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MEASUREMENT OF TRIPLE GAUGE-BOSON COUPLINGS
IN ALEPH

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The triple gauge-boson couplings involving the W are determined using data samples collected with the ALEPH detector at mean centre-of-mass energies between 183 GeV and 208 GeV, corresponding to an integrated luminosity of 683.6 pb⁻¹.

The triple gauge-boson couplings, \( \Delta g_Y^Z \), \( \Delta \kappa _Z \), and \( \lambda _Z \), are measured using an optimal observable analysis of W-pair event topology. Results from single-W and single-\( \gamma \) production are included. The three couplings are measured individually assuming the two other couplings to be fixed at zero (Standard Model value). In addition, we use W-pair events to set limits on the C- and P-violating couplings \( g_Y^W, g_Y^Z, \kappa _Y, \) and \( \lambda _Y \), where \( Y \) denotes either \( \gamma \) or \( Z \). No deviations from the Standard Model expectations are observed.

1 Introduction

Triple Gauge-Boson Couplings can be separated in two main categories: vertices which involve only neutral bosons \( Z \) or \( \gamma \) and vertices with charged bosons \( W \). The former \( VZ\gamma \) and \( VZZ \) (\( V = Z'/\gamma' \)) are not present in the standard model at tree level. They are searched at LEP2 in the production of \( ZZ \) pairs and in \( Z\gamma \) events and won’t be treated in the following note. The latter \( VW^+W^- \) can be found in three different physics processes at LEP2: \( WW \) pair production, single \( W \) production and single \( \gamma \) production. The \( VW^+W^- \) vertices are a direct consequence of the \( SU(2)_L \times U(1)_Y \) gauge theory and are present in the standard model at Born level. Their study represents a fundamental test of the non-Abelian nature of the Standard Model.

The most general Lorentz invariant parametrisation of the \( \gamma W^+W^- \) and \( ZW^+W^- \) vertices can be described by 14 independent complex couplings \( 2^3 \times 7 \) for each vertex: \( g_Y^W, g_Y^Z, g_Y^\gamma, \kappa _Y, \kappa _Z, \kappa _\gamma, \lambda _Y, \lambda _Z, \) and \( \lambda _\gamma \), where \( Y \) denotes either \( \gamma \) or \( Z \). Assuming electromagnetic gauge invariance, C- and P-conservation, the set of 14 couplings can be reduced to 5 parameters: \( g_Y^Z, \kappa _Z, \kappa _\gamma, \lambda _Z, \) and \( \lambda _\gamma \), with Standard Model values \( g_Y^Z = \kappa _Z = \kappa _\gamma = 1 \) and \( \lambda _Z = \lambda _\gamma = 0 \). Finally, local \( SU(2)_L \times U(1)_Y \) gauge invariance introduces the constraints:

\[
\Delta \kappa _Z = - \Delta \kappa _\gamma \tan^2 \theta _W + \Delta g_Y^Z ,
\]

\[
\lambda _Z = \lambda _\gamma ,
\]

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where $\Delta$ denotes the deviation of the respective quantity from its non-zero Standard Model value, and $\theta_W$ is the weak mixing angle. Hence, only three parameters remain: $\Delta g_1^Z$, $\Delta \kappa$, and $\lambda$. This paper presents preliminary results on the three couplings $\Delta g_1^Z$, $\Delta \kappa$, and $\lambda$ using all ALEPH data, but also updates the results from single-parameter fits to the unconstrained real and imaginary parts of the 8 C- or P-violating couplings.

2 The ALEPH Detector

A detailed description of the ALEPH detector may be found in. The central part of the ALEPH detector is dedicated to the reconstruction of the trajectories of charged particles. Following a charged particle from the interaction point outwards, the trajectory is measured by a two-layer silicon strip vertex detector (VDET), a cylindrical drift chamber (ITC) and a large time projection chamber (TPC). They are immersed in a 1.5 T axial field and combined, they measure charged tracks with a momentum resolution of $\delta p_T/p_T = 6 \times 10^{-4} p_T \oplus 0.005$. Photons and electrons are identified in the electromagnetic calorimeter (ECAL), situated between the TPC and the coil. It yields a relative energy resolution of $0.18/\sqrt{E} \oplus 0.009$. The iron return yoke is equipped of 23 layers of streamer tubes and forms the hadron calorimeter (HCAL). Combined with ECAL it provides a relative energy resolution of charged and neutral hadrons of $0.85/\sqrt{E}$. Muons are distinguished from hadrons by their distinct pattern in HCAL and by the muon chambers outside the HCAL.

3 Event selection and kinematic reconstruction

The selection of $W^+W^-$ candidates is highly dependent of the event topology. Selected events are exclusively classified with the following order of priority: $e\nu q\bar{q}$, $\mu\nu q\bar{q}$, $\tau\nu q\bar{q}$, $qqq\bar{q}$, and $l\nu l\nu$ according to the way each $W$ is decaying.

3.1 $W^+W^- \rightarrow e\nu q\bar{q}$ and $W^+W^- \rightarrow \mu\nu q\bar{q}$ events

Semileptonic events are selected such that they contain a high energy lepton candidate and two jets. The selection of the lepton is using track isolation. The DURHAM-PE clustering algorithm is then applied to all objects that are not used to construct the lepton four-momentum, and these are forced in two jets. After this preselection, the probability for the event being signal is determined using a Neural Networks based on the momentum of the lepton, the total missing transverse momentum and the lepton isolation. To improve
the resolution on the reconstructed four-momenta of the W decay products, 
the events are subjected to a kinematic fit. Typical efficiency of semileptonic 
channels is roughly 80% for a purity of 95%.

3.2 $W^+W^- \rightarrow \tau\nu\bar{q}q$ events

Selection of semileptonic events with a $\tau$ is slightly different from the previous 
case, since $\tau$ lepton can decay into hadrons. In that case, an iterative method 
is applied to search for the most isolated jet amongst the jets resulting from 
a low $y_{cut}$ value of 0.75 GeV/c$^2$ with the JADE algorithm. To improve the 
resolution of the angular observables a kinematic fit is performed where the 
direction of the $\tau$ is approximated by its visible decay products. Efficiency of 
$\tau\nu\bar{q}q$ selection is about 54% and purity is roughly 76%.

3.3 $W^+W^- \rightarrow q\bar{q}q\bar{q}$ events

Fully hadronic events are identified by having four separated jets contained 
in the detector. To extract the hadronic $W^+W^-$ signal with high purity 
($\approx 85\%$) and efficiency ($\approx 80\%$), the selection is based on the output of a 
nearl network based on 14 variables$^7$. Moreover, for the hadronic $W^+W^-$ 
events the reconstruction of the relevant information is more complicated since 
there is no clean signature of the $W^-$ direction nor any information of the 
particle flavors in either W systems. In this case the four jets can be paired 
in three different ways. To select the best pairing with a purity of 75%, a 
6-constraint kinematic fit is applied to all three possible pairings. To assign 
a jet pair to the $W^+$ or $W^-$, a jet charge algorithm is used. The jet charge is 
obtained from the pseudorapidity-weighted charge for the particles forming a 
jet.

3.4 $W^+W^- \rightarrow l\nu l\nu$ events

The efficient of the selection of purely leptonic events is low 27%, but with a 
high purity 97%. Selection is based on missing transverse momentum, missing 
mass and kinematic properties of the lepton candidates. For purely leptonic 
$W^+W^-$ events the momenta of the two neutrinos are unknown. However 
in the absence of Initial State Radiation and neglecting the W width, the 
constraint that the two $l\nu$ systems should have the W mass in combination 
with the usual four-momentum conservation allows a reconstruction of the 
neutrino momenta.
4 Determination of the TGCs

4.1 Coupling extraction

All the information on the couplings is contained in a five angles distribution and the electric charge of the fermions. Since triple gauge-boson couplings contribute only linearly to the amplitude of the considered processes, the differential cross section can be expanded in these couplings \( g_i \) as a second order polynomial

\[
\frac{d\sigma}{d\Omega} = S_0(\Omega) + \sum_i S_{1,i}(\Omega)g_i + \sum_{ij} S_{2,ij}(\Omega)g_ig_j. \tag{3}
\]

Couplings estimatons are then extracted with an optimal observable method. The general idea of optimal observables is to extract the couplings \( g_i \) by measuring the mean values \( \langle \mathcal{O} \rangle \) of distributions of suitably defined observables \( \mathcal{O} \). In addition to the total number of selected events, the two optimal observables defined are

\[
\langle \mathcal{O}_{1,i}(\Omega) \rangle = \frac{S_{1,i}(\Omega)}{S_0(\Omega)} \quad \text{and} \quad \langle \mathcal{O}_{2,ij}(\Omega) \rangle = \frac{S_{2,ij}(\Omega)}{S_0(\Omega)}. \tag{4}
\]

With only Gaussian distributed variables, likelihood function is then equivalent to a least square method. In particular, including systematic errors is easy.

4.2 Systematic uncertainties

A complete list of all the systematics errors computed can be found in. The main sources are coming from uncertainties on the Monte Carlo model used to generate the \( W^+W^- \) signal. They were estimated as the effect of higher order correction for these results, but a reduction of the error size is forseen for the final results. The other main systematic uncertainties are due to fragmentation or final state interactions not perfectly modeled, i.e. Color Reconnection and Bose-Einstein effects.

5 Results and conclusion

The triple gauge-boson couplings have been measured using \( W \)-pair events at all LEP2 energies. Combining with the ALEPH measurement from single-\( W \) production and single-\( \gamma \) production, the three couplings \( \Delta g_1^Z \), \( \Delta \kappa \), and \( \lambda_\gamma \) have been measured individually. The results are

\[
\Delta g_1^Z = 0.015^{+0.035}_{-0.020}
\]
\[ \Delta \kappa_\gamma = -0.020^{+0.078}_{-0.073} \]
\[ \lambda_\gamma = -0.001^{+0.004}_{-0.003}. \]

where the error includes systematic uncertainties. The corresponding 95\% confidence level limits,

\[-0.048 < \Delta g_1^Z < 0.080 \]
\[-0.164 < \Delta \kappa_\gamma < 0.132 \]
\[-0.059 < \lambda_\gamma < 0.065, \]

are in good agreement with the Standard Model expectation.

In addition, W-pair events were used to set limits on the C- or P-violating couplings \( g_4^V, \tilde{g}_5^V, \tilde{\kappa}_V \) and \( \tilde{\lambda}_V \), where \( V \) denotes either \( \gamma \) or \( Z \). Results are shown on Table 1.

Table 1. Combined results for the real and imaginary parts of the C- or P-violating couplings from W-pair production at 183-208 GeV. Each coupling is determined setting all other couplings to their Standard Model value. The error includes systematic uncertainties. The corresponding 95\% confidence intervals are listed in the last column.

<table>
<thead>
<tr>
<th>Coupling</th>
<th>Fit result</th>
<th>95% confidence limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Re(( \tilde{\kappa}_\gamma ))</td>
<td>(-0.027^{+0.114}_{-0.111} )</td>
<td>([-0.236, 0.191] )</td>
</tr>
<tr>
<td>Re(( \lambda_\gamma ))</td>
<td>0.001 (+0.002) (-0.000)</td>
<td>([-0.170, 0.173] )</td>
</tr>
<tr>
<td>Re(( \tilde{\kappa}_Z ))</td>
<td>(-0.006^{+0.001) (-0.000)</td>
<td>([-0.123, 0.111] )</td>
</tr>
<tr>
<td>Re(( \lambda_Z ))</td>
<td>(-0.004^{+0.003) (-0.004)</td>
<td>([-0.096, 0.089] )</td>
</tr>
<tr>
<td>Re(( g_4^\gamma ))</td>
<td>0.116 (+0.14) (-0.138)</td>
<td>([-0.193, 0.418] )</td>
</tr>
<tr>
<td>Re(( g_5^\gamma ))</td>
<td>(-0.186^{+0.189) (-0.190)</td>
<td>([-0.557, 0.181] )</td>
</tr>
<tr>
<td>Re(( g_4^Z ))</td>
<td>0.103 (+0.110) (-0.120)</td>
<td>([-0.134, 0.334] )</td>
</tr>
<tr>
<td>Re(( g_5^Z ))</td>
<td>(-0.130^{+0.138) (-0.138)</td>
<td>([-0.400, 0.141] )</td>
</tr>
<tr>
<td>Im(( \tilde{\kappa}_\gamma ))</td>
<td>(-0.022^{+0.06) (-0.057)</td>
<td>([-0.134, 0.090] )</td>
</tr>
<tr>
<td>Im(( \lambda_\gamma ))</td>
<td>0.037 (+0.04) (-0.046)</td>
<td>([-0.053, 0.125] )</td>
</tr>
<tr>
<td>Im(( \tilde{\kappa}_Z ))</td>
<td>(-0.045^{+0.067) (-0.067)</td>
<td>([-0.116, 0.027] )</td>
</tr>
<tr>
<td>Im(( \lambda_Z ))</td>
<td>0.048 (+0.050) (-0.059)</td>
<td>([-0.015, 0.100] )</td>
</tr>
<tr>
<td>Im(( g_4^\gamma ))</td>
<td>0.286 (+0.130) (-0.132)</td>
<td>([0.027, 0.539] )</td>
</tr>
<tr>
<td>Im(( g_5^\gamma ))</td>
<td>(-0.180^{+0.210) (-0.216)</td>
<td>([-0.600, 0.251] )</td>
</tr>
<tr>
<td>Im(( g_4^Z ))</td>
<td>0.167 (+0.082) (-0.082)</td>
<td>([0.005, 0.326] )</td>
</tr>
<tr>
<td>Im(( g_5^Z ))</td>
<td>(-0.089^{+0.142) (-0.142)</td>
<td>([-0.366, 0.190] )</td>
</tr>
</tbody>
</table>
References