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EFT Parametrization of Anomalous Couplings

CERN, 11 December 2015

LHC EWWG di-boson discussion on aGC for run-2

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

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

Cutoff scale of EFT

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

For D=6 Lagrangian several complete non-redundant set of operators (so-called basis) proposed in the literature

D=6 Bases

SILH basis — Giudice et al hep-ph/0703164, Contino et al 1303.3876

HISZ basis — Hagiwara et al (1993)

$$\mathcal{L}^{D=6}$$

Higgs basis — LHCHXSWG-INT-2015-001

Warsaw Basis — Grządkowski et al. 1008.4884

Primary basis — Gupta et al 1405.0181

arXiv:1508.05895

- All bases are equivalent, but some may be more ~~equivalent~~ convenient for specific applications
- Physics description (EWPT, Higgs, RG running) in any of these bases contains the same information, provided all operators contributing to that process are taken into account

EFT vs ATGC

Some (not all independent) D=6 operators that yield triple gauge interaction vertices:

$$
\begin{aligned}
O_{WB} &= g_L g_Y H^\dagger \sigma^i H \, W^i_{\mu\nu} B_{\mu\nu} \\
O_W &= \frac{i}{2} g_L \left(H^\dagger \sigma^i \overleftrightarrow{D}_\mu H \right) D_\nu W^i_{\mu\nu} \\
O_{HW} &= i g_L \left(D_\mu H^\dagger \sigma^i D_\nu H \right) W^i_{\mu\nu} \\
O_{HB} &= i g_Y \left(D_\mu H^\dagger D_\nu H \right) B_{\mu\nu} \\
O_{WW} &= g_L^2 H^\dagger H W^i_{\mu\nu} W^i_{\mu\nu} \\
O_{2W} &= D_\mu W^i_{\mu\nu} D_\rho W^i_{\rho\nu} \\
O_{3W} &= g_L^3 \epsilon^{ijk} W^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}
\end{aligned}
$$

- Several dimension-6 operators induce new contributions to triple gauge couplings of electroweak gauge bosons in the effective Lagrangian
- Thus, aTGCs are O(1/Λ^2) in the EFT expansion
- However, some care is needed to properly take into account their contribution to physical processes

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

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

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

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.

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

e.g.

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

Mass Eigenstate Lagrangian

LHCHXSWG-INT-2015-001

- EFT Lagrangian with D=6 operators can be recast in terms of 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

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

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

- 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: 2 more technical requirements concerning Higgs (self-)interactions

- 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

Effective Lagrangian: Z and W couplings to fermions

- By construction, photon and gluon couplings as in the SM. Only W and Z couplings are affected

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

- Effects of dimension-6 operators are parametrized by a 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

Yukawa

$[O_e]_{IJ}$	$-(H^\dagger H - \frac{v^2}{2})\frac{\sqrt{m_I m_J}}{v} e^c_I H^\dagger \ell_J$
$[O_u]_{IJ}$	$-(H^\dagger H - \frac{v^2}{2})\frac{\sqrt{m_I m_J}}{v} u^c_I \widetilde{H}^\dagger q_J$
$[O_d]_{IJ}$	$-(H^\dagger H - \frac{v^2}{2})\frac{\sqrt{m_I m_J}}{v} d^c_I H^\dagger q_J$

Vertex

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

Dipole

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

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

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

$$\delta v = ([c'_{H\ell}]_{11} + [c'_{H\ell}]_{22})/2 - [c_{\ell\ell}]_{1221}/4$$

$$f(T^3,Q) = I_3\left[-Qc_{WB}\frac{g^2 g'^2}{g^2-g'^2} + (c_T - \delta v)\left(T^3 + Q\frac{g'^2}{g^2-g'^2}\right)\right],$$

$$\delta m = \frac{1}{g^2-g'^2}\left[-g^2 g'^2 c_{WB} + g^2 c_T - g'^2 \delta v\right]$$

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

Basis-independent
relations between vertex corrections

TGCs in mass eigenstate Lagrangian

After necessary redefinitions are done, CP-even TGCs take the usual form

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

ATGCs related to Wilson coefficients of D=6 operators in Warsaw and SILH basis by

$$
\begin{aligned}
\delta g_{1,z} =& \frac{g_L^2+g_Y^2}{g_L^2-g_Y^2}\left(-g_Y^2 c_{WB} - \frac{g_L^2-g_Y^2}{4}c_{HW} - \frac{g_L^2}{4}(c_W+c_{2W})\right. \\
&\left. + c_T - \frac{g_Y^2}{4}(c_B+c_{2B}) - \frac{1}{2}[c'_{H\ell}]_{11} - \frac{1}{2}[c'_{H\ell}]_{22} + \frac{1}{4}[c_{\ell\ell}]_{1221}\right)\frac{v^2}{\Lambda^2} \\
\delta\kappa_\gamma =& \frac{g_L^2}{4}\left(4c_{WB} - c_{HW} - c_{HB}\right)\frac{v^2}{\Lambda^2} \\
\lambda_z =& -\frac{3}{2}g_L^4 c_{3W}\frac{v^2}{\Lambda^2}
\end{aligned}
$$

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

← Basis-independent relations between aTGCs

Note that 2nd line in δg1z are contributions from 4-fermion, vertex, Higgs, and 4-derivative gauge operators. They enter indirectly via the rescaling necessary to arrive at the phenomenological effective Lagrangian !

e.g.

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

TGCs and Higgs synergy

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

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

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

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

There are basis-independent relations between ATGC and parameters
describing Higgs couplings to electroweak gauge bosons:

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

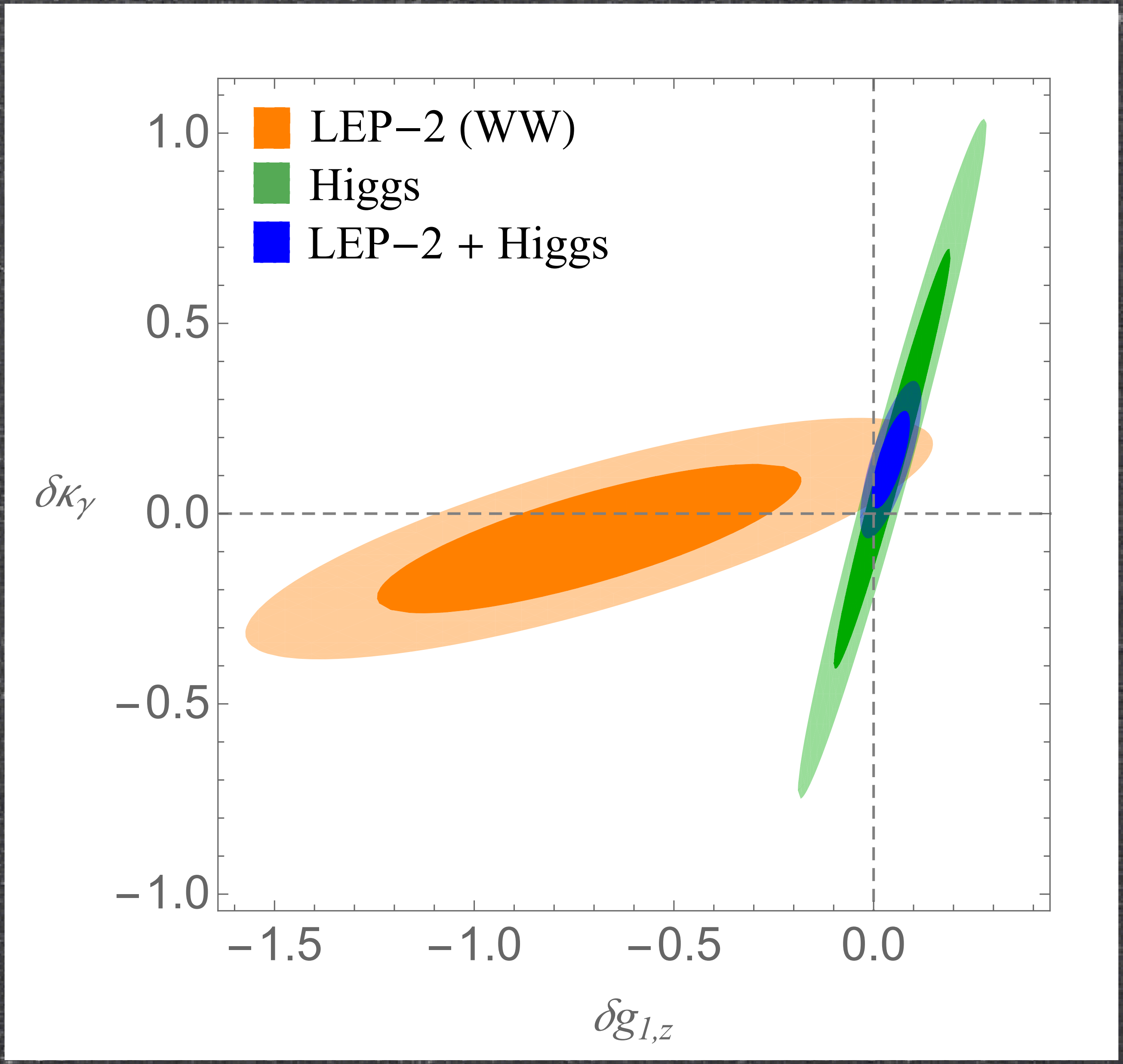
$$\delta\kappa_\gamma = -\frac{g_L^2}{2}\left(c_{\gamma\gamma}\frac{e^2}{g_L^2 + g_Y^2} + c_{z\gamma}\frac{g_L^2 - g_Y^2}{g_L^2 + g_Y^2} - c_{zz}\right),$$

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

TGC – Higgs Synergy

Previous combinations of Higgs and TGC

Corbett et al 1304.1151
Dumont et al 1304.3369
Pomarol Riva 1308.2803
Masso 1406.6377
Ellis et al 1410.7703



Our work

AA, Gonzalez-Alonso, Greljo, Marzocca 1508.00581

Consistent EFT analysis at O(1/Λ^2)

$$\begin{pmatrix} \delta g_{1,z} \\ \delta\kappa_\gamma \\ \lambda_z \end{pmatrix} = \begin{pmatrix} 0.037 \pm 0.041 \\ 0.133 \pm 0.087 \\ -0.152 \pm 0.080 \end{pmatrix},$$

$$\rho = \begin{pmatrix} 1 & 0.62 & -0.84 \\ 0.62 & 1 & -0.85 \\ -0.84 & -0.85 & 1 \end{pmatrix}$$

- LHC Higgs and LEP-2 WW data by itself do not constrain TGCs robustly due to each suffering from 1 flat direction in space of 3 TGCs
- However, the flat directions are orthogonal and combined constraints lead to robust O(0.1) limits on aTGCs

Quartic gauge couplings

- In D=6 EFT, quartic gauge couplings involving W bosons receive corrections from the SM

- QGC coefficients can be expressed by TGC ones

$$
\begin{aligned}
\mathcal{L}_{\rm qgc} &= e^2\left(W^+_\mu A_\mu W^-_\nu A_\nu - W^+_\mu W^-_\mu A_\nu A_\nu\right) \\
&+ (1+\delta g_{1,z})\frac{g_L^2}{2}\left(W^+_\mu W^+_\mu W^-_\nu W^-_\nu - W^+_\mu W^-_\mu W^+_\nu W^-_\nu\right) \\
&+ (1+\delta g_{1,z})\, g_L^2 c_\theta^2\left(W^+_\mu Z_\mu W^-_\nu Z_\nu - W^+_\mu W^-_\mu Z_\nu Z_\nu\right) \\
&+ (1+\delta g_{1,z})\, e g_L c_\theta\left(W^+_\mu Z_\mu W^-_\nu A_\nu + W^+_\mu A_\mu W^-_\nu Z_\nu - 2W^+_\mu W^-_\mu Z_\nu A_\nu\right) \\
&- \frac{g_L^2}{2}\frac{\lambda_z}{m_W^2}\left(W^+_{\mu\nu}W^-_{\nu\rho} - W^-_{\mu\nu}W^+_{\nu\rho}\right)\left(W^+_\mu W^-_\rho - W^-_\mu W^+_\rho\right) \\
&- g_L^2 c_\theta^2\frac{\lambda_z}{m_W^2}\left[W^+_\mu\left(Z_{\mu\nu}W^-_{\nu\rho} - W^-_{\mu\nu}Z_{\nu\rho}\right)Z_\rho + W^-_\mu\left(Z_{\mu\nu}W^+_{\nu\rho} - W^+_{\mu\nu}Z_{\nu\rho}\right)Z_\rho\right] \\
&- e^2\frac{\lambda_z}{m_W^2}\left[W^+_\mu\left(A_{\mu\nu}W^-_{\nu\rho} - W^-_{\mu\nu}A_{\nu\rho}\right)A_\rho + W^-_\mu\left(A_{\mu\nu}W^+_{\nu\rho} - W^+_{\mu\nu}A_{\nu\rho}\right)A_\rho\right] \\
&- e g_L c_\theta\frac{\lambda_z}{m_W^2}\left[W^+_\mu\left(A_{\mu\nu}W^-_{\nu\rho} - W^-_{\mu\nu}A_{\nu\rho}\right)Z_\rho + W^-_\mu\left(A_{\mu\nu}W^+_{\nu\rho} - W^+_{\mu\nu}A_{\nu\rho}\right)Z_\rho\right] \\
&- e g_L c_\theta\frac{\lambda_z}{m_W^2}\left[W^+_\mu\left(Z_{\mu\nu}W^-_{\nu\rho} - W^-_{\mu\nu}Z_{\nu\rho}\right)A_\rho + W^-_\mu\left(Z_{\mu\nu}W^+_{\nu\rho} - W^+_{\mu\nu}Z_{\nu\rho}\right)A_\rho\right]
\end{aligned}
$$

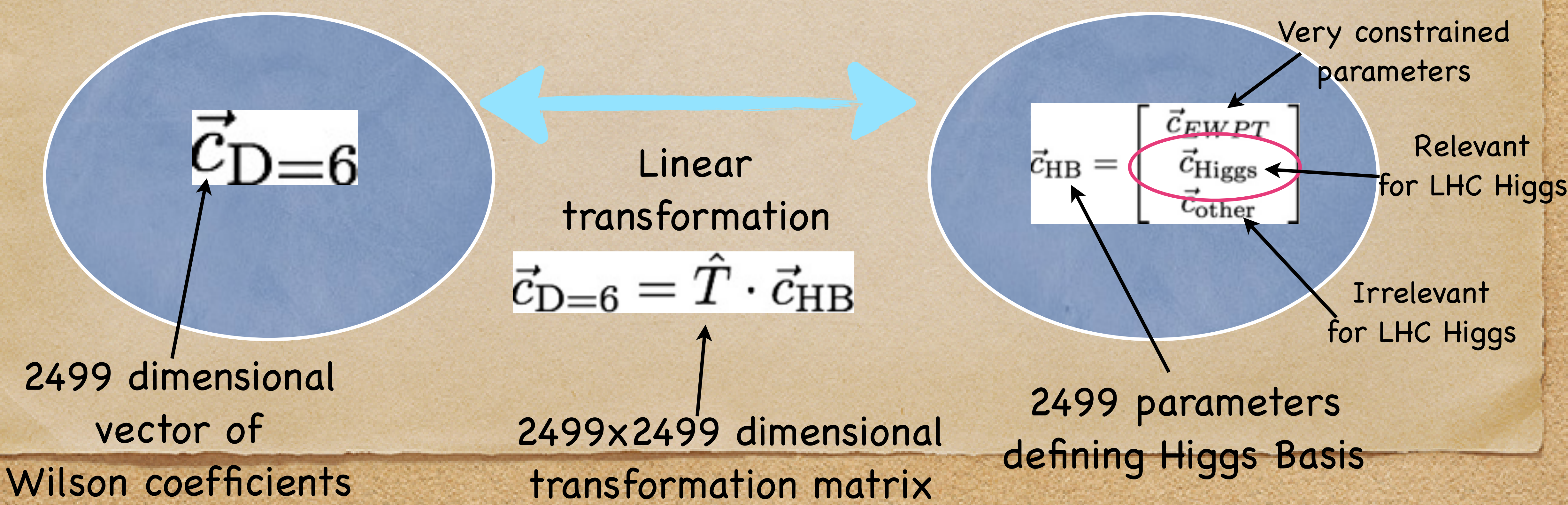
In EFT with only D=6 operators, triple and quartic gauge couplings with only neutral gauge bosons (like ZZZ or ZZAA) do not arise

Similar “EFT Primaries” of Gupta et al 1405.0181

LHCHXSWG-INT-2015-001

Higgs Basis

- Connection between operators and observables a bit obscured in Warsaw or SILH basis. Also, EW precision measurements place constraints on complicated linear combinations of Wilson coefficients.
- For some applications, it may be simpler to work with couplings of mass eigenstate rather than Wilson coefficients of D=6 operators
- Higgs basis proposed by LHCHXSWG2 uses subset of couplings in mass eigenstate Lagrangian to span D=6 basis. Effectively, a rotation of any other D=6 basis



Higgs Basis - parameters

Instead of Wilson coefficients in some basis, use directly a subset of eigenstates couplings to parametrize the D=6 EFT space

Higgs couplings to gauge bosons

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

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

Higgs couplings to fermions

CP even : $\delta y_u \quad \delta y_d \quad \delta y_e$

CP odd : $\phi_u \quad \phi_d \quad \phi_e$

Triple gauge couplings

CP – even : λ_z

CP – odd : $\tilde{\lambda}_z$

Vertex and mass Corrections

$$\delta m,$$
$$\delta g_L^{Ze},\ \delta g_R^{Ze},\ \delta g_L^{W\ell},$$
$$\delta g_L^{Zu},\ \delta g_R^{Zu},\ \delta g_L^{Zd},\ \delta g_R^{Zd},\ \delta g_R^{Wq}$$

....

Equivalent D=6 basis with TGC as parameters

One can use relations between TGCs and Higgs couplings
to trade 3 Higgs couplings for 3 TGCs in basis definition

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

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

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

Higgs couplings to gauge bosons

CP even : δc_z [redacted] $c_{z\gamma}$ $c_{\gamma\gamma}$ c_{gg}

CP odd : [redacted] $\tilde c_{z\gamma}$ $\tilde c_{\gamma\gamma}$ $\tilde c_{gg}$

Higgs couplings to fermions

CP even : δy_u δy_d δy_e

CP odd : ϕ_u ϕ_d ϕ_e

Triple gauge couplings

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

$\mathrm{CP-odd}: \quad \delta\tilde\kappa_\gamma,\ \tilde\lambda_z$

Vertex and mass Corrections

$$\delta m,$$
$$\delta g_L^{Ze},\ \delta g_R^{Ze},\ \delta g_L^{W\ell},$$
$$\delta g_L^{Zu},\ \delta g_R^{Zu},\ \delta g_L^{Zd},\ \delta g_R^{Zd},\ \delta g_R^{Wq}$$

....

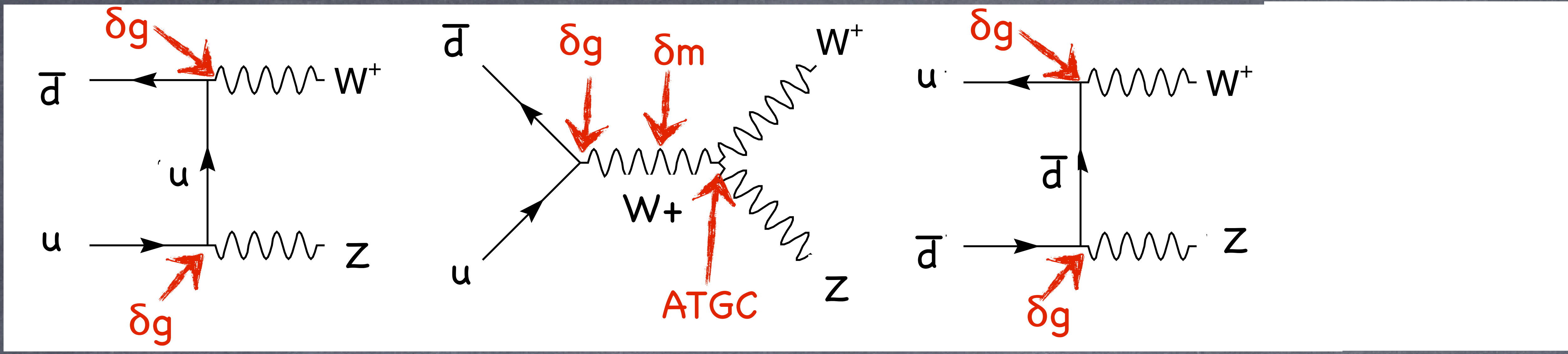
Many equivalent parametrizations exist.
What stays unchanged is 1) physics, 2) number of parameters

TGC - Physical significance

Low-energy perspective

- ATGCs affect WW production. In particular, they change energy dependence of s-channel amplitudes and spoil unitarity cancellations, thus leading to amplitudes growing with energy
- Note that similar effects are induced by vertex corrections δg
- Different helicity amplitudes are affected by different combinations of aTGCs, therefore exploring s- and θ- dependence of WW production allows one, in principle, to simultaneously constrain all 3 CP-even ATGCs
- Leading $O(1/\Lambda^2)$ (tree-level D=6 in EFT) corrections to total and differential partonic production cross section can be computed analytically

WZ production in LHC



ATGC and vertex corrections lead to WZ production amplitudes growing with energy for s > mZ^2

$$\mathcal{M}(0,0) \approx \sin\theta \frac{g_L\sqrt{g_L^2+g_Y^2}}{2\sqrt{2}m_W m_Z}\left[c_\theta^2 \delta g_{1,z} + \delta g_L^{Wq}\right] s$$

$$\mathcal{M}(\pm1,\mp1) \approx -\sin\theta \frac{c_\theta g_L^2}{2\sqrt{2}m_W^2}\left[\lambda_z \mp i\tilde{\lambda}_z\right] s$$

$$\mathcal{M}(\pm1,0) \approx (\mp1+\cos\theta)\frac{g_L\sqrt{g_L^2+g_Y^2}}{4m_W}\left[c_\theta^2\left(2\delta g_{1,z}+\lambda_z \pm i\tilde{\lambda}_z\right) - s_\theta^2(\delta\kappa_\gamma \pm i\tilde{\kappa}_\gamma) + 2\delta g_L^{Wq}\right]\sqrt{s}$$

$$\mathcal{M}(0,\pm1) \approx (\mp1+\cos\theta)\frac{g_L\sqrt{g_L^2+g_Y^2}}{4m_Z}\left[2c_\theta^2\delta g_{1,z}+\lambda_z \pm i\tilde{\lambda}_z + 2\delta g_L^{Wq}\right]\sqrt{s}$$

scattering angle

cosinus of weak mixing angle

Note that both longitudinal and transverse amplitudes may be fast growing!

TGC - Physical significance

High-energy perspective

- ATGCs and δg arise as effective description of effects of heavy particles from beyond the SM
- δg and g_{1z} can arise from tree-level new physics effects, e.g. from integrating out vector resonances mixing with W and/or Z bosons
- $\delta\kappa_\gamma$ and λ_z arise only at 1-loop level; note however that models where δg and g_{1z} arise at tree-level are typically strongly constrained by EWPT, so I personally see no strong motivation to ignore $\delta\kappa_\gamma$ and λ_z for this reason

Example BSM Model #1: SU(2)L triplet vector

Here, coupled do quarks only

$$\Delta\mathcal{L} = -\frac{1}{4}V^i_{\mu\nu}V^i_{\mu\nu} + \frac{m_V^2}{2}V^i_\mu V^i_\mu + \frac{i}{2}g_L\kappa_H V^i_\mu H^\dagger\sigma^i\overleftrightarrow{D}_\mu H + \frac{g_L}{2}V^i_\mu \kappa_{q,J}\bar{f}_J\sigma^i\bar{\sigma}_\mu f_J + \ldots$$

Low Energy EFT Lagrangian:

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} - \frac{g_L^2}{8m_V^2}\left(i\kappa_H H^\dagger\sigma^i\overleftrightarrow{D}_\mu H + \kappa^{q,J}\bar{q}_J\sigma^i\bar{\sigma}_\mu q_J\right)^2 + \mathcal{O}(m_V^{-4})$$

$$\delta c_w = \delta c_z = -\frac{3g_L^2v^2}{8m_V^2}\kappa_H^2$$

$$\delta y_f = -\frac{g_L^2v^2}{8m_V^2}\kappa_H^2$$

$$[\delta g_L^{Zu}]_{JJ} = -[\delta g_L^{Zd}]_{JJ} = -\frac{g_L^2v^2}{8m_V^2}\kappa_H\kappa_{q,J}$$

$$[\delta g_L^{Wq}]_{JJ} = -\frac{g_L^2v^2}{4m_V^2}\kappa_H\kappa_{q,J}$$

EWPT constraints:

$$-1.3\times10^{-3} < \delta g_L^{Wq} < 2.2\times10^{-3}$$ (1st generation quark couplings only)

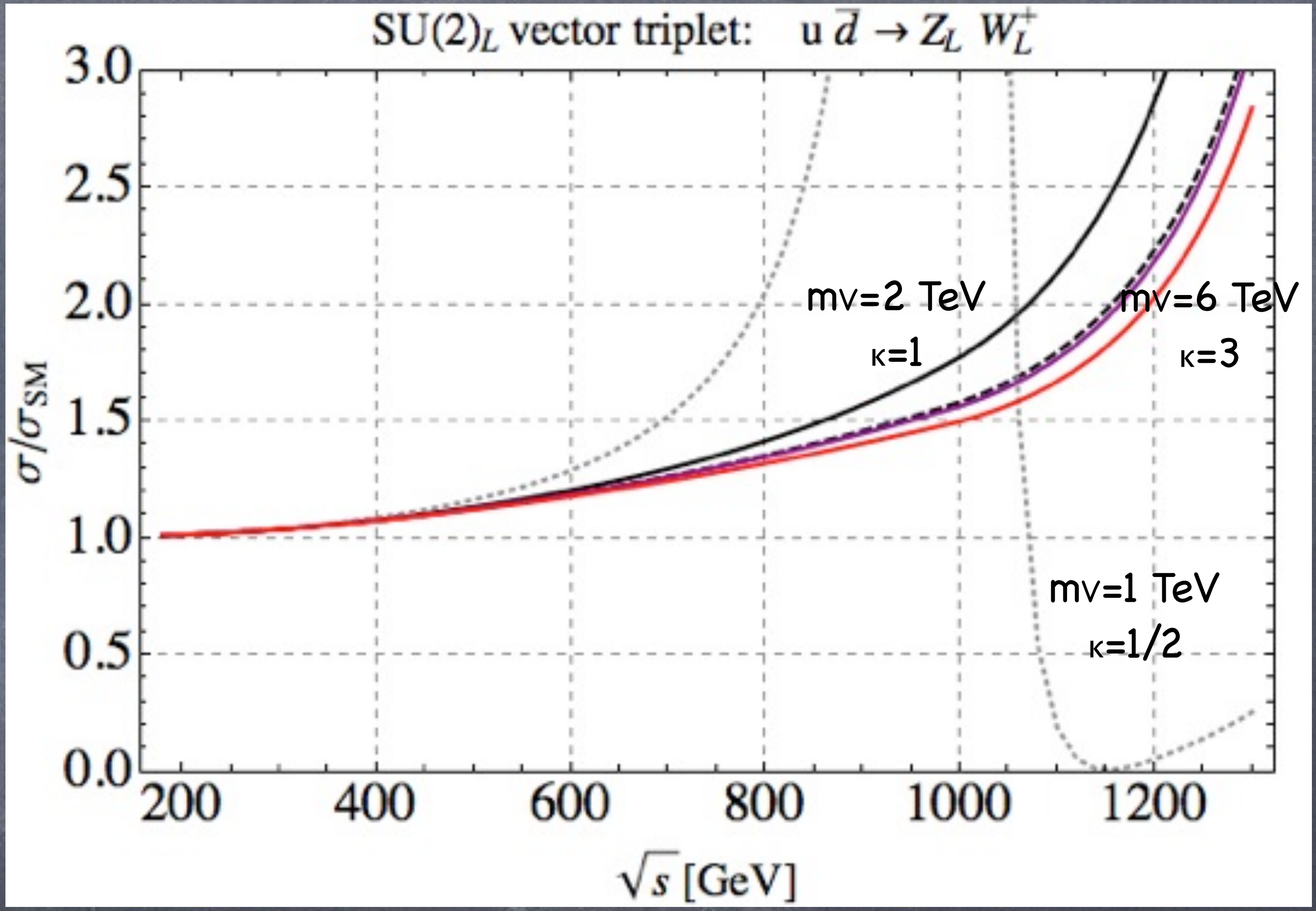
$$-1.0\times10^{-3} < \delta g_L^{Wq} < 0.5\times10^{-3}$$ (flavor universal quark couplings)

BSM vs EFT description of WZ production

Compare WZ 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

All 3 benchmark points correspond to same EFT with

$$\delta g_L^{Wq} = 1.6 \times 10^{-3}$$



Weak coupling:
- "Truth" well approximated by EFT for E<<Λ
- EFT starts to diverge for E approaching Λ, due to D=8 operators becoming non-negligible

Strong couplings
- For same Λ, larger range where "Truth" well approximated by EFT
- When NP >> SM linear approximation is useless, but quadratic is still OK

Example 2: SU(2)xU(1) model with only TGC

$$
\begin{aligned}
\Delta\mathcal{L} &= -\frac{1}{4}V^i_{\mu\nu}V^i_{\mu\nu} - \frac{1}{4}V^0_{\mu\nu}V^0_{\mu\nu} + \frac{m_V^2}{2}V^i_\mu V^i_\mu + \frac{m_V^2}{2}V^0_\mu V^0_\mu \\
&- \frac{i}{2}g_L\kappa_H V^0_\mu H^\dagger \overleftrightarrow{D_\mu} H + g_L V^0_\mu \sum_{f\in\ell,q}\kappa_f Y_f \bar{f}\bar{\sigma}_\mu f + g_L V^0_\mu \sum_{f\in e,u,d}\kappa_f Y_{\bar{f}^c} f^c\sigma_\mu \bar{f}^c \\
&+ \frac{i}{2}g_L\kappa'_H V^i_\mu H^\dagger\sigma^i \overleftrightarrow{D_\mu} H + \frac{g_L}{2}V^i_\mu \sum_{f\in\ell,q}\kappa'_f \bar{f}\sigma^i\bar{\sigma}_\mu f,
\end{aligned}
$$

$$
\begin{aligned}
\kappa'_f &= -\frac{g_L^2}{2g_Y^2}\frac{\kappa_H^2}{\kappa'_H}, \qquad f = \ell, q \\
\kappa_f &= -\frac{\kappa_H}{2}, \qquad f = \ell, q, e, u, d
\end{aligned}
$$

$$
\begin{aligned}
V^i_{\mu\nu} &= D_\mu V^i_\nu - D_\nu V^i_\mu, \qquad D_\mu V^i_\nu = \partial_\mu V^i_\nu + g_L\epsilon^{ijk}W^j_\mu V^k_\nu, \\
H^\dagger\sigma^i\overleftrightarrow{D_\mu} H &= H^\dagger\sigma^i D_\mu H - D_\mu H^\dagger\sigma^i H, \\
H^\dagger\overleftrightarrow{D_\mu} H &= H^\dagger D_\mu H - D_\mu H^\dagger H.
\end{aligned}
$$

+ fine-tuned contribution to GF
Tunings cancel *all* vertex
and W mass corrections

Low Energy EFT:

$$
\delta g_{1,z} = -\kappa_H^2 \frac{g_L^2 + g_Y^2}{2g_Y^2}\frac{m_W^2}{m_V^2}
$$

$$
\begin{aligned}
\delta c_w = \delta c_z &= -\frac{3(g_L^2\kappa_H^2 + g_Y^2\kappa_H'^2)}{2g_Y^2}\frac{m_W^2}{m_V^2} \\
\delta y_f &= -\frac{g_L^2\kappa_H^2 + g_Y^2\kappa_H'^2}{2g_Y^2}\frac{m_W^2}{m_V^2} \\
c_{w\Box} &= \frac{\kappa_H^2}{g_Y^2}\frac{m_W^2}{m_V^2} \\
c_{z\Box} &= \kappa_H^2\frac{g_L^2 - g_Y^2}{g_L^2 g_Y^2}\frac{m_W^2}{m_V^2} \\
c_{\gamma\Box} &= \frac{2\kappa_H^2}{g_Y^2}\frac{m_W^2}{m_V^2}
\end{aligned}
$$

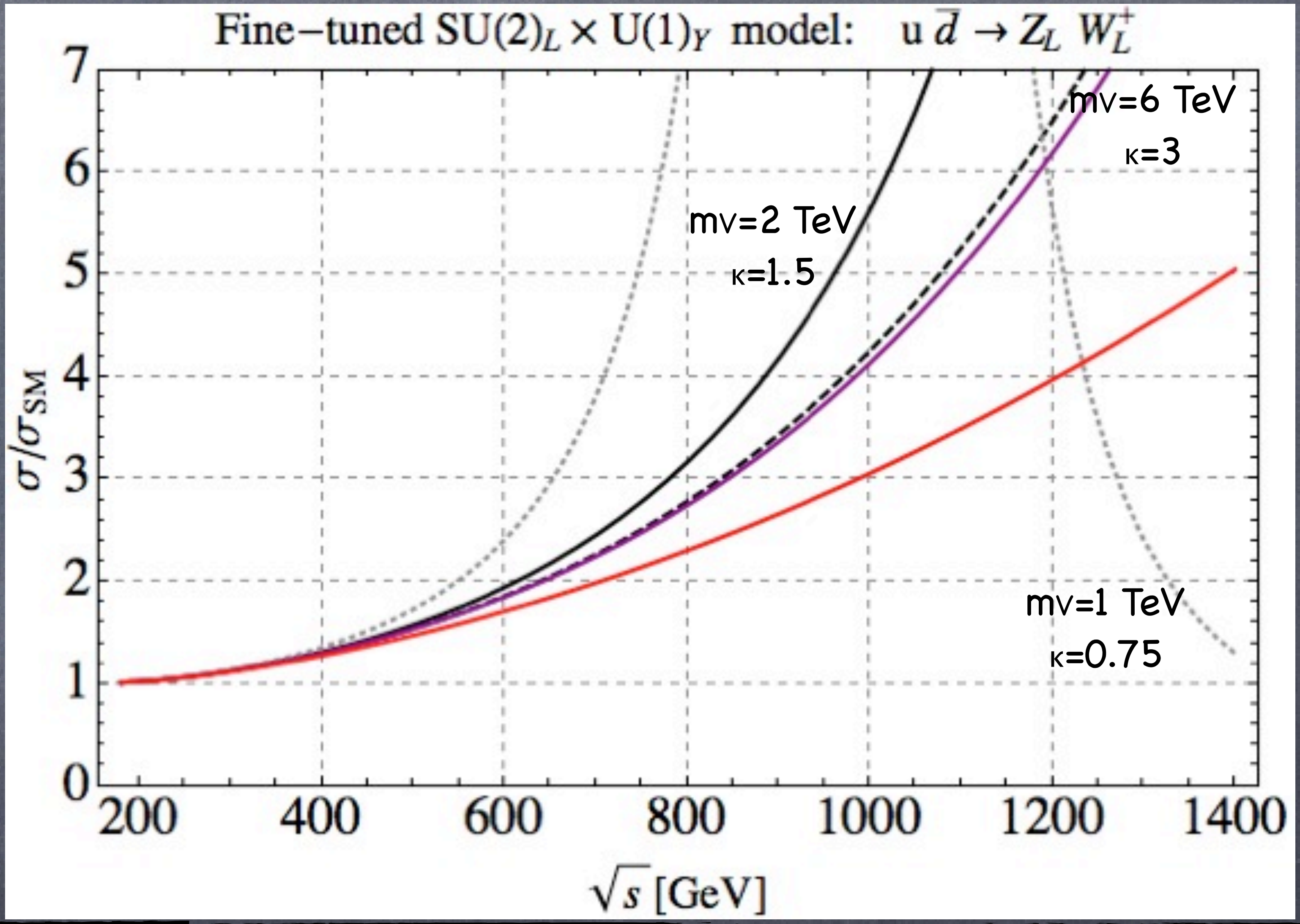
WZ production in SU(2)xU(1) model

Compare WZ production calculated in:

- (Black): model with SU(2)LxU(1)Y triplet and singlet 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

All 3 benchmark points correspond to same EFT with

$$\delta g_{1,z} = -0.009$$



Weak coupling:

- "Truth" well approximated by EFT for E<<Λ
- EFT starts to diverge for E approaching Λ, due to D=8 operators becoming non-negligible

Strong couplings

- For same Λ, larger range where "Truth" well approximated by EFT
- When NP >> SM linear approximation is useless, but quadratic is still OK

Conclusions for TGC at LHC

Any parametrization is good (ATGC, D=6 HISZ operators, D=6 SILH operators), as long as *all* D=6 operators contributing to diboson production are taken into account. This means number of parameters probed may vary for different bases, but number of probed *linear combinations* of parameters is always the same

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

- Likelihood should be given for all 3 aTGCs simultaneously, together with the correlation matrix. In the best of all worlds, 5D likelihood for 3ATGC and 2 light quark vertex corrections

- 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

This kind of presentation will allow theorists to use TGC constraints from LHC to probe much larger class of BSM models, and to consistently combine TGC and Higgs constraints

Back-up

Example: Warsaw Basis

Grządkowski et al. 1008.4884

59 different kinds of operators, of which 17 are complex

2499 distinct operators, including flavor structure and CP conjugates

Alonso et al 1312.2014

Bosonic CP-even		Bosonic CP-odd	
O_H	$\left[\partial_\mu (H^\dagger H)\right]^2$		
O_T	$\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$		
O_{6H}	$\lambda (H^\dagger H)^3$		
O_{GG}	$H^\dagger H\, G^a_{\mu\nu} G^a_{\mu\nu}$	$O_{\widetilde{GG}}$	$H^\dagger H\, \widetilde{G}^a_{\mu\nu} G^a_{\mu\nu}$
O_{WW}	$H^\dagger H\, W^i_{\mu\nu} W^i_{\mu\nu}$	$O_{\widetilde{WW}}$	$H^\dagger H\, \widetilde{W}^i_{\mu\nu} W^i_{\mu\nu}$
O_{BB}	$H^\dagger H\, B_{\mu\nu} B_{\mu\nu}$	$O_{\widetilde{BB}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B_{\mu\nu}$
O_{WB}	$H^\dagger \sigma^i H\, W^i_{\mu\nu} B_{\mu\nu}$	$O_{\widetilde{WB}}$	$H^\dagger \sigma^i H\, \widetilde{W}^i_{\mu\nu} B_{\mu\nu}$
O_{3W}	$\epsilon^{ijk} W^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$	$O_{\widetilde{3W}}$	$\epsilon^{ijk} \widetilde{W}^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$
O_{3G}	$f^{abc} G^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$	$O_{\widetilde{3G}}$	$f^{abc} \widetilde{G}^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$

Yukawa	
$[O_e]_{IJ}$	$-(H^\dagger H - \frac{v^2}{2}) \frac{\sqrt{m_I m_J}}{v} e^c_I H^\dagger \ell_J$
$[O_u]_{IJ}$	$-(H^\dagger H - \frac{v^2}{2}) \frac{\sqrt{m_I m_J}}{v} u^c_I \widetilde{H}^\dagger q_J$
$[O_d]_{IJ}$	$-(H^\dagger H - \frac{v^2}{2}) \frac{\sqrt{m_I m_J}}{v} d^c_I H^\dagger q_J$

+4 fermion operators

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

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

Example: SILH Basis

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

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

Bosonic CP-even		Bosonic CP-odd	
O_H	$\left[\partial_\mu (H^\dagger H)\right]^2$		
O_T	$\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$		
O_{6H}	$(H^\dagger H)^3$		
O_{GG}	$H^\dagger H\, G^a_{\mu\nu} G^a_{\mu\nu}$	$O_{\widetilde{GG}}$	$H^\dagger H\, \widetilde{G}^a_{\mu\nu} G^a_{\mu\nu}$
O_{BB}	$H^\dagger H\, B_{\mu\nu} B_{\mu\nu}$	$O_{\widetilde{BB}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B_{\mu\nu}$
O_W	$\frac{i}{2}\left(H^\dagger \sigma^i \overleftrightarrow{D}_\mu H\right) D_\nu W^i_{\mu\nu}$		
O_B	$\frac{i}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right) \partial_\nu B_{\mu\nu}$		
O_{HW}	$i\left(D_\mu H^\dagger \sigma^i D_\nu H\right) W^i_{\mu\nu}$	$O_{H\widetilde{W}}$	$i\left(D_\mu H^\dagger \sigma^i D_\nu H\right) \widetilde{W}^i_{\mu\nu}$
O_{HB}	$i\left(D_\mu H^\dagger D_\nu H\right) B_{\mu\nu}$	$O_{H\widetilde{B}}$	$i\left(D_\mu H^\dagger D_\nu H\right) \widetilde{B}_{\mu\nu}$
O_{2W}	$\frac{1}{g_L^2} D_\mu W^i_{\mu\nu} D_\rho W^i_{\rho\nu}$		
O_{2B}	$\frac{1}{g_Y^2} \partial_\mu B_{\mu\nu} \partial_\rho B_{\rho\nu}$		
O_{2G}	$\frac{1}{g_s^2} D_\mu G^a_{\mu\nu} D_\rho G^a_{\rho\nu}$		
O_{3W}	$\epsilon^{ijk} W^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$	$O_{3\widetilde{W}}$	$\epsilon^{ijk} \widetilde{W}^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$
O_{3G}	$f^{abc} G^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$	$O_{3\widetilde{G}}$	$f^{abc} \widetilde{G}^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$

Yukawa	
$[O_e]_{IJ}$	$-(H^\dagger H - \frac{v^2}{2})\frac{\sqrt{m_I m_J}}{v} e^c_I H^\dagger \ell_J$
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$[O'_{Hq}]_{IJ}$	$i\bar{q}_I \sigma^i \bar{\sigma}_\mu q_J H^\dagger \sigma^i \overleftrightarrow{D}_\mu H$
$[O_{Hu}]_{IJ}$	$iu^c_I \sigma_\mu \bar{u}^c_J H^\dagger \overleftrightarrow{D}_\mu H$
$[O_{Hd}]_{IJ}$	$id^c_I \sigma_\mu \bar{d}^c_J H^\dagger \overleftrightarrow{D}_\mu H$
$[O_{Hud}]_{IJ}$	$iu^c_I \sigma_\mu \bar{d}^c_J \widetilde{H}^\dagger D_\mu H$

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

+4 fermion operators

Constraints on vertex corrections

Efrati,AA,Soreq
1503.07872

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

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

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

$$\delta m = (2.6 \pm 1.9) \cdot 10^{-4}. \qquad [\delta g_L^{Zd}]_{ii} = \begin{pmatrix} -1.0 \pm 4.4 \\ 0.9 \pm 2.8 \\ 0.33 \pm 0.16 \end{pmatrix} \times 10^{-2}, \quad [\delta g_R^{Zd}]_{ii} = \begin{pmatrix} 2.9 \pm 16 \\ 3.5 \pm 5.0 \\ 2.30 \pm 0.82 \end{pmatrix} \times 10^{-2}.$$

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

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

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

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

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

- D=6 EFT with linearly realized SU(3)xSU(2)xU(1) enforces relations between Higgs couplings to gauge bosons (otherwise, more parameters)

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

relative correction to W mass

- 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

LHCHXSWG-INT-2015-001

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

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

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