Experimental Summary of the Electroweak Working Group

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The experimental contributions to the electroweak working group are summarised and, where applicable, similar results from different contributions are compared.

1. INTRODUCTION

Currently there are four places where significant results on electroweak physics are obtained:

- e^+e^- annihilation on the Z resonance (LEP1, SLC),
- e^+e^- annihilation above the W-pair threshold (LEP2),
- $p\bar{p}$ interactions (TEVATRON),
- deep inelastic scattering (νN at CERN and FERMILAB, $e^{\pm}p$ at HERA).

All places obtain measurements with comparable accuracy, so that useful cross checks are possible and the complementary of the different reactions allows for a significant gain in knowledge if the different results are combined.

2. THE $\sin^2\theta^l_{eff}$ PROBLEM

If all asymmetry measurements on the Z-resonance are interpreted as measurements of the weak mixing angle, $\sin^2\theta^l_{eff}$, only a poor agreement of the different results is obtained [1]. The three principle methods to measure $\sin^2\theta^l_{eff}$ have been discussed: leptonic asymmetries at LEP [2], hadronic asymmetries at LEP [3] and the left-right asymmetry using polarised beams at SLD [4].

All measurements are sensitive to the coupling parameter

$$\mathcal{A}_f = \frac{2g_{V,f}g_{A,f}}{g^2_{V,f}+g^2_{A,f}},$$

which is sensitive to the weak mixing angle according to $\frac{g_{V,f}}{g_{A,f}} = 1 - 4Q_f \sin^2\theta^f_{eff}$.

At LEP the forward-backward asymmetries measure the product of the initial and final state coupling $A^f_{FB} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_f$. The τ-polarisation is used to measure $\mathcal{A}_\tau$ from its average value and $\mathcal{A}_e$ from its forward-backward asymmetry. These two measurements are statistically and systematically nearly uncorrelated. All measurements at LEP are well consistent with lepton universality so that the assumption of a universal $\sin^2\theta^l_{eff}$ will be made. The leptonic forward backward asymmetries at LEP are close to final and no major problems can be found. The τ polarisation still misses the major part of the ALEPH dataset which is the most sensitive detector for τ physics. All analyses of the τ-polarisation assume $V-A$ structure for the τ decay. However most of the weight in the τ polarisation analyses comes from the hadronic τ decays where only one free parameter, the ν_τ-helicity h_τ has to be added if this assumption is dropped. h_τ is currently known with a precision of 2.7% [5] so that even non-standard τ-decays cannot significantly alter the picture. Averaging over all leptonic measurements from LEP yields $\mathcal{A}_\ell = 0.1475 \pm 0.0033$ corresponding to $\sin^2\theta^l_{eff} = 0.23141 \pm 0.00042$.

From the hadronic asymmetries at LEP the by far most accurate one is $A^{\mathrm{b}}_{\mathrm{FB}}$. Due to the small b-quark charge and because of $\frac{d\mathcal{A}_f}{d(g_V/g_A)} = 0$ for $g_V/g_A = 1$ the sensitivity of $A^{\mathrm{b}}_{\mathrm{FB}}$ to $\sin^2\theta^b_{eff}$ is suppressed by two orders of magnitude compared to its sensitivity to $\sin^2\theta^l_{eff}$ so that $A^{\mathrm{b}}_{\mathrm{FB}}$ can be considered as a clean measurement of $\sin^2\theta^l_{eff}$. The total error on $A^{\mathrm{b}}_{\mathrm{FB}}$ (0.0022) is dominated by statistics (0.0020) and detector systematics (0.0009) leaving only 0.0006 to uncertainties from physics effects. The QCD corrections to $A^{\mathrm{b}}_{\mathrm{FB}}$ are slightly larger than the current error assuming full acceptance, however they are theoretically well under control and due to experimental selection biases towards high momentum particles they are typically reduced by about a factor two.

The second most accurate measurement of $\sin^2\theta^l_{eff}$ is the left-right asymmetry measured with polarised beams at SLD:

$$A_{LR} = \frac{A_m}{P}(1+\delta) = \mathcal{A}_{\mathrm{e}},$$

where A_m is the measured asymmetry and P is the beam polarisation. δ represents a couple of very small corrections which add up to a few percent of the total error. Since A_m doesn't depend on the final state, with the exception of $e^+e^- \rightarrow e^+e^-$, a high statistical precision can be obtained. The most difficult part in the A_{LR} analysis is the measurement of the beam polarisation. However the total error of the polarisation measurement is at present only about a third of the statistical error on A_{LR}.

In addition to A_{LR} SLD measures the left-right-forward-backward asymmetries for quarks and leptons which are only sensitive to the final state couplings. The leptonic asymmetries provide a marginal improvement of the SLD $\sin^2\theta^l_{eff}$ result. The asymmetries for b and c quarks are not sensitive to $\sin^2\theta^l_{eff}$ however they test new Born level physics and, since similar methods as at LEP are used, provide a useful cross check of the quark asymmetries measured at LEP.

Fig. 1 shows $\mathcal{A}_{\mathrm{e}}$ and $\mathcal{A}_{\mathrm{b}}$ under the assumption of lepton universality as measured at LEP and SLD compared to the Standard Model prediction. It can be seen that it is rather improbable that all measurements and the standard model are compatible with each other. The dotted line indicates where the SLD measurement would slide if the polarisation is measured incorrectly. Forcing A_{LR} to agree with $\sin^2\theta^l_{eff}$ obtained from $A^{\mathrm{b}}_{\mathrm{FB}}$ would destroy the agreement of the SLD $\mathcal{A}_{\mathrm{b}}$ measurement with the model prediction.

As a conclusion no obvious problem in any of the accurate $\sin^2\theta^l_{eff}$ measurements can be found so that a statistical fluctuation still remains the most probable explanation.

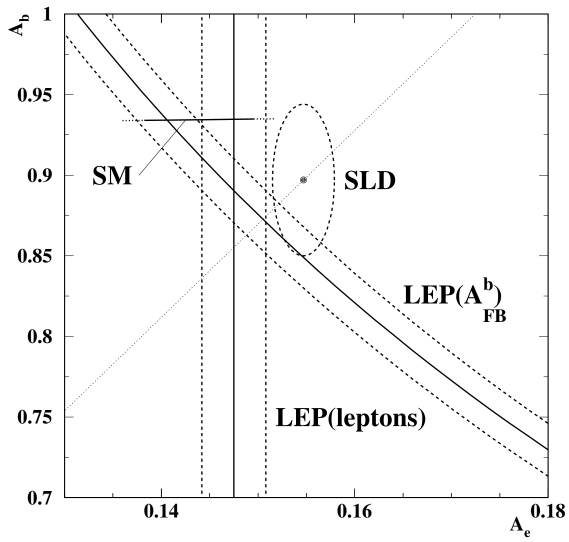

Figure 1. Measurement of $\mathcal{A}_{\mathrm{e}}$ and $\mathcal{A}_{\mathrm{b}}$ at LEP and SLD compared to the Standard Model prediction. The dotted line indicates where the SLD measurement would slide if the polarisation is measured incorrectly.

3. MEASUREMENT OF THE W MASS

The mass of the W is measured directly at the TEVATRON [6] and LEP [7]. In addition the measurement of $\sin^2\theta_W$ in deep inelastic $\nu - N$ scattering [8] is almost equivalent to a measurement of m_W.

At the TEVATRON Ws are produced in $q\bar{q}'$-annihilation. Due to the high background in the jet-jet decay channel only leptonic W-decays can be used. The neutrino has to be reconstructed from the missing momentum in the detector. Since an unknown part of the energy is lost in the proton remnants down the beam pipe only the transverse momentum of the neutrino can be reconstructed reliably leading to uncertainties from parton distribution functions. These uncertainties are however well under control using the forward-backward asymmetry of W production [9]. The most important detector systematics are coming from the knowledge of the energy scale and can be tested using other particles like J/ψ and Z. So for future running at the TEVATRON the largest part of the systematic uncertainties should scale like the statistical error. For run II an error of $\sim 40\,\mathrm{MeV}$ seems thus realistic.

At LEP m_W is measured in two different ways. Close to the W-pair production threshold the production cross section depends strongly on m_W. Due to the different phase space suppression factors the production is dominated by t-channel ν-exchange involving only well known couplings. At higher energies m_W is measured at LEP by reconstruction of the invariant mass of the W decay products. For this method the events where both Ws decay hadronically and where one W decays hadronically and the other leptonically can be used adding up to about 90% of the W pairs. Since in e^+e^- colliders, apart from small initial state photon radiation, the full energy is contained in the detector, the resolution can be improved significantly using constrained fitting techniques. As a further advantage of these techniques the hadronic energy scale cancels out completely. However the reconstructed W-mass becomes sensitive to the knowledge of the beam energy. In $WW \rightarrow 4-$jets events two further complications arise. There exist three different pairings to construct two Ws out of four jets. The decision on the pairing has to be made on the basis of the fitted masses and is not always correct leading to a degradation of the statistical precision. In addition the lifetime of a W is about 0.1 fm compared to a typical fragmentation radius of about 1 fm. It is thus possible that the quarks originating from different Ws interact with each other shifting the apparent W mass. Preliminary studies show effects of up to 100 MeV [10] however further studies using the data are possible, once more luminosity is available. With an integrated luminosity of $500\,\mathrm{pb}^{-1}$ per experiment a total error on m_W of 30 MeV can be expected if the colour reconnection effects can be understood. If only the mixed channel can be used the expected error is around 50 MeV.

The weak mixing angle measured in deep inelastic νN scattering is almost identical to its on-shell definition $\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2}$. Up to now $\sin^2\theta_W$ is measured using the Llevellyn Smith sum rule from $\frac{\sigma^{\nu,\bar{\nu}}(NC)}{\sigma^{\nu,\nu}(CC)}$. A new measurement has been reported by CCFR of

$$\sin^2\theta_W = 0.2236 \pm 0.0027(exp) \pm 0.0030(mod).$$

The modelling error is dominated by the knowledge of charm quark mass that contributed 0.0027 to it. From the experimental error a contribution of 0.0015 is coming from the uncertainty of the ν_e content in the beam.

Currently the NuTev experiment is running at the upgraded FERMILAB neutrino beam. The new beam line can produce separate neutrino and antineutrino beams so that $\sin^2\theta_W$ can be obtained from $\frac{\sigma^{\nu}(NC)-\sigma^{\bar{\nu}}(NC)}{\sigma^{\nu}(CC)-\sigma^{\bar{\nu}}(CC)}$ using the Pachos Wolfenstein relation. Due to the cross section differences the dependence on the charm quark mass will be reduced to 0.009. In addition the new beamline has a reduced content of ν_e reducing this source of error to 0.006. The new measurement of $\sin^2\theta_W$ is thus expected to have an equivalent error on m_W of about 100 MeV.

Fig. 2 compares the results currently obtained with the different methods. Also shown is the prediction from the Standard Model fits to the LEP/SLD data imposing the top quark mass [11]. Good agreement between all the numbers can be observed. If the projected errors for the future LEP and TEVATRON running can be achieved a severe test of the Standard Model can be performed comparing the measured with the predicted W mass.

At HERA the W-mass enters in the propagator for charged current events. At fixed target νN-scattering the total cross section is rising linearly with the centre of mass energy consistent with an infinitely heavy W. H1 at HERA measures [12] $\sigma^{CC}_{e^+p} = (25.2 \pm 2.5 \pm 0.8)\,\mathrm{pb}$ ($\mathrm{p_t} > 12.5\,\mathrm{GeV}, 0.1 < \mathrm{y} < 0.9$) inconsistent with expected $45\,\mathrm{pb}$ for an infinitely heavy W. If this is translated into a measurement of the W mass one obtains $m_W = 84^{+9+5}_{-6-4}\,\mathrm{GeV}$ for H1 and $m_W = 79^{+8+4}_{-7-4}\,\mathrm{GeV}$ for ZEUS. This is not competitive with the other m_W measurements, however it shows that the charged current propagator behaves in the space like region as predicted.

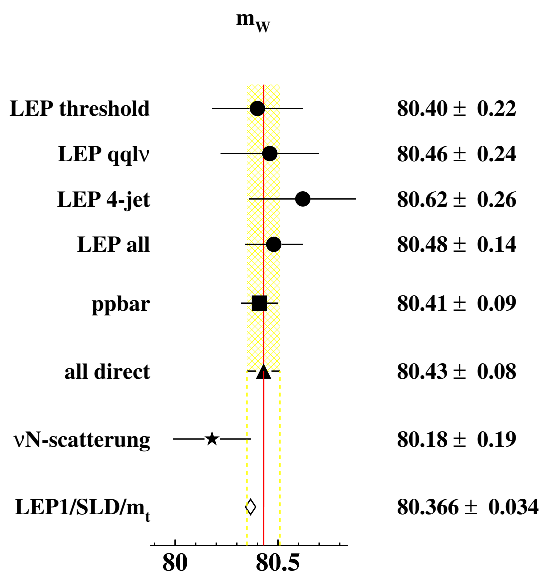

Figure 2. Measurement of m_W using different methods at LEP and the TEVATRON. Also shown are the indirect measurements from CCFR and the LEP1/SLD data, imposing the top-quark mass.

4. TRIPLE GAUGE COUPLINGS

The Standard Model needs trilinear WWZ and $WW\gamma$ couplings to prevent the $e^+e^- \to W^+W^-$ cross section from passing the unitarity bound at high energy. The size of these couplings can be tested at e^+e^- and $p\bar{p}$ colliders. In principle five different C and P conserving couplings exist with dimension not larger than six. To avoid that the anomalous couplings destroy the cross section behaviour at high energy they can be regularised by a cutoff. At LEP all interactions take place at the same scale, so that this cutoff is irrelevant for the analyses whereas at the TEVATRON it makes a small difference to the results.

CDF and D0 measure mainly the cross section for $W\gamma$, WW and a mixture of WW and WZ events. In the second selection both Ws are required to decay into leptons whereas in the third selection one particle is searched for in its leptonic decay channel and the other in the two jet mode. Because of the limited resolution of the two jet mass, W and Z cannot be distinguished [13].

At LEP most of the information comes from W-pair production [14]. Apart from the cross section also the W-production angle and the W polarisation is accessible. However for hadronically decaying Ws quark and antiquark cannot be distinguished leaving an ambiguity between the two transverse polarisation states. For $W^+W^- \to$ 4jet events also the W^+ and the W^- can only be separated with a limited efficiency.

Currently none of the experiments is able to perform a simultaneous fit to all five coupling parameters. To reduce the set of parameters to one or two, assumptions on the relations between the five couplings have to be made. Unfortunately at the present these assumptions are different at LEP and the TEVATRON so that no meaningful comparisons can be made.

At present typical results are

$$
\begin{aligned}
-0.33 < \Delta\kappa_\gamma &= \Delta\kappa_Z < 0.45, \\
-0.20 < \Delta\lambda_\gamma &= \Delta\lambda_Z < 0.20,
\end{aligned}
$$

at 90% c.l. for D0 and

$$\alpha_{W\Phi} = -0.02^{+0.18}_{-0.17}$$

for LEP.

The TEVATRON limits might improve by a factor two to four in run II, while LEP should be able to reduce their errors by around a factor six. If the two labs can agree until then on a common representation of the coupling parameters the different sensitivities of the two processes might allow for a large gain in a combination of the results.

At both colliders also anomalous $ZV\gamma$-couplings ($V = Z, \gamma$) have been analysed. In this case a common parametrisation has been used and as it can be seen from fig. 3 one largely gains from the combination.

5. NEW PHYSICS

New physics induced by very heavy particles can be efficiently described in a nearly model independent way by contact terms $\Lambda = \sqrt{4\pi}\frac{M}{\lambda}$, where M denotes the mass of the new particle and λ its coupling. Since most of the sensitivity

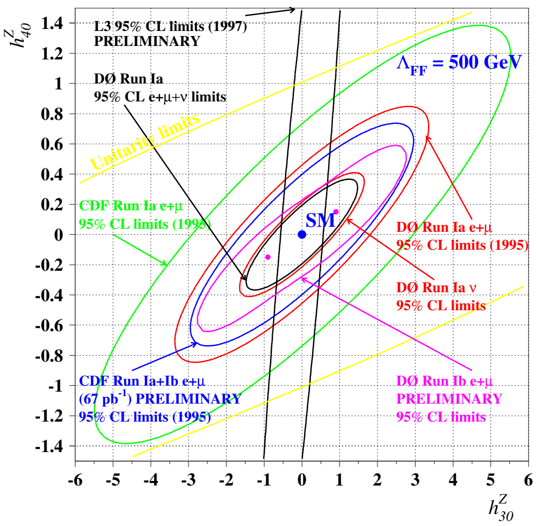

Figure 3. Limits on anomalous $ZZ\gamma$ couplings at LEP and the TEVATRON.

to Λ comes from the interference with the Standard Model processes, apart from the involved particles the helicity structure of the assumed new interaction and a global sign for the interference needs to be specified. Contact interaction limits have been presented at this conference from HERA [12], LEP [15], the TEVATRON collider [9] and CCFR at the TEVATRON neutrino beam [8]. All machines set limits between roughly 2 TeV and 6 TeV depending on the helicity structure for all accessible fermion combinations, so that, combining the different limits, practically no room is left for new interactions at scales below 2 TeV.

If the new physics scale is close enough that propagator effects are relevant more concrete models have to be used. For heavy Z' the tightest limits at present come from CDF who exclude Z' between 550 and 700 GeV depending on the model invoked [9].

A possible hint to new physics is currently seen in the excess of events at high Q^2 at HERA [12,16] which can, if not a statistical fluctuation, be interpreted as s-channel exchange of a leptoquark-type particle. In addition H1 has observed two events of similar kinematics where the outgoing particle is a muon, which fits nicely into this interpretation. The leptoquark interpretation is however severely constrained by the TEVATRON limits.

6. OTHER CONTRIBUTIONS

The calibration of the beam energies for the Z scan is finalised by now [17]. In the recent past progress has been made on the understanding of short term variations induced by trains and the complicated temperature behaviour of the dipole magnets. The errors on m_Z and Γ_Z due to the knowledge of the beam energy are now 1.5 MeV compared to 1.3 MeV and 2.0 MeV from other sources.

Since long the LEP and SLC collaborations measure the couplings of the Z to b and c quarks [1]. OPAL has now measured as well the coupling of the Z to individual light quark flavours [18]. Good agreement with the Standard Model prediction is observed.

Recent results from the CHARM II collaboration have been presented [19]. An analysis of the charm quark mass shows good agreement with the results from other collaborations. The process $\nu_\mu N \rightarrow \nu_\mu \mu^+ \mu^- N$ can proceed via Z or W exchange and in the Standard Model prediction an interference between the two graphs is present. An analysis of this process shows evidence for the WZ-interference term with a sensitivity comparable to $\nu_e e$ scattering.

Almost all properties of the τ-neutrino are known with good precision by now, however its existence is not yet proven. The DONUT experiment running in a beam dump at FNAL is aimed to finally prove the existence of the ν_τ [20]. ν_τ's are produced at a low rate in the decay $D_s \rightarrow \tau \nu_\tau$ where the D_s are produced in the hadronic interactions in the target. The ν_τ is then identified by the reaction $\nu_\tau N \rightarrow \tau X$ in an emulsion target where the τ is identified by its short lifetime. Within the large uncertainties of the D_s production cross section about a hundred ν_τ induced reactions should be identified by DONUT.

7. CONCLUSIONS

Electroweak physics is currently a very active field being studied in different reactions at several places. Results are obtained with a typical precision of less than a percent. With the possible exception of the HERA high Q^2 events the Standard Model of electroweak interactions describes all phenomena very well.

The measurement of the same electroweak quantities using different observables provide useful cross checks. In many cases the measurements are complementary so that one gains a lot by their combination.

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