DPF '96: THE TRIUMPH OF THE STANDARD MODEL

S. DAWSON

Physics Department
Brookhaven National Laboratory
Upton, N.Y. 11973

I summarize some of the highlights of the 1996 DPF meeting, paying particular attention to new measurements of the W, Z, and top quark masses. Precision electroweak measurements from LEP are discussed with emphasis on recent measurements of R_b and values of the coupling constants $\alpha(M_Z^2)$ and $\alpha_s(M_Z^2)$ are presented. Taken as a whole, the data are in spectacular agreement with the predictions of the Standard Model.

1 Introduction

This meeting saw many beautiful experimental results presented, the overwhelming majority of which support the correctness of our basic understanding of particle physics. Many of the puzzles and data which did not fit into our picture from last year's conferences have become less compelling, leaving a wealth of data forming a consistent picture. The first observations of W pairs from LEP were presented, along with new measurements of the W, Z, and top quark masses. The errors on all of these masses are significantly reduced from previous values. Numerous electroweak precision measurements were presented, along with new measurements of $\alpha(M_Z^2)$ and $\alpha_s(M_Z^2)$.

In this note, I give a (very subjective!) lightning review of some of the highlights of the meeting. Unfortunately, there are many exciting and important results which I will not be able to cover. This has been truly a productive year for particle physics.

2 Precision Measurements of Masses

2.1 The Z Mass

The mass of the Z boson is usually taken as an input parameter in studies of electroweak physics. At the Z resonance, the error on the Z mass is directly related to the precision with which the beam energy is measured. Previous measurements have taken into account the phases of the moon and the weight of Lake Geneva on the ring. The latest measurement incorporates the time schedules of the TGV trains (which generate vagabond currents in the beam) and leads to a measurement with errors[1]

$$\begin{aligned} \Delta M_Z &= \pm 1.5\ MeV \\ \Delta\Gamma_Z &= \pm 1.7\ MeV \quad . \end{aligned} \tag{1}$$

These errors yield a new combined LEP result from the Z lineshape, [1]

$$\begin{aligned} M_Z &= 91.1863 \pm .0020\ GeV \\ \Gamma_Z &= 2.4946 \pm .0027\ GeV \quad . \qquad\qquad \text{LEP} \end{aligned} \tag{2}$$

The Z mass is down 4 MeV from the previous measurement. This shift is due almost entirely to understanding the effects of the trains!

2.2 The W Mass

The LEP experiments have presented preliminary measurements of the W pair production cross section. W^+W^- pairs have been observed in the $q\overline{q}q\overline{q}$, $q\overline{q}l\nu$, and $l\nu l\nu$ decays modes, with the number of W pairs increasing daily. Because of the sharp threshold behaviour of the production cross section, $\sqrt{s} \sim 161\ GeV$ is the optimal energy at which to measure the W mass and the M_W dependance of the cross section at this point is relatively insensitive to new physics effects. The combined result from the 4 LEP experiments at $\sqrt{s} = 161.3 \pm .2\ GeV$ is, [2]

$$\sigma(e^+e^- \rightarrow W^+W^-) = 3.6 \pm .7\ pb \quad . \qquad\qquad \text{LEP} \tag{3}$$

Assuming the validity of the Standard Model, this gives a new measurement of the W mass,[2]

$$M_W = 80.4 \pm .3 \pm .1\ GeV \quad . \qquad\qquad \text{LEP} \tag{4}$$

Since the error is dominated by statistics, it should be reduced considerably with further running. The data presented correspond to 3 pb^{-1} per experiment.

W^+W^- pair production at LEP will also be used to measure deviations of the W^+W^-Z and $W^+W^-\gamma$ couplings from their Standard Model values and OPAL presented preliminary limits on these couplings as a "proof of principle".[2] These limits are not yet competitive with those obtained at the Tevatron.

The D0 collaboration presented a new measurement of the W mass from the transverse mass spectrum of $W \rightarrow e\nu$, [3]

$$M_W = 80.37 \pm .15\ GeV \quad . \qquad\qquad \text{D0} \tag{5}$$

This error is considerably smaller than previous CDF and D0 W mass measurements. These results contribute to a new world average,[4]

$$M_W = 80.356 \pm .125\ GeV \quad . \qquad \text{WORLD} \tag{6}$$

2.3 The Top Quark Mass

The top quark has moved from being a newly discovered particle to a mature particle whose properties can be studied in detail. CDF and D0 each have more than 100 pb^{-1} of data which means that about 500 $t\bar{t}$ pairs have been produced in each experiment. Together, the experiments have identified around 13 dilepton, 70 lepton plus jets, and 60 purely hadronic top events and the top quark cross section and mass have been measured in many channels. The cross sections and masses obtained from the various channels are in good agreement and the combined results from CDF and D0 at $\sqrt{s} = 1.8\ TeV$ are, [5,6]

$$\begin{aligned} \sigma_{t\bar{t}} &= 6.4^{+1.3}_{-1.2}\ pb \\ M_T &= 175 \pm 6\ GeV \quad . \qquad \text{CDF, D0} \end{aligned} \tag{7}$$

The error on M_T of $\pm 6\ GeV$ is a factor of 2 smaller than that reported in February, 1995 due both to greater statistics and to improved analysis techniques. The dominant source of error remains the jet energy correction.

There has been considerable theoretical effort devoted to computing the top quark cross section in QCD beyond the leading order. In order to sum the soft gluon effects, (which are numerically important), the non-perturbative regime must be confronted, leading to some differences between the various calculations.[7] The theoretical cross section is slightly higher than the experimental value, but is in reasonable agreement.

The direct measurement of M_T can be compared with the indirect result inferred from precision electroweak measurements at LEP and SLD,[4,9]

$$M_T = 179 \pm 7^{+16}_{-19}\ GeV \quad . \qquad \text{INDIRECT} \tag{8}$$

(The second error results from varying the Higgs mass between 60 and 1000 GeV with the central value taken as 300 GeV.) This is truly an impressive agreement between the direct and indirect measurements!

Measurements of the top quark properties can be used to probe new physics. For example, by measuring the branching ratio of $t \rightarrow Wb$ (and assuming 3 generations of quarks plus unitarity), the $t - b$ element of the Kobayashi-Maskawa matrix can be measured,[5,8]

$$\mid V_{tb} \mid = .97 \pm .15 \pm .07 \quad . \qquad \text{CDF} \tag{9}$$

3 Precision Electroweak Measurements

There were many results from precision electroweak measurements presented at this meeting, most of which are in spectacular agreement with the predictions of the Standard Model. (See the talks by P. Langacker [9] and M. Demarteau [4] for tables of electroweak measurements and the comparisons with Standard Model predictions). Here, I will discuss two of those measurements,

$$\begin{aligned} R_b &\equiv \frac{\Gamma(Z \rightarrow b\overline{b})}{\Gamma(Z \rightarrow \text{hadrons})} \\ A_b &\equiv \frac{2g_V^b g_A^b}{[(g_V^b)^2 + (g_A^b)^2]} \qquad . \end{aligned} \tag{10}$$

Both of these measurements differ from the Standard Model predictions and are particularly interesting theoretically since they involve the couplings of the third generation quarks. In many non-standard models, the effects of new physics would first show up in the couplings of gauge bosons to the b and t quarks.

A year ago, the value of R_b was about 3σ above the Standard Model prediction. At this meeting new results were presented by the SLC collaboration and by the 4 LEP experiments. Numerous improvements in the analyses have been made, including measuring many of the charm decay rates directly instead of inputting values from other experiments. The ALEPH and SLD experiments have employed a new analysis technique utilizing a lifetime and mass tag. This technique allows them to obtain b quark samples which are $\sim 97\%$ pure, while maintaining relatively high efficiencies. This purity is considerably larger than that obtained in previous studies of R_b. The new ALEPH [10] and SLD [11] results are right on the nose of the Standard Model prediction,

$$R_b = \begin{cases} .21582 \pm .00087(\text{stat}) & \text{ALEPH} \\ .2149 \pm .0033(\text{stat}) \pm .0021(\text{syst}) \pm .00071(\text{R}_\text{c}) & \text{SLD} \\ .2156 \pm .0002 \qquad . & \text{SM} \end{cases} \tag{11}$$

(The theory error results from varying M_H).[9] Incorporating all measurements leads to a new world average, [4,9]

$$R_b = .2178 \pm .0011 \quad , \qquad\qquad \text{WORLD} \tag{12}$$

which is 1.8σ above the Standard Model. Advocates of supersymmetric models remind us that it is difficult to obtain effects larger than 2σ in these models, so the possibility that R_b may indicate new physics remains, although the case for it has certainly been weakened. (The value of R_c is now within 1σ of the Standard Model prediction.)

The only electroweak precision measurement which is in serious disagreement with the Standard Model prediction is A_b, which is sensitive to the axial vector coupling of the b quark. The new SLD result obtained using a lepton sample,[12]

$$A_b = .882 \pm .068(\text{stat}) \pm .047(\text{syst}) \qquad \text{SLD} \tag{13}$$

leads to a revised world average,

$$A_b = .867 \pm .022 \quad , \qquad \text{WORLD} \tag{14}$$

about 3σ below the Standard Model prediction of $A_b = .935$. There are,however, assumptions involved in comparing the SLD and LEP numbers which may help resolve this discrepancy.[13]

The LEP and SLD electroweak precision measurements can also be used to infer a preferred value for the Higgs mass, (including also the direct measurement of M_T as an input), [4]

$$M_H = 149^{+148}_{-82\ GeV} \quad . \qquad \text{INDIRECT} \tag{15}$$

This limit is driven by R_b and A_{LR}. Since the observables depend only logarithmically on M_H, there are large errors, but it is interesting that a relatively light value of M_H seems to be preferred. Such a light Higgs boson mass is predicted in supersymmetric theories.

The electromagnetic coupling constant can also be extracted from electroweak precision measurements,

$$\frac{1}{\alpha_{EM}(M_Z^2)} = 128.894 \pm .090 \qquad . \tag{16}$$

This leads to an error of $\delta \sin^2 \theta_W = .00023$, which is roughly the same size as the experimental error. This emphasizes the need for a more precise measurement of α_{EM}.

4 QCD and Measurements of α_s

At the summer meetings a year ago, it seemed that the values of $\alpha_s(M_Z^2)$ as extracted from lattice calculations and low energy experiments were smaller than the values extracted from measurements at the Z pole. This led to numerous speculations of the possibilities for new physics to cause this effect. At this meeting the CCFR collaboration presented a new measurement of

$\alpha_s(M_Z^2)$ obtained by fitting the Q^2 dependance of the ν deep inelastic structure functions, F_2 and xF_3, [14]

$$\alpha_s(M_Z^2) = .119 \pm .0015(\text{stat}) \pm .0035(\text{syst}) \pm .004(\text{scale}) \quad . \quad \text{CCFR} \quad (17)$$

This value is higher than the previous values of $\alpha_s(M_Z^2)$ extracted from deep inelastic scattering experiments. We can compare with the value extracted from the lineshape at LEP [9]

$$\alpha_s(M_Z^2) = .123 \pm .004 \qquad \text{LEP} \qquad (18)$$

to see that there does not seem to be any systematic discrepancy between the values of $\alpha_s(M_Z^2)$ measured at different energies. A world average for $\alpha_s(M_Z^2)$ (not including the new CCFR point) can be found, [4]

$$\alpha_s(M_Z^2) = .121 \pm .003 \pm .002 \quad . \qquad \text{WORLD} \qquad (19)$$

Most of the extracted values of $\alpha_s(M_Z^2)$ are within 1σ of this value.[9]

The inclusive jet cross sections measured at the Tevatron continue to show an excess of events at high E_T when compared with the theoretical predictions.[15] When corrections are made for differences in the rapidity coverages, etc, between the detectors, the CDF and D0 data on inclusive jet cross sections are in agreement.[16] The data can be partially explained by adjusting the gluon structure function at large x,[17] although considerable theoretical work remains to be done before this effect is completely understood.

5 ν Puzzles

The deficit of solar neutrinos from the Homestake mine, Kamiokande, SAGE, and GALLEX experiments remains a puzzle, as it is not easily explained by adjustments to the solar model. These results could be interpreted in terms of oscillations.[18] The LSND collaboration presented positive evidence for the oscillation $\overline{\nu_\mu} \leftrightarrow \overline{\nu_e}$. [19] They now have 22 events with an expected background of $4.6 \pm .6$. Their claim is that the excess events are consistent with the oscillation hypothesis. Hopefully, an upgraded KARMEN detector will be able to clarify the LSND results.[20]

6 The τ lepton, b and c quarks

This summary would not be complete without mentioning the τ, b and c. Although each of these particles was discovered some years ago, interesting new results on lifetimes, branching ratios, and mixing angles continue to be reported. See the reviews by H. Yamamoto [21] and P. Sphicas.[22]

7 New Physics

There were many talks at this meeting devoted to searches for physics beyond the Standard Model. They can best be summarized by stating that there is no experimental evidence for such physics. Many theorist's favorite candidate for physics beyond the Standard Model is supersymmetry and there were a large number of parallel talks with limits on the SUSY spectrum, (see the reviews by W. Merritt[23] and M. Schmitt[24]). In many cases, the limits are in the interesting $100 - 200\ GeV$ range and seriously restrict models with supersymmetry at the electroweak scale.

Considerable attention has been paid to a single CDF event with an $e^+e^-\gamma\gamma$ in the final state, along with missing energy. This event is particularly clean and lends itself to various supersymmetric interpretations. At this meeting, however, the $E_T^{\rm miss}$ distribution in the $\gamma\gamma$ spectrum was presented by the CDF collaboration and there is no additional evidence (besides this one event) for unexplained physics in this channel.[25]

8 Conclusions

The theoretical predictions and experimental data discussed at this meeting form a coherent picture in which the predictions of the standard $SU(3) \times SU(2) \times U(1)$ model have been validated many, many times. We need to remind ourselves, however, that this is not the end of particle physics and that there are large areas in which we continue to be almost totally ignorant. There remain many unanswered questions: "How is the electroweak symmetry broken?", "Why are there three generations of quarks and leptons?", "Why do the coupling constants and masses have their measured values?" .... The list goes on and on and our questions can only be answered by future experiments.

Acknowledgments

I am grateful to all the speakers who so generously shared their transparencies and knowledge with me. This manuscript has been authored under contract number DE-AC02-76CH00016 with the U.S. Department of Energy. Accordingly, the U.S. Government retains a non-exclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U.S. Government purposes.

References

1. T. Camporesi, contribution to these proceedings.
2. G. Bella, contribution to these proceedings.
3. A. Kotwal, contribution to these proceedings.
4. M. Demarteau, contribution to these proceedings.
5. B. Winer, contribution to these proceedings.
6. See also the talks by E. Varnes, B. Kehoe, K. Tollefson, and R. Yamada.
7. E. Berger, contribution to these proceedings.
8. T. Stelzer, contribution to these proceedings.
9. P. Langacker, contribution to these proceedings.
10. A. Bazarko, contribution to these proceedings.
11. E. Weiss, contribution to these proceedings.
12. G. Mancinelli, contribution to these proceedings.
13. J. Hewett, contribution to these proceedings.
14. P. Spentzouris, contribution to these proceedings.
15. M. Battacharjee, A. Bhatti, contributions to these proceedings.
16. E. Buckley-Geer, contribution to these proceedings.
17. H. Lai, contribution to these proceedings.
18. H. Sobel, contribution to these proceedings.
19. H. Kim, contribution to these proceedings.
20. S. Misra, contribution to these proceedings.
21. H. Yamamoto, contribution to these proceedings.
22. P. Sphicas, contribution to these proceedings.
23. W. Merritt, contribution to these proceedings.
24. M. Schmitt, contribution to these proceedings.
25. D. Toback, contribution to these proceedings.