UNIFICATION OR COMPOSITENESS?

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ABSTRACT

The status of precision electroweak data, tests of the standard model, determination of its parameters, and constraints on new physics, are surveyed.

1. Unification or Compositeness?

Most extensions of the standard model fall into one of two general categories, unification or compositeness. Unification theories, which include grand unification and string theories, typically involve a grand desert between the electroweak and the string or unification scales. They usually include elementary Higgs fields. The most popular versions involve supersymmetry, broken at the electroweak or TeV scales, and employ the cancellation between ordinary and superpartner contributions to the Higgs mass renormalization to avoid large radiative corrections to the electroweak scale. The approximate unification of gauge couplings is perhaps a hint that this approach is correct. In that case, the most likely types of new physics at the TeV scale are generally limited to superpartners; an extra Higgs doublet; and possibly additional heavy $Z$ bosons, certain types of exotic vector multiplets, and gauge singlets. In such models, the new physics tends to decouple from precision observables, i.e., to yield corrections which vanish as the particle masses become large. In particular, flavor changing neutral currents and new sources of CP violation should be small (but not necessarily negligible), and corrections to precision experiments such as $Z$ pole measurements are expected to be very small for most of parameter space.

Another possibility is compositeness - composite fermions and/or dynamical mechanisms for electroweak symmetry breaking instead of elementary Higgs fields. Composite quarks or leptons would not be analogous to previous levels of compositeness, all of which were weakly bound: experimental limits indicate that any quark or lepton constituent masses should be at least of the TeV scale, so that any new level must involve very strong binding. Dynamical symmetry breaking models avoid elementary Higgs fields and therefore avoid naturalness problems associated with quadratic

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divergences in the self-energies of elementary Higgs fields. Models with composite fermions tend to have large flavor changing neutral current effects due to constituent interchange. Dynamical symmetry breaking models usually have unacceptable flavor changing effects due to the exchange of new gauge bosons or bound states unless the relevant mass scales are very large. Even if flavor changing problems are avoided, simple examples of these schemes usually involve sizable (several per cent) contributions to precision observables, either due to new four-fermion operators or to non-decoupling effects (radiative corrections that do not vanish as the mass scale increases). Such models also do not generally predict the apparent gauge unification, although the latter could conceivably be an accident.

The precision electroweak measurements, especially the LEP and SLD Z pole observables, have verified the standard model predictions at the level of a few tenths of a percent. This is consistent with the expectations of typical unification-type models, but not with most of the simple compositeness models. This may be considered a strong encouragement for the unification/supersymmetry approach, which reinforces the hint from gauge unification. However, it is certainly not a proof that this is the approach followed by nature - that would require the direct observation of superpartners at colliders. Depending on one’s point of view, the compositeness/dynamical symmetry breaking route is either disfavored, or at least one is guided to look for versions which decouple from both flavor changing effects and precision electroweak observables.

In this talk we update our previous analyses of the precision data for testing the standard model, determining its parameters, and constraining classes of new physics, using the data presented at the time of the Warsaw Conference.

2. Recent Data

The LEP and SLD values of the main Z-pole observables are displayed in Table 1, along with their standard model expectations. Along with the Z mass and (partial) widths, many asymmetries and polarizations have been observed. The latter depend on

\[ A_f^0 = \frac{2\tilde{g}_{Vf} \tilde{g}_{Af}}{\tilde{g}_{Vf}^2 + \tilde{g}_{Af}^2}, \]  

where \( \tilde{g}_{V,Af} \) are the vector and axial vector couplings to fermion \( f \). \( M_Z \) has been determined at LEP to the incredible precision (for high energy) experiments of around 0.002%. Using \( M_Z \) (as well as \( \alpha \) and \( G_F \)) as input one can predict the other observables (in Table 1 we use the values of \( m_t \), \( \alpha_s \), and \( \Delta \alpha_{had} \) obtained from the global fits, and a reasonable range for \( M_H \)).

There is generally impressive agreement between the standard model predictions and the data. However, there are two discrepancies at the 2\( \sigma \) level. The first is the value of the leptonic coupling \( A_\ell^0 \sim 2\tilde{g}_{V\ell}/\tilde{g}_{A\ell} \) from SLD, which is dominated
Table 1. $Z$-pole observables from LEP and SLD compared to their standard model expectations. The standard model prediction is based on $M_Z$ and uses the global best fit values for $m_t$, $\alpha_s$, and $\Delta\alpha_{had}$, with $M_H$ in the range $60 - 1000$ GeV. August 1996.

| Quantity | Value | Standard Model |
|----------|-------|----------------|
| $M_Z$ (GeV) | 91.1863 ± 0.0020 | input |
| $\Gamma_Z$ (GeV) | 2.4946 ± 0.0027 | 2.496 ± 0.001 ± 0.001 ± [0.002] |
| $R = \Gamma$(had)/$\Gamma$(\ell\ell) | 20.778 ± 0.029 | 20.76 ± 0.003 ± 0.001 ± [0.02] |
| $\sigma_{had} = \frac{12\pi}{M_Z^2} \frac{\Gamma(\ell\ell)\Gamma$(had$)}{\Gamma_Z^2}$ | 41.508 ± 0.056 | 41.46 ± 0.002 ± 0.002 ± [0.02] |
| $R_b = \Gamma(bb)/\Gamma$(had) | 0.2178 ± 0.0011 | 0.2156 ± 0 ± 0.0002 |
| $R_c = \Gamma(c\bar{c})/\Gamma$(had) | 0.1715 ± 0.0056 | 0.172 ± 0 ± 0 |
| $A_{FB}^{0} = \frac{3}{4} (A_{T}^{0})^2$ | 0.0174 ± 0.0010 | 0.0157 ± 0.0003 ± 0.0003 |
| $A_{T}^{0} (P_\tau)$ | 0.1401 ± 0.0067 | 0.145 ± 0.001 ± 0.001 |
| $A_{C}^{0} (P_\tau)$ | 0.1382 ± 0.0076 | 0.145 ± 0.001 ± 0.001 |
| $A_{FB}^{0} = \frac{3}{4} A_{T}^{0} A_{b}^{0}$ | 0.0979 ± 0.0023 | 0.101 ± 0.001 ± 0.001 |
| $A_{0e} = \frac{3}{4} A_{T}^{0} A_{c}^{0}$ | 0.0735 ± 0.0048 | 0.072 ± 0.001 ± 0.001 |
| $s_{\ell}^2 (A_{FB}^{0})$ | 0.2320 ± 0.0010 | 0.2318 ± 0.0002 ± 0.0001 |
| $A_{\mu,\tau}^{0} (A_{LR}^{0}, A_{e,\mu,\tau}^{0})$ (SLD) | 0.1542 ± 0.0037 | 0.145 ± 0.001 ± 0.001 |
| $A_{b}^{0}$ (SLD) | 0.863 ± 0.049 | 0.935 ± 0 ± 0 |
| $A_{c}^{0}$ (SLD) | 0.625 ± 0.084 | 0.667 ± 0.001 ± 0.001 |
| $N_{\nu}$ | 2.989 ± 0.012 | 3 |

by the polarization asymmetry $A_{LR}^{0} = A_{e}^{0}$. The SLD collaboration obtains $A_{LR}^{0} = 0.1542(37)$, which is $2.2\sigma$ above the standard model prediction 0.145(2) for the allowed $m_t$ range (Figure [1]). This is most likely a fluctuation, because the LEP collaborations obtain $A_{T}^{0} = 0.141(6)$ and $A_{C}^{0} = 0.147(3)$ from final state asymmetries/polarizations, in agreement with the standard model. New, physics, such as a negative $S$ parameter, mixing of the $e_R$ with a heavy exotic lepton, of mixing of the $Z$ with a heavy $Z'$ should affect both types of observables the same way. The only way to break the relation would be to have an important contribution to the experiments that is not directly related to the properties of the $Z$, but it is difficult to find a sufficiently large mechanism that is not excluded by other observations [3]. The SLD value for $A_{LR}^{0}$ (combined with the $Z$ mass) implies $m_t = 217^{+13+20}_{-14-24}$ GeV, where the second uncertainty is from $M_H$, well above the direct measurement 175(6) GeV obtained by CDF [4] and D0 [5]. Thus, the effect of $A_{LR}^{0}$ on the global fits is to favor small values of $M_H$, near the present direct limit of $\sim 65$ GeV.

The other discrepancy is in the ratio $R_b = \Gamma(bb)/\Gamma$(had). The current value, 0.2178(11) is now $2\sigma$ above the standard model expectation, much closer than the $3.4\sigma$ excess reported the year before. The change is mainly due to new ALEPH results, which are in agreement with the standard model. ($R_c = \Gamma(c\bar{c})/\Gamma$(had), which had been $1.8\sigma$ low, is now in agreement.) The small excess in $R_b$ could still be due to new physics, such as supersymmetry [6], mixing with a heavy $Z'$ [7], or new extended
Fig. 1. Values of $A_e$ from SLD and LEP, as well as the standard model prediction as a function of $m_t$ for $M_H = 60, 300,$ and $1000$ GeV. The direct measurement of $m_t$ from CDF and D0 is $175 \pm 6$ GeV. August 1996.

technicolor$^a$(ETC) interactions $^4$. The effect is not statistically compelling, but it should be recalled that most attempts to invoke new physics for the previous larger discrepancy concluded that it was not possible to obtain $R_b$ larger than 0.218 or to explain a significant shift in $R_c$, i.e., they predicted precisely the current values.

Nevertheless, the most likely possibility is a statistical fluctuation. Assuming no new physics, the large $R_b$ value favors a small $m_t$, as seen in Figure 2. $R_b$ is by itself insensitive to the Higgs mass, but when combined with other observables, for which the $m_t$ and $M_H$ dependences are strongly correlated, $R_b$ favors smaller values of $M_H$.

There is also a strong correlation between $R_b$ and the strong fine structure constant $\alpha_s(M_Z)$. As will be seen in the Section on $\alpha_s(M_Z)$, a precise value of $\alpha_s(M_Z)$ is obtained from observables related to the hadronic $Z$ width. Any new physics contribution to $\Gamma(b\bar{b})$ would imply a smaller standard model hadronic width, and therefore a smaller $\alpha_s(M_Z)$.

There are a number of additional observables, such as the $W$ mass, results from atomic parity violation, neutral current $\nu - e$ and $\nu -$ hadron scattering, the direct measurement of the top quark mass $m_t$ from CDF and D0, and direct limits on the Higgs mass, $M_H$, from LEP. Some of the more recent results are listed in Table 2.

$^a$The simplest ETC models yield large contributions of the wrong sign.
3. Fits to the Standard Model and Beyond

In the global fits to be described, all of the earlier low energy observables not listed in Table 2 are fully incorporated. The electroweak corrections are now quite important. The results presented include full 1-loop corrections, as well as dominant 2-loop effects, QCD corrections, and mixed QCD-electroweak corrections. For the renormalized weak angle, we use the modified minimal subtraction ($\overline{MS}$) definition \[ \sin^2 \hat{\theta}_W(M_Z) \equiv \hat{s}_Z^2 \]. This basically means that one removes the $\frac{1}{n-4}$ poles and some associated constants from the gauge couplings. The fits also include full statistical, systematic, and theoretical uncertainties, and correlations between the uncertainties. Our standard model fits are in excellent agreement with those of the LEP Electroweak Working Group.

3.1. The Standard Model and the Decoupled MSSM with Fixed $M_H$

There are enough independent precision observables to simultaneously determine $\sin^2 \hat{\theta}_W(M_Z)$, $\alpha_s(M_Z)$, and $m_t$, as well as to constrain additional parameters such as $M_H$, the hadronic contribution to the running of $\alpha$, or parameters representing the
Table 2. Recent observables from the W mass and other non-Z-pole observations compared with the standard model expectations. Direct limits and values on $M_H$ and $m_t$ are also shown. August 1996.

| Quantity       | Value               | Standard Model                        |
|----------------|---------------------|---------------------------------------|
| $M_W$ (GeV)    | 80.36 ± 0.13        | 80.33 ± 0.01 ± 0.03                   |
| $Q_W (C_S)$    | $-71.04 ± 1.58 ± [0.88]$ | $-72.85 ± 0.04 ± 0.02$               |
| $g_A^{\mu e}$ (CHARM II) | $-0.503 ± 0.017$ | $-0.506 ± 0 ± 0.0002$               |
| $g_V^{\mu e}$ (CHARM II) | $-0.035 ± 0.017$ | $-0.038 ± 0.0004 ± 0.0002$          |
| $s_W^2 = 1 - \frac{M_W^2}{M_Z^2}$ | $0.2213 ± 0.0048$ [CCFR] | $0.2239 ± 0.0002 ± 0.0006$          |
| $M_H$ (GeV)    | ≥ 65 LEP            | < $O(600)$, theory                    |
| $m_t$          | 175 ± 6 CDF/D0      | 177 ± 5$^{+7}_{-8}$ with indirect     |

The second row in Table 3 represents the global fit to all indirect precision data, but not including the direct CDF/D0 determination $m_t = 175(6)$ GeV. The fit predicts $m_t = 179 ± 7^{+16}_{-19}$ GeV, in remarkable agreement with the CDF/D0 value. The first row is the global fit, including the direct $m_t$ value. The decoupled MSSM fit in the last row yields parameters that are slightly shifted due to the lower $M_H$ range.

3.2. The Standard Model or Decoupled MSSM with $M_H$ Free

Assuming the validity of the standard model one can use the precision data to constrain the Higgs mass, $M_H$. Unlike $m_t$, which affects the radiative corrections quadratically, the $M_H$ dependence is only logarithmic. Furthermore, the weaker $M_H$ dependence can be comparable to the effects of new physics, so any constraints or predictions on $M_H$ are less robust than those on $m_t$, i.e., they can be modified or lost if there is any significant contribution from new physics. Nevertheless, the current
Table 3. Results for the electroweak parameters in the standard model from various sets of data. The central values assume $M_H = 300 \text{ GeV}$, while the second errors are for $M_H \to 1000(+)$ and $60(-)$. The last column is the increase in the overall $\chi^2$ of the fit as $M_H$ increases from 60 to 1000. The last row is for the decoupled MSSM, with a central value $M_H = M_Z$. The second errors are for $M_H \to 150(+)$ and $60(-)$. August 1996.

| Set                              | $s_Z^2$      | $\alpha_s(M_Z)$ | $m_t$ (GeV) | $\Delta \chi^2_H$ |
|----------------------------------|--------------|-----------------|-------------|-------------------|
| Standard Model                   |              |                 |             |                   |
| Indirect + CDF + D0              | 0.2316(2)    | 0.121(3)(2)     | 177 ± 5 +7 8 | 9.9               |
| All indirect                     | 0.2315(2)(1) | 0.121(3)(2)     | 179 ± 7 +16 | 7.5               |
| All LEP                          | 0.2318(2)(1) | 0.122(3)(2)     | 172 ± 8 +19 | 4.2               |
| Z-pole (LEP + SLD)               | 0.2315(2)(1) | 0.121(3)(2)     | 178 +7 +17 8 | 7.6               |
| SLD + $M_Z$                      | 0.2305(5)(0) | —                | 217 +13 +20 |                   |
| Decoupled MSSM                   |              |                 |             |                   |
| Indirect + CDF + D0              | 0.2313(2)(1) | 0.119(3)(1)     | 171 ± 5 ±2  |                   |

data shows a strong tendency towards low values of $M_H$. This can be seen from the last column of Table 3, which shows the increase in $\chi^2$ in the best fit (with respect to the other parameters) as $M_H$ is increased from 60 to 1000 GeV. This tendency for a small $M_H$ is consistent with the MSSM in the decoupling limit, which differs from the standard model for the existing precision data only by the expectation that the (standard-like) Higgs scalar should be light (less than $\sim 150 \text{ GeV}$). Of course, even if a light Higgs were observed directly at LEP II or elsewhere it would not by itself prove the existence of supersymmetry, but it would be extremely encouraging to supersymmetry advocates.

The tendency for a light Higgs is shown in more detail in Table 4 and in Figures 3 and 4. Leaving $M_H$ as a free parameter, one obtains $M_H = 124^{+125}_{-71}$ GeV, and slightly lower central values for $\sin^2 \hat{\theta}_W(M_Z)$ and $\alpha_s(M_Z)$ than in the $M_H = 300 \text{ GeV}$ fit in Table 3 (but consistent with the Decoupled MSSM fit).

The $\chi^2$ distribution as a function of $M_H$ is shown in Figure 3. The corresponding upper limits on $M_H$, which properly take into account the direct lower limit $M_H > 65 \text{ GeV}$ and the fact that $M_H$ enters the observables logarithmically, are given in the caption. Some caution is in order: much of the $M_H$ sensitivity and constraint is due to $R_b$ and $A_{LR}$, both of which differ from the standard model expectation at $\sim 2\sigma$. If there is any new physics contribution to these quantities, the $M_H$ constraint would be weakened or modified, as is also displayed in Figure 3.

Table 4. Results for the electroweak parameters in the standard model, leaving the Higgs mass, $M_H$, free. The direct constraint $M_H > 65 \text{ GeV}$ is not included. August 1996.

| Set                              | $s_Z^2$      | $\alpha_s(M_Z)$ | $m_t$ (GeV) | $M_H$             |
|----------------------------------|--------------|-----------------|-------------|------------------|
| Indirect + CDF + D0              | 0.2314(2)    | 0.119(3)        | 172(6)      | $124^{+125}_{-71}$ |
3.3. Values of $\alpha_s$ at the $Z$-pole

The hadronic $Z$ width and partial widths receive significant QCD corrections. Neglecting fermion mass effects (the $m_b$ and $m_t$ effects are important and are included in the numerical analysis),

$$\Gamma(q\bar{q}) = \Gamma^0(q\bar{q}) \left[ 1 + \frac{\alpha_s(M_Z)}{\pi} + 1.409 \left( \frac{\alpha_s(M_Z)}{\pi} \right)^2 - 12.77 \left( \frac{\alpha_s(M_Z)}{\pi} \right)^3 + \text{H.O.T.} \right]$$

(2)

The $Z$ lineshape data is probably the cleanest determinant of $\alpha_s(M_Z)$ as far as theoretical QCD uncertainties are involved. From Table 3 we see that $\alpha_s(M_Z) = 0.121(3)(2)$ for the Standard Model fit, and $0.119(3)(1)$ in the Decoupled MSSM\textsuperscript{b}. These have come down by $\sim 0.002$ compared to previous results, and are now consistent with most other determinations \textsuperscript{4}, as seen in Table 4. In particular, the value $0.118 \pm 0.003$ obtained from lattice calculations of the $b\bar{b}$ spectrum \textsuperscript{4} has moved up

\textsuperscript{b}There is an additional theoretical uncertainty of $\sim 0.001$ from higher order terms \textsuperscript{4}.
Fig. 4. Allowed regions in $M_H$ and $m_t$ at various confidence levels, including the direct $m_t$ constraint. August 1996.

by 0.003 from the previously quoted value. The value given in Table 3 for deep inelastic scattering is still low, but preliminary recent results from CCFR and BCDMS (not included) are expected to increase the deep inelastic value. Thus, most determinations are converging on the value $\alpha_s(M_Z) \sim 0.118$ that has been quoted in the Particle Data Book for some time, and the argument for a discrepancy between the $Z$-lineshape value of $\alpha_s(M_Z)$ and those obtained by extrapolating low energy data (including QCD sum rule results not listed in Table 3) are considerably weakened.

These values of $\alpha_s(M_Z)$ are reasonably consistent with the prediction $\alpha_s(M_Z) \sim 0.130 \pm 0.010$ of supersymmetric gauge coupling unification, in which the precisely known $\alpha$ and $\sin^2 \theta_W(M_Z)$ are used as inputs to predict the unification scale and $\alpha_s(M_Z)$. However, the observed values are on the low side, implying O(10%) corrections from threshold effects, non-renormalizable operators, exotic multiplets, etc. In contrast, the prediction $\sim 0.07$ of non-supersymmetric gauge unification would require much larger corrections.

There is still one uncertainty, however; the lineshape value of $\alpha_s(M_Z)$ is sensitive to any new physics which affects the hadronic width. In particular, if the $2\sigma$ excess in $R_b$ is real, and not just a fluctuation, the extracted $\alpha_s(M_Z)$ would decrease. This can be quantified by introducing a new physics parameter $\delta_{bb}^{new}$ such that

$$\Gamma(b\bar{b}) = \Gamma^{SM}(b\bar{b})(1 + \delta_{bb}^{new}).$$

(3)
\( \delta_{bb}^{new} \) and \( \alpha_s(M_Z) \) are strongly correlated, and one obtains \( \alpha_s(M_Z) = 0.111(5)(2) \) in the combined fit, consistent with some low energy values.

Thus, if the apparent excess in \( R_b \) is due to a fluctuation, the true value of \( \alpha_s(M_Z) \) is most likely around 0.118-0.119, consistent with supersymmetric gauge unification with moderate theoretical uncertainties. If the excess is really due to new physics, then a low value for \( \alpha_s(M_Z) \) is called for, requiring large corrections to gauge unification or abandoning the concept.

Table 5. Values of \( \alpha_s \) at the \( Z \)-pole extracted from various methods. August 1996.

| Source                        | \( \alpha_s(M_Z) \) |
|-------------------------------|---------------------|
| \( R_\tau \)                 | 0.119 \( \pm \) 0.004 |
| Deep inelastic \( \Upsilon, J/\Psi \) | 0.112 \( \pm \) 0.005 |
| \( c\bar{c} \) spectrum (lattice) | 0.111 \( \pm \) 0.005 |
| \( b\bar{b} \) spectrum (lattice) | 0.118 \( \pm \) 0.003 |
| LEP, lineshape               | 0.121 \( \pm \) 0.004 |
| LEP, event topologies        | 0.123 \( \pm \) 0.006 |

3.4. The Standard Model with \( \Delta \alpha_{had} \) Free

The largest theoretical uncertainty in the standard model is the value of \( \Delta \alpha_{had} \) from hadronic loops, which determines \( \alpha(M_Z) \):

\[
\alpha(M_Z) = \frac{\alpha}{1 - \Delta \alpha_{had} - \Delta \alpha_t - \Delta \alpha_{lep}},
\]

where \( \Delta \alpha_{lep} = 0.03142 \) and \( \Delta \alpha_t = -0.000061 \) represent the leptonic and \( t \) quark loops. \( \Delta \alpha_{had} \) can be calculated non-perturbatively from a dispersion integral over experimental low energy \( e^+e^- \rightarrow \) hadrons data. There has been considerable recent work reevaluating \( \Delta \alpha_{had} \), with the results in Table 6 now in reasonable agreement with each other. In most of our fits, we use the value 0.0280(7) of Eidelman and Jegerlehner.

Despite the agreement, \( \Delta \alpha_{had} \) is still a significant uncertainty (ten times more important than the experimental error in \( M_Z \)). A closely related effect dominates the uncertainty in the theoretical prediction for the muon anomalous magnetic moment, which will be considerably larger than the projected experimental error from the new Brookhaven \( g_\mu = 2 \) experiment unless new measurements are made of the low energy cross section for \( e^+e^- \rightarrow \) hadrons.

It is amusing that the precision data itself can constrain \( \Delta \alpha_{had} \), which enters in the relation between \( M_Z \) and \( \sin^2 \hat{\theta}_W(M_Z) \), since \( \sin^2 \hat{\theta}_W(M_Z) \) is independently constrained by the asymmetry measurements, and \( m_t \) is measured directly. The
values for $\Delta \alpha_{\text{had}}$ and the corresponding $\alpha(M_Z)$ are shown in Table 6 for both the standard model and constrained MSSM Higgs mass ranges. It is seen that for fixed $M_H$ the precision is comparable to the independent estimates. For the standard model case, the uncertainty from $M_H$ in the range 60-1000 GeV is considerably larger, while for the constrained MSSM the Higgs uncertainty is reasonably small. It is remarkable that the precision data are so good as to allow the extraction of $\Delta \alpha_{\text{had}}$ simultaneously with the other parameters (such as $\sin^2 \hat{\theta}_W(M_Z)$ and $\alpha_s(M_Z)$). The values of $\Delta \alpha_{\text{had}}$ using both the precision data and the independent Eidelman and Jegerlehner value are also listed in Table 6.

Table 6. It is now possible to determine $\Delta \alpha_{\text{had}}$ directly from the precision data, with a value comparable to independent theoretical estimates 19-22 using low energy $e^+e^-$ data. Other fits include Eidelman and Jegerlehner (95) as a separate constraint. August 1996.

| Source                     | $\Delta \alpha_{\text{had}}$  | $\alpha(M_Z)$  |
|----------------------------|-------------------------------|----------------|
| Eidelman, Jegerlehner (95) | 0.0280(7)                     | 128.90 (9)     |
| Martin, Zeppenfeld (95)    | 0.0273(4)                     | 128.99 (5)     |
| Burkhardt, Pietrzyk (95)   | 0.0280(7)                     | 128.89 (9)     |
| Swartz (95)                | 0.0275(5)                     | 128.96 (6)     |
| SM fit, including EJ (95)  | 0.0274(5)                     | 128.98 (7) ( +8 ) | 128.98 (7) ( -12 ) |
| MSSM fit, including EJ (95)| 0.0281(5)                     | 128.89 (7) ( +4 ) | 128.89 (7) ( -3 ) |
| unconstrained SM fit       | 0.0265(9)                     | 129.11 (12) ( +25 ) | 129.11 (12) ( -32 ) |
| unconstrained MSSM fit     | 0.0282(9)                     | 128.87 (12) ( +10 ) | 128.87 (12) ( -8 ) |

4. Beyond the Standard Model

There are many types of new physics that are constrained by the precision data, including new contact operators, heavy $Z'$ bosons, and mixing between ordinary and exotic fermions. Here we briefly state the current results for a few parametrizations of certain classes of new physics. More detailed discussions, as well as model independent analyses, more discussion of gauge coupling unification, etc., may be found in 2.

4.1. The Standard Model or Decoupled MSSM with a $Zb\bar{b}$ Vertex Correction

The apparent excess in $R_b$ has already been discussed in the Sections on the data and on $\alpha_s(M_Z)$. If one introduces a new physics parameter $\delta_{bb}^{\text{new}}$, as in (3), then the other extracted standard model parameters are modified somewhat, as can be seen in Table 7.

A more detailed analysis allows separate corrections to the left and right chiral
Table 7. One can parametrize possible new physics in the $Zb\bar{b}$ vertex by $\Gamma(b\bar{b}) = \Gamma_{\text{SM}}(b\bar{b})(1 + \delta_{bb}^{\text{new}})$. Allowing $\delta_{bb}^{\text{new}} \neq 0$ leads to a lower value of $\alpha_s$ extracted from the lineshape. August 1996.

| Set                | $s_Z^2$        | $\alpha_s(M_Z)$ | $m_t$ (GeV) | $\delta_{bb}^{\text{new}}$ |
|--------------------|----------------|-----------------|-------------|-----------------------------|
| Indirect + CDF + D0 | 0.2316(2)($\frac{2}{4}$) | 0.121(3)(2)   | 177 ± 5$^{+7}_{-8}$ | fixed at 0                  |
| Indirect + CDF + D0 | 0.2315(2)(3)  | 0.111(5)($\frac{2}{1}$) | 178 ± 5$^{+7}_{-8}$ | 0.014(7)(2)                 |

$Zb\bar{b}$ vertices, $\delta_L^b$ and $\delta_R^b$, i.e.

$$g_L^b \simeq -\frac{1}{2} + \frac{1}{3}s_W^2 + \delta_L^b \sim -0.42 + \delta_L^b$$

$$g_R^b \simeq \frac{1}{3}s_W^2 + \delta_R^b \sim 0.077 + \delta_R^b.$$  

(5)

A global fit yields $\delta_L^b = 0.002(3)(2)$, $\delta_R^b = 0.02(1)(1)$, and $\alpha_s(M_Z) = 0.111(5)(1)$. Thus, the data now favor an anomaly, if any, in $\delta_R^b$, and the correlation with $\alpha_s(M_Z)$ is essentially unchanged with respect to the single new parameter case. The allowed region in $\delta_L^b$ vs $\delta_R^b$ is shown in Figure 5.

Fig. 5. 90% CL allowed region in $\delta_L^b$ vs $\delta_R^b$. August 1996.
4.2. The $\rho_0$ Parameter

One parameterization of certain new types of physics is the parameter $\rho_0$, which is introduced to describe new sources of $SU_2$ breaking other than the ordinary Higgs doublets or the top/bottom splitting. One defines $\rho_0 \equiv M_W^2/(M_Z^2 c_Z^2 \hat{\rho})$, where $c_Z^2 \equiv 1 - \hat{s}_Z^2$; $\hat{\rho} \sim 1 + 3G_F m_t^2/8\sqrt{2}\pi^2$ absorbs the relevant standard model radiative corrections so that $\rho_0 \equiv 1$ in the standard model. New physics can affect $\rho_0$ at either the tree or loop-level, $\rho_0 = \rho_{0\text{tree}}^0 + \rho_{0\text{loop}}^0$. The tree-level contribution is given by Higgs representations larger than doublets, namely,

$$\rho_{0\text{tree}}^0 = \frac{\sum_i \left( t_i^2 - t_{3i}^2 + t_i \right) |\langle \phi_i \rangle|^2}{\sum_i 2t_{3i}^2 |\langle \phi_i \rangle|^2},$$

where $t_i$ ($t_{3i}$) is the weak isospin (third component) of the neutral Higgs field $\phi_i$. For Higgs singlets and doublets ($t_i = 0, \frac{1}{2}$) only, $\rho_{0\text{tree}}^0 = 1$. However, $\rho_{0\text{tree}}^0$ can differ from unity in the presence of larger representations with non-zero vacuum expectation values.

One can also have loop-induced contributions similar to that of the top/bottom, due to non-degenerate multiplets of fermions or bosons. For new doublets

$$\rho_{0\text{loop}}^0 = \frac{3G_F}{8\sqrt{2}\pi^2} \sum_i \frac{C_i}{3} F(m_{1i}, m_{2i}),$$

where $C_i = 3(1)$ for color triplets (singlets) and

$$F(m_1, m_2) = m_1^2 + m_2^2 - \frac{4m_1^2 m_2^2}{m_1^2 - m_2^2} \ln \frac{m_1}{m_2} \geq (m_1 - m_2)^2.$$ (8)

Loop contributions to $\rho_0$ are generally positive, and if present would lead to lower values for the predicted $m_t$. $\rho_{0\text{tree}}^0 - 1$ can be either positive or negative depending on the quantum numbers of the Higgs field. The $\rho_0$ parameter is extremely important because one expects $\rho_0 \sim 1$ in most superstring theories, which generally do not have higher-dimensional Higgs representations, while typically $\rho_0 \neq 1$ from many sources in models involving compositeness.

It has long been known that $\rho_0$ is close to 1. However, until recently it has been difficult to separate $\rho_0$ from $m_t$, because in most observables one has only the combination $\rho_0 \hat{\rho}$. The one exception has been the $Z \rightarrow bb$ vertex. However, the direct measurement of $m_t$ by CDF and D0 allows one to calculate $\hat{\rho}$ and therefore separate $\rho_0$. In practice one fits to $m_t$, $\rho_0$ and the other parameters, using the CDF/D0 value of $m_t$ as an additional constraint. One can determine $\hat{s}_Z^2$, $\rho_0$, $m_t$, and $\alpha_s$ simultaneously, yielding the results listed in Table 8. Even in the presence of the

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\(^{1}\)One can have $\rho_{0\text{loop}}^0 < 0$ for Majorana fermions or boson multiplets with vacuum expectation values.
Table 8. One can parametrize new sources of vector $SU_2$ breaking, such as nondegenerate new fermion or scalar multiplets, or higher dimensional Higgs multiplets, by a parameter $\rho_0$, which is exactly unity in the standard model. Allowing $\delta_{bb}^{new} \neq 0$ as well, one obtains $\rho_0 = 1.0006(9)(18)$, $\alpha_s = 0.111(6)(1)$, $\delta_{bb}^{new} = 0.013(7)$, with negligible change in the other parameters. August 1996.

| Set                  | $s_Z^2$     | $\alpha_s(M_Z)$ | $m_t$ (GeV) | $\rho_0$  |
|----------------------|-------------|-----------------|-------------|-----------|
| Indirect + CDF + D0  | 0.2316(2)(  | 0.121(3)(2)    | 177 ± 5$^{+7}_{-8}$ | fixed at 1 |
|                      | 1/4         |                 |             |           |
| Indirect + CDF + D0  | 0.2315(2)(  | 0.119(4)(1)    | 173(6)     | 1.0009(9)(18) |
|                      | 1/2         |                 |             |           |

classes of new physics parameterized by $\rho_0$ one still has robust predictions for the weak angle and a good determination of $\alpha_s$. Most remarkably, given the CDF/D0 constraint, $\rho_0$ is constrained to be very close to unity, causing serious problems for compositeness models. The allowed region in $\rho_0$ vs $s_Z^2$ are shown in Figure 6. This places limits $|\langle \phi_i \rangle|/|\langle \phi_{1/2} \rangle| < \text{few }%$ on non-doublet vacuum expectation values, and places constraints $\frac{C}{\frac{2}{3}} F(m_1, m_2) \leq (100 \text{ GeV})^2$ on the splittings of additional fermion or boson multiplets.

Fig. 6. 90% CL allowed region in $\rho_0$ vs $\sin^2 \hat{\theta}_W(M_Z)$. August 1996.

4.3. The $S_{\text{new}}$, $T_{\text{new}}$, and $U_{\text{new}}$ Parameters

$S_{\text{new}}$, $T_{\text{new}}$, and $U_{\text{new}}$ generalize the $\rho_0$ parametrization of new physics. $S_{\text{new}}$
represents new sources of axial $SU_2$ breaking, such as degenerate chiral multiplets, $T_{\text{new}} = (\rho_0 - 1)/\alpha$ represents vector $SU_2$ breaking, including both tree level and loop effects, while $U_{\text{new}}$, which affects $M_W$, is small in most models. The $S_{\text{new}}, T_{\text{new}},$ and $U_{\text{new}}$ presented here are due to new physics only ($m_t$ and $M_H$ effects are treated separately), and they have a factor of $\alpha$ removed so that deviations from new physics are expected to be of order unity. The expectations for these parameters for various types of new physics and their relation to other equivalent parametrizations are given in \textsuperscript{2}. The current values of $S_{\text{new}}, T_{\text{new}},$ and $U_{\text{new}}$ and the standard model parameters are given in Table \textsuperscript{3}. The allowed regions in $S_{\text{new}}$ and $T_{\text{new}}$ are shown in Figure \textsuperscript{4}.

Table \textsuperscript{9}. Current values of $S_{\text{new}}, T_{\text{new}},$ and $U_{\text{new}}$. Fits are shown with and without $\delta_{b\bar{b}}^{\text{new}}$, and for the equivalent $\rho_0$ and $\epsilon_i$ parameters \textsuperscript{1}. The standard model (SM) parameters are also shown. August 1996.

| Parameter | SM | $\delta_{b\bar{b}}^{\text{new}} = 0$ | $\delta_{b\bar{b}}^{\text{new}}$ free |
|-----------|----|---------------------------------|----------------------------------|
| $s_Z^2$   | 0.2316(2)$^{\pm 2}_{-4}$ | 0.2313(2)$^{\pm 1}_{-0}$ | 0.2313$^0$ |
| $\alpha_s(M_Z)$ | 0.121(3)(2) | 0.121(4)$^{\pm 1}_{-0}$ | 0.112$^6$ |
| $m_t$ (GeV) | $177 \pm 5^{+7}_{-8}$ | 173$^6$ | 175$^6$ |
| $S_{\text{new}}$ | $-0.18(16)^{-8}_{+17}$ | $-0.19(16)^{-8}_{+17}$ | $-0.19(16)^{-8}_{+17}$ |
| $T_{\text{new}}$ | $-0.04(20)^{17}_{-11}$ | $-0.08(19)^{17}_{-11}$ | $-0.08(19)^{17}_{-11}$ |
| $U_{\text{new}}$ | $0.07^{42}_{-0}$ | $0.06^{42}_{-0}$ | $0.06^{42}_{-0}$ |
| $\delta_{b\bar{b}}^{\text{new}}$ | fixed at $0$ | $0.013^{7}_{-0}$ | $0.013^{7}_{-0}$ |
| $\rho_0$ | $0.9997^{12}_{-18}$ | $0.9994^{12}_{-18}$ | $0.9994^{12}_{-18}$ |
| $\epsilon_3$ | $-0.0014^{13}_{-7+13}$ | $-0.0015^{13}_{-7+13}$ | $-0.0015^{13}_{-7+13}$ |
| $\epsilon_1$ | $-0.0003^{14}_{-8}$ | $-0.0006^{13}_{-8}$ | $-0.0006^{13}_{-8}$ |
| $\epsilon_2$ | $-0.0005^{33}$ | $-0.0005^{33}$ | $-0.0005^{33}$ |

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