Experimental Studies of Strong Electroweak Symmetry Breaking in Gauge Boson Scattering and Three Gauge Boson Production

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Abstract. If no light Higgs boson exist, the interaction among the gauge bosons becomes strong at high energies ($\sim$ 1TeV). The effects of strong electroweak symmetry breaking (SEWSB) could manifest themselves as anomalous couplings before they give rise to new physical states, thus measurement of all couplings and their possible deviation from Standard Model (SM) values could give valuable information for understanding the true nature of symmetry breaking sector. Here we present a detail study of the measurement of quartic gauge couplings in weak boson scattering processes and a possibility for same measurement in triple weak boson production. Expected limits on the parameters $\alpha_4, \alpha_5, \alpha_6, \alpha_7$ and α_{10} in electroweak chiral Lagrangian are given.

1. INTRODUCTION

Investigation of the true mechanism that triggers electroweak symmetry breaking is one of the most intriguing questions that are still open in the SM. If we start with minimal set of assumptions and adopt an effective Lagrangian approach [1] then all our knowledge and ignorance about the underlying working theory is parameterized in set of couplings that are associated with operators making the theory finite to a given order. In the Higgs-less scenario anomalous quartic couplings $\alpha_4, \alpha_5, \alpha_6, \alpha_7$ and α_{10} of (longitudinally polarized) W and Z boson are of interest since they give information on the underlying dynamic of the new symmetry. The set of operators that we consider

$$L_4 = \frac{\alpha_4}{16\pi^2} tr(V_\mu V_\nu) tr(V^\mu V^\nu) \quad , L_5 = \frac{\alpha_5}{16\pi^2} tr(V_\mu V^\mu) tr(V_\nu V^\nu) \tag{1}$$

$$L_6 = \frac{\alpha_6}{16\pi^2} tr(V_\mu V_\nu) tr(TV_\mu)) tr(TV^\nu) \quad , L_7 = \frac{\alpha_7}{16\pi^2} tr(V_\mu V_\mu) tr(TV_\nu)) tr(TV^\nu) \quad , L_{10} = \frac{\alpha_{10}}{32\pi^2} (tr(TV_\mu)) tr(TV_\nu))^2 \tag{2}$$

uses the same notation as in [2], thus the results can be directly compared. Equation (1) contains SU$(2)_c$ conserving operators and (2) ones that are allowed if isospin symmetry is not conserved. Full set of possible scattering processes that could be used to extract the couplings is given in Table I, where we have tried to cover all of them with at least one decay channel (fully hadronic). Only in the multi-parameter analysis do mutual interplay of the couplings come in to the result, thus making the prediction more realistic.

Table I: Sensitivity to quartic anomalous couplings for all possible scattering processes

$e^+e^- \to$	$e^-e^- \to$	α_4	α_5	α_6	α_7	α_{10}
$W^+W^- \to W^+W^-$	$W^-W^- \to W^-W^-$	+	+			
$W^+W^- \to ZZ$		+	+	+	+	
$W^\pm Z \to W^\pm Z$	$W^-Z \to W^-Z$	+	+	+	+	
$ZZ \to ZZ$	$ZZ \to ZZ$	+	+	+	+	+

Table II: Generated processes and cross sections of signal and background for $\sqrt{s} = 1$TeV, polarization 80% left for electron and 40% right for positron beam

Channel	$\sigma[fb]$	**Channel**	$\sigma[fb]$
$e^+e^- \to \nu_e\bar{\nu}_e W^+W^- \to \nu_e\bar{\nu}_e q\bar{q}q\bar{q}$	23.19	$e^-e^- \to \nu_e\bar{\nu}_e W^-W^- \to \nu_e\bar{\nu}_e q\bar{q}q\bar{q}$	27.964
$e^+e^- \to \nu_e\bar{\nu}_e ZZ \to \nu_e\bar{\nu}_e q\bar{q}q\bar{q}$	7.624	$e^-e^- \to e^-\nu_e W^-Z \to e^-\nu_e q\bar{q}q\bar{q}$	80.2
$e^+e^- \to \nu\bar{\nu}q\bar{q}q\bar{q}$ (3V contribution)	9.344	$e^-e^- \to e^-e^-ZZ \to e^-e^-q\bar{q}q\bar{q}$	3.16
$e^+e^- \to \nu eWZ \to \nu eq\bar{q}q\bar{q}$	132.3	$e^-e^- \to e^-e^-W^+W^- \to e^-e^-q\bar{q}q\bar{q}$	443.9
$e^+e^- \to e^+e^-ZZ \to e^+e^-q\bar{q}q\bar{q}$	2.09	$e^-e^- \to e^-e^-t\bar{t} \to e^-e^-X$	0.774
$e^+e^- \to e^+e^-W^+W^- \to e^+e^-q\bar{q}q\bar{q}$	414.6	$e^-e^- \to ZZ \to q\bar{q}q\bar{q}$	232.875
$e^+e^- \to t\bar{t} \to X$	331.768	$e^-e^- \to e^-\nu_e W^- \to e^-\nu_e q\bar{q}$	235.283
$e^+e^- \to W^+W^- \to q\bar{q}q\bar{q}$	3560.108	$e^-e^- \to e^-e^-Z \to e^-e^-q\bar{q}$	125.59
$e^+e^- \to ZZ \to q\bar{q}q\bar{q}$	173.221		
$e^+e^- \to e\nu W \to e\nu q\bar{q}$	279.588		
$e^+e^- \to e^+e^-Z \to e^+e^-q\bar{q}$	134.935		
$e^+e^- \to q\bar{q} \to X$	1637.405		

2. VECTOR BOSON SCATTERING

2.1. General Layout

We assume a center of mass energy of 1TeV and a total luminosity of 1000fb^{-1} in e^+e^- and 350fb^{-1} in e^-e^- mode. Beam polarization of 80% for electrons and 40% for positrons is also assumed. The six fermion processes under study correspond to the scattering of longitudinal weak bosonos. Since triple weak boson production is also sensitive to quartic anomalous couplings (ZZ or W^+W^- with neutrinos of second and third generation as well as a part of $\nu_e\bar{\nu}_e WW(ZZ)$, $e\nu_e WZ$ and $e^+e^-W^+W^-$ final states) there is no distinct separation of signal and background. Signal processes in separate analysis are thus affected by all other signal processes as well as pure background. In comparison to the previous study [2] single weak boson production was included in background for completeness and in order to get closer to the experimental conditions initial state radiation was taken into account when generating events. For the generation of $t\bar{t}$ events Pythia [3] was used, for all other processes the full six fermion generator WHIZARD [4] was used. No flavor summation was done since all possible quark final states were generated. Hadronisation was done with Pythia. The SIMDET [5] program was used to produce the detector response of a possible ILC detector. Table II contains a summary of all generated processes used for analysis and corresponding cross sections. For pure background processes a full 1ab^{-1} sample was generated, all signal processes were generated with higher statistics. Single weak boson processes and $q\bar{q}$ events were generated with an additional cut on M($q\bar{q}$)>130GeV to reduce number of generated events.

The observables sensitive to the quartic couplings are the total cross section (either reduction or increase depending on the interference term in the amplitude and the point in parameter space), and modification of the differential corross section distributions over polar angle as well over decay angle. This is not a full set of observables but some sensitive event variables, for example transverse momentum, cannot be used since contribution of longitudinally polarized weak bosons is dropping faster then for transversally polarized wak bosons with increasing transverse momentum and a transverse momentum cut is an unavoidable tool to suppress background in analysis.

2.2. Event selection

Event selection was done using a cut based approach similar to previous analysis [2]. The general steps in the analysis were the use of final state $e^-(e^+)$ to tag background (signal in $e\nu_e WZ$ case), a cut on transverse momentum, and missing mass and energy. Realistic ZVTOP b-tagging [6] was used when possible to enhance signal to background

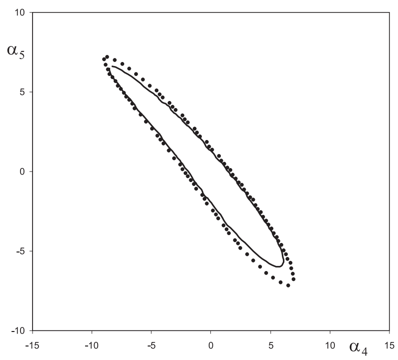

Figure 1: The influence of ISR on result for W^+W^- scattering at 800GeV, 68% confidence level contour, full line with ISR, dotted no ISR

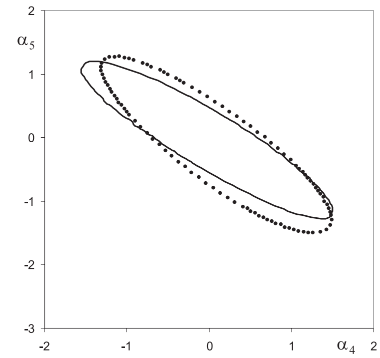

Figure 2: Reachable sensitivity using only the e^+e^- mode (full line) and combination of e^+e^- and e^-e^- equally sharing time (dotted line) at 1TeV, 68% confidence level contour

separation. Finally cuts around the nominal masses of weak boson were used to accept only well reconstructed events. The effects of the introduction of ISR were investigated at center of mass energy of 800GeV and W^+W^- scattering as an example. The signal event sample was generated with and without ISR and the fit results were compared without taking background into consideration. The difference in the fit result, Fig. 1 show, as expected, deterioration of the result to a small extent. The significant effect of ISR is on the smearing of kinematic distributions and making harder signal background separation.

2.3. Fit method and results

Extraction of quartic gauge couplings from reconstructed kinematic variables was done with a binned likelihood fit. For each signal process statistics much larger than the nominal one (1000fb^{-1} for e^+e^-) were generated and passed through the detector simulation. Each event is described by reconstructing four kinematic variables - event mass, absolute value of production angle cosine and absolute values of decay angle cosines of each reconstructed weak boson. The absolute value of the production and decay angles were used since there is no possibility to resolve quark antiquark and W^+W^- ambiguities. Matrix element calculation from WHIZARD was used to obtain weights to reweight the event as a function of quartic gauge couplings. Each Monte Carlo SM event is weighted by:

$$R(\alpha_i, \alpha_j) = 1 + A\alpha_i + B{\alpha_i}^2 + C\alpha_j + D{\alpha_j}^2 + E\alpha_i\alpha_j \tag{3}$$

Function $R(\alpha_i, \alpha_j)$ describes the quadratic dependence of the differential cross-section on the couplings. It is obtained in the following way: using the generated SM events ($\alpha_i = 0, i = 4, 5, 6, 7, 10$) we recalculated the matrix elements of the event for a set of five different points in α_i, α_j space and solve a set of linear equations for A,B,C,D and E. Due to the linear combination in which couplings contribute in amplitude [7], in any case five points are enough to determine the constants for weighting function. Choice of the points varied from process to process in order to fulfill the following conditions: distance of the point from SM value should be large enough not to come in numerical instabilities problem when solving equations and at the same time small enough not to come in to the region were phase space population would be significantly different from the SM. Four dimensional event distributions are fitted with MINUIT [8] maximizing the likelihood as a function of α_i,α_j taking the SM Monte Carlo sample as “data”.

$$L(\alpha_p, \alpha_q) = -\sum_{i,j,k,l} N^{SM}(i,j,k,l)\ln\left(N^{\alpha_p,\alpha_q}(i,j,k,l)\right) + \sum_{i,j,k,l} N^{\alpha_p,\alpha_q}(i,j,k,l) \tag{4}$$

where i runs over the reconstructed event energy, j over the production angle, k and l over the decay angles,$N^{SM}(i,j,k,l)$ are the “data” which correspond to the SM Monte Carlo sample and $N^{\alpha_p,\alpha_q}(i,j,k,l)$ is the sum of same SM events in the bin each weighted by $R(\alpha_p, \alpha_q)$. Pure background events have $R(\alpha_p, \alpha_q) = 1$, and for

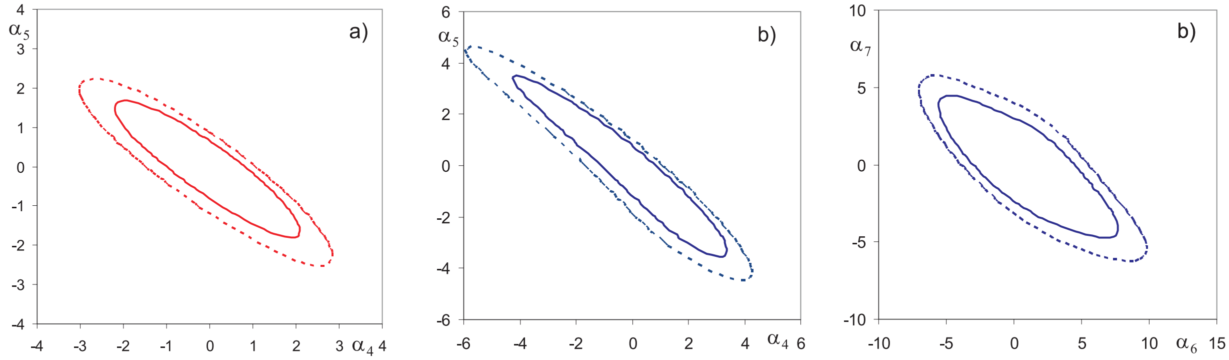

Figure 3: Expected sensitivity (combined fit to all sensitive processes) to quartic anomalous couplings form 1000fb^{-1} e^+e^- sample full line (inner one) represents 68% and dotted (outer one) 90% confidence level a) conserved SU(2)$_c$ case b) broken SU(2)$_c$ case

background coming from other sensitive processes the proper weight is taken into account. After separate analysis of each process from Table I a combined fit was done. Small fraction of double counted events that remains after single process analysis was uniquely assigned to one or another set according to the distance from the nominal mass of the weak boson pair (for example WW or ZZ). The analysis was primarily focused on e^+e^- mode since we expect significantly larger integrated luminosity in this mode. Effects of possible e^-e^- option were considered in following way. If available time for running the collider at a given center of mass energy is fixed and e^-e^- option exists we can divide running time between e^+e^- and e^-e^- assuming that the ratio of their integrated luminosities is 3:1 and then do the fit to the whole data sample. A combined fit for 2ab$^-$1 e^+e^- was done and compared with the combined result from 1ab$^-$1 e^+e^- together with a 350fb$^-$1 e^-e^- sample. The confidence level contours in Fig. 2 show negligible difference in reachable sensitivity in these two cases.

Table III: The expected sensitivity from 1000fb$^{-1}e^+e^-$ sample at 1TeV in SU(2)$_c$ conserving case, positive and negative one sigma errors given separately.

coupling	$\sigma-$	$\sigma+$
α_4	-1.41	1.38
α_5	-1.16	1.09

Table IV: The expected sensitivity from 1000fb$^{-1}e^+e^-$ sample at 1TeV in broken SU(2)$_c$ case, positive and negative one sigma errors given separately.

coupling	$\sigma-$	$\sigma+$
α_4	-2.72	2.37
α_5	-2.46	2.35
α_6	-3.93	5.53
α_7	-3.22	3.31
α_{10}	-5.55	4.55

Table III and Table IV contain results for weak boson scattering assuming integrated luminosity of 1000fb^{-1} in e^+e^- mode in SU(2)$_c$ conserving case and broken SU(2)$_c$.

3. TRIPLE BOSON PRODUCTION

We consider now the reactions $e^+e^- \to W^+W^-Z$ and $e^+e^- \to ZZZ$. On tree level the elementary process producing the WWZ final state is driven by 15 Feynman diagrams. Only one of the diagrams contains the quartic coupling and has to be extracted from the other interfering terms. Only the part containing a longitudinal gauge boson is expected to give a sizable signal related to electroweak symmetry breaking. For WWZ this part is substantially enhanced using polarized beams. We investigate several cases: i) unpolarized, ii) 80% right polarized electrons, and iii) 80% right polarized electrons along with 60% left polarized positrons. For ZZZ polarization is not substantial, since the standard model background is much smaller (two diagrams). Calculations are done using the Whizard event generator [4]. Since the gauge bosons are short lived states they decay. Presently we consider on-shell gauge bosons only (narrow width approximation) and hadronize the final state using PYTHIA [3].The three-boson state is characterized by three four-momenta and the bosonic spins. In general three momenta lead to 12 kinematical variables that are reduced by four through energy momentum conservation, by three because of the on-shell condition mentioned before, and by two due to rotational invariance. Hence in total three independent kinematical variables are left. We choose two invariant masses of the Dalitz plot, M^2_{WZ}, M^2_{WW} and the angle θ between the beam axis and the direction of the Z-boson. Spin of the bosons leads to additional degrees of freedom, and we may distinguish longitudinal (L) from transverse (T) polarization. Presently, we do not yet analyze the bosonic spins.

The three independent kinematical variables lead to a three dimensional histogram. If the angle θ is not measured the resulting two dimensional histogram leads a Dalitz plot. We investigate the differences on the histograms as a function of α_4 and α_5. The observable are discretize into bins and χ^2 is given by

$$\chi^2 = \sum_{i,j,k} \frac{N^{\rm exp}_{ijk} - N^{\rm theo}_{ijk}(\alpha_4, \alpha_5)}{\sigma^2_{ijk}} \tag{5}$$

where σ_{ijk} denotes the error, and i, j, k the sums over bins of M^2_{WZ}, M^2_{WW}, and θ.

We use the Whizard generator to produce standard model events corresponding to a luminosity of 1000 fb^{-1}. The detector efficiency is simulated using the fast simulation SIMDET [5]. To reconstruct WWZ, we use the decay $WWZ \to 6$ jets. The dominant background is due to $t\bar{t} \to b\bar{b}WW \to 6$ jets. In the absence of a full simulation at 1000 GeV we estimate from our previous studies at 500 GeV [9] a combined effect of efficiency and purity to be 42%. A full simulation at 1000 GeV is presently under development. The probabilities of standard model events are reweighted when introducing anomalous couplings α_4, α_5. Since the effective Lagrangian is linear in α_4, α_5 any observable is of second order in the parameters and can be expressed by a polynomial with five parameters. The parameters are determined by evaluation of $N^{\rm theo}_{ijk}(\alpha_4, \alpha_5)$ for each event and for five pairs of fixed values (α_4, α_5). By inversion $N^{\rm theo}_{ijk}(\alpha_4, \alpha_5)$ is know for arbitrary values of (α_4, α_5), viz.

$$N^{\rm theo}_{ijk}(\alpha_4, \alpha_5) = N^{\rm sm}_{ijk} + N^{\rm A}_{ijk}\alpha_4 + N^{\rm B}_{ijk}\alpha_4^2 + N^{\rm C}_{ijk}\alpha_5 + N^{\rm D}_{ijk}\alpha_5^2 + N^{\rm E}_{ijk}\alpha_4\alpha_5 \tag{6}$$

for each bin i, j, k. Finally we calculate χ^2 and determine $\Delta\alpha_4(\alpha_4, \alpha_5)$ and $\Delta\alpha_5(\alpha_4, \alpha_5)$ for the specific values $\chi^2 = 2.30$ (68.3% confidence) and $\chi^2 = 4.61$ (90% confidence). Results are shown in Fig. 4. We find that the sensitivity drastically increases with polarization. Sensitivity can be improved even further by utilizing meaningful cuts, which has not been done in the present stage of analysis and by using the information of angular distribution of the jets that depends on the polarization stage of the final bosons.

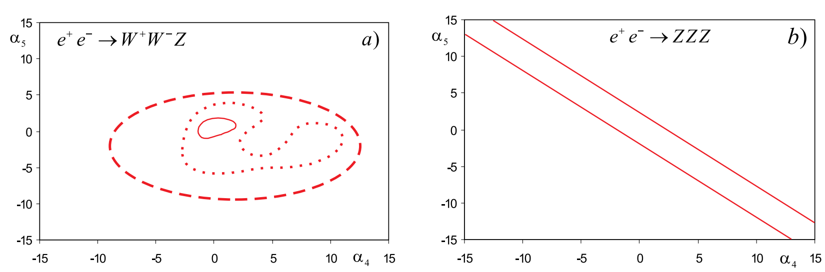

Figure 4: Expected sensitivity for α_4 and α_5 at $\sqrt{s} = 1000$ GeV. The lines represent 90% confidence level. Luminosity assumption 1000 fb^{-1}. a) $e^+e^- \to WWZ$: unpolarized case dashed line , e^- right-polarized to 80% dotted line , e^+ additionally left-polarized to 60% full line b) $e^+e^- \to ZZZ$ unpolarized.

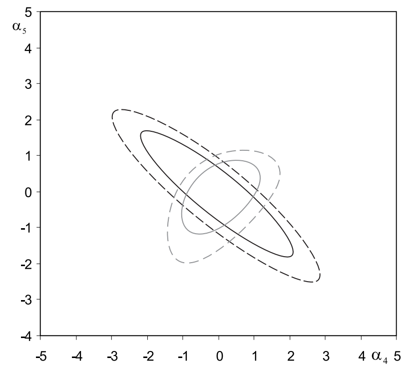

Figure 5: Comparison of estimated sensitivities for α_4 and α_5 at $\sqrt{s} = 1000$GeV from weak boson scattering (black) ad triple boson production (gray). Lines represent 68% (full) and 90% (deshed) confidence level contours.

4. Conclusion

Expected limits on the measurement of anomalous quartic couplings from all possible weak boson scattering processes were presented. In Fig. 5 we make a comparison of estimated sensitivities from weak boson scattering processes and ongoing triple boson production analysis. With the same integrated luminosity and 80% left e^- and 40% right e^+ polarization for scattering and 80% right e^+ and 60% left e^- polarization for triple production we obtain comparable results. This shows that luminosity sharing of opposite polarization can probably lead to the same overall accuracy for the measurement of quartic boson couplings. The same luminosity based conclusion was made after comparison of e^+e^- and e^-e^- running modes leaving the experimental physicist several ways to achieve the desired precision.

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