

## ELECTROWEAK PHYSICS\*

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The results of high precision weak neutral current (WNC),  $Z$ -pole, and high energy collider electroweak experiments have been the primary prediction and test of electroweak unification. The electroweak program is briefly reviewed from a historical perspective. The current status and the implications for the standard model and beyond are discussed.

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**1. The  $Z$ , the  $W$ , and the weak neutral current**

The weak neutral current was a critical prediction of the electroweak standard model (SM) [1,2]. Following its discovery in 1973 by the Gargamelle and HPW experiments, there were generations of ever more precise WNC experiments, typically at the few % level. These included pure weak  $\nu N$  and  $\nu e$  scattering processes, and weak-electromagnetic interference processes such as polarized  $e^{\uparrow\downarrow}D$  or  $\mu N$ ,  $e^+e^- \rightarrow$  (hadron or charged lepton) cross-sections and asymmetries below the  $Z$ -pole, and parity-violating effects in heavy atoms (APV). There were also early direct observations of the  $W$  and  $Z$  by UA1 and UA2. The early 1990's witnessed the very precise  $Z$ -pole experiments at LEP and the SLC, in which the lineshape, decay modes, and various asymmetries were measured at the 0.1% level. The subsequent LEP 2 program at higher energies measured  $M_W$ , searched for the Higgs and other

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new particles, and constrained anomalous gauge self-interactions. Parallel efforts at the Tevatron by CDF and DØ led to the direct discovery of the  $t$  and measurements of  $m_t$  and  $M_W$ , while a fourth generation of weak neutral current experiments continued to search for new physics to which the (more precise)  $Z$ -pole experiments were blind. The program was supported by theoretical efforts in the calculation of QCD, electroweak, and mixed radiative corrections; the expectations for observables in the standard model, large classes of extensions, and alternative models; and global analyses of the data.

The precision program has established that the standard model (SM) is correct and unique to first approximation, establishing the gauge principle as well as the SM gauge group and representations; shown that the SM is correct at loop level, confirming the basic principles of renormalizable gauge theory and allowing the successful prediction or constraint on  $m_t$ ,  $\alpha_s$ , and the Higgs mass  $M_H$ ; severely constrained new physics at the TeV scale, with the ideas of unification favored over TeV-scale dynamics or compositeness; and yielded precise values for the gauge couplings, consistent with (super-symmetric) gauge unification.

## 2. Results before the LEP/SLD era

Even before the beginning of the  $Z$ -pole experiments at LEP and SLC in 1989, the precision program had established [2, 5]:

- Global analyses of all data carried more information than the analysis of individual experiments, but care has to be taken with systematic and theoretical uncertainties.
- The SM is correct to first approximation. The four-fermion operators for  $\nu q$ ,  $\nu e$ , and  $e q$  were uniquely determined, in agreement with the standard model, in model (*i.e.*, gauge group) independent analyses. The  $W$  and  $Z$  masses agreed with the expectations of the  $SU(2) \times U(1)$  gauge group and canonical Higgs mechanism, eliminating more complicated alternative models with the same four-fermi interactions as the standard model.
- QCD evolved structure functions and electroweak radiative corrections were necessary for the agreement of theory and experiment.
- The weak mixing angle (in the on-shell renormalization scheme) was determined to be  $\sin^2 \theta_W = 0.230 \pm 0.007$ ; consistency of the various observations, including radiative corrections, required  $m_t < 200$  GeV.
- Theoretical uncertainties, especially in the  $c$  threshold in deep inelastic weak charge current (WCC) scattering, dominated.

- The combination of WNC and WCC data uniquely determined the SU(2) representations of all of the known fermions, *i.e.*,  $\nu_e$  and  $\nu_\mu$ , as well as the L and R components of the  $e$ ,  $\mu$ ,  $\tau$ ,  $d$ ,  $s$ ,  $b$ ,  $u$ , and  $c$  [6]. In particular, the left-handed  $b$  and  $\tau$  were the lower components of SU(2) doublets, implying unambiguously that the  $t$  quark and  $\nu_\tau$  had to exist. This was independent of theoretical arguments based on anomaly cancellation (which could have been evaded in alternative models involving a vector-like third family), and of constraints on  $m_t$  from electroweak loops.
- The electroweak gauge couplings were well-determined, allowing a detailed comparison with the gauge unification predictions of the simplest grand unified theories (GUT). Ordinary SU(5) was excluded (consistent with the non-observation of proton decay), but the supersymmetric extension was allowed, “perhaps even the first harbinger of supersymmetry” [4].
- There were stringent limits on new physics at the TeV scale, including additional  $Z'$  bosons, exotic fermions (for which both WNC and WCC constraints were crucial), exotic Higgs representations, leptoquarks, and new four-fermion operators.

### 3. The LEP/SLC era

The LEP/SLC era greatly improved the precision of the electroweak program. It allowed the differentiation between non-decoupling extensions to the SM (such as most forms of dynamical symmetry breaking and other types of TeV-scale compositeness), which typically predicted several % deviations, and decoupling extensions (such as most of the parameter space for supersymmetry), for which the deviations are typically 0.1%.

The first phase of the LEP/SLC program involved running at the  $Z$ -pole,  $e^+e^- \rightarrow Z \rightarrow \ell^+\ell^-$ ,  $q\bar{q}$ , and  $\nu\bar{\nu}$ . During the period 1989–1995 the four LEP experiments ALEPH, DELPHI, L3, and OPAL at CERN observed  $\sim 2 \times 10^7$   $Z$  bosons. The SLD experiment at the SLC at SLAC observed some  $5 \times 10^5$  events. Despite the much lower statistics, the SLC had the considerable advantage of a highly polarized  $e^-$  beam, with  $P_{e^-} \sim 75\%$ . There were quite a few  $Z$ -pole observables, including:

- The lineshape:  $M_Z$ ,  $\Gamma_Z$ , and the peak cross-section  $\sigma$ .
- The branching ratios for  $e^+e^-$ ,  $\mu^+\mu^-$ ,  $\tau^+\tau^-$ ,  $q\bar{q}$ ,  $c\bar{c}$ ,  $b\bar{b}$ , and  $s\bar{s}$ . One could also determine the invisible width,  $\Gamma(\text{inv})$ , from which one can derive the number  $N_\nu = 2.985 \pm 0.009$  of active (weak doublet) neutrinos with  $m_\nu < M_Z/2$ , *i.e.*, there are only 3 conventional families

with light neutrinos.  $\Gamma(\text{inv})$  also constrains other invisible particles, such as light sneutrinos and the light majorons associated with some models of neutrino mass.

- A number of asymmetries, including forward–backward (FB) asymmetries; the  $\tau$  polarization,  $P_\tau$ ; the polarization asymmetry  $A_{\text{LR}}$  associated with  $P_{e^-}$ ; and mixed polarization-FB asymmetries.

The expressions for the observables are summarized in [1, 2], and the experimental values and SM predictions in Table I. The precision of the  $Z$  mass determination was extraordinary for a high energy experiment. These combinations of observables could be used to isolate many  $Z$ -fermion couplings, verify lepton family universality, determine  $\sin^2 \theta_W$  in numerous ways, and determine or constrain  $m_t$ ,  $\alpha_s$ , and  $M_H$ . LEP and SLC simultaneously carried out other programs, most notably studies and tests of QCD, and heavy quark physics.

LEP 2 ran from 1995–2000, with energies gradually increasing from  $\sim 140$  to  $\sim 209$  GeV. The principal electroweak results were precise measurements of the  $W$  mass, as well as its width and branching ratios (these were measured independently at the Tevatron); a measurement of  $e^+e^- \rightarrow W^+W^-$ ,  $ZZ$ , and single  $W$ , as a function of center of mass (CM) energy, which tests the cancellations between diagrams that is characteristic of a renormalizable gauge field theory, or, equivalently, probes the triple gauge vertices; limits on anomalous quartic gauge vertices; measurements of various cross-sections and asymmetries for  $e^+e^- \rightarrow f\bar{f}$  for  $f = \mu^-, \tau^-, q, b$  and  $c$ , in reasonable agreement with SM predictions; a stringent lower limit of 114.4 GeV on the Higgs mass, and even hints of an observation at  $\sim 116$  GeV; and searches for supersymmetric or other exotic particles.

In parallel with the LEP/SLC program, there were precise ( $< 1\%$ ) measurements of atomic parity violation (APV) in cesium at Boulder, along with the atomic calculations and related measurements needed for the interpretation; precise new measurements of deep inelastic scattering by the NuTeV collaboration at Fermilab, with a sign-selected beam which allowed them to minimize the effects of the  $c$  threshold and reduce uncertainties to around 1%; and few % measurements of  $\bar{\nu}_\mu e$  by CHARM II at CERN. Although the precision of these WNC processes was lower than the  $Z$ -pole measurements, they are still of considerable importance: the  $Z$ -pole experiments are blind to types of new physics that do not directly affect the  $Z$ , such as a heavy  $Z'$  if there is no  $Z$ - $Z'$  mixing, while the WNC experiments are often very sensitive. During the same period there were important electroweak results from CDF and DØ at the Tevatron, most notably a precise value for  $M_W$ , competitive with and complementary to the LEP 2 value; a direct measure of  $m_t$ , and direct searches for  $Z'$ ,  $W'$ , exotic fermions, and

TABLE I

Principal  $Z$ -pole observables, their experimental values, theoretical predictions using the SM parameters from the global best fit with  $M_H$  free (yielding  $M_H = 77^{+28}_{-22}$  GeV), pull (difference from the prediction divided by the uncertainty), and Dev. (difference for fit with  $M_H$  fixed at 117 GeV, just above the direct search limit of 114.4 GeV), as of 11/07, from [2]. See [1,2] for definitions of the quantities.  $\Gamma(\text{had})$ ,  $\Gamma(\text{inv})$ , and  $\Gamma(\ell^+\ell^-)$  are not independent.

Quantity	Value	Standard Model	Pull	Dev.
$M_Z$ [GeV]	$91.1876 \pm 0.0021$	$91.1874 \pm 0.0021$	0.1	-0.1
$\Gamma_Z$ [GeV]	$2.4952 \pm 0.0023$	$2.4968 \pm 0.0010$	-0.7	-0.5
$\Gamma(\text{had})$ [GeV]	$1.7444 \pm 0.0020$	$1.7434 \pm 0.0010$	—	—
$\Gamma(\text{inv})$ [MeV]	$499.0 \pm 1.5$	$501.59 \pm 0.08$	—	—
$\Gamma(\ell^+\ell^-)$ [MeV]	$83.984 \pm 0.086$	$83.988 \pm 0.016$	—	—
$\sigma_{\text{had}}$ [nb]	$41.541 \pm 0.037$	$41.466 \pm 0.009$	2.0	2.0
$R_e$	$20.804 \pm 0.050$	$20.758 \pm 0.011$	0.9	1.0
$R_\mu$	$20.785 \pm 0.033$	$20.758 \pm 0.011$	0.8	0.9
$R_\tau$	$20.764 \pm 0.045$	$20.803 \pm 0.011$	-0.9	-0.8
$R_b$	$0.21629 \pm 0.00066$	$0.21584 \pm 0.00006$	0.7	0.7
$R_c$	$0.1721 \pm 0.0030$	$0.17228 \pm 0.00004$	-0.1	-0.1
$A_{\text{FB}}^{(0,e)}$	$0.0145 \pm 0.0025$	$0.01627 \pm 0.00023$	-0.7	-0.6
$A_{\text{FB}}^{(0,\mu)}$	$0.0169 \pm 0.0013$		0.5	0.7
$A_{\text{FB}}^{(0,\tau)}$	$0.0188 \pm 0.0017$		1.5	1.6
$A_{\text{FB}}^{(0,b)}$	$0.0992 \pm 0.0016$	$0.1033 \pm 0.0007$	-2.5	-2.0
$A_{\text{FB}}^{(0,c)}$	$0.0707 \pm 0.0035$	$0.0738 \pm 0.0006$	-0.9	-0.7
$A_{\text{FB}}^{(0,s)}$	$0.0976 \pm 0.0114$	$0.1034 \pm 0.0007$	-0.5	-0.4
$\bar{s}_\ell^2(A_{\text{FB}}^{(0,q)})$	$0.2324 \pm 0.0012$	$0.23149 \pm 0.00013$	0.8	0.6
	$0.2238 \pm 0.0050$		-1.5	-1.6
$A_e$	$0.15138 \pm 0.00216$	$0.1473 \pm 0.0011$	1.9	2.4
	$0.1544 \pm 0.0060$		1.2	1.4
	$0.1498 \pm 0.0049$		0.5	0.7
$A_\mu$	$0.142 \pm 0.015$		-0.4	-0.3
$A_\tau$	$0.136 \pm 0.015$		-0.8	-0.7
	$0.1439 \pm 0.0043$		-0.8	-0.5
$A_b$	$0.923 \pm 0.020$	$0.9348 \pm 0.0001$	-0.6	-0.6
$A_c$	$0.670 \pm 0.027$	$0.6679 \pm 0.0005$	0.1	0.1
$A_s$	$0.895 \pm 0.091$	$0.9357 \pm 0.0001$	-0.4	-0.4

supersymmetric particles. The Tevatron program continues to the present day, and there have been recent precise measurements of the  $e^-e^-$  (Møller) polarization asymmetry at SLAC; polarization asymmetries in  $e^-$ -hadron scattering at MIT-Bates, Mainz, and Jefferson Lab; asymmetry measurements at the Tevatron; and measurements of the  $W$  propagator and of  $Z$  exchange effects at HERA. Many of these non- $Z$ -pole results are summarized in Table II.

TABLE II

Non- $Z$ -pole observables, 11/07. The SM values are from [2].

Quantity	Value	Standard Model	Pull	Dev.
$m_t$ [GeV]	$170.9 \pm 1.8 \pm 0.6$	$171.1 \pm 1.9$	-0.1	-0.8
$M_W$ ( $\bar{p}p$ )	$80.428 \pm 0.039$	$80.375 \pm 0.015$	1.4	1.7
$M_W$ (LEP)	$80.376 \pm 0.033$		0.0	0.5
$g_L^2$	$0.3010 \pm 0.0015$	$0.30386 \pm 0.00018$	-1.9	-1.8
$g_R^2$	$0.0308 \pm 0.0011$	$0.03001 \pm 0.00003$	0.7	0.7
$g_V^{\nu e}$	$-0.040 \pm 0.015$	$-0.0397 \pm 0.0003$	0.0	0.0
$g_A^{\nu e}$	$-0.507 \pm 0.014$	$-0.5064 \pm 0.0001$	0.0	0.0
$A_{PV} \times 10^7$	$-1.31 \pm 0.17$	$-1.54 \pm 0.02$	1.3	1.2
$Q_W$ (Cs)	$-72.62 \pm 0.46$	$-73.16 \pm 0.03$	1.2	1.2
$Q_W$ (Tl)	$-116.4 \pm 3.6$	$-116.76 \pm 0.04$	0.1	0.1
$\frac{\Gamma(b \rightarrow s\gamma)}{\Gamma(b \rightarrow X e \nu)}$	$(3.55^{+0.53}_{-0.46}) \times 10^{-3}$	$(3.19 \pm 0.08) \times 10^{-3}$	0.8	0.7
$\frac{1}{2}(g_\mu - 2 - \frac{\alpha}{\pi})$	$4511.07(74) \times 10^{-9}$	$4509.08(10) \times 10^{-9}$	2.7	2.7
$\tau_\tau$ [fs]	$290.93 \pm 0.48$	$291.80 \pm 1.76$	-0.4	-0.4

The effort required the calculation of the needed electromagnetic, electroweak, QCD, and mixed radiative corrections to the predictions of the SM. Careful consideration of the competing definitions of the renormalized  $\sin^2 \theta_W$  was needed. The principal theoretical uncertainty is the hadronic contribution  $\Delta\alpha_{\text{had}}^{(5)}(M_Z)$  to the running of  $\alpha$  from its precisely known value at low energies to the  $Z$ -pole, where it is needed to compare the  $Z$  mass with the asymmetries and other observables. The radiative corrections, renormalization schemes, and running of  $\alpha$  are further discussed in [1, 2]. The LEP Electroweak Working Group (LEPEWWG) [7] combined the results of the four LEP experiments, and also those of SLD and some WNC and Tevatron results, taking proper account of common systematic and theoretical uncertainties. Much theoretical effort also went into the development, testing, and comparison of radiative corrections packages, and into the study of how various classes of new physics would modify the observables, and how they could most efficiently be parametrized.

#### 4. Comments on the data

- As can be seen in Table I most of the  $Z$ -pole measurements are in excellent agreement with the standard model predictions using the parameters from the global best fit. One exception is the LEP value for  $A_{\text{FB}}^{(0,b)}$ , the forward-backward asymmetry into  $b$  quarks, which is  $2.5\sigma$  below the best fit expectation, and  $2.0\sigma$  below the fit with  $M_H = 117$  GeV. If not just a statistical fluctuation or systematic problem,  $A_{\text{FB}}^{(0,b)}$  could be a hint of new physics. However, any such effect should not contribute too much to  $R_b$ . The deviation is only around 3.9%, but if the new physics involved a radiative correction to the coefficient  $\kappa$  of  $\sin^2 \theta_W$ , the change would have to be around 20%. Hence, the new physics would most likely be at tree-level type affecting preferentially the third generation. Examples include the decay of a scalar neutrino resonance [8], mixing of the  $b$  quark with heavy exotics [9], and a heavy  $Z'$  with family-nonuniversal couplings [10, 11].
- There is a strong correlation between  $A_{\text{FB}}^{(0,b)}$  and the predicted Higgs mass  $M_H$  in the global fits, and in fact a fit to  $A_{\text{FB}}^{(0,b)}$ ,  $A_{\text{FB}}^{(0,c)}$ , and  $M_Z$  alone yields a prediction  $M_H = 326_{-136}^{+224}$  GeV [2]. In contrast, the SLD polarization asymmetry  $A_{\text{LR}}$  combined with  $M_Z$  yields a lower value  $M_H = 25_{-15}^{+23}$  GeV, with the other measurements closer to the average  $77_{-22}^{+28}$  GeV. It has been emphasized [12] that if one eliminated  $A_{\text{FB}}^{(0,b)}$  from the fit (*e.g.*, because it is affected by new physics) then the global fit prediction for  $M_H$  would be lowered, with the central value well below the lower limit of 114.4 GeV from the direct searches at LEP 2. One resolution, assuming  $A_{\text{FB}}^{(0,b)}$  is due to new physics or a large fluctuation, is to invoke a supersymmetric extension of the standard model with light sparticles and second Higgs doublet [13], which modify the radiative corrections and Higgs constraints.
- The NuTeV collaboration at Fermilab [14] has reported the results of its deep inelastic measurements of  $\frac{\nu_{\mu} N \rightarrow \nu_{\mu} X}{\nu_{\mu} N \rightarrow \mu^{\mp} X}$ . They greatly reduce the uncertainty in the charm quark threshold in the charged current denominator by taking appropriate combinations of  $\nu_{\mu}$  and  $\bar{\nu}_{\mu}$ . They find a value for the on-shell weak angle  $s_W^2$  of 0.2277(16), which is  $3.0\sigma$  above the global fit value of 0.2231(3). Most of the difference is in the left handed neutral current coupling  $g_L^2$ . The discrepancy is reduced to  $\sim 2\sigma$  if one incorporates (as is done here) the effects of the difference between the strange and antistrange quark momentum

distributions,  $S^- \equiv \int_0^1 dx x [s(x) - \bar{s}(x)] = 0.00196 \pm 0.00135$ , from dimuon events, recently reported by NuTeV [15]. Other possible effects that could contribute are large isospin violation in the nucleon sea, next to leading order QCD effects and electroweak corrections, and nuclear shadowing [2,16]. A full reanalysis of all deep inelastic data taking into account these issues and all of the uncertainties would be extremely useful. Possible new physics explanations of the NuTeV anomaly, such as a  $Z'$  with specific couplings and neutrino mixing are reviewed in [16].

- The Brookhaven  $g_\mu-2$  experiment has reported a very precise value [17], leading to a world average  $a_\mu^{\text{exp}} = \frac{g_\mu-2}{2} = (1165920.80 \pm 0.63) \times 10^{-9}$ . The QED contribution has been calculated to four loops, and the predicted SM electroweak contribution is  $a_\mu^{\text{EW}} = (1.52 \pm 0.03) \times 10^{-9}$  [18]. The largest uncertainty in the standard model prediction is from the hadronic vacuum polarization contribution, which has been estimated to two loops. This cannot be calculated perturbatively, but involves a dispersion relation that can be evaluated using experimental data from  $e^+e^- \rightarrow$  hadrons or hadronic  $\tau$  decays. A recent analysis [19] indicates a  $3.3\sigma$  discrepancy between the standard model prediction and the experimental value of  $a_\mu$  when the  $e^+e^-$  data are used, but only a  $0.9\sigma$  difference using the hadronic  $\tau$  decays. The issue is still not settled, but most recent authors advocate the  $e^+e^-$  value because the  $\tau$  decays involve uncertainties from isospin violation. There is also a small but hard to pin down uncertainty from the hadronic light by light scattering diagrams.

Because of the confused situation with the vacuum polarization, it is hard to know how seriously to take the discrepancy. Nevertheless,  $a_\mu$  is more sensitive than the electron moment to most types of new physics, so it is important. One obvious candidate for a new physics explanation would be supersymmetry [20], with relatively low masses for the relevant sparticles and high  $\tan\beta$  (roughly, one requires an effective mass scale of  $\tilde{m} \sim 55 \text{ GeV} \sqrt{\tan\beta}$ ). There is a correlation between the theoretical uncertainty in the vacuum polarization and in the hadronic contribution to the running of  $\alpha$  to the  $Z$ -pole [21], leading to a slight reduction in the predicted Higgs mass when  $a_\mu$  is included in the global fit assuming the standard model (as is done here).

- $\Delta\alpha_{\text{had}}^{(5)}(M_Z)$ , the hadronic contribution to the running of  $\alpha$  up to the  $Z$ -pole, introduces the largest theoretical uncertainty into the precision program, in particular to the relation between  $M_Z$  and the  $\overline{\text{MS}}$  weak angle  $\hat{s}_Z^2$  (extracted mainly from the asymmetries). The uncertainty is closely related to that in  $a_\mu^{\text{had}}$ .

- The LEP and SLC  $Z$ -pole experiments are the most precise tests of the standard electroweak theory, but they are insensitive to any new physics that does not affect the  $Z$  or its couplings. Non- $Z$ -pole experiments are therefore extremely important, especially given the possible NuTeV anomaly. The recent measurement of polarized Møller scattering from SLAC [22] is in agreement with the standard model and observes the running of the weak mixing angle in the  $\overline{\text{MS}}$  scheme at the  $6.4\sigma$  level, as can be seen in Fig. 1. An even more precise result is anticipated from the Qweak polarized electron experiment at Jefferson Lab [24]. The running is observed to even lower  $Q^2$  in atomic parity violation [25].

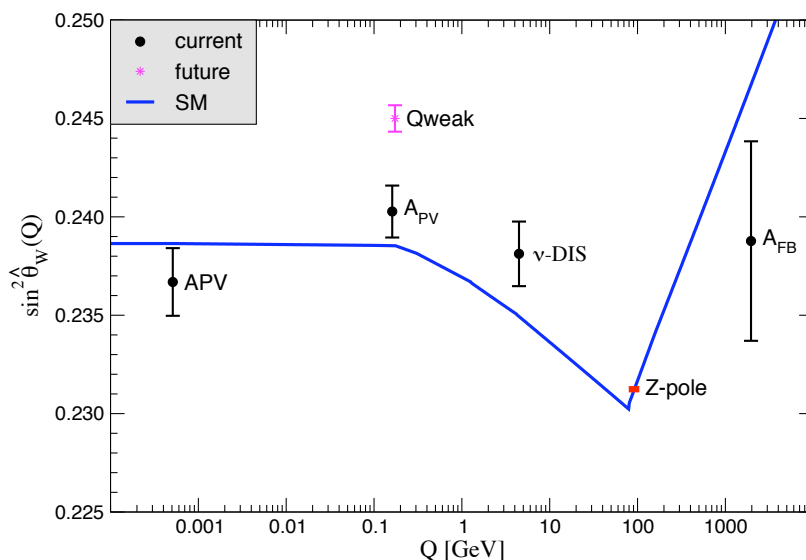


Fig. 1. Running of the weak angle in the  $\overline{\text{MS}}$  scheme, compared to the theoretical expectation [23]. APV, PV, and  $\nu$ -DIS refer to atomic parity violation, the Møller asymmetry, and  $\nu$  deep inelastic scattering, respectively. From [2].

- Although the  $Z$ -pole program has ended for the time being, there are prospects for future programs using the Giga- $Z$  option at a linear collider, which might yield a factor  $10^2$  more events. This would enormously improve the sensitivity [26], but would also require a large theoretical effort to improve the radiative correction calculations.

### 5. Fit results

A global fit to all data contains more information than the individual experiments, but care must be taken with experimental and theoretical systematics and correlations. Here we report our most recent fits for the Particle Data Group [2]. They utilize the fully  $\overline{\text{MS}}$  program GAPP for the radiative corrections [27]. The results are generally in good agreement with those of the LEP Electroweak Working Group [7] (which uses the on-shell renormalization scheme). However, the PDG fits use a more complete set of low energy data, which can be important for constraining certain types of new physics.

As of November, 2007, the result of the global fit was

$$\begin{aligned}
 M_H &= 77_{-22}^{+28} \text{ GeV}, \\
 m_t &= 171.1 \pm 1.9 \text{ GeV}, \\
 \alpha_s &= 0.1217 \pm 0.0017, \\
 \hat{\alpha}(M_Z)^{-1} &= 127.909 \pm 0.019, \\
 \hat{s}_Z^2 &= 0.23119 \pm 0.00014, \\
 \bar{s}_\ell^2 &= 0.23149 \pm 0.00013, \\
 s_W^2 &= 0.22308 \pm 0.00030, \\
 \Delta\alpha_{\text{had}}^{(5)}(M_Z) &= 0.02799 \pm 0.00014,
 \end{aligned} \tag{1}$$

with a good overall  $\chi^2/df$  of 49.4/42. The three values of the weak angle  $s^2$  refer respectively to the  $\overline{\text{MS}}$ , effective  $Z$ -lepton vertex, and on-shell values [2]. The latter has a larger uncertainty because of a stronger dependence on the top mass.

The precision data alone yield  $m_t = 174.7_{-7.8}^{+10.0}$  GeV from loop corrections, in impressive agreement with the direct Tevatron value  $170.9 \pm 1.9$ . The fit actually uses the  $\overline{\text{MS}}$  mass  $\hat{m}_t(\hat{m}_t)$ , which is  $\sim 10$  GeV lower, and converts to the pole mass at end. The Tevatron value and the global fit value that it dominates is lower than the value obtained during Run I, which leads to a lower predicted Higgs mass.

The result  $\alpha_s = 0.1217 \pm 0.0017$  for the strong coupling is somewhat above the previous world average  $\alpha_s = 0.1176(20)$ , which includes other determinations, most of which are dominated by theoretical uncertainties [28]. This is in part due to the inclusion of the  $\tau$  lifetime result [29]. (Without it, one would obtain  $\alpha_s = 0.1198 \pm 0.0020$  from the  $Z$ -pole data.) The  $Z$ -pole value has negligible theoretical uncertainty if one assumes the exact validity of the standard model, and is also insensitive to oblique (propagator) new physics. However, it is very sensitive to non-universal new physics, such as those which affect the  $Zb\bar{b}$  vertex. The  $\tau$  decay value, on the other hand, is less sensitive to new physics but is dominated by theoretical uncertainties.

The prediction for the Higgs mass from indirect data,  $M_H = 77_{-22}^{+28}$  GeV, should be compared with the direct LEP 2 limit  $M_H \gtrsim 114.4$  (95%) GeV [30]. There is no direct conflict given the large uncertainty in the prediction, but the central value is in the excluded region, as can be seen in Figs. 2 and 3. Including the direct LEP 2 exclusion results, one finds  $M_H < 167$  GeV at 95%. The theoretical range in the standard model is  $115 \text{ GeV} \lesssim M_H \lesssim 750 \text{ GeV}$ , where the lower (upper) bound is from vacuum stability (triviality). In the MSSM, one has a theoretical upper limit  $M_H \lesssim 130$  GeV, while  $M_H$  can be as high as 150 GeV in generalizations. In the decoupling limit in which the second Higgs doublet is much heavier the direct search lower limit is similar to the standard model. However, the direct limit is considerably lower in the non-decoupling region in which the new supersymmetric particles and second Higgs are relatively light [13,30].  $M_H$  enters the expressions for the radiative corrections logarithmically. It is fairly robust to many types of new physics, with some exceptions. In particular, a much larger  $M_H$  would be allowed for negative values for the  $S$  parameter or positive values for  $T$ . The predicted value would decrease if new physics accounted for the value of  $A_{\text{FB}}^{(0b)}$  [12].

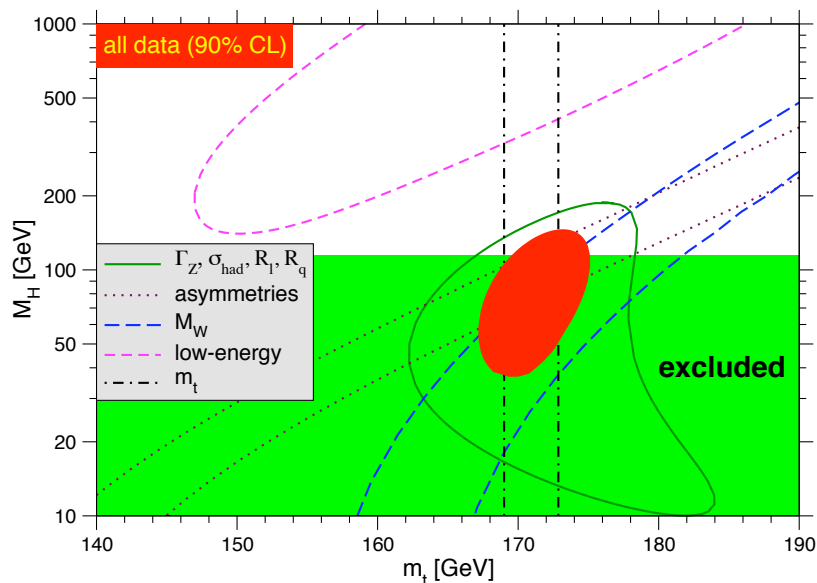


Fig. 2.  $1\sigma$  allowed regions in  $M_H$  versus  $m_t$  and the 90% C.L. global fit region from precision data, compared with the direct exclusion limits from LEP 2, from [2].

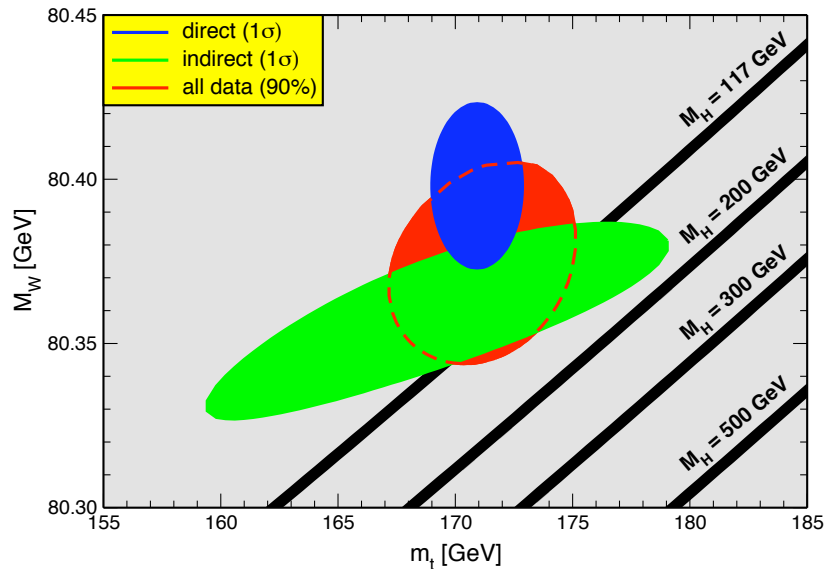


Fig. 3. Allowed regions in  $M_W$  versus  $m_t$  from direct (Tevatron and LEP 2) and indirect data, and from the global fit. Also shown are the standard model expectations as a function of the Higgs mass  $M_H$ . From [2].

## 6. Beyond the Standard Model

The  $\rho_0$  or  $S$ ,  $T$ , and  $U$  parameters describe the tree level effects of Higgs triplets, or the loop effects on the  $W$  and  $Z$  propagators due to such new physics as nondegenerate fermions or scalars, or chiral families (expected, for example, in extended technicolor). The current values are<sup>1</sup>:

$$\begin{aligned} S &= -0.04 \pm 0.09 \text{ } (-0.07), \\ T &= 0.02 \pm 0.09 \text{ } (+0.09), \end{aligned} \quad (2)$$

for  $M_H = 117$  GeV and  $U = 0$ , where these represent the effects of new physics only (the  $m_t$  and  $M_H$  effects are treated separately). The numbers in parentheses are the changes in the central values when one assumes  $M_H = 300$  GeV instead. Similarly,  $\rho_0 \sim 1 + \alpha T = 1.0004^{+0.0008}_{-0.0004}$  and  $114.4$  GeV  $< M_H < 215$  GeV (for  $S = U = 0$ ), implying limits on doublet mass

<sup>1</sup> The plot of  $T$  versus  $S$  produced by the LEP Electroweak Working Group [7] shows larger values,  $S \sim 0.07$  and  $T \sim 0.13$ , based on the  $Z$ -pole data and  $M_W$ . We almost exactly reproduce their values for the same inputs. The lower values reported here are due to the inclusion of the low-energy data, such as atomic parity violation and neutrino scattering, as well as allowing  $\alpha_s$  to float and a different evaluation of  $\Delta\alpha^{(5)}(M_Z)$ .

splittings  $\sum_i C_i \Delta m_i^2 / 3 < (98 \text{ GeV})^2$  at 95% cl, where  $C_i = 1(3)$  for leptons (quarks). The standard model Higgs mass limits are weakened or can be evaded entirely for  $S < 0$  and  $T > 0$ , as can be seen in Fig. 4. Most types of new physics lead to positive contributions to  $S$ , but negative values can be obtained due to Higgs doublet or triplet loops or Majorana fermions.

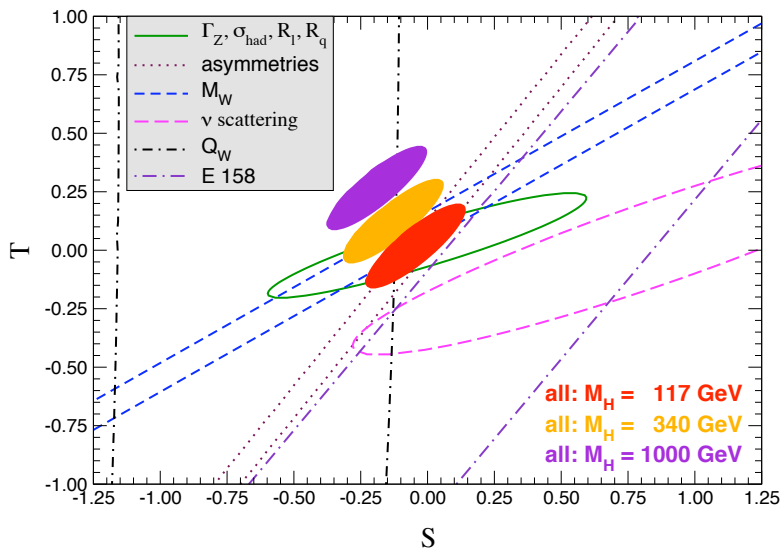


Fig. 4. 90% allowed contours in  $S$  and  $T$  from a global fit to all of the data assuming  $U = 0$ , for  $M_H = 117, 340$ , and  $1000 \text{ GeV}$ . Also shown are the  $1\sigma$  constraints from individual inputs for  $M_H = 117 \text{ GeV}$ .  $S$  and  $T$  are defined to include only the contributions of new physics, *i.e.*,  $m_t$  and  $M_H$  are treated separately. From [2].

The  $S$  constraints strongly restrict the possibility of additional chiral fermions. For example, a *degenerate* heavy family or mirror family is excluded at  $6\sigma$ . A nondegenerate additional family (with a neutrino mass heavier than  $M_Z/2$  to evade the lineshape constraint) can to some extent balance the effects of  $S > 0$  and  $T > 0$  [31], but is still significantly disfavored compared to the standard model fit [2].

In the decoupling limit of supersymmetry, in which the sparticles and second Higgs doublet are heavier than  $\gtrsim 200\text{--}300 \text{ GeV}$ , there is little effect on the precision observables, other than that there is necessarily a light SM-like Higgs, consistent with the data. There is little improvement on the SM fit, and in fact one can somewhat constrain the supersymmetry breaking parameters [13, 32]. However, in the light Higgs/sparticle limit the tension between the direct Higgs searches and the indirect precision results is relaxed. Light sparticles could also account for a muon magnetic moment anomaly.

Heavy  $Z'$  bosons are predicted by many grand unified and string theories [33]. Limits on the  $Z'$  mass are model dependent, but are typically around  $M_{Z'} > 800\text{--}900$  GeV from direct searches at the Tevatron, with (usually) weaker limits from indirect constraints from WNC and LEP 2 data. The  $Z$ -pole data severely constrains the  $Z$ - $Z'$  mixing, typically  $|\theta_{Z-Z'}| < \text{few} \times 10^{-3}$ . A heavy  $Z'$  would have many other theoretical and experimental implications [33].

Precision data constrains mixings between ordinary and exotic fermions, large extra dimensions, new four-fermion operators, and leptoquark bosons [2].

Gauge unification is predicted in GUTs and some string theories. The simplest non-supersymmetric unification is excluded by the precision data. For the MSSM, and assuming no new thresholds between 1 TeV and the unification scale, one can use the precisely known  $\alpha$  and  $\hat{s}_Z^2$  to predict  $\alpha_s = 0.130 \pm 0.010$  and a unification scale  $M_G \sim 3 \times 10^{16}$  GeV [34]. The  $\alpha_s$  uncertainties are mainly theoretical, from the TeV and GUT thresholds, *etc.*  $\alpha_s$  is high compared to the experimental value, but barely consistent given the uncertainties.  $M_G$  is reasonable for a GUT (and is consistent with simple seesaw models of neutrino mass), but is somewhat below the expectations  $\sim 5 \times 10^{17}$  GeV of the simplest perturbative heterotic string models. However, this is only a 10% effect in the appropriate variable  $\ln M_G$ . The new exotic particles often present in such models (or higher Kač–Moody levels) can easily shift the  $\ln M_G$  and  $\alpha_s$  predictions significantly, so the problem is really why the gauge unification works so well. It is always possible that the apparent success is accidental (*cf.*, the discovery of Pluto).

## 7. Conclusions

The precision  $Z$ -pole, LEP 2, WNC, and Tevatron experiments have successfully tested the SM at the 0.1% level, including electroweak loops, thus confirming the gauge principle, SM group, representations, and the basic structure of renormalizable field theory. The standard model parameters  $\sin^2 \theta_W$ ,  $m_t$ , and  $\alpha_s$  were precisely determined. In fact,  $m_t$  was successfully predicted from its indirect loop effects prior to the direct discovery at the Tevatron, while the indirect value of  $\alpha_s$ , mainly from the  $Z$ -lineshape, agreed with more direct QCD determinations. Similarly,  $\Delta\alpha_{\text{had}}^{(5)}(M_Z)$  and  $M_H$  were constrained. The indirect (loop) effects implied  $M_H = 77_{-22}^{+28}$  GeV, while direct searches at LEP 2 yielded  $M_H > 114.4$  GeV, with a hint of a signal at 116 GeV. The combined direct and indirect data imply  $M_H < 167$  GeV at 95% C.L. This range is consistent with, but does not prove, the expectations of the supersymmetric extension of the SM (MSSM), which predicts a light SM-like Higgs for much of its parameter space. The agreement of the

data with the SM imposes a severe constraint on possible new physics at the TeV scale, and points towards decoupling theories (such as most versions of supersymmetry and unification), which typically lead to 0.1% effects, rather than new TeV-scale dynamics or compositeness (*e.g.*, Little Higgs, dynamical symmetry breaking or composite fermions), which usually (but not always) imply deviations of several %, and often large flavor changing neutral currents. Finally, the precisely measured gauge couplings were consistent with the simplest form of grand unification if the SM is extended to the MSSM.

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