SYMMETRIES

P PARITY RIGHT $\leftrightarrows$ LEFT

T TIME REVERSAL $t \rightleftarrows -t$

C Charge conjugation $\bar{p} \leftrightarrows p$

"Discovered" in Q.E.D.

1930's $\rightarrow$ Invent

$\mathcal{H}_{weak}$ $\mathcal{H}_{strong}$

Fermi:

$$\mathcal{H}_{weak} = G_F \, \bar{p} \, \gamma_\mu \, n \; \bar{e} \, \gamma_\mu \, \nu \cdot \delta(\vec{r})$$

It is easy to invent interactions that violate C or P or T but <u>not</u> <u>C · P · T</u>.

New interaction

C	P	T	
×	×	✓	× (V−A) theory
✓	×	×	
×	✓	×	

$$\mathcal{H}_W = \frac{G_F}{\sqrt{8}}\, \bar{p}\,\gamma_\mu (g_V - g_A \gamma_5)\, n \; \bar{e}\,\gamma_\mu (1-\gamma_5)\,\nu$$

In 1964

Fitch, Cronin, Christenson, Turlay

found $K_2 \rightarrow 2\pi$

indicating CP violation

3~~6~~ years later

The only CP or T

violation known was in the

K^0 system.

Now first signs in the B^0

system

K system

K^0 $\quad$ K^+ $\quad$ $S = +1$

$\bar{s}d$ $\quad$ $\bar{s}u$

$\overline{K^0}$ $\quad$ K^- $\quad$ $S = -1$

$s\bar{d}$ $\quad$ $s\bar{u}$

Mass eigenstates are not K^0, $\overline{K^0}$
because of ΔS

CP invariance $\rightarrow$

$$\begin{array}{ll} & CP \\ K_1 = (K_0 + \overline{K^0})/\sqrt{2} & + \\ K_2 = (K^0 - \overline{K^0})/\sqrt{2} & - \end{array}$$

where $|\overline{K^0}\rangle = CP|K^0\rangle$

Before 1964

$$K_S \rightarrow \begin{cases} \pi^+ \pi^- \\ \pi^0 \pi^0 \end{cases} \qquad \tau_S = 0.9 \times 10^{-10}\,s.$$

$$K_L \rightarrow \begin{array}{c} 3\pi \\ \pi \ell \nu \end{array} \qquad \tau_L = 5.2 \times 10^{-8}\,s.$$

$$m_L - m_S = 0.48\ \Gamma_S \qquad \sim 10^{-5}\,eV$$

CP Violation $\quad K_L \rightarrow 2\pi$ also

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

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

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

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

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

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

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

ORIGIN OF CP VIOLATION

1. $\Delta S = 1$ interactions

   Modify V-A theory

2. $\Delta S = 2$ interactions

   New superweak physics violates CP

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

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

Superweak predictions

1. Only CP violation is in mixing
2. No new CP violation will be found
3. Phase of ϵ

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 $SU_{weak}(2)$ 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 3×3 instead of 2×2 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 $\Delta S\neq 0$ 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

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

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 (Cabib Kobayashi-Maskawa) matrix, the 3×3 generalization the Cabibbo mixing matrix. A convenient parametri tion of V due to Maiani (1977) is

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

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

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

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

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

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

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

where the errors are primarily theoretical.

Expanding V in powers of λ to order λ^3, we see t the matrix has the simple form

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

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 λ^2, and CP

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

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

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

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

$$w = \frac{Re\, A_2}{Re\, A_0} = .045$$

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

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

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

$$\epsilon' = -\frac{1}{\sqrt{2}} e^{i\theta'} \underbrace{\frac{Re\, A_2}{Re\, A_0}}_{.045} \left(\frac{Im\, A_2}{Re\, A_2} - \frac{Im\, A_0}{Re\, A_0} \right)$$

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

ϵ'/ϵ EXPERIMENTS $\times 10^{-4}$

OLD FERMILAB $7.4 \pm 5.2 \pm 2.9$

OLD CERN $23 \pm 3.6 \pm 5.4$

NEW FERMILAB 28 ± 3

NEW CERN 15 ± 3

(Average ? $(18 \pm 3) \times 10^{-4}$)

ϵ'/ϵ THEORY

TRIESTE $6 \times 10^{-3}\, \eta \left(1 \,^{+0.8}_{-0.6}\right)$

ROME $1.3 \times 10^{-3}\, \eta\, (1 \pm 0.7)$

MÜNCHEN $2 \times 10^{-3}\, \eta \left(1 \,^{+0.8}_{-0.5}\right)$

DORTMUND $(15 \pm 5) \times 10^{-4}$

REVIEW: BERTOLINI et al

Rev. Mod. Phys. JAN 2000

CP VIOLATION FOR B

$$e^{-i\gamma}$$

$$\begin{pmatrix} & & V_{ub} \\ & & V_{cb} \\ V_{td} & & V_{tb} \end{pmatrix}$$

$$e^{-i\beta}$$

$$V_{ub} = A\lambda^3(\rho - i\eta)$$

$$V_{td} = A\lambda^3(1-\rho-i\eta)$$

Phase β from B-$\bar{B}$ mixing

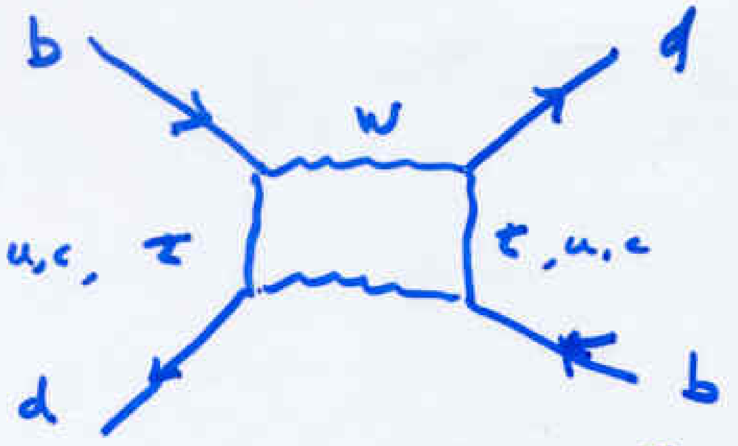
$$A_{\psi K_s} = (B \to \psi K_s) - (\bar{B} \to \psi K_s) \qquad \text{"}\epsilon_\beta\text{"}$$

$$\longrightarrow \sin 2\beta$$

Phase γ = Relative phase of $b \to u$ to $b \to c$

$$A_{\pi\pi} \longrightarrow \sin 2(\beta + \gamma + \varphi_p) \qquad \epsilon'_\beta$$

$B^0 - \bar{B}^0$ Mixing



$$\Rightarrow \quad V_{tb} V_{td}^* = 1 \cdot A\lambda^3 \overbrace{(1-\rho+i\eta)}^{e^{i\beta}}$$

$$V_{cb} V_{cd}^* = -A\lambda^3$$

$$V_{ub} V_{ud}^* = A\lambda^3(\rho - i\eta)$$

Re m and Im m are **both** $\sim \lambda^6$

$$x_d = \frac{\Delta m_{B_d}}{\Gamma_{B_d}} = A^2\left[(1-\rho)^2 + \eta^2\right]\left(\frac{m_t}{m_W}\right)^{1.6}$$

$$\times \frac{1}{6}\left(\frac{\sqrt{B_B \eta_2}\, f_B}{120\ \text{MeV}}\right)^2$$

$$\Delta m_{B_d} / \Gamma_B = 0.7 \quad \text{Expt}$$

$B - \overline{B}$ mixing from diagram is

$$\sim \left(V_{tb} V_{td}^*\right)^2 = A^2\lambda^6\left[(1-\rho)^2 + \eta^2\right] e^{2i\beta}$$

Experiment	$\sin 2\beta$
BABAR	$.75 \pm .09 \pm .06$
BELLE	$.82 \pm .12 \pm .05$

Fit to standard model

$\sin 2\beta = .47$ to $.89$

New Physics

Effective "superweak" interactions

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

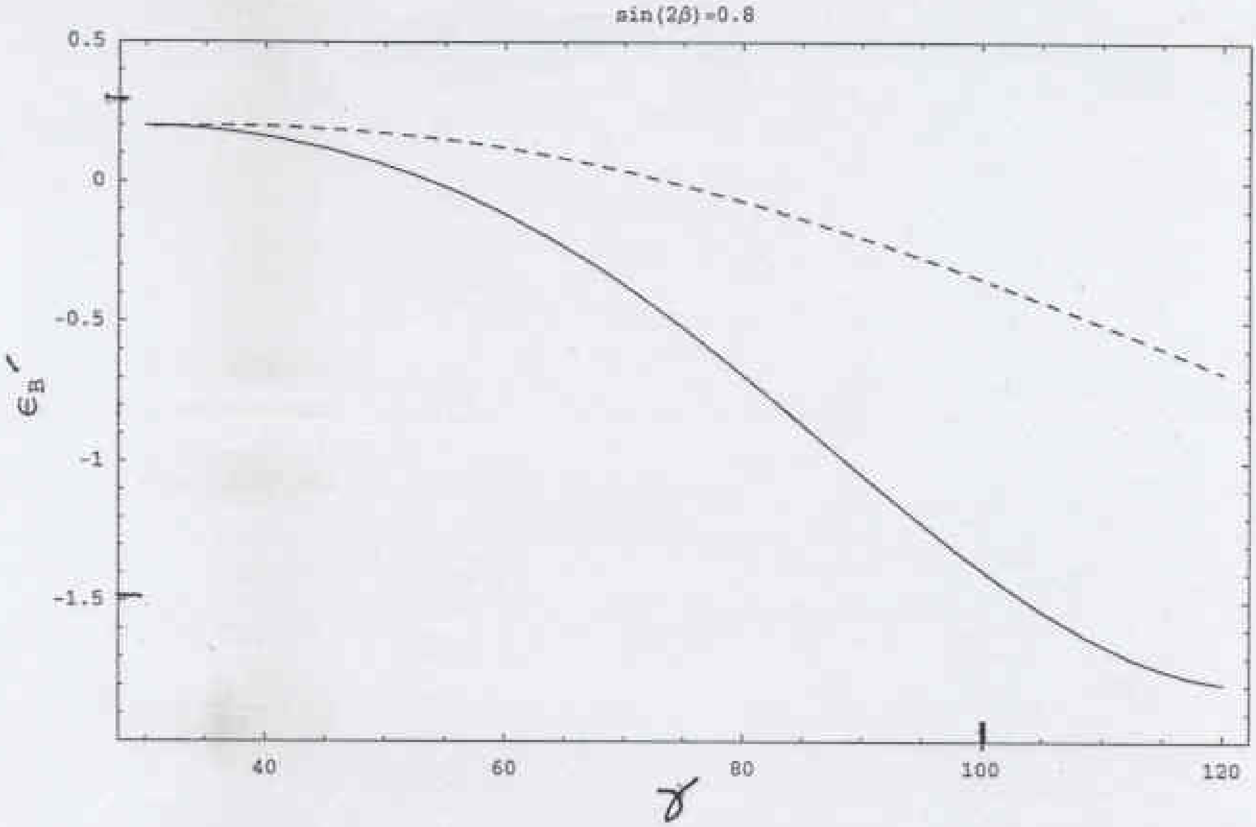
$\Delta S = 2$, $\cancel{CP}$

important for ϵ $\qquad G_{sw} \sim 10^{-10} - 10^{-11} \, G_F$

$\Delta b = 2$

important for $\tilde{\beta}$ $\qquad G_{sw} \sim 10^{-7} \, G_F$

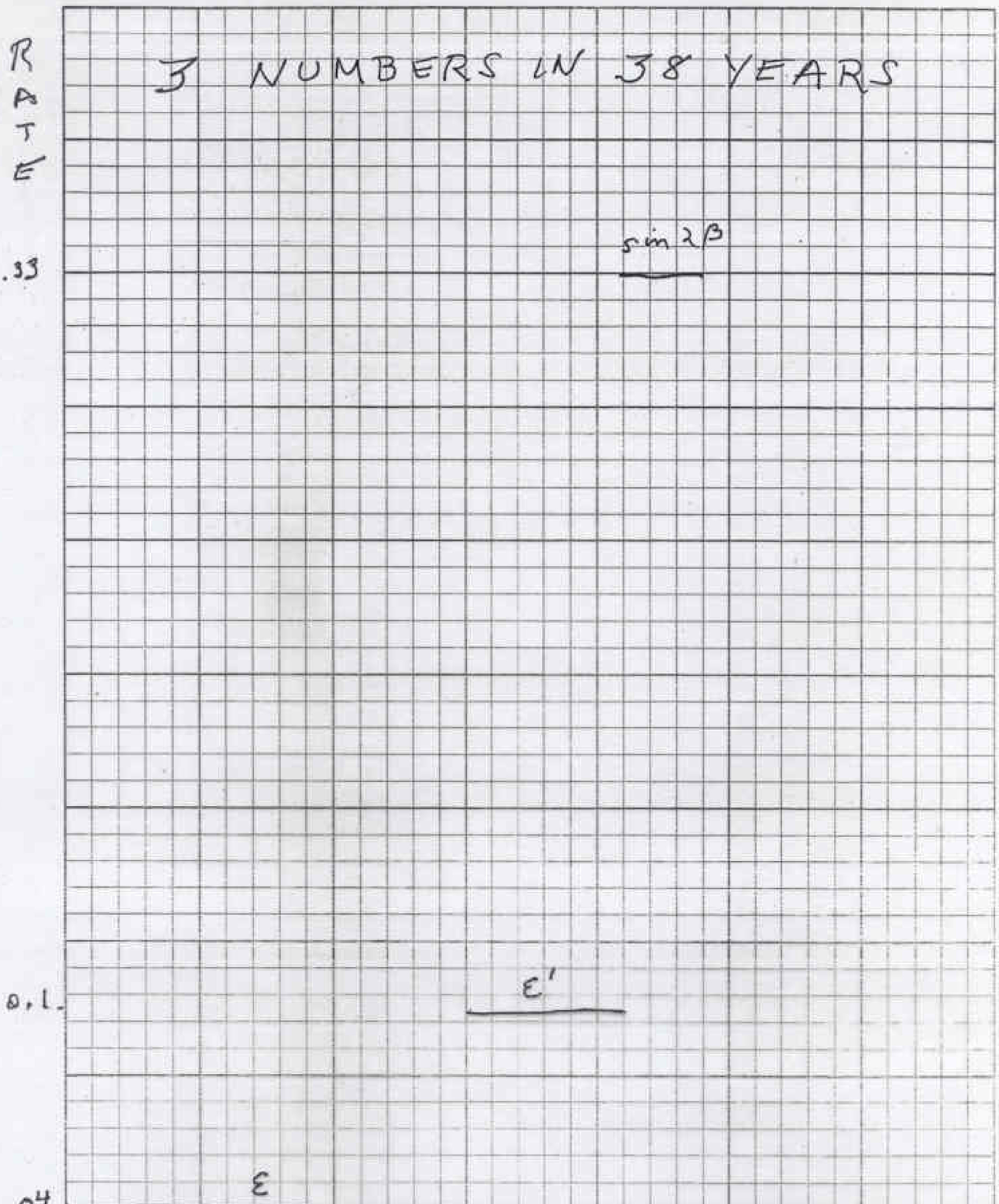
and for x_d



— $\epsilon'_{B_1} = A_{\pi\pi} - \sin 2\beta$

- - - $\epsilon'_{B_2} = \sin(2\beta + \gamma) - \sin 2\beta$

L. Wu and F. Wu, Europhysics Letters


RATE
3 NUMBERS IN 38 YEARS
sin 2β
.33
ε'
0.1
ε
.04
1964
1989
1999

LONG TERM FRONTIER FOR $\cancel{CP}$

1. SIGNALS of PHYSICS BEYOND S.M

   New particle effects on
   - Boxes (MIXING)
   - Loops (PENGUINS)
   - Electric Dipole MOMENTS

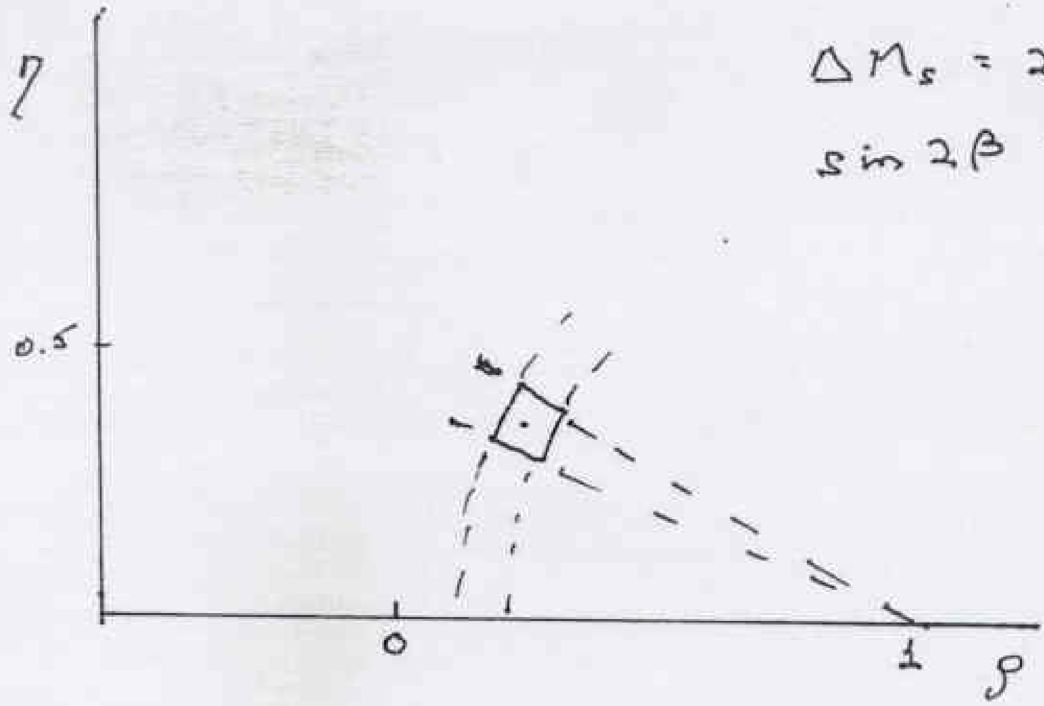
2. $\cancel{CP}$ in LEPTON PHYSICS
   NEUTRINO MIXING

3. IS $\cancel{CP}$ a SPONTANEOUSLY BROKEN SYMMETRY (θ_{QCD})

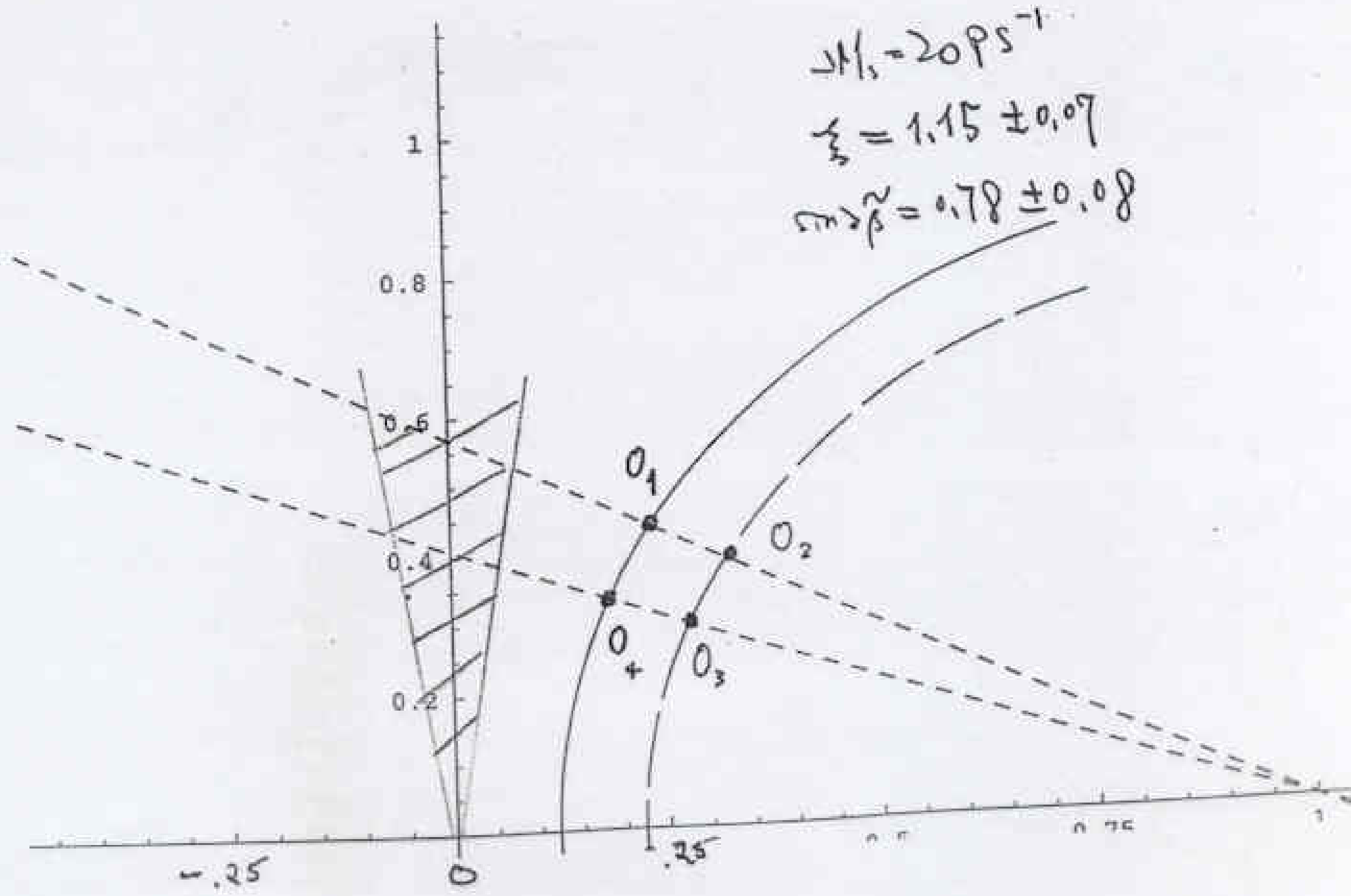
4. $\cancel{CP}$ AT A HIGH MASS SCALE
   TO EXPLAIN BARYON ASYMMETR

$\Delta m_s = 20\ \mathrm{psec}^{-1}$

$\sin 2\beta = .78$

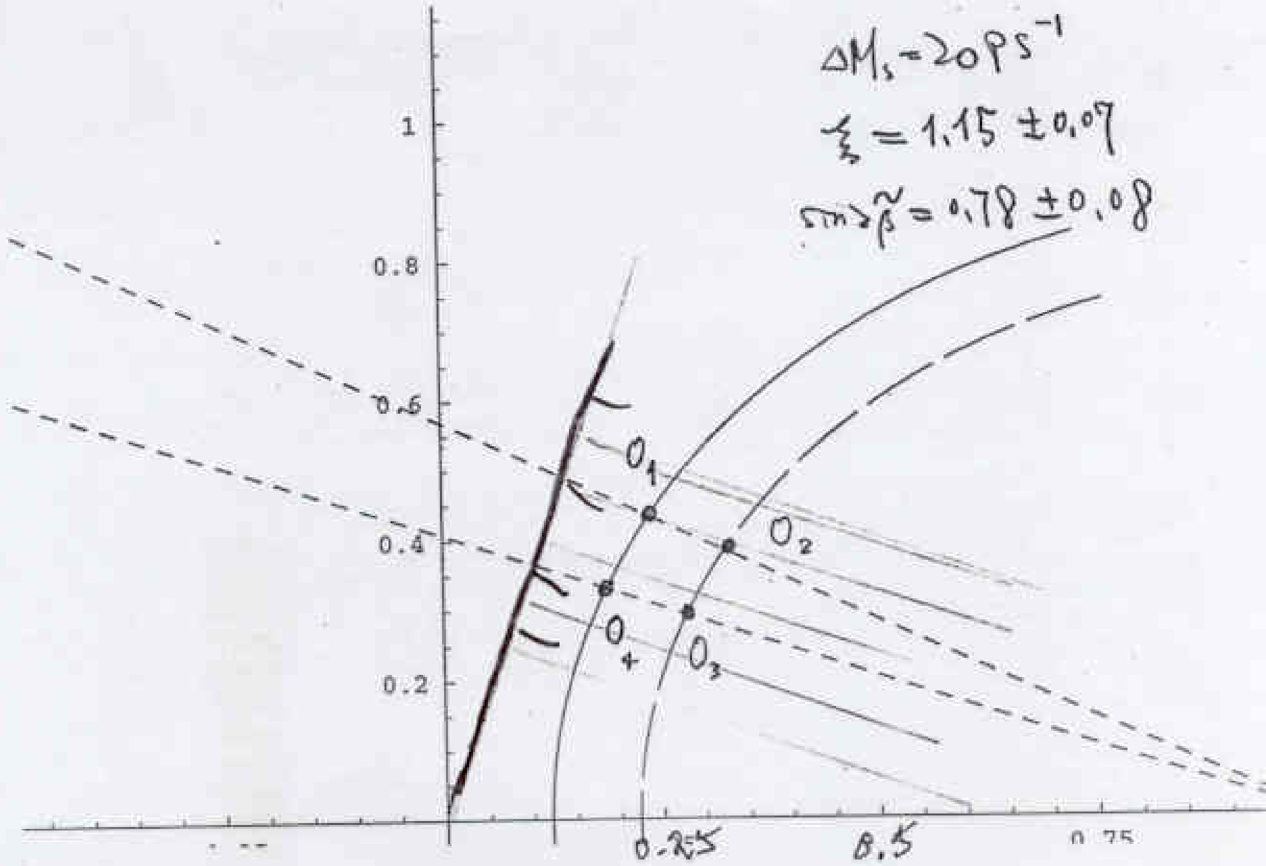


$$\left| \frac{V_{td}}{V_{ts}} \right| = \left[\frac{\Delta m_d}{\Delta m_s} \right]^{1/2} \xi$$



$\sin(2\tilde{\beta} + \gamma) = 0.5$ to 0.7

Signal of new physics



$\sin(2\tilde{\beta} + \gamma) = 0.8$ to 1.0

$\rightarrow \gamma < 75^\circ$

CONCLUSSION

1. 3 NUMBERS IN
   38 YEARS : $\epsilon, \epsilon', \sin 2\beta$
2. MANY QUESTIONS
   TO BE ANSWERED