be Z-mediated FCNC. The conditions for that are given in Eq. (17.16). But the hadronic B decays of relevance are still dominated by SM W-mediated diagrams and $\Gamma_{12}(B_q) \ll M_{12}(B_q)$, so that CP asymmetries can be cleanly interpreted. Mixing in the B_s system cannot be dominated by Z-mediated FCNC. Mixing in the neutral K system can be dominated by Z-mediated FCNC if Eq. (17.14) is satisfied. CP violation in the neutral K system can be dominated by Z-mediated FCNC if Eq. (17.15) is satisfied.

17.4. AN EXPLICIT PARAMETRIZATION

It is convenient to use an explicit parametrization for the mixing matrices. We use the parametrization of Refs. [79,80] (appropriately modified to the 3×4 case). Assuming that all mixing angles θ_{ij} are small, we put $\cos\theta_{ij} = 1$. We use the following constraints from SM tree-level processes and from the unitarity of K:

$$\begin{aligned} s_{12} &= 0.22; \quad s_{23} \approx 0.04; \quad s_{13} \approx 0.004; \\ s_{14} &\leq 0.07; \quad s_{24} \leq 0.5. \end{aligned} \tag{17.21}$$

($s_{ij} \equiv \sin\theta_{ij}$.) We further assume that the unmeasured mixing angles fulfill the hierarchy $s_{14} < s_{24} < s_{34}$. More specifically, we assume that

$$q_{24} \equiv s_{24}/(s_{23}s_{34}), \quad q_{14} \equiv s_{14}/(s_{12}s_{23}s_{34}), \tag{17.22}$$

are both $\mathcal{O}(1)$. We remind the reader that a similar relation for the three generation mixing angles is experimentally verified:

$$q_{13} \equiv s_{13}/(s_{12}s_{23}) = 0.45 \pm 0.15. \tag{17.23}$$

Thus, V has the approximate form:

$$V = \begin{pmatrix} 1 & s_{12} & s_{13}e^{-i\delta_{13}} & s_{14}e^{-i\delta_{14}} \\ -s_{12} & 1 & s_{23} & s_{24}e^{-i\delta_{24}} \end{pmatrix}. \tag{17.24}$$

requirement that mixing of B_d mesons is dominated by Z-mediated FCNC in Eq.

This gives for the relevant U_{pq} elements:

$$\begin{aligned} U_{ds} &= s_{12}s_{23}^2 s_{34}^2 \left[(1 - q_{13}e^{-i\delta_{13}} - q_{24}e^{-i\delta_{24}} + q_{14}e^{i\delta_{14}})(1 - q_{24}e^{i\delta_{24}})\right], \\ U_{db} &= -\, s_{12}s_{23}s_{34}^2 \left[1 - q_{13}e^{-i\delta_{13}} - q_{24}e^{-i\delta_{24}} + q_{14}e^{-i\delta_{14}}\right], \\ U_{sb} &= s_{23}s_{34}^2 \left[1 - q_{24}e^{-i\delta_{24}}\right]. \end{aligned} \tag{17.25}$$

All the experimental constraints in Eqs. (17.11) and (17.12) as well as the condition on $|U_{db}|$ in Eq. (17.16) can be fulfilled with

$$s_{34}^2 \sim 0.04, \quad q_{24} \sim 1, \quad q_{14} \sim 3. \tag{17.26}$$

In this case, the dominant mechanism for B_d mixing will be the Z mediated FCNC, while B_s mixing is dominated by the Standard Model box diagram. On the other hand, we expect Im U_{ds} to be of the same order of magnitude as Re U_{ds}. Consequently, Eq. (17.14) is not satisfied, so that ΔM_K gets no significant contributions from the Z-mediated FCNC, but Eq. (17.15) may still be satisfied, in which case ϵ does get significant contributions from the Z mediated diagrams.

Equation (17.25) implies that the phases in the mixing of B_d and B_s may depend on phases of the mixing matrix other than the single phase of the SM. This may give CP asymmetries which are very different from those predicted by the SM.

17.5. CP ASYMMETRIES IN B DECAYS

Our study involves the three types of CP asymmetries in B decays for which the direct decay is dominated by the W-mediated tree level diagram: $a_{\psi K_S}$, a_{DD} and $a_{\pi\pi}$. These asymmetries still arise almost purely from interference of mixing and decay. Furthermore, as the first unitarity relation is practically maintained, we still have (taking into account CP-parities)

$$a_{\psi K_S} = -a_{DD}. \tag{17.27}$$

In summary, the dominant mechanism for mixing in neutral B_d systems could mediated tree level diagram,

$$\left(\frac{q}{p}\right)_B = \frac{U^*_{db}}{U_{db}}. \tag{17.28}$$

It is now straightforward to evaluate Im$\lambda_{\psi K_S}$ and Im$\lambda_{\pi\pi}$. We find that the various asymmetries simply measure angles of the unitarity quadrangle shown in Fig. 7:

$$a_{\psi K_S} = -a_{DD} = -\sin 2\bar{\beta}, \quad a_{\pi\pi} = -\sin 2\bar{\alpha}, \tag{17.29}$$

where

$$\bar{\alpha} \equiv \arg\left(\frac{V_{ud}V^*_{ub}}{U^*_{db}}\right); \;\; \bar{\beta} \equiv \arg\left(\frac{U^*_{db}}{V_{cd}V^*_{cb}}\right). \tag{17.30}$$

The important point about the modification of the Standard Model predictions is not that the angles α, β and γ may have very different values from those predicted by the SM, but rather that the CP asymmetries do not measure these angles anymore.

As there are no experimental constraints on $\bar{\alpha}$ and $\bar{\beta}$ so that the full range $[0, 2\pi]$ is allowed for each of them, the full range $[-1, +1]$ is possible for each of the asymmetries. This is clearly seen when using the explicit parametrization given in Eqs. (17.24) and (17.25):

$$\begin{aligned} \text{Im}\ \lambda_{\psi K_S} = &- \text{Im}\ \lambda_{DD} = -\text{Im}\left[\frac{1 - q_{13}e^{i\delta_{13}} - q_{24}e^{i\delta_{24}} + q_{14}e^{i\delta_{14}}}{1 - q_{13}e^{-i\delta_{13}} - q_{24}e^{-i\delta_{24}} + q_{14}e^{-i\delta_{14}}}\right], \\ \text{Im}\ \lambda_{\pi\pi} = &\text{Im}\left[\frac{e^{-i\delta_{13}}(1 - q_{13}e^{i\delta_{13}} - q_{24}e^{i\delta_{24}} + q_{14}e^{i\delta_{14}})}{e^{i\delta_{13}}(1 - q_{13}e^{-i\delta_{13}} - q_{24}e^{-i\delta_{24}} + q_{14}e^{-i\delta_{14}})}\right]. \end{aligned} \tag{17.31}$$

It is rather obvious that our ignorance of the phases δ_{14} and δ_{24} allows any value for the various asymmetries. This model demonstrates that there exist extensions of the Standard Model where dramatic deviations from the Standard Model predictions for CP asymmetries in B decays are not unlikely.

Finally, let us mention an interesting point about this model. As mixing of the B_s system is dominated by the Standard Model process, we have, as in the Standard Model,

$$\left(\frac{q}{p}\right)_{B_s}\left(\frac{\bar{A}_{B_s\to\psi\phi}}{A_{B_s\to\psi\phi}}\right) \approx 0. \tag{17.32}$$

As shown in Ref. [81], this is a sufficient condition for the angles extracted from $B \to \psi K_S$, $B \to \pi\pi$ and $B_s \to \rho K_S$ to sum up to π. This happens in spite of the fact that the first two measurements do not correspond to β and α of the unitarity triangle.

18. Extending the Scalar Sector:

Neutral Scalar Exchange

18.1. INTRODUCTION

CP violation could appear in neutral scalar exchange in models with at least two Higgs doublets [82, 83]. If we require both spontaneous CP violation and NFC then at least three scalar doublets [84] (or two doublets and a singlet) are required. (For a discussion of CP violation in multi-scalar models and no NFC, see Refs. [85 – 88].)

We denote scalar doublets by Φ_i, with

$$\Phi_i = \sqrt{\tfrac{1}{2}}\begin{pmatrix}\phi^+_i \\ \phi^0_i\end{pmatrix}, \quad \phi^0_i = v_i + R_i + iI_i. \tag{18.1}$$

The normalization of the VEVs v_i is such that

$$v^2 \equiv \sum_{i=1}^{k} v_i^2 = (\sqrt{2}G_F)^{-1} \approx (246\ GeV)^2. \tag{18.2}$$

We assume NFC with only Φ_1 coupled to D_R and only Φ_2 coupled to U_R:

$$-\mathcal{L}_Y = \overline{Q^I_{Li}} G_{ij} \Phi_1 d^I_{Rj} + \overline{Q^I_{Li}} F_{ij} \Phi_2 u^I_{Rj} + \text{h.c.}. \tag{18.3}$$

The quark mass matrices are then

$$M_d = \sqrt{\tfrac{1}{2}} G\, v_1, \quad M_u = \sqrt{\tfrac{1}{2}} F\, v_2. \tag{18.4}$$

The neutral Higgs interaction with quark mass eigenstates is

$$-\mathcal{L}^n_Y = \frac{R_1}{v_1} \bar{D} M_d^{\text{diag}} D + \frac{I_1}{v_1} \bar{D} M_d^{\text{diag}} i\gamma_5 D + \frac{R_2}{v_2} \bar{U} M_u^{\text{diag}} U + \frac{I_2}{v_2} \bar{U} M_u^{\text{diag}} i\gamma_5 U. \tag{18.5}$$

We now rotate to the scalar mass eigenbasis,

$$\begin{pmatrix} H_1^0 \\ H_2^0 \\ \cdot \\ \cdot \\ \cdot \\ G^0 \end{pmatrix} = O \begin{pmatrix} R_1 \\ I_1 \\ R_2 \\ I_2 \\ \cdot \\ \cdot \end{pmatrix}, \tag{18.6}$$

where G^0 is the would-be Goldstone boson eaten by the Z^0. The Yukawa Lagrangian for neutral Higgs, bottom and top mass eigenstates is given by [89]

$$-\mathcal{L}^n_Y = \sum_{i=1}^{2k-1} \left[(m_b/v_1) \bar{b} (O_{i1} + i\gamma_5 O_{i2}) b + (m_t/v_2) \bar{t} (O_{i3} + i\gamma_5 O_{i4}) t \right] H_i^0, \tag{18.7}$$

and similarly to other quarks. (Another common notation in the literature is

$$g_{1i} = -\frac{v}{v_1} O_{i1}, \quad g_{2i} = -\frac{v}{v_1} O_{i2}, \quad g_{3i} = -\frac{v}{v_2} O_{i3}, \quad g_{4i} = -\frac{v}{v_2} O_{i4}.) \tag{18.8}$$

CP violation in the neutral Higgs sector comes from mixing of CP even and CP odd fields. The quantities that appear in CP violating observables are

$$\begin{aligned} \text{Im } A_1(q) &= \frac{2}{v_1^2} \sum_i \frac{O_{i1} O_{i2}}{q^2 - m_{H_i}^2}, \\ \text{Im } A_2(q) &= \frac{2}{v_2^2} \sum_i \frac{O_{i3} O_{i4}}{q^2 - m_{H_i}^2}. \end{aligned} \tag{18.9}$$

There are two more CP violating quantities, $g_{1i} g_{4i}$ and $g_{2i} g_{3i}$, which correspond to combinations of A_0 and $\tilde{A}_0$ in Ref. [90]. Dimensionless quantities Z_j are defined through

$$A_j(q^2) = \sum_i \frac{\sqrt{2} G_F Z_j}{q^2 - m_{H_i}^2}. \tag{18.10}$$

It has been shown [90, 91] that in a two doublet model, there is a unitarity bound,

$$\begin{aligned} |\text{Im} Z_1| &= 2 \left| \sum_{i=1}^{3} g_{1i} g_{2i} \right| \le \left| \frac{v_u}{v_d} \right| \left(1 + \left| \frac{v_u}{v_d} \right|^2 \right)^{1/2} = \begin{cases} \sqrt{2} & |v_d| = |v_u|, \\ |v_u/v_d|^2 & |v_d| \ll |v_u|, \end{cases} \\ |\text{Im} Z_2| &= 2 \left| \sum_{i=1}^{3} g_{3i} g_{4i} \right| \le \left| \frac{v_d}{v_u} \right| \left(1 + \left| \frac{v_d}{v_u} \right|^2 \right)^{1/2} = \begin{cases} \sqrt{2} & |v_d| = |v_u|, \\ |v_d/v_u| & |v_d| \ll |v_u|. \end{cases} \end{aligned} \tag{18.11}$$

It was further shown that a plausible value of the couplings is close to this unitarity bound [90, 92].

18.2. CP VIOLATION IN NEUTRAL MESON DECAYS

With NFC, neutral Higgs exchange cannot mediate flavor changing processes. Thus it cannot contribute to ϵ at $\mathcal{O}(G_F^2)$ and to ϵ'/ϵ at $\mathcal{O}(G_F)$. Similarly, it cannot contribute significantly to either $B-\bar{B}$ mixing or B decays. Neutral Higgs exchange in models that incorporate NFC is then irrelevant for CP violation in neutral meson systems.

18.3. $\mathcal{D}_N$

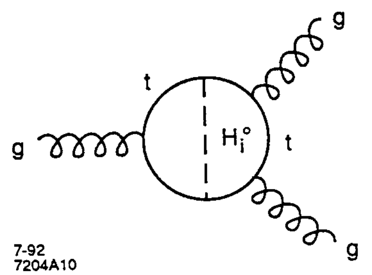

Figure 8. A contribution to the three gluon operator in a two scalar doublet model.

A two loop diagram involving a top quark and neutral Higgs (see Fig. 8) would contribute to $\mathcal{D}_N$ through the three gluon operator [45, 93],

$$C = \frac{2\sqrt{2}G_F g_s^3}{(4\pi)^4} \mathrm{Im} Z_2 h(m_t, m_H), \tag{18.12}$$

so that

$$\mathcal{D}_N \sim 4 \times 10^{-21} e\zeta \mathrm{Im} Z_2 h(m_t, m_H) \text{ cm}. \tag{18.13}$$

ζ is a QCD correction factor [94],

$$\zeta = \left[\frac{g_s(\mu)}{g_s(m_t)}\right]^{-108/23} \left[\frac{g_s(\mu)}{4\pi}\right]^3 \sim 10^{-4}. \tag{18.14}$$

The function $h(m_t, m_H)$ is a result of the two loop integration [93],

$$h(m_t, m_H) = \frac{m_t^4}{4} \int_0^1 dx \int_0^1 du \frac{u^3 x^3 (1-x)}{[m_t^2 x(1-ux) + m_H^2 (1-u)(1-x)]^2}. \tag{18.15}$$

For m_H not much larger than m_t, $h(m_t, m_H) = \mathcal{O}(0.1)$. If, furthermore, $\mathrm{Im} Z_2$ is indeed close to the unitarity bound (18.11), then

$$\mathcal{D}_N \sim 4 \times 10^{-26} |v_d/v_u| \ e \text{ cm}, \tag{18.16}$$

for $|v_d| \ll |v_u|$, and even larger ($\sim 6 \times 10^{-26}$ e cm) for $|v_d| = |v_u|$. Other operators induced by neutral Higgs exchange give contributions comparable to (18.16) [42, 95].

Neutral Higgs exchange could also contribute to $\mathcal{D}_e$, the EDM of the electron. Two loop diagrams may induce values close to the experimental bound [96 – 99].

18.4. SUMMARY

CP violation from neutral Higgs exchange in models with NFC is negligible for the neutral kaon system. It could however give $\mathcal{D}_N$ (and $\mathcal{D}_e$) close to the experimental upper bound.

It was recently realized that, due to the large Yukawa coupling of the top quark, neutral Higgs exchange could induce interesting *CP* violating phenomena in top physics [100].

Charged Scalar Exchange

18.5. INTRODUCTION

CP violation could arise in charged scalar exchange if there are at least three Higgs doublets [83]. This is also the minimal number of doublets required when *CP* breaking is spontaneous only and NFC is maintained [84]. In this case, $\delta_{KM} = 0$ and all *CP* violation comes from the mixing of scalar fields. It is, of course, possible that *CP* is explicitly broken, in which case both quark and Higgs mixings provide *CP* violation.

The charged Higgs interaction with quark mass eigenstates is

$$-\mathcal{L}_Y^c = -\frac{\phi_1^+}{v_1}\bar{U}_L V M_d^{\rm diag} D_R + \frac{\phi_2^+}{v_2}\bar{U}_R M_u^{\rm diag} V D_L + \text{h.c.} \tag{18.17}$$

We now rotate to the scalar mass eigenbasis,

$$\begin{pmatrix} H_1^+ \\ H_2^+ \\ \cdot \\ \cdot \\ G^+ \end{pmatrix} = Y \begin{pmatrix} \phi_1^+ \\ \phi_2^+ \\ \cdot \\ \cdot \\ \cdot \end{pmatrix}, \tag{18.18}$$

where G^+ is the would-be Goldstone boson eaten by the W^+. The Lagrangian for charged Higgs mass eigenstates coupling to quark mass eigenstates is

$$\mathcal{L}_Y^c = \frac{1}{v}\sum_{j=1}^{k-1}(\alpha_j \overline{U_L} V M_d^{\rm diag} D_R + \beta_j \overline{U_R} M_u^{\rm diag} V D_L) H_j^+ + \text{h.c.}, \tag{18.19}$$

where

$$\alpha_j = -\frac{v}{v_1}Y_{j1}^* = -\frac{Y_{j1}^*}{Y_{k1}^*}, \quad \beta_j = -\frac{v}{v_2}Y_{j2}^* = -\frac{Y_{j2}^*}{Y_{k2}^*}. \tag{18.20}$$

CP violation in the charged Higgs sector comes from phases in the mixing matrix for charged scalars (and requires, therefore, at least three doublets). The quantity that appears in CP violating observables is

$$\text{Im } A(q) = 2\sqrt{2}G_F \sum_{i=1}^{2} \frac{\text{Im}\alpha_i\beta_i^*}{q^2 - m_{H_i^+}^2}. \tag{18.21}$$

With only two physical charged scalars, there is only one CP violating parameter in the charged Higgs sector,

$$\text{Im}Z = 2\text{Im}(\alpha_1\beta_1^*) = -2\text{Im}(\alpha_2\beta_2^*), \tag{18.22}$$

where, again, a dimensionless quantity Z was defined through

$$A(q^2) = \sum_i \frac{\sqrt{2}G_F Z_i}{q^2 - m_{H_i^+}^2}. \tag{18.23}$$

There is an interesting question of whether charged Higgs exchange could be the *only* source of CP violation. In other words, we would like to know whether a model of extended Higgs sector with spontaneous CP violation and natural flavor conservation is viable. The answer has been subject to controversy [101 – 104]. In recent years, there have been two attempts [105, 106] to show that this possibility is not yet ruled out. We repeat the analysis (incorporating new data) and find that CP violation cannot result from charged Higgs exchange only, thus confirming the conclusion of Ref. [107].

18.6. THE ϵ PARAMETER

In this framework, neither short distance contributions nor long distance contributions from an intermediate 2π-state can produce large enough ϵ. Thus, to account for ϵ, one needs to assume that the dominant contribution comes from an intermediate η_0 (the $SU(3)$-singlet component of the pseudoscalar nonet):

$$\epsilon \approx \frac{e^{i\pi/4}}{\sqrt{2}\Delta M_K}\text{Im}\frac{\langle K^0 | H_{\Delta S=1} |\eta_0\rangle \langle \eta_0 | H_{\Delta S=1} |\bar{K}^0\rangle}{m_K - m_{\eta_0}}. \tag{18.24}$$

We followed the analyses of Refs. [105, 106].* We find that, to account for the

* We were unable to reproduce the result of Eq. (16) in Ref. [106]. It seems to us that they may have used a numerically wrong value for $\langle K^0 | H | \pi^0 \rangle$. In Ref. [105], in their definition of $G(x)$, there is an overall factor of $1/(1-x)$ missing. This may have enhanced the top contribution in their calculation.

experimental value of ϵ, the Higgs parameters should fulfill

$$\frac{\mathrm{Im}Z}{2m_H^2}\left[\ln\frac{m_H^2}{m_c^2}-\frac{3}{2}\right]=0.11\ GeV^{-2}. \tag{18.25}$$

With $m_{H^+}\geq 42\ GeV$, this gives

$$\mathrm{Im}Z \gtrsim 80. \tag{18.26}$$

18.7. $\mathcal{D}_N$

A large contribution to $\mathcal{D}_N$ comes from the electric dipole moment of the down quark:

$$\mathcal{D}_N=\frac{\sqrt{2}g_G e}{9\pi^2}m_d\mathrm{Im}(\alpha\beta^*)\left[\bar{\eta}_c|V_{cd}|^2\bar{g}\left(\frac{m_c^2}{m_H^2}\right)+\bar{\eta}_t|V_{td}|^2\bar{g}\left(\frac{m_t^2}{m_H^2}\right)\right], \tag{18.27}$$

with

$$g(x)=\frac{x}{(1-x)^2}\left[\frac{5x}{4}-\frac{1-3x/2}{1-x}\ln x-\frac{3}{4}\right]. \tag{18.28}$$

We neglect the contribution of the top quark (it adds to the charm contribution) and we take the current mass at 1 GeV for m_d ($m_d=9\ MeV$). It is more plausible that we should actually use the constituent $m_d\approx 330\ MeV$.† Thus, we may be underestimating $\mathcal{D}_N$ by as much as a factor of ~ 40. The result is

$$\mathcal{D}_N\approx 2.5\times 10^{-25}\ e\ \mathrm{cm}. \tag{18.29}$$

We conclude that in a model where ϵ arises from charged Higgs exchange, $\mathcal{D}_N$ is at least two times larger and more probably two orders of magnitude larger than the experimental upper bound.

† See a discussion of this point in Ref. [108].

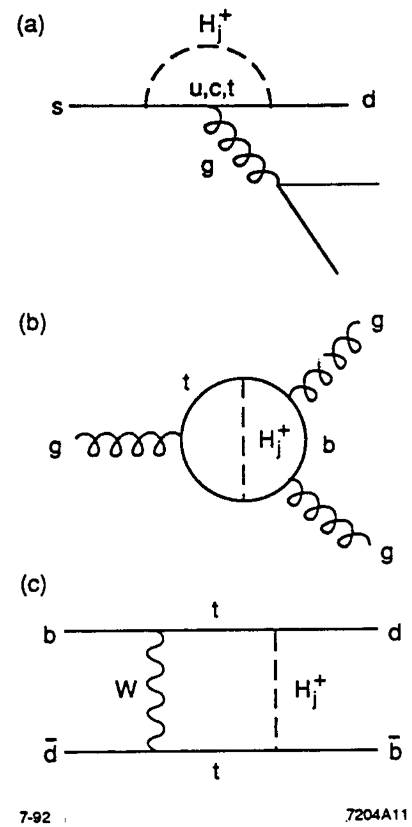

Figure 9. CP violating contributions from charged scalar exchange: (a) A contribution to $\Delta S=1$ processes. It affects both ϵ and ϵ'. (b) A contribution to the three gluon operator. (c) A contribution to $B\to\bar{B}$ mixing.

CP violation in the charged Higgs sector would also contribute to the three gluon operator with [93]

$$C = 4\sqrt{2}\zeta G_F g_s^3 (4\pi)^{-4} \mathrm{Im}(\alpha\beta^*) h'(m_b, m_t, m_H), \tag{18.30}$$

where h' is a function of m_b, m_t and m_H which, for $m_t \gg m_b$ is given by

$$h'(m_t \gg m_b) = \frac{m_t^2 m_H^4}{4(m_H^2 - m_t^2)^3}\left[\ln\frac{m_H^2}{m_t^2} - \frac{3}{2} + 2\frac{m_t^2}{m_H^2} - \frac{1}{2}\frac{m_t^2}{m_H^4}\right]. \tag{18.31}$$

For $m_H^2 \ll m_t^2$, $h' \approx h/2$, while for $m_H^2 \gg m_t^2$, $h' \approx h$. The QCD correction factor ζ is given by [109, 110]

$$\zeta = \left[\frac{g_s(m_b)}{g_s(m_t)}\right]^{\gamma_b/\beta_5} \left[\frac{g_s(m_c)}{g_s(m_b)}\right]^{\gamma_g/\beta_4} \left[\frac{g_s(\mu)}{g_s(m_c)}\right]^{\gamma_g/\beta_3}, \tag{18.32}$$

where $\gamma_g = -18$, $\gamma_b = -14/4$ and $\beta_n = (33-2n)/6$. It follows then from (18.25) that, if charged Higgs exchange accounts for ϵ,

$$\mathcal{D}_N \approx 10^{-23}\ e\ \mathrm{cm}, \tag{18.33}$$

two orders of magnitude above the experimental upper bound.

18.8. ϵ'/ϵ

Early calculations of ϵ'/ϵ, using PCAC relations for the physical $K_L \to 2\pi$ amplitude, found $\epsilon'/\epsilon \approx -1/22$ [101, 102]. It was later realized [103] that actually the contribution to $\mathrm{Im}A(K^0 \to \pi\pi)$ is chirally suppressed,

$$\langle \pi^+\pi^- | \mathcal{L}_- | K^0 \rangle = -\frac{i\sqrt{2}D}{2f_\pi} \langle \pi^0 | \mathcal{L}_- | K^0 \rangle. \tag{18.34}$$

The suppression factor D is expected to be of $\mathcal{O}(m_K^2/4\pi^2 f_\pi^2)$, and leads to ϵ'/ϵ of $\mathcal{O}(10^{-3})$. Note that in this framework the value of ϵ'/ϵ is independent of $\langle \pi | \mathcal{L}_- | K \rangle$ and consequently of the CP violating parameters of the Higgs sector.

18.9. CP ASYMMETRIES IN B DECAYS

The Y-matrix introduces new phases into the charged scalar couplings to quarks. However, the leading contribution from ϕ_j^+-exchange diagrams to $B-\bar{B}$ mixing comes from the term proportional to m_t. This gives $(Y_{j2}^* V_{td})(Y_{j2}^* V_{tb})^*$, and has exactly the same phase as the Standard Model W-exchange box diagram. Consequently, $(q/p)_B = (M_{12}^*/M_{12})$ remains unchanged, and there is no modification to the Standard Model predictions for CP asymmetries in B decays [111]. Note that this conclusion is independent of whether charged scalar exchange contributes significantly to $B - \bar{B}$ mixing or not.

18.10. SUMMARY

A relative phase between VEVs in a multi-Higgs model with NFC ***cannot*** be the only source of CP violation. Of course, in a model with explicit CP violation, such that $\delta_{KM} \neq 0$, a relative phase between VEVs could be an additional source of CP violation. It would not affect ϵ significantly, but it may saturate the upper bound on $\mathcal{D}_N$. An order of magnitude estimate suggests that if the contribution to ϵ is small, so is the contribution to ϵ'/ϵ independently of the Higgs parameters. There is no effect on CP asymmetries in B decays.

19. Extending the Gauge Sector:

Left-Right Symmetry (LRS)

19.1. INTRODUCTION

We study a specific version of LRS models, where P, C and CP are symmetries of the Lagrangian that are spontaneously broken [112 – 117]. The electroweak gauge group is $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$. Left-handed quarks reside in $(2,1)_{1/3}$ representations and right-handed ones in $(1,2)_{1/3}$. The scalar content [118] of the minimal LRS model is $\Phi(2,2)_0$, $\Delta_L(3,1)_2$ and $\Delta_R(1,3)_2$. A model with only minimal scalar content and spontaneous CP violation predicts unacceptably large FCNC [119]. To avoid this, one has to add scalar singlets or triplets but these do not affect our analysis. The only specific assumption about the scalar sector that we make is the existence of a single Φ-field. (At least one such field is necessary to induce fermion masses.) The VEV of Φ is

$$\langle\Phi\rangle = \begin{pmatrix} k & 0 \\ 0 & k'e^{i\eta} \end{pmatrix}. \tag{19.1}$$

The relative phase η between k and k' spontaneously breaks CP: in principle, it is the only source of CP violation in this model. Eventually there are seven CP violating phases in the mass eigenbasis. They all vanish when $\eta = 0$ but they are independent parameters.

The phase η appears explicitly in the mixing of the charged gauge bosons:

$$\begin{aligned} W_1 &= \cos\xi\ W_L + e^{-i\eta}\sin\xi\ W_R, \\ W_2 &= -\,e^{i\eta}\sin\xi\ W_L + \cos\xi\ W_R, \end{aligned} \tag{19.2}$$

where

$$\xi = \frac{kk'}{v_R^2}. \tag{19.3}$$

The Yukawa couplings are given by

$$\mathcal{L}_{\text{Yukawa}} = \overline{Q_L^I}(A\Phi + B\tau_2\Phi^*\tau_2)Q_R^I + \text{h.c.}, \tag{19.4}$$

where $Q^I_{L(R)}$ are quark doublets of $SU(2)_{L(R)}$, τ_2 is the Pauli matrix acting in the $SU(2)_L$ or $SU(2)_R$ space, A and B are matrices in generation space.

P symmetry requires that A and B are hermitian; C symmetry requires that A and B are symmetric; and CP invariance implies that A and B are real. The mass matrices,

$$\begin{aligned} M_u &= kA + k'e^{-i\eta}B, \\ M_d &= k'e^{i\eta}A + kB, \end{aligned} \tag{19.5}$$

are symmetric. The symmetry of the mass matrices implies

$$V_R = F_u V_L^* F_d^\dagger, \tag{19.6}$$

where V_L and V_R are the mixing matrices for left-handed and right-handed quarks, respectively, and F_u and F_d are diagonal unitary matrices:

$$F_u = \text{diag}(e^{i\phi_u}, e^{i\phi_c}, e^{i\phi_t}); \quad F_d = \text{diag}(e^{i\phi_d}, e^{i\phi_s}, e^{i\phi_b}). \tag{19.7}$$

On top of the single CP violating phase of V_L there are five CP violating phase differences in F_u and F_d.

For the purpose of studying *new* contributions to ϵ, $\mathcal{D}_N$ and ϵ'/ϵ, it is simpler to work in a two generation framework. In this case V_L is real and there are three phases in F_u and F_d. We define:

$$\begin{aligned} \gamma &= (\phi_c + \phi_u - \phi_s - \phi_d)/2 + \eta, \\ \delta_1 &= (\phi_c - \phi_u + \phi_s - \phi_d)/2, \\ \delta_2 &= (\phi_c - \phi_u - \phi_s + \phi_d)/2. \end{aligned} \tag{19.8}$$

Choosing a basis where V_L is real and the mixing of $W_L - W_R$ is real, these phases appear in V_R only:

$$V_W = \begin{pmatrix} c_\xi & s_\xi \\ -s_\xi & c_\xi \end{pmatrix}; \quad V_L = \begin{pmatrix} c_\theta & s_\theta \\ -s_\theta & c_\theta \end{pmatrix}; \quad V_R = e^{i\gamma}\begin{pmatrix} e^{-i\delta_2}c_\theta & e^{-i\delta_1}s_\theta \\ -e^{i\delta_1}s_\theta & e^{i\delta_2}c_\theta \end{pmatrix}. \tag{19.9}$$

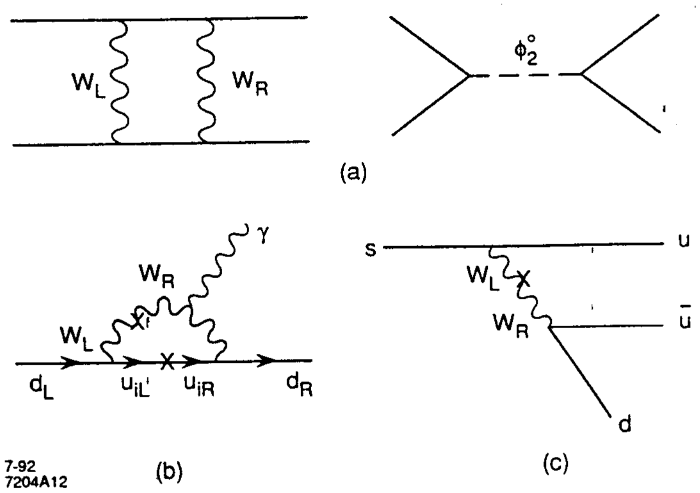

Figure 10. *CP* violating diagrams in a LRS framework. (a) Contributions to ϵ from a box diagram with W_R and from a tree diagram with neutral scalar. (b) A contribution to the EDM of the down quark. (c) A contribution to ϵ'.

19.2. THE ϵ PARAMETER

For ϵ, the dominant contributions come from the diagrams of Fig. 10(a). $W_L - W_R$ mixing can be safely neglected. The value of $M_{12}(K)$ in this model is [114, 117]

$$\frac{M_{12}^{\rm LRS}}{M_{12}^{\rm SM}} = 1 - e^{i(\delta_2-\delta_1)}\left[430\beta - 15\beta\ln\beta + Q_H^2\left(11600\beta_H - 15\beta_H\ln\beta_H\right)\right], \quad (19.10)$$

where

$$\beta = \frac{m_{W_1}^2}{m_{W_2}^2}, \quad \beta_H = \frac{m_{W_1}^2}{m_{H^0}^2}, \quad Q_H = \frac{k^2+k'^2}{k^2-k'^2}, \quad (19.11)$$

and we assumed $m_{H^0} \sim m_{A^0} \sim m_{H^+}$. The factor of 430 was first calculated in Ref. [120], and is the product of three factors of $\mathcal{O}(1)$: a factor of 2 since two diagrams contribute, a factor of $4[\ln(m_{W_1}^2/m_c^2)-1] \sim 28$ from loop integration and a factor of 7.6 due to the Lorentz structure of the relevant matrix element. The factor of 11600 arises because H^0 contributes at tree level. Requiring $2{\rm Re}M_{12}^{\rm LRS} \le \Delta M_K$ gives

$$m_{W_2} \ge 1.7\ TeV, \quad m_H \ge 8.8\ TeV. \quad (19.12)$$

Note that the bound $\beta \lesssim 1/430$ implies

$$\xi \le 2.2\times 10^{-3}. \quad (19.13)$$

Equation (19.10) leads to

$$|\epsilon| = \frac{\sin(\delta_2-\delta_1)}{2\sqrt{2}}\left[430\beta - 15\beta\ln\beta + Q_H^2\left(11600\beta_H - 15\beta_H\ln\beta_H\right)\right]. \quad (19.14)$$

To derive an upper bound on $\sin(\delta_2-\delta_1)$, we take $m_H^2/m_{W_2}^2 \le 4\pi/g_R^2 \sim 30$. Then

$$\beta\sin(\delta_2-\delta_1) \lesssim \frac{2\sqrt{2}|\epsilon|}{820} \sim 10^{-5} \Longrightarrow \sin(\delta_2-\delta_1) \le \left(\frac{m_{W_2}}{30\ TeV}\right)^2. \quad (19.15)$$

Conversely, for ϵ to be dominated by the LRS contribution, we need (assuming $m_H \gtrsim m_{W_2}$)

$$\beta\sin(\delta_2-\delta_1) \gtrsim \frac{2\sqrt{2}|\epsilon|}{12000} \sim 5\times10^{-7} \Longrightarrow m_{W_2} \lesssim 120\ TeV\,[\sin(\delta_2-\delta_1)]^{1/2}. \quad (19.16)$$

19.3. $\mathcal{D}_N$

The most important LRS contributions to $\mathcal{D}_n$ arise from quark EDMs [see Fig. 10(b)]. All phases in V_R contribute to $\mathcal{D}_N$ [121], but $(\gamma+\delta_1)$ which contributes to $\mathcal{D}_d$ proportionally to m_c is the most important one. A recent calculation [122] gives

$$\mathcal{D}_N = 2\times10^{-23}\xi[4.5\sin(\gamma-\delta_2)+74\sin(\gamma+\delta_1)-1.1\sin(\gamma-\delta_1)+16\sin(\gamma+\delta_2)]e \text{ cm}. \tag{19.17}$$

The upper bound (19.13) implies $\mathcal{D}_N \le 4\times10^{-24}$ e cm. Assuming no strong cancellations among the various terms in (19.17), we get

$$\xi\sin(\gamma+\delta_1) \lesssim 10^{-4}. \tag{19.18}$$

There are also LRS contributions to $\mathcal{D}_n$ through the three gluon operator. These contributions are estimated to be an order of magnitude smaller than those from the quark EDMs [123].

19.4. ϵ'/ϵ

The contribution to ϵ'/ϵ [Fig. 10 (c)] comes from all phases in V_R but the phases in the first row, $(\gamma-\delta_1)$ and $(\gamma-\delta_2)$, contribute at tree level with W_L-W_R mixing [112, 113]. A recent calculation [122] gives

$$|\epsilon'/\epsilon| = 276\xi|\sin(\gamma-\delta_2)+\sin(\gamma-\delta_1)-0.1\sin(\gamma+\delta_1)-0.1\sin(\gamma+\delta_2)|. \tag{19.19}$$

The bound (19.13) implies $|\epsilon'/\epsilon| \le 1.3$. Assuming no strong cancellations among the various terms in (19.19), we get

$$\xi[\sin(\gamma-\delta_1)+\sin(\gamma-\delta_2)] \lesssim 10^{-5}. \tag{19.20}$$

19.5. CP asymmetries in B decays

The effect of LRS on CP asymmetries in B decays is very small because LRS contributions to $B-\bar{B}$ mixing are small in magnitude. The reason for that is as follows. One of the enhancement factors for LRS contribution to $K-\bar{K}$ mixing is the hadronic matrix element,

$$\frac{\langle K^0|\,\bar{d}_L s_R \bar{d}_R s_L\,|\bar{K}^0\rangle}{\langle K^0|\,(\bar{d}_L\gamma^\mu s_L)^2\,|\bar{K}^0\rangle} = \frac{3}{4}\left[\left(\frac{m_K}{m_s+m_d}\right)^2+\frac{1}{6}\right] \approx 7.6. \tag{19.21}$$

However, as $m_B \approx m_b$, there is no similar enhancement in the B system. (The corresponding factor in B is very close to 1.) This implies that if LRS contributions to $K-\bar{K}$ mixing are as large as the Standard Model contribution, then the LRS contributions to $B-\bar{B}$ mixing are $\mathcal{O}(0.1)$ of the Standard Model contribution.

19.6. Summary

Even though all the phases in the LRS model with spontaneously broken CP arise from the single phase η in the VEV $\langle\Phi\rangle$, it is difficult to relate their values unless one makes additional assumptions. Thus, the three bounds that we found could all be saturated simultaneously [124]:

$$\begin{aligned} |\beta\sin(\delta_2-\delta_1)| &\lesssim 10^{-5},\\ |\xi\sin(\gamma+\delta_1)| &\lesssim 10^{-4},\\ |\xi[\sin(\gamma-\delta_1)+\sin(\gamma-\delta_2)]| &\lesssim 10^{-5}. \end{aligned} \tag{19.22}$$

However, without (at least mild) fine-tuning, saturation of the ϵ'/ϵ bound would imply that the contribution to $\mathcal{D}_N$ is one to two orders of magnitude below the present experimental limit. If $k'/k \le 0.1$ and all phases are of the same order of magnitude, then the ϵ-bound is the strongest.

For $k'/k \ll 1$, one can find relations among the various phases:

$$\delta_2 = -\frac{1}{2}\frac{k'}{k}\frac{m_c}{m_s}\sin\eta, \quad \delta_1 = -3\delta_2, \quad \gamma = \eta - \delta_2. \tag{19.23}$$

If, furthermore, $k'/k \ll m_s/m_c$, then (19.22) gives

$$|\xi(m_c/m_s)\sin\eta| \lesssim 10^{-5}, \quad |\xi\sin\eta| \lesssim 10^{-4}, \quad |\xi\sin\eta| \lesssim 5\times 10^{-6}, \tag{19.24}$$

namely, the ϵ-bound is the strongest. Furthermore, ϵ'/ϵ and $\mathcal{D}_N$ are related in this case [113, 122]

$$|\mathcal{D}_N| = 3.6\times 10^{-24}|\epsilon'/\epsilon|\ e\ \text{cm}. \tag{19.25}$$

20. SUSY

20.1. SOURCES OF CP VIOLATION IN MINIMAL SUSY

CP violation in SUSY theories has been the subject of intensive theoretical study [125 – 133]. Our discussion here follows for the most part the very clear discussion in Ref. [126].

The simplest and most predictive among SUSY models is the low energy effective theory of the minimal $N = 1$ supergravity. The low energy gauge group is $SU(3)\times SU(2)\times U(1)$. There are three generations of left chiral matter fields, $Q(3,2)_{1/6}$, $\bar{U}(\bar{3},1)_{-2/3}$, $\bar{D}(\bar{3},1)_{1/3}$, $L(1,2)_{-1/2}$, $\bar{E}(1,1)_1$, and a pair of Higgs supermultiplets, $H_u(1,2)_{1/2}$ and $H_d(1,2)_{-1/2}$. The Yukawa couplings and scalar potential in the supersymmetric limit are derived from the superpotential,

$$W = \bar{U}\lambda_U Q H_u + \bar{D}\lambda_D Q H_D + \bar{E}\lambda_E L H_D + \mu H_u H_d. \tag{20.1}$$

The λ_i are general 3×3 matrices. The SUSY breaking is due to the hidden sector and gives rise to three types of soft SUSY breaking operators:

(*i*) Trilinear scalar self couplings (ξ_i are general 3×3 matrices):

$$[\bar{U}\xi_U Q H_u + \bar{D}\xi_D Q H_d + \bar{E}\xi_E L H_d + \mu B H_u H_d] + \text{h.c.}. \tag{20.2}$$

(*ii*) Gaugino Majorana masses:

$$\tfrac{1}{2}M_1\lambda_1\lambda_1 + \tfrac{1}{2}M_2\lambda_2\lambda_2 + \tfrac{1}{2}M_3\lambda_3\lambda_3 + \text{h.c.} \tag{20.3}$$

(*iii*) Masses for the scalar fields z_a of the chiral superfields

$$M^2_{ab} z^*_a z_b + \text{h.c.} \tag{20.4}$$

It became a common practice to restrict

$$M^2_{ab} = m^2_{3/2}\delta_{ab} \tag{20.5}$$

at the renormalization point of the Planck scale. This is essentially a phenomenological requirement: in order that the contribution from box diagrams with squarks and winos does not exceed the measured value of ΔM_K, one needs

$$\left(V^\dagger \frac{M_Q^2}{m^2_{3/2}} V\right)_{12} \lesssim \frac{1}{100}\frac{m_{3/2}}{M_W}. \tag{20.6}$$

(M_Q^2 is the mass matrix (20.5) for the scalar partners of left-handed quarks; V is the CKM matrix.) One could also implement (20.5) as a requirement on the properties of the Kähler potential. A second phenomenological constraints is that, if we write

$$\xi_i = m_{3/2}A\lambda_i + \tilde{\xi}_i, \tag{20.7}$$

then $\tilde{\xi}_i$ are small. Otherwise, large contributions to ΔM_K from strong superbox diagrams with LR current structure arise. If the superpotential is separable into a hidden sector piece (which breaks SUSY) and observable sector piece, then $\tilde{\xi} = 0$. We put

$$\tilde{\xi} = 0, \tag{20.8}$$

and assume grand unification,

$$M_1 = M_2 = M_3. \tag{20.9}$$

Then the theory at the Planck scale can be written as

$$\begin{aligned} &[\bar{U}\lambda_U QH_u + \bar{D}\lambda_D QH_D + \bar{E}\lambda_E LH_D + \mu H_u H_d]_F + \text{h.c.} \\ &+m_{3/2}[A\bar{U}\lambda_U QH_u + A\bar{D}\lambda_D QH_D + A\bar{E}\lambda_E LH_D + \mu BH_u H_d]_A + \text{h.c.} \\ &+\tfrac{1}{2}\tilde{m}(\lambda_1\lambda_1 + \lambda_2\lambda_2 + \lambda_3\lambda_3) + \text{h.c.} + m_{3/2}^2 z_a^* z_a. \end{aligned} \tag{20.10}$$

Note that even with the constraints (20.5), (20.8) and (20.9) imposed at the Planck scale, they do not hold at low energy. The RGEs generate flavor changing and CP violating contributions to the squark mass matrices and to the trilinear scalar self couplings. The crucial point in analyses of FCNC and CP violation in minimal SUSY is that the deviation of the mass matrices for down squarks from a unit matrix is almost negligible for $\tilde{D}_R$ while it is $\propto M_u^\dagger M_u$ for $\tilde{D}_L$:

$$\Delta M_Q^2 \approx \frac{m_{3/2}^2 \ln(M_P^2/m_W^2)}{8\pi^2}(3 + |A|^2)\lambda_U^\dagger \lambda_U. \tag{20.11}$$

This relates FCNC and CP violation in the K^0 and B^0 systems to the CKM parameters. Let us count the number of CP violating phases in (20.10).

- While λ_E can be made real and diagonal, there is one unremovable phase in λ_U and λ_D which we call δ_P. This is the usual KM phase, with a subscript P to denote the renormalization point of the Planck scale.

- The strong CP parameter now gets contributions from gaugino masses:

$$\bar{\theta} = \theta - \arg\det \lambda_U \lambda_D - 3\arg\tilde{m}. \tag{20.12}$$

- There are four more complex parameters: A, B, μ and $\tilde{m}$. But two of these phases are removable. Thus, in the low energy supersymmetric model described by (20.10), there are two new phases beyond the Standard Model:

$$\phi_A = \arg(A\tilde{m}^*), \quad \phi_B = \arg(B\tilde{m}^*), \tag{20.13}$$

(where we fixed the phase of μ to give $\arg(\mu B){=}0$). The simplest hidden sector yields $\phi_A = \phi_B = 0$.

To summarize, SUSY effects on CP violation are of three types:

a. The values of CKM parameters deduced from experiments may change, because there are additional contributions to the relevant (CP violating as well as CP conserving) processes.

b. The two Standard Model sources, δ and θ may contribute in new ways, either because they appear in interactions of SUSY particles, or because of their effects through radiative corrections.

c. There may be two new sources of CP violation, ϕ_A and ϕ_B.

20.2. $\mathcal{D}_N$ FROM ϕ_A AND ϕ_B

The most stringent bound on the phases ϕ_A and ϕ_B comes from their contribution to the finite renormalization of $\bar{\theta}$ (through their contribution to quark mass matrices) [126]:

$$\delta\bar{\theta} \sim \frac{6\alpha_3}{4\pi}(\phi_A + \phi_B). \tag{20.14}$$

This leads to

$$|\phi_A + \phi_B| \lesssim 10^{-7}. \tag{20.15}$$

This suggests that, if ϕ_A and ϕ_B are different from zero, the theory should have an axion. In such a case, the most stringent bound comes from the direct contribution of ϕ_A and ϕ_B to quark EDMs [Fig. 11(a)] [126]:

$$\begin{aligned}\mathcal{D}_N \sim & \frac{e\alpha_3}{4\pi}\frac{|M_3 m_u \mu \langle H_d\rangle / \langle H_u\rangle|}{m_{3/2}^2 \max(m_{3/2}^2, |M_3|^2)} \arg(M_3^* B) \\ & + \frac{\alpha_3}{4\pi}\frac{|M_3 \xi_{U11}/\lambda_{U11}|}{m_{3/2}^2 \max(m_{3/2}^2, |M_3|^2)} \arg(M_3^* \xi_{U11}).\end{aligned} \tag{20.16}$$

Taking all supersymmetric parameters to equal $m_{3/2}$, this gives

$$\mathcal{D}_N \sim \left[\frac{100\ GeV}{m_{3/2}}\right]^2 \left[\frac{\arg(M_3^* B) + \arg(M_3^* \xi_U)}{10^{-3}}\right] 10^{-25}\ e\ \mathrm{cm}. \tag{20.17}$$

For $m_{3/2} \sim 100\ GeV$ this gives a bound of $\mathcal{O}(10^{-3})$ on ϕ_A and ϕ_B. For a higher SUSY breaking scale, $m_{3/2} \sim 1\ TeV$, the bound is milder, $\mathcal{O}(0.1)$. The SUSY contributions to the three gluon operator give similar bounds [131]. In any case, (20.17) implies that ϕ_A and ϕ_B have no interesting role in CP violation in neutral meson systems.

20.3. THE NEUTRAL K SYSTEM

There are several supersymmetric contributions to $M_{12}(K)$ [Fig. 11(b)]:

1. The supersymmetric partners of the Standard Model box diagrams: For this not to exceed the experimental value of ΔM_K, near degeneracy among squarks is required [see (20.6)] and $\tilde{\xi}$ is required to be small.

2. The strong superbox diagrams with LR current structure: The experimental values of ΔM_K and ϵ require [126]

$$\begin{aligned}\mathrm{Re}\left(\frac{M_{DS}^2 M_{\tilde{S}D}^{*2}}{m_{3/2}^4}\right) & \lesssim 2 \times 10^{-5}\frac{m_{3/2}^2}{m_W^2}, \\ \mathrm{Im}\left(\frac{M_{DS}^2 M_{\tilde{S}D}^{*2}}{m_{3/2}^4}\right) & \lesssim 6 \times 10^{-8}\frac{m_{3/2}^2}{m_W^2}.\end{aligned} \tag{20.18}$$

For $\tilde{\xi} = 0$ so that $\Delta\xi_D$ arises from RG scaling only, the contribution is negligible

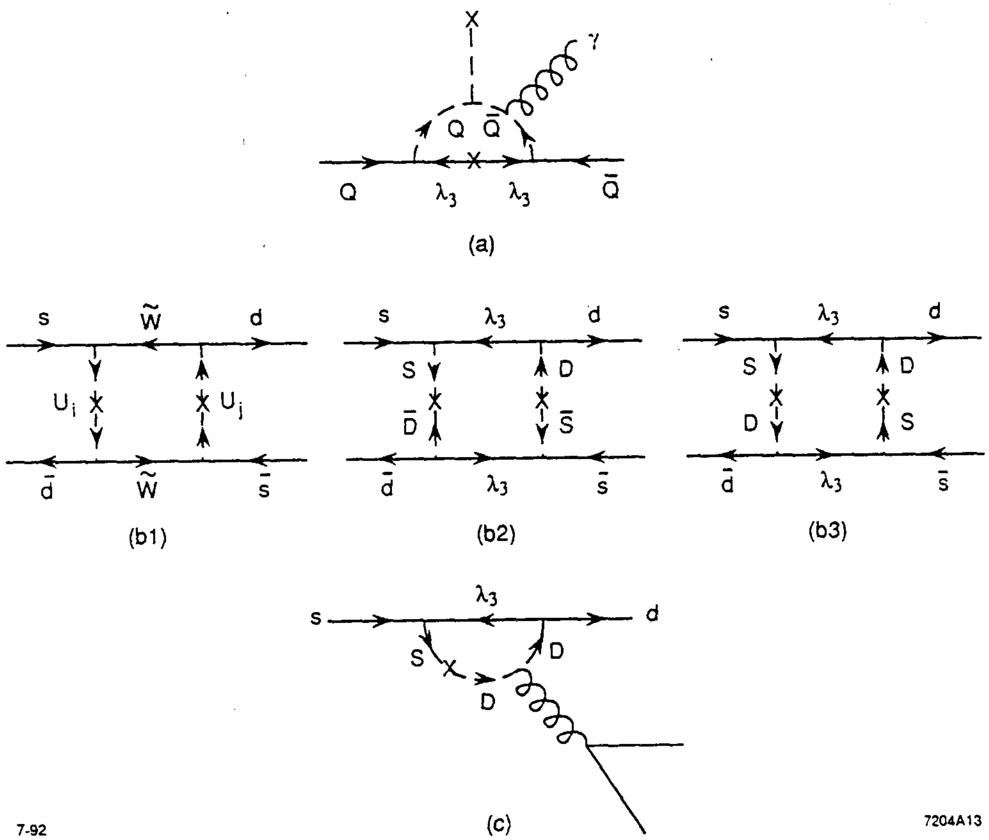

Figure 11. CP violating diagrams in the minimal SUSY framework. (a) A contribution to the EDM of the down quark. (b) Contributions to ϵ from box diagrams with (1) winos and squarks, (2) gluinos and squark doublets and singlets, and (3) gluinos and squark doublets. (c) A contribution to ϵ'.

because there is an extra power of a small quark mass,

$$\Delta\xi_D = \left(\frac{m_D}{m_W} V^\dagger \frac{m_U^2}{m_W^2} V\right). \tag{20.19}$$

Actually, the phase ϕ_A discussed in the previous section contributes through a similar diagram, and it is this extra suppression which renders its effect negligible.

3. The strong superbox diagrams with LL current structure: the contribution to ΔM_K is small. The contribution to ϵ is estimated to be

$$|\epsilon|_{susy} = 300 \frac{m_t^4}{m_{3/2}^2 m_W^2} \frac{\mathrm{Im}[(V_{td}^* V_{ts})^2]}{2|V_{us}|^2}. \tag{20.20}$$

This leads roughly to

$$|J| \lesssim \frac{m_W^2 m_{3/2}^2}{m_t^4} 4 \times 10^{-4}, \tag{20.21}$$

which is weaker than direct bound on $|J|$. Conversely, the strong superbox diagram does not dominate over the Standard Model contribution to ϵ, but may be comparable for large m_t.

Supersymmetric penguin diagrams [Fig. 11(c)] give additional contributions to ϵ'/ϵ. While the GIM mechanism gives a logarithmic dependence on m_t for the Standard Model penguin, it gives a quadratic dependence on m_t for the SUSY penguin:

$$\frac{(\epsilon'/\epsilon)_{spen}}{(\epsilon'/\epsilon)_{peng}} \approx \frac{1}{5}\left(\frac{g_3}{g}\right)^2 \frac{(m_t/m_{3/2})^2}{\ln(m_t/m_c)^2}. \tag{20.22}$$

Again, for large m_t the SUSY contribution to ϵ'/ϵ may be large but will not change the order of magnitude estimate from the Standard Model.

20.4. CP ASYMMETRIES IN B DECAYS

The strong superbox diagrams contribute to $B - \bar{B}$ mixing. However, in the minimal SUSY models as defined above, the weak phases are exactly the CKM phases of the Standard Model. Consequently, $(q/p)_B = (M_{12}^*/M_{12})^{1/2}$ remains unchanged and the Standard Model predictions are not modified. This conclusion is independent of whether the SUSY contributions to $M_{12}(B)$ are large or not.

20.5. SUMMARY

The two new sources of CP violation that appear in minimal SUSY models, ϕ_A and ϕ_B, may saturate the upper bound on the EDM of the neutron even if the SUSY breaking scale is a few TeV. However, they have no impact on CP violation in neutral meson systems.

There are additional contributions to CP violation in the neutral K system which arise from δ_{KM} due to the existence of supersymmetric box diagrams that contribute to ϵ and supersymmetric penguin diagrams that contribute to ϵ'/ϵ. However, these contributions are at most comparable to the Standard Model contributions, and thus no significant constraints on the relevant parameters arise. If the SUSY breaking scale is above the electroweak breaking scale, then SUSY contributions to FCNC processes and, in particular, to CP violating processes are too small to have observable effects. The same seems to hold for models where electroweak breaking is induced radiatively, even if the SUSY breaking scale is not particularly large.

In the minimal SUSY model, the Standard Model predictions for CP asymmetries in B decays remain unchanged.

In extensions of the minimal SUSY models, such that $\tilde{\xi} \neq 0$, or where $M_{ab}^2 /\!\!\propto \delta_{ab}$, most of the above considerations do not hold and many different supersymmetric effects on CP violating observables may occur (see *e.g.*, Refs. [132, 133]). In Ref. [130] it was shown that in non-minimal SUSY models there could be significant modifications of CP asymmetries in B decays. All asymmetries may have any value in the full range $[-1, 1]$.

21. Reducing the Number of Parameters:

Schemes for Quark Mass Matrices

Various schemes for mass matrices predict relations among parameters of the quark sector. The hope is that, if these relations are experimentally verified, it will lead us to find symmetries that operate differently on different generations ("horizontal symmetries").

Some of these schemes are very powerful in their predictions for CP asymmetries in B decays. Instead of the Standard Model allowed range for the asymmetries depicted in Fig. 6, a much smaller range is allowed when the various mass and mixing parameters are related. Thus, the measurement of $a_{\psi K_S}$ and $a_{\pi\pi}$ will provide a stringent test for these schemes. In Fig. 12 we present the predictions of five schemes of quark parameters [71].

The Fritzsch scheme [134] assumes that the quark mass matrices have the following form:

$$M_d = \begin{pmatrix} 0 & a_d e^{i\phi_1} & 0 \\ a_d e^{-i\phi_1} & 0 & b_d e^{i\phi_2} \\ 0 & b_d e^{-i\phi_2} & c_d \end{pmatrix}, \quad M_u = \begin{pmatrix} 0 & a_u & 0 \\ a_u & 0 & b_u \\ 0 & b_u & c_u \end{pmatrix}. \tag{21.1}$$

The scheme by Giudice [135] assumes that, at the GUT scale, the fermion mass matrices have the following form:

$$M_d = \begin{pmatrix} 0 & f e^{i\phi} & 0 \\ f e^{-i\phi} & d & 2d \\ 0 & 2d & c \end{pmatrix}, \quad M_u = \begin{pmatrix} 0 & 0 & b \\ 0 & b & 0 \\ b & 0 & a \end{pmatrix}, \quad M_\ell = \begin{pmatrix} 0 & f & 0 \\ f & -3d & 2d \\ 0 & 2d & c \end{pmatrix}. \tag{21.2}$$

The scheme by Dimopoulos, Hall and Raby [136] assumes that, at the GUT scale,

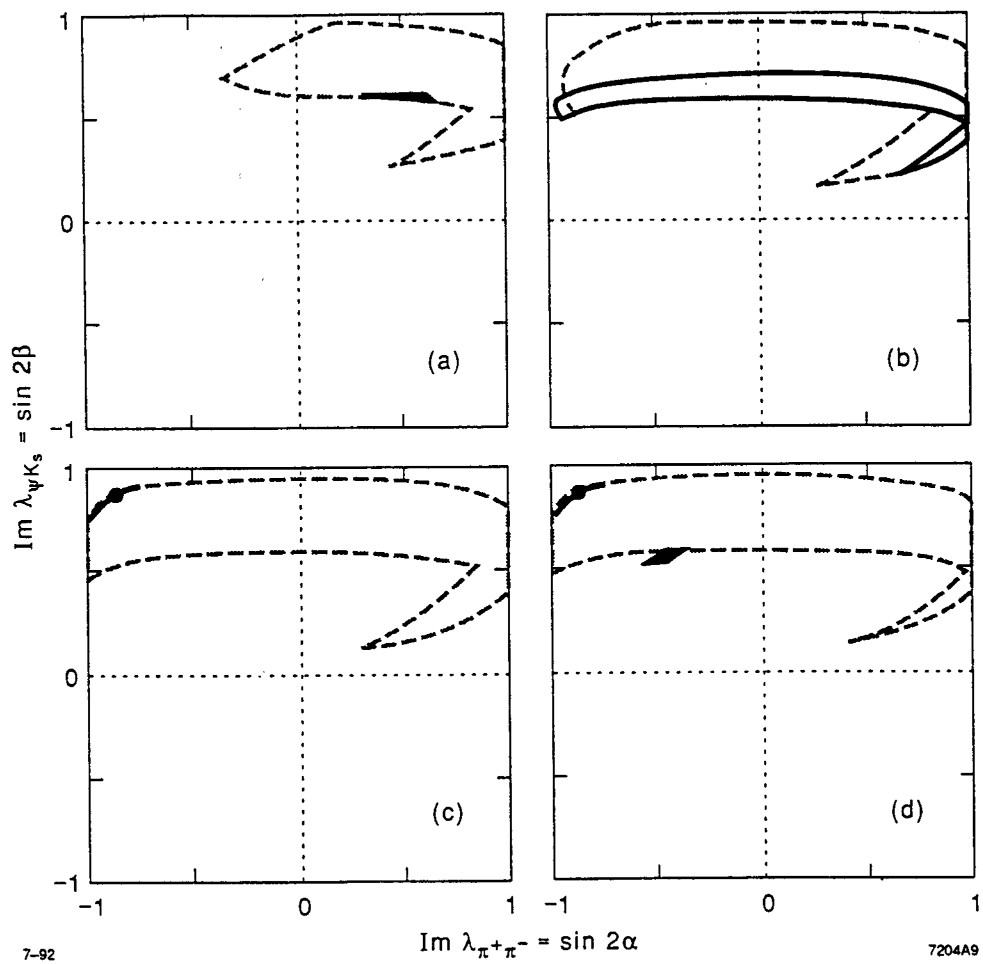

Figure 12. The predicted range for CP asymmetries in $B \to \psi K_S$ and $B \to \pi^+\pi^-$ in the Standard Model (dashed curves) and in various schemes for quark mass matrices. (a) $m_t = 90$ GeV. The black area gives the Fritzsch scheme prediction. (b) $m_t = 130$ GeV. The solid curve gives the Giudice scheme prediction. (c) $m_t = 160$ GeV. The solid curve gives the symmetric CKM prediction, while the dot is the prediction of Kielanowski's scheme. (d) $m_t = 185$ GeV. The solid curve gives the symmetric CKM prediction, the dot is the prediction of Kielanowski's scheme and the black area corresponds to the DHR scheme.

the fermion mass matrices have the following form:

$$M_d = \begin{pmatrix} 0 & fe^{i\phi} & 0 \\ fe^{-i\phi} & e & 0 \\ 0 & 0 & d \end{pmatrix}, \quad M_u = \begin{pmatrix} 0 & c & 0 \\ c & 0 & b \\ 0 & b & a \end{pmatrix}, \quad M_\ell = \begin{pmatrix} 0 & f & 0 \\ f & -3e & 0 \\ 0 & 0 & d \end{pmatrix}. \tag{21.3}$$

The "symmetric CKM" ansatz [137] assumes for the elements of the CKM matrix

$$|V_{ij}| = |V_{ji}|. \tag{21.4}$$

The ansatz by Kielanowski [138] assumes, in addition to (21.4),

$$|V_{23}| = \frac{|V_{12}V_{13}|}{|V_{12}|^2 + |V_{13}|^2}(3 - |V_{12}|^2 - |V_{13}|^2)^{1/2}. \tag{21.5}$$

Taking into account the expected experimental accuracy in a B factory ($\mathcal{O}(0.05)$ in $a_{\psi K_S}$ and $\mathcal{O}(0.10)$ in $a_{\pi\pi}$), we conclude that each of these schemes may be clearly excluded when the asymmetries are measured.

22. Conclusions

Most extensions of the Standard Model suggest that there are many new sources of CP violation, beyond the single phase of the CKM matrix. Such additional phases have two typical consequences:

(i) If the phases occur in flavor changing couplings to quarks, the very strong Standard Model relation between CP violation in the K system and in the B system is lost. Instead of the narrow range allowed by the Standard Model for CP asymmetries in neutral B decays, the whole possible range may be allowed in such extensions.

(ii) If the phases occur in flavor-diagonal couplings, the value of the electric dipole moment of the neutron is orders of magnitudes above its Standard Model value. In many models the experimental bound on $\mathcal{D}_n$ is almost saturated. Similarly, the value of $\mathcal{D}_e$ may be very close to the experimental bound.

The conclusion is that constructing a B factory to measure the CP asymmetries in neutral B decays, and the experimental efforts to improve the sensitivity to the EDMs of the neutron and the electron may be well rewarded: it is not unlikely that new physics will be discovered in these experiments.

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