From D=6 operators
to collider observables

Operators to Observables

- Lagrangian is fully defined, so in principle it is trivial to find mass eigenstates, calculate vertices, and study phenomenology
- In practice, at the level of D=6 Lagrangian some subtleties appear that require some effort to properly take into account

Operators to Observables

Difficulties in the presence of D=6 operators

- Affect relations between couplings and input observables
- 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.

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

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

e.g.

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

Phenomenological effective Lagrangian

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- 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

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

Phenomenological effective Lagrangian

Problem

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

Fix

$$g_L \to g_L \left(1 + c_T \frac{g_L^2}{g_L^2 - g_Y^2}\right)$$
$$g_Y \to g_Y \left(1 - c_T \frac{g_Y^2}{g_L^2 - g_Y^2}\right)$$

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

$$D_\nu W^i_{\mu\nu} = \frac{i g_L}{2} H^\dagger \sigma^i \overleftrightarrow{D}_\mu H + \frac{g_L}{2} \sum_{f \in \ell, q} \bar{f} \sigma^i \bar{\sigma}_\mu f$$

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

$$-c_{WB} \frac{g_L g_Y}{2} W^3_{\mu\nu} B_{\mu\nu}$$
$$\to c_{WB} e^2 \left[\frac{(v+h)^2}{4} \left(g_L W^3_\mu - g_Y B_\mu\right)^2 - g_L W^3_\mu j^Y_\mu - g_Y B_\mu j^3_\mu \right.$$
$$\left. - \frac{g_L^2}{2 g_Y} \epsilon^{3jk} W^j_\mu W^k_\nu B_{\mu\nu} - g_Y \epsilon^{3jk} B_\mu W^j_\nu W^k_{\nu\mu} \right]$$

Phenomenological effective Lagrangian

- Once Lagrangian is brought to the form of phenomenological effective Lagrangian, studying collider effects becomes straightforward
- In the following focus on 2 aspect: electroweak precision observables in LEP-1, and LHC Higgs observables
- Any other process can be studied along the same lines

Z and W couplings to fermions

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

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

- Effects of dimension-6 operators are parametrized by a set of vertex corrections

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

Vertex corrections are probed by precision measurements at LEP and other colliders
Correction to W boson mass are also probed very precisely
Other precision measurements constraint 4-fermion and dipole operators that are also affected at the level of the D=6 EFT Lagrangian (not discussed here)

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

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

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

Dipole

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

Table 3: Two-fermion d=6 operators in the Warsaw basis. Here, I, J are the flavor indices. For complex operators the complex conjugate operator is implicit.

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

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

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

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

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

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

- Observation: vertex correction obtained from Warsaw basis are not independent. Corrections to W vertices are determined by corrections to Z vertices

Higgs couplings to matter

Effects of D=6 operators:

- 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

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

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

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Higgs couplings to matter

Map from Warsaw basis

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}	$g_s^2 H^\dagger H\, G^a_{\mu\nu} G^a_{\mu\nu}$	$O_{\widetilde{GG}}$	$g_s^2 H^\dagger H\, \widetilde{G}^a_{\mu\nu} G^a_{\mu\nu}$
O_{WW}	$g_L^2 H^\dagger H\, W^i_{\mu\nu} W^i_{\mu\nu}$	$O_{\widetilde{WW}}$	$g_L^2 H^\dagger H\, \widetilde{W}^i_{\mu\nu} W^i_{\mu\nu}$
O_{BB}	$g_Y^2 H^\dagger H\, B_{\mu\nu} B_{\mu\nu}$	$O_{\widetilde{BB}}$	$g_Y^2 H^\dagger H\, \widetilde{B}_{\mu\nu} B_{\mu\nu}$
O_{WB}	$g_L g_Y H^\dagger \sigma^i H\, W^i_{\mu\nu} B_{\mu\nu}$	$O_{\widetilde{WB}}$	$g_L g_Y H^\dagger \sigma^i H\, \widetilde{W}^i_{\mu\nu} B_{\mu\nu}$
O_{3W}	$g_L^3 \epsilon^{ijk} W^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$	$O_{\widetilde{3W}}$	$g_L^3 \epsilon^{ijk} \widetilde{W}^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$
O_{3G}	$g_s^3 f^{abc} G^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$	$O_{\widetilde{3G}}$	$g_s^3 f^{abc} \widetilde{G}^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$

Table 2: Bosonic $d = 6$ operators in the Warsaw basis.

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		Dipole	
$[O_{H\ell}]_{IJ}$	$i\bar{\ell}_I \bar{\sigma}_\mu \ell H^\dagger \overleftrightarrow{D}_\mu H$	$[O_{eW}]_{IJ}$	$g_L \frac{\sqrt{m_I m_J}}{v} e^c_I \sigma_{\mu\nu} H^\dagger \sigma^i \ell_J W^i_{\mu\nu}$
$[O'_{H\ell}]_{IJ}$	$i\bar{\ell}_I \sigma^i \bar{\sigma}_\mu \ell H^\dagger \sigma^i \overleftrightarrow{D}_\mu H$	$[O_{eB}]_{IJ}$	$g_Y \frac{\sqrt{m_I m_J}}{v} e^c_I \sigma_{\mu\nu} H^\dagger \ell_J B_{\mu\nu}$
$[O_{He}]_{IJ}$	$i e^c_I \sigma_\mu \bar{e}^c_J H^\dagger \overleftrightarrow{D}_\mu H$	$[O_{uG}]_{IJ}$	$g_s \frac{\sqrt{m_I m_J}}{v} u^c_I \sigma_{\mu\nu} T^a \widetilde{H}^\dagger q_J\, G^a_{\mu\nu}$
$[O_{Hq}]_{IJ}$	$i\bar{q}_I \bar{\sigma}_\mu q_J H^\dagger \overleftrightarrow{D}_\mu H$	$[O_{uW}]_{IJ}$	$g_L \frac{\sqrt{m_I m_J}}{v} u^c_I \sigma_{\mu\nu} \widetilde{H}^\dagger \sigma^i q_J\, W^i_{\mu\nu}$
$[O'_{Hq}]_{IJ}$	$i\bar{q}_I \sigma^i \bar{\sigma}_\mu q_J H^\dagger \sigma^i \overleftrightarrow{D}_\mu H$	$[O_{uB}]_{IJ}$	$g_Y \frac{\sqrt{m_I m_J}}{v} u^c_I \sigma_{\mu\nu} \widetilde{H}^\dagger q_J\, B_{\mu\nu}$
$[O_{Hu}]_{IJ}$	$i u^c_I \sigma_\mu \bar{u}^c_J H^\dagger \overleftrightarrow{D}_\mu H$	$[O_{dG}]_{IJ}$	$g_s \frac{\sqrt{m_I m_J}}{v} d^c_I \sigma_{\mu\nu} T^a H^\dagger q_J\, G^a_{\mu\nu}$
$[O_{Hd}]_{IJ}$	$i d^c_I \sigma_\mu \bar{d}^c_J H^\dagger \overleftrightarrow{D}_\mu H$	$[O_{dW}]_{IJ}$	$g_L \frac{\sqrt{m_I m_J}}{v} d^c_I \sigma_{\mu\nu} \bar{H}^\dagger \sigma^i q_J\, W^i_{\mu\nu}$
$[O_{Hud}]_{IJ}$	$i u^c_I \sigma_\mu \bar{d}^c_J \tilde{H}^\dagger D_\mu H$	$[O_{dB}]_{IJ}$	$g_Y \frac{\sqrt{m_I m_J}}{v} d^c_I \sigma_{\mu\nu} H^\dagger q_J\, B_{\mu\nu}$

Table 3: Two-fermion d=6 operators in the Warsaw basis. Here, I, J are the flavor indices. For complex operators the complex conjugate operator is implicit.

$$\delta c_w = -c_H - c_{WB}\frac{4g^2 g'^2}{g^2 - g'^2} + 4c_T\frac{g^2}{g^2 - g'^2} - \delta v\frac{3g^2 + g'^2}{g^2 - g'^2}$$

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

$$\delta c_z = -c_H - 3\delta v$$

$$
\begin{aligned}
c_{gg} &= c_{GG}, \\
c_{\gamma\gamma} &= c_{WW} + c_{BB} - 4c_{WB}, \\
c_{zz} &= \frac{g^4 c_{WW} + g'^4 c_{BB} + 4g^2 g'^2 c_{WB}}{(g^2 + g'^2)^2}, \\
c_{z\Box} &= -\frac{2}{g^2}\left(c_T - \delta v\right), \\
c_{z\gamma} &= \frac{g^2 c_{WW} - g'^2 c_{BB} - 2(g^2 - g'^2)c_{WB}}{g^2 + g'^2}, \\
c_{\gamma\Box} &= \frac{2}{g^2 - g'^2}\left((g^2 + g'^2)c_{WB} - 2c_T + 2\delta v\right) \\
c_{ww} &= c_{WW}, \\
c_{w\Box} &= \frac{2}{g^2 - g'^2}\left(g'^2 c_{WB} - c_T + \delta v\right).
\end{aligned}
$$

$$[\delta y_f]_{ij} \cos\phi^f_{ij} = \frac{1}{\sqrt{2}}\mathrm{Re}[c_f]_{ij} - \delta_{ij}\left(c_H + \delta v\right)$$

$$[\delta y_f]_{ij} \sin\phi^f_{ij} = \frac{1}{\sqrt{2}}\mathrm{Im}[c_f]_{ij}$$

Introducing Higgs basis

- Observation: there's 15 bosonic Higgs couplings in phenomenological effective Lagrangian, but they depend only on 11 distinct combination of Wilson coefficients in the Warsaw basis

- Actually, one of this combination is the same as the one determining the correction to the W mass.

- Similar situation was for vertex corrections, where correction to W are related to corrections to Z

- This is true in any basis: although expression for Higgs couplings, δg and δm in terms of Wilson coefficients will be different in different bases, they will always depend on the same number of distinct combinations of Wilson coefficients

Similar “EFT Primaries” of Gupta et al 1405.0181

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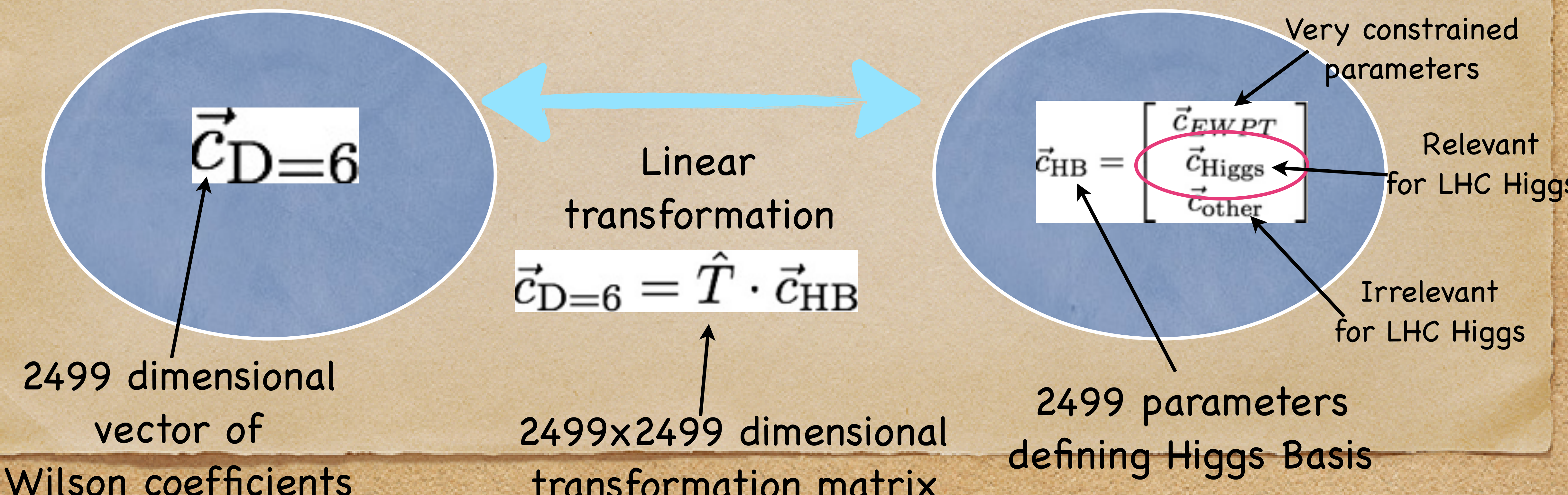
Higgs basis

- Connection between operators and observables a bit obscured in Warsaw or SILH basis. Also, in Warsaw basis EW precision constraints look complicated
- h-basis proposed by LHCHXSWG2 to separate combinations of Wilson coefficients strongly constrained by EWPT from those relevant for LHC Higgs studies
- Rotation of any other D=6 basis such that one isolates linear combinations affecting Higgs observables and not constrained severely by precision tests



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

$$\textbf{Independent}: \quad \delta g_L^{Ze},\ \delta g_R^{Ze},\ \delta g_L^{W\ell},\ \delta g_L^{Zu},\ \delta g_R^{Zu},\ \delta g_L^{Zd},\ \delta g_R^{Zd},\ \delta g_R^{Wq}$$

$$\textbf{Dependent}: \quad \delta g_L^{Z\nu},\ \delta g_L^{Wq}$$

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

Dependent Couplings:

Relations enforced by
linearly realized SU(3)xSU(2)xU(1) symmetry
at the level of dimension-6 operators

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

Higgs couplings to matter

- In HB, Higgs couplings to gauge bosons described by 6 CP even and 4 CP odd parameters that are unconstrained by LEP-1

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

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

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

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

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

$$\text{CP even}: \quad \delta y_u \quad \delta y_d \quad \delta y_e$$
$$\text{CP odd}: \quad \phi_u \quad \phi_d \quad \phi_e$$

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

Constraints from Electroweak 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].

Pole observables - constraints

Efrati,AA,Soreq
1503.07872

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

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

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

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

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

$$\delta m = (2.6 \pm 1.9) \cdot 10^{-4}.$$

- 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 their combination affecting *total* hadronic Z-width is strongly constrained)
- Some off-diagonal vertex corrections can also be constrained

Pole constraints - recast to Warsaw basis

Results

$$[\hat{c}'_{H\ell}]_{ii} = \begin{pmatrix} -1.09 \pm 0.64 \\ -1.45 \pm 0.59 \\ 1.87 \pm 0.79 \end{pmatrix} \times 10^{-2}, \quad [\hat{c}_{H\ell}]_{ii} = \begin{pmatrix} 1.03 \pm 0.63 \\ 1.32 \pm 0.62 \\ -2.01 \pm 0.80 \end{pmatrix} \times 10^{-2},$$

$$[\hat{c}_{He}]_{ii} = \begin{pmatrix} 0.22 \pm 0.66 \\ -0.6 \pm 2.6 \\ -1.4 \pm 1.3 \end{pmatrix} \times 10^{-3}, \quad c'_{\ell\ell} = (-1.21 \pm 0.41) \times 10^{-2},$$

$$\left[\hat{c}'_{Hq}\right]_{ii} = \begin{pmatrix} 0.1 \pm 2.7 \\ -1.2 \pm 2.8 \\ -0.7 \pm 3.8 \end{pmatrix} \times 10^{-2}, \quad [\hat{c}_{Hq}]_{ii} = \begin{pmatrix} 1.8 \pm 7.0 \\ -0.8 \pm 2.9 \\ 0.0 \pm 3.8 \end{pmatrix} \times 10^{-2},$$

$$[\hat{c}_{Hu}]_{ii} = \begin{pmatrix} -3 \pm 10 \\ 0.8 \pm 1.0 \\ \times \end{pmatrix} \times 10^{-2}, \quad [\hat{c}_{Hd}]_{ii} = \begin{pmatrix} -6 \pm 32 \\ -7 \pm 10 \\ -4.6 \pm 1.6 \end{pmatrix} \times 10^{-2}.$$

$$\begin{aligned}
[\hat{c}'_{H\ell}]_{ij} &= [c'_{HL}]_{ij} + \left(g_L^2 c_{WB} - \frac{g_L^2}{g_Y^2} c_T\right) \delta_{ij}, \\
[\hat{c}_{H\ell}]_{ij} &= [c_{HL}]_{ij} - c_T \delta_{ij}, \\
[\hat{c}_{He}]_{ij} &= [c_{HE}]_{ij} - 2c_T \delta_{ij}, \\
\left[\hat{c}'_{Hq}\right]_{ij} &= \left[c'_{HQ}\right]_{ij} + \left(g_L^2 c_{WB} - \frac{g_L^2}{g_Y^2} c_T\right) \delta_{ij}, \\
[\hat{c}_{Hq}]_{ij} &= [c_{HQ}]_{ij} + \frac{1}{3} c_T \delta_{ij}, \\
[\hat{c}_{Hu}]_{ij} &= [c_{HU}]_{ij} + \frac{4}{3} c_T \delta_{ij}, \\
[\hat{c}_{Hd}]_{ij} &= [c_{HD}]_{ij} - \frac{2}{3} c_T \delta_{ij}.
\end{aligned}$$

Dictionary

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

$$f(T^3, Q) = \mathbb{I}\left[-Q c_{WB} \frac{g_L^2 g_Y^2}{g_L^2 - g_Y^2} + (c_T - \delta v)\left(T^3 + Q \frac{g_Y^2}{g_L^2 - g_Y^2}\right)\right].$$

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

Note in Warsaw basis only combinations of Wilson coefficients are constrained by pole observables

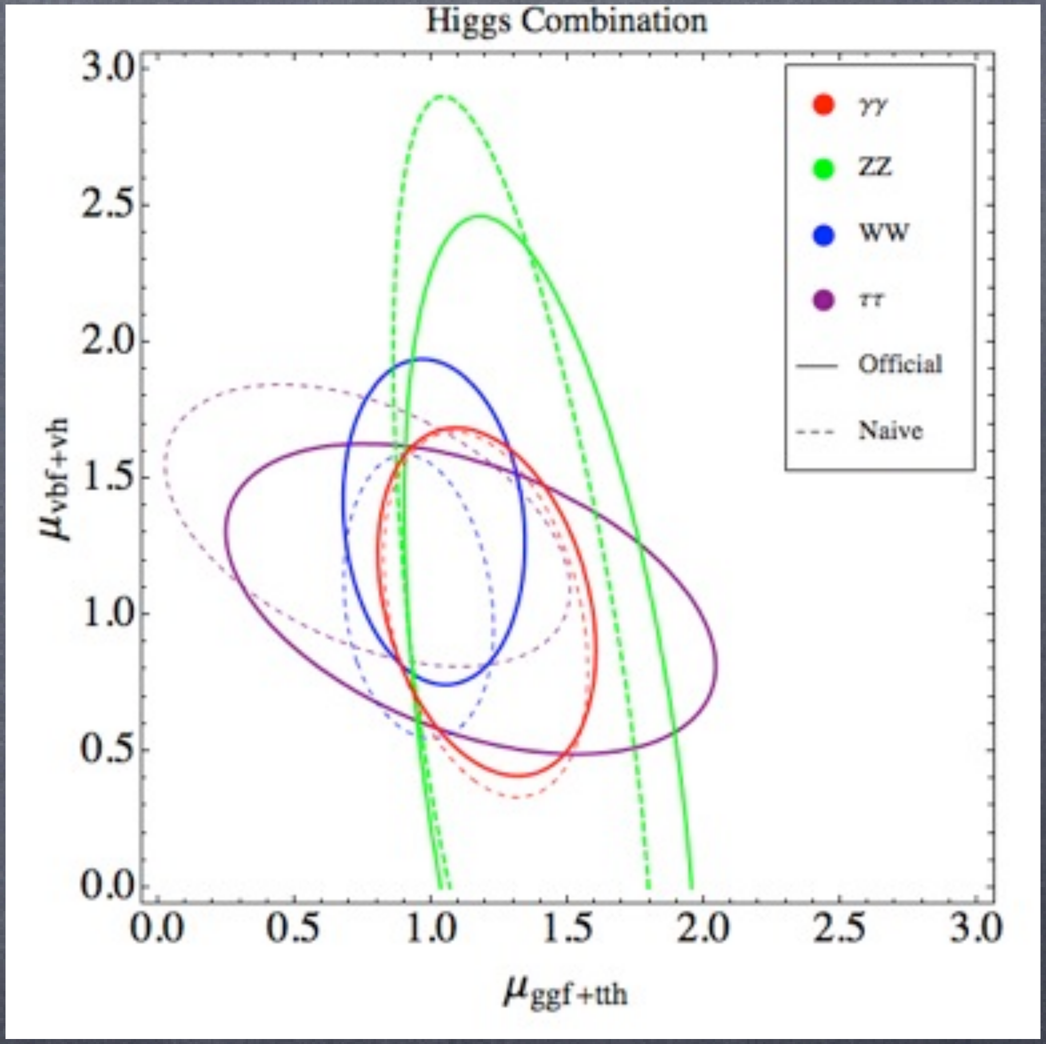
Constraints from LHC Higgs data

Higgs signal strength observables

Channel	μ	Production	Ref.
$\gamma\gamma$	$1.16^{+0.20}_{-0.18}$	2D	[31]
	$1.0^{+1.6}_{-1.6}$	Wh	[34]
	$0.1^{+3.7}_{-0.1}$	Zh	[34]
	$0.58^{+0.93}_{-0.81}$	Vh	[33]
	$1.30^{+2.62}_{-1.75}$ & $2.7^{+2.4}_{-1.7}$	tth	[33, 34]
$Z\gamma$	$2.7^{+4.5}_{-4.3}$ & $-0.2^{+4.9}_{-4.9}$	total	[34, 35]
ZZ^*	$1.31^{+0.27}_{-0.14}$	2D	[31]
WW^*	$1.11^{+0.18}_{-0.17}$	2D	[31]
	$2.1^{+1.9}_{-1.6}$	Wh	[36]
	$5.1^{+4.3}_{-3.1}$	Zh	[36]
	$0.80^{+1.09}_{-0.93}$	Vh	[33]
$\tau\tau$	$1.12^{+0.25}_{-0.23}$	2D	[31]
	$0.87^{+1.00}_{-0.88}$	Vh	[33]
bb	$1.11^{+0.65}_{-0.61}$	Wh	[32]
	$0.05^{+0.52}_{-0.49}$	Zh	[32]
	$0.89^{+0.47}_{-0.44}$	Vh	[33]
	$2.8^{+1.6}_{-1.4}$	VBF	[37]
	$1.5^{+1.1}_{-1.1}$ & $1.2^{+1.6}_{-1.5}$	tth	[38, 39]
$\mu\mu$	$-0.7^{+3.7}_{-3.7}$ & $0.8^{+3.5}_{-3.4}$	total	[34, 40]
multi-ℓ	$2.1^{+1.4}_{-1.2}$ & $3.8^{+1.4}_{-1.4}$	tth	[41, 42]

Including 2D likelihoods from recent ATLAS+CMS combination

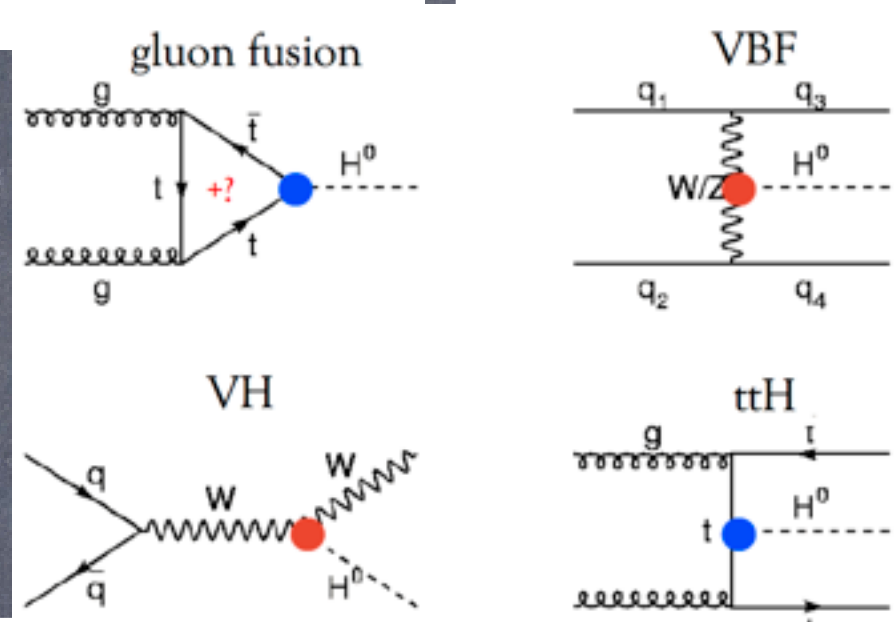
ATLAS-CONF-2015-044
CMS-PAS-HIG-15-002



Higgs production in the Higgs basis

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

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



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

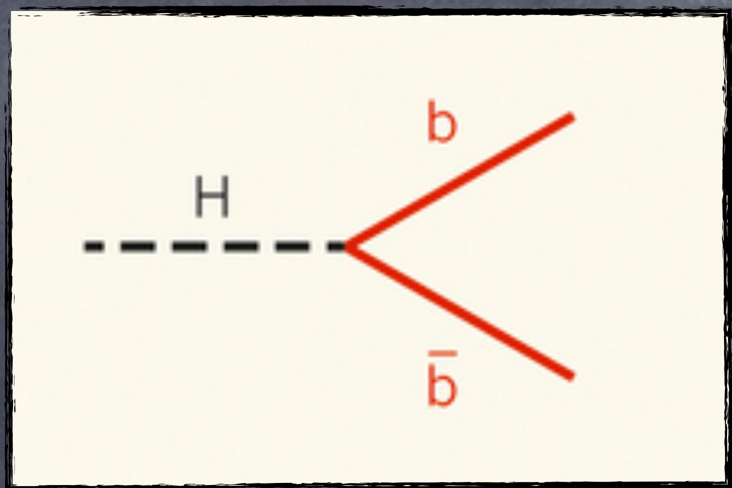
$$\frac{\sigma_{Wh}}{\sigma_{Wh}^{\rm SM}} \simeq 1 + 2\delta c_w + \begin{pmatrix} 6.39 \\ 6.51 \\ 6.96 \end{pmatrix} c_{w\Box} + \begin{pmatrix} 1.49 \\ 1.49 \\ 1.50 \end{pmatrix} c_{ww}$$
$$\to 1 + 2\delta c_z + \begin{pmatrix} 9.26 \\ 9.43 \\ 10.08 \end{pmatrix} c_{z\Box} + \begin{pmatrix} 4.35 \\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

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

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

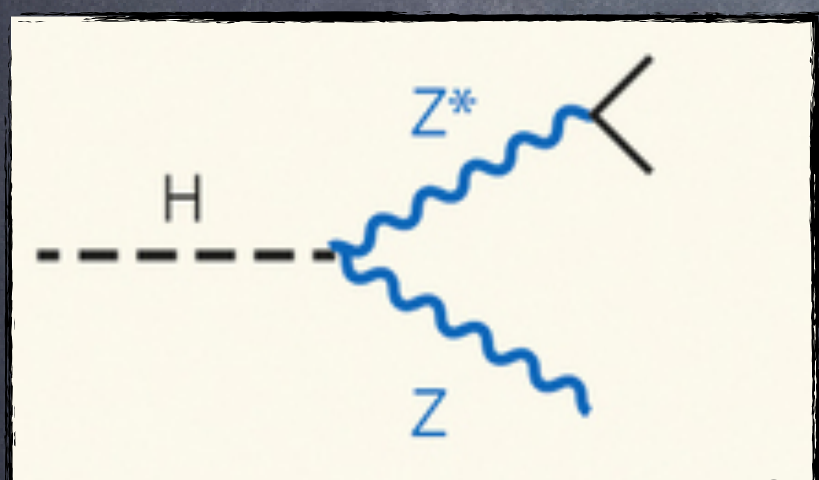
Higgs decay in the Higgs basis

Decays to 2 fermions



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

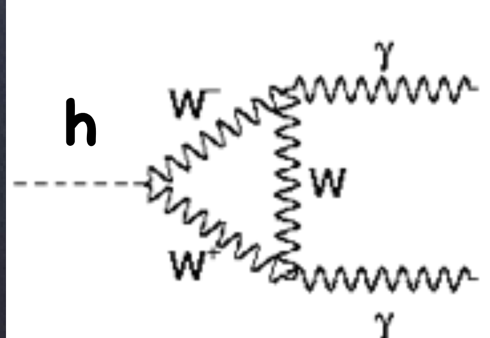
Decays to 4 fermions

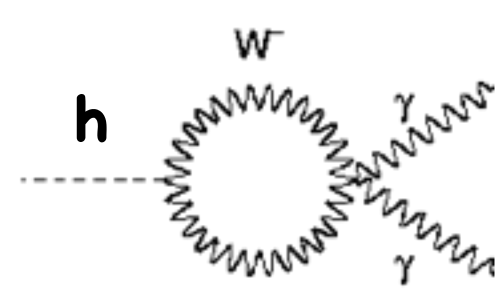


$$\begin{aligned}\frac{\Gamma_{2\ell 2\nu}}{\Gamma_{2\ell 2\nu}^{\rm SM}} &\simeq 1 + 2\delta c_w + 0.46 c_{w\Box} - 0.15 c_{ww} \\ &\to 1 + 2\delta c_z + 0.67 c_{z\Box} + 0.05 c_{zz} - 0.17 c_{z\gamma} - 0.05 c_{\gamma\gamma}.\end{aligned}$$

$\begin{pmatrix} \text{2e2μ} \\ \text{4e} \end{pmatrix}$

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

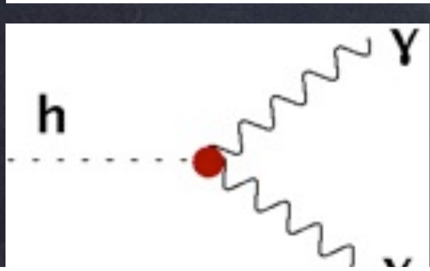


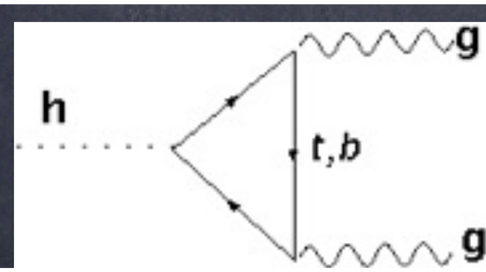


Decays to 2 gauge bosons

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

$$\begin{aligned}\hat c_{\gamma\gamma} &= c_{\gamma\gamma}, \qquad c_{\gamma\gamma}^{\rm SM} \simeq -8.3 \times 10^{-2}, \\ \hat c_{z\gamma} &= c_{z\gamma}, \qquad c_{z\gamma}^{\rm SM} \simeq -5.9 \times 10^{-2},\end{aligned}$$





Higgs observables in the Higgs basis

Signal strength

$$\mu_{X;Y} = \frac{\sigma(pp \to X)}{\sigma(pp \to X)_{\rm SM}} \frac{\Gamma(h \to Y)}{\Gamma(h \to Y)_{\rm SM}} \frac{\Gamma(h \to {\rm all})_{\rm SM}}{\Gamma(h \to {\rm all})}.$$

In EFT, assuming no other degrees of freedom,
so total width is just sum of partial width into SM particle
no invisible width in this analysis

- One can express all measured signal strength in terms of the 9 EFT parameters

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

- Using available LHC signal strength data one can obtain constraints on most of these parameters

Higgs constraints on EFT

	$\mathbf{L}$ $(x_0 \pm 1\ \sigma)$
δc_z	-0.12 ± 0.20
c_{zz}	0.6 ± 1.9
$c_{z\Box}$	-0.25 ± 0.83
$c_{\gamma\gamma}$	0.015 ± 0.029
$c_{z\gamma}$	0.01 ± 0.10
c_{gg}	-0.0056 ± 0.0028
δy_u	0.55 ± 0.30
δy_d	-0.42 ± 0.45
δy_e	-0.18 ± 0.36

AA
1505.00046

Flat direction

$$c_{zz} \approx -2.3 c_{z\Box}$$

Needs more data
on differential distributions
in h->4f decays

- Not all parameters yet constrained enough that EFT approach is valid
- Results sensitive to including corrections to Higgs observables quadratic in EFT parameters which are formally O(1/Λ^4). Thus, in general, results may be sensitive to including dimension-8 operators

TGC - Higgs Synergy

TGC

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

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

$\Longleftrightarrow$

Higgs

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

Linearly realized SU(3)xSU(2)xU(1) at D=6 level enforces relations between TGC and Higgs couplings in the Higgs basis

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

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

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

- In Higgs basis formalism, all but 2 TGCs are dependent couplings and can be expressed by Higgs couplings to gauge bosons
- Therefore constraints on δg1z and δκγ imply constraints on Higgs couplings
- But for that, all TGCs have to be simultaneously constrained in multi-dimensional fit, and correlation matrix should be given
- Note that c_zγ c_zz and c_zBox are difficult to access experimentally in Higgs physics
- Important to combine Higgs and TGC data!

Higgs constraints on EFT

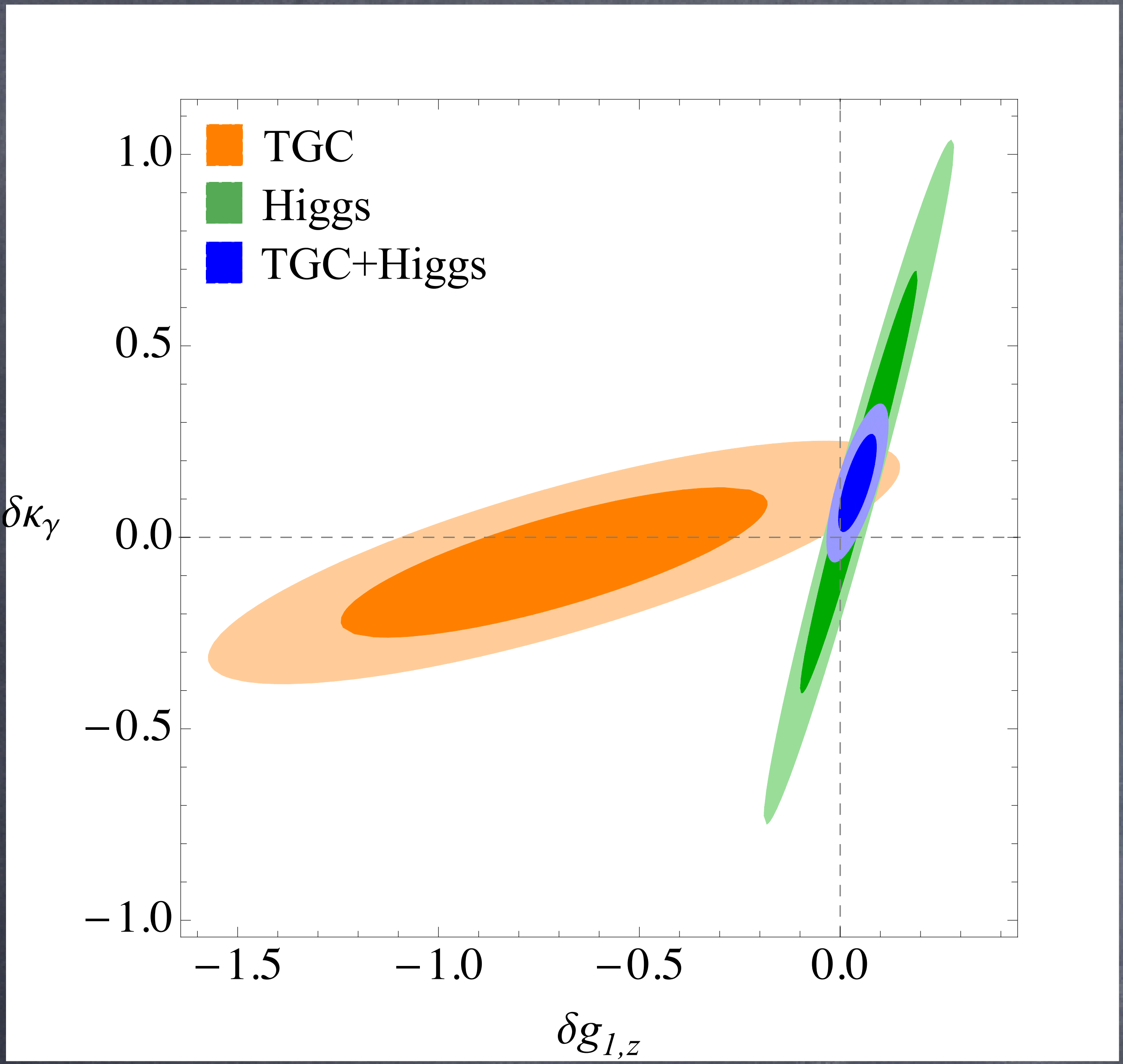
$$\begin{pmatrix} \delta c_z \\ c_{zz} \\ c_{z\Box} \\ c_{\gamma\gamma} \\ c_{z\gamma} \\ c_{gg} \\ \delta y_u \\ \delta y_d \\ \delta y_e \\ \lambda_z \end{pmatrix} = \begin{pmatrix} -0.07 \pm 0.14 \\ 0.65 \pm 0.42 \\ -0.29 \pm 0.21 \\ -0.005 \pm 0.014 \\ -0.005 \pm 0.095 \\ -0.0053 \pm 0.0027 \\ 0.55 \pm 0.30 \\ -0.44 \pm 0.24 \\ -0.22 \pm 0.18 \\ -0.152 \pm 0.080 \end{pmatrix}$$

Correlation matrix

1.	-0.07	-0.23	0.4	-0.05	-0.05	0.03	0.56	0.49	-0.24
-0.07	1.	-0.92	0.34	0.18	0.	0.02	-0.3	-0.38	-0.85
-0.23	-0.92	1.	-0.43	-0.12	0.03	0.	0.21	0.21	0.94
0.4	0.34	-0.43	1.	0.09	0.4	-0.47	-0.11	-0.12	-0.42
-0.05	0.18	-0.12	0.09	1.	0.01	-0.01	-0.1	-0.13	-0.12
-0.05	0.	0.03	0.4	0.01	1.	-0.89	0.18	0.06	0.03
0.03	0.02	0.	-0.47	-0.01	-0.89	1.	0.1	0.04	0.01
0.56	-0.3	0.21	-0.11	-0.1	0.18	0.1	1.	0.66	0.19
0.49	-0.38	0.21	-0.12	-0.13	0.06	0.04	0.66	1.	0.18
-0.24	-0.85	0.94	-0.42	-0.12	0.03	0.01	0.19	0.18	1.

- Flat direction between c_zz and c_zBox lifted to large extent by WW data!
- Much better constraints on some parameters.
  Most parameters (marginally) within the EFT regime
- Lower sensitivity to the quadratic terms (though still not completely negligible, especially for δcz and δyd)

Corollary: constraints on TGCs



- 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

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

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

Take away

- EFT approach is an important tool that allows one to place constraints on large classes of new physics models in a model independent way
- It is currently possible to study LHC and precision data without unnecessarily constraining assumptions, allowing all D=6 operators to be present simultaneously
- There are strong constraints on certain combinations of dimension-6 operators from the pole observables measured at LEP-1 and other colliders. These can be conveniently presented as correlated constraints on vertex corrections and W mass corrections.
- Assuming MFV, these constraints allow one to describe LO EFT deformations of single Higgs signal strength LHC observables by just 9 parameters
- There are non-trivial constraints on all of these 9 parameters from Higgs and WW data
- Synergy of TGC and Higgs coupling measurements is crucial for deriving meaningful bounds