# SUMMARY OF EXPERIMENTAL ELECTROWEAK PHYSICS[a]

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Progress continues on many fronts of experimental testing of electroweak symmetry breaking. Updates were presented on LEP, SLC, Brookhaven g-2 ring, Tevatron Collider, HERA, CESR and Tevatron neutrino experiments. Perhaps most exciting is the Higgs search at LEP2, complementing the indirect constraints. However, the standard model with one Higgs doublet remains viable.

## 1 Introduction

Electroweak physics had its experimental beginning in inelastic neutrino scattering neutral current measurements. Particular measurements may be interpreted directly or combined in global fits to constrain the Higgs mass and possibilities for new physics. The increasingly precise magnetic moment measurement of the muon at Brookhaven will limit nonstandard possibilities.[1]

The $Z$ mass measurement has developed a precision in the same league with $G_F^\mu$ and $\alpha_{EM}$, and the shape and decays show that we understand the decay process as well as what states are available.[2] For example there is room for only three neutrinos. The various $Z$ asymmetries from LEP [3] and SLC [4] give the strongest indirect constraint on the Higgs mass. With $e^+e^- \rightarrow hadrons$ measurements at BES [5] and Novosibirsk [6] complementing or confirming PQCD calculations,[6] the precision of $\alpha_{EM}$ evolved to the $Z$ mass has improved, and this constraint is becoming stronger.

The combination of $W$ mass [7,8] and top quark mass [9] is more of a check at the moment. The Tevatron analyses for $W$ and top masses with existing data are becoming mature, and substantial improvement will come with data from the next run, which should start in 2000. Considerable improvement on the $W$ mass is anticipated from the LEP collaborations with recent data, and more data at higher energy is coming.

New strategies in neutrino scattering make neutral current measurements interesting,[10] and deep inelastic scattering at HERA is becoming of interest from the electroweak point of view.[11] The absence of the Higgs particle in

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direct searches [12] is becoming as significant an influence on what possibilities remain as the indirect limits.

Precision electroweak studies are continuing on many fronts including $\tau$ studies,[13] and the pending observation of $\nu_\tau$ interactions.[14] None of these efforts has allowed us to break out of the standard framework. I summarize results as presented, but update to Moriond 99 numbers.[15]

## 2 BNL 821 Muon g-2

The study of the magnetic moment of the muon at CERN was precise enough to demonstrate the presence of hadronic corrections.[16] The goal of the ongoing program at Brookhaven is to become precise enough to demonstrate the electroweak corrections. More accurate calculations of the hadronic corrections are helping to make this realistic.[6]

The experiment is a muon storage ring consisting of a continuous, finely adjustable, iron dominated super-conducting magnet. Mapping and adjusting the field has been an ongoing program. The momentum of the muons is adjusted to minimize the effect of the embedded electrostatic quadrupoles on muon spin precession. Decays are observed at instrumented windows around the ring, with high energy decay electrons acting to spin analyze the muons.

A measurement from an initial run with pion decay injection approaches the CERN accuracy.[17] The numbers are listed in Table 1. This result was limited by low intensity and detector effects, particularly due to pion injection, as well as the field quality. In two more recent runs, muon injection was established, detectors improved, and the field much improved. The available data should produce a $\pm 1$ ppm measurement. The fringe field of the inflector magnet will be improved in order for future runs to reach the goal of $\pm 0.3$ ppm for both signs.

Table 1: Muon g-2 measurements ($\times 10^{-9}$).

| Measurement | Result |
|---|---|
| CERN | $1165923.5 \pm 8.4$ |
| BNL E821 initial run | $1165925 \pm 15$ |
| Standard Model Prediction | $1165916.3 \pm 0.8$ |

## 3 Measurements of the $Z$

The precision $Z$ line shape has been an adventure story with significant implications. The measurement is

$$m(Z) = 91.1867 \pm 0.0021 \text{ GeV/c}^2 \quad (1)$$

$$\Gamma(z) = 2.4939 \pm 0.0024 \text{ GeV}. \quad (2)$$

The mass is precise enough to rank with the weak and electromagnetic couplings as precision input. That nothing seems missing in $Z$ decay places serious constraints on new physics possibilities. Heavy flavor decay rates were a problem but the popular interpretation was otherwise ruled out even before the deviation went away. Agreement continues in the tail of the $Z$ at LEP2.

There is one residual small discrepancy seen at LEP and less at Moriond by SLC, and that is in the asymmetry in b decays. At 2.6 $\sigma$ or less, depending on input details, the effect is not convincing.

The $Z$ asymmetries from LEP have had some updates in $\tau$ polarization, and though some further fine tunings are expected, most of the analyses are pretty much complete. SLD has gotten a lot more data recently, and the preliminary results for the last two years data dominate the measurement. The discrepancy between the SLD $A_{LR}$ and the average of the LEP effective weak mixing continues but has become a lot less jarring, as seen in Table 2. Note that the overall average is pulled up a bit a by the LEP $b$ asymmetry, and down a bit by SLD $A_{LR}$. A slight residual discrepancy seems historically appropriate.

Table 2: Weak mixing measurements ($sin\Theta_{Weff}$) from $Z$ forward backward and polarization asymmetries.

| Measurement | Result |
|---|---|
| LEP lepton fb | $0.23117 \pm 0.00054$ |
| LEP $\tau$ pol. $A_\tau$ | $0.23202 \pm 0.00057$ |
| LEP $\tau$ pol. $A_e$ | $0.23141 \pm 0.00065$ |
| LEP $b$ fb | $0.23223 \pm 0.00036$ |
| LEP $c$ fb | $0.2321 \pm 0.0010$ |
| LEP jet charge fb | $0.2321 \pm 0.0010$ |
| SLD pol. $A_{LR}$ | $0.23109 \pm 0.00029$ |
| Average ($\chi^2$/DF 7.8/6) | $0.23157 \pm 0.00018$ |

The impact of the effective weak mixing measurement is improving as $\alpha_{EM}(m(Z))$ is better determined with PQCD calculations. There is discrepancy with old SPEAR hadron rates but new points from BES agree. Both PQCD and data driven calculations are agreeing and improving.[6]

## 4 Measurements of the $W$

The Tevatron Collider experiments have advanced the program begun at the CERN $S\bar{p}pS$ collider, including $W$ mass measurements using leptonic decay transverse mass. Updates at Moriond had DØ adding plug electrons, and CDF adding the most recent electron sample. Beyond that, further improvement will come with the next run, expected to start in 2000.

The LEP experiments have threshold $W$ mass measurements, and increasingly precise direct reconstruction measurements. Possible QCD systematics in the four quark mode are being confronted. The large sample at $\sqrt{s} = 189$ GeV should allow a precision of $\pm 40 - 45$ MeV/c$^2$ when fully analyzed; the ALEPH and L3 analyses included this sample in the Moriond update. Further data will continue to be collected through 2000. The measurements are listed in Table 3.

Table 3: $W$ mass measurements.

| Measurement | Result |
|---|---|
| LEP threshold | $80.400 \pm 0.221$ |
| LEP $qqqq$ | $80.485 \pm 0.103$ |
| LEP $\ell\nu qq$ | $80.318 \pm 0.073$ |
| Tevatron $\ell\nu$ | $80.448 \pm 0.062$ |
| Direct Average | $80.410 \pm 0.044$ |
| Indirect fit (LEPEWWG) | $80.364 \pm 0.029$ |

Searches for nonstandard $W$ and $Z$ couplings are now dominated by LEP measurements, although DØ makes a notable contribution. The large new data sample at LEP should improve coupling limits by about a factor of three when fully analyzed.

## 5 Measurements of the Top Quark

The impact of improving the $W$ precision will be limited by the precision of the top quark mass measurement. The Tevatron data analyses are largely complete with the two experiments in the different channels consistent, as can be seen in Table 4. A couple of years of new data should improve the precision by a factor of at least two.

Detailed studies of top production and decay, including limits on nonstandard decays, have begun. The expected increase in statistics at the Tevatron once the upgraded collider and detectors get going should have a salutary effect on these.

Table 4: Top quark mass measurements. When two errors are given, the first is statistical and the second systematic.

| Measurement | Result |
|---|---|
| CDF $\ell\nu qqqq$ | $175.9 \pm 4.8 \pm 5.3$ |
| CDF $\ell\nu\ell\nu qq$ | $167.4 \pm 10.3 \pm 4.8$ |
| CDF $qqqqqq$ | $186.0 \pm 10.0 \pm 5.7$ |
| DØ $\ell\nu qqqq$ | $173.3 \pm 5.6 \pm 5.5$ |
| DØ $\ell\nu\ell\nu qq$ | $168.4 \pm 12.3 \pm 3.6$ |
| Average | $174.3 \pm 5.1$ |

## 6 Deep Inelastic Scattering

The NuTeV group has revived the contribution of neutrinos to the electroweak program. By using a carefully designed beam, a neutrino beam free of anti-neutrinos and vice versa allows the difference in neutral to charged current rates to be used to measure weak mixing. The new data has similar statistics to CCFR but much improved systematics. The electroweak physics implications are illustrated in Fig. 1.

The HERA experiments still see a small excess at high $Q^2$, but not so dramatic as it seemed a year ago. The data are sufficient to see propagator effects in NC and CC events. The $t$ channel $W$ mass derived is compatible with direct measurements, and an electroweak program is getting started.

A neutrino beam at Fermilab for the NUMI project will have space available for a near detector. There are some possibilities for PDF studies.[18]

## 7 The Higgs Search

The Higgs particle of the minimal standard model has given no direct sign of its presence. The lower limit on its mass is growing with the LEP energy as searches are made for the process $e^+e^- \to Z^* \to ZH$. Most signatures involve $H \to \bar{b}b$, so that $Z$ pairs give an irreducible background. Fortunately $Z \to \bar{b}b$ is now well understood. The 189 GeV data has now been analyzed by the individual collaborations giving limits as high as

$$m(H) > 95.2 \text{ GeV/c}^2 \text{ 95\% CL.} \tag{3}$$

The combination of experiments will give some improvement. With data at 200 GeV, a limit or discovery reach up to $\sim 109$ GeV/c$^2$ is in prospect.

The recent PDG global fits to electroweak data,[19] using the data as of Vancouver 98, gives a most favored Higgs mass is 107 GeV/c$^2$, so the search

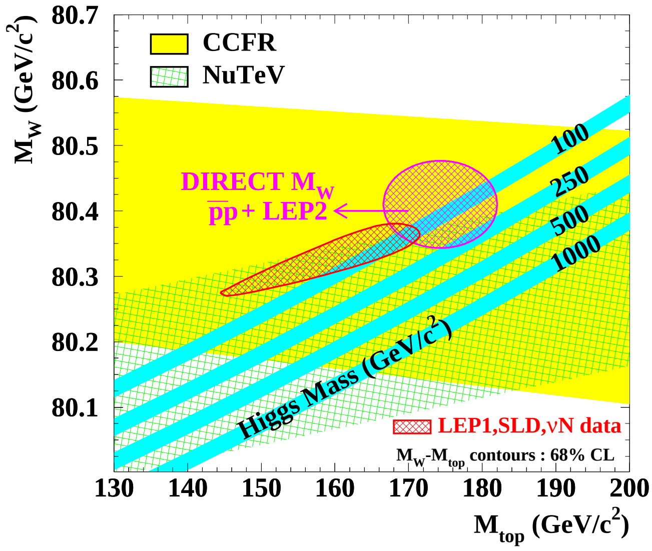


Figure 1: $W$ Mass versus Top Mass showing 68% CL allowed regions for the combined direct measurements, the SLC/LEP combined indirect measurement, NuTeV and CCFR with Higgs mass predictions. Note the different slope for the different neutrino analyses.

is covering quite interesting territory. The limit is threatening the viability of various popular scenarios for extending the standard model.

If the Higgs is still missing at the end of the LEP program, with enough luminosity the Tevatron detectors could extend the Higgs search. Eventually LHC detectors will make the search comprehensive.

## 8 Tau Physics

The detailed study of $\tau$ decays involves precise decay parameters, neutrino mass limits, and rare decay searches including lepton number violation and CP violation in the $K_s^0\pi\nu$ angular distribution. There is plenty of room for non-standard model physics. The program being pursued at CLEO will be being joined at Babar and Belle.

The E872 collaboration at Fermilab is searching for evidence of $\nu_\tau$ interactions in emulsion at Fermilab. With part of the data measured and analyzed, they have six candidates. Although this corresponds well to expectations, systematic studies to eliminate background possibilities are pending, but an announcement that interactions have been observed is expected soon.

## 9 Conclusions

The simplest scenario for the standard model, with one residual Higgs particle, remains viable. In the global fits, the strongest constraint comes from measurements of $Z$ asymmetries. These dominate the thinness of the indirect allowed region of Fig. 1. Some updates on these measurements are pending, but more progress seems likely from $\alpha_{EM}(m(Z))$ improvement.

The $W$ mass measurement is improving considerably, and further improvement and an improved top mass measurement, as will come with the next Tevatron run, is needed to compete with the $Z$ asymmetries.

The direct Higgs search is beginning to cut into the indirect fit allowed region. Perhaps a positive finding will come soon, but it seems like LHC will be needed to create a contradiction. Perhaps a contradiction, which would break us out of our mold, will come from one of the many electroweak studies which do not directly contribute to the Higgs picture.

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## References

1. B. L. Roberts, L. Nodulman, these proceedings.
2. P. Renton, these proceedings.
3. G. Duckeck, these proceedings.
4. P. Rowson, these proceedings.
5. A. Blondel, these proceedings.
6. M. Steinhauser, these proceedings.
7. A. Straessner, these proceedings.
8. M. Demarteau, these proceedings.
9. J. Konigsberg, these proceedings.
10. R. Johnson, these proceedings.
11. V. Brisson, these proceedings.
12. M. Pepe-Altarelli, these proceedings.
13. C. Jessop, these proceedings.

14. R. Rameika, these proceedings.
15. LEP Electroweak Working Group, see http://www.cern.ch/LEPEWWG.
16. J. Bailey *et al., Nucl. Phys.* B **150**, 1 (1979)
17. R. M. Carey *et al., Phys. Rev. Lett.* **82**, 1632 (1999)
18. J. Morfin, these proceedings.
19. J. Erler, these proceedings.