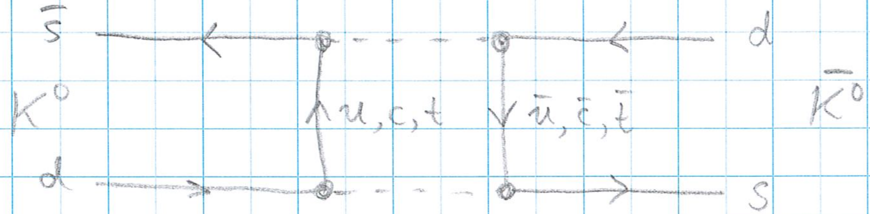
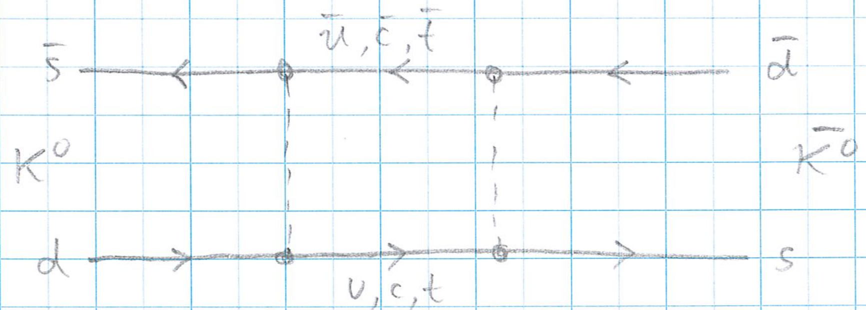
CP Violation

$K_L^0 \to \pi^+\pi^-$ CP-odd $\to$ CP-even

Three possible sources of CP violation.

1. Mixing induced CP violation



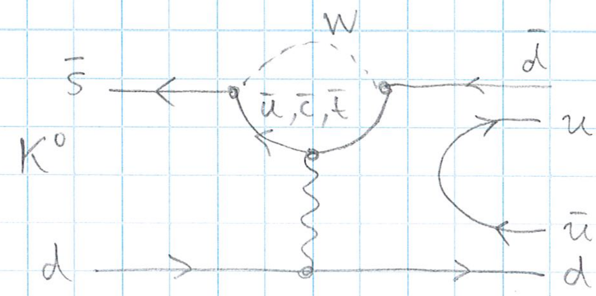


$$\varepsilon \propto \text{Im}\left(V_{td} V_{ts}^*\right) F\left(m_t^2, m_c^2\right)$$

$$V_{ckm} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \qquad VV^{\dagger} = 1.$$

Weak eigenstates: $\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{ckm} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$

2. Direct CP violation



3. CP violation by interference

Different time dependence of particle and anti-particle.

The neutral B system

$B^0 = \bar{b}d \qquad \bar{B}^0 = b\bar{d}$

Again, there are two possible CP eigenstates

$$B_h(t) = (p B^0 - q \bar{B}^0)\, e^{i m_h t - \Gamma t/2} \qquad \varepsilon = \frac{p-q}{p+q}$$

$$B_l(t) = (p B^0 + q \bar{B}^0)\, e^{i m_l t - \Gamma t/2}$$

Because the B is much heavier than the K system the decay rates are equal

$$\Gamma_L = \Gamma_H = \Gamma$$

Probability of observing a B^0 decaying in a mixed state is

$$P(B^0 \to \bar{B}^0) = \frac{1}{2}\left|\frac{q}{p}\right|^2 e^{-\Gamma t}\left(1 - \cos(\Delta m_d t)\right)$$

$$P(\bar{B}^0 \to B^0) = \frac{1}{2}\left|\frac{p}{q}\right|^2 e^{-\Gamma t}\left(1 - \cos(\Delta m_d t)\right)$$

In the B-system $|p/q| = 1$ within $\mathcal{O}(10^{-3})$.

How can we tell what the initial state was?

1. Coherent production of B^0 and $\bar{B}^0$

$e^+e^- \rightarrow \Upsilon(4s) \rightarrow B^0 \bar{B}^0$

Strong decay so parity is conserved. Both mesons oscillate but the oscillation is coherent.

If one B decays at time t to $D^- \ell^+ \nu_\ell$ then it must have been in a B^0 state ($\bar{b} \rightarrow \bar{c} \ell^+ \nu_e$) and at that instant the other B must be in a $\bar{B}^0$ state.

Measure the time difference between the decays, Δt.

$$N(B^0 B^0) = N(\bar{B}^0 \bar{B}^0) = C e^{-\Gamma|\Delta t|}\left(1 - \cos(\Delta m_d \Delta t)\right)$$

Number of unmixed decays

$$N(B^0 \bar{B}^0) = C e^{-\Gamma|\Delta t|}\left(1 + \cos(\Delta m_d \Delta t)\right)$$

Asymmetry:

$$A(\Delta t) = \frac{N(B^0 B^0) - N(B^0 \bar{B}^0)}{N(B^0 B^0) + N(B^0 \bar{B}^0)} = \cos(\Delta m_d \Delta t)$$

Amplitude = 1, frequency is Δm_d.

If the flavor determination is wrong some fraction of the time, f, then what we measure is

$$N(B^0 \bar{B}^0) = C e^{-\Gamma|\Delta t|}\left[(1-f)\left(1 - \cos(\Delta m_d \Delta t)\right) + f\left(1 + \cos(\Delta m_d t)\right)\right]$$

Leading to

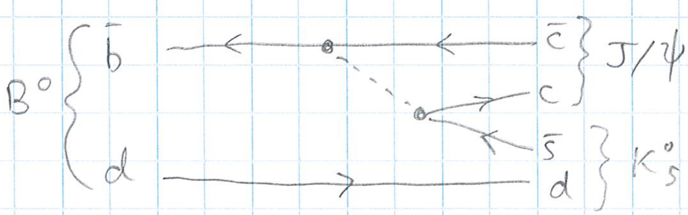
$$A(\Delta t) = (1-2f)\cos(\Delta m_d \Delta t).$$

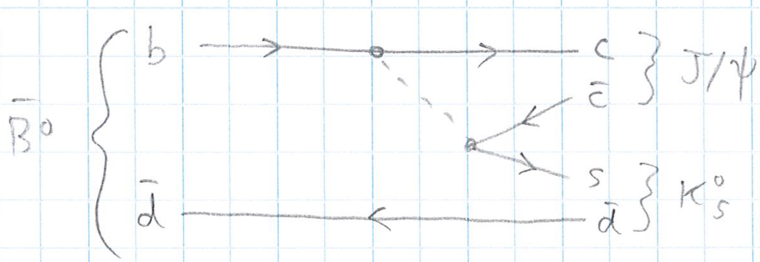
$\Delta m_d = 0.489 \pm 0.008 \ ps^{-1}$ (2002)

$0.5096 \pm 0.0034 \ ps^{-1}$ (2016)

CP violation.

B^0 and $\bar{B}^0$ can both decay to the same CP eigenstate





CP asymmetry manifests itself as a difference in the rates of B^0 and $\bar{B}^0$ decaying to $J/\psi K^0_s$:

$$A(t) = \frac{\Gamma(\bar{B}^0(t) \to J/\psi K^0_s) - \Gamma(B^0(t) \to J/\psi K^0_s)}{\Gamma(B^0(t) \to J/\psi K^0_s) + \Gamma(B^0(t) \to J/\psi K^0_s)}$$

$$= -\sin 2\beta \sin \Delta m_d \Delta t$$

$\sin 2\beta$ is the amplitude where

$$\beta = \operatorname{Arg}\left(-(V_{cd} V^*_{cb})/(V_{td} V^*_{tb})\right)$$

Interference between mixing and decay.