Study of Trilinear Gauge Boson Couplings $ZZZ$, $ZZ\gamma$ and $Z\gamma\gamma$

Preliminary

P. Bambade,
LAL, Orsay
G. Borissov
CERN
C. Matteuzzi, V. Verzi
Dipartimento di Fisica, Università di Milano and INFN sez.Milano, Italy
J. Rehn
Inst. fur Exper. Kernphysik, Karlsruhe
I. van Vulpen
NIKHEF, Amsterdam
M. Witek
INP, Krakow

Abstract
Trilinear neutral gauge boson couplings $ZZZ$, $ZZ\gamma$ and $Z\gamma\gamma$ have been studied with the DELPHI detector, using data at energies between 189 and 208 GeV. Limits are derived on these couplings from an analysis of the reactions $e^+e^- \rightarrow \gamma ff$ with $f = q$ or $\nu$ and of the reactions $e^+e^- \rightarrow fff'f'$ using all the visible channels except $\tau^+\tau^-qq$, $\tau^+\tau^-\nu\nu$ and $l^+l^-l^+l^-$. 
1 Introduction

This note describes a measurement of the neutral triple gauge boson couplings $ZZZ$, $ZZ\gamma$ and $Z\gamma\gamma$ by DELPHI using LEP2 data taken between 1997 and 2000 at energies between 189 and 208 GeV.

The neutral coupling sector is probed by means of the reactions $e^+e^- \rightarrow Z\gamma$ and $e^+e^- \rightarrow ZZ$. As shown in figure 1, within the Standard Model (SM) these processes receive contributions from the $t$-channel exchange of an electron. The same figure shows new physics contributions that come from the $s$-channel exchange of a virtual or $Z$, leading to $Z\gamma$ or $ZZ$ production via a triple vector boson coupling with subsequent decay of the $Z$ in the final state.

The parametrization of the $ZZZ$, $ZZ\gamma$ and $Z\gamma\gamma$ vertex functions used here follows that suggested in [1]. There are twelve independent anomalous couplings. Calling $V$ the exchanged boson ($V = Z, \gamma$), one has the couplings $f_i^V$ ($i = 4,5$) for $ZZ$ final state and $h_i^V$ ($i = 1, \cdots, 4$) for $Z\gamma$ final state. The couplings $f_4^V$, $h_1^V$ and $h_2^V$ are CP-violating and $f_5^V$, $h_3^V$ and $h_4^V$ are CP-conserving.

When the final photon is on-shell, the $Z\gamma$ production contributes to the $f\bar{f}\gamma$ final state. The differential cross-section for this process in presence of anomalous couplings has been calculated using code [2] with vertex factors modified by a factor $i$ according to the correction suggested in [3]. The kinematic region with high photon energy and large photon polar angle is sensitive to the anomalous couplings. In this region, the anomalous interactions give rise to a change in the total rate and to an enhancement of the production of longitudinally polarized $Z$ bosons [4].

The differential cross-section for the process $e^+e^- \rightarrow f\bar{f}\gamma f'$ with anomalous couplings has been calculated using code from the generator DELTGC [5]. The visible four-fermion final states receive contributions from both $ZZ$ and $Z\gamma\gamma$ production when the final photon is virtual. Therefore one can use this process to derive limits also on $h_i^V$ couplings. However, due to the higher $e^+e^- \rightarrow f\bar{f}\gamma$ cross-section, the sensitivity is much better when the photon is on-shell. In the following the four-fermion production is considered only in the kinematic region that maximizes the sensitivity to $ZZ$ diagrams [6, 7].

The total $ZZ$ cross-section is very sensitive to the anomalous couplings and the sensitivity strongly increases with $\sqrt{s}$. Large interference between SM and anomalous am-

---

Figure 1: Feynman diagrams for the production of two on-shell gauge bosons $ZZ$ and $Z\gamma$. The first two on the left represent the Standard Model contribution, while the third one involves an anomalous interaction among three neutral gauge bosons.
plitudes arises for CP-conserving couplings (especially for $f_5^Z$) when one considers the differential cross-section $d\sigma/d\cos\theta_Z$, where $\theta_Z$ is the $Z$ production angle with respect to the beam axis [3].

Compared to [4] and [6, 7], the analyses presented in this note include the data collected in the year 2000 at energies ranging up to $\sqrt{s} \sim 208$ GeV corresponding to an integrated luminosity of about $225\,pb^{-1}$. Moreover, the analysis of the $ZZ$ final state is improved in sensitivity because the measurement of the anomalous $f_i^V$ couplings is based on a maximum likelihood fit to $d\sigma/d\cos\theta_Z$.

2 Selection of events

Events were recorded in the DELPHI detector. Detailed descriptions of the DELPHI components can be found in [8] and the description of its performance, as well as of the trigger system and of the luminosity monitor, can be found in [9].

2.1 $Z\gamma$ final state

Events with only a very energetic photon in the final state were searched for in the region covered by the HPC, the barrel electromagnetic calorimeter of DELPHI, in the range $45^\circ < \theta_\gamma < 135^\circ$ where $\theta_\gamma$ is the polar angle of the photon. The selection criteria and the data samples obtained at $\sqrt{s}$ from 189 to 202 GeV are described in [4]. Table 1 shows the results of the selection of events from the data collected in the year 2000.

The experimental signature of $Z\gamma$ events where the $Z$ decays into jets of particles is an energetic and well isolated photon recoiling against a hadronic system. Events with this topology, and where the photon has an energy greater than 50 GeV and is produced in the region $45^\circ < \theta_\gamma < 135^\circ$, have been selected at energies ranging from 189 GeV to 208 GeV. For $\nu\bar{\nu}\gamma$ channel, the selection criteria and the results obtained at $\sqrt{s}$ ranging from 189 to 202 GeV are described in [4] while the results at higher energies are shown in table 1. The expected number of $q\bar{q}\gamma$ events has been calculated with PYTHIA relying on JETSET 7.4 [10] for quark fragmentation while the expected number of $\nu\bar{\nu}\gamma$ events has been computed with KORALZ [11].

The total numbers of observed (expected) events used in this note are 296 (298.8) and 1581 (1601.5) in the $\nu\bar{\nu}\gamma$ and $q\bar{q}\gamma$ channels, respectively.

<table>
<thead>
<tr>
<th>Channel</th>
<th>$L(\rm{pb}^{-1})$</th>
<th>$\sqrt{s}$ (GeV)</th>
<th>$N_{\text{DATA}}$</th>
<th>$N_{\text{MC}}$</th>
<th>efficiency(%)</th>
<th>purity(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu\bar{\nu}\gamma$</td>
<td>214.6</td>
<td>206.1</td>
<td>98</td>
<td>102.3</td>
<td>51.0 ± 1.7</td>
<td>$\sim 100$</td>
</tr>
<tr>
<td>$q\bar{q}\gamma$</td>
<td>218.8</td>
<td>205.9</td>
<td>507</td>
<td>515.1</td>
<td>77.0 ± 0.1</td>
<td>97.3 ± 0.2</td>
</tr>
</tbody>
</table>

Table 1: Results of the selection of $\nu\bar{\nu}\gamma$ and $q\bar{q}\gamma$ events collected in the year 2000.

2.2 ZZ final state

The same $ZZ$ events selected by DELPHI to measure the $ZZ$ cross-section are used here. A detailed description is reported in [7]. The measurement of the anomalous couplings has been done using all the visible channels except $\tau^+\tau^-q\bar{q}$, $\tau^+\tau^-\nu\bar{\nu}$ and $l^+l^-l^+l^-$. 
The $ZZ \to q\bar{q}q\bar{q}$ process represents 49% of the $ZZ$ final states and produces four or more jets in the final state. After a four-jet preselection, in order to discriminate the $ZZ$ signal from the large background from $WW$ and $q\bar{q}(\gamma)$ processes, a probability corresponding to $ZZ$ production has been calculated. This probability is based on invariant mass information, on the $b$-tag probability per jet and on topological information.

The process $e^+e^- \to l^+l^-q\bar{q}$ has a branching ratio of $4.7 \times 2\%$. High efficiency and high purity are attainable with a cut-based analysis thanks to the clear experimental signature given by the two leptons typically well isolated from all other particles.

The decay mode $\nu\bar{\nu}q\bar{q}$ represents 28% of the $ZZ$ final states. The signature of this decay mode is a pair of rather acoplanar jets with visible and recoil masses compatible with the $Z$ mass. The most difficult backgrounds arise from single resonant $We\nu$ processes, from $WW$ processes where one of the $W$ bosons decays into $\tau\nu\tau$, and from $q\bar{q}$ events accompanied by energetic isolated photons escaping detection. The selection of events is done using a combined discriminant variable obtained with an Iterative Discriminant Analysis program (IDA) [12].

Finally the final state $l^+l^-\nu\bar{\nu}$ has a branching ratio of $2 \times 2.7\%$, and has been selected with a sequential cut-based analysis.

3 Results on anomalous couplings

Values of the neutral triple gauge boson coupling parameters $h_i^V (V = Z/\gamma, i = 1, 2, 3, 4)$, were derived from the data in the channel $e^+e^- \to \nu\bar{\nu}\gamma$ by comparing the observed number of events with the number predicted from the total cross-section for this process, and in the channel $e^+e^- \to q\bar{q}\gamma$ by comparing the observed distribution of the decay angle $\alpha^*$ of the $Z$ in its rest frame with predictions derived from the differential distribution $d\sigma/d\cos\alpha^*$. The definition and reconstruction of $\alpha^*$ are described in [4] and its distribution for the full data sample collected between 1998 and 2000 is compared to Standard Model expectations, in figure 2. The same figure shows the expected distributions for $h_3^Z = \pm 0.2$ obtained by reweighting [13] events generated under the Standard Model hypothesis with the inclusion of the full detector simulation.

The results of the fit of each $h_i^V$ coupling are shown in table 2. These results have been obtained by combining the likelihoods for both $q\bar{q}\gamma$ and $\nu\bar{\nu}\gamma$ channels and for the different centre-of-mass energies. In the fit to each coupling parameter, the value of the others were put to zero, their Standard Model value. Figure 3 shows the combined likelihoods.

In performing 2-parameter fits to the couplings, a total of 28 combinations ($h_i^V, h_j^V$) are possible for the 8 couplings considered. Despite this large number of pairs, there are essentially only three situations that are conceptually different and they are described in [4]: they correspond to different regimes of interference between the two anomalous terms and the Standard Model term in the production amplitude. The unexcluded regions at the 95% and 68% of confidence level are shown in figure 4 for the pairs $(h_1^Z, h_2^Z)$, $(h_3^Z, h_4^Z)$, $(h_1^Z, h_2^Z)$ and $(h_3^Z, h_4^Z)$, in the upper part of figure 5 for the pairs $(h_2^Z, h_3^Z)$ $(h_4^Z, h_3^Z)$, and in the lower part of figure 5 for the pairs $(h_1^Z, h_2^Z)$ $(h_2^Z, h_3^Z)$, corresponding to examples of the three different situations.

Several sources of systematic effects have been studied for data at $\sqrt{s}$ ranging from 189 to 202 GeV [4]. They have not yet been evaluated for data collected in 2000, but their effect is expected to be similar to that estimated at lower energies: $\Delta h_{\text{syst}}/\Delta h_{\text{stat}} \sim 40\%$
for couplings $h_1^2$, $h_2^2$, $h_3^2$, $h_4^2$, $h_5^2$, and $h_6^2$, and $\Delta h^{\text{sys}}/\Delta h^{\text{stat}} \sim 100\%$ for $h_3^2$ and $h_4^2$.

The neutral triple gauge boson coupling parameters $f_i^V (V = Z/\gamma, i = 4, 5)$, have been measured by means of an extended maximum likelihood fit of the $Z$ production angle ($\cos \theta_Z$) distribution for the channels selected with cut-based analyses ($q\bar{q}l^+l^\nu\nu$). For $q\bar{q}q\bar{q}$ ($qq\nu\nu$) channels, in order to benefit from the performance of the analysis to distinguish the signal from the large background, the $\cos \theta_Z$ distribution has been fitted simultaneously to the ZZ probability (IDA output variable) distribution. The reconstruction of $\theta_Z$ is free from ambiguity for all channels, except for $q\bar{q}q\bar{q}$ where the indistinguishability of the jets leads to wrong pairing. The combination with the minimum value of the $\chi^2$ obtained on application to the event of a 4C kinematic fit has been retained.

Figure 2 shows the $\cos \theta_Z$ distributions for the full data sample and the Standard Model expectations. For illustrative purposes, only $q\bar{q}q\bar{q}$ and $qq\nu\nu$ candidates in a high purity region are shown.

Using the information of the $Z$ production angle differential cross-section improves the sensitivity with respect to the analysis described in [6]. Also the correct dependence of the efficiency and purity on the anomalous couplings has been taken into account in this updated analysis. It was obtained by reweighting [13] events generated within the Standard Model hypothesis, including all the detector effects. Figure 2 shows the distributions obtained with this technique for $f_5^Z = \pm 1.5$.

The preliminary results of the single parameter fit of $f_i^V$ couplings, obtained combining all channels and energies, are shown in table 2. The corresponding likelihoods are reported in figure 6, together with the unexcluded regions for 2-parameter fits for pairs $(f_4^Z, f_4^Z)$ and $(f_5^Z, f_5^Z)$. Systematic effects are expected from both experimental and theoretical sources but they have not yet been evaluated.

<table>
<thead>
<tr>
<th>Vertex</th>
<th>Coup.</th>
<th>68% C.L.</th>
<th>95% C.L.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ZZZ$</td>
<td>$f_4^Z$</td>
<td>$-0.13^{+0.33}_{-0.21}$</td>
<td>$[-0.49, +0.42]$</td>
</tr>
<tr>
<td></td>
<td>$f_5^Z$</td>
<td>$+0.11^{+0.29}_{-0.28}$</td>
<td>$[-0.42, +0.69]$</td>
</tr>
<tr>
<td>$ZZ\gamma$</td>
<td>$f_4^Z$</td>
<td>$+0.05^{+0.14}_{-0.20}$</td>
<td>$[-0.26, +0.28]$</td>
</tr>
<tr>
<td></td>
<td>$f_5^Z$</td>
<td>$+0.15^{+0.27}_{-0.38}$</td>
<td>$[-0.49, +0.61]$</td>
</tr>
<tr>
<td></td>
<td>$h_1^Z$</td>
<td>$+0.10^{+0.09}_{-0.26}$</td>
<td>$[-0.24, 0.24]$</td>
</tr>
<tr>
<td></td>
<td>$h_2^Z$</td>
<td>$-0.07^{+0.17}_{-0.05}$</td>
<td>$[-0.14, 0.14]$</td>
</tr>
<tr>
<td></td>
<td>$h_3^Z$</td>
<td>$-0.18^{+0.28}_{-0.08}$</td>
<td>$[-0.32, 0.17]$</td>
</tr>
<tr>
<td></td>
<td>$h_4^Z$</td>
<td>$+0.10^{+0.04}_{-0.17}$</td>
<td>$[-0.11, 0.18]$</td>
</tr>
<tr>
<td>$Z\gamma$</td>
<td>$h_1^Z$</td>
<td>$+0.05^{+0.05}_{-0.16}$</td>
<td>$[-0.14, 0.14]$</td>
</tr>
<tr>
<td></td>
<td>$h_2^Z$</td>
<td>$+0.037^{+0.031}_{-0.103}$</td>
<td>$[-0.086, 0.087]$</td>
</tr>
<tr>
<td></td>
<td>$h_3^Z$</td>
<td>$+0.003^{+0.015}_{-0.017}$</td>
<td>$[-0.030, 0.034]$</td>
</tr>
<tr>
<td></td>
<td>$h_4^Z$</td>
<td>$-0.003^{+0.011}_{-0.010}$</td>
<td>$[-0.023, 0.018]$</td>
</tr>
</tbody>
</table>

Table 2: Preliminary results of fits of the neutral trilinear gauge coupling parameters $f_i^V$ and $h_i^V$ at the 68% and 95% confidence intervals. In the fit to each coupling parameter, the other couplings were set to their Standard Model value. The errors shown are statistical only.
4 Conclusions

The neutral triple gauge boson coupling parameters $h_V^i$ ($i = 1,4, V = \gamma/Z$) and $f_V^i$ ($i = 4,5, V = \gamma/Z$), have been measured studying the production of two neutral gauge bosons ($Z\gamma, ZZ$). No deviation from the expectations of the Standard Model was found.

5 Acknowledgements

We are grateful to our DELPHI colleagues in the TGC and 4-fermion working group for useful discussions.

References

Figure 2: Upper plot: distribution of the decay angle of the $Z$ in its rest frame in hadronic $Z\gamma$ events. Lower plot: distribution of the $Z$ polar angle in $ZZ$ events. In both cases, all the data selected at different centre-of-mass energies are included, except for $q\bar{q}q\bar{q}$ and $q\bar{q}\nu\bar{\nu}$ channels where only candidates in high purity region have been considered.
Figure 3: Likelihoods ($-2\log L$) obtained for the single parameter fits in the $e^+e^-\rightarrow \nu\bar{\nu}\gamma$ and $e^+e^-\rightarrow q\bar{q}\gamma$ channels. In the fits, the values of the other couplings were fixed to zero, their Standard Model values.
Figure 4: The regions accepted at the 95% (external contour) and at 68% confidence level (internal contour) for pairs of couplings whose amplitudes interfere strongly. The fits were made combining the measurements for $qq\gamma$ and $\nu\nu\gamma$ channels and for the different centre-of-mass energies. The points represent the Standard Model expectations for these couplings.
Figure 5: The regions accepted at the 95% (external contour) and at 68% confidence level (internal contour) for pairs of couplings \((h_i^\gamma, h_i^Z)\). The fits were made combining the measurements for \(q\bar{q}\gamma\) and \(\nu\bar{\nu}\gamma\) channels and for the different centre-of-mass energies. The points represent the Standard Model expectations for these couplings.
Figure 6: Upper figures show the likelihoods ($-2\log L$) obtained for the single parameter fits to the $f_i^V$ couplings. Lower figures show the regions accepted at the 95% (external contour) and at 68% confidence level (internal contour) for pairs of couplings with the same CP behaviour. The likelihoods have been obtained combining the measurements performed in all channels at the different centre-of-mass energies.