Triple Gauge Couplings (at FCC-ee)

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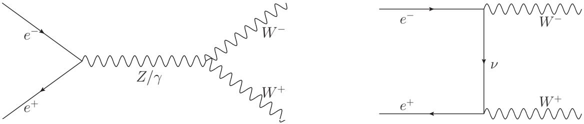
WG1 & WG2 working meeting
Feb 6, 2018

TGC from $e^+e^- \to WW$



- We can measure the triple gauge couplings (TGC) from the diboson process $e^+e^- \to WW$.
- Focusing on the anomalous TGC parameters generated by CP-even D6 operators,

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

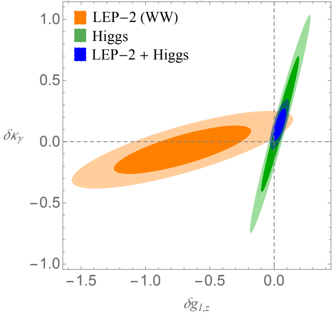
TGC

- 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!
- They correspond to 3 linear combinations of Wilson coefficients in the EFT not constrained by Z-pole measurements.
  - Even if the Z-pole measurements are infinitely precise, the 3 aTGCs remain unconstrained!
  - In a convenient basis they correspond to $\mathcal{O}_{HW} = ig(D^\mu H)^\dagger\sigma^a(D^\nu H)W^a_{\mu\nu}$, $\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu}$ and $\mathcal{O}_{3W} = \frac{1}{3!}g\epsilon_{abc}W^{a\,\nu}_{\mu}W^{b}_{\nu\rho}W^{c\,\rho\mu}$. See *e.g.* **[arXiv:1411.0669] Falkowski & Riva** for a general parameterization.
- $\delta g_{1,Z}$ and $\delta\kappa_\gamma$ are generated by operators that also contribute to Higgs couplings.

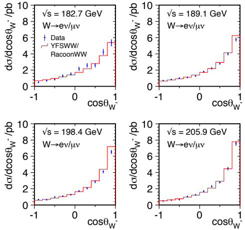
Impacts on EFT fits, LHC + LEP

- $\delta g_{1,Z}$ and $\delta\kappa_\gamma$ are generated by operators that also contribute to Higgs couplings.
- Higgs better measured $\Rightarrow$ Higgs helps TGC;
- TGC better measured $\Rightarrow$ TGC helps Higgs.

[arXiv:1508.00581] Falkowski *et al.*



[arXiv:1302.3415] LEP *WW* paper



- Note: LEP bounds should have been better!
  - LEP did not perform global fits with all 3 aTGCs.
  - The distributions of W decay angles were not provided.

FCC-ee

W-pairs at FCCee :the OkuW

$\sqrt{s} \approx 91$ GeV $\sim 10^{12}$ Z

√s=161 : L~3 10^{35} collect 8/ab
30 10^6 WW decays

√s=240 : L~0.7 10^{35} collect 5/ab
80 10^6 WW decays

$\sim 10^6$ **H**

√s=350 : L~ 10^{34} collect 1.5/ab
15 10^6 WW decays

$\sim 2\times10^5$ **H**

FCC-ee

W-pairs at FCCee :the OkuW

$\sqrt{s} \approx 91$ GeV $\sim 10^{12}$ Z
(systematics dominated)

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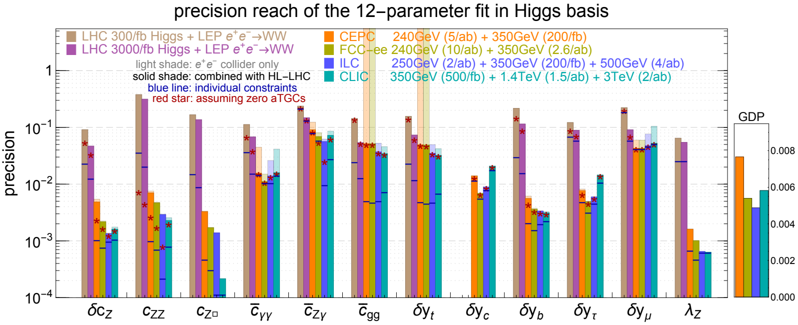
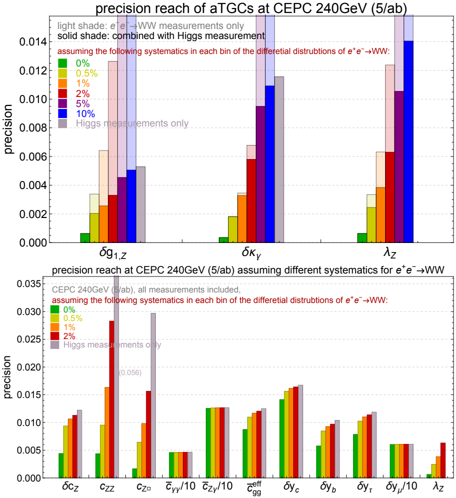
# of WW $\sim 10^2 \times$ # of H

EFT fits at future lepton colliders [arXiv:1704.02333] G. Durieux, C. Grojean, JG, K. Wang



- $\delta g_{1,Z}, \delta\kappa_\gamma \to \quad c_{ZZ}\,, \quad c_{Z\Box}\,, \quad c_{\gamma\gamma}\,, \quad c_{Z\gamma}$
- see also
  - [arXiv:1510.04561, 1701.04804] Ellis *et al.*,
  - [arXiv:1708.08912, 1708.09079] Peskin *et al.*
  - [arXiv:1711.04046] Wang *et al.*

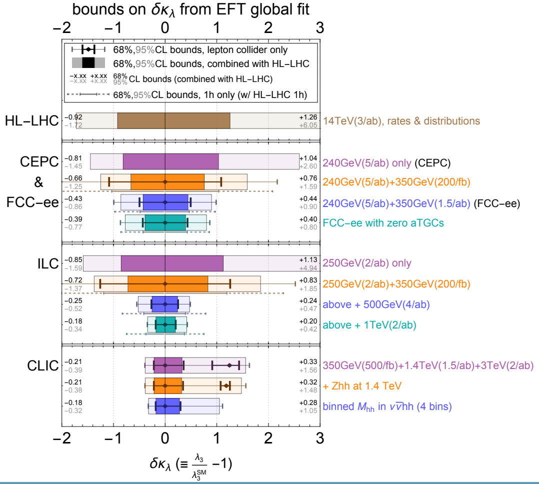
Impact on EFT fits from TGC measurements

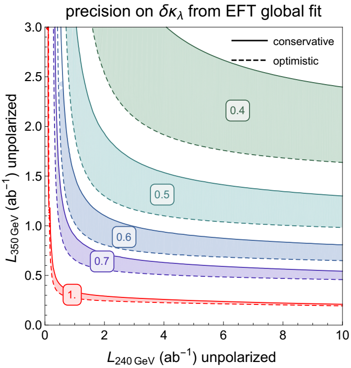


- $\delta g_{1,Z}$, $\delta\kappa_\gamma$ $\leftrightarrow$ c_{ZZ} , $c_{Z\Box}$, $c_{\gamma\gamma}$, $c_{Z\gamma}$
- We try different assumptions on the systematic uncertainties (in each bin with the differential distribution divided into 20 bins).
- Detailed study of $e^+e^- \to WW$ required to estimate the systematic uncertainties!

Impact on the triple Higgs coupling

[arXiv:1711.03978] S. Di Vita, G. Durieux, C. Grojean, JG, Z. Liu, G. Panico, M. Riembau, T. Vantalon





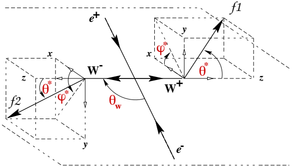
- Circular colliders can probe the triple Higgs coupling via its loop contributions.

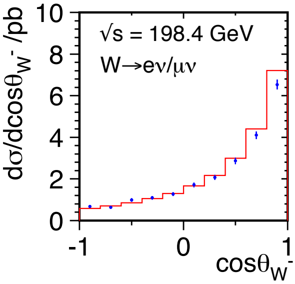
towards a real TGC analysis...

- We need a real TGC analysis for circular colliders (CEPC or FCC-ee)!
  - One-sigma bounds & correlations from global fits!
- Rate measurements are not enough.
  - At least 3 measurements are needed to independently constrain 3 aTGCs. (OK for FCC-ee)
  - The aTGCs are sensitive to the angular distributions. (*e.g.* The region with small θ_{W^-} is dominated by the t-channel diagram which does not contain the TGC vertex.)
- What's the best way to extract information from the differential (angular) observables?
- Which channels to use?
  - **semi-leptonic** ($\sim$ 42% BR, good reconstruction)
  - hadronic (hard to reconstruct, angles are folded)
  - di-leptonic (can solve the neutrino momenta but with ambiguities)

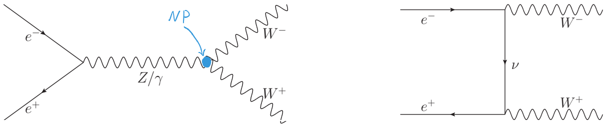
How to extract information from the angles

- 5 angles (1 production, 2 decays for each W)
- 1D histogram(s)
  - easy to do for θ_{W-}
  - can also include decay angles, but the correlations among angles are not taken account of.
- 5D histogram (would need a very large simulated sample)
  - or 3D histogram focusing on the leptonic decay angles (used in the ILC TGC analysis)
- fancier methods (see *e.g.* **hep-ph/9601233**)
  - likelihood (unbinned)
  - optimal observables
- ??





The TGC dominance assumption



- Assumption: New physics contributes to $e^+e^- \to WW$ only through the TGC vertex.
- Reality: In principle there can be many other contributions!
- Other contributions are constrained by Z-pole measurements.
  - With the Z-pole run, the TGC dominance assumption should be valid at FCC-ee.
  - Ultimately, a full EFT analysis is desired... (Z-pole + WW + Higgs)

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Conclusion

- TGC measurements are important (*e.g.* for the EFT fit of Higgs couplings)!
- We need to find a good way to extract the information from angular distributions.
- The TGC dominance assumption is probably OK.
- A global fit to the $e^+e^- \to WW$ data with all 3 aTGCs parameters, $\delta g_{1,Z}$, $\delta\kappa_\gamma$ and λ_Z!
  - One-sigma bounds & correlations!

backup slides

The "12-parameter" framework in the Higgs basis

- The relevant terms in the EFT Lagrangian are

$$\mathcal{L} \supset \mathcal{L}_{hVV} + \mathcal{L}_{hff} + \mathcal{L}_{\rm tgc} \,, \tag{2}$$

- the Higgs couplings with a pair of gauge bosons

$$\begin{aligned}\mathcal{L}_{hVV} = \frac{h}{v}\Big[& (1+\delta c_W)\frac{g^2v^2}{2}W^+_\mu W^-_\mu + (1+\delta c_Z)\frac{(g^2+g'^2)v^2}{4}Z_\mu Z_\mu \\ & + c_{WW}\frac{g^2}{2}W^+_{\mu\nu}W^-_{\mu\nu} + c_{W\Box}\, g^2 (W^-_\mu \partial_\nu W^+_{\mu\nu} + \text{h.c.}) \\ & + c_{gg}\frac{g_s^2}{4}G^a_{\mu\nu}G^2_{\mu\nu} + c_{\gamma\gamma}\frac{e^2}{4}A_{\mu\nu}A_{\mu\nu} + c_{Z\gamma}\frac{e\sqrt{g^2+g'^2}}{2}Z_{\mu\nu}A_{\mu\nu} \\ & + c_{ZZ}\frac{g^2+g'^2}{4}Z_{\mu\nu}Z_{\mu\nu} + c_{Z\Box}\, g^2 Z_\mu \partial_\nu Z_{\mu\nu} + c_{\gamma\Box}\, gg' Z_\mu \partial_\nu A_{\mu\nu}\Big] \,. \end{aligned} \tag{3}$$

The "12-parameter" framework in the Higgs basis

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

$$\delta c_W = \delta c_Z + 4\delta m\,,$$
$$c_{WW} = c_{ZZ} + 2s^2_{\theta_W} c_{Z\gamma} + s^4_{\theta_W} c_{\gamma\gamma}\,,$$
$$c_{W\Box} = \frac{1}{g^2 - g'^2}\left[g^2 c_{Z\Box} + g'^2 c_{ZZ} - e^2 s^2_{\theta_W} c_{\gamma\gamma} - (g^2 - g'^2) s^2_{\theta_W} c_{Z\gamma}\right]\,,$$
$$c_{\gamma\Box} = \frac{1}{g^2 - g'^2}\left[2g^2 c_{Z\Box} + (g^2 + g'^2) c_{ZZ} - e^2 c_{\gamma\gamma} - (g^2 - g'^2) c_{Z\gamma}\right]\,, \quad (4)$$

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

$$\mathcal{L}_{hff} = -\frac{h}{v}\sum_{f=t,c,b,\tau,\mu} m_f(1+\delta y_f)\bar{f}_R f_L + \text{h.c.}\,. \quad (5)$$

TGC

$$
\begin{aligned}
\mathcal{L}_{\rm tgc} = \; & igs_{\theta_W} A^\mu (W^{-\nu} W^+_{\mu\nu} - W^{+\nu} W^-_{\mu\nu}) \\
& + ig(1+\delta g_1^Z) c_{\theta_W} Z^\mu (W^{-\nu} W^+_{\mu\nu} - W^{+\nu} W^-_{\mu\nu}) \\
& + ig\left[(1+\delta\kappa_Z) c_{\theta_W} Z^{\mu\nu} + (1+\delta\kappa_\gamma) s_{\theta_W} A^{\mu\nu}\right] W^-_\mu W^+_\nu \\
& + \frac{ig}{m_W^2} (\lambda_Z c_{\theta_W} Z^{\mu\nu} + \lambda_\gamma s_{\theta_W} A^{\mu\nu}) W^{-\rho}_v W^+_{\rho\mu} \,, \qquad (6)
\end{aligned}
$$

- $V_{\mu\nu} \equiv \partial_\mu V_\nu - \partial_\nu V_\mu$ for $V = W^\pm, Z, A,$. Imposing Gauge invariance one obtains $\delta\kappa_Z = \delta g_{1,Z} - t_{\theta_W}^2 \delta\kappa_\gamma$ 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

$$
\begin{aligned}
\delta g_{1,Z} &= \frac{1}{2(g^2-g'^2)} \left[-g^2(g^2+g'^2) c_{Z\Box} - g'^2(g^2+g'^2) c_{ZZ} + e^2 g'^2 c_{\gamma\gamma} + g'^2(g^2-g'^2) c_{Z\gamma}\right] \\
\delta\kappa_\gamma &= -\frac{g^2}{2}\left(c_{\gamma\gamma}\frac{e^2}{g^2+g'^2} + c_{Z\gamma}\frac{g^2-g'^2}{g^2+g'^2} - c_{ZZ}\right) . \qquad (7)
\end{aligned}
$$