Single- W versus W -pair production at LEP II

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ABSTRACT

This paper is a study of the single- W and W -pair production at LEP II. I show that the sensitivity of the single- W production channel on the anomalous trilinear couplings of W is essentially the same as the sensitivity of the channel $e^+e^- \rightarrow W^+W^-$. Therefore, even without the reconstruction of the W boson, deviations from the Standard Model predictions on trilinear couplings can be measured at the level of $0.2 - 1$, using single- W production at LEP II.

Electroweak precision tests at the Z^0 pole using LEP I data, constrain in a rather important way the physics that can be probed in the near future [1, 2]. Taking into account also the Tevatron results [3], it will be very difficult to study directly the top quark or the Higgs scalar particle at LEP II. If this is true, then LEP II experiments should focus on W -physics. Moreover, given the limiting rates expected at LEP II energies (in contrast with LEP I), it will be rather difficult to have a new precision-test experiment. Therefore the main, well-defined area of experimental and phenomenological research will be the study of the interactions of W , and especially the measurement of the trilinear and quadrilinear couplings among the gauge bosons [4, 5, 6, 7, 8].

The interest of these measurements lies in the fact that the Standard Model prediction for them is strongly related to the existence of the underlying symmetry: its non-Abelian character will be tested directly by measuring these couplings. On the other hand any ‘new physics’ manifests itself at low energies by modifying these couplings: the difference between different models is the strength of this modification. In particular large deviations from Standard Model predictions will point in the direction of a composite structure, whereas small ones can be accommodated by renormalizable theories.

In order to study the anomalous couplings one usually introduces an interaction Lagrangian [5], which in the unitary (physical) gauge and considering only CP-conserving couplings, is written in the following form:

$$\begin{aligned} \mathcal{L} = & \sum_{V=\gamma,Z} \left\{ g_V (V_\mu W^{-\mu\nu} W^{+\nu} - V_\mu W^{+\mu\nu} W^{-\nu} + \kappa_V V_{\mu\nu} W^{+\mu} W^{-\mu\nu}) \right. \\ & \left. + g_V \frac{\lambda_V}{M_W^2} V_{\mu\rho} W^{+\rho\nu} W_\rho^{-\mu} \right\} \end{aligned} \quad (1)$$

where

$$W_{\mu\nu}^+ = \partial_\mu W_\nu^+ - \partial_\nu W_\mu^+$$

$W^\pm$ is the W -boson field, and $g_\gamma = e$, $g_Z = e \cotg \theta_w$, $\kappa_\gamma = \kappa_Z = 1$ and $\lambda_\gamma = \lambda_Z = 0$ at tree order in the Standard Model. It is more convenient to express the different couplings in terms of their deviations from the Standard Model values. For this we define the following deviation parameters:

$$\begin{aligned} \delta_Z &= g_Z - \cotg \theta_w \\ x_\gamma &= \kappa_\gamma - 1 \\ x_Z &= (\kappa_Z - 1)(\cotg \theta_w + \delta_Z) \end{aligned} \quad (2)$$

It is worth while to note that the interaction Lagrangian becomes linear with respect to the above parameters (including also λ_γ and λ_Z).

During the last years, considerable progress has been achieved concerning the understanding of the physics underlying the anomalous couplings. As Gounaris and

Renard [9] showed, these anomalous couplings can be parametrized in a manifestly gauge-invariant (but still non-renormalizable) way: gauge-invariant operators involving higher-dimensional interactions among gauge bosons and Higgs field are hidden beyond them. It is the dynamics of the unknown Higgs sector that is essentially probed by studying the trilinear couplings of the massive vector bosons. Precise electroweak tests at LEP I already impose severe restrictions on the possible operators considered [10, 11]. Operators contributing to the W to Z mass ratio, and thus affecting the so-called ρ parameter, which has been measured with very high accuracy at LEP I, should be excluded. Moreover, these gauge-invariant operators are multiplied by powers of v^2/Λ^2 , where $v = (\sqrt{2}G_F)^{-1/2}$, is the vacuum expectation value of the Higgs field and Λ the scale where new physics is expected to appear. In the limit $v/\Lambda \rightarrow 1$, operators with arbitrary dimension have to be considered: this is a ‘democratic’ scenario, which in the language of the old parametrization means that all anomalous couplings are treated as independent. Of course, this scenario suffers several drawbacks. First of all it will be difficult experimentally to disentangle the different contributions. At the same time, from a theoretical point of view, it seems to be rather unexpected, the new physics scale to be of the order of the electroweak scale¹. On the other hand, in the limit $v/\Lambda \ll 1$, one could have a ‘hierarchical’ scenario [14], which considerably simplifies both experimental and theoretical studies of anomalous couplings. Adopting this last scenario, and restricting ourselves to $SU(2)_L \times U(1)_Y$ -invariant operators with dimension up to 8, we can have the following list:

$$\begin{aligned}
\mathcal{O}_{B\Phi} &= B^{\mu\nu}(D_\mu\Phi)^\dagger(D_\nu\Phi) \\
\mathcal{O}_{W\Phi} &= (D_\mu\Phi)^\dagger \boldsymbol{\tau} \cdot \mathbf{W}^{\mu\nu}(D_\nu\Phi) \\
\mathcal{O}_W &= \frac{1}{3!}(\mathbf{W}_\rho^\mu \times \mathbf{W}_\nu^\rho) \cdot \mathbf{W}_\mu^\nu \\
\mathcal{O}'_{W\Phi} &= (\Phi^\dagger \boldsymbol{\tau} \cdot \mathbf{W}^{\mu\nu} \Phi)(D_\mu\Phi)^\dagger(D_\nu\Phi) \\
\mathcal{O}'_W &= (\mathbf{W}_\rho^\mu \times \mathbf{W}_\nu^\rho) \cdot (\Phi^\dagger \frac{\boldsymbol{\tau}}{2} \Phi) B_\mu^\nu
\end{aligned} \tag{3}$$

where $\tau_i = \frac{1}{2}\sigma_i$ (the Pauli matrices),

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$$

where B_μ is the $U(1)_Y$ gauge field,

$$\mathbf{W}_{\mu\nu} = \partial_\mu \mathbf{W}_\nu - \partial_\nu \mathbf{W}_\mu - g_2 \mathbf{W}_\mu \times \mathbf{W}_\nu$$

where $\mathbf{W}$ are the $SU(2)_L$ gauge fields and

$$\Phi = \begin{pmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}(v + H + i\phi^0) \end{pmatrix}$$

¹However, it is fair to emphasize that at higher energies [12, 13], when it could be possible to test the one-loop corrections in the Standard Model, a ‘democratic’ scenario has to be considered.

is the Higgs doublet. The covariant derivative D_μ is given, as usual, by

$$D_\mu = \partial_\mu + i g_2 \boldsymbol{\tau} \cdot \mathbf{W}_\mu - i g_1 B_\mu$$

and $e = g_2 \sin \theta_w = g_1 \cos \theta_w$.

The interaction Lagrangian can be written now as

$$\mathcal{L} = \mathcal{L}_{SM} + \sum g_i \mathcal{O}_i \quad (4)$$

where $\mathcal{O}_i$ are the operators given in Eq.(3). The different contributions of the above operators to the anomalous couplings Eq.(2) are summarized in table 1. In the present analysis I only consider one g_i coupling at a time to be non-zero. Since at LEP II energies it is not expected to test the one loop corrections to the trilinear couplings, this approach is justified. At higher energies, where these corrections could be tested, one should consider the case that all $\mathcal{O}_i$ are equally, or almost equally, contributing to the effective Lagrangian. This is because the radiative corrections to the trilinear couplings cannot be parametrized in terms of a single operator: for instance one-loop relations between κ_γ and κ_Z are energy dependent [12] and are generically different from the relations given in table 1.

$\mathcal{O}_{W\Phi}$	$x_\gamma \neq 0, \delta_Z = \frac{x_\gamma}{s_w c_w}, x_Z = -x_\gamma \text{tg } \theta_w$
$\mathcal{O}_{B\Phi}$	$x_\gamma \neq 0, x_Z = -x_\gamma \text{tg } \theta_w$
$\mathcal{O}_W$	$\lambda_\gamma \neq 0, \lambda_Z = \lambda_\gamma$
$\mathcal{O}'_{W\Phi}$	$x_\gamma \neq 0, x_Z = x_\gamma \text{ctg } \theta_w$
$\mathcal{O}'_W$	$\lambda_\gamma \neq 0, \lambda_Z = \lambda_\gamma \text{tg}^2 \theta_w$

Table 1: Contribution of different gauge-invariant operators to the anomalous couplings ($s_w = \sin \theta_w$ and $c_w = \cos \theta_w$).

In this paper I study the single- W and W -pair production and their sensitivity with respect to the anomalous trilinear couplings as defined above. By single- W production I mean the process $e^+e^- \rightarrow W^\pm \ell^\mp \nu_\ell$, where ℓ can be either an electron or a muon. In the case of a muon, it is easy to see that the main contribution is expected to come from the region where the muon and the corresponding neutrino have a mass very close to the mass of the W : the so-called resonant graphs are dominant. On the other hand, the electron case is expected to be more interesting since t -channel graphs are also present and therefore the non-resonant contribution should be important. In the rest of the analysis I focus on the electron channel, using the angular distribution of the electron as the main tool to investigate the sensitivity of the single- W production with respect to the anomalous couplings. The amplitudes have been calculated in ref.[7] using the E-vector formulation of the spinor-product technique [15]. The main advantage of this channel is that it does not require the reconstruction of the produced

$\sqrt{s}$ (GeV)	170	190	230	500
$W e \nu$ (pb)	1.1(1)	1.4(1)	1.3(1)	0.55(5)
WW (pb)	1.11(5)	1.37(5)	1.21(5)	0.31(3)

Table 2: Cross sections in pb for different center-of-mass energies.

W , which is, in contrast, very important for the W -pair channel. In order to exclude or minimize possible backgrounds such as $b\bar{b}$ or $Z^0 Z^0$ production it is sufficient to detect an electron well separated from the hadronic activity (jets) and identify, using the overall centre-of-mass energy, the existence of missing energy. Still there is the contribution of $e^+ e^- \rightarrow e^\pm \bar{\nu} q \bar{q}'$ channel when the invariant mass of the two quarks is well away from the W mass, but one expects that this is at least an order of magnitude smaller than the contribution of the single- W channel.

Bin number	1	2	3	4	5	6
$\sigma_{0,i}$	0.87(2)	1.22(3)	1.76(4)	2.65(7)	4.2(1)	8.1(2)
$\sigma_{0,i}^*$	0.87	1.22	1.73	2.57	4.20	8.31

Table 3: Bin contents in pb; $\sigma_{0,i}^*$ are taken from ref.[16].

In table 2, I have summarized the total cross-section rates for $W e \nu$ production, taking into account the following cuts on the energy and the angle of the electron:

$$E_e \geq 10 \text{ GeV} \quad |\cos \vartheta_e| \leq 0.95 \quad , \quad (5)$$

as a function of the centre-of-mass energy, from 170 to 500 GeV. The branching ratio $\text{BR}(W^\pm \rightarrow \text{hadrons}) = 2/3$ has been taken into account. The cross sections for WW production are also displayed, multiplied by the appropriate branching ratio ($\frac{2}{27}$). The calculation is done using the same method as for the $W e \nu$ channel [7], and a cut on the W angle, $|\cos \vartheta_W| \leq 0.98$ is considered. Although this last cut is not necessary for the calculation of the WW cross section (no singularities are present), it is included in order to compare my results (see table 3) with those of ref.[16], where a detailed analysis of the WW channel has been presented. Assuming an integrated luminosity $L=500 \text{ pb}^{-1}$, the events expected from the $W^\pm e^\mp \nu$ channels are of the order of ~ 1400 , a rather good starting point for the angular-distribution analysis. In order to quantify in a rather simple and transparent way the deviation of the angular distribution from its Standard Model prediction, I divide the interval, $-0.95 \leq \cos \vartheta \leq 0.95$, in six equidistant bins and I calculate the χ^2 as follows

$$\chi^2 = \sum_{i=1,6} \frac{(\sigma_{0,i} - \sigma_i)^2}{\delta \sigma_{0,i}^2} \quad (6)$$

where $\sigma_{0,i}$ is the Standard Model cross section contained in the i th bin, σ_i is the corresponding cross section calculated at non-zero deviation-parameter values and $\delta\sigma_{0,i}$ represent the statistical errors defined as

$$\delta\sigma_{0,i} = \sqrt{\frac{\sigma_{0,i}}{\varepsilon L}}$$

where ε is the ‘efficiency’ factor, which in this case is simply 1, since no reconstruction of the W is required. For WW production the analysis is the same, except that the angle ϑ is taken to be the angle of W^- , being reconstructed via its decay products. In order to compare the two channels one has to consider an extra ‘efficiency’ factor taking into account reconstruction uncertainties: I take as rather typical values $\varepsilon = 0.8$ for the total WW cross section and $\varepsilon = 0.64$ for the angular distribution. I also evaluate a more ‘theoretical’ (and less experimentally biased) χ_{th}^2 , defined as

$$\chi_{th}^2 = \frac{1}{6} \sum_{i=1,6} \frac{(\sigma_{0,i} - \sigma_i)^2}{\sigma_{0,i}^2}$$

which is simply a measure of the relative deviation, in order to have a comparison of the ‘theoretical’ sensitivities on the anomalous couplings.

In Fig.1, I show the angular distribution for single- W as well as for WW production. Both channels exhibit similar characteristics and they have, qualitatively, the same sensitivity with respect to the anomalous couplings. In Fig.2, χ_{th}^2 is presented as a function of the deviation parameter x_γ (for the $\mathcal{O}_{W\Phi}$ operator). As expected, angular distribution is more sensitive, with respect to the deviation parameters, than the total cross section. Also the angular distribution of the W -boson angle (ϑ_W) is more sensitive than the corresponding quantity for electrons. Of course in this ‘theoretical’ comparison, any problem concerning W -reconstruction is simply ignored. On the other hand, Fig.3 shows the χ^2 as a function of the same parameter, but now including all statistical effects. It is possible to use the χ^2 to estimate the region in deviation-parameter-space, which is incompatible with Standard Model predictions. For the total cross section, limits are extracted requiring that $\chi^2 \geq 4$, which corresponds to two standard deviations ($\sim 95\%$ CL). For the angular distribution, limits are extracted requiring that $\chi^2 \geq 11.07$ at 95% CL: for this the corresponding number of degrees of freedom ($6 - 1 = 5$) is considered [17]. It is worth while to emphasize that present results disagree with the results of ref.[16], where, although not explicitly written, an artificially small $\chi^2 \sim 1$ has been considered. Table 4 summarizes the limits on the parameters describing the deviations from the Standard Model predictions both for WW and single- W production. Although the results from the angular distribution of W are in general better, the gain cannot be considered significant, since they cover a rather small and less important region in the parameter space. Furthermore, if reconstruction efficiencies for W are lowered by a factor ~ 0.8 , the above-mentioned region disappears. On the other hand, if reconstruction uncertainties are overcome, the limits are not essentially affected: if instead of $\varepsilon = 0.64$ one takes $\varepsilon = 1$, the

Operator	$W\epsilon\nu$	WW
$\mathcal{O}_{W\Phi}$	$-0.24 \ 0.36$	$-0.22 \ 0.42$
x_γ	$-0.26 \ 0.40$	$-0.14 \ 0.20$
$\mathcal{O}_{B\Phi}$	$-0.55 \ 1.12$	$-0.50 \ 1.41$
x_γ	$-0.44 \ 1.20$	$-0.52 \ 1.64$
$\mathcal{O}_W$	$-0.34 \ 0.46$	$-0.32 \ 0.49$
λ_γ	$-0.38 \ 0.52$	$-0.24 \ 0.42$
$\mathcal{O}'_{W\Phi}$	$-0.35 \ 0.63$	$-0.33 \ 0.78$
x_γ	$-0.37 \ 0.62$	$-0.23 \ 0.30$
$\mathcal{O}'_W$	$-0.50 \ 0.85$	$-0.52 \ 0.90$
λ_γ	$-0.48 \ 0.92$	$-0.54 \ 1.10$

Table 4: Limits on deviation parameters. The first row corresponds to the total cross section and the second row to the angular-distribution analysis, as explained in the text.

limits for the $\mathcal{O}_{W\Phi}$ operator, for instance, change only from $-0.14 \leq x_\gamma \leq 0.20$ to $-0.12 \leq x_\gamma \leq 0.16$.

In summary, I have shown that single- W production is essentially as sensitive as the WW channel with respect to the trilinear couplings of vector bosons. The reconstruction of the W will not play an important role in limiting the anomalous couplings, at least for one-parameter CP-conserving deviations. Single- W production at $\sqrt{s} = 190$ GeV will be able to set limits of the order of $0.2 - 1$ on the anomalous couplings, improving by a factor of $5 - 10$ the existing limits [18] and by a factor of $2 - 3$ those expected from HERA [19].

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Figure 1: Angular distribution for $W e \nu$ and $W W$ channels. The ‘experimental’ points correspond to the Standard Model predictions and the errors are purely statistical. The dot-dashed lines correspond to $x_\gamma = 1$ and the dashed ones to $x_\gamma = 0.5$.

Figure 2: The χ_{th}^2 function, defined in Eq.(7), for the operator $\mathcal{O}_{W\Phi}$. For the $W\ell\nu$ (WW) channel, the solid (dot-dashed) line corresponds to the total cross section and the dashed (dotted) line to the angular distribution.

Figure 3: The χ^2 function for the operator $\mathcal{O}_{W\Phi}$. For the $W\ell\nu$ (WW) channel, the solid (dot-dashed) line corresponds to the total cross section and the dashed (dotted) line to the angular distribution.