Physics 662

Particle Physics Phenomenology

January 27, 2004

Weak Interactions

- Classification ✓
- Lepton Universality ✓
- Nuclear β-decay: Fermi theory ✓
- Inverse β-
- Parity nonc
- Helicity of
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- The weak b
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- (continued)
- Observation of $W^{\pm}$ and Z^0 bosons in $p\bar{p}$ collisions ✓
- Z^0 production at e^+e^- colliders ✓
- Weak decays of quarks. The GIM model and the CKM matrix ✓
- Neutral K mesons
- CP violation in the neutral kaon system
- Cosmological CP violation
- D^0-$\bar{D}^0$ and B^0-$\bar{B}^0$ mixing

Neutral K mesons

I	I_3	S	Meson	Quark combination	Decay	Mass, MeV
$\frac{1}{2}$	$\frac{1}{2}$	$+1$	K^+	$u\bar{s}$	$K^+ \to \mu\nu$	494
$\frac{1}{2}$	$-\frac{1}{2}$	$+1$	K^0	$d\bar{s}$	$K^0 \to \pi^+\pi^-$	498
$\frac{1}{2}$	$-\frac{1}{2}$	-1	K^-	$\bar{u}s$	$K^- \to \mu\nu$	494
$\frac{1}{2}$	$\frac{1}{2}$	-1	$\bar{K}^0$	$\bar{d}s$	$\bar{K}^0 \to \pi^+\pi^-$	498

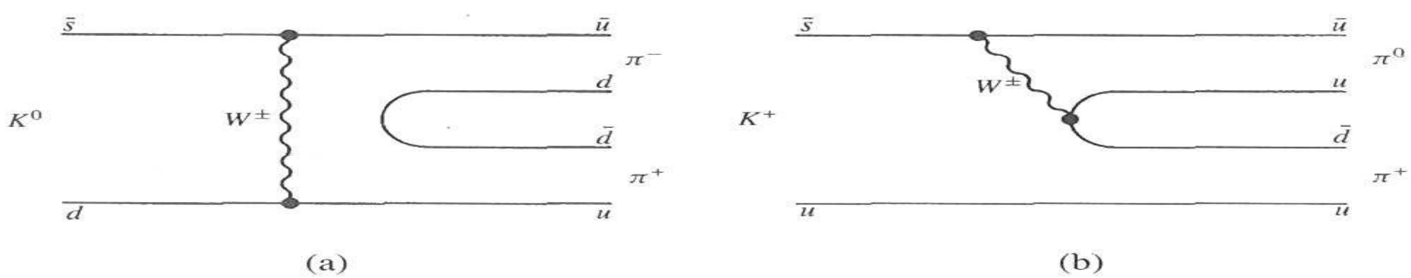


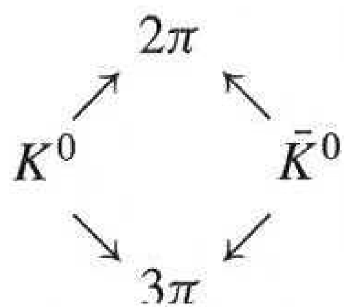
Fig. 7.18. Quark diagrams for $K \to 2\pi$ decay. (a) $K^0 \to \pi^+\pi^-$; (b) $K^+ \to \pi^+\pi^0$.

Neutral K mesons

K^0 and $\overline{K^0}$ are particle and antiparticle
related by charge conjugation
reversal of I_3 and change of strangeness $\Delta S = 2$

These particles are clearly distinctive in strong interaction,
since SI conserves isospin and strangeness

However, in propagating through free space, mixing occurs:



a pure K^0 state at t=0 will become a mixed state:

$$|K(t)\rangle = \alpha(t)|K^0\rangle + \beta(t)|\bar{K}^0\rangle$$

Neutral K mesons

CP eigenstates can be defined for the K^0 mesons

K^0 and $\overline{K}^0$ are not CP eigenstates:

$$CP|K^0\rangle \rightarrow \eta|\bar{K}^0\rangle, \qquad CP|\bar{K}^0\rangle \rightarrow \eta'|K^0\rangle$$

we can form the linear combinations:

$$|K_S\rangle = \sqrt{\tfrac{1}{2}}\left(|K^0\rangle + |\bar{K}^0\rangle\right), \qquad CP = +1$$

$$|K_L\rangle = \sqrt{\tfrac{1}{2}}\left(|K^0\rangle - |\bar{K}^0\rangle\right), \qquad CP = -1$$

resulting in:

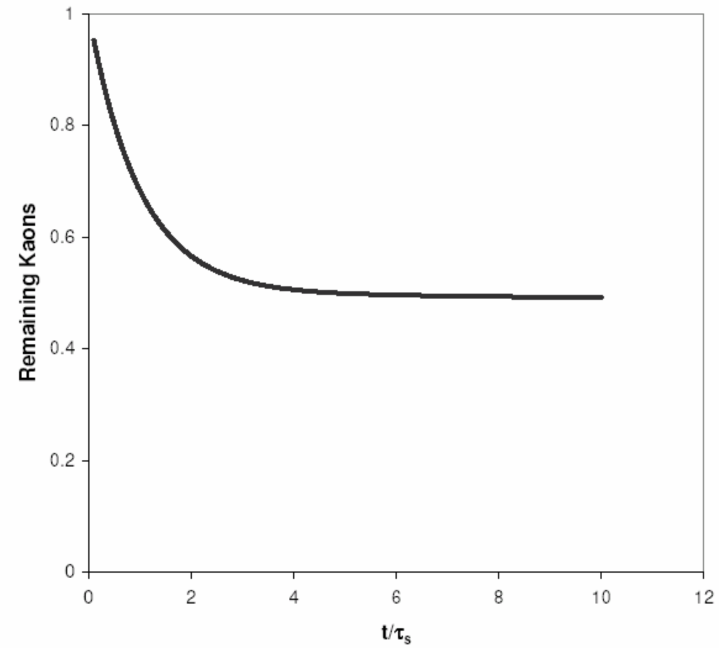
$$CP|K_S\rangle \rightarrow |K_S\rangle, \qquad CP|K_L\rangle \rightarrow -|K_L\rangle$$

Neutral K mesons

Consider K^0 production and subsequent decay

Why don't the K^0's decay away with a single exponential?

K^0's are mixtures of K_S and K_L



$$K_S \rightarrow 2\pi(CP = +1), \qquad \tau_S = 0.893 \times 10^{-10}\ \text{s}$$
$$K_L \rightarrow 3\pi(CP = -1), \qquad \tau_L = 0.517 \times 10^{-7}\ \text{s}$$

Neutral K mesons

It can be shown that the 2π state has CP = +1, and the 3π state has CP = -1

Thus, if CP is conserved,

$$K_S = \sqrt{\tfrac{1}{2}}(K^0 + \bar{K}^0) \rightarrow 2\pi(CP = +1),$$
$$K_L = \sqrt{\tfrac{1}{2}}(K^0 - \bar{K}^0) \rightarrow 3\pi(CP = -1),$$

Since the 2 and 3-pion decays have different Q values, the decay rates are different:

$$K_S \rightarrow 2\pi(CP = +1), \qquad \tau_S = 0.893 \times 10^{-10}\ \text{s}$$
$$K_L \rightarrow 3\pi(CP = -1), \qquad \tau_L = 0.517 \times 10^{-7}\ \text{s}$$

which is why the CP=+1 state is called K-short(K_S) and the CP=-1 state is called K-long (K_L)

Neutral K mesons

Strangeness oscillations

$$A_S(t) = A_S(0)e^{-(\Gamma_S/2+im_S)t}$$

$$A_L(t) = A_L(0)e^{-(\Gamma_L/2+im_L)t}$$

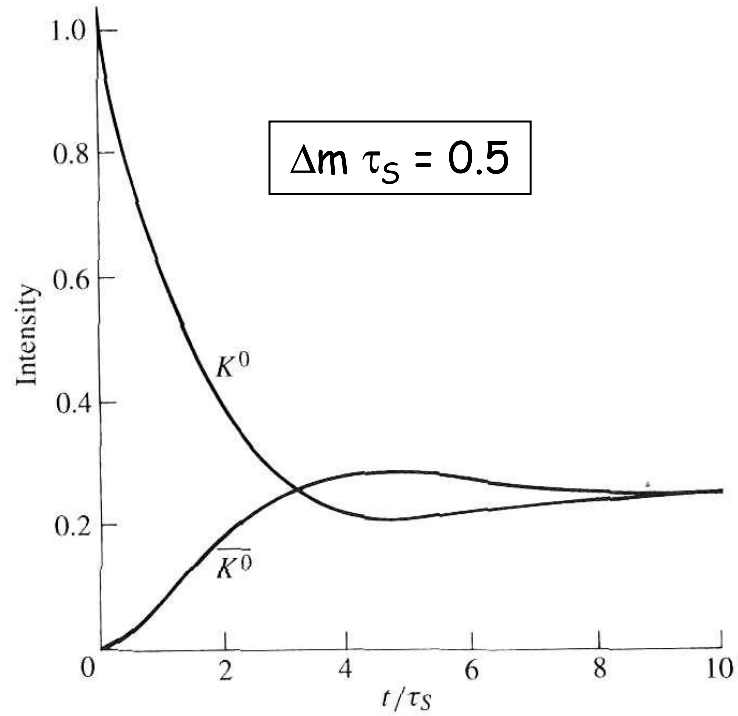
$$I(K^0) = \tfrac{1}{2}[A_S(t) + A_L(t)][A_S^*(t) + A_L^*(t)]$$

$$= \tfrac{1}{4}\left[e^{-\Gamma_S t} + e^{-\Gamma_L t} + 2e^{-(\Gamma_S+\Gamma_L)t/2}\cos\Delta m t\right]$$

Assuming an initially pure K^0 beam, so $A_S(0) = A_L(0) = 1/\sqrt{2}$

$$\Delta m = m_L - m_S$$

$$I(\bar{K}^0) = \tfrac{1}{4}[e^{-\Gamma_S t} + e^{-\Gamma_L t} - 2e^{-(\Gamma_S+\Gamma_L)t/2}\cos\Delta m t]$$



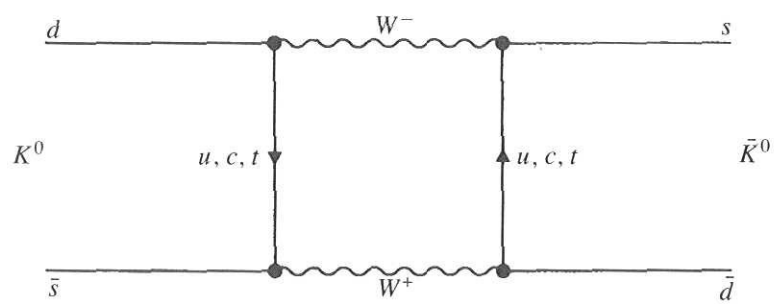
$$\Delta m = (3.491 \pm 0.009) \times 10^{-12}\ \text{MeV}$$

Neutral K mesons

$$\Delta m = (3.491 \pm 0.009) \times 10^{-12}\ \text{MeV}$$

This mass difference corresponds to the rate at which K^0 oscillates into $\overline{K}^0$.

This oscillation proceeds through the second-order weak interaction



The c quark dominates (CKM matrix)

$$\Delta m = \frac{G^2}{4\pi} m_K f_K^2 m_c^2 \cos^2\theta_c \sin^2\theta_c$$

Neutral K mesons

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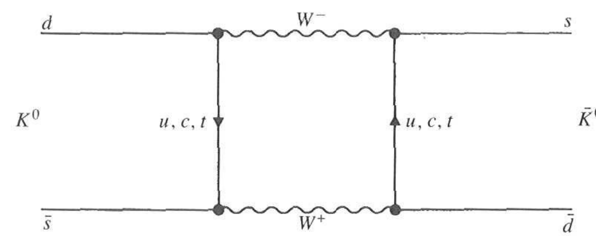


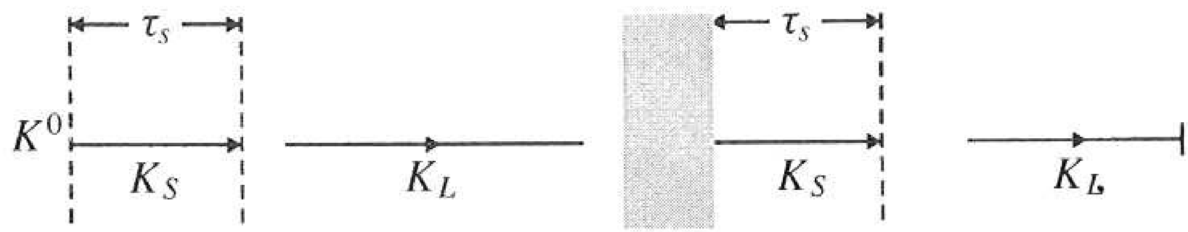
f_K is the called the "kaon decay constant"
$f_K \approx 1.2\ m_\pi$

$m_K f_K^2$ relates to $|\psi(0)|^2$, the wavefunction at the origin, or the point at which the quarks interact

measurement of m allowed the mass of the charmed quark to be estimated ($m_c \approx 1.5$ GeV) before it was discovered.

Neutral K mesons

K^0 Regeneration



$$K_L = \frac{1}{\sqrt{2}}(K^0 - \bar{K}^0)$$

K^0 and $\overline{K^0}$ are absorbed differently

$$\frac{1}{\sqrt{2}}(fK^0 - \bar{f}\overline{K^0}) = \frac{1}{2}(f+\bar{f})K_L + \frac{1}{2}(f-\bar{f})K_S$$

CP violation in the neutral kaon system

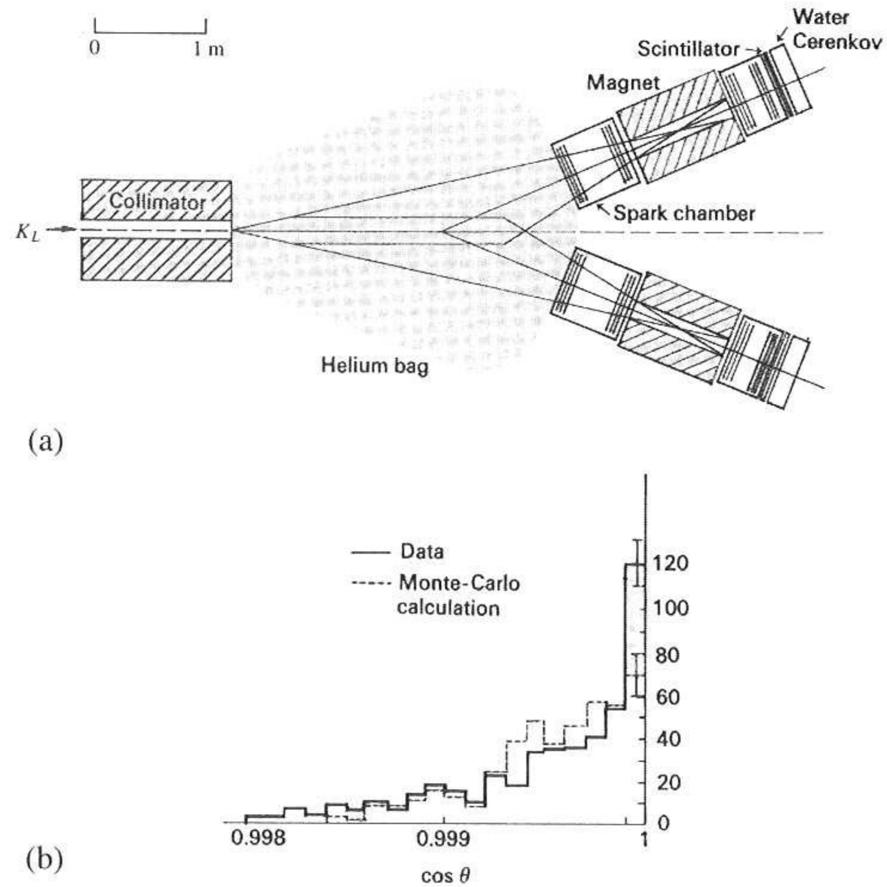
K_L is the CP=-1 eigenstate, and is not supposed to decay to two pions, just to three pions

1964 - experiment finds that K_L does decay to two pions with BR = 0.003

$K_L \to \pi^+\pi^-$ (0.002)

$K_L \to \pi^0\pi^0$ (0.001)

This violates CP since K_L was is the CP=-1 eigenstate, but the CP of two pions is +1



CP violation in the neutral kaon system

Let K_1 represent the CP = +1 state and K_2 the CP = -1 state

$$K_L = \frac{1}{\sqrt{1+|\varepsilon|^2}}(K_2 + \varepsilon K_1)$$
$$K_S = \frac{1}{\sqrt{1+|\varepsilon|^2}}(K_1 - \varepsilon K_2)$$

ε is a small parameter quantifying the CP violation, which must be determined experimentally

$$|\eta_{+-}| = \frac{\mathrm{ampl}(K_L \to \pi^+\pi^-)}{\mathrm{ampl}(K_S \to \pi^+\pi^-)} = (2.29 \pm 0.02) \times 10^{-3}$$

$$|\eta_{00}| = \frac{\mathrm{ampl}(K_L \to \pi^0\pi^0)}{\mathrm{ampl}(K_S \to \pi^0\pi^0)} = (2.28 \pm 0.02) \times 10^{-3}$$

CP violation in the neutral kaon system

Interference between K_S and K_L Amplitudes

$$\frac{I_{2\pi}(t)}{I_{2\pi}(0)} = e^{-\Gamma_S t} + |\eta_{+-}|^2 e^{-\Gamma_L t} + 2|\eta_{+-}|\, e^{-[(\Gamma_L+\Gamma_S)/2]t} \cos(\Delta m\, t + \phi_{+-})$$

where ϕ is the phase angle between the K_s and K_L amplitudes

CPLEAR

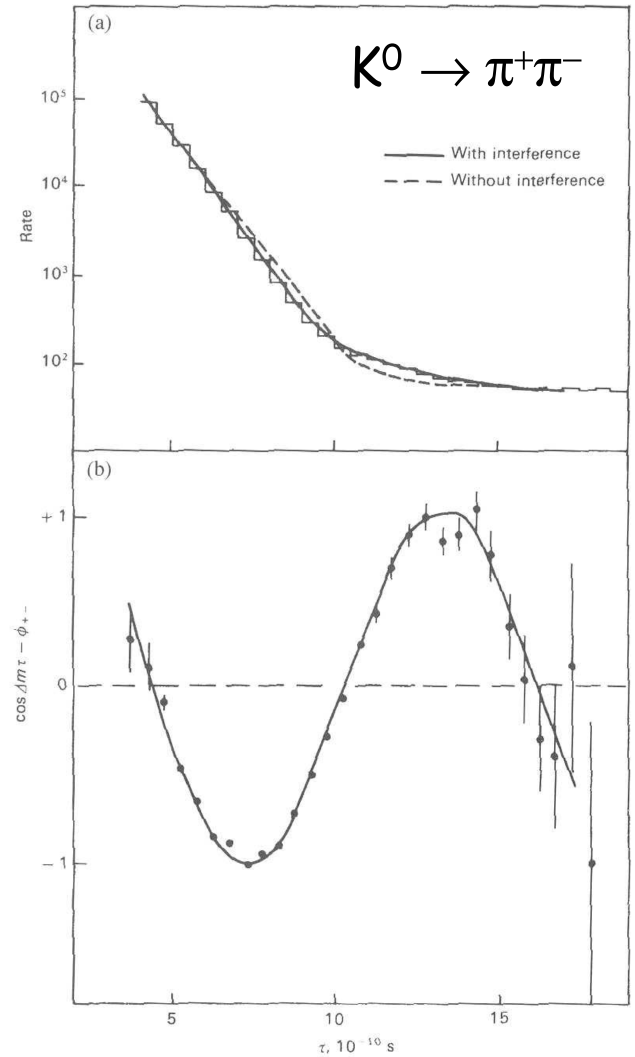
$$p\bar{p} \to K^-\pi^+K^0$$
$$p\bar{p} \to K^+\pi^-\bar{K}^0$$

Measured asymmetry between K^0 and $\overline{K^0}$

$$A_{+-}(t) = \frac{2|\eta_{+-}|e^{[(\Gamma_S-\Gamma_L)/2]t}\cos(\Delta m\, t + \phi_{+-})}{1 + |\eta_{+-}|^2 e^{(\Gamma_S-\Gamma_L)t}}$$

$$\phi_{+-} = 43.7^\circ \pm 0.6^\circ \qquad \phi_{00} = 43.5^\circ \pm 1.0^\circ$$

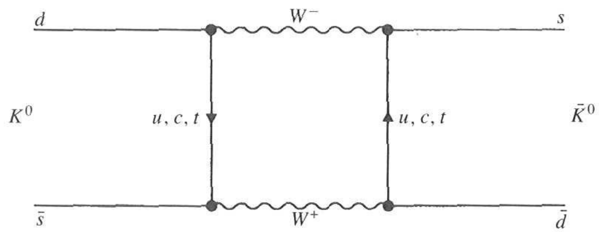
$K^0 \to \pi^+\pi^-$



CP violation in the neutral kaon system

There are two possible sources of CP violation in the K^0 decay:

1. Indirect CP violation - admixture of ε



2. Direct CP violation $\Rightarrow$ ε', from interference

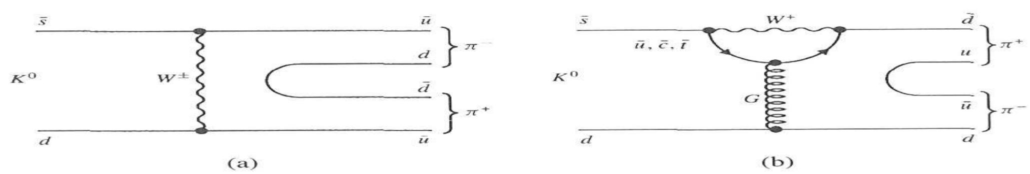


Fig. 7.24. (a) 'Tree' diagram showing $K^0 \to 2\pi$ decay via $W^\pm$ exchange; (b) 'penguin' diagram showing $K^0 \to 2\pi$ decay via the intermediary $\bar{u}$, $\bar{c}$, $\bar{t}$ quark states. The interference between diagrams (a) and (b) gives rise to a non-trivial phase factor and 'direct' CP violation shown in the decay process itself, rather than the 'indirect' CP violation shown in the 'box' diagram of Figure 7.20, where the mass eigenstates themselves are mixed states of even and odd CP.

Penguin diagram

$$\eta_{+-} = |\eta_{+-}|e^{i\phi_{+-}} \simeq \varepsilon + \varepsilon'$$
$$\eta_{00} = |\eta_{00}|e^{i\phi_{00}} \simeq \varepsilon - 2\varepsilon'$$

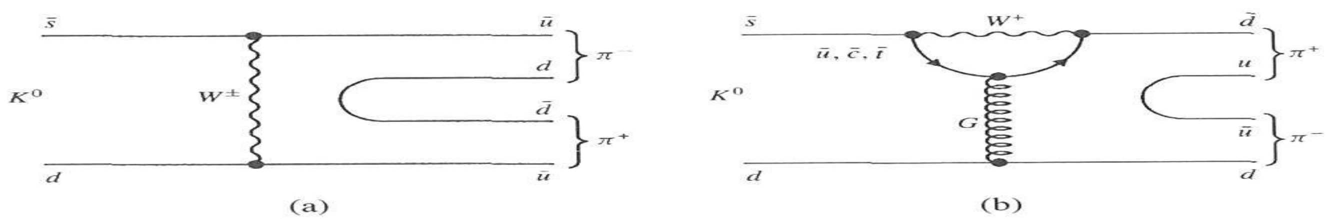
CP violation in the neutral kaon system

Measuring precisely ε′/ε has been a major effort at CERN and Fermilab for many years

$$\frac{\varepsilon'}{\varepsilon} = (2.2 \pm 0.4) \times 10^{-3}$$

Direct CP violation is established.

This is a puzzle for the Standard Model because the interference (and therefore ε′) should be small with m_t = 175 GeV



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CP violation in the neutral kaon system

CP Violation in leptonic decays

$$K_L \rightarrow e^+ + \nu_e + \pi^-$$
$$K_L \rightarrow e^- + \bar{\nu}_e + \pi^+$$

These decays transform into one another under the CP operation, so CP-invariance demands they be equal

$$\Delta = \frac{\text{rate}(K_L \rightarrow e^+ + \nu_e + \pi^-) - \text{rate}(K_L \rightarrow e^- + \bar{\nu}_e + \pi^+)}{\text{rate}(K_L \rightarrow e^+ + \nu_e + \pi^-) + \text{rate}(K_L \rightarrow e^- + \bar{\nu}_e + \pi^+)}$$
$$= (0.327 \pm 0.012) \times 10^{-2}$$

Since e^+ must come from K^0 and e^- from $\overline{K^0}$

$$\Delta = \frac{|1+\varepsilon|^2 - |1-\varepsilon|^2}{|1+\varepsilon|^2 + |1-\varepsilon|^2} \simeq 2\,\mathrm{Re}\,\varepsilon$$

$$\Rightarrow \quad \Delta(\varepsilon' = 0) = 2\eta\cos\phi = (0.332 \pm 0.004) \times 10^{-2}$$

CP violation in the neutral kaon system

Superweak Interaction?

Wolfenstein postulated (1964) that CP violation arises from a new superweak interaction ($\Delta S = 2$)

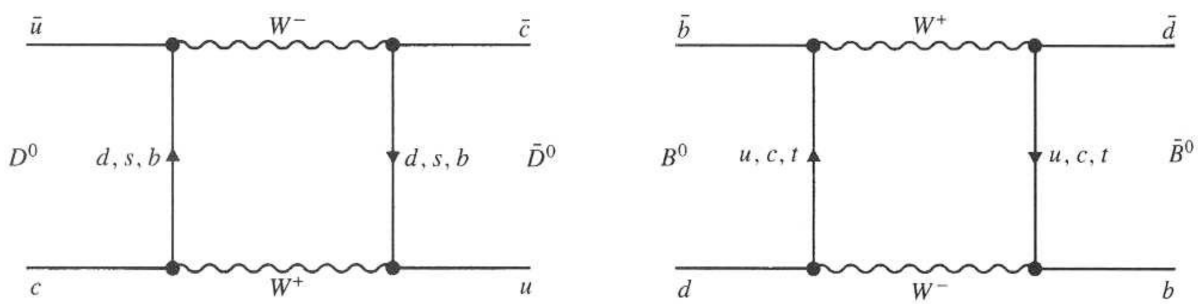
Prediction:

$\varepsilon' = 0$ (no Direct CP violation)

which now appears to be ruled out

D^0-$\overline{D^0}$ and B^0-$\overline{B^0}$ mixing

Mixing which is seen for Kaons, can also occur in charm and bottom mesons



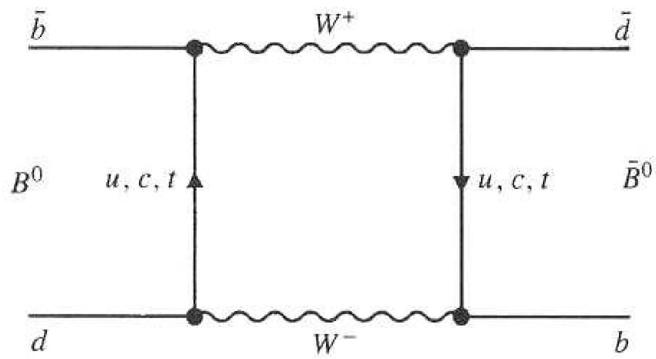
Mixing in the charm meson is very small:

the b quark diagram depends on
$|V_{cb}V_{ub}|^2 \approx |0.04 \times 0.005|^2 \approx |0.0002|^2 \approx 4 \times 10^{-8}$

and the s quark diagram is suppressed by the small value of the s quark mass

D^0-$\overline{D^0}$ and B^0-$\overline{B^0}$ mixing

Mixing in the bottom meson is dominated by the t quark exchange, and is substantial



for kaons we had $P(t)dt = \frac{\Gamma e^{-\Gamma t}}{2}\left[\frac{e^{-y\Gamma t}}{2} + \frac{e^{+y\Gamma t}}{2} \pm \cos x\Gamma t\right]dt$

$\Gamma = (\Gamma_S + \Gamma_L)/2 \approx \Gamma_S/2$; $y = (\Gamma_S - \Gamma_L) / 2\Gamma \approx 1$; $x = \Delta m / \Gamma \approx 0.95$

For Bs, $\Gamma = (\Gamma_S + \Gamma_L)/2$

$y = (\Gamma_S - \Gamma_L) / 2\Gamma \approx 0$ (B^0 and $\overline{B^0}$ decay to common channels)

$x = \Delta m / \Gamma$

$$P(t)dt = \frac{\Gamma e^{-\Gamma t}}{2}\left[1 \pm \cos x\Gamma t\right]dt$$

$\Rightarrow$ $x = 0.72$

D^0-$\overline{D^0}$ and B^0-$\overline{B^0}$ mixing

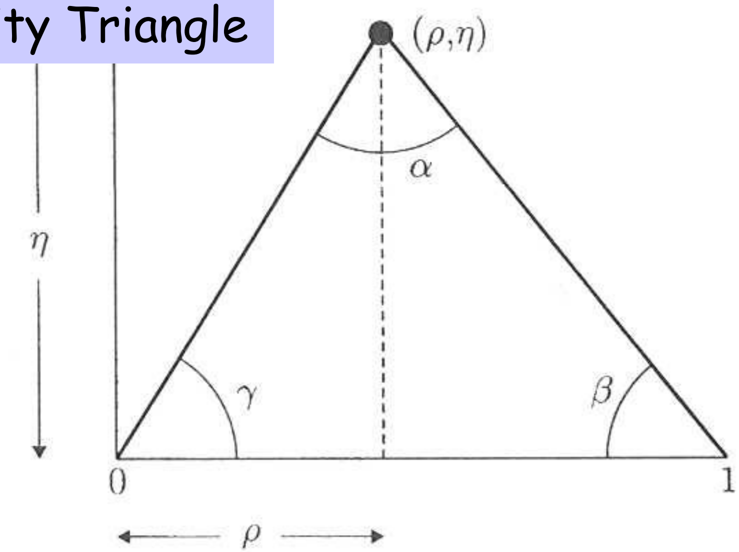
CKM matrix should be unitary

$$V_{\mathrm{CKM}} = \begin{vmatrix} V_{ud} = 0.975 & V_{us} = 0.221 & V_{ub} = 0.005 \\ V_{cd} = 0.221 & V_{cs} = 0.974 & V_{cb} = 0.04 \\ V_{td} = 0.01 & V_{ts} = 0.041 & V_{tb} = 0.999 \end{vmatrix}$$

Therefore off-diagonal terms will vanish, such as: $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$

$$V_{\mathrm{CKM}} = \begin{vmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{vmatrix}$$

Unitarity Triangle



CP Violation in the B System

CP violation shows up as large asymmetries in decay modes with very small BRs

eg. $B^0 \rightarrow J/\psi\ K_S^0$

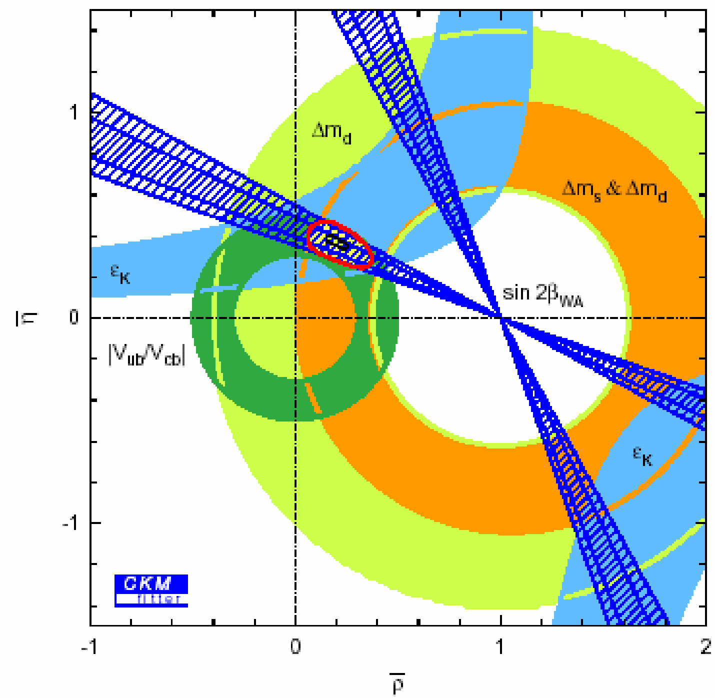
$$R \propto e^{-t/\tau}(1 \pm \sin 2\beta \sin \Delta m\, t)$$

BaBar

$\sin 2\beta = 0.741 \pm 0.067\ (\mathit{stat}) \pm 0.034\ (\mathit{syst})$

hep-ex/0207042

88 million BB decays



Cosmological CP violation

1966 - Sakharov

showed that three conditions are required for the baryon asymmetry of the Universe to have developed

1) B-violating interactions
2) a non-equilibrium situation
3) CP and C violation

The CP violation observed in the K and B systems is not sufficient to explain the baryon asymmetry

additional CP violation must occur

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