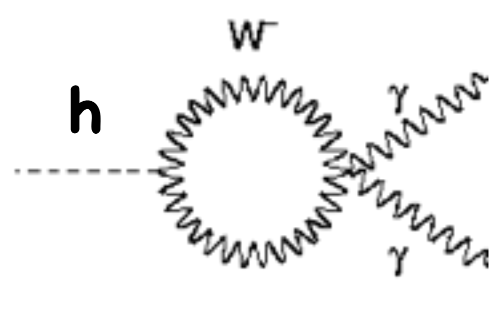


$$\begin{aligned}\frac{\Gamma_{2\ell 2\nu}}{\Gamma_{2\ell 2\nu}^{\rm SM}} &\simeq 1+2\delta c_w + 0.46 c_{w\Box} - 0.15 c_{ww} \\ &\to 1+2\delta c_z + 0.67 c_{z\Box} + 0.05 c_{zz} - 0.17 c_{z\gamma} - 0.05 c_{\gamma\gamma}.\end{aligned}$$

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

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

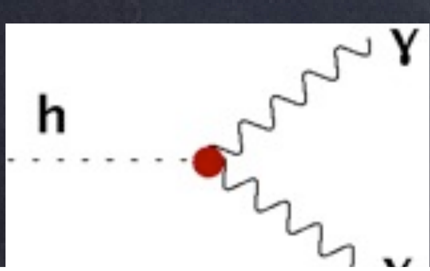


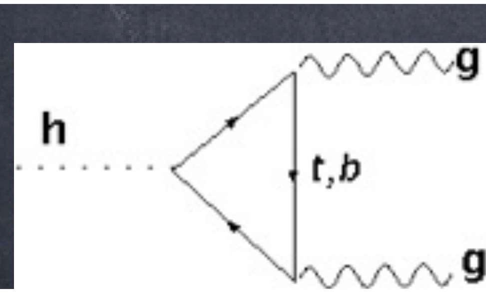


Decays to 2 gauge bosons

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

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





Global constraints on Higgs coupling in SM EFT

Combined constraints from LHC Higgs and electroweak precision constraints

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

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

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

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

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

Future directions

- Constraints on Higgs couplings and vertex corrections to be constantly updated (more results are coming)
- Model-independent tree-level constraints on remaining dimension-6 operators
- Interfacing likelihoods to Rosetta
- Additional constraints from Higgs differential distributions (once better statistics available)
- Electroweak precision constraints including 1-loop corrections from dimension-6 operators
- Experimental identification of deviations from SM and of interpreting them in language of dimension-6 operators in SM EFT. Using this, pinpointing scale and form of new physics, so as to create a beacon for next generation experiments