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Single W Production at LEP2

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SINGLE W PRODUCTION AT LEP2

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Single W and single gamma productions which are sensitive to the trilinear gauge coupling $WW\gamma$ have been studied at LEP. It is shown that single W production has particular sensitivity to the ‘anomalous’ magnetic moment κ_γ of the W boson, complementary to WW production at LEP and $W\gamma$ production at hadron colliders. The invisible decay of W boson has been searched and the limit on the invisible decay width of 27 MeV at 95% C.L. has been obtained.

1 Introduction

The existence of the trilinear gauge couplings (TGC) is the direct consequence of the non-Abelian $SU(2) \times U(1)$ gauge theory which has not been studied in detail. Precise measurements of these couplings make it possible to test the standard model. Any deviation from the standard model would indicate the new physics. There are 2×7 parameters of couplings in the effective Lagrangian¹. By requiring C- and P-invariance, also $g_1^\gamma = 1$ by electromagnetic gauge invariance, the number of parameters reduces to 5: $\Delta g_1^Z \equiv g_1^Z - 1$, $\Delta \kappa_\gamma \equiv \kappa_\gamma - 1$, $\Delta \kappa_Z \equiv \kappa_Z - 1$, λ_γ and λ_Z where all these parameters are vanishing in the standard model. For W^+ boson, these parameters can be related to the electromagnetic charge: $e_W = e g_1^\gamma$, and the static moments² as, magnetic dipole moment: $\mu_W = \frac{e}{2m_W}(g_1^\gamma + \kappa_\gamma + \lambda_\gamma)$, and electric quadrupole moment: $Q_W = -\frac{e}{m_W^2}(\kappa_\gamma - \lambda_\gamma)$, and also those associated with the weak boson Z.

At LEP2, it became, for the first time in the e^+e^- collider, to perform the direct measurement of TGC. W pair production plays a principal role to study $WW\gamma$ and WWZ couplings³. However, these two couplings cannot be separated each other. Single W production, $e^+e^- \rightarrow e\nu W$ ^{4,5}, or single gamma production, $e^+e^- \rightarrow \nu\nu\gamma$ ⁶, can be used to test the $WW\gamma$ coupling. At hadron colliders, $W\gamma$ production has been studied to probe the $WW\gamma$ vertex^{7,8,9} where the form factor Λ is introduced to assure the unitarity¹⁰. The TGC limits derived at LEP are insensitive to the form factor scale and power. To relate WWZ and WWg couplings, $SU(2) \times U(1)$ constraints, $\Delta g_1^Z = \Delta \kappa_Z + \Delta \kappa_\gamma \tan^2 \theta_W$ and $\lambda_Z = \lambda_\gamma$, are imposed.

In the search for supersymmetric particles, chargino pair production ($e^+e^- \rightarrow \chi^+\chi^-$) where charginos decay predominantly into sneutrinos and leptons, it is experimentally difficult if the mass difference between chargino and sneutrino is small. This is due to the huge backgrounds from two photon process. Therefore the search for single W events in $e^+e^- \rightarrow W^+W^-$ process where one W boson decays to undetected chargino and neu-

trino and the other W to the standard model particles has been proposed¹¹. A search for this scenario has been performed by ALEPH.

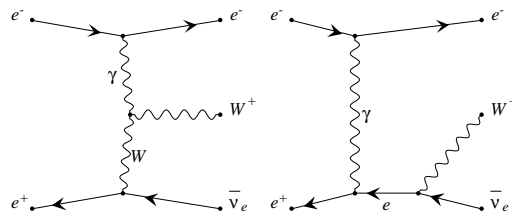
All results presented in this paper are preliminary except L3 results.

2 $e\nu W$ Production

2.1 Sensitivity to TGC ($WW\gamma$)

The single W production, $e^+e^- \rightarrow e\nu W$, is the standard model process¹² as shown in Fig.1. The total cross section is $\sigma_{e\nu W} = 0.6$ pb at the centre-of-mass energy of 183 GeV which is much smaller than WW production $\sigma_{WW} = 15.7$ pb. Contributions from Z boson exchange diagrams are negligible at LEP energies. Thus this process offers almost pure sensitivity to the $WW\gamma$ coupling⁵.

The sensitivity for TGC parameters for the four fermion process of $e^+e^- \rightarrow e^-\bar{\nu}_e u\bar{d}$ is shown in Fig. 2. The total cross section has been calculated with the $SU(2) \times U(1)$ constraints. While WW production cross section is minimum at $\Delta g_1^Z = \Delta \kappa_\gamma = \lambda_\gamma = 0$, $e\nu W$ production cross section is minimum at $\Delta \kappa_\gamma = -1$ and $\lambda_\gamma = 0$. It can be seen that single W production is sensitive to κ_γ , while it has the modest sensitivity to λ_γ . This should be compared to the $W\gamma$ production at hadron colliders^{7,8,9} which is sensitive to λ_γ or to $b \rightarrow s\gamma$ ^{13,14} which is sensitive to κ_γ in the $WW\gamma$ vertex.



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Figure 1: Feynman diagrams for $e^+e^- \rightarrow e^-\bar{\nu}_e W^+$.

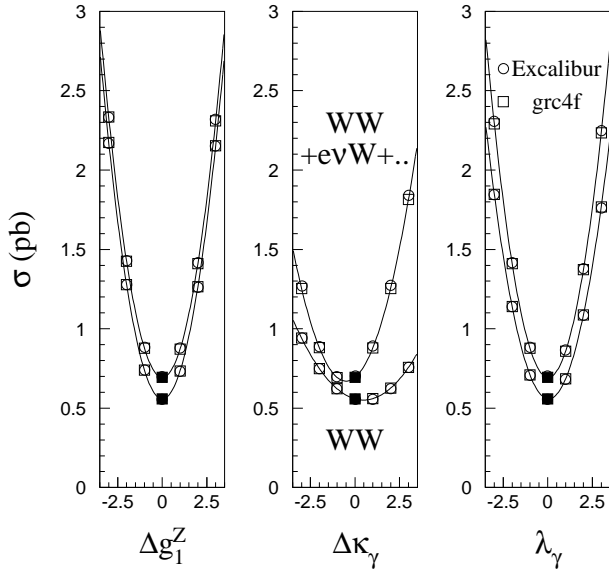


Figure 2: The total cross section for $e^+e^- \rightarrow e^-\bar{\nu}_e\bar{u}\bar{d}$ as functions of 3 coupling parameters. The lower curves show the cross sections for W pair production alone, and the upper curves are for all four fermion diagrams. For one plot, the other two parameters are fixed to the standard model values. Closed points indicate the standard model prediction.

2.2 Single W signal

Event characteristics of the single W production are as follows. Due to its small momentum transfer, the outgoing electron escapes in the beam direction. In the analysis, it is required that the electron to be un-tagged. This is important to suppress the contribution from W pair production. The associated neutrino may carry a large transverse momentum, thus the signature of single W production is characterized by the large missing momentum. For leptonic decay channel of W boson ($W \rightarrow l\nu$), an isolated high P_t lepton with energy at about 40 GeV is the signal. The dominant backgrounds are from $ll\nu\nu$ (eeZ) processes. For hadronic W decay channel ($W \rightarrow q\bar{q}'$), the signature is the acoplanar two jets whose invariant mass is equal to W mass. The main background is W pair production ($WW \rightarrow \tau\nu_\tau q\bar{q}'$). If ν_τ carries away large fraction of energy, τ becomes invisible. It is practically impossible to distinguish this case from the single W production, thus becoming irreducible backgrounds.

The definitions of the single W signal are different among LEP experiments. The ALEPH collaboration, for example, defines the signal as ¹⁹:

$$\begin{cases} \theta_e < 34 \text{ mrad,} \\ E_\ell > 20 \text{ GeV and } |\cos \theta_\ell| < 0.95 \text{ for } W \rightarrow l\nu, \\ M_{qq'} > 60 \text{ GeV}/c^2 & \text{for } W \rightarrow q\bar{q}', \end{cases}$$

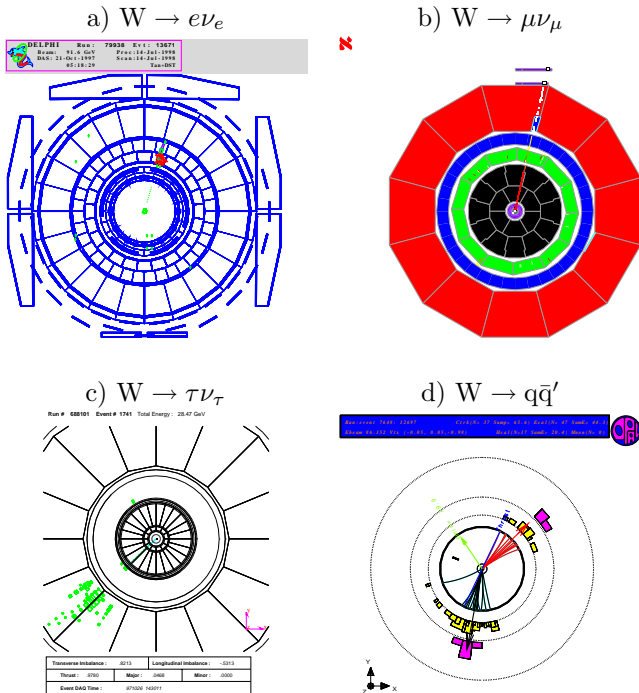


Figure 3: Candidate events for $e^+e^- \rightarrow e\nu W$ observed by a) DELPHI, b) ALEPH, c) L3 and d) OPAL experiments.

where θ_e is the polar angle of the scattered electron, E_ℓ and θ_ℓ are the energy and polar angle of leptons from the W decay, respectively. $M_{qq'}$ is the invariant mass of the quark pair. These cuts on W decay final states are necessary to remove the non-resonant four fermion backgrounds. The selected events are displayed in Fig. 3 for four W decay modes.

Monte Carlo generators of GRC4F ¹⁵, EXCALIBUR ¹⁶ and DELTGC ¹⁷ have been used to simulate the $e\nu W$ production.

2.3 Total cross section

The summary of analyzed data and observed number of events is given in Table 1. In addition to W decay to electron or muon, ALEPH and L3 collaborations have also analyzed the tau decay channel. ALEPH ¹⁹ has measured the total cross section of $e\nu W$ production at 183 GeV as $\sigma_{e\nu W} = 0.40 \pm 0.17(\text{stat.}) \pm 0.04(\text{syst.})$ pb where the standard model predicts 0.41 pb. L3 ²¹ has also measured the cross section at 183 GeV as $\sigma_{e\nu W} = 0.62^{+0.19}_{-0.18}(\text{stat.}) \pm 0.04(\text{syst.})$ pb where 0.50 pb is expected from the standard model. All these results are consistent with the standard model expectation. In Fig. 4, the cross section as a function of the centre-of-mass energy is shown as measured by L3 experiment.

Table 1: Summary of single W measurement for leptonic and hadronic channels. N_{obs} is the number of selected data events. N_{SM} and $N_{e\nu W}$ are the expected number of total events (signal plus backgrounds) and $e\nu W$ signal events, respectively.

	E_{CMS}	Lumi.	$W \rightarrow l\nu$			$W \rightarrow q\bar{q}'$		
	(GeV)	(pb^{-1})	N_{obs}	N_{SM}	($N_{e\nu W}$)	N_{obs}	N_{SM}	($N_{e\nu W}$)
ALEPH ¹⁹	161-183	78.9	11	11.1	(7.3)	21	21.5	(8.8)
DELPHI ²⁰	161-183	73.0	9	5.4	(5.2)	44	52.6	(19.9)
L3 ²¹	130-183	88.5	12	10.2	(6.0)	109	103.3	(14.7)
OPAL ²²	161-172	20.3	2	2.0	(0.8)	4	2.5	(1.3)

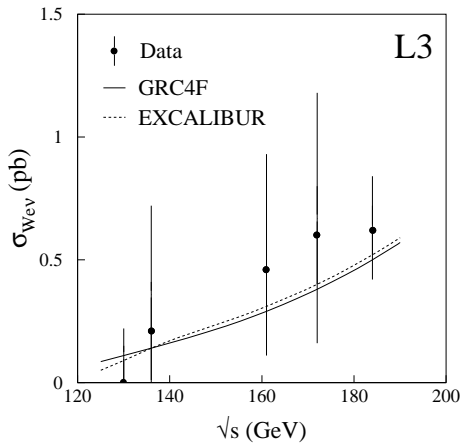


Figure 4: The measured cross section of $e\nu W$ production as a function of the centre-of-mass energy by L3.

2.4 Limits on TGC

Since WW backgrounds in hadronic W decay channel are irreducible ($S/N=1/1$ at best) and the 2/3 of W's decay hadronically, the pure sensitivity to $WW\gamma$ vertex of $e\nu W$ production is lost. This is because W pair production contains both WWZ and $WW\gamma$ vertices that cannot be separated. One is therefore obliged to either a) fix the irreducible WW backgrounds in hadronic W decay as the standard model (ALEPH, OPAL), or b) vary the WW backgrounds simultaneously according to TGC values assuming $SU(2)\times U(1)$ constraints (DELPHI, L3). The former takes the conservative approach, and the latter benefits the information contained in WW backgrounds.

The sensitivity to κ_γ of single W production which is superior to WW production is demonstrated in Fig. 5. However there are two minima at $\Delta\kappa_\gamma = 0$ (the standard model) and at -2 for single W alone due to the fact that total cross section has the same value at these points. This double minima structure can be solved by combining it with the results from single gamma and/or WW

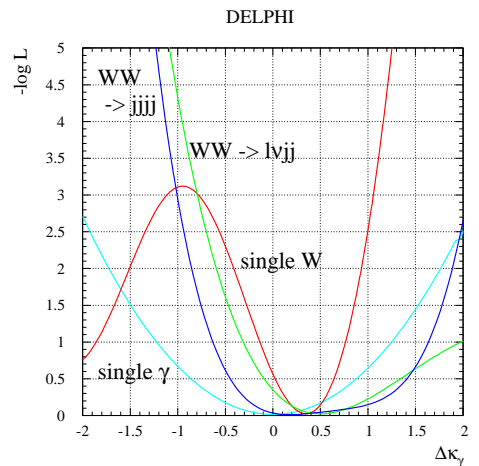


Figure 5: The log-likelihood functions on $\Delta\kappa_\gamma$ parameter measured by DELPHI. The results from W pair production (hadronic, semi-leptonic), single W and single gamma are shown separately.

productions.

In Table 2, the limits on TGC parameters are summarized. The event yields have been analyzed by Bayesian approach (ALEPH) or by maximum likelihood fits to event rate (OPAL) and to kinematical distributions (DELPHI, L3). One should note that the results on λ_γ obtained by DELPHI and L3 experiments benefit information contained in W pair production. The intrinsic

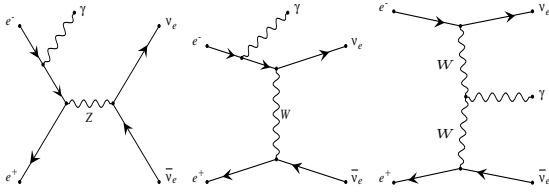
Table 2: The 95% C.L. limits on TGC couplings. Note that L3 gives 95% C.L. limits with 2 parameter fit, and the other experiments give 1 parameter fit result fixing the rest as the standard model values.

ALEPH	$-2.6 < \Delta\kappa_\gamma < 0.5$	$-1.6 < \lambda_\gamma < 1.6$
DELPHI	$-0.4 < \Delta\kappa_\gamma < 0.9$	$-1.5 < \lambda_\gamma < 1.5$
L3	$-0.46 < \Delta\kappa_\gamma < 0.57$	$-0.86 < \lambda_\gamma < 0.75$
OPAL	$-3.6 < \Delta\kappa_\gamma < 1.6$	$-3.1 < \lambda_\gamma < 3.1$

sic sensitivity of single W production alone at the current statistics of LEP is $|\Delta\kappa_\gamma| < 0.5$ ($\lambda_\gamma = 0$) and $|\lambda_\gamma| < 1.6$ ($\Delta\kappa_\gamma = 0$) at 95% C.L. provided that the double minima structure for $\Delta\kappa_\gamma$ is resolved.

3 $\nu\bar{\nu}\gamma$ Production

Amongst various physics opportunities such as counting the number of light neutrino species, the process $e^+e^- \rightarrow \nu\bar{\nu}\gamma$ is also sensitive to $WW\gamma$ coupling⁶. There are three types of diagrams which contribute to the $\nu\bar{\nu}\gamma$ final state as shown in Fig. 6. The first diagram is the radiative return to Z by emitting hard photon, the second one is t-ch W boson exchange, and the last one is W boson fusion type which contains a $WW\gamma$ vertex. The photon in the radiative return process has energy peaked at $x_\gamma = E_\gamma/E_{\text{beam}} = 0.74$ at 183 GeV. Monte Carlo programs based on KORALZ¹⁸ and DELTGC¹⁷ are used.



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Figure 6: Feynman diagrams for $e^+e^- \rightarrow \nu_e\bar{\nu}_e\gamma$.

Isolated photons have been searched in the analysis. It is found that the data are in good agreement with the standard model expectation. When extracting coupling parameters with the maximum likelihood method, the total yield of observed events, the energy and angular distributions are used as shown in Fig. 7. The photon energy region of $x_\gamma \in [0.67, 0.76]$ is not used in ALEPH's analysis. ALEPH²³ has obtained the fitted results of $\Delta\kappa_\gamma = 0.05^{+1.2}_{-1.1} \pm 0.3$ ($\lambda_\gamma = 0$) and $\lambda_\gamma = -0.05^{+1.6}_{-1.5} \pm 0.3$ ($\Delta\kappa_\gamma = 0$), where the first error is statistical and the second is systematic. DELPHI²⁰ performs the binned likelihood fit to the whole photon energy spectrum, and gets $\Delta\kappa_\gamma = 0.00^{+1.01}_{-1.01} \pm 0.36$ ($\lambda_\gamma = 0$) and $\lambda_\gamma = 0.72^{+1.12}_{-1.12} \pm 0.36$ ($\Delta\kappa_\gamma = 0$). Both results are consistent with the coupling parameters equal to zero.

The sensitivity of $\nu\bar{\nu}\gamma$ to TGC parameters is 2 ~ 3 times weaker than that of $e\nu W$, but nevertheless, it contributes to solve the double minima structure for $\Delta\kappa_\gamma$ in $e\nu W$ production as discussed above.

4 Invisible W Decay

The ALEPH collaboration¹⁹ has performed the search for the invisible W decay in $e^+e^- \rightarrow W^+W^-$. The mixed

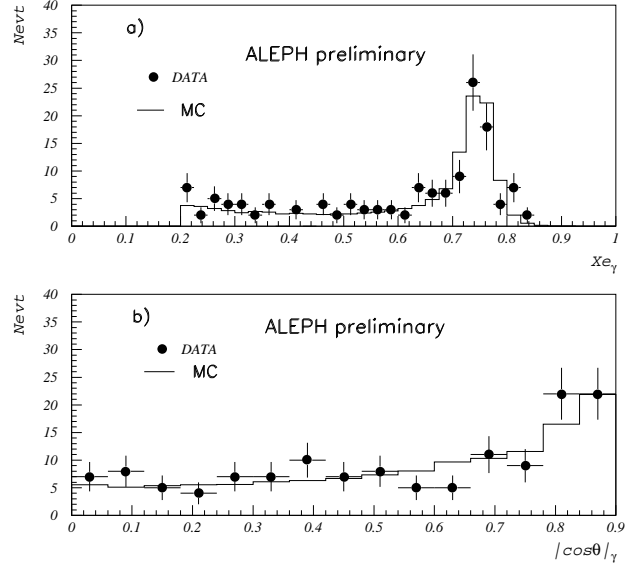


Figure 7: ALEPH measurements on a) photon energy (normalized to the beam energy) and b) angular distribution of photons for $\nu\bar{\nu}\gamma$ production at 183 GeV.

supersymmetric/standard model decay has been studied. One W boson decays to chargino and neutralino, followed by the chargino decay to sneutrino and lepton. The other W boson decays to the standard model particles. The whole decay cascade can be illustrated as,

$$e^+ e^- \rightarrow W \quad W$$

$$\hookrightarrow \text{SM} \hookrightarrow \chi^\pm \chi$$

$$\hookrightarrow \ell \tilde{\nu}$$

$$\hookrightarrow \nu \chi.$$

The supersymmetric decay of W boson becomes practically invisible if the mass difference between the chargino and the sneutrino ($\Delta M \equiv m_{\chi^\pm} - m_{\tilde{\nu}}$) is less than about $3 \text{ GeV}/c^2$. However this process still can be tagged by the W decay to the standard model particles. Three event topologies of the final state, single lepton (e/μ), acoplanar lepton pair (one is soft) and hadrons (missing mass equal to W mass) have been studied.

No excess of the signal has been observed and the results are consistent with the standard model expectation. The limits at 95% C.L. on the W boson supersymmetric branching ratio have been obtained as:

$$\mathcal{B}_{\text{susy}} (\Delta M \approx 0 \text{ GeV}/c^2) < 1.3 \%,$$

$$\mathcal{B}_{\text{susy}} (\Delta M = 3 \text{ GeV}/c^2) < 1.9 \%,$$

assuming $\mathcal{B}(\chi^\pm \rightarrow \ell\tilde{\nu}) = 100\%$ and $m_{\chi^\pm} = 45 \text{ GeV}/c^2$. Degenerate ($\Delta M \approx 0 \text{ GeV}/c^2$) case gives the quasi model-independent limit on the invisible W decay width via direct search. The result translates as $\Gamma(W \rightarrow \text{inv}) < 27 \text{ MeV}$ at 95% C.L..

5 Conclusion

Single W production has been studied at LEP. The production cross section is consistent with the standard model expectation. It has been shown that $e\nu W$ production is sensitive to the $WW\gamma$ coupling, in particular to κ_γ . However, the irreducible WW background in hadronic decay channel of $e\nu W$ does not allow the clear separation of $WW\gamma$ and WWZ couplings. Single gamma production has also been studied. No deviation from the standard model is found.

Search for invisible W decay has been performed by ALEPH and the stringent limit on invisible W decay width of 27 MeV has been obtained at 95 % C.L..

The current status and the future perspective on the $WW\gamma$ coupling measurement are summarized in Table 3. One sees that the $W\gamma$ production at Tevatron and $e\nu W$ production at LEP provide complementary information on TGC. It is anticipated that $e\nu W$ production at LEP has the sensitivity of $|\Delta\kappa_\gamma| \sim 0.1$ with 500 pb^{-1} data at higher energies. In future, one may combine leptonic decay channel of $e\nu W$ and $\nu\bar{\nu}\gamma$ alone that are purely sensitive to the $WW\gamma$ coupling. It is expected that the use of kinematical information and the spin analysis will further improve the limits.

Table 3: The current and future TGC limits at 95% C.L. per single experiment.

Tevatron ⁹	$W\gamma$	93 pb^{-1}	$ \Delta\kappa_\gamma < 0.9$	$ \lambda_\gamma < 0.3$
LEP	$e\nu W$	80 pb^{-1}	$ \Delta\kappa_\gamma < 0.5$	$ \lambda_\gamma < 1.6$
LEP2000	$e\nu W$	500 pb^{-1}	$ \Delta\kappa_\gamma < 0.1$	$ \lambda_\gamma < 0.6$

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