RESULTS OF ELECTROWEEK INTERACTION FROM LEP-II EXPERIMENT AT CERN

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1. Introduction

Experiments with the Large Electron-Positron Collider at CERN have been started in 1989. Four large detectors have been constructed at LEP: ALEPH, DELPHI, L3, and OPAL. The simultaneous operation of all these detectors provided powerful cross checks of the obtained results that made them highly reliable. PNPI took an active part in construction and operation of the L3 detector. In the first period of 1989 – 1995, LEP operated at the center-of mass energy of m_z (LEP-I phase). The main motivation was investigations of electroweak (EW) processes and verification of the validity of the most complete theory – the Standard Model (SM). The first target was the intermediate neutral vector boson, already experimentally discovered, *Z* boson. In the six years period several millions of *Z*'s was produced, its mass and widths (total and partial), branching ratios into all possible final states were measured. The SM parameters were determined with high accuracy. There was no evidence of deviations from the SM predictions. Some free parameters of the theory were estimated. The number of leptons families was established to be equal to three, the same as the number of quarks families in the strong interaction sector of the SM. The high precision reached provided a possibility to constrain the mass of not yet discovered top quark from the calculations of the loop correction to the bare *Z*-boson mass using in the calculations the value of the charged vector boson mass m_w, already observed in the experiments on hadron colliders. The correction is rather strongly, quadratically, depends on the quark mass, but there are also contributions from the scalar bosons. To explain the mass splitting of the EW intermediate bosons – photon, *Z* and *W* – there should be at least one scalar Higgs boson (*H*), which also enters into the loop calculations. It was not found any scalar boson in the experiments, *i.e*. the mass of the boson is high (m_H > 58 GeV), moreover the loops correction from this source is only weakly (logarithmically) dependent on the Higgs boson mass. For this reason, the prediction of the mass of top quark was rather accurate ($m_t = 197^{+30}_{-16}$ GeV). Such low limit gave a chance to observe the top quark production on the proton-antiproton collider at Fermilab[1,2]. After several years of very difficult studies the top quark was discovered by Fermilab experiments, confirming once more the high predictive power of the SM. The main results of the L3 experiments during LEP-I operation have been already presented in the previous reports [1, 2].

Already at the early stage of the LEP project, it was decided to rise up the beam energy to 100 GeV (LEP-II). At this energy the EW cross section of production of the *W* pairs is rising first and then is flattened out. Copious *W* production studies make possible to determine the parameters of the *W* boson with higher accuracy, making the theoretical constraints much tougher, in particular predicting the range of the Higgs boson mass.

The data taking on LEP-II was terminated in 2000 but sophisticated analysis is still under way. For example, during last 5 years the L3 collaboration has published more than 30 papers with the final results. At the same time, all four LEP experiments – ALEPH, DELPHI, L3, and OPAL – in the frame of the LEP Working groups (WG) – carried out combined studies of different topics of the SM, with consideration of all available data including the relevant Fermilab results. Some of the WG reports are already published or presented during international conferences. In this report, the most spectacular results from the LEP-II experiments on the SM verifications will be reviewed [3].

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[1] F. Abo *et al.* (CDF Collaboration), Phys. Rev. Lett. **79**, 4327 (1997).

[2] B. Abbott *et al.* (D0 Collaboration), Phys. Rev. Lett. **80**, 2051 (1998).

2. e^+e^--annihilation into two photons or two fermions

During 1996-2000 LEP was running at the center-of-mass energies above the Z pole 130–209 GeV (LEP-II), and the total luminosity per experiment of $700\ \text{pb}^{-1}$ has been collected.

The reaction $e^+e^- \to \gamma\gamma(\gamma)$ provides a clean test of the theory (QED) up to the highest energy available, and it can be a good tool for search of non-standard physics signals. The total cross sections measured were found to be in a good agreement with the QED. Table 1 shows the results.

Table 1

Cross section ratios $\sigma_{meas}/\sigma_{QED}$ of the process $e^+e^- \to \gamma\gamma(\gamma)$ from the LEP experiments

Experiment	cross-section ratio
ALEPH	0.953±0.024
DELPHI	0.976±0.032
L3	0.978±0.018
OPAL	0.999±0.016
global	0.982±0.010

The differential cross sections are also in good agreement with QED (Fig. 1).

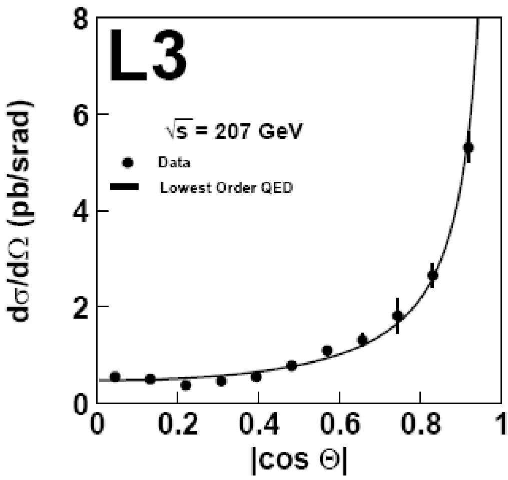

Fig. 1. An example for photon angular distribution of the process $e^+e^- \to \gamma\gamma(\gamma)$, total energy 207 GeV

The modification of the QED model for two photon annihilation is a short-range exponential deviation from the Coulomb field with the cut-off parameters $\Lambda_\pm$:

$$\left(\frac{d\sigma}{d\Omega}\right)_{\Lambda_\pm} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Born}} \pm \frac{\alpha^2 \pi s}{\Lambda_\pm^4}(1+\cos^2\theta)\ .$$

The combined fit of the four LEP experiments provides limits for these parameters $\Lambda_+ > 392$ GeV and $\Lambda_- > 364$ GeV.

The process of two fermions production is interesting in particular for a search of new objects, outside of the SM: an additional heavy vector boson Z', leptoquark, influence of the extra dimensions. Different models of the new physics have different sensitivity to such objects. The lower limit of Z' mass is 340–1800 GeV, depending on the model; the leptoquark mass should be higher than 100–1000 GeV for different quark type. Limit on the scale of gravity in models with large extra dimensions is higher than 1 TeV.

3. *W*-boson production and its properties

LEP-II operated above the *W*-pair production threshold. The *W*-pair cross sections and the *W*-decay branching ratios have been measured in the whole energy range of LEP-II. Figure 2 shows the comparison of the SM prediction with the experimental data with the *W*-mass fixed at 80.35 GeV.

There is good agreement: $\boldsymbol{\sigma^{meas}/\sigma^{theo} = 0.995 \pm 0.009}$.

Close to the threshold, the cross section is sensitive to the W boson mass. Such estimates are summarized in Table 2. At higher energies, the cross section has little sensitivity to m_W. For these energies, the direct reconstruction of the *W* boson invariant mass was done from the observed jets and leptons. At the same time the *W* width was also estimated. Tables 3 and 4 show the results.

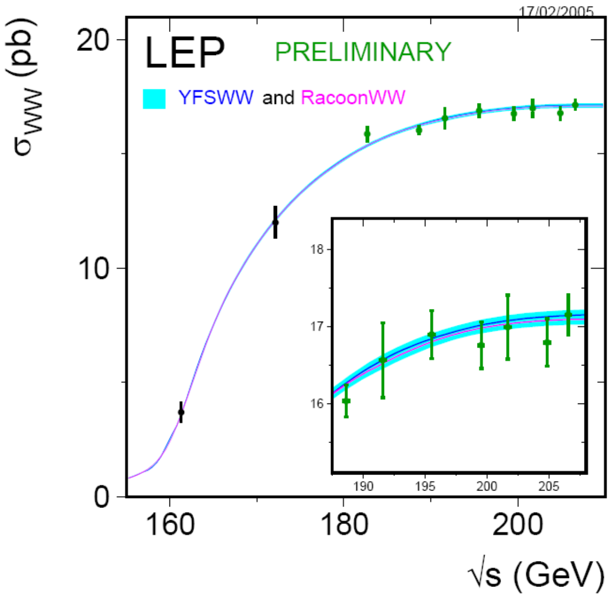

Fig. 2. Measurement of the *W*-pair production cross section compared with the SM prediction

Table 2

The *W* mass measurement from *W*-pair threshold cross section

Experiment	m_W(threshold)/GeV
ALEPH	80.14 ± 0.35
DELPHI	80.40 ± 0.45
L3	$80.80^{+0.48}_{-0.42}$
OPAL	$80.40^{+0.46}_{-0.43}$

Table 3

The *W* mass measurements from direct reconstruction

	DIRECT RECONSTRUCTION		
Experiment	$W^+W^- \to q\bar{q}\ell\bar{\nu}_\ell$ m_W/GeV	$W^+W^- \to q\bar{q}q\bar{q}$ m_W/GeV	Combined m_W/GeV
ALEPH	80.429 ± 0.059	80.475 ± 0.082	80.444 ± 0.051
DELPHI	80.340 ± 0.076	80.310 ± 0.102	80.330 ± 0.064
L3	80.213 ± 0.071	80.323 ± 0.091	80.253 ± 0.058
OPAL	80.449 ± 0.062	80.353 ± 0.081	80.415 ± 0.052

Table 4

The W width estimations

Experiment	Γ_W (GeV) published	Γ_W (GeV) common
ALEPH	2.14 ± 0.11	2.14 ± 0.11
DELPHI	2.40 ± 0.17	2.39 ± 0.17
L3	2.18 ± 0.14	2.24 ± 0.15
OPAL	2.00 ± 0.14	2.00 ± 0.14

The 'published' column is taken from the individual publications. In the last column, final state interaction correction common for all experiment was applied.

The combined LEP results for m_W and Γ_W are :

$$m_W = 80.376 \pm 0.033 \text{ GeV},$$
$$\Gamma_W = 2.196 \pm 0.083 \text{ GeV}.$$

The branching ratios measured are presented in Table 5. As one can see, the probability of the W decay into τ lepton is more than 2 standard deviations above the SM prediction (10.83%) for all **four** LEP experiments. However, the averaged leptonic branching ratio ***BR*(*W* → leptons) = (10.84 ± 0.08)%** in a good agreement with the SM value.

Within the SM, the W branching fractions are determined by 6 matrix elements $|V_{qq'}|$ of the Cabibbo-Kabayashi-Maskava (CKM) quark mixing matrix. Using the strong coupling constant $\boldsymbol{\alpha_s(M_W)}$ **=0.119 ± 0.002** and the sum $|V_{ud}|+|V_{us}|+|V_{ub}|+|V_{cd}|+|V_{cb}|$ **= 1.0476 ± 0.0074** one can get an estimate of $|V_{cs}|$ **= 0.976 ± 0.014**, where the dominant contribution into the error is statistical.

Table 5

Summary of W branching fractions

	Lepton non–universality			Lepton universality
Experiment	$\mathcal{B}(W \to e\overline{\nu}_e)$ [%]	$\mathcal{B}(W \to \mu\overline{\nu}_\mu)$ [%]	$\mathcal{B}(W \to \tau\overline{\nu}_\tau)$ [%]	$\mathcal{B}(W \to \text{hadrons})$ [%]
ALEPH	$10.78 \pm 0.29^*$	$10.87 \pm 0.26^*$	$11.25 \pm 0.38^*$	$67.13 \pm 0.40^*$
DELPHI	$10.55 \pm 0.34^*$	$10.65 \pm 0.27^*$	$11.46 \pm 0.43^*$	$67.45 \pm 0.48^*$
L3	$10.78 \pm 0.32^*$	$10.03 \pm 0.31^*$	$11.89 \pm 0.45^*$	$67.50 \pm 0.52^*$
OPAL	10.40 ± 0.35	10.61 ± 0.35	11.18 ± 0.48	67.91 ± 0.61
LEP	10.65 ± 0.17	10.59 ± 0.15	11.44 ± 0.22	67.48 ± 0.28
χ^2/d.o.f.	6.3/9			15.4/11

In addition to the total W^+W^- cross section, the differential cross sections were also measured (Fig. 3). The data are described rather well by the SM predictions.

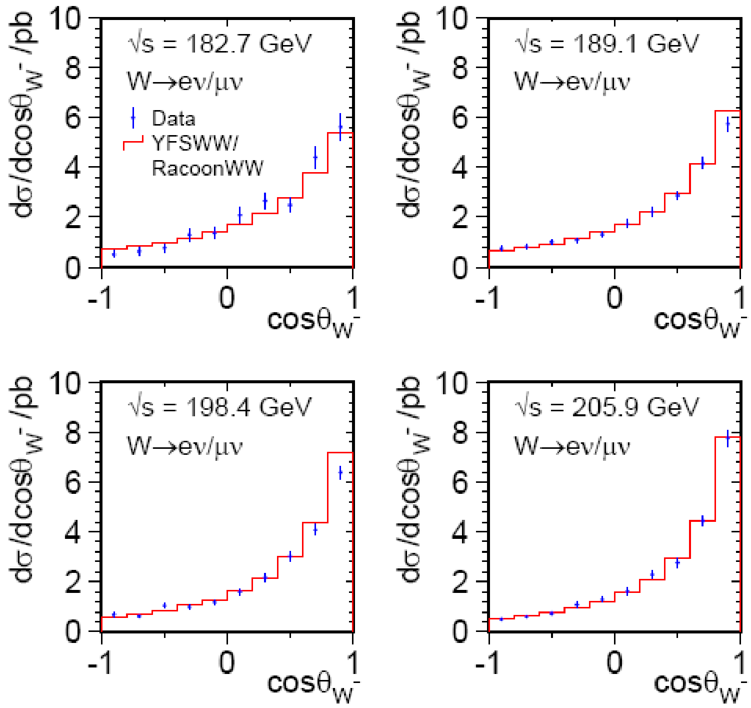

Fig. 3. Differential cross sections for the W-pair production. 4 different energy regions are selected. OPAL,DELPHI and L3 results are combined and compared with the SM predictions

4. Triple gauge boson coupling and search for anomalous vertices

The measurement of gauge boson couplings and the search for possible anomalous contributions are among the main goals of LEP-II. The W-pair production process involves charged triple gauge boson vertices – W^+W^-Z and $W^+W^-\gamma$. Single W and single photon production is also sensitive to these couplings. The most general description of the triple gauge coupling (TGC) includes 14 complex constants. The electromagnetic gauge invariance and C and P conservation decrease this number to five: g_1^Z, κ_Z, κ_γ, λ_Z, λ_γ. In the SM $g_1^Z = \kappa_Z = \kappa_\gamma = 1$, $\lambda_Z = \lambda_\gamma = 0$. In the LEP analysis, 3 real parameters g_1^Z, κ_γ, λ_γ are used. Moreover, only one- and two-parameter fits are done (Tables 6 and 7). No deviations from the SM predictions are found.

Similar analysis has been done for reactions with production of $Z\gamma$ and Z-pair. In these cases, neutral gauge vertices do not occur in the SM. Within SM quadric gauge boson vertices exist, but effects of such couplings are below experiments sensitivities.

Anomalous vertices search has been performed with the negative results.

Table 6

Results of one parameter fit for charged triple gauge boson couplings

Parameter	ALEPH	DELPHI	L3	OPAL
g_1^Z	$1.026^{+0.034}_{-0.033}$	$1.002^{+0.038}_{-0.040}$	$0.928^{+0.042}_{-0.041}$	$0.985^{+0.035}_{-0.034}$
κ_γ	$1.022^{+0.073}_{-0.072}$	$0.955^{+0.090}_{-0.086}$	$0.922^{+0.071}_{-0.069}$	$0.929^{+0.085}_{-0.081}$
λ_γ	$0.012^{+0.033}_{-0.032}$	$0.014^{+0.044}_{-0.042}$	$-0.058^{+0.047}_{-0.044}$	$-0.063^{+0.036}_{-0.036}$

Table 7

Results of two parameters fit for charged triple gauge boson couplings

Parameter	68% C.L.	95% C.L.	Correlations	
g_1^Z	$1.004^{+0.024}_{-0.025}$	[+0.954, +1.050]	1.00	+0.11
κ_γ	$0.984^{+0.049}_{-0.049}$	[+0.894, +1.084]	+0.11	1.00
g_1^Z	$1.024^{+0.029}_{-0.029}$	[+0.966, +1.081]	1.00	-0.40
λ_γ	$-0.036^{+0.029}_{-0.029}$	[−0.093, +0.022]	-0.40	1.00
κ_γ	$1.026^{+0.048}_{-0.051}$	[+0.928, +1.127]	1.00	+0.21
λ_γ	$-0.024^{+0.025}_{-0.021}$	[−0.068, +0.023]	+0.21	1.00

5. Constraints of the Standard Model

The precise measurements performed at LEP-I and LEP-II together with results from other colliders (SLC and Tevatron) allow to check the SM and to make some predictions for the mass of the Higgs boson m_H. Figure 4 illustrates the results of the combined analysis.

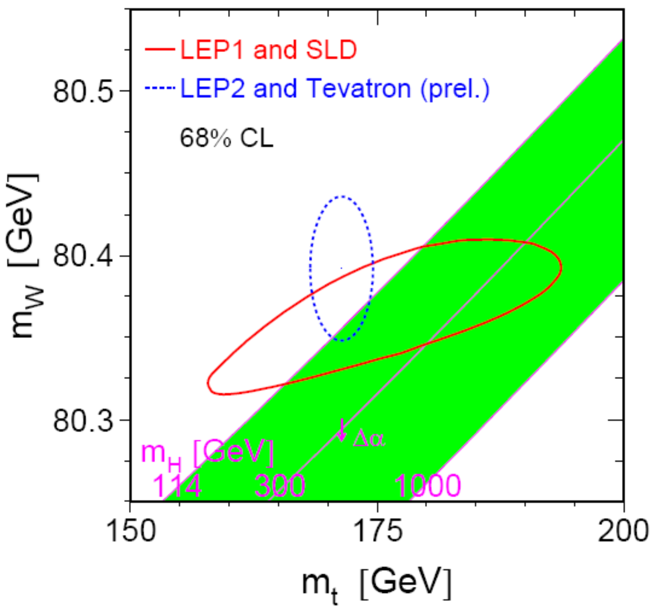

Fig. 4. The comparison of indirect measurements of m_W and m_t (LEP-I and SLD) and direct mass reconstruction (LEP-II and Tevatron). Correlation of these quantities with the SM Higgs boson mass is also shown. The arrow indicates the change of the correlation if $\alpha(m_Z)$ is changed by one standard deviation.

References

1. A.A. Vorobyov, A.G. Krivshich and V.A. Schegelsky, in *PNPI-XXV, High Energy Physics Division. Main Scientific Activities 1971–1996*, Gatchina, 1998, p. 65.
2. V.A. Andreev *et al.*, in *PNPI-XXX, High Energy Physics Division. Main Scientific Activities 1997–2001*, Gatchina, 2002, p. 82.
3. The LEP Electroweak Working Group, hep-ex/0612034, 14 December 2006.