Implications of high precision experiments and the CDF top quark candidates

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(Received 31 October 1994)

We discuss the consequences of recent experimental results from CDF, SLC, CERN, LEP, and elsewhere for the standard model and for new physics. A global fit to all indirect precision data yields $m_t = 175 \pm 11^{+17}_{-19}$ GeV, $\sin^2\hat{\theta}_{\overline{MS}} = 0.2317(3)(2)$, and $\alpha_s = 0.127(5)(2)$, where the central values are for $M_H = 300$ GeV and the second uncertainties are for $M_H \to 1000$ GeV (+) and 60 GeV (−). The m_t value is in remarkable agreement with the value $m_t = 174 \pm 16$ GeV suggested by the CDF candidate events. There is a slight preference for a light Higgs boson with $M_H < 730$ (880) GeV at 95% C.L. if the CDF m_t value is (not) included. The sensitivity is, however, due almost entirely to the anomalously large observed values for the $Z \to b\bar{b}$ width and left-right asymmetry. The value of α_s (from the line shape) is clean theoretically assuming the standard model, but is sensitive to the presence of new physics contributions to the $Z \to b\bar{b}$ vertex. Allowing a vertex correction $\delta_{b\bar{b}}^{\rm new}$ one obtains the significantly lower value $\alpha_s = 0.111 \pm 0.009$, in better agreement with low energy determinations, and $\delta_{b\bar{b}}^{\rm new} = 0.023 \pm 0.011$. There is now enough data to perform more general fits to parameters describing new physics effects and to separate these from m_t and M_H. Allowing the parameter ρ_0, which describes sources of SU(2) breaking beyond the standard model, to be free one finds $\rho_0 = 1.0012 \pm 0.0017 \pm 0.0017$, remarkably close to unity. One can also separate the new physics contributions to the oblique parameters $S_{\rm new}$, $T_{\rm new}$, and $U_{\rm new}$, which all take values consistent with zero. The effects of supersymmetry on the determination of the standard model parameters are discussed.

PACS number(s): 12.60.−i, 12.15.Lk, 13.38.Dg, 14.65.Ha

I. INTRODUCTION

In April 1994 the Collider Detector at Fermilab (CDF) Collaboration [1] reported evidence for top quark production at the Tevatron. The collected events are consistent with a top quark (pole) mass $m_t = 174 \pm 16$ GeV. Electroweak radiative corrections to standard model (SM) observables have large m_t effects, so that its direct determination is of the upmost importance. Significant indirect bounds on the Higgs boson mass M_H can only be obtained after m_t is known independently. Top quark effects impede the setting of bounds on or the discovery of new physics beyond the standard model from precision observables. In this paper we study the implications of the m_t range suggested by the CDF candidate events for high precision measurements. For comparison, we carry out analyses of the standard model parameters with and without the CDF constraint.

Only one month prior to the announcement from Tevatron, the SLD Collaboration [2] at SLAC published a precise measurement of the left-right asymmetry A_{LR}. The polarization of the SLAC Linear Collider (SLC) electron beam was increased from 22% to 63% and the number of Z events increased by a factor of 5 compared to the 1992 run. At about the same time the CERN e^+e^- collider LEP groups [3] presented a first analysis of their 1993 data. The integrated luminosity in 1993 amounted to 40 pb^{-1}, a number only slightly smaller than the integrated luminosities from the previous years combined. Thus, the new (and preliminary) data contribute with a high statistical weight. Moreover, systematic uncertainties were significantly reduced, most notably in the total Z width, increasing the significance of the 1993 run even further.

The experimental results are summarized in Table I, together with the SM expectations using the global best fit values $m_t = 175 \pm 11$ GeV (for $M_H = 300$ GeV) and $\alpha_s = 0.127 \pm 0.005$ (see below). The three errors in the SM predictions correspond, respectively, to (1) the uncertainties in M_Z and $\alpha(M_Z)$, (2) the (correlated) uncertainties from m_t and M_H (which can vary from 60 to 1000 GeV, with a central value of 300 GeV), and (3) the uncertainty in α_s. $\sigma^0_{\rm had}$ is the bare hadronic peak cross section, i.e., the cross section at $\sqrt{s} = M_Z$ after correcting for photonic contributions. Similarly, $A^{0f}_{\rm FB} = \frac{3}{4}A^0_e A^0_f$ is the bare forward-backward asymmetry for $e^+e^- \to Z \to f\bar{f}$, $A^{0l}_{\rm FB}$ is the asymmetry for charged leptons assuming family universality (after correcting for m_τ), $\bar{s}^2_e(Q_{\rm FB})$ is the effective weak angle determined from the hadronic charge asymmetry, and $A^0_{LR} = A^0_e$ is the bare left-right polarization asymmetry. The quantity A^0_f for flavor f is defined by[1]

$$A^0_f = \frac{2\bar{g}_{V_f}\bar{g}_{A_f}}{\bar{g}^2_{V_f} + \bar{g}^2_{A_f}}. \tag{1}$$

[1] $\bar{s}^2_f$ and $\bar{g}_{V,A_f}$ are flavor-dependent effective mixing angles and vector (axial-vector) couplings. They include propagator and vertex corrections evaluated at $s = M_Z^2$.

TABLE I. Z-pole observables from LEP and SLD and other recent measurements 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 and α_s, with 60 GeV $< M_H <$ 1000 GeV. The fits include the (M_Z, Γ_Z, R, $\sigma^0_{\rm had}$, $A^{0l}_{\rm FB}$) and (R_b, R_c; $\rho = -0.4$) correlations.

Quantity	Value	Standard model
M_Z [GeV]	91.1888 ± 0.0044	input
Γ_Z [GeV]	2.4974 ± 0.0038	$2.497 \pm 0.001 \pm 0.003 \pm [0.002]$
$R = \Gamma({\rm had})/\Gamma(l^+l^-)$	20.795 ± 0.040	$20.784 \pm 0.006 \pm 0.003 \pm [0.03]$
$\sigma^0_{\rm had} = \frac{12\pi}{M_Z^2}\frac{\Gamma(e^+e^-)\Gamma({\rm had})}{\Gamma_Z^2}$ [nb]	41.49 ± 0.12	$41.44 \pm 0.004 \pm 0.01 \pm [0.02]$
$R_b = \Gamma(b\bar{b})/\Gamma({\rm had})$	0.2202 ± 0.0020	$0.2156 \pm 0 \pm 0.0004$
$R_c = \Gamma(c\bar{c})/\Gamma({\rm had})$	0.1583 ± 0.0098	$0.171 \pm 0 \pm 0$
$A^{0l}_{\rm FB} = \frac{3}{4}\left(A^0_l\right)^2$	0.0170 ± 0.0016	$0.0151 \pm 0.0005 \pm 0.0006$
$A^0_\tau\,(P_\tau)$	0.143 ± 0.010	$0.142 \pm 0.003 \pm 0.003$
$A^0_e\,(P_\tau)$	0.135 ± 0.011	$0.142 \pm 0.003 \pm 0.003$
$A^{0b}_{\rm FB} = \frac{3}{4}A^0_e A^0_b$	0.0967 ± 0.0038	$0.0994 \pm 0.002 \pm 0.002$
$A^{0c}_{\rm FB} = \frac{3}{4}A^0_e A^0_c$	0.0760 ± 0.0091	$0.071 \pm 0.001 \pm 0.001$
$\bar{s}^2_e \quad (Q_{FB})$	0.2320 ± 0.0016	$0.2322 \pm 0.0003 \pm 0.0004$
$A^0_e = A^0_{LR}$ (SLD)	0.1637 ± 0.0075 (92 + 93)	$0.142 \pm 0.003 \pm 0.003$
	$(0.1656 \pm 0.0076$ (93))	
N_ν	2.988 ± 0.023	3
M_W [GeV]	80.17 ± 0.18	$80.31 \pm 0.02 \pm 0.07$
M_W/M_Z (UA2)	0.8813 ± 0.0041	$0.8807 \pm 0.0002 \pm 0.0007$
Q_W (Cs)	$-71.04 \pm 1.58 \pm [0.88]$	$-72.93 \pm 0.07 \pm 0.04$
$g_A^{\nu e}$ (CHARM II)	-0.503 ± 0.017	$-0.506 \pm 0 \pm 0.001$
$g_V^{\nu e}$ (CHARM II)	-0.035 ± 0.017	$-0.037 \pm 0.001 \pm 0$
$s^2_W = 1 - \frac{M_W^2}{M_Z^2}$	0.2218 ± 0.0059 (CCFR)	$0.2245 \pm 0.0003 \pm 0.0013$
	0.2260 ± 0.0048 (All)	
M_H [GeV]	> 61 (LEP)	$< \begin{cases} O(600) \text{ (theory)} \\ O(800) \text{ (indirect)} \end{cases}$
m_t [GeV]	> 131 (D0)	$175 \pm 11^{+17}_{-19}$ (indirect)
	174 ± 16 (CDF)	
$\alpha_s(M_Z)$	0.123 ± 0.006 (event shapes)	$0.127 \pm 0.005 \pm 0.002 \pm [0.001]$
	0.116 ± 0.005 (event shapes + low energy)	(Z line shape)

N_ν is the number of active neutrinos (with $m_\nu \leq M_Z/2$), Q_W is the effective weak charge in atomic parity violation [4], $g^{\nu e}_{V,A}$ are effective four-fermion couplings for neutrino electron scattering [5], and $s^2_W = 1 - M_W^2/M_Z^2$ is the on-shell weak mixing angle from deep inelastic neutrino nucleon scattering [6]. Our fits include the older low energy data [7] as well.

The agreement between theory and experiment is generally excellent, with the exceptions[2] of A^0_{LR} and R_b. Of course, given the plethora of precision measurements one expects deviations at some level, and it would be premature to take the deviating quantities described below as serious problems for the SM. However, these quantities, especially R_b, have a significant effect on some of the conclusions, and so it is worthwhile to comment on them.

The left-right asymmetry A_{LR}, as measured at SLC, is the most precise single determination of the effective weak angle $\bar{s}^2_e$ [2]. SLD quotes $A_{LR}(\sqrt{s} = 91.26\text{ GeV}) = 0.1628 \pm 0.0076$. Correcting for photon exchange, electroweak interference, and initial-state radiation yields

$$A^0_{LR} = A^0_e = 0.1656 \pm 0.0076. \tag{2}$$

This corresponds to

$$\bar{s}^2_e = \frac{1}{4|Q_e|}\left(1 - \frac{\bar{g}_{V_e}}{\bar{g}_{A_e}}\right) = 0.2292 \pm 0.0010. \tag{3}$$

Inclusion of the 1992 result [9] $A^0_{LR} = 0.100 \pm 0.044$ yields combined values $A^0_{LR} = 0.1637 \pm 0.0075$ and $\bar{s}^2_e = 0.2294 \pm 0.0010$, which is about a 2.5σ deviation from global SM fits and at least 2σ from the values derived from LEP asymmetries. The 1992 + 1993 result (combined with the LEP value of M_Z) yields $m_t = 251^{+24}_{-26}$ GeV for $M_H = 300$ GeV. Relaxing the universality assumption or even allowing for the most general fermion couplings to the Z does not considerably improve the goodness of the fits [8]. Also, using results from Ref. [10]

[2]Also, the individual forward-backward (FB) τ asymmetry $A^{0\tau}_{FB} = 0.0228 \pm 0.0028$ is 2.8σ above SM expectations and renders the test of lepton universality only moderately successful. If the FB asymmetries into the three lepton species are used, one finds that universality is excluded at the 93% C.L. [8]. There is also a direct discrepancy between $A^{0\tau}_{\rm FB}$ and $A^0_\tau(\mathcal{P}_\tau)$ (which is consistent with the SM) of about 2.5σ.

it was argued in [8] that no kind of new physics can account for the SLD result without simultaneously conflicting one or several other observables, most notably the W mass. Thus assuming that these experiments are completely governed by γ and Z amplitudes we look at a direct experimental conflict. One possible loophole, namely, the presence of new effective interactions which contribute significantly to the line shape and asymmetries, is discussed in Ref. [11].

The $Z \to b\bar{b}$ vertex has long been advertised [12] as the "ideal top quark mass meter" since it is virtually independent of M_H, and the terms quadratic in m_t enter in a different way than in $\hat{\rho} \equiv M_W^2/M_Z^2 \cos^2\hat{\theta}_{\overline{\rm MS}}$ which governs other electroweak observables, where $\overline{\rm MS}$ denotes the modified minimal subtraction scheme. At the same time it is sensitive to many kinds of physics beyond the SM. The LEP groups obtain [3]

$$R_b = \frac{\Gamma(b\bar{b})}{\Gamma(\text{had})} = 0.2202 \pm 0.0020, \qquad (4)$$

from a fit with $R_c = \Gamma(c\bar{c})/\Gamma(\text{had})$ left free.[3] This is 2.3 standard deviations from the SM prediction $R_b = 0.2156 \pm 0.0004$. R_b drives the fits to smaller values of m_t, independent of M_H. Because of the correlation of top quark and Higgs boson effects in the $\hat{\rho}$ parameter, this in turn favors smaller values of M_H.

With the possible exception of these measurements, experiments and the minimal standard model are in spectacular agreement with each other.

II. RADIATIVE CORRECTIONS

One of the goals of the Z factories at SLAC and CERN is to test electroweak theory at the quantum level. m_t, M_H, and α_s enter only through radiative corrections. They are obscured by pure QED corrections, which are large but calculable and under control, with the possible exception of small-angle $O(\alpha^2)$ Bhabba scattering. Experimenters usually present data with all QED corrections other than final-state radiation removed.

The hadronic contribution[4] to the vacuum polarization [16] induces an uncertainty of 0.0003 in $\sin^2\theta_W$. Omitting this error in the global fits can change the extracted value of m_t by about 3 GeV.

QCD corrections are calculated [17] and included up to $O(\alpha_s^3)$. We did not include $O(\alpha_s^4)$ corrections, which are estimated to contribute with a negative sign and with about 0.4 MeV to the hadronic Z width [18], corresponding to an additional uncertainty of 0.001 in α_s. As pointed out in [19] the $O(\alpha_s^2)$ corrections to the vector and axial-vector parts of the partial Z width into b quarks exhibit different dependences on m_t. They are important and included along with the analogous results for the $O(\alpha_s^3)$ corrections [20]. Higher order QCD corrections proportional to m_b^2/M_Z^2 are incorporated as well [21].

As for the electroweak sector, full one-loop corrections are taken into account. Because of the heavy top quark, two-loop effects of $O(\alpha^2 m_t^4)$ are included with their full M_H dependence [22], as well as $O(\alpha\alpha_s m_t^2)$ corrections to the ρ parameter [23] and to the $Z \to b\bar{b}$ vertex [24]. Threshold effects corresponding to $O(\alpha\alpha_s^2 m_t^2)$ corrections are incorporated by making use of the detailed work of Fanchiotti, Kniehl, and Sirlin [25]. They can also be estimated [26] by employing $\alpha_s(0.15 m_t)$ rather than $\alpha_s(m_t)$. The numerical difference between the two approaches is negligible, and either way threshold effects increase the extracted top mass by about 3 GeV.

In practice we used the routine ZFITTER [27] for the calculation of form factors. The improved Born formulas were then dressed with the aforementioned QED and QCD corrections for the Z partial widths. The agreement with ZFITTER version 4.6 is excellent with differences being at the 0.1 MeV level in the total Z width. For the most important form factor $\hat{k}_e(M_Z^2)$ [see Eq. (5) below], we used the update by Gambino and Sirlin [28].

On the quantum level the exact definition of the weak mixing angle becomes ambiguous [28–36]. In addition to the conceptually most simple on-shell definition [29] $s_W^2 \equiv 1 - M_W^2/M_Z^2 = 0.2243 \pm 0.0012$, there are two other definitions[5] which are numerically very close to each other.

One is based on the coupling constants $\tan\hat{\theta}_W(M_Z) \equiv g'/g$, which are radiatively corrected according to the $\overline{\rm MS}$ prescription [32]. This makes the $\overline{\rm MS}$ quantity $\sin^2\hat{\theta}_W \equiv \hat{s}_Z^2 = 0.2317 \pm 0.0004$ particularly convenient for grand unified theory (GUT) predictions and insensitive to new physics. However, it is a quantity designed by theorists and is not related simply to any single observable. Rather, it is best determined by a global fit. Also, there are variant forms of $\hat{s}_Z^2$ which differ in the treatment of heavy top quark effects. A variant [33] in which the heavy top quark is not decoupled is a few times 10^{-4} larger [28] than the one introduced in [34]. In the latter, which is used here, the $\ln m_t$ effects in γ-Z mixing are decoupled, so that the Z-pole asymmetries are essentially

[3] We will always use the experimental values of R_b and R_c with their correlation of -0.4 [3]. Alternatively, one could use the value $R_b = 0.2192 \pm 0.0018$, obtained [3] by fixing R_c to its SM value of 0.171. We have checked that the two methods yield virtually identical results.

[4] After the submission of the original version of this paper, three new calculations of this contribution appeared [13–15]. Two of these agree within uncertainties with the estimate used here. The central value of the third [13] is 1.9σ away from the old calculation. The major effect of this most extreme new estimate is to lower the predicted value of m_t by 7–10 GeV, depending on the fit. The effects on other parameters are largely compensated by the shifted m_t and are therefore small. These issues are currently under further investigation.

[5] Yet another definition $s_{M_Z}^2 = 0.2312 \pm 0.0003$ is obtained by removing the m_t dependence from the expression for M_Z [30]. The m_t uncertainty reenters when other observables are expressed in terms of $s_{M_Z}^2$. The various definitions are further discussed in [31].

independent of m_t.

The other is the effective mixing angle [35] defined in Eq. (3), with analogous definitions for other flavors. It is defined through observables (the Z-pole asymmetries), which makes it conceptually simple, but for the exact relation to other quantities a computer code is needed due to the need to compute three-point functions. That also makes it difficult to relate $\bar{s}_e^2$ to non-Z-pole observables.

The two definitions above share a smaller sensitivity to m_t compared to the on-shell s_W^2. For the relation between s_W^2 (or M_W), $\hat{s}_Z^2$, and M_Z we rely on Ref. [25].[6] $\hat{s}_Z^2$ and $\bar{s}_e^2$ are related by

$$\bar{s}_e^2 = \hat{s}_Z^2 \text{Re}\, \hat{k}_e(M_Z^2), \tag{5}$$

with the form factor Re $\hat{k}_e(M_Z^2)$ from Ref. [28]. Relation (5) is a very good approximation due to the smallness of Im $\hat{k}_e(M_Z^2)$. For m_t in the relevant range, (5) implies

$$\bar{s}_e^2 \sim \hat{s}_Z^2 + 0.00028. \tag{6}$$

III. FIT RESULTS

We regard the deviations in some of the observables as consistent with statistical fluctuations and have therefore refrained from using scale factors to increase error bars, and instead simply combined the data.[7]

Table II summarizes the results of various fits to $\hat{s}_Z^2$, $\alpha_s(M_Z)$, and m_t based on different data sets. The central values[8] correspond to $M_H = 300$ GeV and the second errors indicate the results for $M_H = 1000$ GeV (+) and $M_H = 60$ GeV (−). The increase in χ^2 when changing M_H from 60 to 1000 GeV, $\Delta\chi_H^2 \equiv \chi^2(1000) - \chi^2(60)$, is also indicated. The first row is the fit to all indirect precision data.[9] The prediction $m_t = 175 \pm 11^{+17}_{-19}$ GeV is in remarkable agreement with the CDF value 174 ± 16 GeV. Not surprisingly, including the CDF value as an additional constraint (second row) has little impact on the global fit within the standard model. It will, however, be of great importance in non-standard-model fits. The third row is a fit in which the indirect data are combined with the additional constraint $\alpha_s(M_Z) = 0.116 \pm 0.005$ obtained from data other than the Z line shape [37]. As expected, the extracted α_s (which can be regarded as a simultaneous fit to the line shape and other α_s data) is somewhat lower than the value from the line shape alone. The other rows are fits to subsets of the data, which show the sensitivity to the various inputs. From the fourth row (LEP + low energy) we see that the predicted m_t is 7 GeV lower without A_{LR} from SLD, while when averaging A_e^0 from A_{LR}^0 and from $\mathcal{P}_\tau$ with a scale factor of 2.2 (fifth row) it is lower by 5 GeV. The results from the Z pole (LEP + SLD), LEP, and SLD + M_Z are also shown. The large value of m_t in the last case reflects the high value of A_{LR}^0.

It is useful to compare these results with the fits performed by the LEP electroweak working group [3]. Their fits for Z-pole, M_W, and recent neutrino data (which corresponds roughly to our first "all indirect" fit), as well as

TABLE II. Results for the electroweak parameters in the standard model from various sets of data. The central values assume $M_H = 300$ GeV, while the second errors are for $M_H \to 1000$ GeV (+) and 60 GeV (−). The last column is the increase in the overall χ^2 to the fit as the Higgs boson mass increases from 60 to 1000 GeV. The last two rows are the results of fits performed by the LEP electroweak working group (LEP-EWG), with the appropriate translation of $\bar{s}_e^2$ into $\hat{s}_Z^2$.

Set	$\hat{s}_Z^2$	$\alpha_s(M_Z)$	m_t [GeV]	$\Delta\chi_H^2$
All indirect	$0.2317(3)(^1_2)$	0.127(5)(2)	$175 \pm 11^{+17}_{-19}$	4.4
Indirect + CDF (174 ± 16)	$0.2317(3)(^2_3)$	0.127(5)(2)	$175 \pm 9^{+12}_{-13}$	4.4
Indirect + α_s (0.116 ± 0.005)	$0.2316(3)(^1_2)$	0.122(3)(1)	$178^{+10}_{-11}{}^{+17}_{-19}$	6.0
LEP + low energy	0.2320(3)(2)	0.128(5)(2)	$168^{+11}_{-12}{}^{+17}_{-19}$	2.7
All indirect ($S = 2.2$)	$0.2319(3)(^1_2)$	0.128(5)(2)	$170^{+11}_{-12}{}^{+17}_{-19}$	3.3
Z pole	0.2316(3)(1)	0.126(5)(2)	$179^{+11}_{-12}{}^{+17}_{-19}$	4.2
LEP	$0.2320(4)(^1_2)$	0.128(5)(2)	$170^{+12}_{-13}{}^{+18}_{-20}$	2.6
SLD + M_Z	0.2291(10)(0)	—	$251^{+24}_{-26}{}^{+21}_{-23}$	—
Z pole, M_W, recent ν (LEP-EWG)	$0.2317(3)(^0_2)$	0.125(5)(2)	$178 \pm 11^{+18}_{-19}$	
LEP (LEP-EWG)	$0.2319(4)(^1_2)$	0.126(5)(2)	$173^{+12}_{-13}{}^{+18}_{-20}$	

[6] We are indebted to Bernd Kniehl, who made his computer code on which the numerical results of Ref. [25] are based available to us.

[7] A scale factor of 2.2 for the uncertainties in A_e from A_{LR} and $\mathcal{P}_\tau$, as suggested by the Particle Data Group [37], would decrease the value of m_t predicted by the indirect data by 5 GeV.

[8] The predictions in Table I, especially for $\bar{s}_e^2(Q_{\rm FB})$, differ slightly from the values at the best fit point, because the former use the central value of $\alpha^{-1}(M_Z) = 127.9 \pm 0.1$ [25], incorporating the ± 0.1 in the first listed uncertainty, while the best fit occurs at $\alpha^{-1}(M_Z) = 128.0$.

[9] The overall χ^2 is 181 for 206 DF. This is rather low (mainly due to the earlier neutral current data), but statistically acceptable: The probability of $\chi^2 \le 181$ is 10%. The correlation coefficients are $\rho_{\hat{s}_Z^2 \alpha_s} = 0.30$, $\rho_{\hat{s}_Z^2 m_t} = -0.67$, $\rho_{\alpha_s m_t} = -0.20$. The correlations for the other data sets are similar.

to the LEP data are displayed in the last two rows of Table II. The agreement between their results and ours is excellent, with the small (correlated) differences in α_s and m_t a reflection of the completely independent implementation of radiative corrections.

There is a slight preference for a light Higgs boson (as is predicted in the minimal supersymmetric extension of the SM) but it is weak statistically. Combining all indirect data we can set an upper limit on $M_H < 570$ (880) GeV at the 90% (95%) C.L. Adding the CDF result this limit is strengthened to $M_H < 510$ (730) GeV. Moreover, the preference is driven mainly by the anomalous values of R_b and A_{LR}. Removing them from the data set leads to an almost flat χ^2 distribution with respect to M_H, as is shown in Fig. 1. Hence, caution is called for in drawing any conclusion on M_H from the present data.

In the context of the SM, $R = \Gamma(\text{had})/\Gamma(l^+l^-)$ is a theoretically clean measurement of $\alpha_s(M_Z)$. In the presence of new physics which increases the hadronic or $b\bar{b}$ event sample, however, R loses its sensitivity to the strong coupling constant. Similar remarks hold for Γ_Z, which is also sensitive to α_s. In 1993 the LEP groups collected data at the Z peak and at ± 1.8 GeV away from the peak. That allowed for a precise measurement of the Z line shape. The extracted Γ_Z is about one standard deviation higher than in 1992 and the error decreased by almost 50%. It should be noted, however, that a line shape scan involving only three scan points cannot by itself be sensitive to any non-Z-pole contribution to the cross section. An overconstrained line shape fit is only possible when the lower statistics 1990–1991 scan is included.

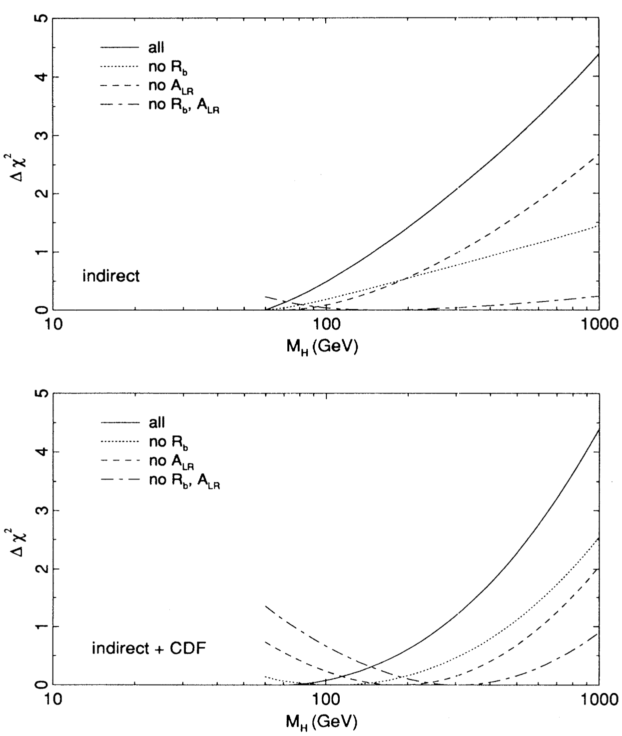

FIG. 1. Increase in χ^2 from the best fit for all data, with and without the CDF constraint $m_t = 174 \pm 16$ GeV, and distributions omitting R_b and/or A_{LR}.

The extracted value of $\alpha_s = 0.127 \pm 0.005 \pm 0.002$ is consistent with the LEP jet event shape analysis, which yields $\alpha_s = 0.123 \pm 0.006$, and with the value 0.122 ± 0.005 from the hadronic τ decay fraction [37–39]. It is also in perfect agreement with grand desert supersymmetric (SUSY) grand unified theory (GUT) expectations, favoring $\alpha_s = 0.127 \pm 0.002 \pm 0.008$, where the first error is due to m_t and M_H and the second arises from the lack of knowledge of the sparticle and GUT particle spectra (thresholds) and from the unknown effects of possible nonrenormalizable operators [40]. It is, however, significantly higher than the values [37–39] obtained from deep inelastic neutrino and lepton scattering (0.112 ± 0.005), from J/ψ and Υ decays (0.113 ± 0.006), and from determinations relying on lattice calculations of the charmonium (0.110 ± 0.006) [41] and bottomonium (0.115 ± 0.002) [42] spectra. (The lower energy determinations must of course be extrapolated to M_Z.) As will be discussed in the next section, if one allows for the possibility of new physics in the $Zb\bar{b}$ vertex to account for R_b, the extracted value of α_s decreases to a lower value ($0.111 \pm 0.009 \pm 0.001$) consistent with these latter values.

IV. NEW PHYSICS

In this section we describe the effects on the fits when additional parameters describing new physics are allowed for. We mention the two most popular classes of new physics which are currently under discussion, namely, supersymmetry and compositeness ideas, and give our fit results for the minimal supersymmetric standard model (MSSM). A more detailed discussion can be found, e.g., in [43]. We then introduce our new physics parameters, namely, S, T (ρ_0), U, and $\delta^b_{L/R}$ ($\delta^{\text{new}}_{b\bar{b}}$). Finally, we present and discuss our results.

In the context of the MSSM and all its extensions under discussion, the lightest Higgs eigenstate is known to be light, in the range 60 GeV $< M_H <$ 150 GeV. Taking as a central value $M_H = M_Z$ the extracted top mass is lowered to $m_t = 160^{+11}_{-12}\,^{+6}_{-5}$ GeV because of the strong m_t-M_H correlation.[10] In most parts of the MSSM parameter space, i.e., whenever the sparticles and second Higgs doublet are much heavier than M_Z, the decoupling theorem applies and the only signs of supersymmetry in the precision observables are a light Higgs boson and the *absence* of deviations from the SM.

On the contrary, in extended technicolor (ETC) and compositeness models we expect a variety of effects, most notably the observation of large flavor-changing neutral currents (FCNC's). As an example, in models with composite fermions, the effective four-Fermi operators formed by constituent interchange have to be strongly suppressed. If we call the compositeness scale Λ, so that a four-Fermi operator takes the form

[10]The other parameters are $\hat{s}^2_Z = 0.2316(3)(1)$ and $\alpha_s = 0.126(5)(1)$.

$$L = \pm\frac{4\pi}{\Lambda^2}\bar{f}_1\Gamma f_2\bar{f}_3\hat{\Gamma}f_4, \tag{7}$$

from FCNC's we must require $\Lambda \gtrsim 100$ TeV unless a fine-tuning is invoked. Even then, atomic parity violation experiments set lower limits [44] $\Lambda \gtrsim 10$ TeV. They are expected to be increased to ~ 40 TeV with upcoming experiments. In ETC models, again contrary to observations, R_b is usually expected to be below the SM value. Other predictions, at least of the simplest versions based on scaled-up QCD dynamics, are $S_{\rm new} > 0$ and $T_{\rm new} \neq 0$, neither of which are in conformity with the data (see below).

It has become customary to use three quantities, e.g., S, T, and U [45], to parametrize the flavor-independent oblique radiative corrections, or a single parameter ρ_0, to characterize new sources of SU(2) breaking. In addition, new physics may in particular affect the $Z \to b\bar{b}$ vertex [46]. In the past it was difficult to disentangle possible new physics effects from the dominant top mass contributions. With the new CDF result for m_t, however, it is now possible to clearly determine the new physics effect from the data.

For our analyses we introduce the new variables $S_{\rm new}$, $T_{\rm new}$, and $U_{\rm new}$ via

$$\begin{aligned} S &= S_{\rm new} + S_{m_t} + S_{M_H}, \\ T &= T_{\rm new} + T_{m_t} + T_{M_H}, \\ U &= U_{\rm new} + U_{m_t}, \end{aligned} \tag{8}$$

where S_{m_t} and S_{M_H} are, respectively, the m_t and M_H contributions to S, and similarly for T and U. The effects of S, T, and U on the SM expressions for observables are given in [47]. A recent discussion of the predictions of technicolor models when compared with precision electroweak data is given in [48].

We parametrize the new physics entering the $Z \to b\bar{b}$ width by $\delta_{b\bar{b}}^{\rm new}$, defined by [46]

$$\Gamma_{b\bar{b}} = \Gamma_{b\bar{b}}^{\rm SM}(1 + \delta_{b\bar{b}}^{\rm new}). \tag{9}$$

$\delta_{b\bar{b}}^{\rm SUSY}$ for the MSSM was computed in Ref. [49] and found to be positive or negative depending on the part of parameter space considered. If the experimental deviation of $\Gamma_{b\bar{b}}$ from the SM is to be explained by supersymmetry, then there must be one sparticle light enough to be detected soon [50]. In typical ETC models and in particular in the explicit model by Appelquist and Terning [51] in which the ETC gauge bosons are weak singlets and no fine-tuning occurs, $\delta_{b\bar{b}}^{\rm ETC}$ is negative and proportional to m_t [52]. In models in which the ETC gauge bosons are weak doublets, the sign in the corresponding contribution to $\delta_{b\bar{b}}^{\rm ETC}$ is reversed. However, there is a competing effect from weak gauge boson mixing which tends to cancel the former. Hence, a model-independent statement about the sign and the size of $\delta_{b\bar{b}}^{\rm ETC}$ in this class of models is not possible [53]. $\delta_{b\bar{b}}^{\rm new}$ may also be used to set limits on the admixture of extra particles such as an additional [SU(2) singlet] D_L quark, since b_L-D_L mixing reduces $\Gamma_{b\bar{b}}$ [10]. In the fits $\delta_{b\bar{b}}^{\rm new}$ affects and is determined by R_b, R, Γ_Z, and $\sigma_{\rm had}^0$.

One can also study the quantity

$$\rho_0 \equiv \rho_0^{\rm tree} + \rho_0^{\rm loop} \equiv 1 + \alpha T_{\rm new}, \tag{10}$$

which describes nonstandard sources of (vector) SU(2) breaking. In the standard model, by definition $\rho_0 = 1$. That is, ρ_0 is a ρ parameter with all standard model contributions corresponding to the fit value of m_t and to $M_H = 300$ GeV removed. If $\rho_0 \neq 1$, one has to replace

$$\begin{aligned} M_Z &\to \frac{1}{\sqrt{\rho_0}} M_Z^{\rm SM}, \\ \Gamma_Z &\to \rho_0 \Gamma_Z^{\rm SM}, \\ \mathcal{L}_{\rm NC} &\to \rho_0 \mathcal{L}_{\rm NC}^{\rm SM}, \end{aligned} \tag{11}$$

where $\mathcal{L}_{\rm NC}$ is a neutral current amplitude (effective Lagrangian). $\rho_0^{\rm tree}$ differs from unity in the presence of Higgs triplets or higher Higgs representations,

$$\rho_0^{\rm tree} = \frac{\sum_i (t_i^2 - t_{3i}^2 + t_i)|\langle\phi_i\rangle|^2}{\sum_i 2t_{3i}^2|\langle\phi_i\rangle|^2}, \tag{12}$$

where t_i and t_{3i} are the weak isospin and its third component of the neutral Higgs field ϕ_i. $\rho_0^{\rm loop}$ gets a positive definite[11] contribution in the presence of additional nondegenerate scalar or fermion doublets [54],

$$\rho_0^{\rm loop} = \frac{3G_F}{8\sqrt{2}\pi^2}\sum_i \frac{C_i}{3} F(m_{1i}, m_{2i}), \tag{13}$$

where C_i is the color factor and F a positive function of the internal particle masses which vanishes for $m_1 = m_2$. In typical (level 1) superstring models and in grand desert SUSY-GUT models ρ_0 is close to 1, while $\rho_0 \neq 1$ in most compositeness models. Allowing $\rho_0 \neq 1$ is a special case of the $S_{\rm new}$, $T_{\rm new}$, $U_{\rm new}$ parametrization, corresponding to $S_{\rm new} = U_{\rm new} = 0$ and $\rho_0 = 1 + \alpha T_{\rm new}$. (Higher-dimensional Higgs representations are technically not included in the standard definition of $T_{\rm new}$. In practice, however, they cannot be distinguished from oblique contributions from the precision observables alone, and so we will include both in our definition of $T_{\rm new}$.)

With the CDF result we can now simultaneously determine $\hat{s}_Z^2$, α_s, and m_t as well as a variety of parameters describing physics beyond the SM. Table III shows the results of various fits, allowing for different parameters left free. In these fits m_t comes mainly from the direct CDF result and $\hat{s}_Z^2$ from the asymmetries, and since (given the value of M_Z) they are consistent with each other in the SM, they are largely insensitive to the presence of the new physics parameters. With them $T_{\rm new}$ can be extracted from Γ_Z, $S_{\rm new}$ is determined by M_Z, and $U_{\rm new}$ from M_W. These observables are only weakly correlated, with one important exception. When $\delta_{b\bar{b}}^{\rm new}$ is left free the large observed value of R_b drives it significantly to posi-

[11] Nondegenerate multiplets involving Majorana fermions or scalars with nonzero vacuum expectation values can give contributions of either sign.

TABLE III. Results for the electroweak parameters including additional fit parameters describing physics beyond the SM. All fits include the CDF constraint $m_t = 174 \pm 16$ GeV. The central values are for $M_H = 300$ GeV, the upper second errors for $M_H = 1000$ GeV, and the lower ones for $M_H = 60$ GeV. For $T_{\rm new}$ we also list the equivalent $\rho_0 \equiv 1 + \alpha T_{\rm new}$.

$\hat{s}^2_Z$	$\alpha_s(M_Z)$	m_t [GeV]	$S_{\rm new}$	$T_{\rm new}$ (ρ_0)	$U_{\rm new}$	$\delta^{\rm new}_{b\bar{b}}$
0.2317(3)(3)	0.127(5)(2)	$175 \pm 9^{+12}_{-13}$	—	—	—	—
0.2316(3)(2)	0.111(9)(0)	$177 \pm 9 \pm 13$	—	—	—	$0.023 \pm 0.011 \pm 0.003$
0.2316(3)(1)	0.125(6)(1)	$166 \pm 15 \pm 0$	—	$0.16 \pm 0.23 \pm 0.23$ (1.0012(17)(17))	—	—
0.2316(3)(2)	0.111(9)(0)	$174 \pm 16^{+1}_{-0}$	—	$0.05 \pm 0.25 \pm 0.25$ (1.0004(18)(18))	—	$0.022 \pm 0.011 \pm 0$
0.2314(4)(1)	0.125(6)(0)	$167 \pm 15 \pm 0$	$-0.21 \pm 0.24^{-0.08}_{+0.17}$	$0.03 \pm 0.30^{+0.17}_{-0.10}$ $(1.0002(22)(^{12}_{7}))$	-0.50 ± 0.61	—
0.2313(4)(1)	0.112(9)(0)	$175 \pm 16 \pm 0$	$-0.21 \pm 0.24^{-0.08}_{+0.17}$	$-0.09 \pm 0.32^{+0.16}_{-0.11}$ $(0.9993(23)(^{12}_{8}))$	-0.53 ± 0.61	$0.022 \pm 0.011 \pm 0$

tive values. In this case the theoretical expression for the hadronic partial Z width is modified according to

$$\Gamma(\text{had}) = \Gamma(\text{had})^{\rm SM} + \Gamma^{\rm SM}_{b\bar{b}}\delta^{\rm new}_{b\bar{b}}. \tag{14}$$

On the other hand α_s is mainly determined by

$$R = \frac{\Gamma^0(\text{had})(1+\delta_{\rm QCD}) + \Gamma^{\rm SM}_{b\bar{b}}\delta^{\rm new}_{b\bar{b}}}{\Gamma(l^+l^-)}, \tag{15}$$

where Γ^0(had) denotes the standard model hadronic partial width with the QCD correction $\delta_{\rm QCD} \approx \alpha_s/\pi$ removed. Hence, we find a change[12] in the extracted value for α_s of

$$\Delta\alpha_s \approx -\pi R_b \delta^{\rm new}_{b\bar{b}} \approx -0.015, \tag{16}$$

and the error is enlarged. The correlation between $\delta_{b\bar{b}}$ and α_s was already noticed by Blondel and Verzegnassi [55], who could only use R_b to extract independent information on m_t. Now, with the input of m_t from CDF, we observe a significant effect on the determination of α_s.

Before the announcement of the CDF top quark candidates the oblique parameters S, T, and U could only be discussed relative to some arbitrary reference value of m_t. In particular, it was difficult to separate the effects of a heavy top on T (or equivalently on ρ_0) from those of new physics.[13] Including the CDF top quark mass range such a separation became feasible, and from Table III we see that ρ_0 is remarkably close to unity, leaving little room for any new physics which contributes to it. The allowed regions in ρ_0 vs $\hat{s}^2_Z$ from various observables and the global fit are shown in Fig. 2. Similarly, $S_{\rm new}$, $T_{\rm new}$, and $U_{\rm new}$ are well constrained and consistent with zero.[14] The global fit yields a negative central value for $S_{\rm new}$, but consistent with 0 at 1σ. This is in contrast to $S < 0$, as was suggested by earlier data. (A^0_{LR} by itself does favor $S < 0$.) The allowed region in $S_{\rm new}$ and $T_{\rm new}$ is shown in Fig. 3.

So far, we have allowed for new physics in the $Zb\bar{b}$ vertex only by an overall factor in (9). This implicitly assumes that the relative contributions to the vector and axial-vector vertices are such that there is little effect on $A^{0b}_{\rm FB}$. Indeed, $A^{0b}_{\rm FB}$ can be seen in Table I to be in good agreement with the SM expectation. However, one can do a more detailed analysis [57–59] by allowing separate corrections to the left- and right-handed couplings; i.e., the (lowest order) couplings are replaced by

$$\begin{aligned} g_{Lb} &= \tfrac{1}{2}(g_{Vb} + g_{Ab}) \to -\tfrac{1}{2} + \tfrac{1}{3}\sin^2\theta_W + \delta^b_L, \\ g_{Rb} &= \tfrac{1}{2}(g_{Vb} - g_{Ab}) \to \tfrac{1}{3}\sin^2\theta_W + \delta^b_R. \end{aligned} \tag{17}$$

From a global fit we obtain

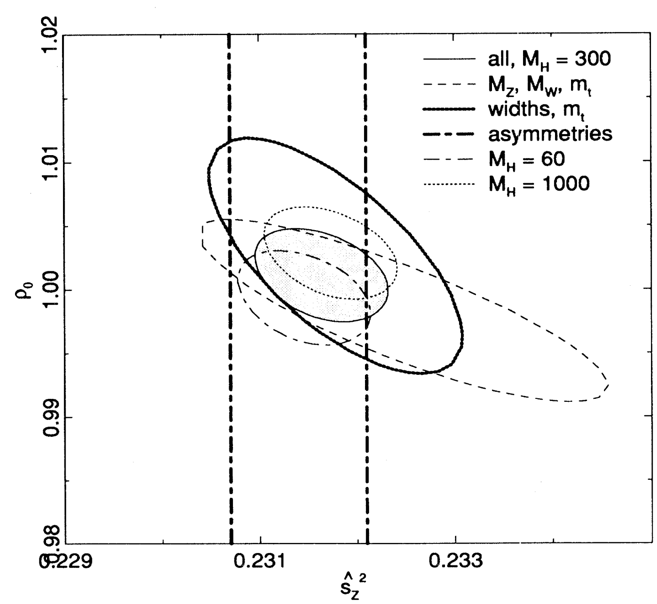

FIG. 2. Allowed regions at 90% C.L. in ρ_0 and $\hat{s}^2_Z$ from the Z-pole asymmetries; the Z widths (and CDF m_t); and M_Z, M_W, and m_t, assuming $M_H = 300$ GeV. Also shown are the allowed regions for all data, including the CDF m_t, for $M_H = 60$, 300, and 1000 GeV.

[12]The same effect on α_s would be obtained if one used the measured value of R_b rather than the standard model formula in the expression for Γ(had).

[13]Some separation was possible using R_b [55] and, earlier, by using Γ_Z and Γ(had), which include the $b\bar{b}$ contribution [56].

[14]The oblique parameters are defined with a factor α factored out so that they are expected to be of order unity if nonzero.

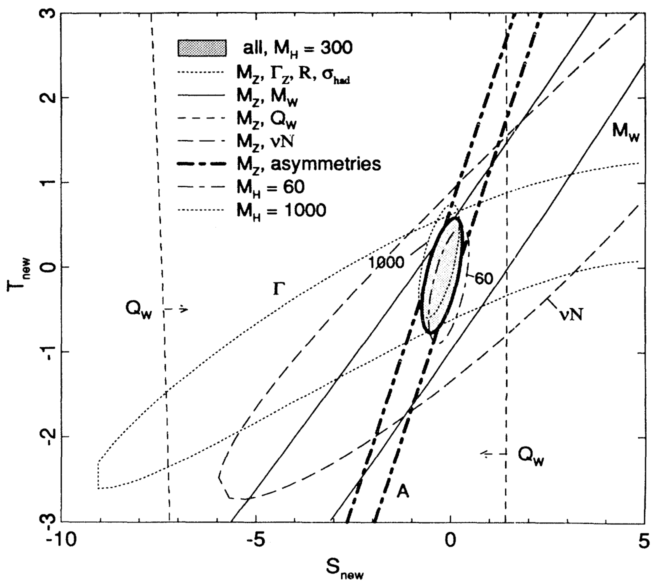

FIG. 3. Allowed regions at 90% C.L. in $S_{\rm new}$ and $T_{\rm new}$ for various observables. The fit to M_Z, M_W assumes $U_{\rm new} = 0$, but $U_{\rm new}$ is left as a free parameter in the other cases. The fits to all data are shown for $M_H = 60$, 300, and 1000 GeV. The CDF m_t constraint is always included in the fits.

$$\delta_L^b = 0.0003 \pm 0.0047,$$
$$\delta_R^b = 0.026 \pm 0.018, \tag{18}$$

with a correlation of 0.86. This result can be understood in the following way: The $Zb\bar{b}$ width and $A_{\rm FB}^{0b}$ are, respectively, proportional to $g_{Lb}^2 + g_{Rb}^2$ and $(g_{Lb}^2 - g_{Rb}^2)/(g_{Lb}^2 + g_{Rb}^2) \sim 1 - 2g_{Rb}^2/g_{Lb}^2$, where the last form follows from the fact that $g_{Rb}^2 \ll g_{Lb}^2$ in the standard model and reasonable deviations. R_b is about 2.3σ above the standard model prediction, while $A_{\rm FB}^{0b}$ is consistent with the prediction but is about 0.5σ below. Clearly, $A_{\rm FB}^{0b}$ does not by itself require a nonzero $\delta_{L,R}^b$, but does suggest that any increase in R_b is most likely due to an increase in g_{Rb}^2 rather than in g_{Lb}^2 (despite the fact that the coefficient of δ_L^b, from the standard model contribution to g_{Lb}, is about 5 times larger in magnitude than that of δ_R^b). The large correlation coefficient is due to the relatively poor determination of $A_{\rm FB}^{0b}$ and its closeness to the standard model prediction.

V. SUMMARY

The indirect determination of $m_t = 175 \pm 11^{+17}_{-19}$ GeV (for $M_H = 300^{+700}_{-240}$ GeV) is in spectacular agreement with the CDF range, $m_t = 174 \pm 16$ GeV, while the somewhat lower value $160^{+11}_{-12}{}^{+6}_{-5}$ expected in supersymmetry is still in reasonable agreement. Also most other observables are in excellent agreement with the predictions of the standard model. One exception is that the left-right asymmetry is in direct conflict with LEP asymmetries. α_s determinations from LEP [0.127(5)(2) from the line shape, 0.123(6) from jets, and 0.122(5) from R_τ] are significantly higher than the ones performed at lower energies. The $Z \to b\bar{b}$ partial width exceeds the standard model value by about 2.3 standard deviations. Interestingly, new physics which can account for $\delta_{b\bar{b}}^{\rm new}$ would simultaneously decrease the extracted α_s from R, bringing it in closer agreement with other measurements. It remains to be seen to what extent these deviations and the one in $A_{\rm FB}^{0\tau}$ persist in the future.

Inclusion of the CDF result does not alter the standard model fits significantly. It is, however, very useful in constraining new types of physics: One can now separate the effects of new physics from m_t. E.g, ρ_0, which describes sources of vector SU(2) breaking beyond the SM, is now known to be very close to and consistent with the SM value (of unity), $\rho_0 = 1.0012 \pm 0.0017 \pm 0.0017$. The same is true for all the oblique parameters. High precision experiments continue to prefer nonpositive values for $S_{\rm new}$ and a vanishing $T_{\rm new}$, but there is no longer a significant indication of $S_{\rm new} < 0$. This is in contrast with standard ETC and/or compositeness models, but is consistent with most of the parameter space of minimal supersymmetry. The new data show a slight preference for a light Higgs boson mass close to the direct lower bound, but this is weak statistically. One finds $M_H < 510$ (730) GeV at 90% (95%) C.L. It should be kept in mind, however, that this limit depends almost entirely on R_b and A_{LR}^0, both of which are high compared to the SM.

ACKNOWLEDGMENTS

We are happy to thank Wolfgang Hollik, Bernd Kniehl, and Alberto Sirlin for discussions. This work was supported by the Texas National Laboratory Research Commission and by the U.S. DOE under Contract No. DE-AC02-76-ERO-3071. One of us (J.E.) was supported in part by the Deutsche Forschungsgemeinschaft.

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