**Anomalous quartic interaction among electroweak gauge bosons**

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August 21, 2012

## 0.1 Quartic interactions

We list here the parity conserving effective Lagrangians leading to pure quartic couplings between the weak gauge bosons assuming that the recently observed Higgs boson belongs to a $SU(2)_L$ doublet, that is, employing the linear representation for the higher order operators. Denoting by $\Phi$ the Higgs doublet and by $U$ an arbitrary $SU(2)_L$ transformation, the basic blocks for constructing the effective Lagrangian and their transformations are:

$$\Phi\ , \quad \text{that transforms as} \quad \Phi' = U\Phi \tag{1}$$

$$D_\mu\Phi\ , \quad \text{that transforms as} \quad D'_\mu\Phi' = UD_\mu\Phi \tag{2}$$

$$\hat{W}_{\mu\nu} \equiv \sum_j W^j_{\mu\nu}\frac{\sigma^j}{2}\ , \quad \text{that transforms as} \quad \hat{W}'_{\mu\nu} = U\hat{W}_{\mu\nu}U^\dagger \tag{3}$$

$$B_{\mu\nu}\ , \quad \text{that transforms as} \quad B'_{\mu\nu} = B_{\mu\nu} \tag{4}$$

where $W^i_{\mu\nu}$ is the $SU(2)_L$ field strength and $B_{\mu\nu}$ is the $U(1)_Y$ one. The covariant derivative is given by $D_\mu\Phi = (\partial_\mu - igW^j_\mu\frac{\sigma^j}{2} - ig'B_\mu\frac{1}{2})\Phi$.

The lowest dimension operator that leads to quartic interactions but does not exhibit two or three weak gauge boson vertices is dimension 8. The counting is straight foward: when can get a weak boson field either from the covariant derivative of $\Phi$ or from the field strength tensor. In either case the vector field is accompanied by a VEV or a derivative. Therefore genuine quartic vertices are of dimension 8 or higher.There are three classes of such operators[1]:

### Operators containing just $D_\mu\Phi$

The two independent operators in this class are

$$\mathcal{L}_{S,0} \quad = \quad \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right] \tag{5}$$

[1]Here we follow the notation of Ref. [1].

$$\mathcal{L}_{S,1} = \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right] \quad (6)$$

$$\mathcal{L}_{quartic} = F_{S0}\ \mathcal{L}_{S,0} + F_{S1}\ \mathcal{L}_{S,1} \quad (7)$$

where the constants $F_{S0(S1)}$ have dimension of GeV$^{-4}$.

The operators $\mathcal{L}_{S,0}$ and $\mathcal{L}_{S,1}$ gives rise to quartic $W^+W^-W^+W^-$, $W^+W^-ZZ$ and $ZZZZ$ interactions (see table 0.1 where we list the quartic vertices affected by the different operators) [2]. In order to simply rescale the SM quartic couplings containing $W^\pm$ and $Z$ it is enough to have $F_{S0} = -F_{S1} = f$ that modifies the SM couplings by a factor $(1 + fv^4/8)$, where $v$ is the Higgs vaccum expectation value ($v \simeq 256$ GeV).

### Operators containing $D_\mu\Phi$ and field strength

The operators in this class are:

$$\mathcal{L}_{M,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] \quad (8)$$

$$\mathcal{L}_{M,1} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] \quad (9)$$

$$\mathcal{L}_{M,2} = \left[B_{\mu\nu}B^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] \quad (10)$$

$$\mathcal{L}_{M,3} = \left[B_{\mu\nu}B^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] \quad (11)$$

$$\mathcal{L}_{M,4} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\mu\Phi\right] \times B^{\beta\nu} \quad (12)$$

$$\mathcal{L}_{M,5} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\nu\Phi\right] \times B^{\beta\mu} \quad (13)$$

$$\mathcal{L}_{M,6} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\nu} D^\mu\Phi\right] \quad (14)$$

$$\mathcal{L}_{M,7} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\mu} D^\nu\Phi\right] \quad (15)$$

In this class of effective operators the quartic gauge-boson interactions depend upon the momenta of the vector bosons due to the presence of the field strength in their definitions. Therefore, the Lorentz structure of these operators can not be reduced to the SM one.

### Operators containing just the field strength tensor

The following operators containing just the field strength tensor also lead to quartic anomalous couplings:

[2] Gauge invariance leads to vertices containing more than 4 particles. This fact is true for all effective operators that are listed here.

$$\mathcal{L}_{T,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}\right] \quad (16)$$

$$\mathcal{L}_{T,1} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right] \quad (17)$$

$$\mathcal{L}_{T,2} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\beta\nu}\hat{W}^{\nu\alpha}\right] \quad (18)$$

$$\mathcal{L}_{T,5} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times B_{\alpha\beta}B^{\alpha\beta} \quad (19)$$

$$\mathcal{L}_{T,6} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times B_{\mu\beta}B^{\alpha\nu} \quad (20)$$

$$\mathcal{L}_{T,7} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times B_{\beta\nu}B^{\nu\alpha} \quad (21)$$

$$\mathcal{L}_{T,8} = B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta} \quad (22)$$

$$\mathcal{L}_{T,9} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha} \quad (23)$$

| | WWWW | WWZZ | ZZZZ | WWAZ | WWAA | ZZZA | ZZAA | ZAAA | AAAA |
|---|---|---|---|---|---|---|---|---|---|
| $\mathcal{L}_{S,0}$, $\mathcal{L}_{S,1}$ | X | X | X | O | 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 | 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 | O |
| $\mathcal{L}_{T,0}$ ,$\mathcal{L}_{T,1}$ ,$\mathcal{L}_{T,2}$ | X | 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 | X |
| $\mathcal{L}_{T,9}$ ,$\mathcal{L}_{T,9}$ | O | O | X | O | O | X | X | X | X |

Table 1: Quartic vertices modified by each dimension-8 operator are marked with $X$.

# Bibliography

[1] O. J. P. Eboli, M. C. Gonzalez-Garcia and J. K. Mizukoshi, "$pp \to jje^{\pm}\mu^{\mp}\nu\nu$ and $jje^{\pm}\mu^{\mp}\nu\nu$ at $\mathcal{O}(\alpha^{/}_{\rceil\Updownarrow})$ and $\mathcal{O}(\alpha_{em}^{4}\alpha_{s}^{2})$ for the study of the quartic electroweak gauge boson vertex at CERN LHC," Phys. Rev. D **74**, 073005 (2006) [hep-ph/0606118].