EFT fits and anomalous couplings...

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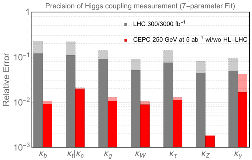
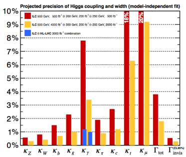
based on [arXiv:1704.02333] G. Durieux, C. Grojean, JG, K. Wang

κ framework vs. EFT





From the CEPC preCDR and "Physics Case for the ILC" ([arXiv:1506.05992])

- Conventionally, the constraints on Higgs couplings are obtained from global fits in the so-called "κ" framework.

$$g_h^{\rm SM} \to \kappa\, g_h^{\rm SM} .$$

- Anomalous couplings such as $hZ^{\mu\nu}Z_{\mu\nu}$ or $hZ_\mu \partial_\nu Z^{\mu\nu}$ are assumed to be zero.
- EFT framework
  - Assuming $v \ll \Lambda$, leading contribution from BSM physics are well-parameterized by D6 operators.
  - Gauge invariance is built in the parameterization.
- Lots of parameters! (Is it practical to perform a global fit?)

The "12-parameter" framework in EFT

- Assume the new physics
  - is CP-even,
  - does not generate dipole interaction of fermions,
  - only modifies the diagonal entries of the Yukawa matrix,
  - has **no corrections to Z-pole observables** and W mass (more justified if the machine will run at Z-pole).
- Additional measurements
  - Triple gauge couplings from $e^+e^- \to WW$. (The LEP constraints will be improved at future colliders.)
  - Angular observables in $e^+e^- \to hZ$. (see *e.g.* [arXiv:1512.06877] N. Craig, JG, Z. Liu, K. Wang)
  - $h \to Z\gamma$ is also important.
- Only 12 combinations of operators are relevant for the measurements considered (with the inclusion of the Yukawa couplings of t, c, b, τ, μ).
- All 12 EFT parameters can be constrained reasonably well in the global fit!

EFT basis

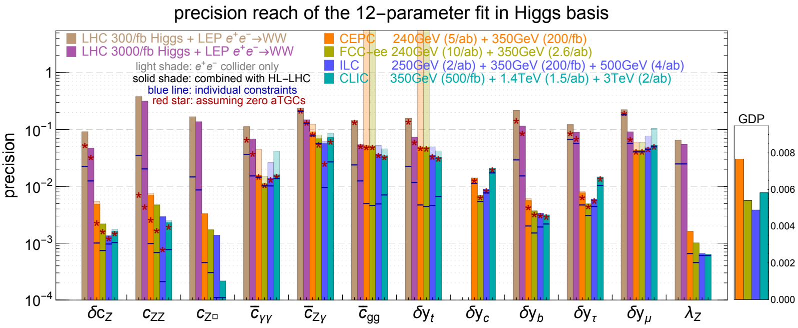
- We work in the Higgs basis (LHCHXSWG-INT-2015-001, A. Falkowski) with the following 12 parameters,

$$\delta c_Z\,,\quad c_{ZZ}\,,\quad c_{Z\Box}\,,\quad c_{\gamma\gamma}\,,\quad c_{Z\gamma}\,,\quad c_{gg}\,,\quad \delta y_t\,,\quad \delta y_c\,,\quad \delta y_b\,,\quad \delta y_\tau\,,\quad \delta y_\mu\,,\quad \lambda_Z\,.$$

- The Higgs basis is defined in the broken electroweak phase.
  - $\delta c_Z \leftrightarrow hZ^\mu Z_\mu, \quad c_{ZZ} \leftrightarrow hZ^{\mu\nu} Z_{\mu\nu}, \quad c_{Z\Box} \leftrightarrow hZ_\mu \partial_\nu Z^{\mu\nu}.$
- Couplings of h to W are written in terms of couplings of h to Z and γ.
- 3 aTGC parameters ($\delta g_{1,Z}$, $\delta\kappa_\gamma$, λ_Z), 2 written in terms of Higgs parameters.
- It can be easily mapped to the following basis with D6 operators.

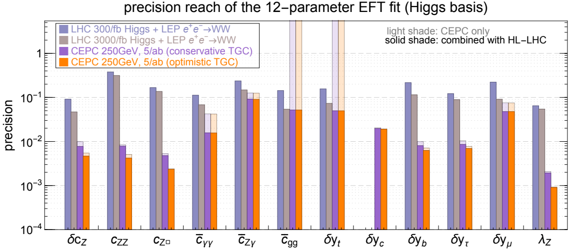
$\mathcal{O}_H = \frac{1}{2}(\partial_\mu \lvert H^2 \rvert)^2$	$\mathcal{O}_{GG} = g_s^2 \lvert H\rvert^2 G^A_{\mu\nu} G^{A,\mu\nu}$
$\mathcal{O}_{WW} = g^2 \lvert H\rvert^2 W^a_{\mu\nu} W^{a,\mu\nu}$	$\mathcal{O}_{y_u} = y_u \lvert H\rvert^2 \bar{Q}_L \tilde{H} u_R \quad (u \to t,\ c)$
$\mathcal{O}_{BB} = g'^2 \lvert H\rvert^2 B_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{y_d} = y_d \lvert H\rvert^2 \bar{Q}_L H d_R \quad (d \to b)$
$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$	$\mathcal{O}_{y_e} = y_e \lvert H\rvert^2 \bar{L}_L H e_R \quad (e \to \tau,\ \mu)$
$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$	$\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon_{abc} W^{a\,\nu}_\mu W^b_{\nu\rho} W^{c\,\rho\mu}$

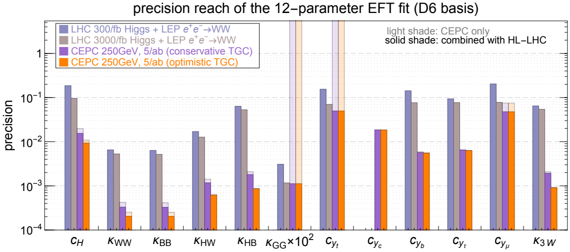
Results of the “12-parameter” fit



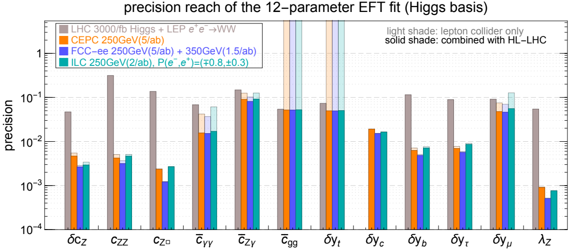
- Assuming the following run plans (no official plan for CEPC 350 GeV run)
  - CEPC 240 GeV(5/ab) + 350 GeV(200/fb)
  - FCC-ee 240 GeV(10/ab) + 350 GeV(2.6/ab)
  - ILC 250 GeV(2/ab) + 350 GeV(200/fb) + 500 GeV(4/ab)
  - CLIC 350 GeV(500/fb) + 1.4 TeV(1.5/ab) + 3 TeV(2/ab)

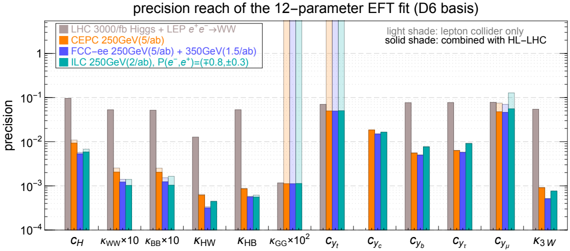
some updated results...





some updated results...





The CP-odd operators

- only enters at quadratic level for inclusive measurements (but can contribute to angular observables at linear level)
- are usually strongly constrained elsewhere (*e.g.* by EDM experiments), but with assumptions (*e.g.* the electron Yukawa coupling is SM like)
- are not included in the global fit (but are still important!)

a simplified picture

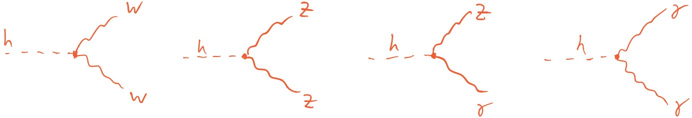
$\mathcal{O}_H = \frac{1}{2}(\partial_\mu \lvert H^2 \rvert)^2$	$\mathcal{O}_{GG} = g_s^2 \lvert H \rvert^2 G^A_{\mu\nu} G^{A,\mu\nu}$
$\mathcal{O}_{WW} = g^2 \lvert H \rvert^2 W^a_{\mu\nu} W^{a,\mu\nu}$	$\mathcal{O}_{y_u} = y_u \lvert H \rvert^2 \bar{Q}_L \tilde{H} u_R \quad (u \to t,\, c)$
$\mathcal{O}_{BB} = g'^2 \lvert H \rvert^2 B_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{y_d} = y_d \lvert H \rvert^2 \bar{Q}_L H d_R \quad (d \to b)$
$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$	$\mathcal{O}_{y_e} = y_e \lvert H \rvert^2 \bar{L}_L H e_R \quad (e \to \tau,\, \mu)$
$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$	$\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon_{abc} W^{a\,\nu}_\mu W^b_{\nu\rho} W^{c\,\rho\mu}$

- $\mathcal{O}_{HW}$ and $\mathcal{O}_{HB}$ can be constrained by TGC measurements ($e^+e^- \to WW$). (They generates $c_{Z\Box}$ ($hZ_\mu \partial_\nu Z^{\mu\nu}$).)
- $\mathcal{O}_H$ shifts the SM Higgs couplings universally.
- Note: At leading order, $\mathcal{O}_{WW}$ and $\mathcal{O}_{BB}$ can only be probed by Higgs measurements! (So is any operator in the form $\lvert H \rvert^2 \mathcal{O}_{SM}$.)

a simplified picture

$$O_H = \frac{1}{2}(\partial_\mu |H|^2)^2 \qquad O_{WW} = g^2 |H|^2 W^a_{\mu\nu} W^{a,\mu\nu} \qquad O_{BB} = g'^2 |H|^2 B_{\mu\nu} B^{\mu\nu}$$

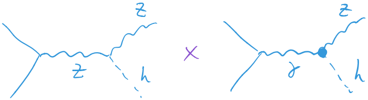
$$h Z_\mu Z^\mu,\ h W_\mu W^\mu,\ \ldots \qquad h W_{\mu\nu} W^{\mu\nu},\ h Z_{\mu\nu} Z^{\mu\nu},\ h Z_{\mu\nu} A^{\mu\nu},\ h A_{\mu\nu} A^{\mu\nu}$$



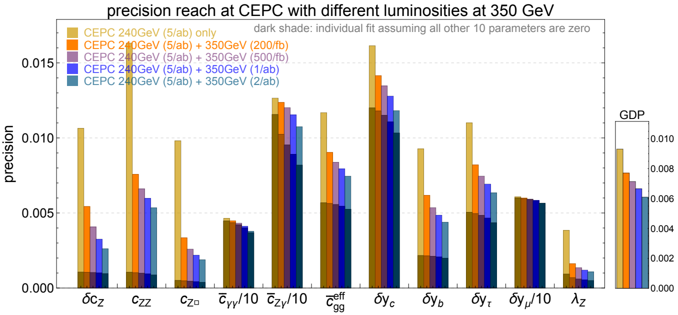
$$hZ, \quad WW \to h, \quad h \to ZZ^* / WW^* / Z\gamma / \gamma\gamma$$

Impact of energy scales, beam polarizations ...

- The EFT framework has features that are not present in the "κ" framework.
- Different parameters have different energy dependences.
  - δc_Z ($hZ^\mu Z_\mu$) modifies the SM HZZ coupling (no energy dependence).
  - $e^+e^- \to hZ$ is more sensitive to c_{ZZ} ($hZ^{\mu\nu}Z_{\mu\nu}$), $c_{Z\Box}$ ($hZ_\mu\partial_\nu Z^{\mu\nu}$) at higher energies.
  - c_{ZZ} and $c_{Z\Box}$ have negative coefficients for WW fusion (virtual Ws).
  - $h \to WW^*/ZZ^*$ also probes these couplings at a different energy scale.
- The following interference term is sensitive to beam polarizations

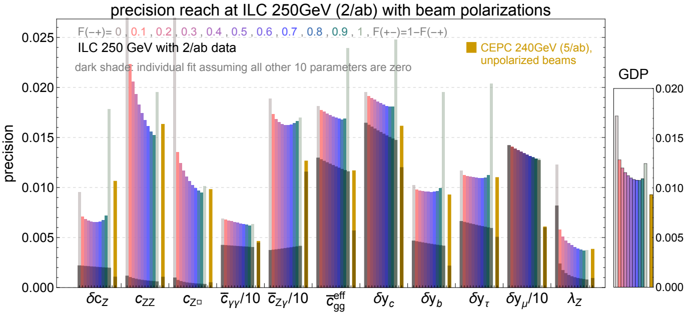


Impact of a 350 GeV run



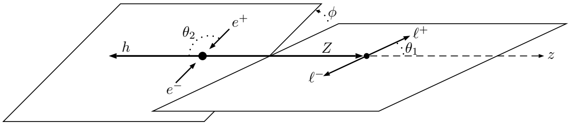
- Advantages of the runs at higher energies
  - Much better measurement of the WW fusion process ($e^+e^- \to \nu\bar{\nu}h$).
  - Probing $e^+e^- \to hZ$ at different energies.
  - Improving constraints on aTGCs ($e^+e^- \to WW$).
- Very helpful in resolving the degeneracies among parameters!

Impact of beam polarization



- Beam polarization helps discriminate different parameters.
  - Two polarization configurations are considered, $P(e^-, e^+) = (-0.8, +0.3)$ and $(+0.8, -0.3)$.
  - $F(-+)$ in the range of 0.6-0.8 gives an optimal overall results.
- Runs with different polarizations probe different combinations of EFT parameters in Higgs production.

angular observables in $e^+e^- \to hZ$



- Angular distributions in $e^+e^- \to hZ$ can provide information in addition to the rate measurement alone.
- Previous studies
  - [arXiv:1406.1361] M. Beneke, D. Boito, Y.-M. Wang
  - [arXiv:1512.06877] N. Craig, JG, Z. Liu, K. Wang
- 6 independent asymmetry observables from 3 angles

$$\mathcal{A}_{\theta_1}\,,\quad \mathcal{A}_{\phi}^{(1)}\,,\quad \mathcal{A}_{\phi}^{(2)}\,,\quad \mathcal{A}_{\phi}^{(3)}\,,\quad \mathcal{A}_{\phi}^{(4)}\,,\quad \mathcal{A}_{c\theta_1,c\theta_2}\,.$$

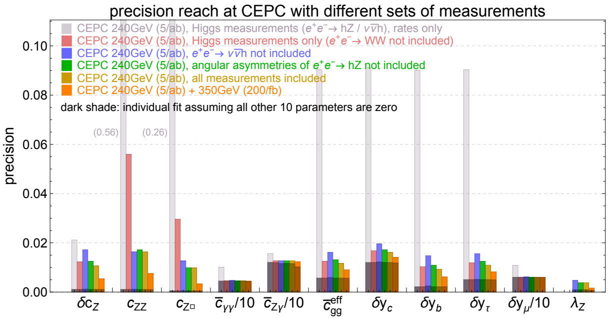
- Focusing on leptonic decays of Z (good resolution, small background, statistical uncertainty dominates).

Asymmetry observables

$$
\begin{aligned}
\mathcal{A}_{\theta_1} &= \frac{1}{\sigma}\int_{-1}^{1} d\cos\theta_1 \,\mathrm{sgn}(\cos(2\theta_1))\, \frac{d\sigma}{d\cos\theta_1}\,, \\
\mathcal{A}_{\phi}^{(1)} &= \frac{1}{\sigma}\int_{0}^{2\pi} d\phi \,\mathrm{sgn}(\sin\phi)\, \frac{d\sigma}{d\phi}\,, \\
\mathcal{A}_{\phi}^{(2)} &= \frac{1}{\sigma}\int_{0}^{2\pi} d\phi \,\mathrm{sgn}(\sin(2\phi))\, \frac{d\sigma}{d\phi}\,, \\
\mathcal{A}_{\phi}^{(3)} &= \frac{1}{\sigma}\int_{0}^{2\pi} d\phi \,\mathrm{sgn}(\cos\phi)\, \frac{d\sigma}{d\phi}\,, \\
\mathcal{A}_{\phi}^{(4)} &= \frac{1}{\sigma}\int_{0}^{2\pi} d\phi \,\mathrm{sgn}(\cos(2\phi))\, \frac{d\sigma}{d\phi}\,, \qquad (1)
\end{aligned}
$$

$$
\mathcal{A}_{c\theta_1,c\theta_2} = \frac{1}{\sigma}\int_{-1}^{1} d\cos\theta_1 \,\mathrm{sgn}(\cos\theta_1)\int_{-1}^{1} d\cos\theta_2 \,\mathrm{sgn}(\cos\theta_2)\frac{d^2\sigma}{d\cos\theta_1\, d\cos\theta_2}\,, \qquad (2)
$$

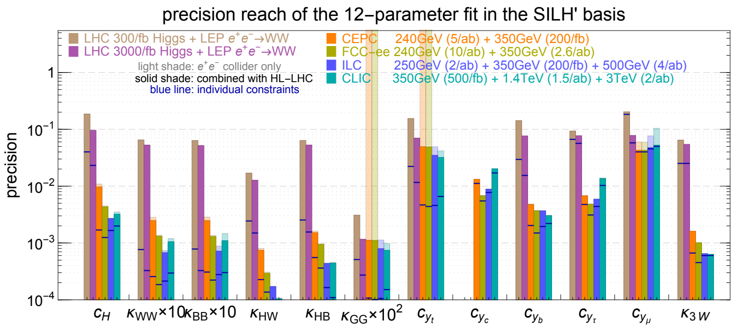
the impact on the global fit...



- The angular observables have a small (but not negligible) impact on the global fit if all other measurements are included.
- Nevertheless, we should try to make use of all possible information!

backup slides

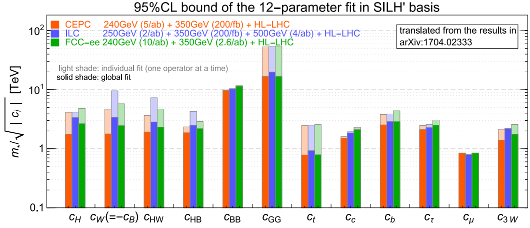
If you don't like the Higgs basis...

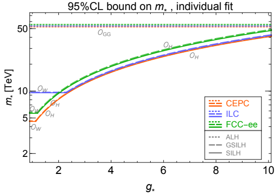


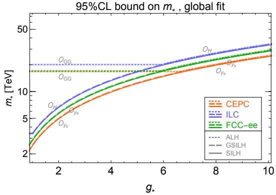
- Results in the SILH'(-like) basis ($\mathcal{O}_{W,B} \to \mathcal{O}_{WW,WB}$)

$$\mathcal{L}_{\rm D6} = \frac{c_H}{v^2}\mathcal{O}_H + \frac{\kappa_{WW}}{m_W^2}\mathcal{O}_{WW} + \frac{\kappa_{BB}}{m_W^2}\mathcal{O}_{BB} + \frac{\kappa_{HW}}{m_W^2}\mathcal{O}_{HW} + \frac{\kappa_{HB}}{m_W^2}\mathcal{O}_{HB}$$
$$+ \frac{\kappa_{GG}}{m_W^2}\mathcal{O}_{GG} + \frac{\kappa_{3W}}{m_W^2}\mathcal{O}_{3W} + \sum_{f=t,c,b,\tau,\mu}\frac{c_{y_f}}{v^2}\mathcal{O}_{y_f}\,.$$

Scale of new physics [arXiv:1709.06103] JG, H. Li, Z. Liu, S. Su, W. Su







	$\mathcal{O}_H$	$\mathcal{O}_W$	$\mathcal{O}_B$	$\mathcal{O}_{HW}$	$\mathcal{O}_{HB}$	$\mathcal{O}_{BB}$	$\mathcal{O}_{GG}$	$\mathcal{O}_{y_u}$	$\mathcal{O}_{y_d}$	$\mathcal{O}_{y_e}$	$\mathcal{O}_{3W}$
ALH	g_*^2	1	1	1	1	1	1	g_*^2	g_*^2	g_*^2	$\frac{g^2}{g_*^2}$
GSILH	g_*^2	1	1	1	1	$\frac{y_t^2}{16\pi^2}$	$\frac{y_t^2}{16\pi^2}$	g_*^2	g_*^2	g_*^2	$\frac{g^2}{g_*^2}$
SILH	g_*^2	1	1	$\frac{g_*^2}{16\pi^2}$	$\frac{g_*^2}{16\pi^2}$	$\frac{y_t^2}{16\pi^2}$	$\frac{y_t^2}{16\pi^2}$	g_*^2	g_*^2	g_*^2	$\frac{g^2}{16\pi^2}$

table obtained from [arXiv:1603.03064] D. Liu, A. Pomarol, R. Rattazzi, F. Riva

- Note: the bounds on Λ (m_*) always depend on the couplings!
- Given estimations on the size of the couplings, we can derive the inferred bounds on the new physic scale (m_*).

The “12-parameter” framework in the Higgs basis

- The relevant terms in the EFT Lagrangian are

$$\mathcal{L} \supset \mathcal{L}_{hVV} + \mathcal{L}_{hff} + \mathcal{L}_{\rm tgc} \,, \tag{3}$$

- the Higgs couplings with a pair of gauge bosons

$$\begin{aligned}\mathcal{L}_{hVV} = \frac{h}{v}\Big[& (1+\delta c_W)\frac{g^2 v^2}{2} W^+_\mu W^-_\mu + (1+\delta c_Z)\frac{(g^2+g'^2)v^2}{4} Z_\mu Z_\mu \\ & + c_{WW}\frac{g^2}{2} W^+_{\mu\nu} W^-_{\mu\nu} + c_{W\Box}\, g^2 (W^-_\mu \partial_\nu W^+_{\mu\nu} + \mathrm{h.c.}) \\ & + c_{gg}\frac{g_s^2}{4} G^a_{\mu\nu} G^2_{\mu\nu} + c_{\gamma\gamma}\frac{e^2}{4} A_{\mu\nu} A_{\mu\nu} + c_{Z\gamma}\frac{e\sqrt{g^2+g'^2}}{2} Z_{\mu\nu} A_{\mu\nu} \\ & + c_{ZZ}\frac{g^2+g'^2}{4} Z_{\mu\nu} Z_{\mu\nu} + c_{Z\Box}\, g^2 Z_\mu \partial_\nu Z_{\mu\nu} + c_{\gamma\Box}\, g g' Z_\mu \partial_\nu A_{\mu\nu} \Big] \,. \end{aligned} \tag{4}$$

The "12-parameter" framework in the Higgs basis

- Not all the couplings are independent, for instance one could write the following couplings as

$$
\begin{aligned}
\delta c_W &= \delta c_Z + 4\delta m\,, \\
c_{WW} &= c_{ZZ} + 2s_{\theta_W}^2 c_{Z\gamma} + s_{\theta_W}^4 c_{\gamma\gamma}\,, \\
c_{W\Box} &= \frac{1}{g^2 - g'^2}\left[g^2 c_{Z\Box} + g'^2 c_{ZZ} - e^2 s_{\theta_W}^2 c_{\gamma\gamma} - (g^2 - g'^2) s_{\theta_W}^2 c_{Z\gamma}\right]\,, \\
c_{\gamma\Box} &= \frac{1}{g^2 - g'^2}\left[2g^2 c_{Z\Box} + (g^2 + g'^2) c_{ZZ} - e^2 c_{\gamma\gamma} - (g^2 - g'^2) c_{Z\gamma}\right]\,, \qquad (5)
\end{aligned}
$$

- we only consider the diagonal elements in the Yukawa matrices relevant for the measurements considered,

$$
\mathcal{L}_{hff} = -\frac{h}{v} \sum_{f=t,c,b,\tau,\mu} m_f (1 + \delta y_f) \bar{f}_R f_L + \text{h.c.}\,. \qquad (6)
$$

TGC

$$
\begin{aligned}
\mathcal{L}_{\rm tgc} = & \; igs_{\theta_W} A^{\mu}(W^{-\nu}W^{+}_{\mu\nu} - W^{+\nu}W^{-}_{\mu\nu}) \\
& + ig(1+\delta g_1^Z) c_{\theta_W} Z^{\mu}(W^{-\nu}W^{+}_{\mu\nu} - W^{+\nu}W^{-}_{\mu\nu}) \\
& + ig\left[(1+\delta\kappa_Z)c_{\theta_W}Z^{\mu\nu} + (1+\delta\kappa_\gamma)s_{\theta_W}A^{\mu\nu}\right] W^-_\mu W^+_\nu \\
& + \frac{ig}{m_W^2}(\lambda_Z c_{\theta_W} Z^{\mu\nu} + \lambda_\gamma s_{\theta_W} A^{\mu\nu}) W^{-\rho}_{v} W^{+}_{\rho\mu} \,, \qquad (7)
\end{aligned}
$$

- $V_{\mu\nu} \equiv \partial_\mu V_\nu - \partial_\nu V_\mu$ for $V = W^{\pm}, Z, A,$. Imposing Gauge invariance one obtains $\delta\kappa_Z = \delta g_{1,Z} - t^2_{\theta_W}\delta\kappa_\gamma$ and $\lambda_Z = \lambda_\gamma$.
- 3 aTGCs parameters $\delta g_{1,Z}$, $\delta\kappa_\gamma$ and λ_Z, 2 of them related to Higgs observables by

$$
\begin{aligned}
\delta g_{1,Z} &= \frac{1}{2(g^2-g'^2)}\left[-g^2(g^2+g'^2)c_{Z\Box} - g'^2(g^2+g'^2)c_{ZZ} + e^2 g'^2 c_{\gamma\gamma} + g'^2(g^2-g'^2)c_{Z\gamma}\right] \\
\delta\kappa_\gamma &= -\frac{g^2}{2}\left(c_{\gamma\gamma}\frac{e^2}{g^2+g'^2} + c_{Z\gamma}\frac{g^2-g'^2}{g^2+g'^2} - c_{ZZ}\right) . \qquad (8)
\end{aligned}
$$