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Triple and quartic gauge couplings at LEP 2

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Abstract. We review the status of published and preliminary measurements of triple and quartic gauge boson couplings from the four LEP experiments. Charged current triple gauge boson couplings (WWZ and WWγ) are measured using W-pair, single-W and single-γ productions with the data collected between 1997 and 2000 (700 pb^{-1} per experiment). Neutral current triple gauge boson couplings are studied with Zγ (Z$\gamma\gamma^*$ and ZγZ* vertices) and ZZ (ZZγ^* and ZZZ* vertices) events. Limits on anomalous quartic gauge boson couplings with at least one photon (WW$\gamma\gamma$, WWZγ and ZZ$\gamma\gamma$) are set from WWγ, $q\bar{q}\gamma\gamma$ and $\nu\bar{\nu}\gamma\gamma$ events. No strong deviations from the Standard Model expectations are found.

1 Introduction

One of the most crucial consequence of the non-Abelian gauge structure of the Standard Model is the existence of triple and quartic gauge boson couplings at tree level. Conversely, a precise measurement of the specific form of non-Abelian self-couplings can be used to tightly constrained the electroweak sector. As a consequence, the measurement of gauge boson couplings and the search for possible anomalous effect due to some new physics is one of the major goal of LEP2 [1]. Trilinear and quartic couplings measurements are complementary as they conceptually probe different aspects of the weak interaction. While triple gauge boson couplings directly test the non-Abelian gauge structure, quartic couplings probe the mechanism for electroweak symmetry breaking [2].
During its second phase of operation, LEP has steadily increased its centre-of-mass energy from 183 GeV to 209 GeV, integrating approximately 700 pb^{-1} per experiment. This increase in energy allows the measurement of different kinds of trilinear and quartic gauge boson couplings:

– Charged triple gauge boson couplings (cTGC) are precisly constrained by W-pair, single-W and single-γ productions. In particular, about 10,000 W-pair events were collected per experiment making measurements sensitive to $\mathcal{O}(\alpha_{em})$ corrections in the WW production process.
– Neutral triple gauge boson couplings (nTGC) are studied with Zγ and ZZ events. Although the vertices are not present in the Standard Model at tree level, some contributions are arising at quantum level which could be sensitive to anomalous effects.
– Quartic gauge boson couplings (QGC) from the WW$\gamma\gamma$, WWZγ and ZZ$\gamma\gamma$ vertices are measured through three different physics processes: $e^+e^- \to W^+W^-\gamma$, $e^+e^- \to \nu\bar{\nu}\gamma\gamma$ and $e^+e^- \to q\bar{q}\gamma\gamma$.

Below, we describe the three different kinds of couplings.

2 Charged triple gauge boson couplings

The most general Lorentz invariant Lagrangian describing the WWV (V=Z or γ) vertices has fourteen complex couplings [3]:

– six of them conserve C and P (g_1^V, κ_V and λ_V),
– two violate C and P but conserve CP (g_5^V),
– six are CP violating (g_4^V, $\tilde{\kappa}_V$ and $\tilde{\lambda}_V$).

Assuming electromagnetic gauge invariance, C and P invariance, the number of remaining free couplings is five. As proposed in [1], further gauge constraints are used by the LEP experiments:

$$\kappa_Z = g_1^Z + (\kappa_\gamma - 1)tan^2\theta_W, \lambda_Z = \lambda_\gamma,$$

where θ_W is the weak mixing angle. In the Standard Model at tree level, $g_1^Z = \kappa_\gamma = 1$ and $\lambda_\gamma = 0$. At quantum level, coupling values are affected by vertex corrections from Standard Model particles ($\simeq 10^{-3}$) and could also be affected by new particles existing at a higher energy scale Λ ($\simeq 10^{-3}$ for MSSM).

2.1 W^+W^- analysis

W pair production is the main process at LEP to constrain charged current TGC. Through the s-channel diagrams, W pair production is sensitive to all kind of couplings. As

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a consequence of the s-channel dependence, the sensitivity to couplings improves with the center of mass energy.
All possible final states, namely $q\bar{q}q'\bar{q}'$, $l\bar{\nu}_l q\bar{q}$ and $l\bar{\nu}_l l'\nu_{l'}$ are used when selecting W pair events. The selection procedure is similar to the cross-section measurement, except we are restricted to well reconstructed events [4].
Charged TGC affect directly the total cross-section, the angular distribution and the polarization of the W bosons. This influence is summarized on the differential cross-section by a quadratic behavior

$$\frac{d\sigma}{d\Omega} = S^0(\Omega) + \sum_i g_i S^1_i(\Omega) + \sum_{i,j} g_i g_j S^2_{i,j}(\Omega),$$

with $g_i = g_1^Z$, κ_γ and λ_γ. Ω represents a phase space element collecting information from W angular distribution and the W polarizations, namely the polar and azimuthal angles of one fermion in each W rest frame. However, some ambiguities in the reconstruction of the angles, depending on the decay channel, reduce the sensitivity to couplings. The hadronic channel suffers from pairing (80% efficiency) and W charge (80% efficiency) misassignements and the fully leptonic channel from low statistics. Consequently, the semileptonic channel is the most sensitive channel to couplings.
In order to extract couplings, an unbinned maximum likelihood method can be performed directly on the angles like ALEPH, DELPHI or L3. Another solution is to create some optimal observables [5] from the five angles and extract the couplings from their averages. This method is used by ALEPH and OPAL.

2.2 Single W and single γ analysis

The processes $e^+e^- \to We\nu_e$ and $e^+e^- \to \nu\bar{\nu}\gamma$ are only sensitive to WWγ couplings through t-channel diagrams. However, single W process has some non-negligible effect on the measurement of κ_γ and both processes produce an independent measurement of WWγ couplings.
Single W events are selected when the final state electron escapes in the beam pipe, leaving only the single W decay products in the detector. In case of hadronic W decays, two jets are visible, whereas a single lepton is observed in leptonic decays. In both cases, a large amount of missing energy and momentum should be observed. Couplings are mainly constrained by the cross-section measurement, although some kinematic information is added to improve the measurement:

- P_t^{W}, $|cos\theta_{jet1} - cos\theta_{jet2}|$, or a neural net output for $\mathrm{W} \to q\bar{q}$,
- E_l, $cos\theta_l$, P_t^l for $\mathrm{W} \to l\nu_l$.

The single γ process is less sensitive to TGC than single W. Sensitivity is mainly coming from energetic photons far from the beam pipe. Consequently, in addition to the cross-section measurement, the energy and angular distributions of the photon are used to constrain TGC.

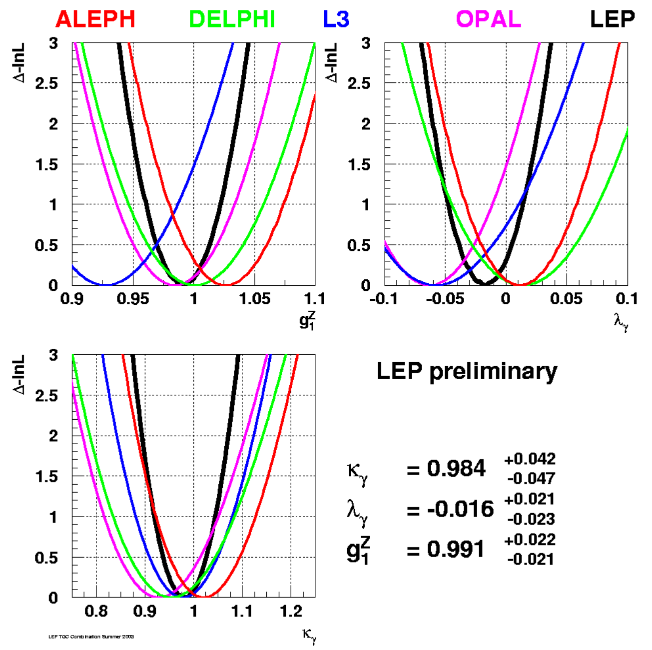

Fig. 1. The $-\Delta log\mathcal{L}$ curves of the four LEP experiments and after combination for the three charged couplings g_1^Z, κ_γ and λ_γ. In each case, only one coupling is allowed to vary, while the other two couplings are set to their Standard Model values

2.3 Systematics

The combination is based on the likelihood curves provided by each experiment. All uncorrelated systematic uncertainties (detector, MC statistics,...) are included in these likelihood curves. However, a special treatment has been setup to take into account correlated systematic uncertainties, independently of the analysis method chosen by the experiment [6]. The systematic uncertainties which are considered as fully correlated between experiments, are the uncertainty on the theoritical prediction on the cross-section (0.5% for W pairs and 5% for single W), the hadronisation effects, the final state interactions (Bose-Einstein correlations and color reconnection) and the theoretical uncertainty on radiative corrections. This last uncertainty is now evaluated from the difference between two generators including $\mathcal{O}(\alpha_{em})$ effects: YFSWW [7] and RacoonWW [8]. The new relative uncertainties on $\mathcal{O}(\alpha_{em})$ effects are roughly 1%, 2% and 1% for g_1^Z, κ_γ and λ_γ respectively.

2.4 Global results

The limits at 95% confidence level, assuming only one parameter deviates from the Standard Model, are

$$0.949 < g_1^Z < 1.034$$
$$0.895 < \kappa_\gamma < 1.069$$
$$-0.060 < \lambda_\gamma < 0.026$$

These preliminary results include all LEP2 data and all channels for WW pair production. Single W is not fully analysed yet, but no major improvement concerning the statistical error is expected. The main improvement from the previous results [9] concerns the reduction of the systematic uncertainty on radiative corrections by a factor two.

3 Neutral triple gauge boson couplings

There are no self-couplings at tree level with neutral gauge bosons in the Standard Model. However, some contributions are possible at quantum level even in the Standard Model.
Assuming Lorentz invariance, $U(1)_{em}$ invariance and Bose symmetries the most general effective Lagrangian contains 15 CP-conserving couplings and 29 CP-violating couplings [10]. In order to reduce the number of couplings, it is often assumed than the two final state bosons are on-shell. As a consequence, the Zγ and ZZ final states are splitted in two categories.

3.1 Zγ analysis

The Zγ final state probe the two vertices γ^*Zγ and Z*Zγ. These vertices are described by four CP-conserving couplings $h_{3,4}^{\mathrm{Z},\gamma}$ and four CP-violating couplings $h_{1,2}^{\mathrm{Z},\gamma}$.
In order to extract the couplings, the total cross-section and the angular distribution of the bosons are used for the two channels $e^+e^- \to q\bar{q}\gamma$ and $e^+e^- \to \nu\bar{\nu}\gamma$. In addition, when the Z is decaying into quarks, the angle between the photon and the nearest jet axis can be used, and when the Z is decaying into neutrinos, the energy of the photon add some kinematic information.
ALEPH, DELPHI and OPAL extract the couplings with an unbinned likelihood method on angles, whereas L3 is using an optimal observable method [11,12,13,14]. The preliminary results obtained after combination of the four LEP experiments are summarized in Table 1. All results are dominated by the statistical errors.

3.2 ZZ analysis

ZZ events constrain the two vertices γ^*ZZ and Z*ZZ which are described by two CP-violating couplings $f_4^{\mathrm{Z},\gamma}$ and two CP-conserving couplings $f_5^{\mathrm{Z},\gamma}$.
As for Zγ events, couplings are extracted from the cross-section and the boson angular distribution. All visible decays are used, namely $q\bar{q}q'\bar{q}'$, $\nu\bar{\nu}q\bar{q}$, $l^+l^-q\bar{q}$, $l^+l^-l'^+l'^-$ and $\nu\bar{\nu}l^+l^-$.
The extraction method is very similar to the Zγ case, as the total cross-section and the Z boson angular distribution are used. All experiments are performing a binned likelihood method directly on the kinematic variables, except OPAL which use an optimal observable method [11, 12,15,16].
Combined preliminary results are summarized in Table 1 and on Fig. 2 for one-dimensional and two-dimensions fits, respectively.

Table 1. 95% confidence level (CL) limits after combination of the four LEP experiments for neutral TGC measured with Zγ and ZZ events. Results are given for each coupling having been extracted separatly

Coupling	95% CL limits	Vertex	CP
h_1^γ	$[-0.056, +0.055]$	γ^*Zγ	−
h_2^γ	$[-0.045, +0.025]$	γ^*Zγ	−
h_3^γ	$[-0.049, -0.008]$	γ^*Zγ	+
h_4^γ	$[-0.002, +0.034]$	γ^*Zγ	+
h_1^{Z}	$[-0.13, +0.13]$	Z*Zγ	−
h_2^{Z}	$[-0.078, +0.071]$	Z*Zγ	−
h_3^{Z}	$[-0.20, +0.07]$	Z*Zγ	+
h_4^{Z}	$[-0.002, +0.034]$	Z*Zγ	+
f_4^γ	$[-0.17, +0.19]$	γ^*ZZ	−
f_5^γ	$[-0.32, +0.36]$	γ^*ZZ	+
f_4^{Z}	$[-0.30, +0.30]$	Z*ZZ	−
f_5^{Z}	$[-0.34, +0.38]$	Z*ZZ	+

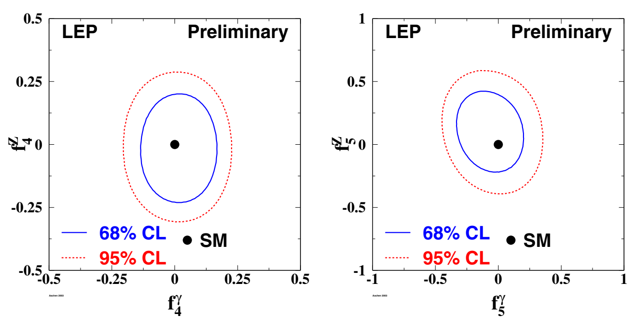

Fig. 2. Contour curves of 68% CL and 95% CL in the plane $(f_4^\gamma, f_4^{\mathrm{Z}})$ and $(f_5^\gamma, f_5^{\mathrm{Z}})$

4 Quartic gauge boson couplings

Within the Standard Model, quartic electroweak gauge boson vertices with at least two charged gauge bosons exist. At LEP2, only vertices with more than one photon (WWZγ and WW$\gamma\gamma$) contribute to WWγ and $\nu\bar{\nu}\gamma\gamma$ productions in the s-channel and the t-channel respectively. However, the effect of the Standard Model quartic vertices is below the LEP2 sentivity. Although they do not exist in the Standard Model at tree level, anomalous QGC with only neutral bosons like ZZ$\gamma\gamma$ are also searched in $Z\gamma\gamma$ events. This summer, only couplings related to the ZZ$\gamma\gamma$ vertex are combined. The combination of couplings linked to the other two vertices is forseen for the final results.
The study of QGC consider only "genuine" couplings which are not giving any contribution to TGC. The parametrisation used by the LEP experiments involve four CP-conserving couplings $a_{0,c}^{\mathrm{W,Z}}$ for the WW$\gamma\gamma$ and ZZ$\gamma\gamma$ vertices, and one CP-violating coupling a_n for the WWZγ vertex [2,17]. By convention, these couplings are normalized to Λ^2, the scale at which new physics appears.

4.1 $e^+e^- \to \nu\bar{\nu}\gamma\gamma$ analysis

$\nu\bar{\nu}\gamma\gamma$ events are caracterized by two acoplanar photons, plus some missing energy. The photon definition is different for each experiment, but mainly reject low angle photons(initial state radiation) and low energy photons(less affected by some anomalous coupling).

In addition to the total cross-section, two kinematic variables are often used to constrain the couplings: the energy of the least energetic photon and the missing mass. In particular, concerning this second observable, sizeable effects are expected around the m_Z missing mass region when the ZZ$\gamma\gamma$ vertex is considered, due to the interference with double bremsstrahlung diagrams. This fact entails a better sensitivity to $a_{0,c}^Z$ than to $a_{0,c}^W$ with $\nu\bar{\nu}\gamma\gamma$ events.

ALEPH, L3 and OPAL have estimated couplings with the $\nu\bar{\nu}\gamma\gamma$ process [18,19,20]. For example, ALEPH is measuring (95% CL preliminary limits)

$$-0.012 \text{ GeV}^{-2} < a_0^Z/\Lambda^2 < 0.019 \text{ GeV}^{-2}$$
$$-0.041 \text{ GeV}^{-2} < a_c^Z/\Lambda^2 < 0.044 \text{ GeV}^{-2}$$
$$-0.060 \text{ GeV}^{-2} < a_0^W/\Lambda^2 < 0.055 \text{ GeV}^{-2}$$
$$-0.099 \text{ GeV}^{-2} < a_c^W/\Lambda^2 < 0.093 \text{ GeV}^{-2}$$

4.2 $e^+e^- \to q\bar{q}\gamma\gamma$ analysis

The $q\bar{q}\gamma\gamma$ signal is defined by phase-space requirements on the energies and angles of the photons, on the propagator invariant mass and on the angle between each photon and the nearest quark. Typically, photons near the beam pipe(initial state radiations), with low energy or close to a quark(final state radiations) are removed. A propagator mass cut around the Z mass enable to select an intermediate on-shell Z.

The total cross-section, the energy of the least energetic photon and $max(|cos\ \theta_{\gamma 1}|, |cos\ \theta_{\gamma 2}|)$ are used to extract limits on couplings. In particular, an anomalous coupling is expected to enhance the number of high energy photons in the central region of the detector.

Two experiments L3 and OPAL have performed the analysis of $q\bar{q}\gamma\gamma$ events [21,22]. When combined with $\nu\bar{\nu}\gamma\gamma$ events, the following limits are set

$$-0.008 \text{ GeV}^{-2} < a_0^Z/\Lambda^2 < 0.021 \text{ GeV}^{-2}$$
$$-0.029 \text{ GeV}^{-2} < a_c^Z/\Lambda^2 < 0.039 \text{ GeV}^{-2}$$

The corresponding likelihood curves are shown in Fig. 3.

4.3 $e^+e^- \to W^+W^-\gamma$ analysis

The $W^+W^-\gamma$ process is the only process at LEP2 sensitive to the WWZγ vertex. It is also used to constrain couplings associated to the WW$\gamma\gamma$ vertex. As for the $q\bar{q}\gamma\gamma$ process, a signal definition is chosen to remove part of initial state radiations and final state radiations. Furthermore, two cuts on the difermion invariant masses are used to select final state on-shell W bosons.

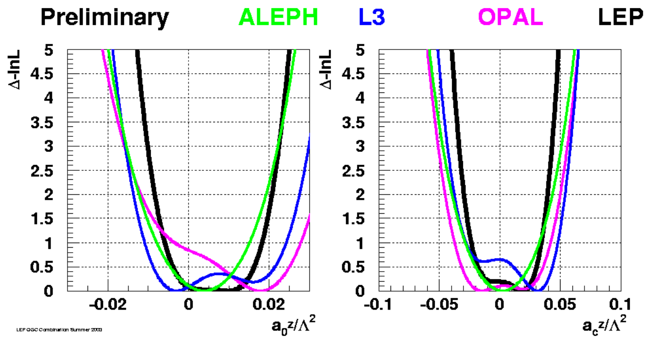

Fig. 3. The $-\Delta log\mathcal{L}$ curves for the QGC a_0/Λ^2 and a_c/Λ^2, associated with the ZZ$\gamma\gamma$ vertex

Selection of $W^+W^-\gamma$ events always start from WW selection, then a search for isolated photons is performed. In order to extract the couplings, the total cross-section and the energy distribution of the photon are used.

The three LEP experiments DELPHI, L3 and OPAL have performed this analysis [23,19,24]. However no combination of the different results has been done yet. The results obtained by L3, for example, are

$$-0.017 \text{ GeV}^{-2} < a_0^W/\Lambda^2 < 0.017 \text{ GeV}^{-2}$$
$$-0.052 \text{ GeV}^{-2} < a_c^W/\Lambda^2 < 0.026 \text{ GeV}^{-2}$$
$$-0.14 \text{ GeV}^{-2} < a_n/\Lambda^2 < 0.113 \text{ GeV}^{-2}$$

It can be noticed that results obtained on $a_{0,c}^{\mathrm{W}}$ with $W^+W^-\gamma$ events are more precise than with $\nu\bar{\nu}\gamma\gamma$ events. Also, the sensitivity to couplings is increasing a lot with the center of mass energy as WWZγ and WW$\gamma\gamma$ vertices are present in s-channel diagrams.

5 Conclusion

The existence of charged triple gauge boson couplings among the electroweak gauge bosons is experimentally verified, thanks to the LEP-combined results. Results agree with the Standard Model expectations at a level of 2% for g_1^Z and 5% for κ_γ. These new preliminary results benefits from the reduction of the theoritical uncertainty on radiative corrections.

As for charged triple gauge boson couplings, neutral triple gauge boson couplings and quartic gauge boson couplings are in good agreement with the Standard Model expectations.

Concerning all couplings, many results are now final and we can expect a final LEP combination by 2004.

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