THEORETICAL SUMMARY, ELECTROWEAK PHYSICS[a]

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Aspects of theoretical electroweak physics are summarized, including the status of electroweak radiative corrections, the hadronic contribution to the running of α, global fits to precision data and their implication for testing the standard model and constraining new physics, and electroweak baryogenesis.

1 The Z, the W, and the weak neutral current

The Z, the W, and the weak neutral current have always been the primary tests of the unification part of the standard electroweak model. Following the discovery of the neutral current in 1973, its effects in pure weak processes such as νN and νe scattering and in weak-electromagnetic interference (e.g., eD asymmetries, e^+e^- annihilation, atomic parity violation) were intensely studied in a series of experiments that were typically of several % precision [1]. The W and Z were discovered directly at CERN in 1983 and their masses determined. In the 90's, the Z pole experiments at LEP and the SLC have allowed precision studies at the 0.1% level of M_Z (0.002%) and the Z lineshape, branching ratios, and asymmetries; and recent measurements at LEP II and the Tevatron have yielded M_W to better than 0.1% [2].

The implications of these results are

- The standard model is correct and unique to zeroth approximation, confirming the gauge principle and the standard model gauge group and representations.
- The standard model is correct at the loop level, verifying the concept of renormalizable gauge theories, and allowing predictions from observed loop effects of m_t, α_s, and M_H.
- Possible new physics at the TeV scale is severely constrained, strongly supporting such new physics as supersymmetry and unification, as opposed to TeV-scale compositeness.

[a] Talk presented at the 17^{th} *International Workshop on Weak Interactions and Neutrinos (WIN 99)*, Cape Town, South Africa, January 24-30, 1999.

- The gauge couplings at the electroweak scale are precisely determined, allowing tests of gauge unification.

2 Electroweak radiative corrections and the hadronic contribution to $\alpha(M_Z)$

J. Erler reviewed the status of electroweak radiation corrections [3,4]. Because of the accuracy of the high precision data, multi-loop perturbative calculations have to be performed. These include leading two-loop electroweak, three-loop mixed electroweak-QCD, and three-loop QCD corrections. $\mathcal{O}(\alpha\alpha_s)$ vertex corrections to Z decays [5] have become available only recently, inducing an increase in the extracted α_s by about 0.001. The inclusion of top mass enhanced two-loop $\mathcal{O}(\alpha^2 m_t^4)$ [6] and $\mathcal{O}(\alpha^2 m_t^2)$ [7] effects is crucial for a reliable extraction of M_H. The latter, for example, lowers the extracted value of the higgs mass by ~ 18 MeV.

Erler has collected all available results in a new radiative correction package. All Z pole and low energy observables are self-consistently evaluated with common inputs. The routines are written entirely within the $\overline{\text{MS}}$ scheme, using $\overline{\text{MS}}$ definitions for all gauge couplings and quark masses. This reduces the size of higher order terms in the QCD expansion.

The largest remaining theoretical uncertainty arises from the M_W–M_Z–$\hat{s}_Z^2$ interdependence, where $\hat{s}_Z^2$ is the weak angle in the $\overline{\text{MS}}$ scheme. The problem is directly related to the renormalization group running of the electromagnetic coupling,

$$\alpha(M_Z) = \frac{\alpha}{1 - \Delta\alpha(M_Z)}. \tag{1}$$

While the contributions from leptons and bosons (and the top quark when not technically decoupled) can be computed with sufficient accuracy, the hadronic contributions from the five lighter quarks escape a first principle treatment due to strong interaction effects. M. Steinhauser [8] reviewed the recent developments in the determination of $\alpha(M_Z)$ and the closely related problem of the hadronic contributions to the anomalous magnetic moment of the muon [9]. These are calculated via dispersion relations involving the cross section for $e^+e^-\to hadrons$. Early estimates used experimental data for the cross section up to around $\sqrt{s} \sim 40$ GeV, and perturbative QCD (PQCD) for higher energies. However, several groups have emphasized that perturbative and non-perturbative QCD (using sum rules and operator product expansions) are more reliable than the data down to around 2 GeV, leading to a shifted value and smaller uncertainty. Steinhauser described the impact of recent improved low energy data (e.g., below 1 GeV), as well the theoretical developments involving PQCD, the charm threshold, QCD sum rules, and unsubtracted dispersion relations. The recent calculations are in excellent agreement with each other, and considerably reduce the theoretical uncertainties.

3 Global fits and their implications

J. Erler [3] described the results of global fits to all precision electroweak data, for testing the standard model, determining its parameters, and searching for or constraining the effects of new physics. We used the complete data sets described in [3,4], and carefully took into account experimental and theoretical correlations, in particular in the Z-lineshape sector, the heavy flavor sector from LEP and the SLC, and for the deep inelastic scattering experiments. Predictions within and beyond the SM were calculated by means of a new radiative correction program based on the $\overline{\mathrm{MS}}$ renormalization scheme (see Section 2). All input and fit parameters are included in a self-consistent way, and the correlation (present in theory evaluations of $\alpha(M_Z)$) between α_s and the hadronic contribution is automatically taken care of [10]. We find very good agreement with the results of the LEPEWWG [11], except for well-understood effects originating from higher orders. We would like to stress that this agreement is quite remarkable as they use the electroweak library ZFITTER [12], which is based on the on-shell renormalization scheme. It also demonstrates that once the most recent theoretical calculations, in particular Refs. [5,7], are taken into account, the theoretical uncertainty becomes quite small, and is in fact presently negligible compared to the experimental errors. The relatively large theoretical uncertainties obtained in the Electroweak Working Group Report [13] were estimated using different electroweak libraries, which did not include the full range of higher order contributions available now.

In the Standard Model analysis we use the fine structure constant, α, and the Fermi constant, $G_F = 1.16637(1) \times 10^{-5}$ GeV^{-2}, as fixed inputs. The error in G_F is now of purely experimental origin after the very recent calculation of the two-loop QED corrections to μ decay have been completed [15]. They lower the central value by 2×10^{-10} GeV^{-2} and the extracted M_H by 1.3%. Moreover, there are five independent fit parameters, which can be chosen to be M_Z, M_H, m_t, α_s, and the hadronic contribution to $\Delta\alpha(M_Z)$. Alternatively, M_Z can be replaced by s_W^2 (the weak angle in the on-shell scheme) or the $\overline{\mathrm{MS}}$ angle $\hat{s}_Z^2$. We do not use α_s determinations from outside the Z lineshape sector. The fit to all precision data is perfect with an overall $\chi^2 = 28.8$ for 36 degrees of freedom, and yields [4],

$$
\begin{array}{lcl}
M_H &=& 107^{+67}_{-45} \text{ GeV}, \\
m_t &=& 171.4 \pm 4.8 \text{ GeV}, \\
\alpha_s &=& 0.1206 \pm 0.0030, \\
\hat{s}^2_Z &=& 0.23129 \pm 0.00019, \\
\bar{s}^2_\ell &=& 0.23158 \pm 0.00019, \\
s^2_W &=& 0.22332 \pm 0.00045,
\end{array}
\tag{2}
$$

where $\bar{s}^2_\ell \sim \hat{s}^2_Z + 0.00029$ is the effective angle usually quoted by the experimental groups [16]. The larger uncertainty in the on-shell quantity s^2_W is due to its greater sensitivity to m_t and M_H. None of the observables deviates from the SM best fit prediction by more than 2 standard deviations.

The low value of of M_H is consistent with the expectations of supersymmetric extensions of the standard model in the decoupling limit (for which the contributions of sparticles to the radiative corrections are negligible). For a detailed discussion of the upper limits on M_H and their significance, see [3]. The value of α_s from the precision measurements is consistent with other determinations [3,4]. The precise determination of $\hat{s}^2_Z$ and α_s allows a test of gauge unification. The values are compatible with minimal supersymmetric grand unified theories, when threshold corrections at the high and low scales are included [17], but not with the simplest non-supersymmetric grand unified theories.

The precision data also allow stringent constraints on physics beyond the standard model. Typically, one expects that new physics at the TeV scale that does not decouple (i.e., the radiative corrections do not become smaller for larger scales for the new physics) should lead to deviations at the few % level, to be compared with the 0.1% observations. This class includes most versions of composite fermions and dynamical symmetry breaking. On the other hand physics which decouples, such as softly broken supersymmetry for sparticle masses $\gg M_Z$, are compatible with the observations. Specific constraints on heavy Z' bosons and on supersymmetry, and constraints on general parametrizations of classes of extensions of the standard model (such as extended technicolor or higher-dimensional Higgs represention), are extremely stringent, and are described in [3].

As one example, consider the ρ-parameter, defined by

$$
\rho_0 = \frac{M^2_W}{M^2_Z \hat{c}^2_Z \hat{\rho}(m_t, M_H)}, \tag{3}
$$

where $\hat{c}^2_Z \equiv 1 - \hat{s}^2_Z$, and $\hat{\rho}$ incorporates standard model radiative corrections. ρ_0 is a measure of the neutral to charged current interaction strength. The

SM contributions are absorbed in $\hat{\rho}$, so that in the SM $\rho_0 = 1$, by definition. Examples for sources of $\rho_0 \neq 1$ include non-degenerate extra fermion or boson doublets, and non-standard Higgs representations.

In a fit to all data with ρ_0 as an extra fit parameter, we obtain,

$$\begin{aligned} \rho_0 &= 0.9996^{+0.0009}_{-0.0006}, \\ m_t &= 172.9 \pm 4.8 \text{ GeV}, \\ \alpha_s &= 0.1212 \pm 0.0031, \end{aligned} \tag{4}$$

in excellent agreement with the SM. The central values are for $M_H = M_Z$, and the uncertainties are 1σ errors and include the range, $M_Z \leq M_H \leq 167$ GeV, in which the minimum χ^2 varies within one unit. Note, that the uncertainties for $\ln M_H$ and ρ_0 are non-Gaussian: at the 2σ level ($\Delta\chi^2 \leq 4$), Higgs masses up to 800 GeV are allowed, and we find

$$\rho_0 = 0.9996^{+0.0031}_{-0.0013} \ (2\sigma). \tag{5}$$

This implies strong constraints on the mass splittings of extra fermion and boson doublets [18],

$$\Delta m^2 = m_1^2 + m_2^2 - \frac{4 m_1^2 m_2^2}{m_1^2 - m_2^2} \ln \frac{m_1}{m_2} \geq (m_1 - m_2)^2, \tag{6}$$

namely, at the 1σ and 2σ levels, respectively,

$$\sum_i \frac{C_i}{3} \Delta m_i^2 < \ (38 \text{ GeV})^2 \text{ and } (93 \text{ GeV})^2, \tag{7}$$

where C_i is the color factor. Generalizations to the S, T, and U parameters, which can describe the effects of degenerate chiral fermions, are described in [3,4,16].

4 Electroweak baryogenesis

J. R. Espinosa surveyed the status of electroweak baryogenesis in the standard model and its supersymmetric extension [19]. As is well known, a baryon asymmetry can be created cosmologically if the three Sakharov conditions are satisfied: (1) baryon number violation; (2) C and CP violation (to distinguish baryons from antibaryons); and (3) thermal non-equilibrium in the baryon number violating processes. Baryon number violation (with $B - L$ conserved) is present in the standard model as a non-perturbative tunneling between degenerate vacua. The tunneling rate is negligibly small at low temperature, but is enhanced by thermal fluctuations for higher temperatures ("sphalerons"), especially above the electroweak phase transition, for which the barrier height vanishes. Such effects at and before the electroweak phase transition would wash out any baryon asymmetry created at an earlier GUT era if the latter have $B - L = 0$. On the other hand, it is possible that a B asymmetry was actually created at the time of the electroweak transition, as first discussed by Kuzmin, Rubakov, and Shaposhnikov [20].

The basic scenario is that if the electroweak transition is first order, it proceeds by the creation and expansion of bubbles, with a broken phase inside and an unbroken phase outside. Baryon number violation can occur outside the expanding bubble, where it is unsuppressed. The C and CP breaking is manifested by CP-asymmetric reflection and transition rates for massless fermions and antifermions as they encounter the expanding wall, leading for example, to an excess of baryons entering the expanding bubble. Necessary conditions for this to occur are not only sufficient CP violation, but also a first order transition, and finally that $v/T_c \geq 1$, where v and T_c are respectively the electroweak scale and the critical temperature for the transition. If the latter is not satisfied, B violation inside the bubble will occur, destroying the asymmetry.

Espinosa surveyed the current situation. Within the standard model, the conditions of a first order transition and $v/T_c \geq 1$ require respectively that the Higgs mass satisfies $M_H < 72$ GeV and 50 GeV, in contradiction with the experimental lower limit of around 97 GeV.

The situation is modified in the MSSM due to (1) new sources of CP violation, (2) an extended Higgs sector with two doublets, and (3) the influence of stops. Many authors [19] have explored the possibilities in detail. The upshot is that baryogenesis in the MSSM is not excluded, but only works for a limited region of parameter space which is explorable at LEP II and the Tevatron. For example, the $v/T_c \geq 1$ condition requires $M_H < 105 - 110$ GeV, $m_{\tilde{t}_R} < m_t$, small $\tan\beta$, and large m_A.

If these conditions are not satisfied, then baryogenesis would require new mechanisms, such as extensions of the MSSM involving additional Higgs fields or additional gauge symmetries. Another possibility, related to non-zero neutrino mass, is that a lepton asymmetry was created at an early epoch, e.g., by out of equiibrium decays of heavy Majorana neutrinos, and then converted to a baryon asymmetry by the $B - L$ conserving sphaleron effects [21].

Acknowledgments

This work was supported by U.S. Department of Energy Grant No. DOE-EY-76-02-3071. It is a pleasure to thank the participants in the electroweak working group, and Jens Erler for collaboration.

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