# ORIGIN OF CP VIOLATION

1. $\Delta S = 1$ interactions

   Modify V-A theory

2. $\Delta S = 2$ interactions

   New superweak physics
   violates CP

$$G_{sw}\ \bar{s}\ O\ d\ \bar{s}\ O\ d$$

$$G_{sw} \sim 10^{-10} \text{ to } 10^{-11}\ G_F$$

Superweak predictions

1. Only CP violation is in mixing

2. No new CP violation will be found

$K^0$ mixing

$$K_+ = (K^0 + \overline{K^0})/\sqrt{2} \qquad CP +$$

$$K_- = (K^0 - \overline{K^0})/\sqrt{2} \qquad CP = -$$

In the $(+\ -)$ representation

$$M - i\frac{\Gamma}{2} = \begin{pmatrix} M_1 & im' \\ -im' & M_2 \end{pmatrix} + \frac{i}{2}\begin{pmatrix} \Gamma_1 & 0 \\ 0 & \Gamma_2 \end{pmatrix}$$

$im'$ is CP - violating effect
Superweak

Phase is fixed by CPT

$$M_1 - M_2 + \frac{i}{2}(\Gamma_1 - \Gamma_2) \approx -\Delta M + i\Gamma_S/2$$

$$K_S = K_+ + \tilde{\epsilon} K_-$$

$$K_L = K_- + \tilde{\epsilon} K_+$$

$$\tilde{\epsilon} = \frac{im'}{\Delta M + i\Gamma_S/2} = |\tilde{\epsilon}| e^{i\,44^\circ}$$

$$\eta_{+-} = \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} = \tilde{\epsilon} \doteq \eta_{00} = \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)}$$

$\sim 2 \cdot 10^{-3}$

1967 – "STANDARD" UNIVERSAL V-A THEORY

In conclusion then we have a reasonably well-defined theory of weak interactions which I summarized at the beginning. Were it not for $CP$-violation we would have no compelling reason to modify the theory. On the other hand the verification of the theory is still quite limited so that there may well be new surprises for us in the conferences to come.

MEANWHILE

S. WEINBERG "A THEORY OF LEPTONS"

SPONT. BROKEN GAUGE THEORY

1970 – GIM : Extension to quarks
required 4th quark

1973 – DISCOVERY OF NEUTRAL CURRENTS.

NEW STANDARD MODEL

NO CP VIOLATION

Next we consider a 6-plet model, another interesting model of $CP$-violation. Suppose that 6-plet with charges $(Q, Q, Q, Q-1, Q-1, Q-1)$ is decomposed into $SU_{\text{weak}}(2)$ multiplets as $2+2+2$ and $1+1+1+1+1+1$ for left and right components, respectively. Just as the case of $(A, C)$, we have a similar expression for the charged weak current with a $3\times3$ instead of $2\times2$ unitary matrix in Eq. (5). As was pointed out, in this case we cannot absorb all phases of matrix elements into the phase convention and can take, for example, the following expression:

$$\begin{pmatrix} \cos\theta_1 & -\sin\theta_1\cos\theta_3 & -\sin\theta_1\sin\theta_3 \\ \sin\theta_1\cos\theta_2 & \cos\theta_1\cos\theta_2\cos\theta_3-\sin\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\cos\theta_2\sin\theta_3+\sin\theta_2\cos\theta_3 e^{i\delta} \\ \sin\theta_1\sin\theta_2 & \cos\theta_1\sin\theta_2\cos\theta_3+\cos\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\sin\theta_2\sin\theta_3-\cos\theta_2\cos\theta_3 e^{i\delta} \end{pmatrix}. \tag{13}$$

Then, we have $CP$-violating effects through the interference among these different current components. An interesting feature of this model is that the $CP$-violating effects of lowest order appear only in $\Delta S\neq0$ non-leptonic processes and in the semi-leptonic decay of neutral strange mesons (we are not concerned with higher states with the new quantum number) and not in the other semi-leptonic, $\Delta S=0$ non-leptonic and pure-leptonic processes.

So far we have considered only the straightforward extensions of the original Weinberg's model. However, other schemes of underlying gauge groups and/or scalar fields are possible. Georgi and Glashow's model[4] is one of them. We can easily see that $CP$-violation is incorporated into their model without introducing any other fields than (many) new fields which they have introduced already.


### References

1) S. Weinberg, Phys. Rev. Letters **19** (1967), 1264; **27** (1971), 1688.
2) Z. Maki and T. Maskawa, RIFP-146 (preprint), April 1972.
3) P. W. Higgs, Phys. Letters **12** (1964), 132; **13** (1964), 508.
G. S. Guralnik, C. R. Hagen and T. W. Kibble, Phys. Rev. Letters **13** (1964), 585.
4) H. Georgi and S. L. Glashow, Phys. Rev. Letters **28** (1972), 1494.

## A. The CKM matrix

In the standard electroweak model, the interactions
the quarks with the charged gauge bosons $W$ are given b

$$g\bar{u}_j V_{ji}\gamma_\lambda(1-\gamma_5)d_i W^\lambda + \text{H.c.} \qquad (3.$$

Here $u_j=(u,c,t)$ are the up-type quarks and $d_j=(d,s,$
are the down type. $V$ is the unitary CKM (Cabibb
Kobayashi-Maskawa) matrix, the $3\times3$ generalization
the Cabibbo mixing matrix. A convenient parametriz
tion of $V$ due to Maiani (1977) is

$$V=\begin{pmatrix} V_{ud} & V_{us} & V_{ub}\\ V_{cd} & V_{cs} & V_{cb}\\ V_{td} & V_{ts} & V_{tb}\end{pmatrix}=\begin{pmatrix} C_\sigma C_\theta & C_\sigma S_\theta & S_\sigma e^{-i\gamma}\\ -C_\tau S_\theta - C_\theta S_\sigma S_\tau e^{i\gamma} & C_\tau C_\theta - S_\theta S_\sigma S_\tau e^{i\gamma} & C_\sigma S_\tau\\ S_\theta S_\tau - C_\theta C_\tau S_\sigma e^{i\gamma} & -C_\theta S_\tau - C_\tau S_\theta S_\sigma e^{i\gamma} & C_\tau C_\sigma \end{pmatrix}, \qquad (3$$

e $C_\theta=\cos\theta$ and $S_\theta=\sin\theta$. As originally noted by
yashi and Maskawa (1973), it is possible by defining
hase of the quark fields to eliminate all but one of
hases in $V$. Thus all $CP$ violation in this model de-
s on the phase $\gamma$. Experimental data on strange-
cle and $B$ decay rates can determine the magnitudes
$_{us}$, $V_{cb}$, and $V_{ub}$. Given these magnitudes, there is
empirical observation (Wolfenstein, 1983) that the
ng angles have a hierarchical structure allowing ex-
ion in powers of $\lambda=\sin\theta=0.22$ with

$$\sin\tau = A\lambda^2 \,, \qquad (3.3a)$$

$$\sin\sigma e^{-i\gamma} = A\lambda^3(\rho - i\eta) \,. \qquad (3.3b)$$

The analysis of experimental data from decay rates d
cussed in Sec. III.C is summarized by

$$A=\cancel{0.9\pm0.1} \,,\ .83 \pm .07 \qquad (3$$

$$(\rho^2+\eta^2)^{1/2}=\cancel{0.4\pm0.2} \,,\ .4 \pm .15 \qquad (3.$$

where the errors are primarily theoretical.

Expanding $V$ in powers of $\lambda$ to order $\lambda^3$, we see th
the matrix has the simple form

$$V=\begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho-i\eta)\\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2\\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1\end{pmatrix}. \qquad (3.6)$$

We have chosen a phase convention (that is, a definition of the phases of quark fields) in Eqs. (3.2) and (3.6) such that $V$ is manifestly $CP$ invariant to order $\lambda^2$, and $CP$

The $CP$-violating part of the $(K^0\text{-}\bar{K}^0)$ mass m
be calculated (Ellis *et al.*, 1976) from the seco
box diagram (Fig. 2). The result of the calculati
and Lim, 1981; Buras *et al.*, 1984), includi
corrections (Gilman and Wise, 1983; Buras *et*
Flynn, 1990), is well represented for $m_t > m_w$ by

$$\epsilon e^{-i\theta}=3.4\times10^{-3}A^2\eta B\left[1+1.3A^2(1-\rho)\left(\frac{m_t}{m_w}\right.\right.$$

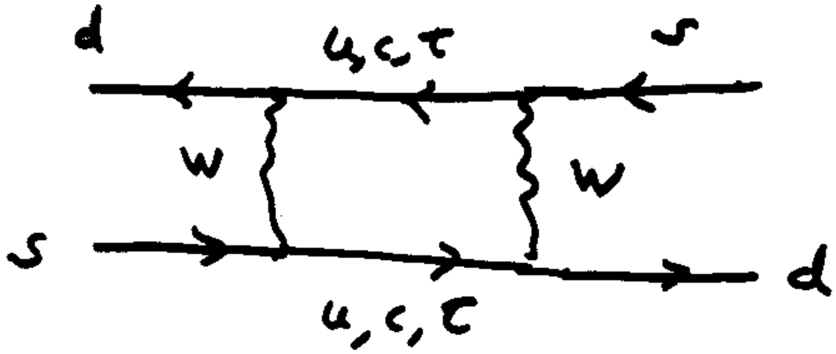
THREE ALTERNATIVES

1. All CP violation is explained by $\eta$.

2. $\eta = 0$. All CP violation is explained by new physics. Superweak. need to explain why $\eta = 0$.

3. $\eta \neq 0$ but there is new physics.

# $\epsilon$ in the Standard Model




Use this to calculate $m'$

$$\epsilon \approx \tilde{\epsilon} = i \frac{m'}{\Delta M + i\Gamma_S/2}$$

$$\epsilon \propto e^{i\theta} A^2 \lambda^6 \eta B \{ - \eta_{cc} m_c^2$$

$$+ \eta_{ct} f(m_c, m_t) + \eta_{tt} \overset{f(m_t)}{m_t^2} A^2 \lambda^4 (1-\rho) \}$$

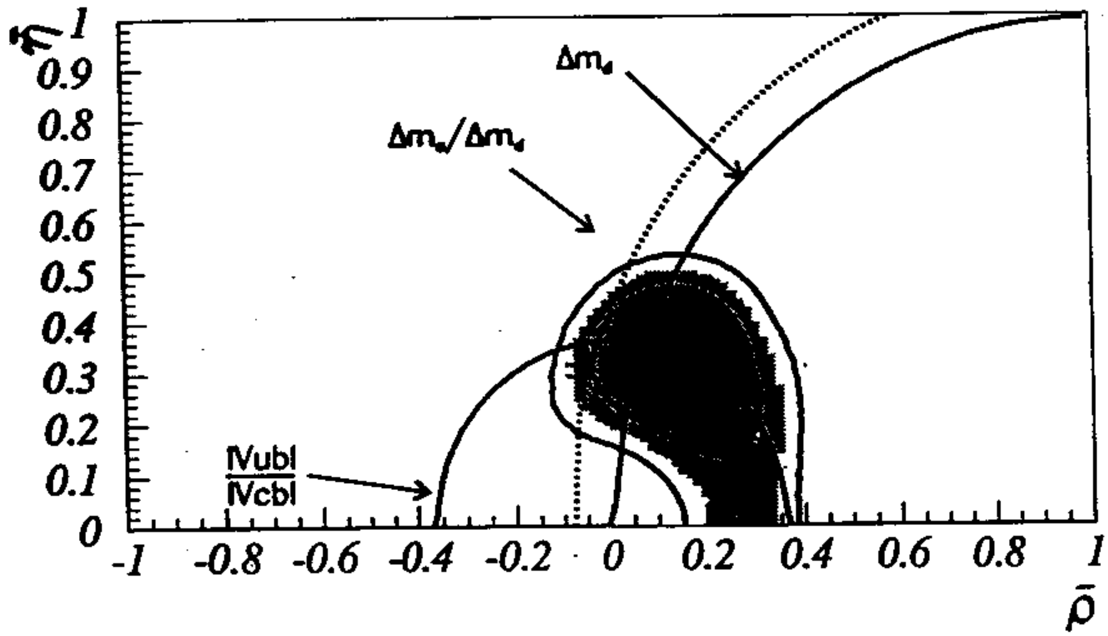
$$\simeq e^{i\theta}\, 3.4 \times 10^{-3} A^2 \eta B_K \{ 1 + A^2 (1-\rho)(1.3)\left(\frac{m_t}{m_W}\right.$$

$$\langle \overline{K^0} | \bar{s} \gamma_\lambda (1-\gamma_5) d\, \bar{s} \gamma^\lambda (1-\gamma_5) d | K^0 \rangle$$

$$= B_K \left[ \frac{4}{3} f_K^2 m_K \right]$$

$B_K \approx 0.5$ to $1.0$

Barbieri et al hep-ph/9712252




e 68% and 95% C.L. contours fits of $|V_{ub}/V_{cb}|, \Delta M_{B_d}$ and $\Delta M_{B_s}$ in the $\bar{\rho}/\bar{\eta}$ standard model. The curves correspond to constraints obtained from mea- $|V_{ub}/V_{cb}|, \Delta M_{B_d}$ and $\Delta M_{B_s}$. $\bar{\rho} = \rho(1-\lambda^2/2), \bar{\eta} = \eta(1-\lambda^2/2)$.

CKM matrix. Comparing Figures 1 and 2 at low $\eta$, one sees that the new nixing has excluded superweak theories with negative $\rho$. This has important gical consequences for pure superweak theories.

$$\eta_{+-} = \epsilon + \epsilon' / 1 + w/\sqrt{2}$$

$$\eta_{00} = \epsilon - 2\epsilon' / 1 - \sqrt{2} w$$

$$\epsilon = \tilde{\epsilon} + i \, \mathrm{Im} A_0 / \mathrm{Re} A_0$$

$$\approx \frac{1}{\sqrt{2}} e^{i\theta} \left( \frac{m'}{\Delta M} + \frac{\mathrm{Im} A_0}{\mathrm{Re} A_0} \right)$$

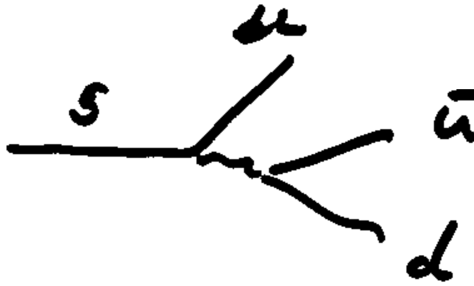
$$\Theta = \tan^{-1} (2 \Delta M / \Gamma_S) = 43.7^\circ$$

$$\epsilon' = \frac{1}{\sqrt{2}} e^{i\Theta'} \frac{\mathrm{Re} A_2}{\mathrm{Re} A_0} \left( \frac{\mathrm{Im} A_2}{\mathrm{Re} A_2} - \frac{\mathrm{Im} A_0}{\mathrm{Re} A_0} \right)$$

$$\theta' = \delta_2 - \delta_0 + \frac{\pi}{2} = 48 \pm 8^\circ$$

Ch. asym $\delta \approx 2 \mathrm{Re}\, \epsilon$

# $\varepsilon'$ in the Standard model




$V_{us} V_{ud}^*$

$\sim \lambda$

Real


$V_{ts} \; V_{td}^*$

$\sim A^2 \lambda^5 (1-\rho+i\eta)$

$\to \text{Im}\, A_0$

For large $m_t$


$\to \text{Im}\, A_2$

$$\epsilon' = .03\, e^{i\theta'} \left( \frac{\text{Im}\, A_2}{\text{Re}\, A_2} - \frac{\text{Im}\, A_0}{\text{Re}\, A_0} \right)$$

$\epsilon'/\epsilon \to 10^{-4}$ to $2 \times 10^{-3}$

Expts. CERN $(23 \pm 3.6 \pm 5.4) \times 10^{-4}$ | Fermilab $(7.4 \pm 5.2 \pm 2.9) \times 10^{-4}$

MOTIVATION FOR SUPERWEAK

1. CP VIOLATION IN STANDARD MODEL INVOLVES LOTS OF ARBITRARY PHASES IN YUKAWAS

2. ORIGIN OF CP VIOLATION AT A HIGHER MASS SCALE:

SPONTANEOUS: $\langle S_i \rangle = v_i e^{i\theta_i}$

or

SOFT $\mu^2_{12} S_1 S_2^+ + h.c$

3. THEN $\eta$ is "calculable"
ALSO now $\theta_{QCD}$ is calculable

4. PROGENITOR OF YUKAWA HAS NO CP VIOLATION →
$\eta$ may be zero:
BARR, PHYS. REV D 34, 1567 (1986)

5. ALTERNATIVE: $\eta \neq 0$
NELSON-BARR MODELS
A. NELSON, PHYS. LETT B 136, 332 (1984)

# SUPERWEAK THEORIES

$$\mathcal{L}_{eff} = \mathcal{L}_0 + \mathcal{L}_{SW}$$

$\mathcal{L}_0$ : S.M. with $\eta \neq 0$

$\mathcal{L}_{SW}$ : $G_{ijkl}\, \bar{q}_i q_j \bar{q}_k q_l$

$G_{ijkl} \ll G_F$

1. How small is $\eta$ ? Why ?
   $\eta \lesssim .01$
   Loop-induced $\eta$ - Georgi + Glashow

2. How small are $G_{ijkl}$ ?
   $G_{ijkl} \lesssim 10^{-6}\, G_F$.
   ($\lesssim 10^{-10}$ "pure" superweak)
   $\epsilon'/\epsilon$ ? ($10^{-6} \to \epsilon'/\epsilon \sim 5\times10^{-4}$)

3. $D_n$ , $\theta_{QCD}$

4. Semileptonic ?

# WHY $\not{CP}$ IS A GOOD PLACE TO LOOK FOR NEW PHYSICS

1. THERE ARE NO PRECISION TESTS OF THE S.M. OF $\not{CP}$

2. $\not{CP}$ IN THE S.M. IS INTRINSICALLY SMALL — $\sim A\lambda^3\eta$

3. $\not{CP}$ IS STUDIED VIA FLAVOR MIXING: $\Delta(\text{FLAVOR}) = 2$
   SENSITIVE TO SUPERWEAK

4. IN S.M. FLAVOR-CONSERVING $\not{CP}$ IS VERY SMALL AS IN ELECTRIC DIPOLE MOMENTS

$G_{SW}\, \bar{q}_1 q_2 \bar{q}_3 q_4$

titative prediction because of the uncertainty in going from quarks

TABLE I

| Selection Rule Violated | Observable | Scalar $G_{SW}/G_F$ |
|---|---|---|
| $\Delta S = 2$ | $\Delta m_K$ | $10^{-9}$ |
| $\Delta b = 2$ | $\Delta m_{Bd}$ | $10^{-7}$ |
| $\Delta S = 2$, CP | $\epsilon$ | $10^{-11}$ |
| $\Delta S = 1$, CP | $\epsilon'/\epsilon \sim 10^{-3}$ | $10^{-6}$ |
| $\Delta S = 1$, FCNE, CP | $P_L(K_L \to \mu^+\mu^-) \sim 10^{-2}$ | $10^{-8}$ |
| $\Delta c = 2$ | $\Delta m_D/\Gamma_D \sim 10^{-2}$ | $10^{-8}$ |
| $\Delta b = 2$, CP | $A(\psi K_s) \sim 0.1$ | $10^{-8}$ |
| $\Delta b = 1$, FCNE | $B(B_d \to \mu^+\mu^-) \sim 10^{-8}$ | $10^{-5}$ |

Possible new information on $\eta$

1. $\mathrm{Im}\,\epsilon'/\epsilon \simeq +10$ to $20 \times 10^{-4}$

implies $\eta > +0.2$

assuming no new physics in decay amplitude

2. $K_L \to \pi^0 \nu \bar{\nu}$

$B.R \propto 4 \cdot 10^{-10} A^4 \eta^2$

$\sim 2 \cdot 10^{-11}$

P926 at BNL $\rightarrow$ 50 events

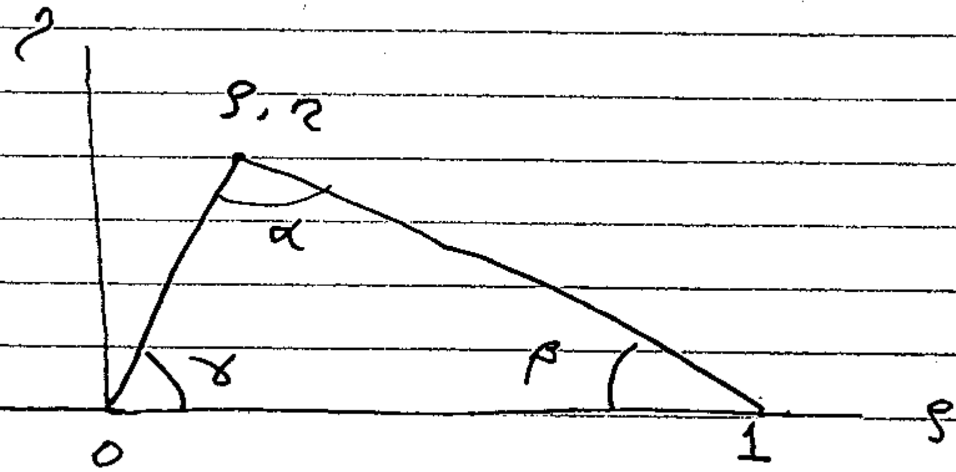
$\rightarrow |\eta|^2 \pm 20\%$

KAMI at Fermilab

$e^{-i\gamma}$

$$V = \begin{bmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix}$$

$e^{-i\beta}$




CP VIOLATION IN $B^0$

$$P_a(t) \propto e^{-\Gamma t}\left[1 \pm \alpha_a \eta_a \sin \Delta m t\right]$$

$\eta_a = \pm 1$ Asymmetry parameter $= \alpha_a$

$b \to c\bar{c}s$

$\alpha(\psi K_s) = \sin 2\tilde{\beta}$ $\epsilon_B$

$b \to u\bar{u}d$

$\alpha(\pi^+\pi^-) = \sin 2(\tilde{\beta} + \gamma)$ $\epsilon'_B$

$\tilde{\beta} = \beta$

# Magnitude of $|V_{td}|$

1. $K^+ \to \pi^+ \nu \bar{\nu}$ (Buchalla-Buras PR D54, 6782)


$$B.R \approx 9.5 \times 10^{-11} \times \left[ A^4 \eta^2 + \left( [1-\rho] A^2 + .26 \pm .04 \right)^2 \right]$$

charm contribution

For $\rho \sim 0$ determine $(1-\rho)$ with theoretical error of 15-20% due to $m_c$ and $A^2$.

2. $B_s - \bar{B}_s$ mixing

$$\frac{x_d}{x_s} = \lambda^2 \left[ (1-\rho)^2 + \eta^2 \right] / K$$

$$K = (1.3 \pm 0.2)$$

$K_L \rightarrow \mu^+\mu^-$


normal CP conserving

$$\text{B.R.} = 7\times10^{-9}$$

$$\rightarrow |\text{odd}\rangle = LL - RR$$

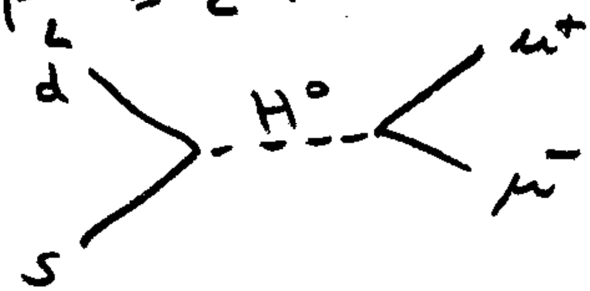
CP violation $\rightarrow |\text{even}\rangle = LL + RR$

Final state $|\text{odd}\rangle e^{i\beta} + i\lambda\,|\text{even}\rangle$

Net polarization of either $\mu$

$$P_L = 2\,\text{Im}(\lambda e^{-i\beta}) \; ; \; \beta = \frac{\pi}{2}$$

Due to $\epsilon$ $\rightarrow$ $P_L \simeq 2 \text{ to } 3\times10^{-3}$




Superweak effect

with $\frac{G_{SW}}{G_F} \sim 10^{-8}$ $\longrightarrow$ $P_L \sim 10^{-2}$

# Conclusion

I. First job is to kill superweak

[that is, all $\not{CP}$ is $\Delta F = 2$]

K 1. Find $\epsilon' \neq 0$

B 2. $\alpha(\psi K_s) \neq \alpha(\pi^+\pi^-)$

II. Second job is quantitative tests of CKM model in search of new physics

K 1. $K_L \to \pi^0 \nu \bar{\nu}$

B 1. $\sin 2\beta = 0.3$ to $0.9$

2. Consistency of $(\beta, \gamma)$ or $(\rho, \eta)$

e.g. $\sin 2(\beta + \gamma)$ together

$\Gamma(K^+ \to \pi^+ \nu \bar{\nu})$

III. Direct search for new physics

1. $D^0 - \overline{D^0}$ mixing

2. Electric dipole moment of n, e