Anomalous QGC in the effective lagrangian framework

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I. Basic facts

- What we know:

fixed by $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ gauge symmetry

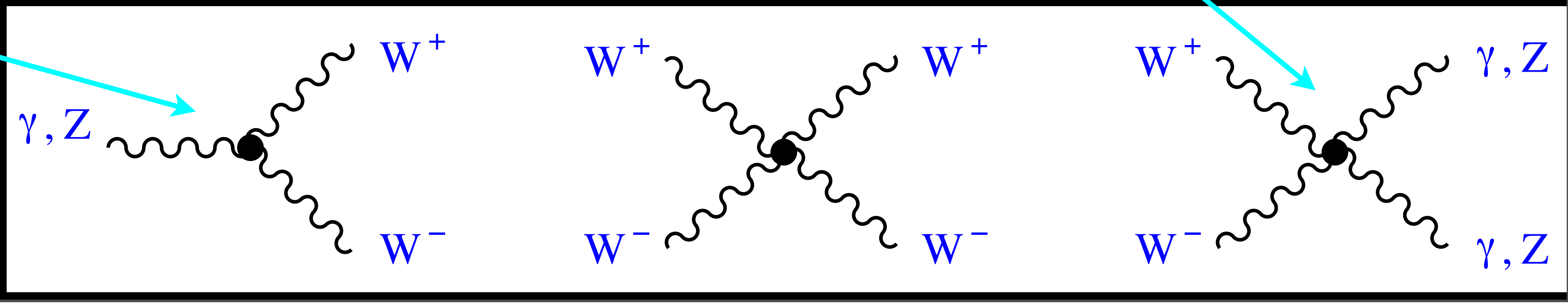
starting to explore

$$\mathcal{L} = \mathcal{L}^{\mathbf{f}}_{\rm kinetic} + \mathcal{L}^{\mathbf{GB}}_{\rm kinetic} + \mathcal{L}_{\rm ffv} + \mathcal{L}_{\rm vvv} + \mathcal{L}_{\rm vvvv} + \mathcal{L}_{\rm EWSB}$$

tested to 0.1%

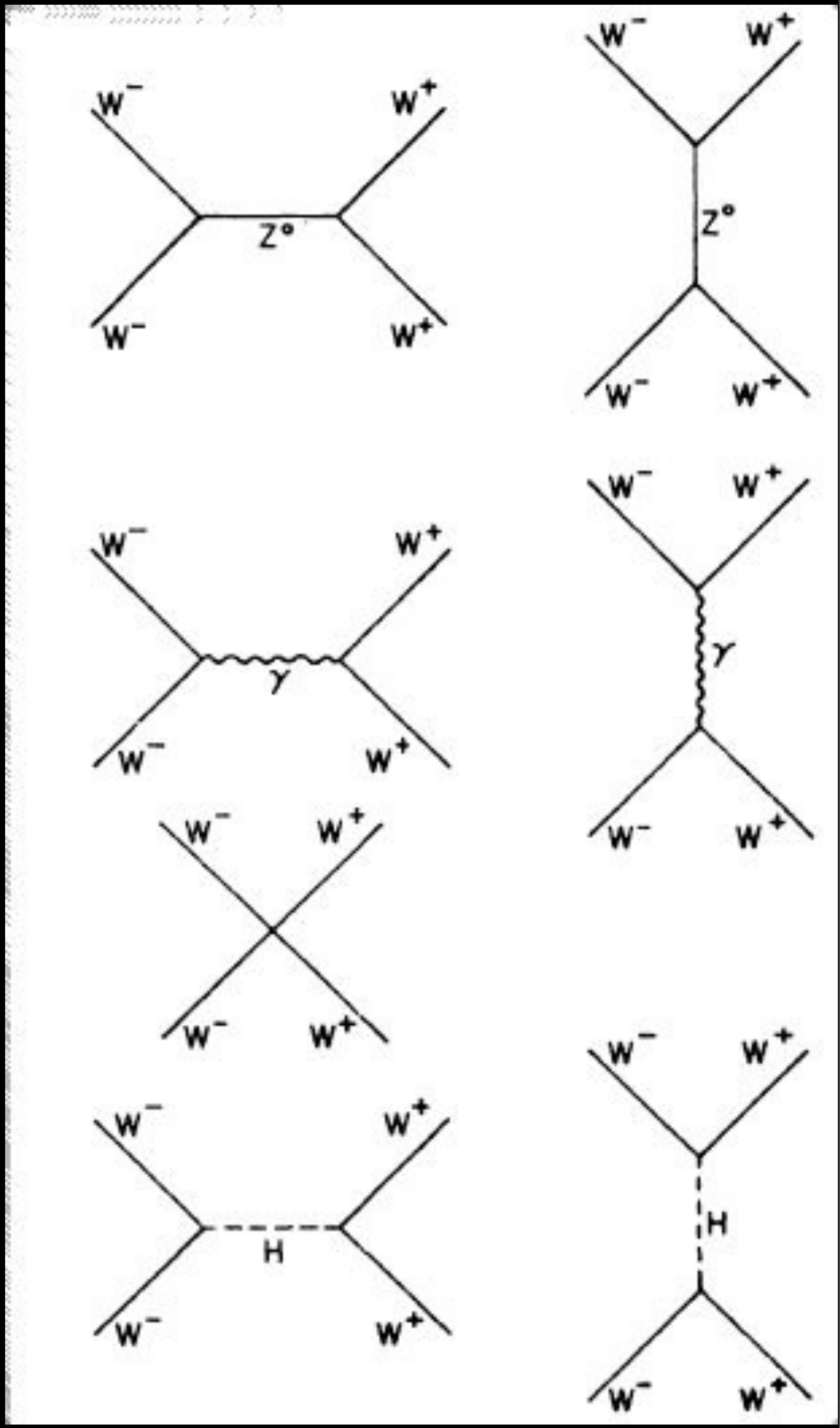
scarce information

known to ~ 5%



> Quartic couplings play in important role: $W_L^+ W_L^- \to W_L^+ W_L^-$

[Cornwall; Lee-Quigg-Thacker;etc]



- J=0 partial wave

$$A = A_4 \frac{E^4}{M_W^4} + A_2 \frac{E^2}{M_W^2} + \cdots$$

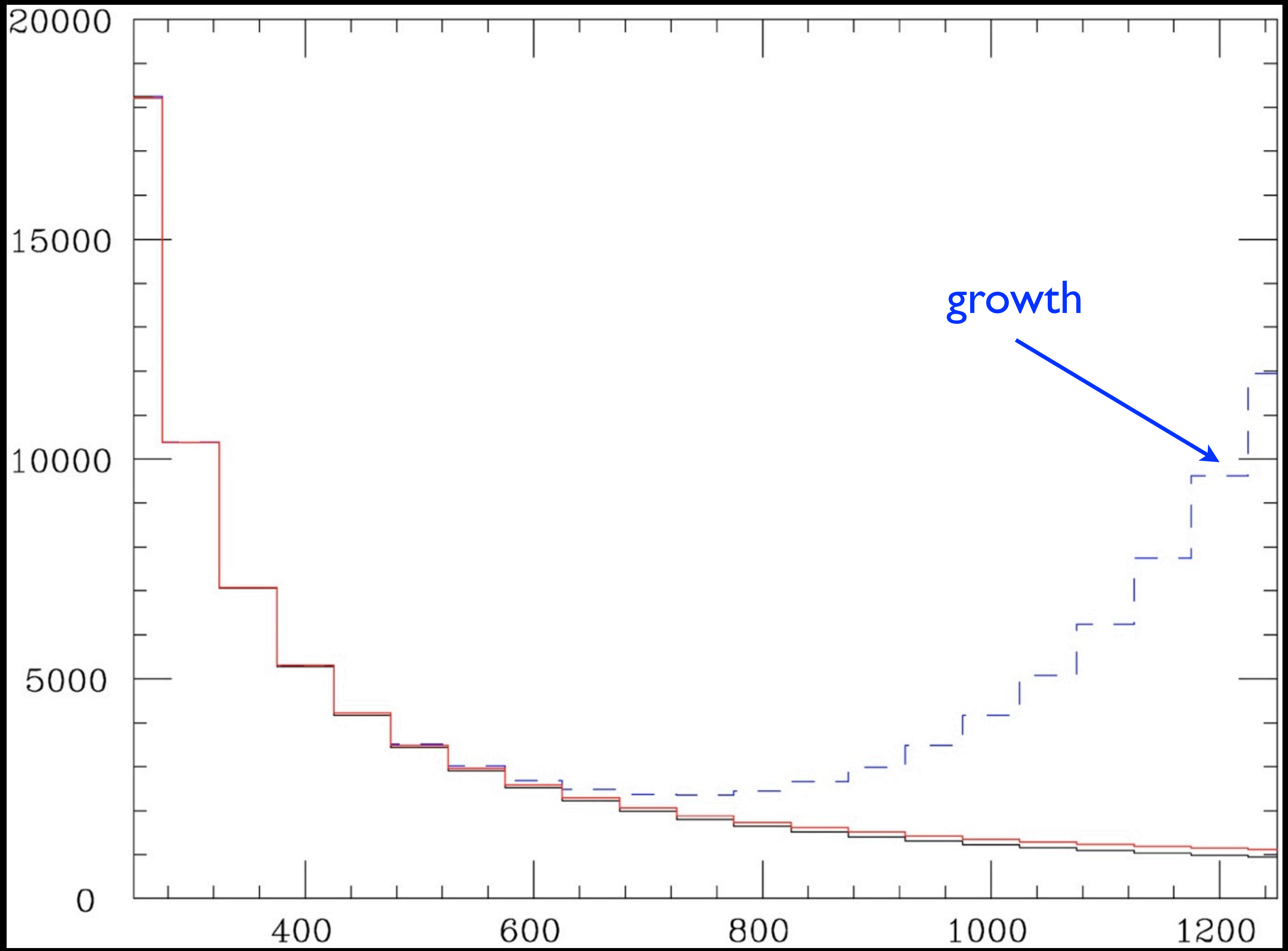
lead to unitarity violation at tree level

- In the SM

$$A_4 \propto g_{WWWW} - g^2_{WWZ} - g^2_{WW\gamma} \equiv 0$$

- H takes part into $A_2 = 0$

Deviations from SM prediction lead to growth of the cross section



VBF

$$\frac{\mathbf{d}\sigma}{\mathbf{dM_{WW}}}(\mathbf{WW} \rightarrow \mathbf{WW}) \quad \text{for} \quad \mathbf{g_{WWWW} = 1.01 g^{SM}_{WWWW}}$$

2. Effective lagrangians

> Effective lagrangians describe residual effects of new physics

> It is a bottom-up approach to study departures from the SM

> It should contain all terms compatible with

- low energy particle content
- symmetries

> It should be invariant under local $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$

> Linear realization of the symmetry if the Higgs belongs to an SU(2) doublet

> The low energy can be written as

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{f_{6j}}{\Lambda^2}\mathcal{O}_{6j} + \frac{f_{8j}}{\Lambda^4}\mathcal{O}_{8j} + \cdots$$

- Operators connected by the eqs. of motion are equivalent, so we must choose a basis. [e.g. Arzt hep-ph/9304230]

- Nice feature: symmetry relates different processes.

- For instance, to describe the Higgs interactions we can use

[arXiv:1211.4580]

$$(D_\mu\Phi)^\dagger \hat{W}^{\mu\nu}(D_\nu\Phi) \rightarrow \gamma W^+W^- \quad ZW^+W^- \quad \text{(TGC)}$$

$$(D_\mu\Phi)^\dagger \hat{W}^{\mu\nu}(D_\nu\Phi) \rightarrow h\gamma Z \quad hZZ \quad hW^+W^- \quad \text{(Higgs)}$$

- At the lowest order, TGCs are described by three operators

$$(D_\mu\Phi)^\dagger \hat{W}^{\mu\nu}(D_\nu\Phi) \qquad (D_\mu\Phi)^\dagger \hat{B}^{\mu\nu}(D_\nu\Phi) \qquad \mathrm{Tr}\left[\hat{W}^{\mu\nu}\hat{W}_{\nu\beta}\hat{W}^{\beta}{}_{\mu}\right]$$

- dimension-six operators also introduce anomalous QGC

$$(D_\mu\Phi)^\dagger \hat{W}^{\mu\nu}(D_\nu\Phi)$$

$$\Longrightarrow \quad \gamma\gamma W^+W^- \quad \gamma Z W^+W^- \quad ZZW^+W^- \quad W^+W^-W^+W^-$$

$$\mathrm{Tr}\left[\hat{W}^{\mu\nu}\hat{W}_{\nu\beta}\hat{W}^{\beta}{}_{\mu}\right]$$

- TGC and QGC come together in dimension-six operators.

> There are drawbacks to limiting ourselves to dim-6 operators

- TGC will be better measured than QGC so it will be hard to get the information on QGC

- dimension-six operators do not generate the QGCs:

$$\gamma\gamma\gamma\gamma \quad \gamma\gamma\gamma Z \quad \gamma\gamma ZZ \quad \gamma ZZZ \quad ZZZZ$$

- dimension-six operators are generated at loop level, so they might not be dominant depending on the new physics scale

[hep-ph/9405214]

We propose a different strategy: [hep-ph/0606118]

- We use effective lagrangians as "straw man" to target QGCs

- We consider effective operators that do not generate TGCs to assess possible departures from SM predictions

- For that, we need to consider dimension-eight operators

- There are many (18) operators satisfying this requirement, eg,

$$
\begin{aligned}
\mathcal{L}_{S,0} &= \left[(D_\mu \Phi)^\dagger D_\nu \Phi \right] \times \left[(D^\mu \Phi)^\dagger D^\nu \Phi \right] \\
\mathcal{L}_{S,1} &= \left[(D_\mu \Phi)^\dagger D^\mu \Phi \right] \times \left[(D_\nu \Phi)^\dagger D^\nu \Phi \right] \\
\mathcal{L}_{quartic} &= F_{S0}\, \mathcal{L}_{S,0} + F_{S1}\, \mathcal{L}_{S,1}
\end{aligned}
$$

these operators lead to lorentz structures without momenta of the gauge bosons [WWWW ,WWZZ , ZZZZ]

$$\mathcal{O}_0^{WW} = g^{\alpha\beta} g^{\gamma\delta} \left[W^+_\alpha W^-_\beta W^+_\gamma W^-_\delta \right] , \qquad \mathcal{O}_1^{WW} = g^{\alpha\beta} g^{\gamma\delta} \left[W^+_\alpha W^+_\beta W^-_\gamma W^-_\delta \right] ,$$
$$\mathcal{O}_0^{WZ} = g^{\alpha\beta} g^{\gamma\delta} \left[W^+_\alpha Z_\beta W^-_\gamma Z_\delta \right] , \qquad \mathcal{O}_1^{WZ} = g^{\alpha\beta} g^{\gamma\delta} \left[W^+_\alpha W^-_\beta Z_\gamma Z_\delta \right] ,$$
$$\mathcal{O}_0^{ZZ} = \mathcal{O}_1^{ZZ} \equiv \mathcal{O}^{ZZ} = g^{\alpha\beta} g^{\gamma\delta} \left[Z_\alpha Z_\beta Z_\gamma Z_\delta \right] ,$$

- In the SM

$$c^{WW}_{0,\mathrm{SM}} = -c^{WW}_{1,\mathrm{SM}} = \frac{2}{c_W^2} c^{WZ}_{0,\mathrm{SM}} = -\frac{2}{c_W^2} c^{WZ}_{1,\mathrm{SM}} = g^2 \qquad c^{ZZ}_{\mathrm{SM}} = 0$$

- The anomalous contributions to these Lorentz structures are

$$\Delta c_i^{WW} = \frac{g^2 v^4 f_i}{8\Lambda^4} \qquad \Delta c_i^{WZ} = \frac{g^2 v^4 f_i}{16 c_W^2 \Lambda^4} \qquad \Delta c^{ZZ} = \frac{g^2 v^2 (f_0 + f_1)}{32 c_W^4 \Lambda^4}$$

- the connection between different processes is kept
- Example: integrating out a “spin-1 state” leads to

$$\frac{f_0}{\Lambda^4} = -\frac{f_1}{\Lambda^4} = \frac{12\pi}{M_\rho^4} \frac{\Gamma_\rho}{M_\rho}$$

Connection with earlier works using non-linear operators

[pp: hep-ph/ 9805229; e+e-: hep-ph/9711499 and hep-ph/9708310]

$$\mathcal{L}_4^{(4)} = \alpha_4 \left[\mathrm{Tr}\left(\mathbf{V}_\mu \mathbf{V}_\nu\right)\right]^2 \qquad \mathcal{L}_5^{(4)} = \alpha_5 \left[\mathrm{Tr}\left(\mathbf{V}_\mu \mathbf{V}^\mu\right)\right]^2$$

$$\mathbf{V}_\mu \equiv \left(\mathbf{D}_\mu \mathbf{\Sigma}\right) \mathbf{\Sigma}^\dagger \quad \text{with} \quad \mathbf{D}_\mu \mathbf{\Sigma} \equiv \partial_\mu \mathbf{\Sigma} + \mathbf{ig}\frac{\tau^{\mathbf{a}}}{\mathbf{2}} \mathbf{W}^{\mathbf{a}}_\mu \mathbf{\Sigma} - \mathbf{ig}' \mathbf{\Sigma} \frac{\tau^{\mathbf{3}}}{\mathbf{2}} \mathbf{B}_\mu$$

the relation between the linear and non-linear coefficients is

$$\alpha_4 = \frac{\mathbf{v}^4 \mathbf{f_0}}{\mathbf{8}\mathbf{\Lambda}^4} \qquad \alpha_5 = \frac{\mathbf{v}^4 \mathbf{f_1}}{\mathbf{8}\mathbf{\Lambda}^4}$$

the dimension-8 operator list also includes

$$\mathcal{L}_{M,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$

$$\mathcal{L}_{M,1} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$

$$\mathcal{L}_{M,2} = \left[B_{\mu\nu}B^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$

$$\mathcal{L}_{M,3} = \left[B_{\mu\nu}B^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$

$$\mathcal{L}_{M,4} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}D^\mu\Phi\right] \times B^{\beta\nu}$$

$$\mathcal{L}_{M,5} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}D^\nu\Phi\right] \times B^{\beta\mu}$$

$$\mathcal{L}_{M,6} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\nu}D^\mu\Phi\right]$$

$$\mathcal{L}_{M,7} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\mu}D^\nu\Phi\right]$$

$$\mathcal{L}_{T,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}\right]$$

$$\mathcal{L}_{T,1} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right]$$

$$\mathcal{L}_{T,2} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\beta\nu}\hat{W}^{\nu\alpha}\right]$$

$$\mathcal{L}_{T,5} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times B_{\alpha\beta}B^{\alpha\beta}$$

$$\mathcal{L}_{T,6} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times B_{\mu\beta}B^{\alpha\nu}$$

$$\mathcal{L}_{T,7} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times B_{\beta\nu}B^{\nu\alpha}$$

$$\mathcal{L}_{T,8} = B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta}$$

$$\mathcal{L}_{T,9} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}$$

	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA
$\mathcal{L}_{S,0}$, $\mathcal{L}_{S,1}$	X	X	X	O	O	O	O	O
$\mathcal{L}_{M,0}$, $\mathcal{L}_{M,1}$, $\mathcal{L}_{M,6}$, $\mathcal{L}_{M,7}$	X	X	X	X	X	X	X	O
$\mathcal{L}_{M,2}$, $\mathcal{L}_{M,3}$, $\mathcal{L}_{M,4}$, $\mathcal{L}_{M,5}$	O	X	X	X	X	X	X	O
$\mathcal{L}_{T,0}$, $\mathcal{L}_{T,1}$, $\mathcal{L}_{T,2}$	X	X	X	X	X	X	X	X
$\mathcal{L}_{T,5}$, $\mathcal{L}_{T,6}$, $\mathcal{L}_{T,7}$	O	X	X	X	X	X	X	X
$\mathcal{L}_{T,9}$, $\mathcal{L}_{T,9}$	O	O	X	O	O	X	X	X

QGCs with two photons: let's consider M2 and M3

$$\mathcal{L}_{M,2} = [B_{\mu\nu} B^{\mu\nu}] \times \left[(D_\beta \Phi)^\dagger D^\beta \Phi \right] \qquad \mathcal{L}_{M,3} = [B_{\mu\nu} B^{\nu\beta}] \times \left[(D_\beta \Phi)^\dagger D^\mu \Phi \right]$$

In the unitary gauge the induced QGCs are

$$\mathcal{L}_{M,2} = \frac{f_{M,2}}{\Lambda^4} \; [c_w^2 F_{\mu\nu} F^{\mu\nu} + s_w^2 Z_{\mu\nu} Z^{\mu\nu} - 2 s_w c_w F_{\mu\nu} Z^{\mu\nu}] \; \left[\frac{g^2 v^2}{4} W^+_\beta W^{-\beta} + \frac{g^2 v^2}{8 c_w^2} Z_\beta Z^\beta \right]$$

$$\mathcal{L}_{M,3} = \frac{f_{M,2}}{\Lambda^4} \; [c_w^2 F_{\mu\nu} F^{\nu\beta} + s_w^2 Z_{\mu\nu} Z^{\nu\beta} - 2 s_w c_w F_{\nu\beta} Z^{\nu\beta}] \; \left[\frac{g^2 v^2}{4} W^+_\beta W^{-\mu} + \frac{g^2 v^2}{8 c_w^2} Z_\beta Z^\mu \right]$$

Considering just the 2 photons couplings the relation to previous works (theory, experiment, PDG) is

$$\frac{f_{M,2}}{\Lambda^4} = - \frac{a_0}{\Lambda^2} \; \frac{s_w^2}{2 v^2 c_w^2} \qquad \frac{f_{M,3}}{\Lambda^4} = - \frac{a_c}{\Lambda^2} \; \frac{s_w^2}{2 v^2 c_w^2}$$

[similar results for M0,M1]

[PDG; pp:hep-ph/0310141;hep-ph/0009262;arXiv:0907.5299
ee,ea,aa:hep-ph/9306306;hep-ph/0105238;hep-ph/0104057;hep-ph/9903315;PLB 228(92)210]

3. Closing remarks

- LHC and ILC can improve the knowledge on QCGs

- Presently the best limits come from oblique corrections and unitarity

- After the discovery of the "Higgs" it is natural to use effective lagrangians where the symmetry is realized linearly

- dimension-8 operators provide a good framework to test QCG. Tools are available http://feynrules.irmp.ucl.ac.be/wiki/AnomalousGaugeCoupling

- Question: how well do we need to know the TGCs in order to extract limits on QCGs?