Precision Tests of Electroweak Interactions *

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Abstract

The status of the precision tests of the electroweak interactions is reviewed in this paper. An emphasis is put on the Standard Model analysis based on measurements at LEP/SLC and the Tevatron. The results of the measurements of the electroweak mixing angle in the NuTeV experiment and the future prospects are discussed.

1 Introduction

The unification of the electromagnetic and weak interactions in 1968 \cite{1}, the discoveries of the neutral currents in 1973 \cite{2}, of the charm quark in 1974 \cite{3}, of the W and Z bosons in 1983 \cite{4} were very successful steps for the theory of the ElectroWeak (EW) interactions, the Standard Model (SM) \cite{5,6}. After the discoveries of the top quark in 1995 \cite{6} and the tau neutrino in 2000 \cite{7} the electroweak SM became the commonly accepted theory of the fundamental electroweak interactions. It is a gauge invariant quantum field theory based on the symmetry group SU(2) × U(1), which is spontaneously broken by the Higgs mechanism. The renormalizability of the SM \cite{8} allows us to make precise predictions for measurable quantities at higher orders of the perturbative

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expansion, in terms of a few input parameters. The higher-order terms, Radiative Corrections (RC) or quantum corrections, contain the self-coupling of the vector bosons as well their interactions with the Higgs field and the top quark. Their calculation provides the theoretical basis for the EW precision tests.

In the last thirty five years in High Energy Physics two distinct and complementary strategies have been used for gaining new understanding of the Nature:

- The Direct Discovery of the New Phenomena at High Energy accelerators
- The Precision Measurements of the Known Phenomena at existing accelerators with high Luminosity

The excellent example is the ratio (Fig. 1)

\[
R_{e^+e^-} = \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}. \quad (1)
\]

Both strategies have worked very well for the studies of the EW interactions first at SPS and LEP1/SLC, and later at LEP2/SLD and the Tevatron, and in the future such interplay of the proton and electron colliders will be applied for the LHC and ILC/CLIC.

The second strategy has always demanded from the theory the prediction of physical quantities with high precision, i.e. at the level of quantum corrections. For the interpretation of the precision experiments the RC play the crucial role.

Figure 1: World data on the ratio $R_{e^+e^-}$ [9].
2 Electroweak Radiative Corrections

In the context of the SM any electroweak process can be computed at tree level from $\alpha$ (the fine structure constant measured at values of $Q^2$ close to zero), $M_W$ (the W-boson mass), $M_Z$ (the Z-boson mass), and $V_{jk}$ (the Cabbibo-Kobayashi-Maskawa flavor mixing matrix elements) [10].

When higher order corrections are included, any observable can be predicted using the on-shell renormalization scheme [11, 12] as a function of:

$$O_i = f_i(\alpha, \alpha_s, M_W, M_Z, M_H, m_t, V_{jk}),$$

(2)

where the effects of heavy particles do not decouple, and there is the sensitivity to the top mass $m_t$ [13] and to less extend to the Higgs mass $M_H$ [14]. Since the discovery of the presence of hard $m_t^2$ corrections to the $Z\bar{b}b$ vertex (see Fig. 2) [13, 15, 16, 17] the calculation of the EW RC has been theoretically well established and many higher-order contributions of the radiative corrections have become available over past decades to improve and stabilize the SM predictions.

3 Tests of EW Interactions at LEP/SLC and Tevatron

The experimental data for testing of the EW theory have achieved an impressive accuracy. After taking the measured Z mass, besides $\alpha$ and $G_\mu$ (the Fermi
constant measured in the muon decay), for completion of the input,

\[ M_Z = (91.1875 \pm 0.0021) \text{ GeV} \quad \text{(3)} \]
\[ G_\mu = (1.166371 \pm 0.000006) \cdot 10^{-5} \text{ GeV}^{-2} \quad \text{(4)} \]
\[ \alpha^{-1} = 137.035999710 \pm 0.000000096 \quad \text{(5)} \]

each other precision observable provides a test of the electroweak theory (Fig. 3). The predictions are calculated with computer programs ZFITTER [22] and TOPAZ0 [23], which incorporate state-of-the-art calculations of the EW, QED and QCD radiative corrections.

Theoretical predictions of the SM depend on the mass of the top quark and of the as yet experimentally unknown Higgs boson through the virtual presence of these particles in the loops. As a consequence, precision data can be used to pin down the allowed range of the mass parameters. This is shown in Fig. 4, which compares the information on \( M_W \) and \( m_t \) obtained at LEP1 and SLD, with the direct measurements performed at LEP2 and the Tevatron.

The measured at Tevatron mass \( m_t = 172.6 \pm 1.4 \) [24] agrees better than 10 % with the value predicted within the SM on the basis of the precision EW measurements.

Taking all direct and indirect data into account, one obtains the pillar of the precision electroweak physics [25]: the best constraints on the possible mass \( M_H \) of unseen Higgs. The global electroweak fit results in the \( \Delta \chi^2 = \chi^2 - \chi^2_{\text{min}} \) curve shown in Fig. 5. The lower limit on \( M_H \) obtained from direct searches is close to the point of minimum \( \chi^2 \). At 95% C.L., one gets [18, 19]

\[ 114.4 \text{ GeV} < M_H < 160 \text{ GeV}. \]

4 SM Analysis and NuTeV Experiment

In the on-shell scheme [11, 12] the three-level formula \( \sin^2 \theta_W = 1 - \frac{M_W^2}{M_Z^2} \) is a definition of the renormalized \( \sin^2 \theta_W \) to all orders in perturbation theory, \textit{i.e.},

\[ \sin^2 \theta_W^{\text{on-shell}} = s_W^2 = 1 - \frac{M_W^2}{M_Z^2}. \quad \text{(6)} \]
Figure 3: Comparison between the measurements included in the combined analysis of the SM and the results from the global EW fit [18, 19].

Figure 4: Comparison of the direct measurements of $M_W$ and $m_t$ at LEP2/Tevatron with the indirect determination through electroweak radiative corrections at LEP1/SLD. Also shown in the SM relationship for the masses as function of $M_H$ [18, 19].
A precise determination of the on-shell EW mixing angle has been performed by the NuTeV collaboration [26] for the first time through the measurements of the Pashos-Wolfenstein ratio [27]:

\[ R^- = \frac{\sigma(\nu_\mu N \rightarrow \nu_\mu X) - \sigma(\bar{\nu}_\mu N \rightarrow \bar{\nu}_\mu X)}{\sigma(\nu_\mu N \rightarrow \mu^- X) - \sigma(\bar{\nu}_\mu N \rightarrow \mu^+ X)} \] (7)

from deep inelastic neutrino scattering on isoscalar targets. The NuTeV collaboration finds \( s_{W^2} = 0.2277 \pm 0.0016 \) which is 3.0 \( \sigma \) higher than the SM predictions.

From this experimental value one obtains the mass of \( M_W \) boson [26]

\[ M_W = 80.14 \pm 0.08 \text{ GeV} \] (8)

which is smaller than other measurements of \( M_W \) at LEP/SLD and the Tevatron (see Fig. 6). The NuTeV result should be considered as preliminary until a reanalysis of data will be completed including all experimental and theoretical information.
Figure 6: The results of the direct measurements of $M_W$ at LEP2/Tevatron are compared with the indirect determinations at LEP1/SLD and in the NuTeV experiment \cite{18, 19, 26}.

5 Conclusions and Future Prospects

Apart from the still missing Higgs boson, the SM provides an elegant theoretical framework for the description of the known experimental facts in Particle Physics. The SM has been impressively confirmed by successful collider experiments at the particle accelerators LEP, SLC and Tevatron during the last fifteen years.

Future colliders like the upcoming LHC or an ILC/CLIC offer great prospects, and in turn represent a great challenge for theory to provide even more precise calculations. Accurate predictions are necessary not only to increase the level of precision of SM tests, but also to study the indirect effects of possible new particles.

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