Anomalous W/Z Quartic Couplings (QGCs)

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Quartic couplings, $WWZZ$, $WWZ\gamma$, $WW\gamma\gamma$, and $ZZ\gamma\gamma$, were studied at LEP and Tevatron at energies at which the Standard Model predicts negligible contributions to multiboson production. Thus, to parametrize limits on these couplings, an effective theory approach is adopted which supplements the Standard Model Lagrangian with higher dimensional operators which include quartic couplings. The LEP collaborations chose the lowest dimensional representation of operators (dimension 6) which presumes the SU(2)×U(1) gauge symmetry is broken by means other than the conventional Higgs scalar doublet [1–3]. In this representation possible quartic couplings, a_0, a_c, a_n, are expressed in terms of the following dimension-6 operators [1,2];

$$L_6^0 = -\frac{e^2}{16\Lambda^2}\, a_0\, F^{\mu\nu}\, F_{\mu\nu} \vec{W^\alpha} \cdot \vec{W}_\alpha$$

$$L_6^c = -\frac{e^2}{16\Lambda^2}\, a_c\, F^{\mu\alpha}\, F_{\mu\beta} \vec{W^\beta} \cdot \vec{W}_\alpha$$

$$L_6^n = -i\frac{e^2}{16\Lambda^2}\, a_n \epsilon_{ijk}\, W^{(i)}_{\mu\alpha}\, W^{(j)}_\nu\, W^{(k)\alpha} F^{\mu\nu}$$

$$\widetilde{L}_6^0 = -\frac{e^2}{16\Lambda^2}\, \widetilde{a}_0\, F^{\mu\nu}\, \widetilde{F}_{\mu\nu} \vec{W^\alpha} \cdot \vec{W}_\alpha$$

$$\widetilde{L}_6^n = -i\frac{e^2}{16\Lambda^2}\, \widetilde{a}_n \epsilon_{ijk}\, W^{(i)}_{\mu\alpha}\, W^{(j)}_\nu\, W^{(k)\alpha} \widetilde{F}^{\mu\nu}$$

where F, W are photon and W fields, L_6^0 and L_6^c conserve C, P separately ($\widetilde{L}_6^0$ conserves only C) and generate anomalous $W^+W^-\gamma\gamma$ and $ZZ\gamma\gamma$ couplings, L_6^n violates CP ($\widetilde{L}_6^n$ violates both C and P) and generates an anomalous $W^+W^-Z\gamma$ coupling, and Λ is an energy scale for new physics. For the $ZZ\gamma\gamma$ coupling the CP-violating term represented by L_6^n does not contribute. These couplings are assumed to be real and to vanish at tree level in the Standard Model.

Within the same framework as above, a more recent description of the quartic couplings [3] treats the anomalous parts of the $WW\gamma\gamma$ and $ZZ\gamma\gamma$ couplings separately, leading to two sets parametrized as a_0^V/Λ^2 and a_c^V/Λ^2, where $V = W$ or Z.

With the discovery of a Higgs at the LHC in 2012, it is then useful to go to the next higher dimensional representation (dimension 8 operators) in which the gauge symmetry is broken by the conventional Higgs scalar doublet [3,4]. There are 14 operators which can contribute to the anomalous quartic coupling signal. Some of the operators have analogues in the dimension 6 scheme. The CMS collaboration, [5], have used this parametrization, in which the connections between the two schemes are also summarized:

$$\begin{aligned}\mathcal{L}_{AQGC} = &- \frac{e^2}{8}\frac{a_0^W}{\Lambda^2} F_{\mu\nu}F^{\mu\nu}W^{+a}W^-_a \\ &- \frac{e^2}{16}\frac{a_c^W}{\Lambda^2} F_{\mu\nu}F^{\mu a}(W^{+\nu}W^-_a + W^{-\nu}W^+_a)\end{aligned}$$

$$
\begin{aligned}
&- e^2 g^2 \frac{\kappa_0^W}{\Lambda^2} F_{\mu\nu} Z^{\mu\nu} W^{+a} W_a^- \\
&- \frac{e^2 g^2}{2} \frac{\kappa_c^W}{\Lambda^2} F_{\mu\nu} Z^{\mu a} (W^{+\nu} W_a^- + W^{-\nu} W_a^+) \\
&+ \frac{f_{T,0}}{\Lambda^4} Tr[\widehat{W}_{\mu\nu} \widehat{W}^{\mu\nu}] \times Tr[\widehat{W}_{\alpha\beta} \widehat{W}^{\alpha\beta}]
\end{aligned}
$$

The energy scale of possible new physics is Λ, and $g = e/sin(\theta_W)$, e being the unit electric charge and θ_W the Weinberg angle. The field tensors are described in [3,4].

The two dimension 6 operators a_0^W/Λ^2 and a_c^W/Λ^2 are associated with the $WW\gamma\gamma$ vertex. Among dimension 8 operators, κ_0^W/Λ^2 and κ_c^W/Λ^2 are associated with the $WWZ\gamma$ vertex, whereas the parameter $f_{T,0}/\Lambda^4$ contributes to both vertices. There is a relationship between these two dimension 6 parameters and the dimension 8 parameters $f_{M,i}/\Lambda^4$ as follows [3]:

$$
\frac{a_0^W}{\Lambda^2} = -\frac{4M_W^2}{g^2} \frac{f_{M,0}}{\Lambda^4} - \frac{8M_W^2}{g'^2} \frac{f_{M,2}}{\Lambda^4}
$$

$$
\frac{a_c^W}{\Lambda^2} = -\frac{4M_W^2}{g^2} \frac{f_{M,1}}{\Lambda^4} - \frac{8M_W^2}{g'^2} \frac{f_{M,3}}{\Lambda^4}
$$

where $g' = e/cos(\theta_W)$ and M_W is the invariant mass of the W boson. This relation provides a translation between limits on dimension 6 operators $a_{0,c}^W$ and $f_{M,j}/\Lambda^4$. It is further required [4] that $f_{M,0} = 2f_{M,2}$ and $f_{M,1} = 2f_{M,3}$ which suppresses contributions to the $WWZ\gamma$ vertex. The complete set of Lagrangian contributions as presented in [4] corresponds to 19 anomalous couplings in total – $f_{S,i}$, $i = 1, 2$, $f_{M,i}$, $i = 0, \ldots, 8$ and $f_{T,i}, i = 0, \ldots, 9$ – each scaled by $1/\Lambda^4$.

The ATLAS collaboration [6], on the other hand, follows a K-matrix driven approach of Ref. 7 in which the anomalous couplings can be expressed in terms of two parameters α_4 and α_5, which account for all BSM effects.

It is the early stages in the determination of quartic couplings by the LHC experiments. It is hoped that the two collaborations, ATLAS and CMS, will agree to use at least one common set of parameters to express these limits to enable the reader to make a comparison and allow for a possible LHC combination.

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