PRECISION TEST OF ELECTROWEAK INTERACTIONS — WHAT WE HAVE LEARNED FROM LEP AND SLC? *

Krzysztof Doroba

Faculty of Physics, Warsaw University
Hoża 69, 00-681 Warszawa, Poland
and DELPHI Experiment

(Received January 27, 2004)

Presented are results from LEP and SLC accelerators concerning precision tests of the electroweak interactions. Discussed are line shape measurements, asymmetries at the Z^0 pole, measurements of the W mass and results of the global fit to the electroweak data. The results on the Standard Model Higgs are presented as well.

PACS numbers:

1. Introduction

The year 2000 was the last year of the operation for the Large Electron Positon collider (LEP) at European Organization for Nuclear Research (CERN). SLC, linear electron–positon collider at Stanford Linear Accelerator Center (SLAC) was operating with adequate both luminosity and electron beam polarization in the years 1992–1998. The data from the experiments working at these accelerators still are analyzed and discussed within the physics community. Today level of understanding of these data is very high so it is a good time to summarize the results obtained with both machines. In this article we will concentrate on the precision test of the electroweak interactions.

2. Strategy of the test

In the Standard Model (SM) electroweak interactions of leptons, quarks and Higgs boson(s) are described by exchange of the intermediate bosons: $\gamma, W^{\pm}$ and Z^0 [1]. The foreseen by theory $W^{\pm}$ and Z^0 bosons were experimentally discovered and their masses measured by the UA1 and UA2

* Presented at the XXVIII Mazurian Lakes School of Physics, Krzyże, Poland, August 31–September 7, 2003.

experiments performed on $Sp\bar{p}S$ collider at CERN in early eighties [2]. Together with earlier CERN discovery of the neutral currents [3] this was the experimental confirmation of the SM electroweak interactions. The next step towards more precise tests of the electroweak interactions was a construction of e^+e^- collider with $\sqrt{s}$ equal to the Z^0 mass. This would allow to form the Z^0 bozon, which would subsequently decay into fermion–antifermion pair (see Fig. 1).

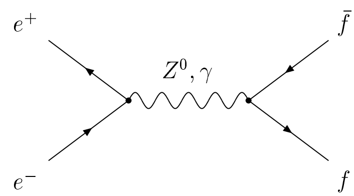

Fig. 1. Formation and decay of the Z^0 resonance.

Such machines have been designed and build at CERN and SLAC. For electroweak tests longitudinal polarization of initial beams is the advantage, so for the SLAC linear collider the polarization of the electron beam was foreseen from the beginning. For LEP as for circular machine the question of the longitudinal polarization was much more delicate, but on the other hand, by increasing a number of RF cavities it was possible for LEP to increase $\sqrt{s}$ well above the threshold of W^+W^- production (see Fig. 2).

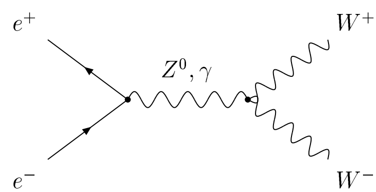

Fig. 2. Production of W^+W^- pair.

LEP was commissioned in 1989. Till 1994 it operated as LEP I at $\sqrt{s} =$ 92 GeV. From 1995 machine energy was gradually increased, first to 131 GeV then to 161 GeV and higher energies (LEP II phase). Maximum energy at which LEP ever operated was 208 GeV in the year 2000. SLC operated with adequate luminosity and beam polarization in the years 1992–1998 and only at Z^0 peak. For the whole period of the machines operation the strategy was the following:

- Study the Z^0 and (when possible) W^+W^- production and decay.
- Examine internal consistency of the Standard Model.
- Look for Higgs particle(s), supersymmetric particles, ...

To obtain any prediction within the Standard Model one has to define the input parameters of the model. One of the possible choices is presented below.

- α — electromagnetic fine coupling constant,
- $G_{\rm F}$ — Fermi constant which describes strength of the charged currents,
- M_Z — Z^0 mass, measured in LEP with high accuracy,
- $\alpha_{\rm s}(q^2 = M_Z^2)$ — strong coupling constants (for the reactions with quarks).

The above three (four) input parameters are sufficient to describe any electroweak process on the tree level. However, for the accuracy of the experiments performed at LEP and SLC the tree level is not enough and one has to take into account the radiative corrections to the tree level diagrams. This brings into the game more parameters (through a virtual loops appearing in the corrections).

- m_f fermion masses (in practice m_t — top quark mass),
- m_H Higgs mass.

3. Radiative corrections

Pure QED corrections of the type shown in Fig. 3 factorize, *i.e.* can be expressed as a correction factor. The electroweak correction can be split into two parts. The first one is presented in Fig. 4. This is so called *Vacuum Polarization Correction* and this type of the correction does not depend on the flavor of the final state. Situation is different when final state fermions couple directly to the virtual loop (see Fig. 5).

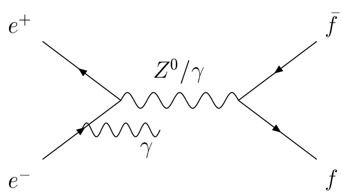

Fig. 3. Example of the pure QED correction.

For this type of the correction (*Vertex Correction*) results depend on the flavor of the final state. Altogether this approach leads to the so called *Improved Born Approximation*. For the process $e^+e^- \to Z^0 \to f\bar{f}$ the

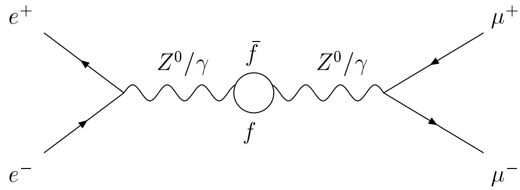

Fig. 4. Vacuum polarization correction.

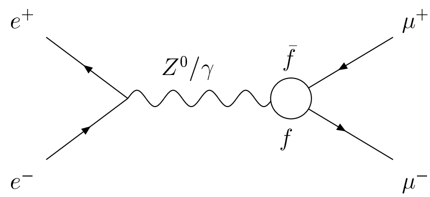

Fig. 5. Vertex correction.

amplitude has the same form as Born amplitude, except the axial and vector coupling constant are replaced by the effective, flavor dependent ones.

$$[\gamma_\mu(g_{Ve}(s) - g_{Ae}(s)\gamma_5)] \times \left[\gamma^\mu(g_{Vf}(s) - g_{Af}(s)\gamma^5)\right] , \tag{1}$$

where $g_{Vf}(s), g_{Af}(s)$ are flavor dependent, effective vector and axial vector coupling constants and γ^μ, γ_μ are standard Dirac matrices.

It is worth to stress that the values of the electroweak corrections depend in a quadratic form on the top quark mass and logarithmically on the Higgs boson mass. For most of the processes two loop level is achieved today. At CERN to obtain numerical values of the corrections two program libraries are used: TOPAZ0 and ZFITTER [4]

4. Z^0 line shape

The formula that describes the observed cross-section at Z^0 peak has the form:

$$\sigma(s) = \int \bar{\sigma}(s')H(s', s)ds' , \tag{2}$$

where $H(s', s)$ is so called radiative function and $\bar{\sigma}(s)$ is the electroweak cross-section, given by formula:

$$\bar{\sigma}(s) = \sigma^{\text{peak}}_{f\bar{f}} \frac{\Gamma_e \Gamma_f}{\left(s - M_Z^2\right) + \left(\frac{s\Gamma_Z}{M_Z}\right)^2} + (Z - \gamma) + \gamma\, , \tag{3}$$

where the terms: $(Z-\gamma)$ and γ describe γZ interference and production of the final state by intermediate γ, respectively. The $\sigma_{f\bar{f}}^{\text{peak}}$

$$\sigma_{f\bar{f}}^{\text{peak}} = \sigma_{f\bar{f}}^{0}\,\frac{1}{1+\delta_{\text{QED}}} = \frac{12\pi}{M_Z^2}\frac{\Gamma_e\Gamma_f}{\Gamma_Z^2}\frac{1}{1+\frac{3Q_f^2\alpha}{4\pi}}\,, \tag{4}$$

where M_Z, Γ_Z, and Γ_f denote, respectively, Z^0 boson mass, its total and partial width for decay into $f\bar{f}$ channel. δ_{QED} is the QED correction to Γ_e and Q_f is the final state fermion charge. $\sigma_{f\bar{f}}^{0}$ is the maximum cross section value for given channel (denoted also σ_{had}^{0} for hadronic final states).

The expression for the forward–backward asymmetry parameter A_{FB} has the form

$$A_{\text{FB}} = \frac{N_{\text{F}}-N_{\text{B}}}{N_{\text{F}}+N_{\text{B}}}\,, \tag{5}$$

where forward direction is identical with that of the incoming electron beam, N_{F} and N_{B} are the numbers of fermions produced forward and backward, respectively.

One can fit the experimental data with properly identified final states $(f = q, e, \mu, \tau)$ with the formula (3). This allows to determine main Z^0 parameters and examine lepton universality. It is important to note, that fitting the experimental data with the formula (3) its last two terms are not let free but instead are calculated from the Standard Model. Therefore the extracted from the experimental data values of M_Z, Γ_Z, Γ_f as well as other fit parameters might carry some model dependence and should be called pseudo-observables rather then observables.

Four experiments working at LEP (ALEPH, DELPHI, L3, OPAL–ADLO for short) collected about 18 M events at Z^0 peak. This is much more than 600 k events acquired by SLAC Linear Detector, so for line shape measurements LEP results are decisive. The ADLO results for Z^0 mass (M_Z), width (Γ_Z), peak hadronic cross-section (σ_{had}^{0}), ratio of the hadronic to the leptonic[1] Z^0 width (R_l^0) and leptonic forward–backward asymmetry at Z^0 peak ($A_{\text{FB}}^{0,l}$) are given in Table I.

4.1. Number of light neutrino families

To determine the number of light neutrino families from line shape measurements one has to write the expression for the total Z^0 width:

$$\Gamma_Z = \Gamma_{\text{had}} + 3\Gamma_l + \Gamma_{\text{inv}} \Longrightarrow \left(\frac{\Gamma_{\text{inv}}}{\Gamma_\nu}\right) \times \left(\frac{\Gamma_\nu}{\Gamma_l}\right) = \left(\frac{\Gamma_Z}{\Gamma_l}\right) - R_l^0 - 3\,,$$

[1] Calculated after confirmation of the leptonic universality.

TABLE I

Line shape ADLO results

pseudo-observable	value
M_Z	91.1875 ± 0.0021 GeV
Γ_Z	2.4952 ± 0.0023 GeV
$\sigma^0_{\rm had}$	41.540 ± 0.037 nb
R^0_l	20.767 ± 0.025
$A^{0,l}_{\rm FB}$	0.0171 ± 0.0010

where $\Gamma_{\rm inv}$ is the invisible decay width, Γ_ν is the decay width per neutrino family and use of the ratios should reduce systematic error. Assuming that the number of light neutrino families $N_\nu = \Gamma_{\rm inv}/\Gamma_\nu$ one has:

$$N_\nu \times \left(\frac{\Gamma_\nu}{\Gamma_l}\right)_{\rm SM} = \left(\frac{12\pi R^0_l}{\sigma^0_{\rm had} M_Z}\right) - R^0_l - 3\,, \tag{6}$$

where the ratio $(\Gamma_\nu/\Gamma_l)_{\rm SM}$ might be calculated from the Standard Model. ADLO experimental result is

$$N_\nu = 2.9841 \pm 0.0083\,. \tag{7}$$

In the other method hadronic cross-section are predicted for two, three and four (massless) neutrino species with SM couplings. The results are compared with experimental data in Fig. 6. The best agreement with data is for $N_\nu = 3$.

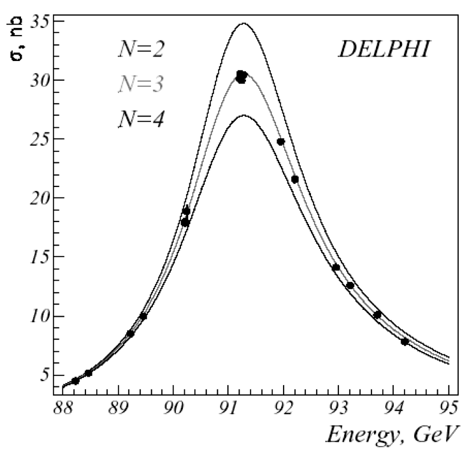

Fig. 6. Hadronic cross-section as a function of e^+e^- energy. Data (black points) are from DELPHI experiment.

5. Z^0 decays to heavy quarks (charm and beauty)

In the process $e^+e^- \to Z^0 \to q\bar{q}$, after hadronization, two (or more) jets are observed in the final state. For electroweak tests however important is a flavor of the quarks coming directly from Z^0 decay. *Flavor Tagging* procedure allows to establish this flavor for heavy (b and c) quarks. In this procedure initial jets direction is established from thrust axis. Heavy flavors are tagged by presence of high momentum (p) or transverse momentum (p_{T}) leptons and/or presence of secondary vertices. Hadron containing b (or c) quark on average travels 3 mm before a decay. The position of secondary vertexes is measured with accuracy of 300 μm. As masses of b and c quarks are about 5 and 1.5 GeV, respectively, the analysis of effective mass at secondary vertex, together with information on eventual lepton p (or p_{T}) allows to distinguish between b and c quarks.

Different methods use different tags combinations to establish flavor of the initial (heavy) quark. For tagged sample one has to know purity of the selected sample and selection efficiency. This requires very good Monte-Carlo programs. Purities up to 96% with efficiency up to 26% are achieved.

Flavor tagging procedure allows to measure $R_b = \Gamma_b/\Gamma_{\mathrm{had}}$ and $R_c = \Gamma_c/\Gamma_{\mathrm{had}}$ pseudo-observables. Most recent [5] experimental values:

$$R_b = 0.21638 \pm 0.00066\,, \quad R_c = 0.1720 \pm 0.0030 \tag{8}$$

are in a good agreement with SM predictions.

6. Asymmetry at Z^0 pole

Z^0 couplings to right-handed and left-handed fermions are different. This means that in the process $e^+e^- \to Z^0 \to f\bar{f}$ even for unpolarized e beams Z^0 is polarized along the beam direction [6]. This polarization will influence angular distributions of the final state particles. Therefore for LEP data one can define the following observables:

$$\begin{aligned} A_{\mathrm{pol}} &= \frac{\sigma_{\mathrm{F,R}} + \sigma_{\mathrm{B,R}} - \sigma_{\mathrm{F,L}} - \sigma_{\mathrm{B,L}}}{\sigma_{\mathrm{F,R}} + \sigma_{\mathrm{B,R}} + \sigma_{\mathrm{F,L}} + \sigma_{\mathrm{B,L}}} = \frac{\sigma_{\mathrm{R}} - \sigma_{\mathrm{L}}}{\sigma_{\mathrm{tot}}}\,, \\ A_{\mathrm{FB}} &= \frac{\sigma_{\mathrm{F,R}} + \sigma_{\mathrm{F,L}} - \sigma_{\mathrm{B,R}} - \sigma_{\mathrm{B,L}}}{\sigma_{\mathrm{tot}}} = \frac{\sigma_{\mathrm{F}} - \sigma_{\mathrm{B}}}{\sigma_{\mathrm{tot}}}\,, \\ A_{\mathrm{pol}}^{\mathrm{FB}} &= \frac{\sigma_{\mathrm{F,R}} + \sigma_{\mathrm{B,L}} - \sigma_{\mathrm{F,L}} - \sigma_{\mathrm{B,R}}}{\sigma_{\mathrm{tot}}}\,, \end{aligned} \tag{9}$$

where index R (L) means right (left) handed fermions in final state and F (B), as before, denotes forward (backward) direction.

For the case of polarized electron beam (SLC) one can also define:

$$\begin{aligned} A_{\mathrm{LR}} &= \frac{1}{\langle P\rangle}\frac{\sigma_{\mathrm{l}}-\sigma_{\mathrm{r}}}{\sigma_{\mathrm{l}}+\sigma_{\mathrm{r}}}\,, \\ A_{\mathrm{LRFB}} &= \frac{1}{\langle P\rangle}\frac{(\sigma_{\mathrm{F,l}}-\sigma_{\mathrm{F,r}})-(\sigma_{\mathrm{B,l}}-\sigma_{\mathrm{B,r}})}{\sigma_{\mathrm{tot}}}\,, \end{aligned} \tag{10}$$

where r (l) means right (left) handed electron beam polarization and $\langle P\rangle$ means beam polarization[2].

At the Z^0 pole these observables are related in the following way to the A_f — *asymmetry parameter for fermion f* (superscript 0 denotes value exactly at the pole):

$$\begin{aligned} A_{\mathrm{pol}}^{0,f} &= -A^f\,, \qquad A_{\mathrm{pol}}^{\mathrm{FB},0,f} = -\frac{3}{4}A_e\,, \\ A_{\mathrm{FB}}^{0,f} &= \frac{3}{4}A_eA_f\,, \\ A_{\mathrm{LR}}^{0,f} &= A_e\,, \qquad A_{\mathrm{LRFB}}^{0,f} = \frac{3}{4}A_f\,. \end{aligned} \tag{11}$$

The A_f is related to the ratio of effective, flavor dependent coupling constants:

$$A_f = 2\frac{g_{Vf}/g_{Af}}{1+\left(g_{Vf}/g_{Af}\right)^2} \tag{12}$$

on the other hand, when couplings conform to the SM structure, their ratio fulfills the following relation:

$$\frac{g_{Vf}}{g_{Af}} = 1+4|Q_f|\sin^2\theta_{\mathrm{eff}}^f\,, \tag{13}$$

where $\sin^2\theta_{\mathrm{eff}}^f$ is the effective, flavor dependent sinus squared of the mixing angle, related to the Weinberg $\sin^2\theta_W$. Studies of asymmetry parameters provide then very sensitive measurement of the $\sin^2\theta_{\mathrm{eff}}^f$, particularly good for leptons.

Particularly cute measurement is that of the A_e at SLC. Study of the hadronic cross sections for left and right handed electron beam polarization allows to determine precisely (Eqs. (10), (11)) purely leptonic observable A_e.

---

[2] As none of the detectors covers 4π, detailed studies of the angular distributions are required to determine $\sigma's$ in Eqs. (9), (10).

Also very precise measurements, this time of the $A^{0,b}_{\rm FB}$ and the $A^{0,c}_{\rm FB}$, were done at LEP. From these measurements and Eqs. (11) one gets $A_b = 0.898 \pm 0.021$ which is in good agreement with SLC direct (with $A^0_{\rm LRFB}$) determination of the $A_b = 0.925 \pm 0.020$. Combined result for this two measurements is:

$$A_b = 0.903 \pm 0.013\,,$$

whereas value predicted by SM reads 0.935.

The LEP and SLC measurements of the A_b are consistent. But the combined A_b value seems to disagree with SM prediction. This is presented in Fig. 7.

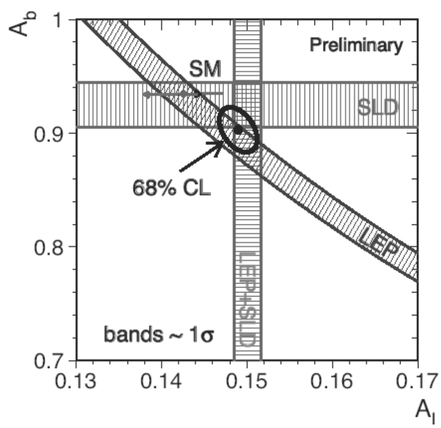

Fig. 7. Asymmetry parameter for b quark A_b *versus* leptonic asymmetry parameter A_l [6].

LEP results concerning A_b (and A_c) can be expressed in terms of $\sin^2\theta^{\rm lept}_{\rm eff}$. This is shown in Fig. 8 together with results from other pseudo-observables. The two most precise results are coming from the SLC measurement of the left right asymmetry and the LEP measurement of the forward backward asymmetry for b quarks. These results are almost 3σ apart. Similar discrepancy has been observed before but the LEP data presented here have been re-analyzed for this year summer conferences [6]. Remaining four results from Fig. 8 agree equally well with both measurements in question. No hint for any source of a systematic error is known. In such situation assumption that discrepancy is due to statistical fluctuation is justified. At the end of this section one should note, that even with much smaller statistics, SLC errors quoted here are similar to those from LEP. This is the advantage of the available electron beam polarization.

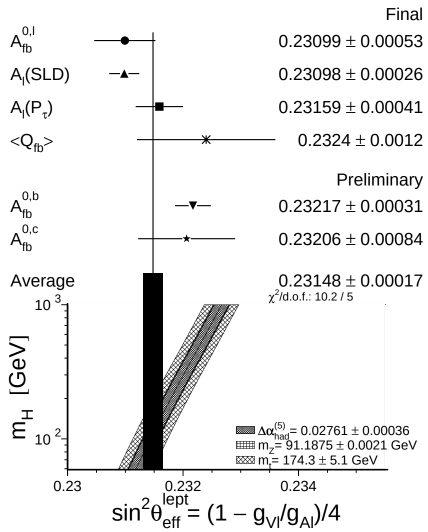

Fig. 8. $\sin^2\theta_{\rm eff}^{\rm lept}$ determined from measurements of different pseudo-observables: $A_{\rm fb}^{l}$ — leptonic forward backward asymmetry, $A_{\rm l}$ (SLD) — left right asymmetry measured at SLC, $A_{\rm l}(P_\tau)$ — relative difference in production of right and left handed τ leptons, $\langle Q_{\rm fb}\rangle$ — forward backward charge asymmetry, $A_{\rm fb}^{0,b}$, $A_{\rm fb}^{0,c}$ — forward backward asymmetry for b and c quarks measured at LEP. The figure (and notation) is from Ref. [8].

7. Direct *W* mass and width measurements

CDF and D0 experiments at TEVATRON, $p\bar{p}$ collider at Fermilab, have measured the W boson mass to be [7]:

$$M_W = 80.454 \pm 0.059 \text{ GeV}\,. \tag{14}$$

The first direct W mass measurement at LEP was based on analysis of the cross-section behavior at the threshold (161 GeV) for the reaction from Fig. 2. The result:

$$M_W = 80.40 \pm 0.22 \text{ GeV} \tag{15}$$

carry relatively big (mainly statistical) error. Much more precise are results coming from the analysis of two following decay channels for the same reaction but at higher LEP energies:

$$WW \to q\bar{q}l\nu\,, \quad WW \to q\bar{q}q\bar{q}\,. \tag{16}$$

In the analysis of above final states there are important corrections to the final result coming from Bose–Einstein correlations and color reconnection problem. Taking correction into account, the most recent LEP result [9] reads:

$$M_W = 80.412 \pm 0.042 \text{ GeV}\,, \quad \Gamma_W = 2.150 \pm 0.091 \text{ GeV}\,. \tag{17}$$

This means very good agreement between hadron and electron colliders. Combined result for LEP and TEVATRON is [9]:

$$M_W = 80.426 \pm 0.034 \text{ GeV}\,, \quad \Gamma_W = 2.139 \pm 0.069 \text{ GeV}\,. \tag{18}$$

Experiment NuTeV [10] at Fermilab measures directly sinus of the Weinberg angle θ_W from the ratio of the numbers of the neutral and charged current interactions induced by the ν and $\bar{\nu}$ beams

$$\sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2} = 0.2277 \pm 0.0016\,. \tag{19}$$

Using the well established value M_Z from LEP and the measured $\sin^2\theta_W$ one gets:

$$M_W = 80.136 \pm 0.084 \text{ GeV}\,. \tag{20}$$

This indirect measurement differs more then 3σ from direct, combined result (18).

The results for W mass measurements are presented in Fig. 9. NuTeV results is in clear disagreement with other measurements. Other two indirect measurements are based on fits of the radiative corrections to LEP data at the Z^0 peak. Most precise result is achieved when in the fitting procedure mass of the top quark m_t is fixed to the value known from TEVATRON measurements [11]. This result is even more precise then direct M_W measurements.

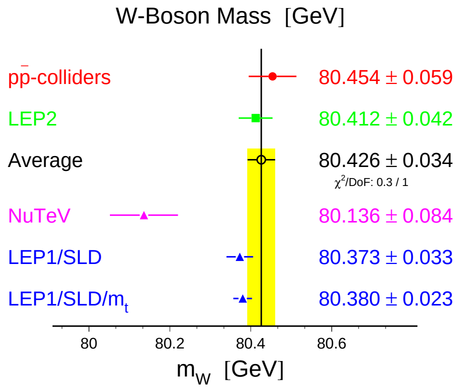

Fig. 9. *W* mass from direct and indirect measurements [8].

8. Standard Model Higgs search

The cross section for the Higgs particle production and its branching ratios for decays into different channels are predicted in the SM as a function of the Higgs (unknown) mass. Graph describing the main production channel (*Higgs Strahlung*) is presented in Fig. 10. Cross-section for this SM process as a function of e^+e^- energy is shown in Fig. 11 for fixed values of m_H [11].

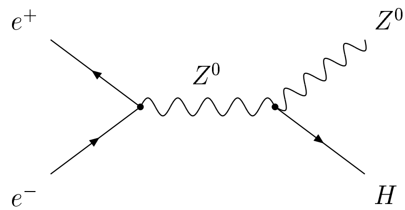

Fig. 10. Higgs Strahlung.

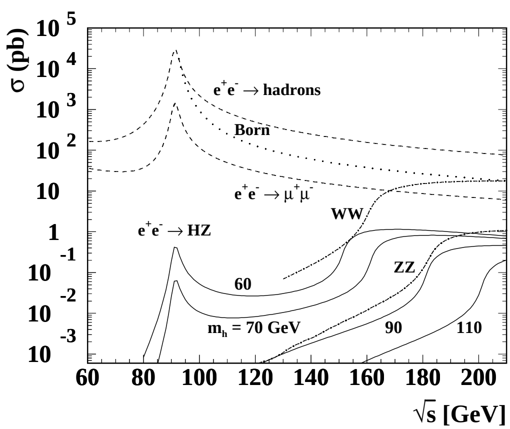

Fig. 11. Cross-section for Higgs Strahlung and for other SM processes for fixed values od m_H as a function of $\sqrt{s}$.

Possible decay channels for ZH system are listed below:

$$\begin{aligned} H &\to b\bar{b} \quad \text{and} \quad Z \to q\bar{q}\,, \\ H &\to b\bar{b} \quad \text{and} \quad Z \to \nu\bar{\nu}\,, \\ H &\to b\bar{b} \quad \text{and} \quad Z \to l\bar{l}\,, \\ H &\to \tau\bar{\tau} \quad \text{and} \quad Z \to b\bar{b}\,. \end{aligned}$$

In all this channels b quarks are present. For the Higgs particle with mass

$m_H = 115$ GeV branching ratio $\mathrm{BR}(H \to b\bar{b}) = 75\%$ which altogether means that b-tagging plays essential role in the Higgs search.

At LEP I Higgs searches in fully hadronic channels have been excluded by background (see Fig. 11). Searches in the other channels have not been successful. At LEP II the main source of background in Higgs search were Z^0Z^0, W^+W^-, and $q\bar{q}$ (with four or even five jets) final states. Information concerning events topology and b-tagging, based on the SM Monte Carlo, has been used for tagging the Higgs events. Results for assumed Higgs mass $m_H = 115$ GeV and two different sets of the cuts (loose and tight) are presented in Fig. 12. The histograms present expected distributions of the reconstructed Higgs mass coming from ZH final state (dark histogram) and from background processes (shadow one). Experimental data collected at $\sqrt{s} = 200$–208 GeV are presented by black dots.

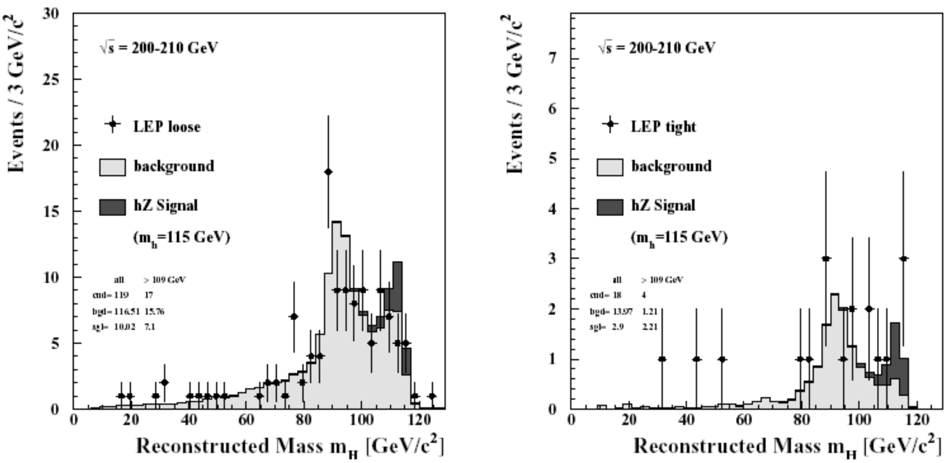

Fig. 12. Reconstructed Higgs mass for selected events (see text).

From Fig. 12 it is impossible to judge if the data sample contains the ZH signal and the background or the background only. Therefore for i-th tagged event variable Q_i was introduced. If $L_{\mathrm{S+B}}$ denotes probability that data contains both ZH signal and background and L_{B} probability that data contains only background then Q_i is equal to the ratio of these probabilities:

$$Q = \frac{L_{\mathrm{S+B}}}{L_{\mathrm{B}}}$$

Q_i is estimated from the topology combined with mass information. Expected Q_i distributions are determined by means of the Monte Carlo calculations. The global likelihood (for all tagged events) is defined as:

$$-2\ln(Q) = -2\sum_i \ln(Q_i) + C\,, \tag{21}$$

where constant C is such that signal + background and background hypothesis are equally likely for $-2\ln(Q)=0$. Most recent ADLO results [12] are presented in Fig. 13. The dashed curve describes expectation for background only hypothesis. Shadowed bands correspond to σ and 2σ limits of this hypothesis. Dot-dashed curve describes expectation for ZH signal + background hypothesis. The experimental data, collected at $\sqrt{s}=200$–208 GeV, are presented by solid line. No evidence for Higgs is seen. Conclusion from further statistical analysis is that Higgs mass

$$m_H < 114.4 \text{ GeV} \tag{22}$$

is excluded at 95% confidence level.

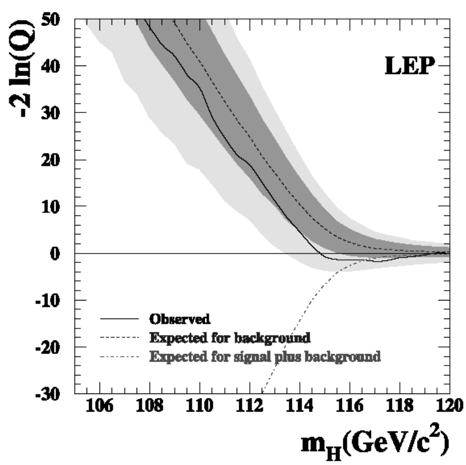

Fig. 13. Distributions of the $-2\ln(Q)$ as a function of Higgs mass.

9. Global fit

Comparison with Standard Model at best fitting point [5] of M_Z, $\alpha(M_Z)$, $\alpha_{\rm s}$, m_t and m_H is presented in Fig. 14. The χ^2 of the fit is equal to 25.4 for 15 degree of freedom which correspond to 4% fit probability, which is low. The largest contributions to the χ^2 are coming from:

- $\sin^2\theta_W$ from NuTeV experiment,
- $A_{\rm FB}^{0,b}$ measurement at LEP I,
- $A_{\rm LR}$ measurement at SLC.

NuTeV result on $\sin^2\theta_W(\nu N)$ is 3σ from SM prediction. If one removes this results from fit the χ^2 and the fit probability change significantly (probability rises to 28%). At the same time the values of the fitted SM parameters do not change much. Influence of the NuTeV result on the parameters (and their consistency) is small.

Fig. 14. Results of the global fit [8].

The discrepancy between $A_{\rm LR}$ and $A^{0,b}_{\rm FB}$ has been discussed in Section 6, where value of the $\sin^2\theta^{\rm lept}_{\rm eff}$ was determined. Statistical fluctuation was one of the possible explanations. Therefore in the global fit one can replace with the $\sin^2\theta^{\rm lept}_{\rm eff}$ the six pseudo-observables which determine its value (see Fig. 8). In this case the global fit probability improves to 13% ($\chi^2 = 15/10$ d.o.f.). Global fit without the $\sin^2\theta_W(\nu N)$ and with the average $\sin^2\theta^{\rm lept}_{\rm eff}$ renders $\chi^2 = 6.4/9$ d.o.f. which correspond to 70% fit probability. This seems to be reasonable for the Standard Model, but we have to have in mind that the $\sin^2\theta_W(\nu N)$ problem remains.

The fit to electroweak data with all but m_H parameters fixed allows to constrain Higgs boson mass within Standard Model. The results of such fit are presented in Fig. 15 for different assumptions concerning model.

Plotted is $\Delta\chi^2$ (*i.e.* excess over minimal χ^2 value) as a function of the Higgs boson mass m_H. Rectangular shadowed area shows the region excluded by experiment, as given by result (22). The solid curve corresponds to the $\Delta^{(5)}_{\rm had}$ value[3] same as the one given in Fig. 14. Dark band reflects theory uncertainty. The other two curves (without NuTeV result and for different value of the $\Delta^{(5)}_{\rm had}$) do not differ much for non-excluded Higgs mass values. From the solid curve one gets the following fit result:

$$\begin{aligned} m_H &= 96^{+60}_{-38}\ \mathrm{GeV}\,, \\ m_H &< 219\ \mathrm{GeV\ at\ 95\%\ CF}\,. \end{aligned} \tag{23}$$

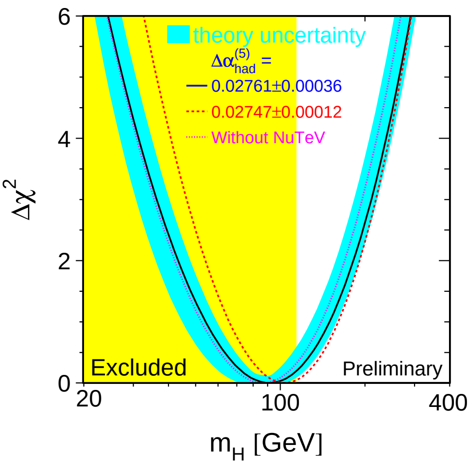

Fig. 15. Fit results for SM Higgs mass [8].

10. Conclusions

This article is by all means not exhaustive. Many subjects like Supersymmetry, Grand Unification, Multidoublet Higgs Models, Minimal Supersymmetric Standard Model and some others have been left behind. But the most important precision (*i.e.* above the tree level) predictions of the Standard Model have been compared with the experimental results from LEP and SLC. It is clear from that comparison that Standard Model looks fine. SM is well established (effective) theory. There is no urgent need for New Physics, but there are still some unresolved questions. Like where (if at

[3] $\Delta^{(5)}_{\rm had}(s)$ is a part of the running coupling constants $\alpha(s)$ dependence on s and can be determined from a low energy e^+e^- scattering [13].

all) is the Higgs boson(s)? Clearly disagreement of the NuTeV result with other experiments needs clarification. Further measurements of M_W, m_t, (m_H?) will make tests more stringent and perhaps will show the road to New Physics. Tools which physicist have in hands now are powerful; TEVATRON, b-factories and neutrino experiments to name most important. In the near future (2007) the Large Hadron Collider will start to operate at CERN. Next Linear Collider, the powerful machine colliding e^+e^- beams will be probably approved soon.

This work was supported by the Polish State Committee for Scientific Research (KBN) grant 2P03B 069 23.

REFERENCES

[1] S.L. Glashow, *Nucl. Phys.* **22**, 579 (1961); S. Weinberg, *Phys. Rev. Lett.* **19**, 1264 (1967); M. Veltman, *Nucl. Phys.* **B7**, 637 (1968); G. 't Hooft, *Nucl. Phys.* **B35**, 167 (1971); G. 't Hooft, M. Veltman, *Nucl. Phys.* **B44**, 189 (1972); G. 't Hooft, M. Veltman, *Nucl. Phys.* **B50**, 318 (1972).

[2] UA1 Collaboration, G. Arnison *et al.*, *Phys. Lett.* **B122**, 103 (1983); UA2 Collaboration, M. Banner *et al.*, *Phys. Lett.* **B122**, 476 (1983); UA1 Collaboration, G. Arnison *et al.*, *Phys. Lett.* **B126**, 398 (1983); UA2 Collaboration, P. Bagnaia *et al.*, *Phys. Lett.* **B129**, 130 (1983).

[3] Gargamelle Neutrino Collaboration, F.J. Hasert *et al.*, *Phys. Lett.* **B46**, 138 (1973).

[4] D.Y. Bardin *et al.*, *Z. Phys.* **C44**, 493 (1989); D.Y. Bardin *et al.*, *Comput. Phys. Commun.* **133**, 229 (2001); G. Montagna *et al.*, *Nucl. Phys.* **B401**, 3 (1993); G. Montagna *et al.*, *Comput. Phys. Commun.* **117**, 278 (1999).

[5] ADLO Collaboration, G. Quast, Talk at the 2003 EPS conference, Aachen, July 2003.

[6] ADLO Collaboration, T. Kramer, Talk at the 2003 EPS conference, Aachen, July 2003; M. Elsing, Talk at the 2003 EPS conference, Aachen, July 2003.

[7] Combination of CDF and D0 Results on W Boson Mass and Width, FERMILAB-FN-0716, July 2002.

[8] The LEP Electroweak Working Group Home Page, `http://lepewwg.web.cern.ch/LEPEWWG/`.

[9] ADLO Collaboration, M. Thomson, Talk at the 2003 EPS conference, Aachen, July 2003.

[10] NuTeV Collaboration, G.P. Zeller *et al.*, *Phys. Rev. Lett.* **88**, 091802 (2002).

[11] Particle Data Group Collaboration, K. Hagiwara *et al.*, *Phys. Rev.* **D66**, 010001 (2002).

[12] ADLO Collaboration, M. Duehrssen, Talk at the 2003 EPS conference, Aachen, July 2003.

[13] W. Hollik, G. Duckeck, Springer Tracts in Modern Physics, Volume 162, Springer, Berlin.