FOUR-FERMIONS PROCESSES AND GAUGE COUPLINGS AT LEP

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In four years of data taking at energies above the W-pair production threshold the four LEP collaborations have collected more than 600 pb^{-1} of integrated luminosity each. The collected data allow to test the production mechanisms of four-fermion final states up to percent level and to measure the trilinear gauge couplings with a precision of few percents.

1 Introduction

The successful running of the LEP collider at CERN and of its four experiments ALEPH, DELPHI, L3 and OPAL above the W-pair production threshold $\sqrt{s} > 2M_W$ (herein called the LEP2 phase) pushed the study of the four-fermion production processes into the "precision" physics regime. The $\sqrt{s}$ and related integrated luminosity per experiment are shown in Figure 1.

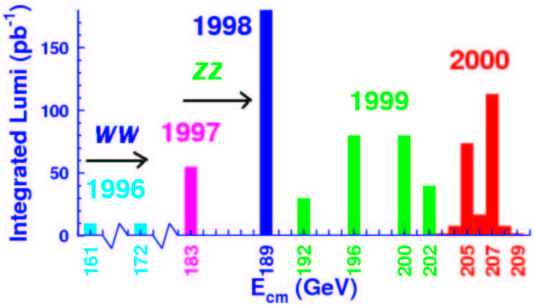

Figure 1. Energies and integrated luminosities delivered by LEP.

The amount of results, many of which are final, forbids a complete report to be contained in the length if this review. Rather, few items are spotted and the interested reader is addressed to Reference [1] for a more detailed collection. If available, combined and final results are privileged against single experiments outputs.

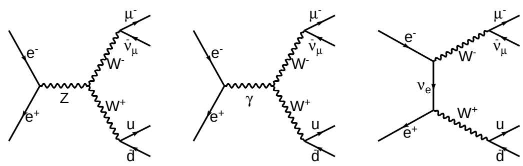

Figure 2. Born-level diagrams contributing to W-pair production at LEP2.

Table 1. W-pair decay modes and Branching Ratios.

# channels	process	BR
1	WW $\rightarrow$ qqqq	*45.6 %*
3	WW $\rightarrow$ qq$\ell\nu$	*43.8 %*
6	WW $\rightarrow \ell\nu\ell\nu$	*10.6 %*

2 W and Z Bosons Production

The W boson pair-production at LEP2 comes from three Born-level diagrams as shown in Figure 2 and known as the CC03 set, where CC stands for Charged Current. The cross section measurements performed at LEP2 involves all possible decay modes as detailed in Table 1. The measured cross sections includes contributions from all processes yielding the same final states such as Z-pair, singly resonant or multiperipheral diagrams. It is then conventional to correct the measured four-fermion cross sections by the theoretically calculated factor $|M(\mathrm{CC03})|^2/|M(\mathrm{full})|^2$ where M is the associated matrix element.

Using the full statistics available from

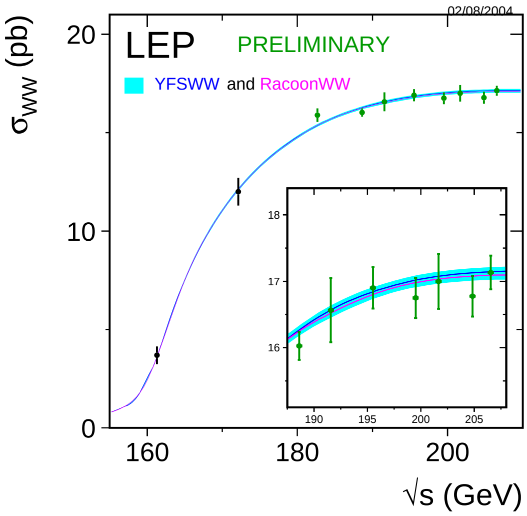

Figure 3. Combined W-pair cross section measurements in function of $\sqrt{s}$. The solid lines represent the theoretical expectations.

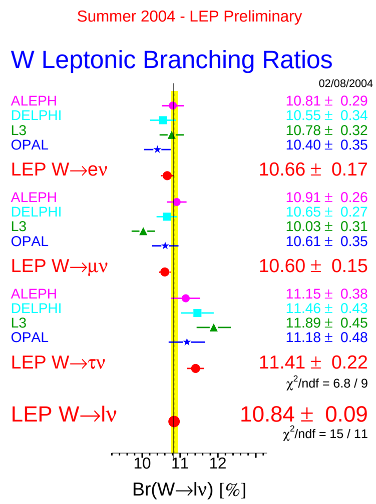

Figure 4. W-boson branching ratios derived from cross section measurements.

the four LEP experiments the total W-pair cross section is measured with a precision of 1.1% as shown in Figure 3. The theoretical accuracy, thanks to the Double Pole Approximation [2] method used by the most accurate programs, is of 0.5%. The dominant systematic error, common to all experiments, is coming from the hadronisation modeling used in the simulations to derive efficiencies and purities. It amounts to 0.6% of the measured cross section. The measurement of separate decay-modes cross sections allows the precise determination of the W-boson branching ratios as shown in Figure 4. The Standard Model [3] predicts the three leptonic branching ratios to be identical. Taking into account correlations, the above measurements show an (in)compatibility of 2.4 equivalent standard deviations with this assumption. The hadronic branching ratio is derived to be $67.48 \pm 0.28\%$. Using the relation:

$$\frac{\mathrm{BR}(W \to qq)}{1 - \mathrm{BR}(W \to qq)} = \left(1 + \frac{\alpha_s(M_W^2)}{\pi}\right) \sum |\mathrm{V}_{ij}^{CKM}|^2$$

the $|V_{cs}|$ matrix element is derived to be 0.976 ± 0.014.

The precise determination of the lepton charge and of the W-boson direction in all LEP experiments allow the measurement of the W^- direction and hence of the differential cross section $\mathrm{d}\sigma/\mathrm{d}\cos\theta_{\mathrm{W}^-}$. While performed currently only by DELPHI and L3, it is considered one of the most important legacy of W-physics studies at LEP2. The measurements are corrected at CC03 level, as for the total cross section, with the additional requirement of a lepton well into the detector active area ($\theta_\ell > 20°$). The first preliminary combinations, compared to the expected distributions, are shown in Figure 5 in different $\sqrt{s}$ ranges.

The presence of a detectable photon, coming from radiation off the initial state electrons or intermediate/final state bosons/fermions, is also tested against theory prediction. It represents a valuable test of radiation effect in the measurements as well as power tool to search for anomalous quartic gauge couplings WWZγ and WW$\gamma\gamma$. No sig-

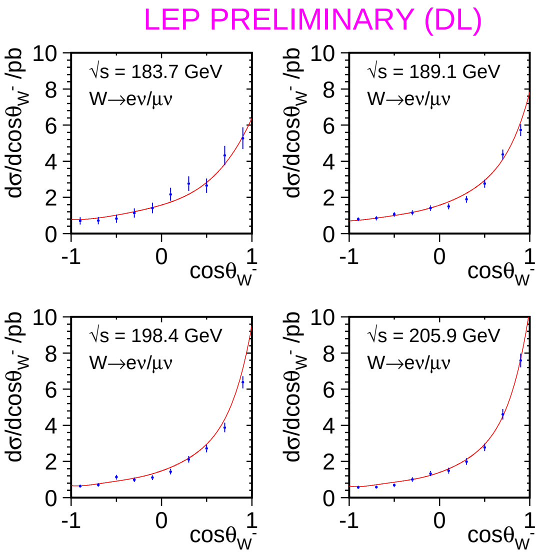

Figure 5. Differential cross sections in function of $\cos\theta_{W-}$ for different $\sqrt{s}$ points.

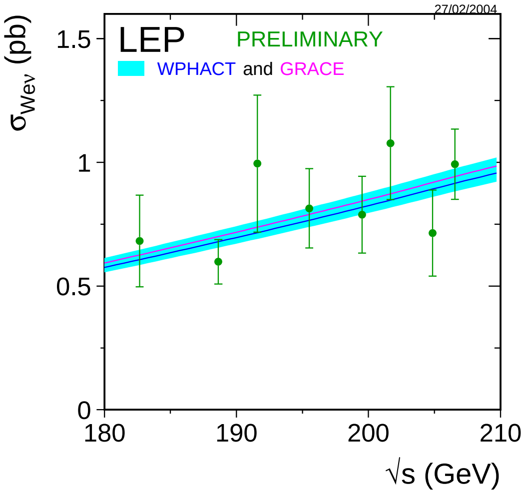

Figure 6. Combined single-W cross sections in function of $\sqrt{s}$.

nificant deviation from the Standard Model is observed.

Single W-boson events, in the form of $qqe\nu$ or $\ell\nu e\nu$ events, are an interesting test-bench to search for anomalous WWγ couplings. In addition, it represents a sizeable and irreducible background source for W-pair production. All LEP experiments have dedicated measurements which are combined in a common cross section measurement, see Figure 6.

Z bosons are produced at LEP2 either in pairs, with cross sections one order of magnitude below their W-boson counterparts, or via singly resonant graphs similar to the single-W processes. In the Standard Model, neutral trilinear gauge couplings do not exist at tree level hence only the t-channel graphs contribute to the Z-pair production. The combined cross sections measurements are shown if Figure 7.

3 Charged Gauge Couplings

Since 1978 a general formalization of couplings in W-pair production has been adopted [4]. The most general Lagrangian, where only Lorentz invariance is assumed, foresees 7×2 complex couplings for a total of 28 parameters. The available statistics do not allow to fit all parameters simultaneously and in addition some of them are trivially deduced by imposing physical assumptions like charge or CP conservation. The presence of anomalous couplings would have peculiar effects on the physical properties of the W-boson and on its production. In particular both the total and differential cross sections would be modified providing a handle to detect such anomalies. Many approaches, for example the Spin Density Matrix analysis or the polarization analysis, are used to test the Standard Model which predicts only four of such couplings being non zero: $g_1^Z = g_1^\gamma = k_Z = k_\gamma = 1$. The most powerful tools to measure (and test) the gauge couplings are anyhow based on analyses using the full phase-space information. This can be achieved either in multi-dimensional fits

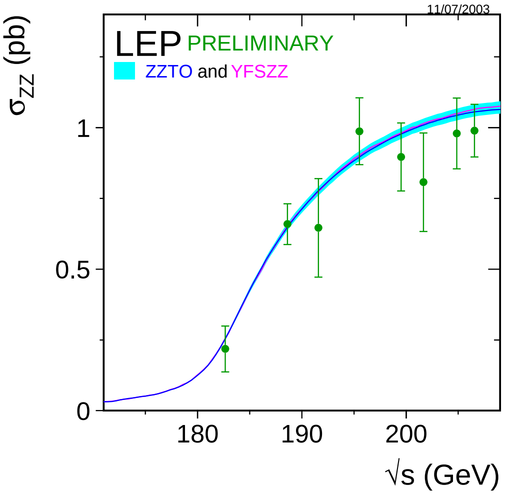

Figure 7. Combined Z-pair cross sections in function of $\sqrt{s}$.

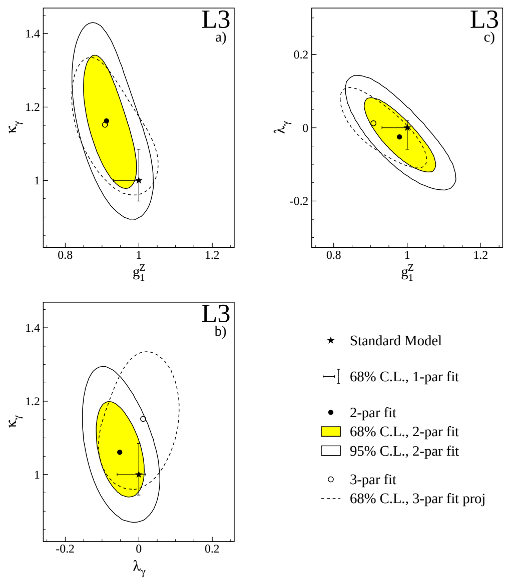

Figure 8. One-, two- and three couplings fit results from L3.

or via optimized estimators which maximize the sensitivity to a particular coupling.

It is conventional to fit W-pair events to three main couplings: g_1^Z, λ_γ and κ_γ with the so called "custodial SU(2)" assumption:

$$g_1^\gamma = 1 \;\; ; \;\; \lambda_\gamma = \lambda_Z$$
$$k_Z = g_1^Z - (\kappa_\gamma - 1)\tan^2\theta_W \; .$$

Fits are performed leaving one, two or all three parameters free to vary in order to check the consistency. An example is given in Figure 8. The one-parameter results, combined among the four LEP collaborations, yield:

$$g_1^Z = \;\; 0.991^{+0.022}_{-0.021} \; ; \; \lambda_\gamma = -0.016^{+0.021}_{-0.023}$$
$$\kappa_\gamma = \;\; 0.984^{+0.022}_{-0.021} \; .$$

The dominant systematic uncertainty, common to all experiments, is related to the implementation of $\mathcal{O}(\alpha)$ corrections. In any case it turns out to be small with respect to the statistical uncertainty which amounts to 2/3 of the total uncertainty.

4 Neutral and Quartic Gauge Couplings

While neutral gauge couplings are inexistent in the Standard Model, the charged quartic gauge couplings are foreseen but too small to be measured at LEP. In both cases the LEP experiments have performed searches for anomalous contributions in a variety of final states.

The h and f couplings describe trilinear neutral vertices with $(Z^\star/\gamma^\star)Z\gamma$ and $(Z^\star/\gamma^\star)ZZ$ boson lines. The search for them is performed in the "two-fermion + photon" or "four-fermion + photon" final states, respectively, with technique similar to the one described for the charged couplings. The two-parameter fit results for the f couplings are presented in Figure 9. See Reference [1] for a detailed list of all results.

Anomalous quartic gauge couplings, conventionally named $a^{W,Z}$, are searched for in W-pair+photon events ($Z/WW\gamma$, $\gamma/WW\gamma$), in two-photon events via the t-channel W exchange ($WW\gamma\gamma$) and in Z-pair+photon

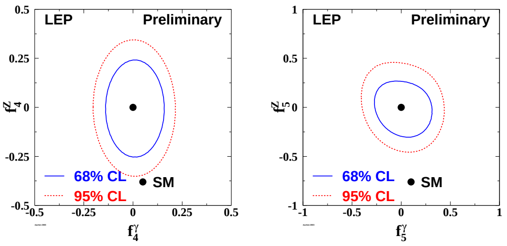

Figure 9. Two parameters contours for f couplings.

events ($ZZ\gamma\gamma$). In all cases at least one visible photon is requested in the final state and its energy spectrum is one of the most coupling-sensitive variables. No excess is found and 95% C.L. limits are derived in all cases

a^W couplings combination from year 2001

$$-0.02 \leq a_0^W/\Lambda^2 \leq 0.02\mathrm{GeV}^{-2}$$
$$-0.03 \leq a_c^W/\Lambda^2 \leq 0.05\mathrm{GeV}^{-2}$$
$$-0.17 \leq a_n^W/\Lambda^2 \leq 0.15\mathrm{GeV}^{-2}$$

a^Z couplings combination from year 2003

$$-0.008 \leq a_0^Z/\Lambda^2 \leq 0.021\mathrm{GeV}^{-2}$$
$$-0.029 \leq a_c^Z/\Lambda^2 \leq 0.039\mathrm{GeV}^{-2}$$

5 Conclusion

After many years of running above W-pair and Z-pair production thresholds, the LEP collaborations succeeded to test the production of four-fermion final states, mainly via doubly resonant boson graphs, up to the percent level. In addition, the quality of the collected data, the refined analysis techniques and the full cooperation among collaborations allowed to test with similar precision the strength of the trilinear gauge couplings and to put stringent limits on extensions of the Standard Model. It is remarkable that only few years ago all this was considered as "New Physics" [4].

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