OVERVIEW OF THE STANDARD MODEL

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ABSTRACT

A brief overview is presented of the standard model of electroweak interactions, including precision tests, the role of the Cabibbo-Kobayashi-Maskawa (CKM) matrix in describing CP violation, windows on intermediate-scale physics, and the nature of the Higgs phenomenon.

1. Introduction

The standard model of electroweak interactions has guided experimental discoveries for more than ten years, starting with the observation of the W and Z bosons and culminating this past year with evidence for the top quark. The new particles’ properties have been very close to those anticipated by theory: reassuring to some physicists, frustrating to others. In this brief overview we describe the present state of electroweak theory and indicate ways in which new insights could emerge from experiments within the next decade.

Precise electroweak tests, described in Sec. 2, show promise of shedding light on the Higgs, and restrict our ability to add large numbers of new particles to the theory, as in some models of dynamical electroweak symmetry breaking. A plausible theory of CP violation, based on phases in the Cabibbo-Kobayashi-Maskawa (CKM) matrix, can be checked by many forthcoming experiments on rare K decays and properties of B mesons, as noted in Sec. 3.

While electroweak physics is based on physics below the TeV scale, unification of electroweak and strong interactions must take place at scales above $10^{15}$ GeV, or protons would decay too rapidly. Although many schemes envision a “desert” between 1 TeV and the unification scale, we describe in Sec. 4 several probes of intermediate scales (such as the interesting range $10^9 - 10^{12}$ GeV), including the study of neutrino masses, the investigation of baryogenesis in the early Universe, and the search for light pseudoscalar particles (“axions”).

The mechanism of electroweak symmetry breaking is still unknown. Does it proceed via fundamental scalars in the theory, whose masses are protected from large radiative corrections by some mechanism such as supersymmetry, or is it dynamically generated through new interactions which are strong at the TeV scale? These questions are briefly considered in Sec. 5. We summarize in Sec. 6. More details on some of the topics presented here may be found in Ref. 1.
2. Precise electroweak tests

2.1. In celebration of the top quark

In April of this past year the CDF Collaboration at Fermilab presented evidence for a top quark with mass $m_t = 174 \pm 10^{+13}_{-12} \text{ GeV}$. The measured cross section is slightly higher than (though consistent with) theoretical expectations based on quantum chromodynamics (QCD). Mechanisms which could give an elevated cross section include the production of more than one flavor of new quark and schemes involving dynamical symmetry breaking. The mass lies in the middle of the range anticipated on the basis of electroweak radiative corrections (to be discussed in this section) and analyses of the CKM matrix (to be discussed in the next). But why is the top quark so heavy?

2.2. Quark and lepton masses

The top quark is the last quark to fit into a set of three families of quarks and leptons, whose masses are shown in Fig. 1:

$$\begin{pmatrix} u \\ d \end{pmatrix} ; \begin{pmatrix} c \\ s \end{pmatrix} ; \begin{pmatrix} t \\ b \end{pmatrix} ; \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

(1)
Only the $\nu_{\tau}$ has not yet been directly observed. The fractional error on the top mass is less than that for the light quarks $u$, $d$, and $s$, whose masses are obscured by QCD effects. In logarithmic terms, the $t$ mass seems not all that anomalous, but we have no theory for the pattern in Fig. 1.

2.3. Electroweak unification

The singular four-fermion beta-decay interaction does not permit calculations to higher order. In a theory where this interaction is the low-energy limit of massive charged particle ($W$) exchange, however, higher-order calculations make sense. The predicted $W$ and a massive neutral particle, the $Z$, entailed by the simplest version of the theory, were both discovered in 1983. The theory also predicted new weak charge-preserving interactions mediated by $Z$ exchange, first seen in neutrino interactions a decade earlier. The theory has an $SU(2) \times U(1)$ symmetry, broken by the masses of the $W$, $Z$, and fermions.

The low-energy limits of $W$ and $Z$ exchange are described by

$$
\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2} , \quad \frac{G_F}{\sqrt{2}\rho} = \frac{g^2 + g'^2}{8M_Z^2},
$$

where $G_F$ is the Fermi constant, $g = e/\sin \theta$ and $g' = e/\cos \theta$ are $SU(2)$ and $U(1)$ coupling constants, $e$ is the proton charge, and $\theta$ is the weak mixing angle. The parameter $\rho$, which can arise from effects of quark loops on $W$ and $Z$ self-energies, is dominated by the top:

$$
\rho \simeq 1 + \frac{3G_Fm_t^2}{8\pi^2\sqrt{2}},
$$

Consequently, if we define $\theta$ by means of the precise measurement at LEP of $M_Z$,

$$
M_Z^2 = \frac{\pi \alpha}{\sqrt{2}G_F \sin^2 \theta \cos^2 \theta},
$$

then $\theta$ will depend on $m_t$, and so will

$$
M_W^2 = \frac{\pi \alpha}{\sqrt{2}G_F \sin^2 \theta}.
$$

One must remember that the electric charge becomes stronger at the short distances characterizing $W$ and $Z$ exchanges as a consequence of vacuum polarization effects in calculating $M_W$ and $M_Z$ from these expressions.

2.4. The Higgs boson

The replacement of the Fermi interaction by massive $W$ exchange does not cure all the problems of the electroweak theory. At high energies, $W^+W^-$ scattering would violate unitarity (i.e., probability conservation) unless a spinless neutral boson (the
The Higgs boson existed below about 1 TeV. The search for this boson is one motivation for multi-TeV hadron colliders. Searches in $e^+e^- \rightarrow$ Higgs boson + ... at LEP have set a lower limit of about 60 GeV on $M_H$. (Here and elsewhere $c = h = 1$.)

The Higgs boson affects the parameter $\rho$ through loop diagrams contributing to $W$ and $Z$ self-energies. It is convenient to express contributions to $\rho$ in terms of deviations of the top quark and Higgs boson masses from nominal values. For $m_t = 175$ GeV, $M_H = 300$ GeV, the measured value of $M_Z$ leads to a nominal expected value of $\sin^2 \theta_0 \equiv x_0 = 0.2320$. Defining a parameter $T$ of order 1 by $\Delta \rho \equiv \alpha T$, we find

$$T \simeq \frac{3}{16\pi\sin^2 \theta} \left[ \frac{m_t^2 - (175 \text{ GeV})^2}{M_H^2} \right] - \frac{3}{8\pi\cos^2 \theta} \ln \frac{M_H}{300 \text{ GeV}} .$$

(7)

This expression is quadratic in $m_t$, but only logarithmic in $M_H$. The weak mixing angle $\theta$, the $W$ mass, and other electroweak observables depend on $m_t$ and $M_W$.

2.5. $S$ and $T$ parameters

The weak charge-changing and neutral-current interactions are probed under a number of different conditions, corresponding to different values of momentum transfer. For example, muon decay occurs at momentum transfers small with respect to $M_W$, while the decay of a $Z$ into fermion-antifermion pairs imparts a momentum of nearly $M_Z/2$ to each member of the pair. Although coupling constants and masses on the right-hand sides of (3) vary fairly rapidly with momentum transfer, their quotients vary much less rapidly, as first pointed out by Veltman. Small “oblique” corrections, logarithmic in $m_t$ and $M_H$, arise from contributions of new particles to the photon, $W$, and $Z$ propagators. Other (smaller) “direct” radiative corrections are important in calculating actual values of observables.

We may then replace (3) by

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2} \left( 1 + \frac{\alpha S_W}{4\sin^2 \theta} \right) , \quad \frac{G_F\rho}{\sqrt{2}} = \frac{g^2 + g'^2}{8M_Z^2} \left( 1 + \frac{\alpha S_Z}{4\sin^2 \theta \cos^2 \theta} \right) ,$$

(8)

where $S_W$ and $S_Z$ are coefficients representing variation with momentum transfer. Together with $T$, they express a wide variety of electroweak observables in terms of quantities sensitive to new physics.

Expressing the “new physics” effects in terms of deviations from nominal values of top quark and Higgs boson masses, we have the expression for $T$ written above, while contributions of Higgs bosons and of possible new fermions $U$ and $D$ with electromagnetic charges $Q_U$ and $Q_D$ to $S_W$ and $S_Z$ are

$$S_Z = \frac{1}{6\pi} \left[ \ln \frac{M_H}{300 \text{ GeV}} + \sum N_C \left( 1 - 4Q \ln \frac{m_U}{m_D} \right) \right] ,$$

(9)

$$S_W = \frac{1}{6\pi} \left[ \ln \frac{M_H}{300 \text{ GeV}} + \sum N_C \left( 1 - 4Q_D \ln \frac{m_U}{m_D} \right) \right] .$$

(10)

The expressions for $S_W$ and $S_Z$ are written for doublets of fermions with $N_C$ colors and $m_U \geq m_D \gg m_Z$, while $Q \equiv (Q_U + Q_D)/2$. The sums are taken over all doublets.
of new fermions. In the limit \( m_U = m_D \), one has equal contributions to \( S_W \) and \( S_Z \). For a single Higgs boson and a single heavy top quark, Eqs. (3) and (10) become

\[
S_Z = \frac{1}{6\pi} \left[ \ln \frac{M_H}{300 \text{ GeV}} - 2 \ln \frac{m_t}{175 \text{ GeV}} \right] \quad ; \quad S_W = \frac{1}{6\pi} \left[ \ln \frac{M_H}{300 \text{ GeV}} + 4 \ln \frac{m_t}{175 \text{ GeV}} \right].
\]

We shall use these expressions, together with previous ones, to express all electroweak observables as functions of \( m_t \) and \( M_H \).

2.6. Electroweak experiments

Recent direct \( W \) mass measurements, in GeV, include 79.92±0.39, 80.35±0.37, 80.37±0.23, 79.86±0.26, with average 80.23±0.18. Recent data on the ratio \( R_\nu \equiv \sigma(\nu N \rightarrow \nu + \ldots)/\sigma(\nu N \rightarrow \mu^- + \ldots) \) lead to information on \( \rho^2 \) times a function of \( \sin^2 \theta \) roughly equivalent to the constraint \( M_W = 80.27 \pm 0.26 \) GeV. Measured \( Z \) parameters include \( M_Z = 91.1888 \pm 0.0044 \) GeV, \( \Gamma_Z = 2.4974 \pm 0.0038 \) GeV, \( \sigma^H_{Z} = 41.49 \pm 0.12 \) nb (the hadron production cross section), and \( R_\ell \equiv \Gamma_{\text{hadrons}}/\Gamma_{\text{leptons}} = 20.795 \pm 0.040 \), which may be combined to obtain the \( Z \) leptonic width \( \Gamma_{\ell\ell}(Z) = 83.96 \pm 0.18 \) MeV. Leptonic asymmetries include the forward-backward asymmetry parameter \( A_{FB} = 0.0170 \pm 0.0016 \), leading to a value \( \sin^2 \theta_\ell \equiv \sin^2 \theta_{\text{eff}} = 0.23107 \pm 0.0090 \), and independent determinations of \( \sin^2 \theta_{\text{eff}} = (1/4)(1 - [g^L_\ell/g^A_\ell]) \) from the parameters \( A_\tau \rightarrow \sin^2 \theta = 0.2320 \pm 0.0013 \), \( A_e \rightarrow \sin^2 \theta = 0.2330 \pm 0.0014 \). The last three values may be combined to yield \( \sin^2 \theta = 0.2317 \pm 0.0007 \). We do not use asymmetries as measured in decays of \( Z \) to \( b\bar{b} \) (which may reflect additional new-physics effects, to \( c\bar{c} \) (which are of limited weight because of large errors), or to light quarks (for which interpretations are more model-dependent). This last result differs by about two standard deviations from that based on the left-right asymmetry parameter \( A_{LR} \) measured with polarized electrons at SLC, \( \sin^2 \theta = 0.2294 \pm 0.0010 \).

Parity violation in atoms, stemming from the interference of \( Z \) and photon exchanges between the electrons and the nucleus, provides further information on electroweak couplings. The most precise constraint at present arises from the measurement of the weak charge (the coherent vector coupling of the \( Z \) to the nucleus), \( Q_W = \rho (Z - N - 4Z \sin^2 \theta) \), in atomic cesium with the result \( Q_W(\text{Cs}) = -71.04 \pm 1.58 \pm 0.88 \). The first error is experimental, while the second is theoretical. The prediction \( Q_W(\text{Cs}) = -73.20 \pm 0.13 \) is insensitive to standard-model parameters, discrepancies are good indications of new physics (such as exchange of an extra \( Z \) boson).

2.7. Results of fits to electroweak observables

We have performed a fit to the electroweak observables listed in Table 1. The “nominal” values (including \( \sin^2 \theta_{\text{eff}} = 0.2320 \)) are calculated for \( m_t = 175 \) GeV and \( M_H = 300 \) GeV. We use \( \Gamma_{\ell\ell}(Z) \), even though it is a derived quantity, because it has little correlation with other variables in our fit. It is mainly sensitive to the axial-vector coupling \( g^A_\ell \), while asymmetries are mainly sensitive to \( g^L_\ell \). We also omit the total width \( \Gamma_{\text{tot}}(Z) \) from the fit, since it is highly correlated with \( \Gamma_{\ell\ell}(Z) \) and mainly provides information on the value of the strong fine-structure constant \( \alpha_s \). With \( \alpha_s = 0.12 \pm 0.01 \), the observed total \( Z \) width is consistent with predictions. The partial width \( \Gamma(Z \rightarrow b\bar{b}) \) will be treated separately below.
| Quantity | Experimental value | Nominal value | Experiment/ | S Coeff. | T Coeff. |
|----------|--------------------|---------------|-------------|----------|----------|
| $Q_W$ (Cs) | $-71.0 \pm 1.8$ a) | $-73.2$ b) | $0.970 \pm 0.025$ | $-0.80$ | $-0.005$ |
| $M_W$ (GeV) | $80.24 \pm 0.15$ c) | $80.320$ d) | $0.999 \pm 0.002$ | $-0.29$ | $0.45$ |
| $\Gamma_{\ell\ell}(Z)$ (MeV) | $83.96 \pm 0.18$ e) | $83.90$ f) | $1.001 \pm 0.002$ | $-0.18$ | $0.78$ |
| $\sin^2 \theta_{\text{eff}}$ | $0.2317 \pm 0.0007$ f) | $0.2320$ | $0.999 \pm 0.003$ | $0.0036$ | $-0.0026$ |
| $\sin^2 \theta_{\text{eff}}$ | $0.2294 \pm 0.0010$ g) | $0.2320$ | $0.989 \pm 0.004$ | $0.0036$ | $-0.0026$ |

a) Weak charge in cesium 22;  b) Calculation 23 incorporating atomic physics corrections 22

c) Average of direct measurements 24 and indirect information from neutral/charged current ratio in deep inelastic neutrino scattering 25

d) Including perturbative QCD corrections 26;  e) LEP average as of July, 1994 27

f) From asymmetries at LEP 22;  g) From left-right asymmetry in annihilations at SLC 21

Each observable in Table 1 specifies a band in the $S - T$ plane with different slope, as seen from the ratios of coefficients of $S$ and $T$. Parity violation in atomic cesium is sensitive almost entirely to $S$. The impact of $\sin^2 \theta_{\text{eff}}$ determinations on $S$ is considerable. The leptonic width of the $Z$ is sensitive primarily to $T$. The $W$ mass specifies a band of intermediate slope in the $S - T$ plane; here we assume $S_W = S_Z$.

The resulting constraints on $S$ and $T$ are shown in Figs. 2, both with (a) and without (b) the SLC data. Conclusions about the allowed range of $S$ (and hence about the number of new fermions or other new particles allowed in the theory) are sensitive to the precise value of $\sin^2 \theta_{\text{eff}}$, though models with large numbers of new fermions (leading to large positive values of $S$) are excluded.

We have evaluated the overall quality of a fit to the standard model of the data in Table 1, when the constraint $m_t = 174 \pm 17$ GeV is added. The result (see also Fig. 5 of Ref. 1) is a minimum $\chi^2 = 8.3$ for 5 degrees of freedom (d.o.f.) at $M_H \approx 260$ GeV. When the SLC data on $\sin^2 \theta$ are omitted, the minimum $\chi^2$ falls to 2.4 at $M_H \approx 700$ GeV for 4 d.o.f. The error in $M_H$ for $\Delta \chi^2 = 1$ corresponds to about a factor of three in either case. Conclusions about the Higgs boson mass clearly are premature!

### 2.8. The decay $Z \to b\bar{b}$

The measured ratio $\Gamma_b(\bar{b}b) \equiv \Gamma(Z \to \bar{b}b)/\Gamma(Z \to \text{hadrons})$ lies about $2\sigma$ above the standard model prediction 28. If this discrepancy becomes more significant, there are many possibilities for explaining it within the context of new physics 29. Two-Higgs-doublet models 30 cannot reduce the discrepancy much without running afoul of other constraints (such as the observed rate for $b \to s\gamma$).

### 3. The CKM Matrix

The unitary Cabibbo-Kobayashi-Maskawa (CKM) matrix describes the weak charge-changing transitions among quarks. Our present understanding of CP violation
Fig. 2. Allowed ranges of $S$ and $T$ at 68% (inner ellipses) and 90% (outer ellipses) confidence levels. Dotted, dashed, and solid lines correspond to standard model predictions for $M_H = 100, 300, 1000$ GeV. Tick marks, from bottom to top, denote predictions for $m_t = 100, 140, 180, 220,$ and $260$ GeV. (a) Based on data in Table 1; (b) based on data in Table 1 aside from last row.

links the observed effect in the neutral kaon system to a phase in this matrix, whose parameters need to be specified as precisely as possible in order to test the theory. Moreover, theories of quark masses necessarily predict the CKM elements, and may thereby be tested.

3.1. Definitions and magnitudes

We use a convenient parametrization of the matrix:

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \end{pmatrix} \approx \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \end{pmatrix}$$

(12)

The four parameters are measured as follows:

1. The parameter $\lambda$ is measured by a comparison of strange particle decays with muon decay and nuclear beta decay, leading to $\lambda \approx \sin \theta \approx 0.22$, where $\theta$ is the Cabibbo angle.

2. The dominant decays of $b$-flavored hadrons occur via the element $V_{cb} = A\lambda^2$. The lifetimes of these hadrons and their semileptonic branching ratios then lead to an estimate $A = 0.79 \pm 0.06$.

3. The decays of $b$-flavored hadrons to charmless final states allow one to measure the magnitude of the element $V_{ub}$ and thus to conclude that $|V_{ub}/V_{cb}| = 0.08 \pm 0.02$ or $\sqrt{\rho^2 + \eta^2} = 0.36 \pm 0.09$.  


4. The least certain quantity is the phase of $V_{ub}$: $\text{Arg} \left( V_{ub}^* \right) = \arctan(\eta/\rho)$. Information on this quantity may be obtained by studying its effect on contributions of higher-order diagrams involving the top quark.

The unitarity of the matrix (up to order $\lambda^3$) is implicit in the parametrization; in particular, the relation $V_{ub}^* + V_{td} \simeq A \lambda^3$, when normalized so that its right-hand side is unity, becomes $\rho + i\eta + (1 - \rho - i\eta) = 1$. We shall be concerned with the allowed region in the $(\rho, \eta)$ plane.

3.2. Indirect information

Two important sources of indirect information on $\rho$ and $\eta$ are $B^0 - \bar{B}^0$ mixing and CP-violating $K^0 - \bar{K}^0$ mixing.

The presence of “wrong-sign” leptons in semileptonic $B$ decays provided the first evidence for $B^0 - \bar{B}^0$ mixing. Many experiments, including recent observations of time-dependent oscillations, have confirmed the effect, leading to a mixing amplitude $\Delta m / \Gamma = 0.71 \pm 0.07$. The dominant contribution to the mixing is expected to arise from one-loop diagrams (“box graphs”) involving internal $W$ and top quark lines, leading to $\Delta m \sim f_B^2 m_t^2 |V_{td}|^2$ times a slowly varying function of $m_t/M_W$. Here the “$B$ decay constant,” $f_B$, describes the amplitude for finding a $b$ antiquark and a light quark at the same point in a $B$ meson. Since $|V_{td}| \sim |1 - \rho - i\eta|$, the $B^0 - \bar{B}^0$ mixing amplitude leads to a constraint in the $(\rho, \eta)$ plane consisting of a circular band with center (1,0).

The main contribution to the width of this band is uncertainty in $f_B$.

A similar set of box diagrams contributes to the parameter $\epsilon$ describing CP-violating $K^0 - \bar{K}^0$ mixing. The imaginary part of the mass matrix is proportional to $f_K^2 m_t^2 \text{Im}(V_{td}^2)$ times a slowly varying function of $m_t$, with a small correction for the charmed quark contribution and an overall factor $B_K$ describing the degree to which the box graphs account for the effect. Since $\text{Im}(V_{td}^2) \sim \eta(1 - \rho)$, the constraint imposed by CP-violating $K^0 - \bar{K}^0$ mixing consists of a hyperbolic band in the $(\rho, \eta)$ plane with focus at (1,0), whose width is dominated by uncertainty in the magnitude of $V_{cb}$.

3.3. Constraints on $\rho$ and $\eta$

The allowed region in $(\rho, \eta)$ is shown in Fig. 3. Parameters used, in addition to those mentioned above, include $B_K = 0.8 \pm 0.2$, $f_B = 180 \pm 30$ MeV (in units where $f_\pi = 132$ MeV), $\eta_{QCD} = 0.6 \pm 0.1$ (a correction to the $B - \bar{B}$ mixing diagrams), and $B_B = 1$ for the factor analogous to $B_K$. The center of the allowed region lies around $\rho \simeq 0$, $\eta \simeq 0.35$. We may ask how our information may be improved.

3.4. Improved tests

We shall concentrate on a few key aspects of $B$ physics, since extensive discussions of processes involving rare kaon decays and the CP-violating parameter $\epsilon'/\epsilon$ appear elsewhere.

3.4.1 Decay constant information. The value of $f_B$ affects the interpretation of $B - \bar{B}$ mixing in terms of $|1 - \rho - i\eta|$. One recent lattice gauge theory calculation obtains $f_B = 187 \pm 10 \pm 34 \pm 15$ MeV, $f_{B_s} = 207 \pm 9 \pm 34 \pm 22$ MeV, $f_D = 208 \pm 9 \pm 35 \pm 12$ MeV, $f_{D_s} = 230 \pm 7 \pm 30 \pm 18$ MeV, where the first error is statistical, the second is
Fig. 3. Region in the $(\rho, \eta)$ plane allowed by various constraints. Dotted semicircles denote central value and ±1σ limits implied by $|V_{ub}/V_{cb}| = 0.08 ± 0.02$. Circular arcs with centers at $(\rho, \eta) = (1, 0)$ denote constraints from $B \rightarrow \overline{B}$ mixing, while hyperbolae describe region bounded by constraints from CP-violating $K \rightarrow \overline{K}$ mixing.

associated with fitting and lattice size, and the third arises from scaling. Several other determinations exist, some of which obtain values outside the limits just cited.

The WA75 Collaboration reports a handful of $D_s \rightarrow \mu\nu$ candidates, leading to $f_{D_s} = 232 \pm 69$ MeV, while the CLEO Collaboration based on several dozen such events and an average by Muheim and Stone obtains $f_{D_s} = 315 \pm 46$ MeV. We average these two values to obtain $f_{D_s} = 289 \pm 38$ MeV. The BES group also has a few candidates for $D_s \rightarrow \mu\nu$ or $D_s \rightarrow \tau\nu$; the E653 Collaboration has candidates for $D_s \rightarrow \mu\nu$ for which results are expected soon.

The lattice determination noted above obtains $f_D / f_{D_s} \simeq 0.9$, while an argument based on the quark model and the observed hyperfine splittings between singlet and triplet charmed nonstrange and strange mesons suggests $f_D / f_{D_s} \simeq 0.8$. Using this last ratio, we obtain $f_D = 231 \pm 31$ MeV, not far below the present upper limit (90% c.l.) of 290 MeV obtained by the Mark III Collaboration on the basis of their search for the decay $D^+ \rightarrow \mu^+\nu$. The BES Collaboration should be able to observe this process in events obtained in the reaction $e^+e^- \rightarrow \psi(3770) \rightarrow D^+D^-$.

Heavy meson decay constants are related to the square of the quark-antiquark wave function at the origin, which can be estimated with the help of spin-dependent
isospin mass splittings in $K$, $D$, and $B$ systems. The end result of this exercise is the result $f_B = 180$ MeV employed above. The error is based on the spread in various theoretical estimates.

3.4.2 $B$ Decays to CP non-eigenstates: pair of light pseudoscalars. A difference between the rates for a process and its charge-conjugate, such as $B^+ \rightarrow \pi^+ K^0$ and $B^- \rightarrow \pi^- K^0$, signifies CP violation. Under charge conjugation, weak phases change sign, but strong phases do not. In order for a rate difference to appear, there must be both a weak phase difference and a strong phase difference in the channels with isospins $I = 1/2$ and 3/2. Recently it has been shown that one may be able to measure weak phases via the rates for $B$ decays to pairs of light pseudoscalar mesons without having any strong phase differences. The presence of electroweak penguins is one possible obstacle to this program, which is under further investigation.

3.4.3 Decays of neutral $B$ mesons to CP eigenstates: $\pi - B$ correlations. Although produced initially as flavor eigenstates, neutral $B$ mesons can undergo $B^0 - \bar{B}^0$ mixing, leading to time-dependent asymmetries in decays to CP eigenstates like $J/\psi K_S$. Time-integrated decays also can display rate asymmetries, whose interpretation is often independent of final-state effects. For example, the asymmetry in decays of $B^0$ or $\bar{B}^0$ to $J/\psi K_S$ is equal to $-x_d/(1 + x_d^2) \sin[\text{Arg}(V_{td}^*)^2]$, where $x_d = (\Delta m/\Gamma)|d = 0.70 \pm 0.07$ is the mixing parameter mentioned earlier. One has to know the flavor of the neutral $B$ at time of production. One proposed means for “tagging” the $B$ involves its correlation with charged pions produced nearby in phase space. The existence of such a correlation is predicted both by fragmentation and resonance decay pictures.

4. Intermediate mass scales

4.1. Neutrino masses and new mass scales

The pattern of neutrino masses in Fig. 1 is at least as puzzling as the large mass of the top quark. Why are neutrinos so light?

One proposed solution to the apparent suppression of the solar neutrino flux, especially for neutrinos with energies of a few MeV, is based on matter-induced oscillations between electron neutrinos and some other species. An acceptable solution involves a muon neutrino mass of several millielectron volts and a much lighter electron neutrino. A large Majorana mass of $10^9 - 10^{12}$ GeV for the right-handed neutrino, combined with a Dirac mass of order 1 GeV linking the right-handed and left-handed muon neutrino, could give such a mass eigenstate.

If the corresponding tau neutrino Dirac mass is related to the top quark mass (as it is in some grand unified theories), $\nu_\tau$ could then have a mass of a few eV. It might well mix with the $\nu_\mu$ with an angle $\theta \geq m_\mu/m_\tau$, leading to a mixing parameter $\sin^2 2\theta \geq 10^{-2}$.

Present limits from Fermilab Experiment E531 restrict the muon and tau neutrinos to have $\Delta m^2 \leq 1$ eV$^2$ for large $\theta$ and $\sin^2 2\theta \leq (a \text{ few}) \times 10^{-3}$ for large $\Delta m^2$. A wider range of parameters are accessible to CHORUS, an emulsion experiment, and NOMAD, a fine-grained detector, both operating at CERN, which should reach $\sin^2 2\theta \leq (a \text{ few}) \times 10^{-4}$ for large $\Delta m^2$. New short- and long-baseline $\nu_\mu \leftrightarrow \nu_\tau$ oscillation experiments are also envisioned for Fermilab, while experiments on at-
mospheric neutrinos and low-energy reactor neutrinos have recently presented tantalizing hints of oscillation phenomena. A new solar-neutrino experiment, sensitive mainly to high-energy electron neutrinos but eventually to other species as well through neutral-current interactions, will begin operating in a couple of years.

4.2. Electroweak-strong unification

The U(1), SU(2), and SU(3) couplings of the electroweak and strong interactions approach one another at high energies, but do not really meet at a single point, in contrast to the predictions of the simplest SU(5) grand unification scheme. One cure for this “astigmatism” is provided by the supersymmetric extension of SU(5), in which the inclusion of superpartners below about 1 TeV modifies the slopes in the relations between $\alpha_i^{-1}$ ($i = 1, 2, 3$) and $\ln M^2$ such that the couplings meet slightly above $10^{16}$ GeV at $\alpha_i^{-1} \approx 26$. Another possibility, however, is to embed SU(5) in an SO(10) model with SO(10) breaking to SU(3) color $\times$ SU(2)$_R$ $\times$ SU(2)$_L$ $\times$ U(1)$_{B-L}$ around $4 \times 10^{17}$ GeV and SU(2)$_R$ $\times$ U(1)$_{B-L}$ breaking to U(1)$_Y$ at an intermediate mass scale of about $10^{10}$ GeV. (An early analysis indicated that this intermediate scale could lie anywhere between $10^9$ and about $10^{12}$ GeV.) These possibilities are compared in Fig. 9 of Ref. 1.

4.3. Baryogenesis

In 1967 Sakharov identified three key elements of any theory seeking to explain the observed baryon abundance of the Universe, $n_B/n_\gamma \approx 4 \times 10^{-9}$: (1) C and CP violation; (2) baryon number violation, and (3) a period during which the Universe was out of thermal equilibrium. A toy model is provided by the decay of SU(5) “$X$” bosons, which couple both to pairs of quarks and to antiquark-lepton pairs. The total rates for $X$ and $\bar{X}$ decays must be the same as a consequence of CPT invariance, but the branching ratios $B(X \to uu)$ and $B(X \to e^+d)$ can differ from $B(\bar{X} \to \bar{u}\bar{u})$ and $B(\bar{X} \to e^-d)$ as a result of CP violation, leading to a baryon asymmetry once the Universe cools below the energy where these decay processes are balanced by the reverse processes. This example conserves $B - L$, where $B$ is baryon number (1/3 for quarks) and $L$ is lepton number (1 for electrons).

It was pointed out by ’t Hooft that the electroweak theory contains an anomaly as a result of nonperturbative effects which conserve $B - L$ but violate $B + L$. If a theory leads to $B - L = 0$ but $B + L \neq 0$ at some primordial temperature $T$, the anomaly can wipe out any $B + L$ as $T$ sinks below the electroweak scale. Thus, the toy model mentioned above and many others are unsuitable in practice.

One proposed solution is the generation of nonzero $B - L$ at a high temperature, e.g., through the generation of nonzero lepton number $L$, which is then reprocessed into nonzero baryon number by the ’t Hooft anomaly mechanism. The existence of a baryon asymmetry, when combined with information on neutrinos, could provide a window to a new scale of particle physics. Large Majorana masses acquired by right-handed neutrinos would change lepton number by two units and thus would be ideal for generating a lepton asymmetry if Sakharov’s other two conditions are met.

The question of baryogenesis is thus shifted onto the leptons: Do neutrinos indeed have masses? If so, what is their “CKM matrix”? Do the properties of heavy Majorana
right-handed neutrinos allow any new and interesting natural mechanisms for violating CP at the same scale where lepton number is violated? Majorana masses for right-handed neutrinos naturally violate left-right symmetry and could be closely connected with the violation of $P$ and $C$ in the weak interactions. An open question in this scenario, besides the form of CP violation at the lepton-number-violating scale, is the manner in which CP violation is communicated to the lower mass scale at which we see CKM phases.

4.4. The strong CP problem

The Lagrangian density of QCD in principle can contain a term $(g_3^2 \tilde{\theta}/32\pi^2)F_{\mu\nu}^a \tilde{F}^{\mu\nu a}$, where $\tilde{\theta} \equiv \theta + \text{Arg det } M$, with $M$ the quark mass matrix and $\theta$ an angle characterizing the vacuum structure. The neutron electric dipole moment receives a contribution of order $d_n \simeq 10^{-16} \tilde{\theta} \text{ e}\cdot\text{cm}$, implying $\tilde{\theta} \leq 10^{-9}$. How can we understand the small value of $\tilde{\theta}$ without fine-tuning?

Proposed solutions include (1) an unconventional and still controversial interpretation of the vacuum as composed of an incoherent mixture of $\theta$ and $-\theta$, in the sense of a density matrix; (2) vanishing of one of the quark masses (e.g., $m_u$), which probably bends chiral symmetry beyond plausible limits; (3) the promotion of $\tilde{\theta}$ to the status of a dynamical variable relaxing to zero, implying the existence of a light Nambu-Goldstone boson, the axion. Searches for this particle by means of RF cavities turn out to be uniquely sensitive to the scale of symmetry breaking in the range we have been discussing, $10^9 - 10^{12}$ GeV!

5. Electroweak symmetry breaking

A key question facing the standard model of electroweak interactions is the mechanism for breaking $\text{SU}(2) \times \text{U}(1)$. We discuss two popular alternatives; Nature may turn out to be cleverer than either.

5.1. Fundamental Higgs boson(s)

If there really exists a relatively light fundamental Higgs boson in the context of a grand unified theory, one has to protect its mass from large corrections. Supersymmetry is the popular means for doing so. Then one expects a richer neutral Higgs structure, charged scalar bosons, and superpartners, all below about 1 TeV.

5.2. Strongly interacting Higgs sector

The scattering of longitudinally polarized $W$ and $Z$ bosons violates unitarity above a TeV or two if there does not exist a Higgs boson below this energy. The behavior is similar to that of pion-pion scattering in the non-linear sigma model above a few hundred MeV, where we wouldn’t trust the model. Similarly, we mistrust the present version of electroweak theory above a TeV. If the theory has a strongly interacting sector, its $I = J = 0$ boson (like the $\sigma$ of QCD) may be its least interesting and most elusive feature. The rich spectrum of resonances in QCD is now understood in terms of the interactions of quarks and gluons. We hope that the exploration of the potentially rich TeV physics of the electroweak sector can proceed through the use of both hadron and electron-positron colliders.
6. Summary

Increasingly precise electroweak and top quark measurements show promise of shedding indirect light on the Higgs sector, when present accuracies are improved by about a factor of three. Electron-positron collisions at LEP and SLC, hadron collisions at Fermilab, and even table-top experiments on atomic parity violation all will play key roles.

The Cabibbo-Kobayashi-Maskawa (CKM) matrix is the leading candidate for the source of the observed CP violation in the neutral kaon system, through phases which require the existence of the third family of quarks. The observation of events consistent with a top quark has given encouragement to this scheme, but further confirmation is needed, through the study of CP-violating and other rare kaon decays and through systematic exploration of the properties of hadrons containing $b$ quarks.

Several prospective windows exist on the “intermediate” mass scale of $10^9$ – $10^{12}$ GeV, including the study of neutrino masses, partial unification of interactions, baryogenesis, and axions. Thus, there appears to be at least a lamppost, if not an oasis, in the grand desert between the TeV scale and the unification scale.

Candidates for understanding the Higgs sector include a theory of fundamental scalars with masses protected by supersymmetry and a composite-Higgs theory which could, in principle, be merely the first hints of compositeness on a deeper level. Perhaps even quarks and leptons are composite. I, for one would not be distressed if we were simply uncovering one more layer of the onion in our journey toward the Planck scale.

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References

1. J. L. Rosner, Enrico Fermi Institute Report No. 94-38, August, 1994, presented at DPF 94 Meeting, Albuquerque, NM, Aug. 2 – 6, 1994, Proceedings to be published by World Scientific
2. CDF Collaboration, F. Abe et al., Phys. Rev. D 50 (1994) 2966; Phys. Rev. Lett. 72 (1994) 225. For earlier limits see S. Abachi et al., Phys. Rev. Lett. 72 (1994) 2138
3. E. Eichten and K. Lane, Phys. Lett. B 327 (1994) 129
4. C. T. Hill and S. J. Parke, Phys. Rev. D 49 (1994) 4454
5. S. L. Glashow, Nucl. Phys. 22 (1961) 579; S. Weinberg, Phys. Rev. Lett. 19 (1967) 1264; A. Salam, in Proceedings of the Eighth Nobel Symposium, ed. by N. Svartholm (Stockholm, Almqvist and Wiksell, and New York, Wiley, 1968) p. 367
6. M. Veltman, Nucl. Phys. B123 (1977) 89
7. M. Veltman, *Acta Physica Polonica* B8 (1977) 475; *Phys. Lett.* 70B (1977) 253; B. W. Lee, C. Quigg, and H. B. Thacker, *Phys. Rev. Lett.* 38 (1977) 883; *Phys. Rev.* D 16 (1977) 1519
8. S. Olsen, plenary talk, DPF 94 Meeting (see Ref. 1)
9. M. Peskin and T. Takeuchi, *Phys. Rev. Lett.* 65 (1990) 964; *Phys. Rev.* D 46 (1992) 381, and references therein
10. J. L. Rosner, *Rev. Mod. Phys.* 64 (1992) 1151. In Eqs. (2.18) – (2.21) of that article the expressions for $S_W$ and $S_Z$ should be interchanged.
11. D. C. Kennedy and P. G. Langacker, *Phys. Rev. Lett.* 65 (1990)
12. CDF Collaboration, F. Abe et al., *Phys. Rev. Lett.* 65 (1990) 2243; *Phys. Rev.* D 43 (1991) 2070
13. UA2 Collaboration, J. Alitti et al., *Phys. Lett.* B 276 (1992) 354
14. CDF Collaboration, F. Abe et al., presented by Y. K. Kim at Moriond Conference on Electroweak Interactions and Unified Theories, Meribel, Savoie, France, Mar. 12–19, 1994
15. D0 Collaboration, S. Abachi et al., Fermilab report FERMILAB-CONF-93-396-E, December, 1993, presented by Q. Zhu at Ninth Topical Workshop on Proton-Antiproton Collider Physics, Oct. 18–22, 1993
16. M. Demarteau et al. in CDF note CDF/PHYS/CDF/PUBLIC/2552 and D0 note D0NOTE 2115, May, 1994
17. CCFR Collaboration, C. G. Arroyo et al., *Phys. Rev. Lett.* 72 (1994) 3452; R. Bernstein, paper no. 51, DPF 94 Meeting (see Ref. 1)
18. CDHS Collaboration, H. Abramowicz et al., *Phys. Rev. Lett.* 57 (1986) 298; A. Blondel et al., *Zeit. Phys.* C 45 (1990) 361
19. CHARM Collaboration, J. V. Allaby et al., *Phys. Lett.* B 177 (1986) 446; *Zeit. Phys.* C 36 (1987) 611
20. LEP report LEPEWWG/94-02, 12 July 1994, submitted to 27th International Conference on High Energy Physics, Glasgow, Scotland, 21-27 July 1994
21. SLD Collaboration, K. Abe et al., *Phys. Rev. Lett.* 73 (1994) 23
22. M. C. Noecker, B. P. Masterson, and C. E. Wieman, *Phys. Rev. Lett.* 61 (1988) 310
23. S. A. Blundell, J. Sapirstein, and W. R. Johnson, *Phys. Rev.* D 45 (1992) 1602
24. W. J. Marciano and J. L. Rosner, *Phys. Rev. Lett.* 65 (1990) 2963; *ibid.* 68 (1992) 898(E)
25. P. G. H. Sandars, *J. Phys.* B 23 (1990) L655
26. G. DeGrassi, B. A. Kniehl, and A. Sirlin, *Phys. Rev.* D 48 (1993) 3963
27. LEP Electroweak Heavy Flavours Working Group, D. Abbaneo et al., report LEPHF/94-03, 15 July 1994
28. Aaron K. Grant, Enrico Fermi Institute report EFI 94-24, June 1994, to be published in Phys. Rev. D
29. S. Chivukula, plenary talk, DPF 94 Meeting (see Ref. 1)
30. CLEO Collaboration, B. Barish et al., CLEO-CONF-94-1, July, 1994, presented at 27th International Conference on High Energy Physics (see Ref. 20)
31. N. Cabibbo, *Phys. Rev. Lett.* 10 (1963) 531
32. M. Kobayashi and T. Maskawa, *Prog. Theor. Phys.* 49 (1973) 652
33. J. L. Rosner, in *B Decays*, edited by S. Stone (World Scientific, Singapore, 1994), p. 470
34. L. Wolfenstein, *Phys. Rev. Lett.* **51** (1983) 1945
35. ARGUS Collaboration, H. Albrecht *et al.* *Phys. Lett.* B **192** (1987) 245
36. V. Sharma, plenary talk, DPF 94 Meeting (see Ref. 1)
37. S. Stone, presented at PASCOS 94 Conference, Syracuse, NY, May 19-24, 1994. Proceedings to be published by World Scientific
38. J. L. Rosner, Enrico Fermi Institute Report No. 94-25, presented at PASCOS 94 Conference (see Ref. 37)
39. C. W. Bernard, J. N. Labrenz, and A. Soni, *Phys. Rev. D* **49** (1994) 2536
40. A. Duncan *et al.*, Fermilab report FERMILAB-PUB-94/164-T, July, 1994 (unpublished); UKQCD Collaboration, R. M. Baxter *et al.*, *Phys. Rev. D* **49** (1994) 1594; P. B. Mackenzie, plenary talk, DPF 94 Meeting (see Ref. 1)
41. WA75 Collaboration, S. Aoki *et al.*, *Prog. Theor. Phys.* **89** (1993) 131
42. CLEO Collaboration, D. Acosta *et al.*, *Phys. Rev. D* **49** (1994) 5690
43. F. Muheim and S. Stone, *Phys. Rev. D* **49** (1994) 3767
44. BES Collaboration, M. Kelsey, paper no. 414, DPF 94 Meeting (see Ref. 1)
45. E653 Collaboration, R. Edelstein and N. W. Reay, private communication
46. J. F. Amundson *et al.*, *Phys. Rev. D* **47** (1993) 3059; J. L. Rosner, *The Fermilab Meeting - DPF 92* (Division of Particles and Fields Meeting, American Physical Society, Fermilab, 10 – 14 November, 1992), ed. by C. H. Albright *et al.* (World Scientific, Singapore, 1993), p. 658
47. Mark III Collaboration, J. Adler *et al.*, *Phys. Rev. Lett.* **60** (1988) 1375; *ibid.* **63** (1989) 1658(E)
48. E. V. Shuryak, *Nucl. Phys.* **B198** (1982) 83
49. M. Gronau, J. L. Rosner, and D. London, *Phys. Rev. Lett.* **73** (1994) 21; M. Gronau, O. F. Hernández, D. London, and J. L. Rosner, *Phys. Rev. D* **50** (1994) 4529; O. F. Hernández, D. London, M. Gronau, and J. L. Rosner, *Phys. Lett. B* **333** (1994) 500
50. N. G. Deshpande and X.-G. He, University of Oregon report OITS-553, August, 1994 (unpublished)
51. M. Gronau, A. Nippe, and J. L. Rosner, *Phys. Rev. D* **47** (1992) 1988; M. Gronau and J. L. Rosner, in *Proceedings of the Workshop on B Physics at Hadron Accelerators*, Snowmass, Colorado, ed. by P. McBride and C. S. Mishra, Fermilab report FERMILAB-CONF-93/267 (Fermilab, Batavia, IL), p. 701; *Phys. Rev. Lett.* **72** (1994) 195; *Phys. Rev. D* **49** (1994) 254
52. S. Bludman, N. Hata, D. C. Kennedy, and P. Langacker, *Phys. Rev. D* **47** (1993) 2220
53. L. Wolfenstein, *Phys. Rev. D* **17** (1978) 2369; S. P. Mikhnev and A. Yu. Smirnov, * Yad. Fiz.* **42** (1985) 1441 [Sov. J. Nucl. Phys. **42** (1985) 913]; *Nuovo Cim. 9C* (1986) 17; *Usp. Fiz. Nauk* **153** (1987) 3 [Sov. Phys. - Uspekhi **30** (1987) 759]
54. M. Gell-Mann, P. Ramond, and R. Slansky in *Supergravity*, edited by P. van Nieuwenhuizen and D. Z. Freedman (Amsterdam, North-Holland, 1979), p. 315; T. Yanagida *Proceedings of the Workshop on Unified Theory and Baryon Number in the Universe*, edited by O. Sawada and A. Sugamoto (Tsukuba, Japan, National Laboratory for High Energy Physics, 1979)
55. Fermilab E531 Collaboration, N. Ushida *et al.*, *Phys. Rev. Lett.* **57** (1986) 2897
56. CHORUS Collaboration, M. de Jong *et al.*, CERN report CERN-PPE-93-131, July, 1993 (unpublished)
57. NOMAD Collaboration, CERN report CERN-SPSLC-93-19, 1993 (unpublished)
58. K. Kodama et al., Fermilab proposal FERMILAB-PROPOSAL-P-803, October, 1993 (approved Fermilab experiment)
59. W. W. M. Allison et al., Fermilab proposal FERMILAB-PROPOSAL-P-822-UPD, March, 1994 (unpublished)
60. Kamiokande Collaboration, Y. Fukuda et al., Phys. Lett. B 335 (1994) 237
61. LSND Collaboration, R. A. Reeder, paper no. 146, DPF 94 Meeting (see Ref. 1)
62. F. Halzen, plenary talk, DPF 94 Meeting (see Ref. 1)
63. E. B. Norman et al., in The Fermilab Meeting - DPF 92 (Ref. 46), p. 1450
64. H. Georgi, H. Quinn, and S. Weinberg, Phys. Rev. Lett. 33 (1974) 451
65. H. Georgi and S. L. Glashow, Phys. Rev. Lett. 32 (1974) 438
66. U. Amaldi et al., Phys. Rev. D 36 (1987) 1385; U. Amaldi, W. de Boer, and H. Fürstenau, Phys. Lett. B 260 (1991) 447; P. Langacker and N. Polonsky, Phys. Rev. D 47 (1993) 4028
67. H. Georgi in Proceedings of the 1974 Williamsburg DPF Meeting, ed. by C. E. Carlson (New York, AIP, 1975) p. 575; H. Fritzsch and P. Minkowski, Ann. Phys. (N.Y.) 93 (1975) 193
68. R. Robinett and J. L. Rosner, Phys. Rev. D 25 (1982) 3036
69. A. D. Sakharov, Pis'ma Zh. Eksp. Teor. Fiz. 5 (1967) 32 [JETP Lett. 5 (1967) 24]
70. G. 't Hooft, Phys. Rev. Lett. 37 (1976) 8
71. V. A. Kuzmin, V. A. Rubakov, and M. E. Shaposhnikov, Phys. Lett. B 155 (1985) 36; ibid. 191 (1987) 171
72. M. Fukugita and T. Yanagida, Phys. Lett. B 174 (1986) 45; P. Langacker, R. Peccei, and T. Yanagida, Mod. Phys. Lett. A 1 (1986) 541
73. B. Kayser, in CP Violation, edited by C. Jarlskog (World Scientific, Singapore, 1989), p. 334
74. R. Peccei, in CP Violation (see Ref. 73), p. 503
75. R. G. Sachs, Phys. Rev. Lett. 73 (1994) 377
76. H. Leutwyler, Bern Univ. report BUTP-94-8, May, 1994, presented at 2nd IFT Workshop on Yukawa Couplings and the Origins of Mass, Gainesville, FL, 11-13 Feb. 1994, Proceedings to be published by International Press
77. R. D. Peccei and H. R. Quinn, Phys. Rev. Lett. 38 (1977) 144; Phys. Rev. D 16 (1977) 1791
78. S. Weinberg, Phys. Rev. Lett. 40 (1978) 223; F. Wilczek, Phys. Rev. Lett. 40 (1978) 279
79. P. Sikivie, in Perspectives in the Standard Model (Theoretical Advanced Study Institute in Elementary Particle Physics, Boulder, Colo., June 2 – 28, 1991), edited by R. K. Ellis, C. T. Hill, and J. D. Lykken (World Scientific, River Edge, NJ, 1992), p. 399
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