Anomalous quartic couplings in six-fermion processes at the Linear Collider

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Abstract

The dimension-four genuine anomalous quartic couplings are studied in processes of six-fermion production via $e^+e^-$ collisions. Complete tree-level electroweak calculations are performed including initial-state-radiation and beamstrahlung. The analysis of final-state distributions can be used to find kinematical cuts to enhance the effects of anomalous couplings. For the parameters of the custodial-symmetry-conserving anomalous couplings a sensitivity in the range between $10^{-3}$ and $10^{-2}$ can be expected at 1 TeV.

Key words: electron-positron collisions, six fermions, anomalous gauge couplings, Monte Carlo.

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1 Introduction

The experimental measurement of the gauge self-couplings is an important test of the Standard Model (SM), that is still at the beginning at present colliders. The trilinear gauge couplings have recently become a subject of studies at LEP II and Tevatron (for recent results, see [1]), and will also be measured at the Linear Collider (LC) [2]. The quartic couplings are very weakly constrained by present experimental data, through loop diagrams [3], while the observation of quartic gauge coupling effects at tree-level at LEP is rather difficult when
photons are involved [4] and is completely outside the reach of LEP when only massive gauge bosons are present.

The determination of quadrilinear gauge couplings is of particular interest in connection with the problem of the electroweak symmetry breaking. Indeed, if a Higgs boson lighter than 1 TeV does not exist, the tree-level amplitudes for the gauge boson scattering in the Standard Model are known to violate the unitarity limits at tree-level, indicating the existence of strong interactions. This scenario can be the result of different models of symmetry breaking and may be described in the general framework of effective lagrangians, where the electroweak interactions in the low-energy limit are represented by one general parameterization [5]. Different values of the parameters correspond to different models. The effective lagrangian is organized as a power series in \( p/4\pi v \), where \( p \) is the scale of momenta of the phenomena under study and \( v \simeq 246 \) GeV is the scale of symmetry breaking. The lowest-order terms of this expansion are model-independent. The higher order terms involve new gauge coupling structures that give rise to anomalous vertices and contain coefficients that are model-dependent.

It is worth noticing that the lowest-order non-trivial quartic couplings in the effective lagrangian (that are the \( O(p^4) \) or dimension-four terms) involve only massive gauge bosons and thus their effects can be observed either in loop contributions, or at tree-level in processes with at least six fermions in the final state.

The measurement of the parameters describing the gauge self-couplings, that gives the opportunity of constraining some possible models of new physics, will be an important objective of the LC, where significant improvements will be possible with respect to present colliders for various reasons. In the first place, the c.m. energy is sufficiently high for the production of up to three gauge bosons in the final state, making it possible to study the quadrilinear couplings at tree-level. Moreover, since the deviations from the SM values of these couplings destroy the unitarity cancellations, their effect is enhanced at high energy. Finally, the special features of the LC, such as the high luminosity and the possibility of having polarized \( e^+ \) and \( e^- \) beams will provide a very high sensitivity to the anomalous couplings.

Several phenomenological studies have been performed on the possibility of constraining the anomalous quartic couplings at \( e^+e^- \) colliders in the approximation of real vector bosons in the final state, both for the couplings including photons [4] and for those involving gauge bosons only [6,7]. In the latter case, however, for more realistic predictions, as observed above, processes with at least six fermions in the final state have to be examined. This kind of processes also allows for the analysis of final-state distributions that are not accessible in the real approximation, and that can give useful information.
The objective of the present study is to analyse a class of six-fermion \((6f)\) processes where the genuine quartic gauge couplings of dimension four are involved. The results that will be shown have been obtained by means of complete tree-level calculations in the framework of the chiral approach to electroweak interactions.

In Section 2 the theoretical framework and some technical details of the calculation are explained. In Section 3 the numerical results are presented and discussed, and Section 4 contains the conclusions.

2 Theoretical framework and calculation technique

The construction of the effective lagrangian for the electroweak interactions satisfying the requirement of \(SU(2) \times U(1)\) gauge invariance may be found in the literature [8]. It will be useful to mention here that in this approach the lagrangian can be written in the form

\[
L = L_{YM} + L_F + L_S ,
\]

(1)

where \(L_{YM}\) is the Yang-Mills lagrangian,

\[
L_{YM} = -\frac{1}{4} W^i_{\mu\nu} W^{i\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} ,
\]

(2)

\(L_F\) is the fermionic contribution and \(L_S\) is the scalar contribution. The standard couplings between gauge bosons are given by the Yang-Mills lagrangian. The scalar sector is represented by means of the unitary matrix

\[
U = \exp \left( i \frac{\tau_i \pi_i}{v} \right) ,
\]

(3)

where \(v = 246\) GeV and \(\pi_i\) are the would-be Goldstone bosons. The gauge-invariant operators contributing to \(L_S\) can be constructed by taking the traces of the following building blocks:

\[
T = U \tau_3 U^\dagger
\]

(4)

\[
V_\mu = (D_\mu U) U^\dagger
\]

(5)

\[
W_{\mu\nu} = \partial_\mu W_\nu - \partial_\nu W_\mu + ig[W_\mu, W_\nu] ,
\]

(6)
where $D_\mu U = \partial_\mu U + i \frac{2}{g} \tau_1 W_\mu^\dagger U - i \frac{2}{g} B_\mu U \tau_3$. At leading order, assuming the custodial symmetry, the following contribution to $\mathcal{L}_S$ is found:

$$
\mathcal{L}_0 = \frac{v^2}{4} \text{Tr} \left( (D_\mu U)^\dagger D^\mu U \right),
$$

that gives the masses to the $W^\pm$ and $Z$ bosons.

At next-to-leading order, that corresponds to dimension four, new couplings appear, and the independent gauge-invariant structures are multiplied by coefficients that are model-dependent. At this order, trilinear and quadrilinear vertices are present. The operators that give rise to quadrilinear and not to trilinear vertices, with the condition of $CP$ conservation, are (using the standard notation):

$$
\begin{align*}
\mathcal{L}_4 &= \alpha_4 (\text{Tr}(V_\mu V_\nu))^2 \\
\mathcal{L}_5 &= \alpha_5 (\text{Tr}(V_\nu V_\mu))^2 \\
\mathcal{L}_6 &= \alpha_6 \text{Tr}(V_\mu V_\nu) \text{Tr}(TV^\mu) \text{Tr}(TV^\nu) \\
\mathcal{L}_7 &= \alpha_7 \text{Tr}(V_\mu V_\nu) (\text{Tr}(TV^\mu))^2 \\
\mathcal{L}_{10} &= \alpha_{10} \frac{1}{2} (\text{Tr}(TV_\mu) \text{Tr}(TV_\nu))^2.
\end{align*}
$$

The custodial symmetry is respected only by the operators $\mathcal{L}_4$ and $\mathcal{L}_5$, and is violated by the other three operators, due to the presence of $T$. In the unitary gauge the above terms are given by:

$$
\begin{align*}
\mathcal{L}_4 &= \alpha_4 g^4 \left( \frac{1}{2} W_\mu^+ W_\nu^+ W_\nu^--W_\mu^- + \frac{1}{2} (W_\mu^+ W_\mu^-)^2 \\
&+ \frac{1}{c_W^2} W_\mu^+ Z_\nu^- Z_\nu^+ + \frac{1}{4c_W^4} (Z_\mu Z_\mu^2) \right) \\
\mathcal{L}_5 &= \alpha_5 \left( (W_\mu^+ W_\mu^-)^2 + \frac{1}{c_W^2} W_\mu^+ W_\mu^- Z_\nu^- Z_\nu^+ \\
&+ \frac{1}{4c_W^4} (Z_\mu Z_\mu^2) \right) \\
\mathcal{L}_6 &= \alpha_6 g^4 \left( \frac{1}{c_W^2} W_\mu^+ Z_\nu^- Z_\nu^+ + \frac{1}{2c_W^4} (Z_\mu Z_\mu^2) \right) \\
\mathcal{L}_7 &= \alpha_7 g^4 \left( \frac{1}{c_W^2} W_\mu^+ W_\nu^- Z_\nu^- Z_\nu^+ + \frac{1}{2c_W^4} (Z_\mu Z_\mu^2) \right) \\
\mathcal{L}_{10} &= \alpha_{10} g^4 \frac{1}{2c_W^4} (Z_\mu Z_\mu^2)^2.
\end{align*}
$$
As can be seen, these operators give the anomalous contributions to the quadrilinear gauge couplings involving the $W^\pm$ and $Z$ vector bosons, to be added to the standard ones that are contained in the Yang-Mills lagrangian. In particular, it is easy to find, in the above formulas, anomalous contributions to the vertices $4W$ ($L_4$ and $L_5$), $WWZZ$ ($L_4$, $L_5$, $L_6$ and $L_7$) and $4Z$ (all the operators).

In this paper, the numerical results of a phenomenological study on $6f$ processes involving these anomalous couplings will be presented. These results have been obtained by means of a computer code already employed in other $6f$ analyses [9,10]. In this code the scattering amplitudes are calculated by the automatic algorithm ALPHA [11], and the Monte Carlo integration procedure is the result of an adaptation of the four-fermion codes HIGGSPV [12] and WWGENPV [13] to the $6f$ calculations. For the present study, the lagrangian in eq. (1) with $L_S = L_0 + L_4 + L_5 + L_6 + L_7 + L_{10}$ has been implemented. The case in which the coefficients $\alpha_i$ are all equal to zero is considered as a reference model, that represents the limit of infinite Higgs mass in the SM at tree-level, and the deviations from such a model when the coefficients are non-vanishing have been studied.

The input parameters are $G_\mu$, $M_W$ and $M_Z$. The widths of the $W$ and $Z^0$ bosons and all the couplings are calculated at tree-level. All the fermions are massless. For the propagators of the gauge bosons, the “fixed-width” scheme has been adopted. The reliability of this approach in $6f$ calculations at energies of the order of the TeV has been discussed in detail in ref. [9].

The aim of the present work is to provide an analysis, that has never been done till now, of the impact of a complete electroweak $6f$ calculation on the study of anomalous quartic couplings. The numerical results contained in the following section are a first illustrative application of the new implementation of anomalous couplings in the code mentioned above, and the processes considered, although not giving a complete picture of the anomalous quartic coupling phenomenology, are relevant due to their sizeable cross-sections, as can be seen below.

3 Physical processes and results

The processes $e^+e^- \rightarrow 2q + 2q'\nu\bar{\nu}$, with $q = u, c$ and $q' = d, s$, have been considered. This choice is motivated by the two objectives of having contributions from all possible quartic vertices involved in the anomalous terms under consideration, and of having no more than two neutrinos in the final state. The first point can be explained by considering the signature $u\bar{d}d\bar{u}\nu\bar{\nu}$: as can be seen in fig. 1, that shows the diagrams with a quadrilinear vertex,
Fig. 1. Diagrams with quadrilinear massive gauge boson vertices contributing to the process \( e^+ e^- \rightarrow u\bar{d} d \bar{u} \nu_e \). Notice that the diagram on the right in the first row (with a 4Z vertex) can be only anomalous, while the others have both standard and anomalous contributions.

This signature includes contributions from the 4W, WWZZ and 4Z vertices. From the point of view of the calculation, in order to obtain the correct sum over colours, with the version of ALPHA used here, that does not contain the colour degrees of freedom, it is necessary to apply a procedure analogous to the one already illustrated in ref. [10]. This procedure consists of the combination, with proper weights, of the results from the different processes and is valid in the approximation of massless quarks and unit CKM matrix. The signatures \( u\bar{d} c \bar{s} \nu_e \), \( u\bar{d} d \nu_d \hat{\nu}_e \) and \( u\bar{s} s \nu_e \hat{\nu}_e \) must be combined according to the following formula:

\[
\sigma_{uudd} + \sigma_{udcs} + \sigma_{uuss} = N_c (\hat{\sigma}_{uudd} + (2N_c - 1)(\hat{\sigma}_{udcs} + \hat{\sigma}_{uuss})) , \tag{14}
\]

where the results directly provided by ALPHA are denoted by \( \hat{\sigma} \), while the cross-sections including the colour degrees of freedom are denoted by \( \sigma \). The interested reader is referred to [10] for more details.

The signatures \( c\bar{s} d \nu_e \hat{\nu}_e \), \( c\bar{c} s \bar{s} \nu_e \hat{\nu}_e \) and \( c\bar{d} \bar{d} \nu_e \hat{\nu}_e \) are obtained from the previous ones by means of the simultaneous exchanges \( u \leftrightarrow c \) and \( d \leftrightarrow s \), and, given the set of parameters adopted here, they give exactly the same result, so that they can be easily taken into account by including a factor of 2 in eq. (14).

In principle, assuming that the \( b \)-tagging technique is applied, and thus the \( b \) quark can be identified, a realistic calculation should take into account all the possible combinations of the remaining flavours, \( u, d, c \) and \( s \) that cannot be distinguished. These combinations include, in addition to those mentioned
above, the final states \( u\bar{u}c\nu_e, u\bar{u}u\nu_e \), \( d\bar{d}s\nu_e, d\bar{d}d\nu_e \), and those obtained from these with the exchanges \( u \leftrightarrow c \) and \( d \leftrightarrow s \). Moreover a sum over the neutrino flavours should be made. Such signatures have been neglected in this first analysis. Nevertheless, it will be possible to examine the most important qualitative features of the phenomenology of anomalous gauge couplings in 6\( f \) processes, while referring to further developments for a better accuracy from a quantitative point of view.

In the following, the results of complete electroweak calculations at tree level are presented, where the above specified class of processes is considered.

As can be seen in the scattering of real gauge bosons, as a consequence of the absence of the Higgs boson and of the gauge cancellations that ensure unitarity, the cross-sections at high energy can be expected to increase rapidly and to violate the unitarity bounds. The energy at which unitarity is violated depends on the values of the parameters \( \alpha_i \); these should then be taken within some bounds if the unitarity condition has to be respected at a given energy. However, it is useful to make a first rough analysis of the dependence of the cross-sections on the anomalous parameters in a wide range, while the sensitivity to the anomalous couplings in a smaller range will be studied in a second step. Thus, in the first set of results, the cross-section has been evaluated at the two c.m. energies of 500 GeV and 1 TeV, and allowing each of the coefficients \( \alpha_i \) to vary in the range \((-0.2, 0.2)\), while keeping all the others equal to zero. A simple set of kinematical constraints has been adopted, by requiring the invariant masses of the “up-anti-up” and “down-anti-down” quark pairs to be greater than 70 GeV (where “up” stands for \( u \) and \( c \) and “down” for \( d \) and \( s \)), so as to eliminate the soft photon contributions to pair production.

In the plots of fig. 2 the cross-section is shown as a function of the various parameters \( \alpha_i \) at the two energies of 500 GeV and 1 TeV. First of all, it should be observed that the effects of the anomalous couplings are greater at 1 TeV than at 500 GeV, as expected, according to the above arguments on unitarity violation. As a consequence, the cross-section turns out to have a very strong growth with energy for large values of the anomalous coefficients. The growth of the cross-section with energy is in agreement with results for the scattering of real longitudinal gauge bosons obtained by means of the equivalence theorem [7]. Moreover it can be observed that the greatest effects are given by the coefficients \( \alpha_4 \) and \( \alpha_5 \), while the coefficient \( \alpha_{10} \) gives the smallest effect. To understand this fact it is useful to examine the expressions of the operators in eqs. (9–13), where it can be seen that \( \mathcal{L}_4 \) and \( \mathcal{L}_5 \) are the only terms where the vertex 4\( W \) appears. This vertex gives a greater enhancement with respect to the others due to the fact that the couplings of the \( W \) boson to the fermions are stronger than those of the \( Z \) boson. For the same reason, the operator \( \mathcal{L}_{10} \) has the smallest effect, since it contributes only to the 4\( Z \) vertex. Moreover the 4\( Z \) vertex, as can be seen in fig. 1, can appear only in s-channel
\[ e^+ e^- \rightarrow \nu_e \bar{\nu}_e + 2U + 2D \ (U=u, c \ D=d, s) \]

Fig. 2. Cross-section in the Born approximation as a function of the anomalous coupling parameters. The invariant masses of the pairs of up-anti-up and down-anti-down quarks are greater than 70 GeV.

diagrams, and has not the advantage of the \( t \)-channel growth at high energy.

The parameters \( \alpha_6, \alpha_7 \) and \( \alpha_{10} \), that induce violation of the custodial symmetry, are more constrained by the radiative corrections to the \( \rho \) parameter with respect to \( \alpha_4 \) and \( \alpha_5 \). For this reason, the latter are more interesting and the remaining part of the study will be restricted to them.

The behaviour of the cross-section as a function of the c.m. energy is considered in fig. 3, where the energy range between 500 GeV and 1 TeV is studied for the case without anomalous couplings and for two choices of the anomalous parameters taken as examples, \( \alpha_4 = 0.05 \) and \( \alpha_5 = 0.05 \). The invariant masses of all the possible quark pairs are required to be above 60 GeV. The solid curves include initial-state radiation [14] (ISR) and beamstrahlung [15] (BS), while the dashed ones are in the Born approximation. The growth with energy is already present when the parameters \( \alpha_i \) are equal to zero, and is enhanced when they are different from zero. The effect of ISR and BS is to reduce the effective c.m. energy, and this explains the observed lowering of 15 – 20% in
Fig. 3. Integrated cross-section with initial-state radiation and beamstrahlung (solid lines) and in the Born approximation (dashed lines) as a function of the c.m. energy. The result with all the coefficients $\alpha_i$ set to zero is compared with the cases $\alpha_4 = 0.05$ (first plot) and $\alpha_5 = 0.05$ (second plot).

...the cross-sections with respect to the Born approximation.

In order to study the sensitivity of some differential distributions to the anomalous couplings, two samples of events have then been generated, one with all the $\alpha_i$ equal to zero and the other with $\alpha_4 = 0.1$. The c.m. energy is 1 TeV and the numbers of events correspond to a luminosity of $1000 \text{ fb}^{-1}$. As in fig. 3, all the quark pairs have an invariant mass greater than 60 GeV. A relatively large value of $\alpha_4$ has been chosen, so as to have sizeable effects: indeed, the objective of this analysis is to obtain clear indications on the cuts to be applied for enhancing the sensitivity to the anomalous couplings under study. Among the variables considered, the ones that turn out to be most sensitive to the parameter $\alpha_4$ are defined in the following way. The invariant mass of the system of four jets is indicated as $M(WW)$. This variable does not require any identification procedure. The other variables that have been studied are based instead on simple identification algorithms, to take into account the fact that the quark flavours are not distinguishable. The $W$ bosons...
are reconstructed as the pairs of quarks $q_iq_j$ and $q_kq_l$ such that the quantity $|m(q_iq_j)^2 - M_W^2| + |m(q_kq_l)^2 - M_W^2|$ is minimized. The angle of one reconstructed $W$ boson with respect to the beam axis is indicated as $\theta(W)$. For each event, the four jets are ordered in transverse momentum and are labelled with $j_1, \ldots, j_4$, where $j_1$ is the one with greatest $p_t$. The invariant masses of pairs of jets are then considered, and one in particular, $M(j_3j_4)$, that is the invariant mass of the pair of jets with lowest $p_t$, is found to be most sensitive to the anomalous couplings under study. In fig. 4 the variables defined above are shown for the sample with $\alpha_4 = 0.1$ (solid histograms) in comparison with the sample where all the anomalous parameters are set to zero (dashed histograms). In these plots, where the different total numbers of events for the two samples, due to the differences of the cross-sections, must be taken into account, significant deviations are found in the shapes of the distributions. This is due to the Lorentz structures of the anomalous vertices involved, that tend to populate the region of phase-space with high transverse momenta for the gauge bosons. In view of a realistic simulation, these distributions include the effects of ISR and BS. It has been verified that these effects do not introduce significant variations with respect to the Born approximation, as can be expected, since the variables considered do not involve the momenta of the neutrinos.

On the contrary, the distribution of the missing mass, defined as $M_{\text{miss}} = \sqrt{P_{\text{miss}}^2}$, where $P_{\text{miss}}$ is the missing momentum, is strongly affected by ISR and BS. This variable, that in the Born approximation is the invariant mass of the neutrino pair, is shown in fig. 5: in the upper plot the case with $\alpha_i = 0$ is considered, while the lower plot refers to $\alpha_4 = 0.1$. The solid histograms include ISR and BS, the dashed histograms are in the Born approximation. In both plots the peaks corresponding to the $Z$ mass are almost cancelled by the effects of ISR and BS.

Results very similar to those illustrated above are obtained for the coupling $\alpha_5$. On the basis of this analysis of distributions, suitable cuts have then been determined to enhance the sensitivity to the anomalous couplings $\alpha_4$ and $\alpha_5$. The results are given in fig. 6, where the cross-section in the Born approximation is shown as a function of the parameters $\alpha_4$ (upper plot) and $\alpha_5$ (lower plot) in the range $(-0.01, 0.01)$.

The cuts are defined as follows: $M(WW)$ is greater than 420 GeV, the invariant mass of the two jets with the lowest transverse momenta, $m(j_3j_4)$, is greater than 80 GeV and the angle of one reconstructed $W$ boson with respect to the beam axis satisfies $\cos \theta(W) < 0.7$. Moreover, the invariant mass of all the quark pairs is greater than 60 GeV. It has been found that neither the addition of a cut on the variable $p_t(W)$ nor its substitution to one of the above cuts can improve the results obtained. In the same plots, the $1\sigma$ limits around the value of the cross-section for $\alpha_i = 0$, with an experimental error
Fig. 4. Comparison between two samples of events with $\alpha_4 = 0.1$ (solid histograms) and $\alpha_5 = 0$ (dashed histograms) in the presence of initial-state-radiation and beam-strahlung. The samples are normalized to a luminosity of 1000 fb$^{-1}$, and have different numbers of events, due to the different cross-sections. (a): invariant mass distribution of the system of four jets; (b): distribution of the transverse momentum of the reconstructed $W$ boson; (c): angular distribution of the reconstructed $W$ boson with respect to the beam axis; (d): invariant mass distribution of the pair of quarks with lowest transverse momenta.

corresponding to a luminosity of 1000 fb$^{-1}$, are shown. It can be seen that the sensitivity to the parameters $\alpha_4$ and $\alpha_5$ turns out to be in the range between $10^{-3}$ and $10^{-2}$. These conclusions are not modified by the introduction of ISR and BS, since the variables used in the cuts are not sensitive to these effects.

4 Conclusions

The analysis of anomalous dimension-four quartic gauge couplings involves processes with at least six fermions in the final state. A set of processes of this kind has been considered in this work. By using a Monte Carlo event
generator that has already been employed for other phenomenological studies on 6f physics, complete tree-level results have been obtained, in the context of the electroweak chiral lagrangian formalism. The five dimension-four operators giving genuine quartic anomalous couplings have been considered, and a special attention has been devoted to the two custodial-symmetry conserving ones, usually indicated by $L_4$ and $L_5$ and involving the parameters $\alpha_4$ and $\alpha_5$. After studying the energy dependence of the cross-section and the effects of initial-state-radiation and beamstrahlung, a set of kinematical cuts has been considered in order to enhance the signals of the anomalous couplings. A sensitivity to the parameters $\alpha_4$ and $\alpha_5$ in the range between $10^{-3}$ and $10^{-2}$ has been found at 1 TeV.

The results discussed above can be seen as an example of the possibilities of study of these phenomena through a complete tree-level simulation of 6f processes. In order to make the calculations quantitatively more accurate, some simplifications that have been adopted here should be eliminated: namely the class of signatures to be taken into account should include a full sum over the indistinguishable neutrino and quark flavour combinations in the final state,
Fig. 6. Integrated cross-section in the Born approximation at a c.m. energy of 1 TeV, as a function of $\alpha_4$ (first plot) and $\alpha_5$ (second plot) with a set of kinematical cuts studied to enhance the sensitivity to the anomalous couplings. The horizontal solid lines are the $1\sigma$ bounds around the $\alpha_i = 0$ value (dashed line), with the experimental uncertainty corresponding to a luminosity of 1000 fb$^{-1}$.

and the effect of QCD backgrounds should be considered. In particular the latter improvement can be achieved by means of the last version of ALPHA [16], that includes the QCD lagrangian. Moreover, the role of polarization of the initial electrons and positrons could be investigated. These points will be the subject of future developments.

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