ABSTRACT

The standard model of electroweak interactions is reviewed, stressing the top quark's impact on precision tests and on determination of parameters of the Cabibbo-Kobayashi-Maskawa (CKM) matrix. Some opportunities for the study of CP violation in the decays of $b$-flavored mesons are mentioned, and the possibility of a new "standard model" sector involving neutrino masses is discussed.

1. Introduction

Precision tests of the electroweak theory have reached a mature stage since their beginnings more than twenty years ago. We can now successfully combine weak and electromagnetic interactions in a description which also parametrizes CP violation through phases in the Cabibbo-Kobayashi-Maskawa (CKM) matrix. The mass quoted recently by the CDF Collaboration for the top quark is one with which this whole structure is quite comfortable. Since this is the first DPF Meeting at which we can celebrate the existence of more than a dozen top quark candidates rather than just one or two, it is appropriate to review the impact of the top quark's observation in the context of a wide range of other phenomena. While the evidence for the top quark could certainly benefit from a factor of four greater statistics, it seems safe to say that the top is here to stay. Looking beyond it for the next aspects of "standard model physics," we shall propose that the study of neutrinos is a key element in this program.

We begin in Section 2 with a brief review of aspects of the top quark, covered more fully in Mel Shochet's plenary talk and in parallel sessions. Section 3 is devoted to electroweak physics, while Section 4 describes the present status of information about the CKM matrix. Some aspects of the study of CP violation in $B$ decays are mentioned in Section 5. We devote Section 6 to a brief overview of neutrino masses and Section 7 to an even briefer treatment of electroweak symmetry breaking. Section 8 concludes.

2. The top quark

2.1. Cross section and mass

The CDF Collaboration has reported $m_t = 174\pm13\pm12$ GeV/c$^2$. The production cross section $\sigma(\bar{p}p \rightarrow t\bar{t} + \ldots) = 13.9^{+6.1}_{-4.8}$ pb at $\sqrt{s} = 1.8$ TeV is on the high side of the QCD prediction (3 to 10 pb, depending on $m_t$). The D0 Collaboration does not claim evidence for the top, but if its seven candidates (with a background of $3.2 \pm 1.1$) are ascribed to top, the cross section for a 174 GeV/c$^2$ top quark is about $7 \pm 5$ pb. A cross
section in excess of QCD predictions could be a signature for new strongly interacting behavior in the electroweak symmetry breaking sector or for the production of new quarks. As we shall see, the mass quoted by CDF is just fine to account for loop effects in electroweak processes (through $W$ and $Z$ self-energies) and in giving rise to $B^0 - \bar{B}^0$ and CP-violating $K^0 - \bar{K}^0$ mixing.

2.2. Family structure.

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:

\[
\begin{pmatrix}
u_e \\ e \\
\end{pmatrix};
\begin{pmatrix}
u_\mu \\ \mu \\
\end{pmatrix};
\begin{pmatrix}
u_\tau \\ \tau \\
\end{pmatrix}.
\]

(1)

\[
\begin{pmatrix}
u_e \\ e \\
\end{pmatrix};
\begin{pmatrix}
u_\mu \\ \mu \\
\end{pmatrix};
\begin{pmatrix}
u_\tau \\ \tau \\
\end{pmatrix}.
\]

(2)

Only the $\nu_\tau$ has not yet been directly observed. If there are any more quarks and leptons, the pattern must change, since the width of the $Z$ implies there are only three light neutrinos.

The question everyone asks, for which we have no answer is: “Why is the top so heavy?” In Section 6 we shall return to this question in another form suggested by
Fig. 1, namely: “Why are the neutrinos so light?” Although the top quark is by far the heaviest, its separation from the charmed quark (on a logarithmic scale) is no more than the $c - u$ separation. (Amusing exercises on systematics of quark mass ratios have been performed[13,14].) The fractional errors on the masses of the heavy quarks $t$, $b$, $c$ are actually smaller than those on the masses of the light quarks $s$, $d$, $u$.

3. Electroweak physics

3.1. Electroweak unification

In contrast to the electromagnetic interaction (involving photon exchange), the four-fermion form of the weak interaction is unsuitable for incorporation into a theory which makes sense to higher orders in perturbation theory. Already in the mid-1930’s, Yukawa proposed a particle-exchange model of the weak interactions. At momentum transfers small compared with the mass $M_W$ of the exchanged particle, one identifies

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2},$$

where $G_F = 1.11639(2) \times 10^{-5}$ GeV$^{-2}$ is the Fermi coupling, and $g$ is a dimensionless constant.

The simplest version of such a theory predicted not only the existence of a charged $W^\pm$, but also a massive neutral boson $Z^0$, both of which were discovered in 1983. The exchange of a $Z^0$ implied the existence of new weak charge-preserving interactions, identified a decade earlier.

The theory involves the gauge group SU(2) $\times$ U(1), with respective coupling constants $g$ and $g'$. Processes involving $Z^0$ exchange at low momentum transfers can be characterized by a four-fermion interaction with effective coupling

$$\frac{G_F}{\sqrt{2}} = \frac{g^2 + g'^2}{8M_Z^2}.$$ (4)

The electric charge is related to $g$ and $g'$ by

$$e = g \sin \theta = g' / \cos \theta,$$ (5)

where $\theta$ is the angle describing the mixtures of the neutral SU(2) boson and U(1) boson in the physical photon and $Z^0$. These relations can be rearranged to yield

$$M_W^2 = \frac{\pi \alpha}{\sqrt{2}G_F \sin^2 \theta};$$ (6)

$$M_Z^2 = \frac{\pi \alpha}{\sqrt{2}G_F \sin^2 \theta \cos^2 \theta}.$$ (7)

Using the $Z$ mass measured at LEP$^2$ and a value of the electromagnetic fine structure constant $\alpha(M_Z^2) \simeq 1/128$ evaluated at the appropriate momentum scale, one obtains a value of $\theta$ and a consequent prediction for the $W$ mass of about 80
GeV/c^2, which is not too bad. However, one must be careful to define \( \alpha \) properly (in one convention it is more like 1/128.9) and to take all vertex and self-energy corrections into account. Crucial contributions are provided by top quarks in \( W \) and \( Z \) self-energy diagrams. Eq. (3) becomes

\[
\sqrt{G_F} \hat{\rho} = \frac{g^2 + g'^2}{8M_W^2},
\]

where

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

so that

\[
M_Z^2 = \frac{\pi\alpha}{\sqrt{2}G_F\hat{\rho}\sin^2\theta\cos^2\theta}.
\]

The angle \( \theta \) and the mass of the \( W \) now acquire implicit dependence on the top quark mass. The quadratic dependence of \( \hat{\rho} \) on \( m_t \) is a consequence of the chiral nature of the \( W \) and \( Z \) couplings to quarks; no such dependence occurs in the photon self-energy, which involves purely vector couplings. Small corrections to the right-hand sides of Eqs. (3) and (4), logarithmic in \( m_t \), also arise. We have ignored a QCD correction which replaces \( m_t^2 \) by approximately 0.9\( m_t^2 \) in Eq. (9). Taking this into account would increase our quoted \( m_t \) values by about 5%.

3.2. The Higgs boson

The electroweak theory requires the existence of something in addition to \( W \)'s and a \( Z \) in order to be self-consistent. For example, \( W^+W^- \) scattering would violate probability conservation ("unitarity") at high energy unless a spinless neutral boson \( H \) (the "Higgs boson") existed below about 1 TeV. This particle has been searched for in electron-positron collisions with negative results below \( M_H = 64 \text{ GeV/c}^2 \).

A Higgs boson contributes to \( W \) and \( Z \) self-energies and hence to \( \hat{\rho} \). We can express the deviation of \( \hat{\rho} \) from its value at some nominal top quark and Higgs boson masses \( m_t = 175 \text{ GeV/c}^2 \) and \( M_H = 300 \text{ GeV/c}^2 \) by means of \( \Delta \hat{\rho} = \alpha T \), where

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

One can also expand \( \sin^2\theta \) about its nominal value \( x_0 \simeq 0.232 \) calculated for the above top and Higgs masses and the \( Z \) mass observed at LEP. The angle \( \theta \), the \( W \) mass, and all other electroweak observables now are functions of both \( m_t \) and \( M_H \) in the standard model. Additional small corrections to the right-hand sides of (3) and (4) arise which are logarithmic in \( M_H \).

3.3. Electroweak experiments

Direct \( W \) mass measurements over the past few years, in GeV/c^2, include 79.92 ± 0.39, 80.35 ± 0.37, 80.37 ± 0.23, 79.86 ± 0.26 (with average 80.23 ± 0.18). The ratio \( R_\nu \equiv \sigma(\nu N \to \nu + \ldots)/\sigma(\nu N \to \mu^- + \ldots) \) depends on \( \hat{\rho} \) and \( \sin^2\theta \) in such a way that it, too, provides information mainly on \( M_W \). The average of a CCFR Collaboration
result presented at this conference \cite{23} and earlier measurements at CERN by the CDHS and CHARM Collaborations \cite{24,25} imply $M_W = 80.27 \pm 0.26 \text{ GeV}/c^2$.

A number of properties of the $Z$, as measured at LEP \cite{26} and SLC \cite{27}, are relevant to precise electroweak tests. Global fits to these data have been presented by Steve Olsen at this conference \cite{12}. For our discussion we use the following:

\begin{align*}
M_Z &= 91.1888 \pm 0.0044 \text{ GeV}/c^2, \quad (12) \\
\Gamma_Z &= 2.4974 \pm 0.0038 \text{ GeV}, \quad (13) \\
\sigma_h^0 &= 41.49 \pm 0.12 \text{ nb} \quad (\text{hadron production cross section}), \quad (14) \\
R_\ell \equiv \Gamma_{\text{hadrons}}/\Gamma_{\text{leptons}} &= 20.795 \pm 0.040 \quad (15)
\end{align*}

which may be combined to obtain the $Z$ leptonic width $\Gamma_\ell(Z) = 83.96 \pm 0.18 \text{ MeV}$. Leptonic asymmetries include the forward-backward asymmetry parameter $A_{FB}^\ell = 0.0170 \pm 0.0016$, leading to a value

$$\sin^2 \theta_\ell \equiv \sin^2 \theta_{\text{eff}} = 0.23107 \pm 0.00090 \quad (16)$$

and independent determinations of $\sin^2 \theta_{\text{eff}} = (1/4)(1 - [g_V^\ell/g_A^\ell])$ from the parameters

\begin{align*}
A_r \rightarrow \sin^2 \theta &= 0.2320 \pm 0.0013 \quad (17) \\
A_e \rightarrow \sin^2 \theta &= 0.2330 \pm 0.0014 \quad (18)
\end{align*}

The last three values may be combined to yield

$$\sin^2 \theta = 0.2317 \pm 0.0007 \quad (19).$$

We do not use values of $\sin^2 \theta$ from forward-backward asymmetries in quark pair production, preferring to discuss them separately. There have been suggestions that the behavior of $Z \rightarrow b\bar{b}$ may be anomalous \cite{28,29}, while the asymmetries in charmed pair production still have little statistical weight and those in light-quark pair production are subject to some model-dependence.

The result of Eq. (19) may be compared with that based on the left-right asymmetry $A_{LR}$ measured with polarized electrons at SLC \cite{27}:

$$\sin^2 \theta = 0.2294 \pm 0.0010 \quad (20).$$

The results are in conflict with one another at about the level of two standard deviations. This is not a significant discrepancy but we shall use the difference to illustrate the danger of drawing premature conclusions about the impact of electroweak measurements on the Higgs boson sector.
3.4. Dependence of $M_W$ on $m_t$

We shall illustrate the impact of various electroweak measurements by plotting contours in the $M_W$ vs. $m_t$ plane. A more general language is better for visualizing deviations from the standard model, but space and time limitations prevent its use here. As mentioned, QCD corrections to Eq. (9) are neglected.

The measurements of $M_W$ via direct observation and via deep inelastic neutrino scattering, together with the CDF top quark mass, are shown as the plotted points in Fig. 2. The results are not yet accurate enough to tell us about the Higgs boson mass, but certainly are consistent with theory. We next ask what information other types of measurements can provide.

The dependence of $\sin^2 \theta_{\text{eff}}$ on $m_t$ and $M_H$ leads to the contours of $\sin^2 \hat{\theta} \approx \sin^2 \theta_{\text{eff}} - 0.0003$ shown in Fig. 3. Here $\sin^2 \hat{\theta}$ is a quantity defined in the $\overline{MS}$ subtraction scheme. Also shown are bands corresponding to the LEP and SLC averages and $(19)$ and $(20)$. Taken by itself, the SLC result prefers a high top quark mass. When combined with information on the $W$ mass, however, the main effect of the SLC data is to prefer a lighter Higgs boson mass (indeed, lighter than that already excluded by experiments at LEP).

The observation of parity violation in atomic cesium together with precise atomic physics calculations leads to information on the coherent vector coupling of the $Z$ to the cesium nucleus, encoded in the quantity $Q_W = \hat{\rho}(Z - N - 4Z \sin^2 \theta)$. Contours of this quantity are shown in Fig. 4. The central value favored by experiment, $Q_W(Cs) = -71.04 \pm 1.58 \pm 0.88$, lies beyond the upper left-hand corner of the figure, but the present error is large enough to be consistent with predictions. Because of a fortuitous cancellation, this quantity is very insensitive to standard-model parameters and very sensitive to effects of new physics (such as exchange of an extra $Z$ boson).

3.5. Fits to electroweak observables

We now present the results of 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/c$^2$ and $M_H = 300$ GeV/c$^2$. 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 $g_A^Z$, while asymmetries are mainly sensitive to $g^V_\ell$. 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 $\Gamma(Z \to b\bar{b})$ will be treated separately below.

In addition to the variables in Table 1, we use the constraint $m_t = 174 \pm 17$ GeV/c$^2$. The results are shown in Fig. 5. To illustrate the impact of the SLD value of $\sin^2 \theta$, we show the effect of omitting it. Conclusions about the Higgs boson mass are premature, especially if they are so sensitive to one input.

3.6. The decay $Z \to b\bar{b}$

The ratio $R_b \equiv \Gamma(Z \to b\bar{b})/\Gamma(Z \to \text{hadrons})$ has been measured to be slightly above the standard model prediction. In view of the extensive discussion of this process
Fig. 2. Dependence of $W$ mass on top quark mass for various values of Higgs boson mass. Curves, from left to right: $M_H = 50, 100, 200, 500, 1000 \text{ GeV}/c^2$. Horizontal error bars on plotted points correspond to CDF measurement of $m_t = 174 \pm 17 \text{ GeV}/c^2$. Square: average of direct measurements of $W$ mass; cross: average of determinations based on ratio of neutral-current to charged-current deep inelastic scattering cross sections.
Fig. 3. Dependence of $W$ mass on top quark mass for various values of Higgs boson mass, together with contours of values of $\sin^2 \tilde{\theta} \approx \sin^2 \theta_{\text{eff}} - 0.0003$ predicted by electroweak theory (dot-dashed lines) and measured by LEP (lower region bounded by dashed lines: 1 $\sigma$ limits) and SLD (upper region).
Fig. 4. Dependence of $W$ mass on top quark mass for various values of Higgs boson mass, together with contours of values of weak charge $Q_W$ for cesium as discussed in text.
### Table 1. Electroweak observables described in fit

| Quantity          | Experimental value   | Nominal value   | Experiment/ Nominal |
|------------------|----------------------|-----------------|---------------------|
| $Q_W$ (Cs)        | $-71.0 \pm 1.8$ a)   | $-73.2$ b)      | $0.970 \pm 0.025$   |
| $M_W$ (GeV/c²)    | $80.24 \pm 0.15$ c)  | $80.320$ d)     | $0.999 \pm 0.002$   |
| $\Gamma_{\ell\ell}(Z)$ (MeV) | $83.96 \pm 0.18$ e) | $83.90$ f)      | $1.001 \pm 0.002$   |
| $\sin^2 \theta_{\text{eff}}$ | $0.2317 \pm 0.0007$ f) | $0.2320$ g)      | $0.999 \pm 0.003$   |
| $\sin^2 \theta_{\text{eff}}$ | $0.2294 \pm 0.0010$ h) | $0.2320$ g)      | $0.989 \pm 0.004$   |

a) Weak charge in cesium
b) Calculation incorporating atomic physics corrections
c) Average of direct measurements and indirect information from neutral/charged current ratio in deep inelastic neutrino scattering
d) Including perturbative QCD corrections
e) LEP average as of July, 1994
f) From asymmetries at LEP
g) As calculated with correction for relation between $\sin^2 \theta_{\text{eff}}$ and $\sin^2 \hat{\theta}$
h) From left-right asymmetry in annihilations at SLC

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Fig. 5. Values of $\chi^2$ for fits to $m_t$ and to electroweak data described in Table. Solid curve: full data set (5 d. o. f.); dashed curve: without SLD data (4 d. o. f.).
elsewhere at this conference we shall be brief.

If one allows $R_b$ and the corresponding quantity for charm, $R_c \equiv \Gamma(Z \to cc)/\Gamma(Z \to \text{hadrons})$, to be free parameters in a combined fit, the results are

$$R_b = 0.2202 \pm 0.0020 ; \quad R_c = 0.1583 \pm 0.0098,$$

(21)

to be compared with the standard model predictions $R_b = 0.2156 \pm 0.0006$ and $R_c \approx 0.171$. If one constrains $R_c$ to the standard model prediction, one finds instead $R_b = 0.2192 \pm 0.0018$. The discrepancy is at a level of about $2\sigma$.

Predictions for $R_b$ in the standard model and in two different two-Higgs-doublet models are shown in Fig. 6. With appropriate choices of masses for neutral and charged Higgs bosons, it is possible to reduce the discrepancy between theory and experiment without violating other constraints on the Higgs sector.

A curious item was reported in one of the parallel sessions of this conference. The forward-backward asymmetries in heavy-quark production, $A_{0,F,B}$ and $A_{0,c,F,B}$, have been measured both on the $Z$ peak and 2 GeV above and below it. All quantities are in accord with standard model expectations except for $A_{0,c,F,B}$ at $M_Z - 2$ GeV. Off-peak asymmetries can be a hint of extra $Z$’s.

4. The CKM Matrix

4.1. Definitions and magnitudes

The CKM matrix for three families of quarks and leptons will have four independent parameters no matter how it is represented. In a parametrization in which the rows of the CKM matrix are labelled by $u$, $c$, $t$ and the columns by $d$, $s$, $b$, we may write

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

(22)

Note the phases in the elements $V_{ub}$ and $V_{td}$. These phases allow the standard $V - A$ interaction to generate CP violation as a higher-order weak effect.

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 $\sqrt{\rho^2 + \eta^2} = 0.36 \pm 0.09$. 
Fig. 6. Dependence of $R_b \equiv \Gamma(Z \to b\bar{b})/\Gamma(Z \to \text{hadrons})$ on top quark mass. Solid curves: predictions of Minimal Standard Model (MSM) for $R_b$ and $R_d \equiv \Gamma(Z \to d\bar{d})/\Gamma(Z \to \text{hadrons})$. Dashed curves: two-Higgs models described in text with $\tan \beta = 70$ (upper) and 1 (lower). Data point: recent LEP and CDF measurements of $R_b$ and $m_{\text{top}}$. 
The least certain quantity is the phase of $V_{ub}$: $\text{Arg} \left( V_{ub}^* \right) = \arctan(\eta/\rho)$. We shall mention ways in which information on this quantity may be improved, in part by indirect information associated with contributions of higher-order diagrams involving the top quark.

The unitarity of $V$ and the fact that $V_{ud}$ and $V_{tb}$ are very close to 1 allows us to write $V_{ub}^* + V_{td} \simeq A \lambda^3$, or, dividing by a common factor of $A \lambda^3$,

$$
\rho + i\eta + (1 - \rho - i\eta) = 1.
$$

(23)

The point $(\rho, \eta)$ thus describes in the complex plane one vertex of a triangle whose other two vertices are $(0,0)$ and $(0,1)$.

**4.2. Indirect information**

Box diagrams involving the quarks with charge $2/3$ are responsible for $B^0 - \bar{B}^0$ and CP-violating $K^0 - \bar{K}^0$ mixing in the standard model. Since the top quark provides the dominant contribution, one obtains mainly information on the phase and magnitude of $V_{td}$.

The evidence for $B^0 - \bar{B}^0$ mixing comes from “wrong-sign” leptons in $B$ meson semileptonic decays and from direct observation of time-dependent oscillations. The splitting $\Delta m$ between mass eigenstates is proportional to $f_B^2 |V_{td}|^2$ times a function of $m_t$ which can now be considered reasonably well-known. Here $f_B$ is the $B$ meson decay constant, analogous to the pion decay constant $f_\pi = 132$ MeV. Given a range of $f_B$ and the experimental average for $B$ mesons of $\Delta m/\Gamma = 0.71 \pm 0.07$, we can then specify a range of $|V_{td}|$, which is proportional to $|1 - \rho - i\eta|$. We then obtain a band in the $(\rho, \eta)$ plane bounded by two circles with center $(1,0)$.

The parameter $\epsilon$ characterizing CP-violating $K^0 - \bar{K}^0$ mixing arises from an imaginary part in the mass matrix which is dominated by top quark contributions in the loop, with small corrections from charm. In the limit of complete top dominance one would have $\text{Im} \mathcal{M} \sim f_K^2 \text{Im}(V_{td}^2) \sim \eta(1 - \rho)$, so that $\epsilon = (2.26 \pm 0.02) \times 10^{-3}$ would specify a hyperbola in the $(\rho, \eta)$ plane with focus $(1,0)$. The effect of charm is to shift the focus to about $(1.4,0)$.

**4.3. Constraints on $\rho$ and $\eta$**

When one combines the indirect information from mixing with the constraint on $(\rho^2 + \eta^2)^{1/2}$ arising from $|V_{ub}/V_{cb}|$, one obtains the allowed region shown in Fig. 7. Here, in addition to parameters mentioned earlier, we have taken $|V_{cb}| = 0.038 \pm 0.003$, the vacuum-saturation factor $B_K = 0.8 \pm 0.2$, and $\eta_B B_B = 0.6 \pm 0.1$, where $\eta_B$ refers to a QCD correction. Standard QCD correction factors are taken in the kaon system. We have also assumed $f_B = 180 \pm 30$ MeV, for reasons to be described presently.

The center of the allowed region is near $(\rho, \eta) = (0, 0.35)$, with values of $\rho$ between $-0.3$ and $0.3$ and values of $\eta$ between $0.2$ and $0.45$ permitted at the $1\sigma$ level. The main error on the constraint from $(\Delta m/\Gamma)_B$ arises from uncertainty in $f_B$, while the main error on the hyperbolae associated with $\epsilon$ comes from uncertainty in the parameter $A$, which was derived from $V_{cb}$. Other sources of error have been tabulated by Stone at this conference.
Fig. 7. Region in the $(\rho, \eta)$ plane allowed by various constraints. Dotted semicircles denote central value and $\pm 1\sigma$ limits implied by $|V_{ub}/V_{cb}| = 0.08 \pm 0.02$. Circular arcs with centers at $(\rho, \eta) = (1,0)$ denote constraints from $B - \overline{B}$ mixing, while hyperbolae describe region bounded by constraints from CP-violating $K - \overline{K}$ mixing.
4.4. Improved tests

We can look forward to a number of sources of improved information about CKM matrix elements.

4.4.1 Decay constant information on $f_B$ affects the determination of $|V_{ud}|$ (and hence $\rho$) via $B^0 - \overline{B}^0$ mixing. Lattice gauge theories have become more bold in predicting heavy meson decay constants. For example, one recent calculation obtains the values

$$f_B = 187 \pm 10 \pm 34 \pm 15 \text{ MeV},$$
$$f_{B_s} = 207 \pm 9 \pm 34 \pm 22 \text{ MeV},$$
$$f_D = 208 \pm 9 \pm 35 \pm 12 \text{ MeV},$$
$$f_{D_s} = 230 \pm 7 \pm 30 \pm 18 \text{ MeV},$$

where the first errors are statistical, the second are associated with fitting and lattice constant, and the third arise from scaling from the static ($m_Q = \infty$) limit. An independent lattice calculation finds a similar value of $f_B$. The spread between these and some other lattice estimates is larger than the errors quoted above, however.

Direct measurements are available for the $D_s$ decay constant. The WA75 collaboration has seen $6 - 7 D_s \to \mu\nu$ events and conclude that $f_{D_s} = 232 \pm 69$ MeV. The CLEO Collaboration has a much larger statistical sample; the main errors arise from background subtraction and overall normalization (which relies on the $D_s \to \phi\pi$ branching ratio). Using several methods to estimate this branching ratio, Muheim and Stone estimate $f_{D_s} = 315 \pm 45$ MeV. We average this with the WA75 value to obtain $f_{D_s} = 289 \pm 38$ MeV. A recent value from the BES Collaboration, $f_{D_s} = 434 \pm 160$ MeV (based on one candidate for $D_s \to \mu\nu$ and two for $D_s \to \tau\nu$), and a reanalysis by F. Muheim using the factorization hypothesis, $f_{D_s} = 310 \pm 37$ MeV, should be incorporated in subsequent averages.

Quark models can provide estimates of decay constants and their ratios. In a non-relativistic model, the decay constant $f_M$ of a heavy meson $M = Q\bar{q}$ with mass $M_M$ is related to the square of the $Q\bar{q}$ wave function at the origin by $f_M^2 = 12|\Psi(0)|^2/M_M$. The ratios of squares of wave functions can be estimated from strong hyperfine splittings between vector and pseudoscalar states, $\Delta M_{\text{hfs}} \propto |\Psi(0)|^2/m_Qm_q$. The equality of the $D_s^* - D_s$ and $D^* - D$ splittings then suggests that

$$f_D/f_{D_s} \approx (m_d/m_s)^{1/2} \approx 0.8 \approx f_B/f_{B_s},$$

where we have assumed that similar dynamics govern the light quarks bound to charmed and $b$ quarks. Using our average for $f_{D_s}$, we find $f_D = (231 \pm 31)$ MeV. One hopes that the Beijing Electron Synchrotron will be able to find the decay $D \to \mu\nu$ via extended running at the $\Psi(3770)$ resonance, which was the method employed by the Mark III Collaboration to obtain the upper limit $f_D < 290$ MeV (90% c.l.).

An absolute estimate of $|\Psi(0)|^2$ can be obtained using electromagnetic hyperfine splittings which are probed by comparing isospin splittings in vector and pseudoscalar mesons. On this basis, we estimate $f_B = (180 \pm 12)$ MeV. [This is the
basis of the value taken above, where we inflated the error arbitrarily.] We also obtain $f_{B_s} = (225 \pm 15)$ MeV from the ratio based on the quark model.

4.4.2 Rates and ratios can constrain $|V_{ub}|$ and possibly $|V_{td}|$. The partial width $\Gamma(B \to \ell \nu)$ is proportional to $f_B^2|V_{ub}|^2$. The expected branching ratios are about $(1/2) \times 10^{-4}$ for $\tau \nu$ and $2 \times 10^{-7}$ for $\mu \nu$. Another interesting ratio is $\Gamma(B \to \rho \gamma)/\Gamma(B \to K^* \gamma)$, which, aside from phase space corrections, should be $|V_{td}/V_{ts}|^2 \simeq 1/20$. At this conference, however, Soni has argued that there are likely to be long-distance corrections to this relation.

4.4.3 The $K^+ \to \pi^+ \nu \bar{\nu}$ rate is governed by loop diagrams involving the cooperation of charmed and top quark contributions, and lead to constraints which involve circles in the $(\rho, \eta)$ plane with centers at approximately $(1.4,0).$ The favored branching ratio is slightly above $10^{-10}$, give or take a factor of 2. A low value within this range signifies $\rho > 0$, while a high value signifies $\rho < 0$. The present upper limit is $B(K^+ \to \pi^+ \nu \bar{\nu}) < 3 \times 10^{-9}$ (90% c.l.).

4.4.4 The decays $K_L \to \pi^0 e^+ e^-$ and $K_L \to \pi^0 \mu^+ \mu^-$ are expected to be dominated by CP-violating contributions. Two types of CP-violating contributions are expected: “indirect,” via the CP-positive component $K_1$ component of $K_L = K_1 + \epsilon K_2$, and “direct,” whose presence would be a detailed verification of the CKM theory of CP violation. These are expected to be of comparable magnitude in most calculations, leading to overall branching ratios of order $10^{-11}$. The “direct” CP-violating contribution to $K_L \to \pi^0 \nu \bar{\nu}$ is expected to be dominant, making this process an experimentally challenging but theoretically clean source of information on the parameter $\eta.$

4.4.5 The ratio $\epsilon'/\epsilon$ for kaons has long been viewed as one of the most promising ways to disprove a “superweak” theory of CP violation in neutral kaon decays. The latest estimates are equivalent (for a top mass of about 170 GeV/$c^2$) to $[\epsilon'/\epsilon]_{kaons} = (6 \pm 3) \times 10^{-4} \eta$, with an additional factor of 2 uncertainty associated with hadronic matrix elements. The Fermilab E731 Collaboration measures $\epsilon'/\epsilon = (7.4 \pm 6) \times 10^{-4}$, consistent with $\eta$ in the range (0.2 to 0.45) we have already specified. The CERN NA31 Collaboration finds $\epsilon'/\epsilon = (23.0 \pm 6.5) \times 10^{-4}$, which is higher than theoretical expectations. Both groups are preparing new experiments, for which results should be available around 1996.

4.4.6 $B_s - \bar{B}_s$ mixing can probe the ratio $(\Delta m)|_{B_s}/(\Delta m)|_{B_d} = (f_{B_s}/f_{B_d})^2(B_{B_s}/B_{B_d}) |V_{ts}/V_{td}|^2$, which should be a very large number (of order 20 or more). Thus, strange $B$’s should undergo many particle-antiparticle oscillations before decaying.

The main uncertainty in an estimate of $x_s \equiv (\Delta m/\Gamma)_{B_s}$ is associated with $f_{B_s}$. The CKM elements $V_{ts} \simeq -0.04$ and $V_{tb} \simeq 1$ which govern the dominant (top quark) contribution to the mixing are known reasonably well. We show in Table 2 the dependence of $x_s$ on $f_{B_s}$ and $m_t$. To measure $x_s$, one must study the time-dependence of decays to specific final states and their charge-conjugates with resolution equal to a small fraction of the $B_s$ lifetime (about 1.5 ps).

The question has been raised: “Can one tell whether $\eta \neq 0$ from $B_s - \bar{B}_s$ mixing?”
Table 2. Dependence of mixing parameter $x_s$ on top quark mass and $B_s$ decay constant.

| $m_t$ (GeV/$c^2$) | 157 | 174 | 191 |
|------------------|-----|-----|-----|
| $f_{B_s}$ (MeV)  |     |     |     |
| 150              | 7.6 | 8.9 | 10.2 |
| 200              | 13.5| 15.8| 18.2 |
| 250              | 21.1| 24.7| 28.4 |

to be $(f_{B_s}/f_{B_d})^2 \approx 1.19 \pm 0.1$.\textsuperscript{[28]} ALEPH claims\textsuperscript{[28]}

\[
\frac{\Delta m_s}{\Delta m_d} = (1.19 \pm 0.10) \left| \frac{V_{ts}}{V_{td}} \right|^2 > 7.9 , \tag{26}
\]

leading to a bound $|1 - \rho - i\eta| < 1.84$. (An even more aggressive bound equivalent to $|1 - \rho - i\eta| < 1.7$ was reported by V. Sharma\textsuperscript{[69]} in the plenary session.) However, in order to show that the unitarity triangle has nonzero area, assuming that $|V_{ub}/V_{cb}| > 0.27$, one must show $0.73 < |1 - \rho - i\eta| < 1.27$. With the above expression, taking the $B_s$ and $B_d$ lifetimes to be equal, and assuming $0.64 < x_d < 0.78$, this will be so if $13 < x_s < 27$. An “ideal” measurement would thus be $x_s = 20 \pm 2$.

5. CP violation and $B$ decays

5.1. Types of experiments

Soon after the discovery of the $\Upsilon$ states it was realized that CP-violating phenomena in decays of $B$ mesons were expected to be observable and informative.\textsuperscript{[70,71]}

5.1.1 Decays to CP non-eigenstates can exhibit rate asymmetries only if there are two different weak decay amplitudes and two different strong phase shifts associated with them. The weak phases change sign under charge conjugation, while the strong phases do not. Thus, the rates for $B^+ \rightarrow K^+\pi^0$ and $B^- \rightarrow K^-\pi^0$ can differ only if the strong phases differ in the $I = 1/2$ and $I = 3/2$ channels, and interpretation of a rate asymmetry in terms of weak phases requires knowing the difference of strong phases. We shall mention in Sec. 5.3 the results of a recent SU(3) analysis\textsuperscript{[72]} which permits the separation of weak and strong phase shift information without the necessary observation of a CP-violating decay rate asymmetry.

5.1.2 Decays of neutral $B$ mesons to CP eigenstates $f$ can exhibit rate asymmetries (or time-dependent asymmetries) as a result of the interference of the direct process $B^0 \rightarrow f$ and the two-step process $B^0 \rightarrow \bar{B}^0 \rightarrow f$ involving mixing. Here one does not have to know the strong phase shifts. Decay rate asymmetries directly probe angles of the unitarity triangle. One very promising comparison involves the decays $B^0 \rightarrow J/\psi K_S$ and $\bar{B}^0 \rightarrow J/\psi K_S$, whose rate asymmetry is sensitive to $\sin [\text{Arg}(V_{td}^2)] \equiv \sin(2\beta)$. It is necessary to know whether the decaying neutral $B$ meson was a $B^0$ or a $\bar{B}^0$ at some reference time $t = 0$. We now remark briefly on one method\textsuperscript{[73]} for tagging such $B^0$ mesons using associated pions.
5.2. \( \pi - B \) correlations

The correlation of a neutral \( B \) meson with a charged pion is easily visualized with the help of quark diagrams. By convention (the same as for kaons), a neutral \( B \) meson containing an initially produced \( \bar{b} \) is a \( B^0 \). It also contains a \( d \) quark. The next charged pion down the fragmentation chain must contain a \( \bar{d} \), and hence must be a \( \pi^+ \). Similarly, a \( \bar{B}^0 \) will be correlated with a \( \pi^- \).

The same conclusion can be drawn by noting that a \( B^0 \) can resonate with a positive pion to form an excited \( B^+ \), which we shall call \( B^{*+} \) (to distinguish it from the \( B^* \), lying less than 50 MeV/\( c^2 \) above the \( B \)). Similarly, a \( \bar{B}^0 \) can resonate with a negative pion to form a \( B^{*-} \). The combinations \( B^0 \pi^- \) and \( \bar{B}^0 \pi^+ \) are exotic, i.e., they cannot be formed as quark-antiquark states. No evidence for exotic resonances exists. Resonant behavior in the \( \pi - B^{(*)} \) system, if discovered, would be very helpful in reducing the combinatorial backgrounds associated with this method.

The lightest states which can decay to \( B \pi \) and/or \( B^* \pi \) are P-wave resonances of a \( b \) quark and a \( \bar{u} \) or \( \bar{d} \). The expectations for masses of these states may be based on extrapolation from the known \( D^{**} \) resonances, for which present data\[^74\] and predictions\[^75\] are summarized in Fig. 8.

The 1S (singlet and triplet) charmed mesons have all been observed, while CLEO\[^74\] has presented at this conference evidence for all six (nonstrange and strange) 1P states in which the light quarks’ spins combine with the orbital angular momentum to form a total light-quark angular momentum \( j = 3/2 \). These states have \( J = 1 \) and \( J = 2 \). They are expected to be narrow in the limit of heavy quark symmetry. The strange
1P states are about 110 MeV heavier than the nonstrange ones. In addition, there are expected to be much broader (and probably lower) \( j = 1/2 \) \( D^{**} \) resonances with \( J = 0 \) and \( J = 1 \).

For the corresponding \( B^{**} \) states, one should add about 3.32 GeV (the difference between \( b \) and \( c \) quark masses minus a small correction for binding). One then predicts\(^\text{72}\) nonstrange \( B^{**} \) states with \( J = (1, 2) \) at (5755, 5767) MeV. It is surprising that so much progress has been made in identifying \( D^{**} \)'s without a corresponding glimmer of hope for the \( B^{**} \)'s, especially since we know where to look.

### 5.3. Decays to pairs of light pseudoscalars

The decays \( B \rightarrow (\pi\pi, \pi K, K \bar{K}) \) are a rich source of information on both weak (CKM) and strong phases, if we are willing to use flavor SU(3) symmetry.

The decays \( B \rightarrow \pi\pi \) are governed by transitions \( b \rightarrow dq \bar{q} \) \((q = u, d, \ldots)\) with \( \Delta I = 1/2 \) and \( \Delta I = 3/2 \), leading respectively to final states with \( I = 0 \) and \( I = 2 \). Since there is a single amplitude for each final isospin but three different charge states in the decays, the amplitudes obey a triangle relation: \( A(\pi^+\pi^-) - \sqrt{2}A(\pi^0\pi^0) = \sqrt{2}A(\pi^+\pi^0) \). The triangle may be compared with that for the charge-conjugate processes and combined with information on time-dependent \( B \rightarrow \pi^+\pi^- \) decays to obtain information on weak phases.\(^{72}\)

The decays \( B \rightarrow \pi K \) are governed by transitions \( b \rightarrow sq \bar{q} \) \((q = u, d, \ldots)\) with \( \Delta I = 0 \) and \( \Delta I = 1 \). The \( I = 1/2 \) final state can be reached by both \( \Delta I = 0 \) and \( \Delta I = 1 \) transitions, while only \( \Delta I = 1 \) contributes to the \( I = 3/2 \) final state. Consequently, there are three independent amplitudes for four decays, and one quadrangle relation \( A(\pi^+K^0) + \sqrt{2}A(\pi^0K^+) = A(\pi^-K^+) + \sqrt{2}A(\pi^0K^0) \). As in the \( \pi\pi \) case, this relation may be compared with the charge-conjugate one and the time-dependence of decays to CP eigenstates (in this case \( \pi^0K^\pm \)) studied to obtain CKM phase information.\(^{77}\)

We re-examined\(^{\text{72}}\) SU(3) analyses of the decays \( B \rightarrow PP \) \((P = \text{light pseudoscalar})\). They imply a number of useful relations among \( \pi\pi \), \( \pi K \), and \( KK \) decays, among which is one relating \( B^+ \) amplitudes alone:

\[
A(\pi^+K^0) + \sqrt{2}A(\pi^0K^+) = \tilde{r}_u \sqrt{2}A(\pi^+\pi^0) .
\]

Here \( \tilde{r}_u \equiv (f_K/f_\pi)|V_{us}/V_{ud}| \). This expression relates one side of the \( \pi\pi \) amplitude triangle to one of the diagonals of the \( \pi K \) amplitude quadrangle, and thus reduces the quadrangle effectively to two triangles, simplifying previous analyses.\(^{\text{72}}\) Moreover, since one expects the \( \pi^+K^0 \) amplitude to be dominated by a penguin diagram (with expected weak phase \( \pi \)) and the \( \pi^+\pi^0 \) amplitude to have the phase \( \gamma = \text{Arg} \, V_{ub}^* \), the comparison of this last relation and the corresponding one for charge-conjugate decays can provide information on the weak phase \( \gamma \). We have estimated\(^{\text{72}}\) that in order to measure \( \gamma \) to 10° one needs a sample including about 100 events in the channels \( \pi^0K^\pm \).

Further relations can be obtained\(^{\text{72}}\) by comparing the amplitude triangles involving both charged and neutral \( B \) decays to \( \pi K \). By looking at the amplitude triangles for these decays and their charge conjugates, one can sort out a number of weak and strong phases.

Some combination of the decays \( B^0 \rightarrow \pi^+\pi^- \) and \( B^0 \rightarrow \pi^-K^+ \) has already been observed\(^{\text{81}}\) and updated analyses in these and other channels have been presented at this conference.\(^{\text{81}}\)
6. Neutrino masses and new mass scales

6.1. Expected ranges of parameters

Referring back to Fig. 1 in which quark and lepton masses were displayed, we see that the neutrino masses are at least as anomalous as the top quark mass. There are suggestions that the known (direct) upper limits are far above the actual masses, enhancing the puzzle. Why are the neutrinos so light?

A possible answer is that light neutrinos acquire Majorana masses of order $m_M = m_D^2 / M^2$, where $m_D$ is a typical Dirac mass and $M$ is a large Majorana mass acquired by right-handed neutrinos. One explanation of the apparent deficit of solar neutrinos as observed in various terrestrial experiments invokes matter-induced $\nu_e \rightarrow \nu_\mu$ oscillations in the Sun with a muon neutrino mass of a few times $10^{-3}$ eV. With a Dirac mass of about 0.1 to 1 GeV characterizing the second quark and lepton family, this would correspond to a right-handed Majorana mass $M = 10^9 - 10^{12}$ GeV. As stressed by Georgi in his summary talk, nobody really knows what Dirac mass to use for such a calculation, which only enhances the value of experimental information on neutrino masses. However, using the above estimate, and taking a Dirac mass for the third neutrino characteristic of the third quark and lepton family (in the range of 2 to 200 GeV), one is led by the ratios in Fig. 1 to expect the $\nu_\tau$ to be at least a couple of hundred times as heavy as the $\nu_\mu$, and hence to be heavier than 1 eV or so. This begins to be a mass which the cosmologists could use to explain at least part of the missing matter in the Universe.

If $\nu_\mu \leftrightarrow \nu_\tau$ mixing is related to ratios of masses, one might expect the mixing angle to be at least $m_\mu / m_\tau$, and hence $\sin^2 2\theta$ to exceed $10^{-2}$.

6.2. Present limits and hints

Some limits on neutrino masses and mixings have been summarized at a recent Snowmass workshop. The E531 Collaboration has set limits for $\nu_\mu \rightarrow \nu_\tau$ oscillations corresponding to $\Delta m^2 < 1$ eV$^2$ for large $\theta$ and $\sin^2 2\theta < (a few) \times 10^{-3}$ for large $\Delta m^2$. The recent measurement of the zenith-angle dependence of the apparent deficit in the ratio of atmospheric $\nu_\mu$ to $\nu_e$-induced events in the Kamioka detector can be interpreted in terms of neutrino oscillations (either $\nu_\mu \rightarrow \nu_e$ or $\nu_\mu \rightarrow \nu_\tau$), with $\Delta m^2$ of order $10^{-2}$ eV$^2$. In either case maximal mixing, with $\theta = 45^\circ$, is the most highly favored. We know of at least one other case (the neutral kaon system) where (nearly) maximal mixing occurs; perhaps this will serve as a hint to the pattern not only of neutrino masses but other fermion masses as well. However, it is not possible to fit the Kamioka atmospheric neutrino effect, the apparent solar-neutrino deficit, and a cosmologically significant $\nu_\tau$ using naive guesses for Dirac masses and a single see-saw scale. Various schemes have been proposed involving near-degeneracies of two or more neutrinos or employing multiple see-saw scales.

6.3. Present and proposed experiments

Opportunities exist and are starting to be realized for filling in a substantial portion of the parameter space for neutrino oscillations. New short-baseline experiments are already in progress at CERN and approved at Fermilab. These are capable of
pushing the $\nu_\mu \leftrightarrow \nu_\tau$ mixing limits lower for mass differences $\Delta m^2$ of at least $1 \text{ eV}^2$. New long-baseline experiments would be sensitive in the same mass range as the Kamioka result to smaller mixing angles. At this conference we have heard a preliminary result from a search for $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations using $\bar{\nu}_\mu$ produced in muon decays. An excess of events is seen which, if interpreted in terms of oscillations, would correspond to $\Delta m^2$ of several eV$^2$. (No evidence for oscillations was claimed.) A further look at the solar neutrino problem will be provided by the Sudbury Neutrino Observatory.

We will not understand the pattern of fermion masses until we understand what is going on with the neutrinos. Fortunately this area stands to benefit from much experimental effort in the next few years.

6.4. Electroweak-strong unification

Another potential window on an intermediate mass scale is provided by the pattern of electroweak-strong unification. If the strong and electroweak coupling constants are evolved to high mass scales in accord with the predictions of the renormalization group, as shown in Fig. 9(a), they approach one another in the simplest SU(5) model but do not really cross at the same point. This “astigmatism” can be cured by invoking supersymmetry, as illustrated in Fig. 9(b). Here the cure is effected not just by the contributions of superpartners, but by the richer Higgs structure in supersymmetric theories. The theory predicts many superpartners below the TeV mass scale, some of which ought to be observable in the next few years.

Alternatively, one can embed SU(5) in an SO(10) model in which each family of quarks and leptons (together with a right-handed neutrino for each family) fits into a 16-dimensional spinor representation. Fig. 9(c) illustrates one scenario for breaking of SO(10) at two different scales, the lower of which is a comfortable scale for the breaking of left-right symmetry and the generation of right-handed neutrino Majorana masses.

6.5. Baryogenesis

The ratio of baryons to photons in our Universe is a few parts in $10^{9}$. In 1967 Sakharov proposed three ingredients of any theory which sought to explain the preponderance of baryons over antibaryons in our Universe: (1) violation of C and CP; (2) violation of baryon number, and (3) a period in which the Universe was out of thermal equilibrium. Thus our very existence may owe itself to CP violation. However, no consensus exists on a specific implementation of Sakharov’s suggestion.

A toy model illustrating Sakharov’s idea can be constructed within an SU(5) grand unified theory. The gauge group SU(5) contains “X” bosons which can decay both to $uu$ and to $e^+d$. By CPT, the total decay rates of $X$ and $\bar{X}$ must be equal, but CP-violating rate differences $\Gamma(X \to uu) \neq \Gamma(\bar{X} \to \bar{u}\bar{u})$ and $\Gamma(X \to e^+d) \neq \Gamma(\bar{X} \to e^-d)$ are permitted. 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.
Fig. 9. Behavior of coupling constants predicted by the renormalization group in various grand unified theories. Error bars in plotted points denote uncertainties in coupling constants measured at $M = M_Z$ (dashed vertical line). (a) SU(5); (b) supersymmetric SU(5) with superpartners above 1 TeV (dotted line) (c) example of an SO(10) model with an intermediate mass scale (dot-dashed vertical line).
Fig. 10. Mass scales associated with one scenario for baryogenesis.
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.\(^{104}\) We illustrate in Fig. 10 some aspects of the second scenario. 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.\(^{105}\)

An open question in this scenario, besides the precise form of CP violation at the lepton-number-violating scale, is how this CP violation gets communicated to the lower mass scale at which we see CKM phases. Presumably this occurs through higher-dimension operators which imitate the effect of Higgs boson couplings to quarks and leptons.

7. Electroweak symmetry breaking

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

7.1. 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.

7.2. Strongly interacting Higgs sector

The scattering of longitudinally polarized \( W \) and \( Z \) bosons becomes strong and violates unitarity above a TeV or two if there does not exist a Higgs boson below this energy.\(^{17}\) The behavior is similar to what one might expect for pion-pion scattering in the non-linear sigma model above a few hundred MeV. We wouldn’t trust such a model above that energy, and perhaps we should not trust the present version of electroweak theory above a TeV. If the theory really has a strongly interacting sector, its \( I = J = 0 \) boson (like the \( \sigma \) of QCD) may be its least interesting and most elusive feature. Consider, for example, the rich spectrum of resonances in QCD, which we now understand in terms of the interactions of quarks and gluons. Such rich physics in electroweak theory was a prime motivation for the construction of the SSC, and we wish our European colleagues well in their exploration of this energy region via the LHC. [I am also indebted to T. Barklow\(^{106}\) for reminding me of the merits of TeV \( e^+ e^- \) colliders in this regard.]
8. Summary

It appears that the top quark, reported by the CDF Collaboration at this meeting, is here to stay. We look forward to its confirmation by the D0 Collaboration and to more precise measurements of its mass and decay properties. Even now, its reported properties are in comfortable accord with standard model expectations based on electroweak physics and mixing effects.

Tests of the electroweak theory continue to achieve greater and greater precision, with occasional excursions into the land of two- and three-standard deviation discrepancies which stimulate our theoretical inventiveness but may be no more than the expected statistical fluctuations. These effects include a low value of \( \sin^2 \theta \) from SLD, a high value of \( R_b \) from the LEP experiments, and an anomalous forward-backward asymmetry in charmed quark pair production at an energy 2 GeV below the \( Z \).

The Cabibbo-Kobayashi-Maskawa matrix provides an adequate framework for explaining the observed CP violation, which is still confined to a single parameter (\( \epsilon \)) in the neutral kaon system. We have no deep understanding of the origin of the magnitudes or phases in the CKM matrix, any more than we understand the pattern of quark and lepton masses. Nonetheless, there are many possibilities for testing the present picture, a number of which involve rare kaon and \( B \) meson decays.

Numerous opportunities exist for studying CP violation in \( B \) decays, and facilities are under construction for doing so. In view of the widespread attention given recently to asymmetric \( B \) factories, I have mentioned a couple of alternatives which can be pursued at hadron machines and/or symmetric electron-positron colliders.

Neutrino masses may provide us with our next “standard” physics. I have suggested that the mass scale of \( 10^9 - 10^{12} \) GeV is ripe for exploration not only through the measurement of mass differences in the eV- and sub-eV range, but also through studies of leptogenesis and partial unification of gauge couplings. Searches for axions, which I did not mention, also can shed some light on this mass window.

Alternatives for electroweak symmetry breaking, each with consequences for TeV-scale physics, include fundamental Higgs bosons with masses protected by supersymmetry, a strongly interacting Higgs sector, some new physics which we may have thought of but not learned how to make tractable (like compositeness of Higgs bosons, quarks, and leptons), or even something we have not thought of at all. We will really have solved the problem only when we understand the bewildering question of fermion masses, a signal that while the “standard” model may work very well, it is far from complete.

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Figure 2
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Figure 3
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Figure 4

Data:
-71.04 ± 1.58 ± 0.88
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The graph shows the variation of $R_d$ (MSM) and $R_b$ (MSM), $R_b$ (2HD) with $m_{top}$ (GeV) over the range of 100 to 250 GeV. The values and trends are indicated with markers and lines on the graph.
