

MEASUREMENT OF TRILINEAR GAUGE BOSON COUPLINGS AT LEP2*

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The preliminary results of charged trilinear gauge boson WWV , $V \equiv Z/\gamma$ coupling values presented in this paper were obtained by the four LEP2 experiments ALEPH, DELPHI, L3 and OPAL by analysing the data collected at LEP energies ranging from $\sqrt{s} = 183 \text{ GeV}$ to $\sqrt{s} = 202 \text{ GeV}$. At these energies, significantly above the kinematic threshold for W^+W^- boson pair production, each of the four experiments collected data equivalent to more than $\mathcal{L} \sim 500 \text{ pb}^{-1}$ of integrated luminosity. The estimation of trilinear gauge boson couplings based on this data provides an independent check of the gauge nature of the Standard Model.

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1. Anomalous couplings

The predictions of the Standard Model seem so far to agree remarkably well with precision measurements (see *e.g.* [1]). One must however stress that the tests were done predominantly in the fermionic sector of the theory while the pure gauge interactions, which would directly confirm the Yang–Mills structure of the theory, are only beginning to be explored. So far the low energy measurements, precision tests at the Z^0 peak and initial measurements at LEP2 exclude only very drastic modifications of the simple gauge structure $SU(2)_L \times U(1)_Y$ as given by the Standard Model, while the knowledge about the trilinear and quadrilinear gauge boson couplings is still lacking the desired precision. Furthermore, the scalar sector of the theory,

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involving the Higgs field is still completely untested and the dynamics in this sector are so far totally unknown. In addition, some undesirable features of the Standard Model, as the naturalness problem (see *e.g.* [2]), implicate that the Higgs field might only be an effective description or that extensions of the present model are needed (offered by various super-symmetric models, technicolour and so on). Thus, an attempt to describe the weak boson $W^+W^-Z^0/\gamma$ interactions in form of a more general effective theory, which extends the predictions of the SM, should be considered.

The most general phenomenological Lagrangian that describes the trilinear $W^+W^-Z^0/\gamma$ boson vertex and still satisfies the Lorentz invariance has been shown to be [3–5]:

$$\begin{aligned}
i\mathcal{L}_{\text{eff}}^{WWV} = & g_{WWV} \left[g_1^V V^\mu (W_{\mu\nu}^- W^{+\nu} - W_{\mu\nu}^+ W^{-\nu}) + \kappa_V W_\mu^+ W_\nu^- V^{\mu\nu} \right. \\
& + \frac{\lambda_V}{m_W^2} V^{\mu\nu} W_\nu^{+\rho} W_{\rho\mu}^- + ig_5^V \varepsilon_{\mu\nu\rho\sigma} ((\partial^\rho W^{-\mu}) W^{+\nu} - W^{-\mu} (\partial^\rho W^{+\nu})) V^\sigma \\
& + ig_4^V W_\mu^- W_\nu^+ (\partial^\mu V^\nu - \partial^\nu V^\mu) - \frac{\tilde{\kappa}_V}{2} W_\mu^- W_\nu^+ \varepsilon^{\mu\nu\rho\sigma} V_{\rho\sigma} \\
& \left. - \frac{\tilde{\lambda}_V}{2m_W^2} W_{\rho\mu}^- W_\nu^{+\mu} \varepsilon^{\nu\rho\alpha\beta} V_{\alpha\beta} \right], \tag{1.1}
\end{aligned}$$

where $V \equiv Z^0$ or γ , m_W is the nominal W^\pm boson mass and the field tensors are given as $W_{\mu\nu} = \partial^\mu W^\nu - \partial^\nu W^\mu$ and $V_{\mu\nu} = \partial^\mu V^\nu - \partial^\nu V^\mu$. Apart from the overall coupling strength g_{WWV} , which can be set to $g_\gamma WW = e$ and $g_{ZW} = e \cot \theta_W$, there are 14 unknown coupling parameters that have been shown to form a complete set [3, 4]. Terms with higher derivatives in Eq. (1.1) add only a dependence of the parameters on the vector boson momenta in a manner analogous to a form-factor behaviour encountered *e.g.* in low energy QCD. It should be stressed at this point that the given Lagrangian describes non-renormalisable and unitarity violating interactions, since the unique cancellation mechanism of the $SU(2)_L \times U(1)_Y$ gauge invariant Standard Model does not apply in this general case.

The symmetric properties of the given couplings are listed in Table I. Within the Standard Model, at tree level, the couplings are set to $g_1^\gamma = g_1^Z = \kappa_\gamma = \kappa_Z = 1$ while all the other couplings vanish. Thus, it is customary to express the parameters in terms of the deviations from the Standard Model as *e.g.* $\Delta g_1^V = g_1^V - 1$ and $\Delta \kappa_V = \kappa_V - 1$, with $V \equiv Z^0$ or γ .

It should be noted that the C and P conserving terms in $\mathcal{L}_{\text{eff}}^{WW\gamma}$ give the charge Q_W , magnetic dipole moment μ_W and electric quadrupole moment q_W of the W^\pm bosons:

$$Q_W = eg_1^\gamma, \quad \mu_W = \frac{e}{2m_W} (g_1^\gamma + \kappa_\gamma + \lambda_\gamma), \quad q_W = -\frac{e}{m_W^2} (\kappa_\gamma - \lambda_\gamma), \tag{1.2}$$

TABLE I

Symmetry conservation of trilinear gauge boson couplings (TGC). In the table the symmetries that are conserved by the couplings are listed, *e.g.* g_5^Z violates C and P but conserves CP symmetry.

Parity	γW^+W^-	$Z^0 W^+W^-$
C, P, CP	$g_1^\gamma, \kappa_\gamma, \lambda_\gamma$	$g_1^Z, \kappa_Z, \lambda_Z$
CP	g_5^γ	g_5^Z
none	$\tilde{\kappa}_\gamma, \tilde{\lambda}_\gamma, g_4^\gamma$	$\tilde{\kappa}_Z, \tilde{\lambda}_Z, g_4^Z$

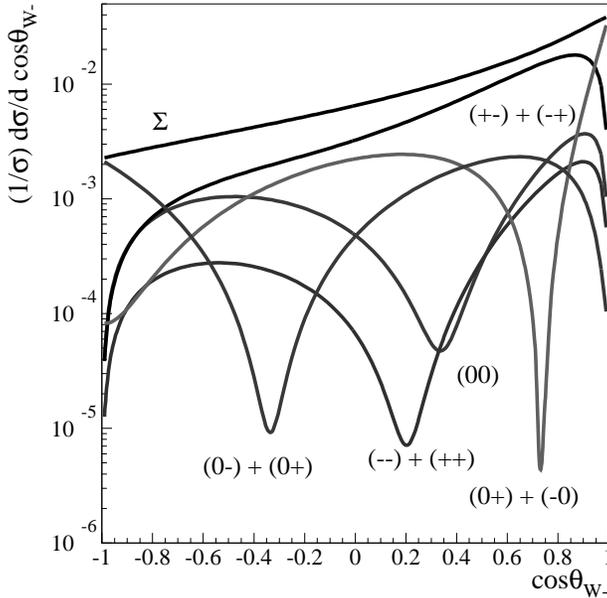
which in turn means that the Lagrangian of Eq. (1.1) can also be interpreted as a simple multi-pole expansion of the W - V interactions.

Given that at LEP2 the measured statistics on the order of thirty thousand events does not enable one to estimate all the 14 parameters to a reasonable accuracy, one has to resort to imposing additional restrictions on the effective description presented above. An initial reduction can be made by requiring the operators to be $U(1)_{\text{QED}}$ invariant, with a further assumption of C , P and CP conservation in the interactions of the bosonic sector of the Standard Model, which reduces the number of independent parameters to five. Finally, one can assume that the possible new physics scale Λ_{NP} , which limits the validity of the given effective description, is high enough (at least of the order of a few TeV) to induce a high suppression of operators with higher dimension [6, 7] and consequently retain only the operators of lowest dimensionality in the Lagrangian¹. With this assumption only three independent parameters ($\Delta\kappa_\gamma$, Δg_1^Z , λ_γ) remain; the given set is the one used in the principal analyses of the four LEP experiments.

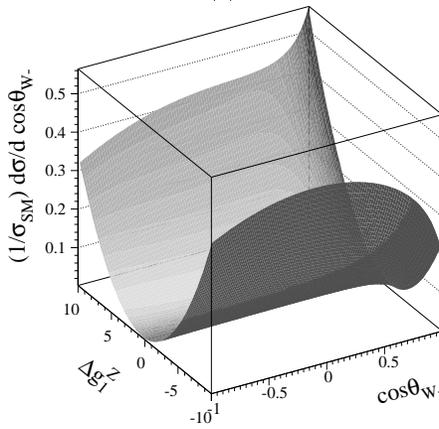
2. Estimation of trilinear gauge couplings

The anomalous trilinear gauge boson couplings directly affect the helicity fractions of the differential cross-section $d\sigma_{\text{TGC}}/d\Omega$, where σ_{TGC} denotes the cross-section of a process containing trilinear boson diagrams and Ω a set of independent kinematic variables of the process [7], as shown in Fig. 1(a). Simulation studies demonstrate that both the differential cross-section as well as the total one exhibit a quadratic dependence on the values of the anomalous TGC parameters (an example is shown in Fig. 1(b). Consequently, the measurable quantities sensitive to the values of TGC parameters are:

¹ This assumption also further justifies the omission of the terms containing CP violating parameters, since it can be shown that these terms can be constructed using $SU(2)_L \times U(1)_Y$ invariant operators of dimension eight or higher and are thus highly suppressed, *c.f.* [6]



(a)



(b)

Fig. 1. (a) — Normalised partial wave (helicity) fractions of the differential cross-section for the process $e^+e^- \rightarrow W^+W^-$ with respect to the W^- production angle are shown. The helicity contributions are drawn for the Standard Model values of the TGC parameters at $\sqrt{s} = 190$ GeV. (b) — The differential cross-section for the process $e^+e^- \rightarrow W^+W^-$ as a function of the Δg_1^Z parameter at $\sqrt{s} = 190$ GeV. The parabolic dependence on the TGC parameter is manifest. The cross-section in the plot is normalized to the Standard Model value.

- The total cross-section of the process (σ_{TGC}).
- The kinematic distributions of the measured events $\frac{1}{\sigma_{\text{TGC}}} \frac{d\sigma_{\text{TGC}}}{d\Omega}$.
- The W^\pm boson polarization fractions (determinable *e.g.* by measuring the angular distributions of the W^\pm decay products in the W^\pm boson rest frame).

The event selection and reconstruction efficiency and thus the subsequent sensitivity of the measurement depend on the interaction process selected for the analysis. Therefore, the approaches and kinematic variables used in the analyses are tailored to the specifics of the analysed processes and vary considerably. The principal ones are sketched in the following subsections.

2.1. W^+W^- pair production at LEP2

With the LEP collider working above the kinematic limit for W^+W^- production ($\sqrt{s} \geq 161 \text{ GeV}$), the trilinear gauge couplings can be directly determined by observing the vector boson pair production $e^+e^- \rightarrow W^+W^-$. The three Feynman diagrams representing the dominant tree level contributions are shown in Fig. 2, two of them describing the trilinear vertex, where W^+W^- are produced via γ or Z^0 and the third diagram representing the W^+W^- production through a t -channel neutrino exchange.

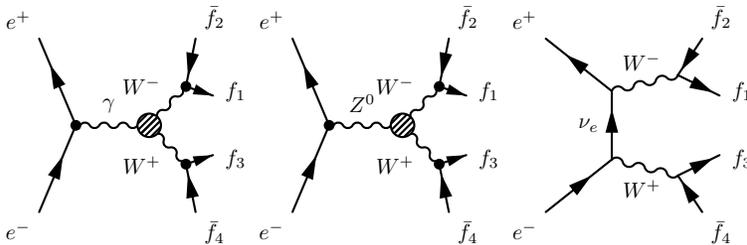
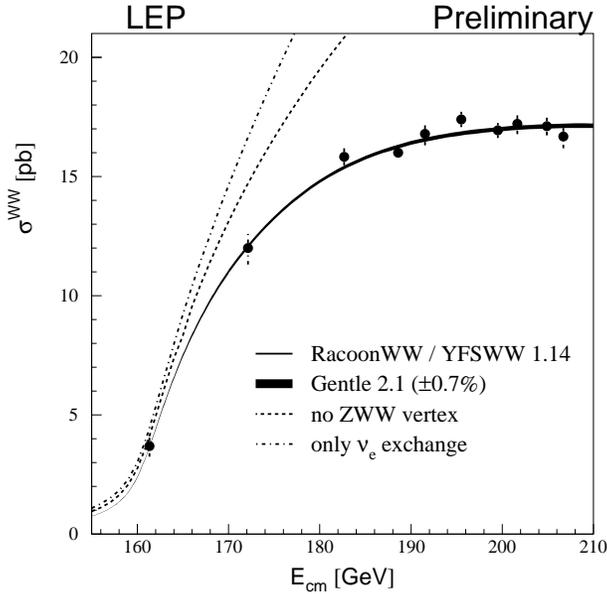


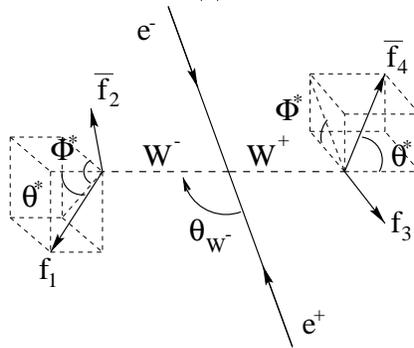
Fig. 2. The three main tree level diagrams contributing to the W^\pm pair production. The third t -channel neutrino exchange diagram does not involve a trilinear boson vertex but gives a major contribution to the amplitude and interferes strongly with the two s -channel diagrams.

The precision measurements of the $e^+e^- \rightarrow W^+W^-$ production cross-section give strong evidence for the existence of the WWZ and $WW\gamma$ vertices [8]. As shown in Fig. 3(a) the analysed LEP2 data indeed favour the Standard Model predictions. Five independent kinematic variables describe the $e^+e^- \rightarrow W^+W^-$ process. They are usually given as the W^- production angle and the polar and azimuthal angles of the W^\pm decay products (*cf.* Fig. 3(b)), with the W^- production angle being the most sensitive one to the

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(a)



(b)

Fig. 3. (a) — The preliminary results of the total cross-section measurement $\sigma(e^+e^- \rightarrow W^+W^-)$ at different centre-of-mass energies combining the data from the four LEP experiments [8]. A good agreement with the Standard Model predictions confirms the existence of trilinear gauge boson vertices. (b) — The usual parameterisation of the five independent variables in the $e^+e^- \rightarrow W^+W^-$ processes is given by five angles as shown in the diagram: The W^- production angle, the polar and azimuthal angles of the fermion in the c.m.s. of the parent W^- and the polar and azimuthal angles of the decaying anti-fermion in the c.m.s of the parent W^+ .

anomalous TGC values. The reconstruction efficiency and thus the information which can be retrieved depends on the decay modes of the W^+W^- boson pair and can be grouped as follows [9–12]:

- **The hadronic $W^+W^- \rightarrow q_1\bar{q}_2q_3\bar{q}_4$ decay channel (BR $\sim 46\%$):**
 The average selection efficiency of the principal analyses performed at LEP2 amounts to about $\varepsilon \simeq 90\%$, with the purity of $\mathcal{P} \simeq 80\%$. The four hadronic jets produced in the fragmentation process hide the flavours of the primary quarks; consequently one is left with a three-fold pairing ambiguity in assigning the jets to an original W^\pm boson. In order to resolve the ambiguity different methods are applied, ranging from simple kinematic cuts to neural networks; the resulting pairing efficiency is in the range between 75–85%. Subsequently, the W^\pm boson charge is determined using the difference of the jet charges of the selected pairs of jets, the charge assignment efficiency amounting to $\varepsilon_p = 75\text{--}85\%$. The flavour assignment of individual jets is generally not attempted, thus the reconstructed polar angles of the W^\pm decay products still contain a twofold ambiguity each.
- **The semileptonic $W^+W^- \rightarrow q_1\bar{q}_2l\bar{\nu}_l$ ($l = e, \mu, \tau$) decay channel (BR $\sim 44\%$):**
 The applied analysis methods reach a selection efficiency in the range $\varepsilon \simeq 70 - 80\%$ with a purity on the order of $\mathcal{P} \simeq 90\%$. This channel is not burdened with any pairing inefficiencies and the W^\pm boson charge assignment is efficiently done by using the charge of the lepton produced in the leptonic W^\pm decay. As such, this channel is most adapted to an efficient estimation of the TGC parameter values and indeed exhibits the highest sensitivity. The only unresolved kinematic ambiguity remains in the angles of the hadronically decaying W^\pm boson, since the flavour of individual quarks remains unknown.
- **The leptonic $W^+W^- \rightarrow l_1\bar{\nu}_1l_2\bar{\nu}_2$ ($l = e, \mu, \tau$) decay channel (BR $\sim 10\%$):**
 The event selection procedures achieve an efficiency of $\varepsilon \simeq 60\text{--}80\%$ with a high purity $\mathcal{P} \simeq 90\%$. In this channel the W^\pm boson charge assignment is also done by using the charge of the produced leptons; the kinematic reconstruction of the events, however, gives a twofold ambiguity in $\cos(\theta_{W^-})$, ϕ_1^* and ϕ_2^* because of the additional degrees of freedom introduced due to the two unobserved neutrinos.

The estimates of the values of anomalous TGC parameters are derived using various statistical approaches [9–12], all aiming at the optimal sensitivity of the analysis. Generally, the information contained in the measured

total cross-section of the selected channel is used to evaluate the point estimates and the confidence intervals of the unknown parameters by using the maximum likelihood method, *i.e.* maximisation of Poisson probability as a function of TGC parameters with respect to the observed number of events in the selected data samples². The derivation of the estimates on the TGC values from the angular distributions $(1/\sigma_{\text{WW}})(d\sigma_{\text{WW}}/d\Omega)$, where Ω represents a set of up to five of the above-mentioned angles, can principally be divided into two approaches:

- **Maximum likelihood fit to the kinematic distributions of measured events:** The performed fits are both binned (using the multinomial probability) and unbinned ones. The probability density functions are extracted either directly from simulation or from the theoretical prediction convoluted with the estimated detector resolution.
- **Optimal observables method:** The method is based on the optimal projection of the initial five variables onto a smaller subspace of parameters whilst minimising the loss of sensitivity [14]. The method is very efficient in the case of TGC measurements due to the parabolic dependence of the differential cross-section on the TGC's. Writing this dependence in the form:

$$\frac{d\sigma(\Omega, \alpha)}{d\Omega} = \mathcal{S}^0(\Omega) + \sum_i \mathcal{S}_i^1(\Omega)\alpha_i + \sum_{i \leq j} \mathcal{S}_{ij}^2(\Omega)\alpha_i\alpha_j, \quad (2.1)$$

a set of optimal observables is determined to be:

$$\mathcal{O}_i^1 = \frac{\mathcal{S}_i^1(\Omega)}{\mathcal{S}^0(\Omega)}, \quad \mathcal{O}_{ij}^2 = \frac{\mathcal{S}_{ij}^2(\Omega)}{\mathcal{S}^0(\Omega)}. \quad (2.2)$$

The estimates on the values of the TGC parameters are consequently derived by performing either a χ^2 fit to the averages of the distributions of optimal observables obtained from the measured events, or by using the distributions of events w.r.t. the optimal observables in an binned maximum likelihood fit.

The principal analyses [9–12] derive the values of the three TGC parameters by performing three separate one-parameter fits, each turn keeping two of the TGC parameters at the Standard Model values. Two and three parameter fits are also being done, however the estimated values of the three

² This method is often coupled to the evaluation of the TGC parameters from the angular distributions which results in the *extended maximum likelihood method* [13].

parameters turn out to be in some cases strongly correlated. In addition, the observed nonlinearities in the confidence interval estimation (see *e.g.* [15]) make the proper estimation of systematic uncertainties in multidimensional fits extremely difficult.

The W^\pm polarisation measurements [16, 17], used to determine the helicity fractions of the $\sigma(e^+e^- \rightarrow W^+W^-)$ cross-section, were also performed in the analyses of the hadronic and semileptonic channels of W^+W^- decays. The helicity fractions of the polarised W^\pm bosons are evaluated either by splitting data in $\cos(\theta_{W^-})$ bins and analysing $\cos\theta^*$ distributions or by evaluation of spin density matrix elements which are directly related to the helicity fractions of the total cross-section. The main advantage of these analyses is that they do not employ any assumptions about the underlying (effective) model but measure the discrepancy from the Yang-Mills theory of the Standard Model directly. In addition, the analyses also present a direct test of the CP invariance in the reactions $e^+e^- \rightarrow W^+W^-$ [16, 17].

2.2. Single W and single γ events

Additional sensitivity in estimation of the trilinear gauge coupling parameters is gained by analysing the $e^+e^- \rightarrow e^\pm W^\pm \nu_e$ (single W) and $e^+e^- \rightarrow \gamma \nu_e \bar{\nu}_e$ (single γ) processes [9–12], which include trilinear $WW\gamma$ coupling diagrams, as shown in Fig. 4.

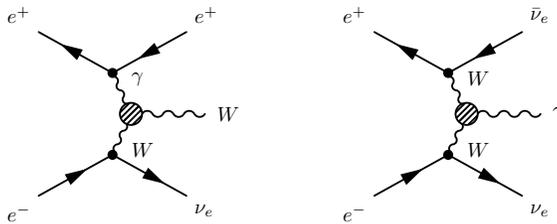


Fig. 4. The two tree level diagrams contributing to the single W and single γ processes which involve a $WW\gamma$ vertex. Beside the two channels shown there are many other diagrams leading to the same final states which do not contain the trilinear vertices but have to be taken into account due to interferences of the amplitudes.

The analysis of these two processes gives access to the $WW\gamma$ vertex alone and thus improves the sensitivity of the estimation of the $\Delta\kappa_\gamma$ and λ_γ parameters. Most information is in both cases obtained from the measurement of the total production cross-section; additional sensitivity is obtained by performing maximum likelihood fits to the distributions of measured events with respect to sensitive kinematic variables (*e.g.* energy and polar angle E_l, θ_l of the lepton, produced in leptonic decays of the W^\pm in

case of single W channel, or energy and polar angle E_γ, θ_γ of the final state photon in the analyses of the single γ channel).

3. Results and conclusions

The preliminary results of the four LEP experiments [9–12] including data taken at energies up to 202 GeV are presented in Fig. 5 together with the corresponding (negative) log-likelihood curves. The combined results were obtained by the combination of these results performed by the LEP EW working group [18]; the estimated systematic uncertainties are already included in the values shown.

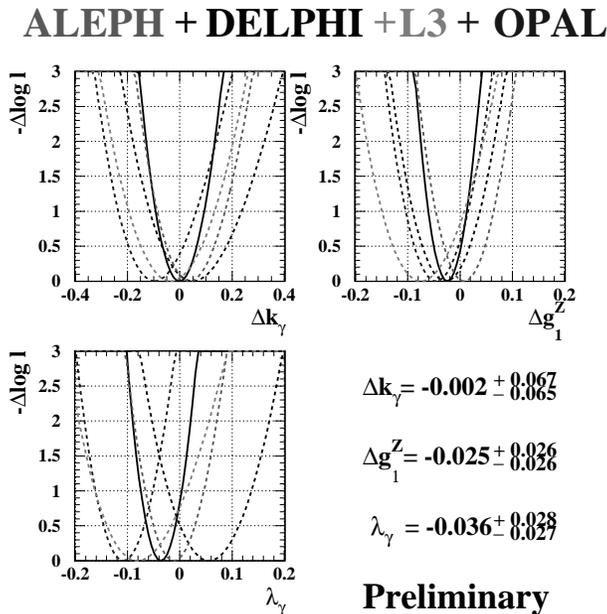


Fig. 5. The preliminary combined results of the principal analyses as obtained by the four LEP experiments using the data collected at the energies up to $\sqrt{s} = 202$ GeV. The confidence limits on the parameter values given in the adjacent table already include the estimated systematic uncertainties.

The principal contributions to the systematic uncertainty of the measurements are listed in the Table II. Some of the uncertainties will be further reduced in the final results of the four LEP experiments; most notably the 2% uncertainty on the expected signal cross-section will be reduced to $\sim 0.5\%$ with the use of new Monte-Carlo generators using improved calculations of the radiative corrections to the production cross-section [19, 20].

TABLE II

The principal contributions to the systematic uncertainty in the estimation of the trilinear gauge boson couplings, as estimated in the combination of the four LEP experiments [18].

Systematic source	Δg_1^Z	λ_γ	$\Delta \kappa_\gamma$
$\sigma(WW) \pm 2\%$	± 0.012	± 0.014	± 0.055
Fragmentation	± 0.013	± 0.014	± 0.051
Colour reconnection	± 0.003	± 0.005	± 0.012
Bose-Einstein effect	± 0.006	± 0.006	± 0.020
$\sigma(We\nu) \pm 5\%$	—	± 0.049	± 0.067

The results show a good agreement with the Standard Model predictions. The statistical uncertainty will in the future be further reduced by including the data collected by the LEP experiments in year 2000 at the energies reaching up to 210 GeV.

REFERENCES

- [1] *Z Physics at LEP1*, eds. G. Altarelli, R. Kleiss, C. Verzegnass *et al.*, Vol. 1, CERN 89-08, 1989.
- [2] J.F. Donoghue, E. Golowitch, B.R. Holstein, *Dynamics of the Standard Model*, Cambridge University Press, Cambridge 1992.
- [3] K. Gaemers, G.J. Gounaris, *Z. Phys.* **C1**, 259 (1979).
- [4] K. Hagiwara, R.D. Peccei, D. Zeppenfeld, K. Hikasa, *Nucl. Phys.* **B282**, 253 (1987).
- [5] G.J. Gounaris *et al.*, BMT Collaboration, Proceedings, e^+e^- Collisions at 500 GeV, Munich/Annecy/Hamburg 1991, p. 735.
- [6] G.J. Gounaris, F.M. Renard, *Z. Phys.* **C59**, 133 (1993).
- [7] G.J. Gounaris, J.-L. Kneur, D. Zeppenfeld, in *Physics at LEP2*, Vol. 1, eds. G. Altarelli, T. Sjöstrand, F. Zwirner, CERN 96-01, 1996, p. 525.
- [8] The LEP Collaborations ALEPH, DELPHI, L3, OPAL and the LEP WW Working Group, LEPEWWG/XSEC/2000-01 (2000). See also: <http://www.cern.ch/LEPEWWG>.
- [9] ALEPH Collaboration, *ALEPH Note* ALEPH 2000-055 (2000). ALEPH Collaboration, *Conf. Note* ICHEP 2000 abstract 304 (2000).
- [10] DELPHI Collaboration, *DELPHI Note* DELPHI 2000-139 (2000). DELPHI Collaboration, *DELPHI Note* DELPHI 2000-146 (2000).

- [11] L3 Collaboration, *L3 Note* L3, 2567 (2000).
- [12] OPAL Collaboration, *OPAL Note* OPAL PN427 (2000). OPAL Collaboration, *OPAL Note* OPAL PN441 (2000).
- [13] L. Lyons, W. Allison, *Nucl. Instrum. Methods Phys. Res.* **A245**, 530 (1986).
- [14] M. Diehl, O. Nachtmann, *Z. Phys.* **C62**, 397 (1994).
- [15] B.P. Kerševan, B. Golob, G. Kernel, T. Podobnik, Proceedings of the Workshop on 'Confidence Limits', eds. L. Lyons, F. James, CERN 2000-005, 2000, p. 259.
- [16] L3 Collaboration, *L3 Note* L3, 2574 (2000).
- [17] OPAL Collaboration, *EP Note* CERN-EP-2000-113 (2000).
- [18] The LEP Collaborations ALEPH, DELPHI, L3, OPAL and the LEP TGC Working Group, LEPEWWG/TGC/2000-02 (2000). See also: <http://www.cern.ch/LEPEWWG>.
- [19] A. Denner *et al.*, *Phys. Lett.* **B475**, 127 (2000).
- [20] D.R. Yennie, S. Frautachi, H. Suura, *Ann. Phys.* **13**, 379 (1961); M. Skrzypek, S. Jadach, W. Placzek, B.F.L. Ward, Z. Was, *Phys. Rev.* **D61**, 113010 (2000); M. Skrzypek, S. Jadach, W. Placzek, B.F.L. Ward, Z. Was, UTHEP-00-0101, (2000).