The status of the electroweak precision measurements as of winter 2004 and the global test of the Standard Model are discussed. Important input data are the precision variables measured on the Z resonance at LEP and SLC and the measurements of the W mass at LEP 2 and Tevatron. A new combination of Tevatron experiments CDF and D0 on the top mass allows to set constraints on the radiative corrections and therefore to put improved limits on the mass of the Higgs boson. Additionally the impact of the NuTeV result on the weak mixing angle and the status of the calculation of the hadronic vacuum polarization are discussed.

1 Measurements at the Z Resonance

The Standard Model (SM) is confirmed at the permille level using electroweak precision data. The analysis of electron-positron collisions at centre-of-mass energies around the Z resonance has delivered a wealth of precisely measured electroweak observables. One observable is the mass of the Z, which is derived mainly from the measurement of the total hadronic cross section as shown in Figure 1 (left). Today the Z mass is known with a precision of 23 ppm:

$$m_Z = 911875 \pm 0.0021 \text{ GeV}$$

Other observables are related to the coupling of the weak current to the fermions and can therefore be expressed in terms of the electroweak mixing angle. The different values of $\sin^2 \theta_{\text{lep}}$, derived from the measurements of the lepton forward-backward asymmetry, $A_{FB}^\ell$, the left-right asymmetry at SLD, $A_1^{\text{(SLD)}}$, the polarization at LEP, $A_1 (P)$, and the forward-backward asymmetry of the b-quark and c-quark final state, $A_{FB}^b$ and $A_{FB}^c$, are compared in Figure 1 (right). A difference of 2.9 standard deviations is observed between the two most precise measurements, the left-right asymmetry and the b-quark forward-backward asymmetry. Combining all measurements results in an accuracy at the sub permille level:

$$\sin^2 \theta_{\text{lep}} = 0.23150 \pm 0.0016$$
Comparison of measurement and theory prediction shows a preference for a light Higgs mass.

2 Measurement of the W mass

Within the SM the Z mass, $m_Z$, the W mass, $m_W$, and the weak mixing angle, $\sin^2 \theta_w$, are related by

$$\cos \theta_w = \frac{m_W}{m_Z};$$

which is naturally predicted by the Higgs mechanism. To test this relation a precise measurement of the W mass is mandatory.

Since 1996 the W mass is measured at LEP 2 studying the four-fermion production through $e^+e^- \rightarrow W^+W^- \rightarrow fff$. The W bosons are reconstructed from the measured momenta of the observed final state fermions. To extract the W mass, the invariant mass spectrum is compared to the one obtained from Monte-Carlo events with complete detector simulation. In the four-jet final state, exchange between the decay products of two W bosons may occur due to colour reconnection or Bose-Einstein effects in the non-perturbative phase of the jet formation. Because of these additional uncertainties compared to the semileptonic channel, the weight of the four-jet channel in the LEP average is currently only about 10%. Further details on the measurement of the W mass at LEP are given elsewhere.

At hadron colliders leptonically W decays with electrons and muons are selected and the transverse mass is calculated. The transverse mass, i.e., the invariant mass of the transverse momentum of the charged lepton and the missing momentum vector in the plane transverse to the beam, is not affected by the unknown missing momentum along the beam axis. Recently the experiments CDF and D0 performed a precise measurement of the W mass using the Run I data set of the Tevatron collider. The precision of the Tevatron W mass measurement is currently limited by data statistics. The uncertainty in the lepton energy scale gives the largest contribution to the systematic error.

The results of the Tevatron and LEP experiments on the W mass are in good agreement as shown in Figure 2 (left). All direct W mass measurements, of which most of them are still preliminary, result in a world average of:

$\sin^2 \theta_w$ = 0.23150 ± 0.00016

Figure 1: Measurement of the total hadronic cross section on the Z resonance (left); measurements of the weak mixing angle from Z decays and comparison with the SM prediction (right).
Another less precise indirect measurement of the W mass is coming from the measurement of neutrino nucleon scattering. Measurements of the NuTeV collaboration\(^\text{(5)}\) show a deviation from the world average of about three standard deviations. But recent theoretical studies\(^\text{(6)}\) suspect that the uncertainties due to QCD corrections and due to electroweak radiative correction may be underestimated in this analysis.

### 3 Other Observables

Electroweak radiative corrections have been calculated up to the two-loop level, but there accuracy is limited by the experimental uncertainties for the masses of the top quark and the unknown mass of the Higgs boson. A test of the quantum structure of the SM therefore requires a precise knowledge of the top quark mass, as the radiative corrections depend quadratically on this parameter.

In the year 1995 the experiments at the Tevatron collider discovered in the mass range predicted by the electroweak measurement at LEP. They observe the top quark in the reaction $p p \rightarrow t\bar{t}X \rightarrow b\bar{b}W^+W^-X$. If the W boson decays into two quarks, the mass of the top quark can be reconstructed from the invariant mass of the $b\bar{b}$ pair and the two jets coming from the W decay. The results based on data collected in Run I and partly in Run II have recently been combined\(^\text{(8)}\):

$$m_t = 178 \pm 2.7 \text{ (stat)} \pm 3.3 \text{ (syst)} \text{ GeV}$$

The new and improved preliminary Run-I based result of the D0 collaboration in the lepton-plus-jets channel is included in this value. A comparison between the different measurement of the top mass is shown in Figure 2 (right).

The calculation of the electromagnetic coupling constant ($m_Z$) at the energy scale of the Z mass is dominated by the knowledge on the hadronic vacuum polarization \(\text{had}\). This part cannot be calculated by the perturbative theory, but has to be extracted using the total hadronic cross section in $e^+e^-$ collisions. A very important part is coming from the region of the resonance. Precise measurements of the CMD-2 detector get now confirmed by new results from KLOE. The most recent compilation\(^\text{(9)}\) gives

\[ m_Z^{\text{had}} = 0.02761 \pm 0.00036 \]
Interpretation within the Standard Model and Higgs mass analysis

The details of the combination of the electroweak precision data and the global SM model are described elsewhere[7]. The results in a rather poor $\chi^2$, but excluding the low $Q^2$ experiments gives a much better quality with a 27% probability.

As stated above, the electroweak radiative corrections include a term proportional to the logarithm of the Higgs mass. Assuming the validity of the SM one can try to extract this term from a global fit of all electroweak precision measurements. This allows to predict the mass of the Higgs boson.

In Figure 3, the constraint from the electroweak precision measurement performed at LEP 1 and SLD in the $m_W$ vs. $m_t$ plane is shown together with the direct measurement of the W and the top quark masses. Additionally the SM prediction using $G_F$ from muon decay is plotted for different Higgs masses. Both the indirect and the direct measurements prefer a low Higgs mass. The SM model prediction for all electroweak data with the Higgs mass as the only free parameter results in a $\chi^2$ curve as shown in Figure 3. It gives a central value of 117 GeV for the Higgs mass, which is consistent with the direct searches for the Higgs excluding masses below 114.4 GeV[10].

At 95% C.L. an upper bound on the Higgs mass of 251 GeV is set.

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