

# Anomalous $ZZ\gamma$ , $Z\gamma\gamma$ , and $ZZV$ Couplings

Revised September 2013 by M.W. Grünewald (U. College Dublin) and A. Gurtu (Formerly Tata Inst.).

In on-shell  $Z\gamma$  production, deviations from the Standard Model for the  $Z\gamma\gamma^*$  and  $Z\gamma Z^*$  couplings may be described in terms of eight parameters,  $h_i^V$  ( $i = 1, 4; V = \gamma, Z$ ) [1]. The parameters  $h_i^\gamma$  describe the  $Z\gamma\gamma^*$  couplings and the parameters  $h_i^Z$  the  $Z\gamma Z^*$  couplings. In this formalism  $h_1^V$  and  $h_2^V$  lead to  $CP$ -violating and  $h_3^V$  and  $h_4^V$  to  $CP$ -conserving effects. All these anomalous contributions to the cross section increase rapidly with center-of-mass energy. In order to ensure unitarity, these parameters are usually described by a form-factor representation,  $h_i^V(s) = h_{i0}^V/(1 + s/\Lambda^2)^n$ , where  $\Lambda$  is the energy scale for the manifestation of a new phenomenon and  $n$  is a sufficiently large power. By convention one uses  $n = 3$  for  $h_{1,3}^V$  and  $n = 4$  for  $h_{2,4}^V$ . Usually limits on  $h_i^V$ 's are put assuming some value of  $\Lambda$ , sometimes  $\infty$ .

In on-shell  $ZZ$  production, deviations from the Standard Model for the  $ZZ\gamma^*$  and  $ZZZ^*$  couplings may be described by means of four anomalous couplings  $f_i^V$  ( $i = 4, 5; V = \gamma, Z$ ) [2]. As above, the parameters  $f_i^\gamma$  describe the  $ZZ\gamma^*$  couplings and the parameters  $f_i^Z$  the  $ZZZ^*$  couplings. The anomalous couplings  $f_5^V$  lead to violation of  $C$  and  $P$  symmetries while  $f_4^V$  introduces  $CP$  violation. Also here, formfactors depending on a scale  $\Lambda$  are used.

All these couplings  $h_i^V$  and  $f_i^V$  are zero at tree level in the Standard Model; they are measured in  $e^+e^-$ ,  $p\bar{p}$  and  $pp$  collisions at LEP, Tevatron and LHC.

## References:

1. U. Baur and E.L. Berger, Phys. Rev. **D47**, 4889 (1993).
2. K. Hagiwara *et al.*, Nucl. Phys. **B282**, 253 (1987).