Adam Falkowski

Introduction to Higgs EFT

GDR Terascale Grenoble

24 November 2015

Several approaches to new physics searches

Model specific

pick one well-defined, “motivated”,
often UV complete model

E.g. 2HDM, MSSM, NMSSM, NNMSSM, ...,
composite Higgs, minimal walking technicolor

Simplified models

pick simple well-defined model
that captures some aspects of phenomenology
of large class of specific models

E.g. singlet scalar, gluino+neutralino, heavy
top quark, vector triplet,

Model independent

parametrize low-energy effects
large class of models as higher-dimensional
contact interaction of light particles

Effective field theory

Effective Theory Approach to BSM

Basic assumptions

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

EFT Lagrangian beyond the SM expanded in operator dimension D,
or, equivalently, in

Standard Model,
operators up to D=4

Lepton number violating, hence
too small to be probed at LHC

By assumption,
subleading
to D=6

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

Cutoff scale of EFT

Appear when starting from L-conserving BSM,
and integrating out heavy particles with m≈Λ

Standard Model part

$$\mathcal{L}_{\rm SM} = -\frac{1}{4g_s^2}G_{\mu\nu,a}^2 - \frac{1}{4g_L^2}W_{\mu\nu,i}^2 - \frac{1}{4g_Y^2}B_{\mu\nu}^2$$
$$+i\sum_{f=q,\ell}\bar{f}\bar{\sigma}_\mu D_\mu f + i\sum_{f=u,d,e} f^c\sigma_\mu D_\mu \bar{f}^c$$
$$-HqY_u u^c - H^\dagger q Y_d d^c - H^\dagger \ell Y_e e^c \qquad \text{+h.c.}$$
$$+D_\mu H^\dagger D_\mu H + m_H^2 H^\dagger H - \lambda(H^\dagger H)^2$$

Some predictions at lowest order

- Couplings of gauge bosons to fermions universal and fixed by fermion's quantum numbers
- Z and W boson mass ratio related to Weinberg angle
- Higgs coupling to gauge bosons proportional to their mass squared

$$\left(\frac{h}{v}+\frac{h^2}{2v^2}\right)\left(2m_W^2\, W_\mu^+ W_\mu^- + m_Z^2\, Z_\mu Z_\mu\right)$$

- Higgs coupling to fermions proportional to their mass

$$-\frac{h}{v}\sum_f m_f \bar{f} f$$

- Triple and quartic vector boson couplings proportional to gauge couplings

EFT and Higgs

Some (not all independent) D=6 operators which contribute to Higgs boson interactions with matter

$$O_H = \left(\partial_\mu (H^\dagger H)\right)^2$$

Changes Higgs kinetic and self-interaction terms

$$O_T = \left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$$

Changes Higgs interactions with W and Z in non-custodial way

$$O_{WB} = g_L g_Y H^\dagger \sigma^i H \, W^i_{\mu\nu} B_{\mu\nu}$$

$$O_W = \frac{i}{2} g_L \left(H^\dagger \sigma^i \overleftrightarrow{D}_\mu H\right) D_\nu W^i_{\mu\nu}$$

$$O_B = \frac{i}{2} g_L \left(H^\dagger \overleftrightarrow{D}_\mu H\right) D_\nu B_{\mu\nu}$$

$$O_{HW} = i g_L \left(D_\mu H^\dagger \sigma^i D_\nu H\right) W^i_{\mu\nu}$$

$$O_{HB} = i g_Y \left(D_\mu H^\dagger D_\nu H\right) B_{\mu\nu}$$

$$O_{WW} = g_L^2 H^\dagger H W^i_{\mu\nu} W^i_{\mu\nu} \quad O_{BB} = g_Y^2 H^\dagger H B_{\mu\nu} B_{\mu\nu}$$

New 2-derivative interactions of Higgs with EW gauge bosons

$$O_{Hf} = i \left(H^\dagger \overleftrightarrow{D}_\mu H\right) \left(\bar{f} \bar{\gamma}_\mu f\right)$$

New contact interactions with fermion

$$O_f = H^\dagger H \bar{f} H f$$

Changes Higgs Yukawa interactions with SM fermions

Operators to Observables

Difficulties in the presence of D=6 operators

- Affect relations between couplings and input observables
- Change normalization of kinetic terms
- Introduce non-standard higher-derivative kinetic terms
- Introduce kinetic mixing between photon and Z boson

e.g.

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

e.g.

$$\frac{c_{WW}}{v^2}O_{WW} = \frac{c_{WW}}{v^2}g_L^2 H^\dagger H W^i_{\mu\nu}W^i_{\mu\nu}$$
$$\to \frac{c_{WW}g_L^2}{2}W^i_{\mu\nu}W^i_{\mu\nu}$$

e.g.

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

e.g.

$$\frac{c_{WB}}{v^2}O_{WB} = \frac{c_{WB}}{v^2}g_L g_Y H^\dagger \sigma^i H W^i_{\mu\nu}B_{\mu\nu}$$
$$\to -c_{WB}\frac{g_L g_Y}{2}W^3_{\mu\nu}B_{\mu\nu}$$

To simplify calculating physical predictions, one can map the theory with dimension-6 operators onto the phenomenological effective Lagrangian

Phenomenological effective Lagrangian

LHCHXSWG-INT-2015-001

- Phenomenological effective Lagrangian is defined using mass eigenstates after electroweak symmetry breaking (photon,W,Z,Higgs boson, top). SU(3)xSU(2)xU(1) is not manifest but hidden in relations between different couplings

- Feature #1: In the tree-level Lagrangian, all kinetic terms are canonically normalized, and there's no kinetic mixing between mass eigenstates. In particular, all oblique corrections from new physics are zero, except for a correction to the W boson mass

$$\mathcal{L}_{\rm kin} = -\frac{1}{2}W^+_{\mu\nu}W^-_{\mu\nu} - \frac{1}{4}Z_{\mu\nu}Z_{\mu\nu} - \frac{1}{4}A_{\mu\nu}A_{\mu\nu} + (1+2\delta m)m_W^2 W^+_\mu W^-_\mu + \frac{m_Z^2}{2}Z_\mu Z_\mu$$

- Feature #2: Tree-level relation between the couplings in the Lagrangian and SM input observables is the same as in the SM.

$$m_Z = \frac{\sqrt{g_L^2+g_Y^2}v}{2}$$
$$\alpha \equiv \frac{e^2}{4\pi} = \frac{g_L^2 g_Y^2}{4\pi(g_L^2+g_Y^2)}$$
$$\tau_\mu = \frac{384\pi^3 v^4}{m_\mu^5}$$

- Feature #3: Photon and gluon couple to matter as in the SM

- Features #1-3 can always be obtained without any loss of generality, starting from any Lagrangian with D=6 operators, using integration by parts, fields and couplings redefinition

$$\mathcal{L} \supset eA_\mu(T_f^3+Y_f)\bar{f}\gamma_\mu f + g_s G^a_\mu \bar{q}\gamma_\mu T^a q$$

Higgs couplings to matter

- Higgs couplings to gauge bosons described by 6 CP even and 4 CP odd parameters that are unconstrained by LEP-1
- D=6 EFT with linearly realized SU(3)xSU(2)xU(1) enforces relations between Higgs couplings to gauge bosons (otherwise, more parameters)
- Corrections to Higgs Yukawa couplings to fermions are also unconstrained by EWPT
- Apart from δm and δg, additional 6+3x3x3 CP-even and 4+3x3x3 CP-odd parameters to parametrize LHC Higgs physics

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

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

relative correction to W mass

LHCHXSWG-INT-2015-001

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

Higgs couplings to matter

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

Gupta et al 1405.0181

Grządkowski et al. 1008.4884

Example: from Warsaw Basis to Higgs couplings

$$
\begin{aligned}
\delta c_w =& - c_H - c_{WB}\frac{4g_L^2 g_Y^2}{g_L^2 - g_Y^2} + c_T\frac{4g_L^2}{g_L^2 - g_Y^2} - \frac{3g_L^2 + g_Y^2}{4(g_L^2 - g_Y^2)}\left(2[c'_{H\ell}]_{11} + 2[c'_{H\ell}]_{22} - [c_{\ell\ell}]_{1221}\right),\\
\delta c_z =& - c_H - \frac{3}{4}\left(2[c'_{H\ell}]_{11} + 2[c'_{H\ell}]_{22} - [c_{\ell\ell}]_{1221}\right),\\
c_{\gamma\gamma} =& c_{WW} + c_{BB} - 4c_{WB},\\
c_{zz} =& \frac{g_L^4 c_{WW} + g_Y^4 c_{BB} + 4g_L^2 g_Y^2 c_{WB}}{(g_L^2 + g_Y^2)^2},\\
c_{z\Box} =& -\frac{2}{g_L^2}\left(c_T - \frac{2[c'_{H\ell}]_{11} + 2[c'_{H\ell}]_{22} - [c_{\ell\ell}]_{1221}}{4}\right),\\
c_{z\gamma} =& \frac{g_L^2 c_{WW} - g_Y^2 c_{BB} - 2(g_L^2 - g_Y^2)c_{WB}}{g_L^2 + g_Y^2},\\
c_{\gamma\Box} =& \frac{4}{g_L^2 - g_Y^2}\left(\frac{g_L^2 + g_Y^2}{2}c_{WB} - c_T + \frac{2[c'_{H\ell}]_{11} + 2[c'_{H\ell}]_{22} - [c_{\ell\ell}]_{1221}}{4}\right),\\
c_{ww} =& c_{WW},\\
c_{w\Box} =& \frac{2}{g_L^2 - g_Y^2}\left(g_Y^2 c_{WB} - c_T + \frac{2[c'_{H\ell}]_{11} + 2[c'_{H\ell}]_{22} - [c_{\ell\ell}]_{1221}}{4}\right).
\end{aligned}
$$

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

Higgs couplings to matter

- Corrections to Higgs couplings in phenomenological effective Lagrangian can be related by linear transformation to Wilson coefficients of any basis of D=6 operators

- Unexpected dependence of fermionic operators due to rescaling of SM couplings

- Corrections to Higgs and other SM couplings are O(1/Λ^2) in EFT expansion. They can be used to define (perhaps more convenient) basis of D=6 operators

Gupta et al 1405.0181

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

Example: from SILH Basis to Higgs couplings

$$
\begin{aligned}
\delta c_w &= -\, s_H - \frac{g_L^2 g_Y^2}{g_L^2 - g_Y^2}\left[s_W + s_B + s_{2W} + s_{2B} - \frac{4}{g_Y^2} s_T + \frac{3g_L^2 + g_Y^2}{2 g_L^2 g_Y^2} [s'_{H\ell}]_{22} \right], \\
\delta c_z &= -\, s_H - \frac{3}{2}[s'_{H\ell}]_{22}, \\
c_{\gamma\gamma} &= s_{BB}, \\
c_{zz} &= -\frac{1}{g_L^2 + g_Y^2}\left[g_L^2 s_{HW} + g_Y^2 s_{HB} - g_Y^2 s_\theta^2 s_{BB} \right], \\
c_{z\Box} &= \frac{1}{2g_L^2}\left[g_L^2 (s_W + s_{HW} + s_{2W}) + g_Y^2 (s_B + s_{HB} + s_{2B}) - 4 s_T + 2[s'_{H\ell}]_{22} \right], \\
c_{z\gamma} &= \frac{s_{HB} - s_{HW}}{2} - s_\theta^2 s_{BB}, \\
c_{\gamma\Box} &= \frac{s_{HW} - s_{HB}}{2} + \frac{1}{g_L^2 - g_Y^2}\left[g_L^2 (s_W + s_{2W}) + g_Y^2 (s_B + s_{2B}) - 4 s_T + 2[s'_{H\ell}]_{22} \right], \\
c_{ww} &= -\, s_{HW}, \\
c_{w\Box} &= \frac{s_{HW}}{2} + \frac{1}{2(g_L^2 - g_Y^2)}\left[g_L^2 (s_W + s_{2W}) + g_Y^2 (s_B + s_{2B}) - 4 s_T + 2[s'_{H\ell}]_{22} \right],
\end{aligned}
$$

Use Rosetta: arXiv:1508.05895
for translations between bases and
consistent implementations of
phenomenological effective Lagrangian

Higgs couplings to matter

- Corrections to Higgs couplings in phenomenological effective Lagrangian can be related by linear transformation to Wilson coefficients of any basis of D=6 operators

- Unexpected dependence of fermionic operators due to rescaling of SM couplings

- Corrections to Higgs and other SM couplings are O(1/Λ^2) in EFT expansion. They can be used to define (perhaps more convenient) basis of for the space of D=6 operators

Gupta et al 1405.0181

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

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

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

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

LHCHXSWG-INT-2015-001

Interplay of Higgs searches and precision experiments

$$\frac{h}{v}[2(1+\delta c_w)m_W^2 W_\mu^+ W_\mu^- + (1+\delta c_z)m_Z^2 Z_\mu Z_\mu$$

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

- In general corrections to SM 0-derivative Higgs boson couplings to WW and ZZ are independent in dimension-6 EFT
- However, one can prove that difference between these two is exactly the same combination of Wilson coefficients as the one that shifts W boson mass away from SM prediction
- Since W boson mass is measured with relative accuracy of 10^-4, these two couplings must be equal for the sake of LHC measurements, as long as D=6 EFT approach is assumed to be valid
- Note this does not mean corrections to h->WW and h->ZZ partial width have to be the same! The two can be affected differently by 2-derivative Higgs couplings to WW and ZZ

$$
\begin{aligned}
&+c_{ww}\frac{g_L^2}{2}W_{\mu\nu}^+ W_{\mu\nu}^- + \tilde{c}_{ww}\frac{g_L^2}{2}W_{\mu\nu}^+ \tilde{W}_{\mu\nu}^- + c_{w\Box}g_L^2\left(W_\mu^-\partial_\nu W_{\mu\nu}^+ + \mathrm{h.c.}\right)\\
&+c_{gg}\frac{g_s^2}{4}G_{\mu\nu}^a G_{\mu\nu}^a + c_{\gamma\gamma}\frac{e^2}{4}A_{\mu\nu}A_{\mu\nu} + c_{z\gamma}\frac{e g_L}{2c_\theta}Z_{\mu\nu}A_{\mu\nu} + c_{zz}\frac{g_L^2}{4c_\theta^2}Z_{\mu\nu}Z_{\mu\nu}\\
&+c_{z\Box}g_L^2 Z_\mu\partial_\nu Z_{\mu\nu} + c_{\gamma\Box}g_L g_Y Z_\mu\partial_\nu A_{\mu\nu}\\
&+\tilde{c}_{gg}\frac{g_s^2}{4}G_{\mu\nu}^a \tilde{G}_{\mu\nu}^a + \tilde{c}_{\gamma\gamma}\frac{e^2}{4}A_{\mu\nu}\tilde{A}_{\mu\nu} + \tilde{c}_{z\gamma}\frac{e g_L}{2c_\theta}Z_{\mu\nu}\tilde{A}_{\mu\nu} + \tilde{c}_{zz}\frac{g_L^2}{4c_\theta^2}Z_{\mu\nu}\tilde{Z}_{\mu\nu}]
\end{aligned}
$$

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

Interplay of Higgs searches and precision experiments

$$\mathcal{L}_{\rm hvff} = \sqrt{2} g_L \frac{h}{v}\left(W_\mu^+ \bar\nu \bar\sigma_\mu \delta g_L^{W\ell} e + W_\mu^+ \bar u \bar\sigma_\mu \delta g_L^{Wq} d + W_\mu^+ u^c \sigma_\mu \delta g_R^{Wq} \bar d^c + \text{h.c.}\right)$$
$$+2\sqrt{g_L^2+g_Y^2} Z_\mu \left[\sum_{f\in u,d,e,\nu} \bar f \bar\sigma_\mu \delta g_L^{Zf} f + \sum_{f\in u,d,e} f^c \sigma_\mu \delta g_R^{Zf} \bar f^c\right].$$

- In general, contact interactions between Higgs, EW gauge boson, and 2 fermions may arise in D=6 EFT. They contribute e.g. h-> VV* -> 4fermion decays, changing differential distributions, or to qq -> VH, affecting energy dependence of x-section
- However, coefficients of these interactions are related to vertex corrections, many of which are strongly constrained by LEP

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

$$[\delta g_L^{We}]_{ii} = \begin{pmatrix} -1.00 \pm 0.64 \\ -1.36 \pm 0.59 \\ 1.95 \pm 0.79 \end{pmatrix} \times 10^{-2},$$

$$[\delta g_L^{Ze}]_{ii} = \begin{pmatrix} -0.26 \pm 0.28 \\ 0.1 \pm 1.1 \\ 0.16 \pm 0.58 \end{pmatrix} \times 10^{-3}, \quad [\delta g_R^{Ze}]_{ii} = \begin{pmatrix} -0.37 \pm 0.27 \\ 0.0 \pm 1.3 \\ 0.39 \pm 0.62 \end{pmatrix} \times 10^{-3},$$

$$[\delta g_L^{Zu}]_{ii} = \begin{pmatrix} -0.8 \pm 3.1 \\ -0.16 \pm 0.36 \\ -0.28 \pm 3.8 \end{pmatrix} \times 10^{-2}, \quad [\delta g_R^{Zu}]_{ii} = \begin{pmatrix} 1.3 \pm 5.1 \\ -0.38 \pm 0.51 \\ \times \end{pmatrix} \times 10^{-2},$$

$$[\delta g_L^{Zd}]_{ii} = \begin{pmatrix} -1.0 \pm 4.4 \\ 0.9 \pm 2.8 \\ 0.33 \pm 0.16 \end{pmatrix} \times 10^{-2}, \quad [\delta g_R^{Zd}]_{ii} = \begin{pmatrix} 2.9 \pm 16 \\ 3.5 \pm 5.0 \\ 2.30 \pm 0.82 \end{pmatrix} \times 10^{-2}.$$

Efrati,AA,Soreq
1503.07872

TGC - Higgs Synergy

TGC

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

Higgs

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

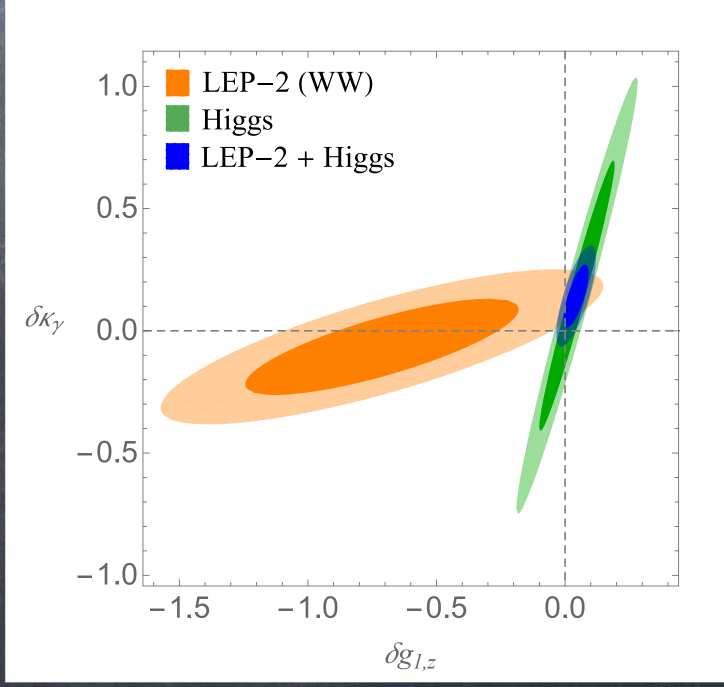
Linearly realized SU(3)xSU(2)xU(1) local symmetry in Lagrangian with operators up to D=6 implies that aTGC and Higgs couplings to EW gauge bosons are related:

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

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

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

- Therefore constraints on δg1z and δκγ imply constraints on Higgs couplings to electroweak gauge bosons, and vice-versa
- 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!



AA, Gonzalez-Alonso, Greljo, Marzocca 1508.00581

EFT validity

- EFT == effective theory, which implies it comes with cutoff Λ above which it is not valid as effective description of the UV theory
- Maximum possible cutoff is when Λmax is the energy where (associated) Higgs production amplitudes become non-unitary
- Typically, the EFT approach with will cease to be valid at energies when D=8 operators are no-longer negligible compared to D=6 ones
- This can happen anywhere between v and Λmax, depending on the coupling strength g* of the underlying BSM theory

$$\Lambda_{\mathrm{max}} \sim \frac{4\pi v}{\mathrm{Max}(\sqrt{|c_i|})}$$

$$\Lambda \sim \frac{g_* v}{\mathrm{Max}(\sqrt{|c_i|})}$$

Tree induced

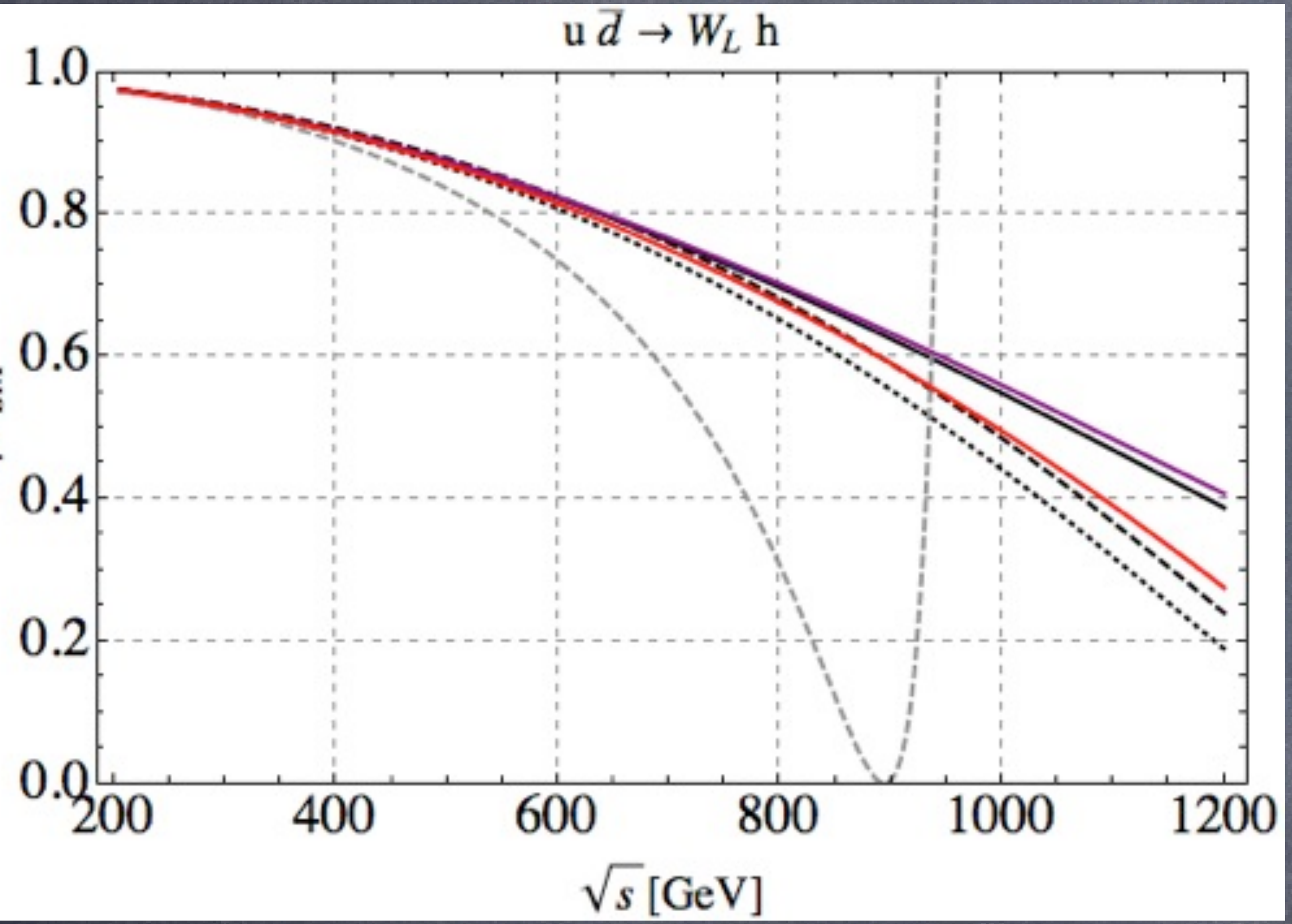
$$\Lambda \sim \frac{g_* v}{4\pi \mathrm{Max}(\sqrt{|c_i|})}$$

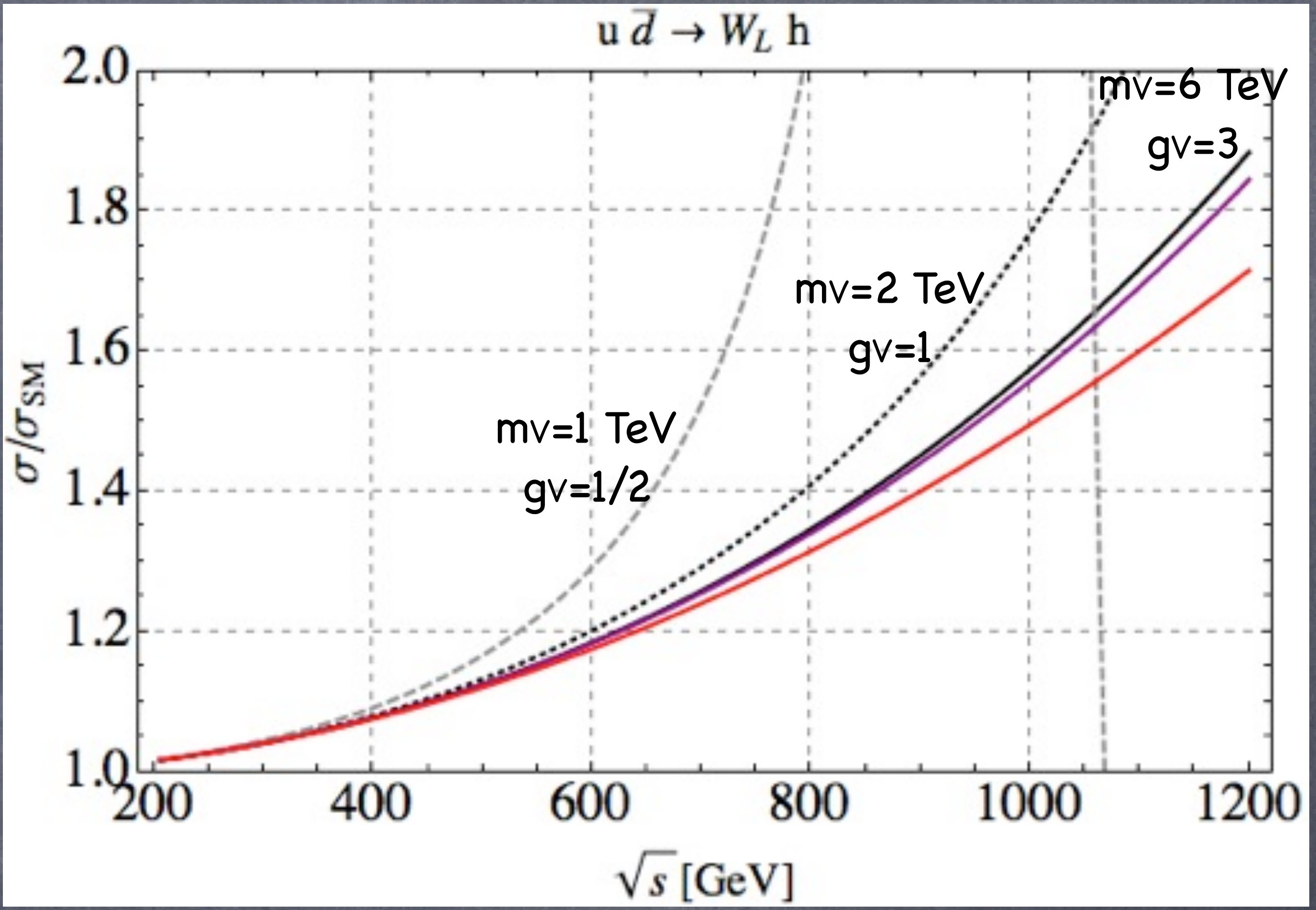
Loop induced

Lessons from WH production

See also Biekotter et al 1406.7320

Compare VH production calculated in:
- (Black): model with SU(2)L triplet of heavy vector resonances
- (Red): in corresponding D=6 EFT at O(1/Λ^2)
- (Purple): in corresponding D=6 EFT keeping also quadratic O(1/Λ^4) terms





Weak coupling:
- "Truth" well approximated by EFT for E<<Λ
- EFT starts to diverge for E~Λ/2,
due to D=8 operators becoming non-negligible
- departure point coincides with the one, where linear and quadratic D=6 approximation diverge from each other

Strong couplings
- For same Λ, smaller range where "Truth" well approximated by EFT
- Quickly NP >> SM at which point linear approximation is useless, but quadratic is still OK

Proposals for EFT at LHC

- The range of center-of-mass energies of partonic collisions used in the analysis should be restricted as E<Emax for several choices of Emax, and results should be quoted as function of Emax.

- Likelihood should be given for all relevant Higgs coupling simultaneously, together with the correlation matrix. This in particular will enable translating results between different bases.

- Analysis should be performed 1) consistently at $O(1/\Lambda^2)$ in the EFT expansion, and 2) keeping also the contribution quadratic in Wilson coefficients of D=6 operators, and the two results should be compared

IMO, this kind of presentation will allow theorists to use LHC Higgs constraints to probe a much larger class of BSM theories, and to consistently combine constraints from different types of experiments

Note: same formalism and very similar comments apply for other EFT applications e.g. for TGC studies at the LHC