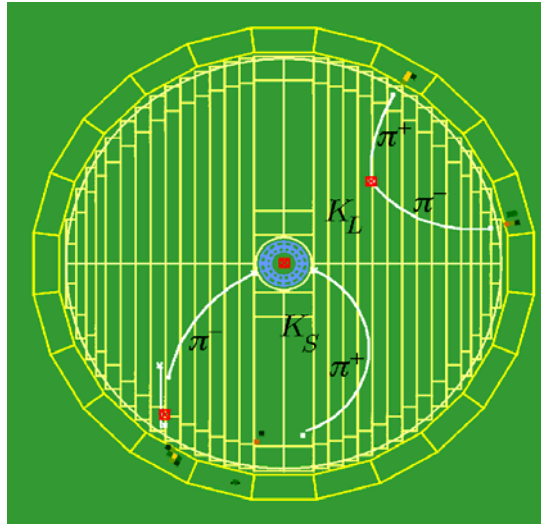


Particle Physics

Michaelmas Term 2009
Prof Mark Thomson



Handout 12 : The CKM Matrix and CP Violation

CP Violation in the Early Universe

- Very early in the universe might expect equal numbers of baryons and anti-baryons
- However, today the universe is matter dominated (no evidence for anti-galaxies, etc.)
- From “Big Bang Nucleosynthesis” obtain the matter/anti-matter asymmetry

$$\xi = \frac{n_B - n_{\bar{B}}}{n_\gamma} \approx \frac{n_B}{n_\gamma} \approx 10^{-9}$$

i.e. for every baryon in the universe today there are 10^9 photons

- **How did this happen?**

- ★ Early in the universe need to create a very small asymmetry between baryons and anti-baryons

e.g. for every 10^9 anti-baryons there were 10^9+1 baryons

baryons/anti-baryons annihilate \Rightarrow

1 baryon + $\sim 10^9$ photons + no anti-baryons

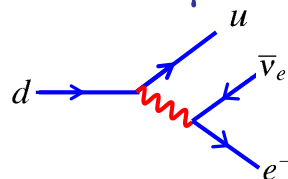
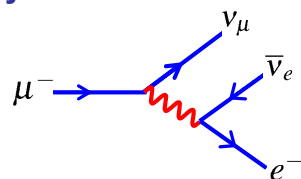
- ★ To generate this initial asymmetry three conditions must be met (Sakharov, 1967):

- ① “Baryon number violation”, i.e. $n_B - n_{\bar{B}}$ is not constant
- ② “C and CP violation”, if CP is conserved for a reaction which generates a net number of baryons over anti-baryons there would be a CP conjugate reaction generating a net number of anti-baryons
- ③ “Departure from thermal equilibrium”, in thermal equilibrium any baryon number violating process will be balanced by the inverse reaction

- CP Violation is an essential aspect of our understanding of the universe
- A natural question is whether the SM of particle physics can provide the necessary CP violation?
- There are two places in the SM where CP violation enters: the **PMNS matrix** and the **CKM matrix**
- To date CP violation has been observed only in the quark sector
- Because we are dealing with quarks, which are only observed as **bound states**, this is a fairly complicated subject. Here we will approach it in two steps:
 - i) Consider **particle – anti-particle oscillations** without CP violation
 - ii) Then discuss the effects of **CP violation**
- ★ Many features in common with neutrino oscillations – except that we will be considering the oscillations of decaying particles (i.e. mesons) !

The Weak Interaction of Quarks

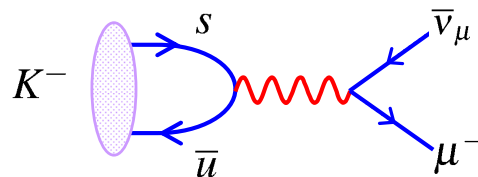
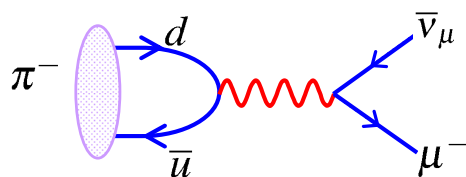
- ★ However, slightly different values of G_F measured in μ decay and nuclear β decay:



$$G_F^\mu = (1.16632 \pm 0.00002) \times 10^{-5} \text{ GeV}^{-2}$$

$$G_F^\beta = (1.136 \pm 0.003) \times 10^{-5} \text{ GeV}^{-2}$$

- ★ In addition, certain hadronic decay modes are observed to be suppressed, e.g. compare $K^- \rightarrow \mu^- \bar{\nu}_\mu$ and $\pi^- \rightarrow \mu^- \bar{\nu}_\mu$. Kaon decay rate suppressed factor 20 compared to the expectation assuming a universal weak interaction for quarks.

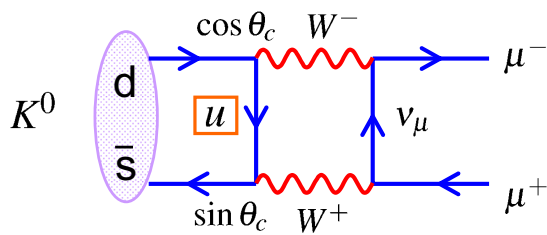


- Both observations explained by Cabibbo hypothesis (1963): weak eigenstates are different from mass eigenstates, i.e. weak interactions of quarks have same strength as for leptons but a u-quark couples to a linear combination of s and d

$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos \theta_c & \sin \theta_c \\ -\sin \theta_c & \cos \theta_c \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

GIM Mechanism

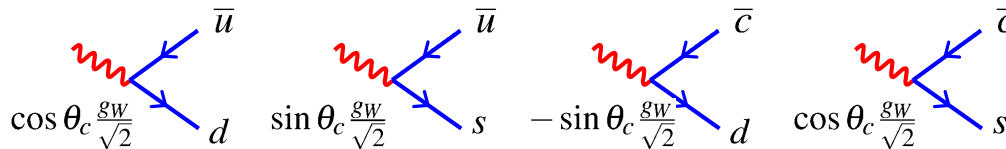
- ★ In the weak interaction have coupling between both ud and us which implies that neutral mesons can decay via box diagrams, e.g.



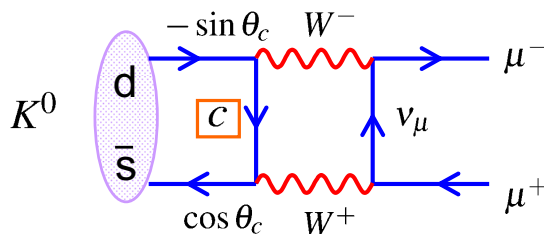
$$M_1 \propto g_W^4 \cos \theta_c \sin \theta_c$$

- Historically, the observed branching was much smaller than predicted

- ★ Led Glashow, Iliopoulos and Maiani to postulate existence of an extra quark - before discovery of charm quark in 1974. Weak interaction couplings become



- ★ Gives another box diagram for $K^0 \rightarrow \mu^+ \mu^-$



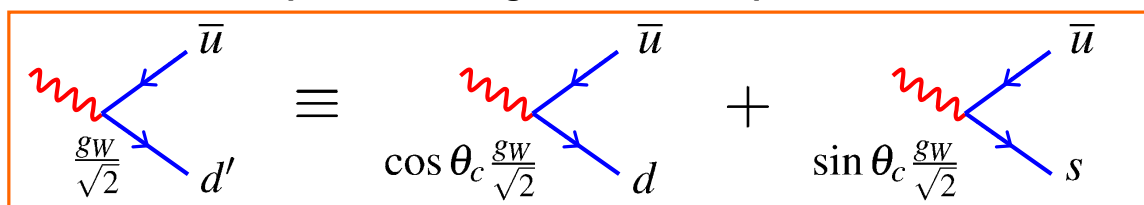
$$M_2 \propto -g_W^4 \cos \theta_c \sin \theta_c$$

- Same final state so sum amplitudes

$$|M|^2 = |M_1 + M_2|^2 \approx 0$$

- Cancellation not exact because $m_u \neq m_c$

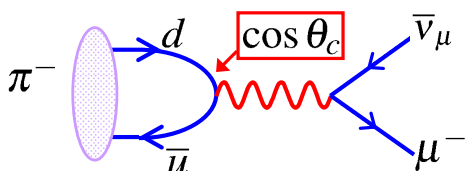
i.e. weak interaction couples different generations of quarks



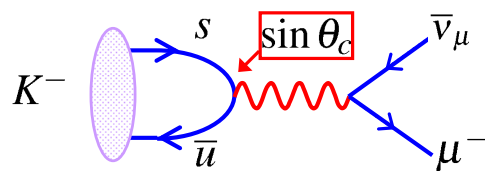
(The same is true for leptons e.g. $e^- \nu_1, e^- \nu_2, e^- \nu_3$ couplings – connect different generations)

- ★ Can explain the observations on the previous page with $\theta_c = 13.1^\circ$

- Kaon decay suppressed by a factor of $\tan^2 \theta_c \approx 0.05$ relative to pion decay

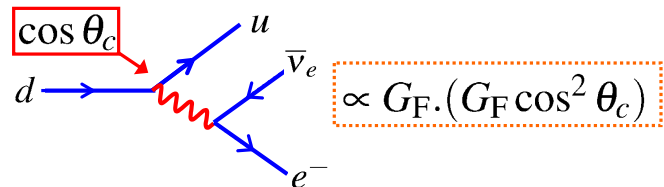
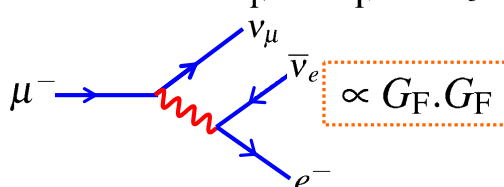


$$\Gamma(\pi^- \rightarrow \mu^- \bar{\nu}_\mu) \propto |M|^2 \propto \cos^2 \theta_c$$



$$\Gamma(K^- \rightarrow \mu^- \bar{\nu}_\mu) \propto |M|^2 \propto \sin^2 \theta_c$$

- Hence expect $G_F^\beta = G_F^\mu \cos \theta_c$



CKM Matrix

- ★ Extend ideas to three quark flavours (analogue of three flavour neutrino treatment)

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

By convention CKM matrix defined as acting on quarks with charge $-\frac{1}{3}e$

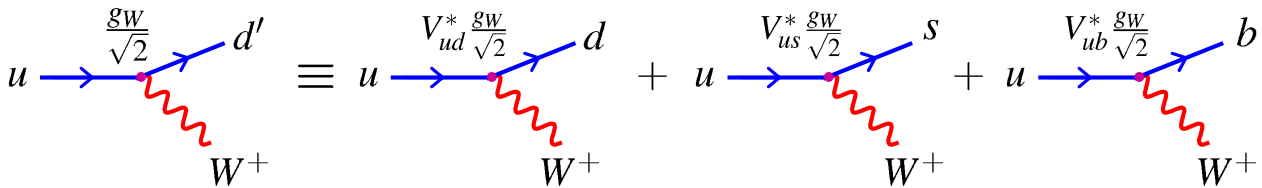
Weak eigenstates

CKM Matrix

Mass Eigenstates

(Cabibbo, Kobayashi, Maskawa)

- ★ e.g. Weak eigenstate d' is produced in weak decay of an up quark:

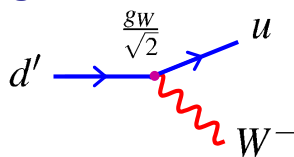


- The CKM matrix elements V_{ij} are **complex constants**
- The CKM matrix is **unitary**
- The V_{ij} are not predicted by the SM – have to **determined from experiment**

Feynman Rules

- Depending on the order of the interaction, $u \rightarrow d$ or $d \rightarrow u$, the CKM matrix enters as either V_{ud} or V_{ud}^*

- Writing the interaction in terms of the WEAK eigenstates



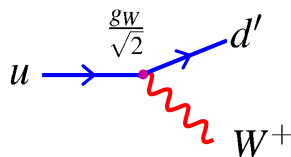
$$j_{d'u} = \bar{u} \left[-i \frac{g_W}{\sqrt{2}} \gamma^\mu \frac{1}{2} (1 - \gamma^5) \right] d'$$

NOTE: \bar{u} is the adjoint spinor not the anti-up quark

- Giving the $d \rightarrow u$ weak current:

$$j_{du} = \bar{u} \left[-i \frac{g_W}{\sqrt{2}} \gamma^\mu \frac{1}{2} (1 - \gamma^5) \right] V_{ud} d$$

- For $u \rightarrow d'$ the weak current is:



$$j_{ud'} = \bar{d}' \left[-i \frac{g_W}{\sqrt{2}} \gamma^\mu \frac{1}{2} (1 - \gamma^5) \right] u$$

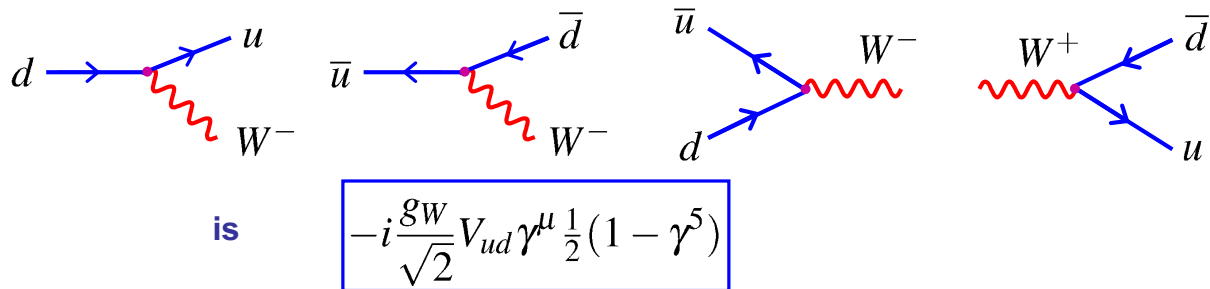
- In terms of the mass eigenstates $\bar{d}' = d'^\dagger \gamma^0 \rightarrow (V_{ud} d)^\dagger \gamma^0 = V_{ud}^* d^\dagger \gamma^0 = V_{ud}^* \bar{d}$

- Giving the $u \rightarrow d$ weak current:

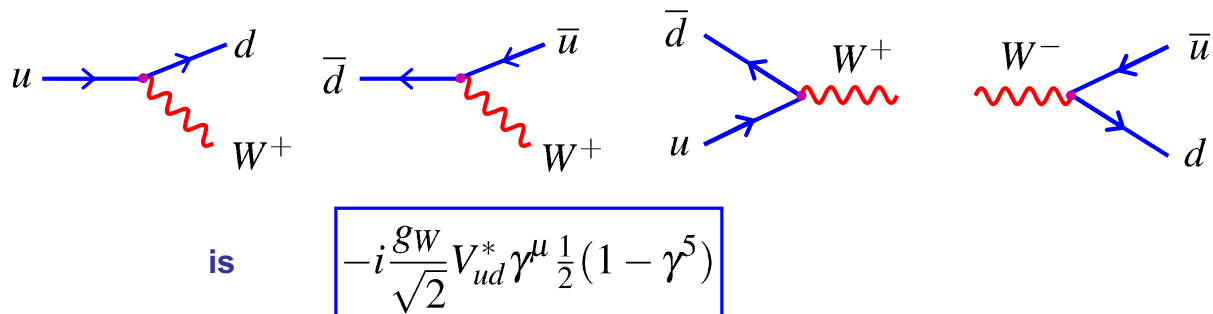
$$j_{ud} = \bar{d} V_{ud}^* \left[-i \frac{g_W}{\sqrt{2}} \gamma^\mu \frac{1}{2} (1 - \gamma^5) \right] u$$

- Hence, when the charge $-\frac{1}{3}$ quark enters as the adjoint spinor, the complex conjugate of the CKM matrix is used

★ The vertex factor the following diagrams:



★ Whereas, the vertex factor for:



★ Experimentally (see Appendix I) determine

$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{pmatrix} \approx \begin{pmatrix} 0.974 & 0.226 & 0.004 \\ 0.23 & 0.96 & 0.04 \\ ? & ? & ? \end{pmatrix}$$

★ Currently little direct experimental information on V_{td}, V_{ts}, V_{tb}

★ Assuming **unitarity** of CKM matrix, e.g. $|V_{ub}|^2 + |V_{cb}|^2 + |V_{tb}|^2 = 1$ gives:

$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{pmatrix} \approx \begin{pmatrix} 0.974 & 0.226 & 0.004 \\ 0.23 & 0.96 & 0.04 \\ 0.01 & 0.04 & 0.999 \end{pmatrix}$$

Cabibbo matrix

Near diagonal – very different from PMNS

★ **NOTE:** within the SM, the charged current, W^\pm , weak interaction:

- ① Provides the only way to **change flavour** !
- ② only way to **change from one generation** of quarks or leptons to another !

★ However, the off-diagonal elements of the CKM matrix are relatively small.

- Weak interaction largest between quarks of the same generation.
- Coupling between first and third generation quarks is very small !

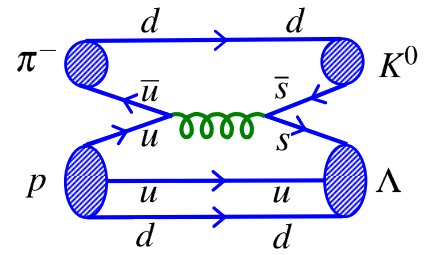
★ Just as for the PMNS matrix – the CKM matrix allows CP violation in the SM

The Neutral Kaon System

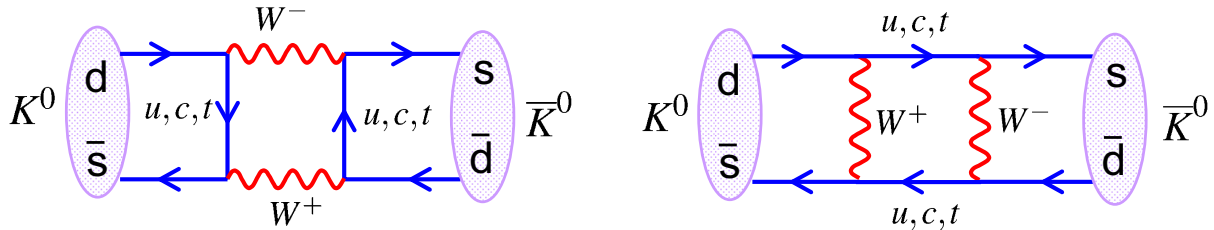
- **Neutral Kaons** are produced copiously in strong interactions, e.g.

$$\pi^- (d\bar{u}) + p(uud) \rightarrow \Lambda(uds) + K^0(d\bar{s})$$

$$\pi^+ (u\bar{d}) + p(uud) \rightarrow K^+(u\bar{s}) + \bar{K}^0(s\bar{d}) + p(uud)$$



- **Neutral Kaons** decay via the weak interaction
- The Weak Interaction also allows **mixing** of neutral kaons via “box diagrams”



- This allows **transitions** between the strong eigenstates K^0, \bar{K}^0
- Consequently, the neutral kaons propagate as eigenstates of the overall strong + weak interaction (**Appendix II**); i.e. as linear combinations of K^0, \bar{K}^0
- These neutral kaon states are called the “**K-short**” K_S and the “**K-long**” K_L
- These states have approximately the same mass $m(K_S) \approx m(K_L) \approx 498 \text{ MeV}$
- But very different lifetimes: $\tau(K_S) = 0.9 \times 10^{-10} \text{ s}$ $\tau(K_L) = 0.5 \times 10^{-7} \text{ s}$

CP Eigenstates

- ★ The K_S and K_L are closely related to eigenstates of the combined charge conjugation and parity operators: CP

- The strong eigenstates $K^0(d\bar{s})$ and $\bar{K}^0(s\bar{d})$ have $J^P = 0^-$

with

$$\hat{P}|K^0\rangle = -|K^0\rangle, \quad \hat{P}|\bar{K}^0\rangle = -|\bar{K}^0\rangle$$

- The charge conjugation operator changes particle into anti-particle and vice versa

$$\hat{C}|K^0\rangle = \hat{C}|d\bar{s}\rangle = +|s\bar{d}\rangle = |\bar{K}^0\rangle$$

similarly

$$\hat{C}|\bar{K}^0\rangle = |K^0\rangle$$

The + sign is purely conventional, could have used a - with no physical consequences

- Consequently

$$\hat{C}\hat{P}|K^0\rangle = -|\bar{K}^0\rangle \quad \hat{C}\hat{P}|\bar{K}^0\rangle = -|K^0\rangle$$

i.e. neither K^0 or \bar{K}^0 are eigenstates of CP

- Form CP eigenstates from linear combinations:

$$|K_1\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle - |\bar{K}^0\rangle)$$

$$|K_2\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle + |\bar{K}^0\rangle)$$

$$\hat{C}\hat{P}|K_1\rangle = +|K_1\rangle$$

$$\hat{C}\hat{P}|K_2\rangle = -|K_2\rangle$$

Decays of CP Eigenstates

- Neutral kaons often decay to pions (the lightest hadrons)
- The kaon masses are approximately **498 MeV** and the pion masses are approximately **140 MeV**. Hence neutral kaons can decay to either 2 or 3 pions

Decays to Two Pions:

★ $K^0 \rightarrow \pi^0 \pi^0$ $J^P: 0^- \rightarrow 0^- + 0^-$

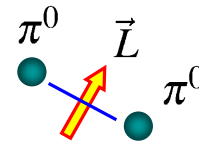
- Conservation of angular momentum $\rightarrow \vec{L} = 0$

$$\Rightarrow \hat{P}(\pi^0 \pi^0) = -1 \cdot -1 \cdot (-1)^L = +1$$

- The $\pi^0 = \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})$ is an eigenstate of \hat{C}

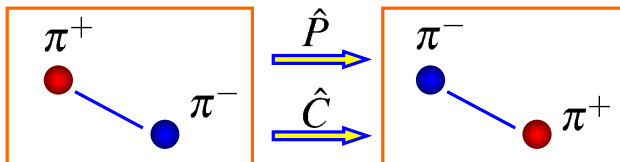
$$C(\pi^0 \pi^0) = C\pi^0 \cdot C\pi^0 = +1 \cdot +1 = +1$$

$$\Rightarrow CP(\pi^0 \pi^0) = +1$$



★ $K^0 \rightarrow \pi^+ \pi^-$ as before $\hat{P}(\pi^+ \pi^-) = +1$

- ★ Here the **C** and **P** operations have the identical effect



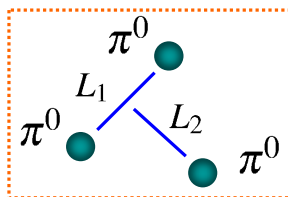
Hence the combined effect of $\hat{C}\hat{P}$ is to leave the system unchanged

$$\hat{C}\hat{P}(\pi^+ \pi^-) = +1$$

Neutral kaon decays to two pions occur in CP even (i.e. +1) eigenstates

Decays to Three Pions:

★ $K^0 \rightarrow \pi^0 \pi^0 \pi^0$ $J^P: 0^- \rightarrow 0^- + 0^- + 0^-$



- Conservation of angular momentum:

$$L_1 \oplus L_2 = 0 \Rightarrow L_1 = L_2$$

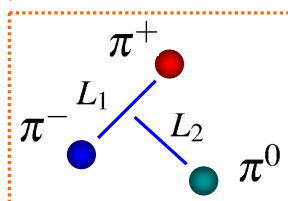
$$P(\pi^0 \pi^0 \pi^0) = -1 \cdot -1 \cdot -1 \cdot (-1)^{L_1} \cdot (-1)^{L_2} = -1$$

$$C(\pi^0 \pi^0 \pi^0) = +1 \cdot +1 \cdot +1$$

$$\Rightarrow CP(\pi^0 \pi^0 \pi^0) = -1$$

Remember L is magnitude of angular momentum vector

★ $K^0 \rightarrow \pi^+ \pi^- \pi^0$

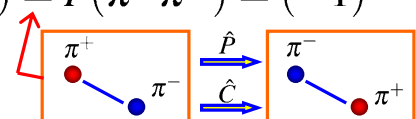


- Again $L_1 = L_2$

$$P(\pi^+ \pi^- \pi^0) = -1 \cdot -1 \cdot -1 \cdot (-1)^{L_1} \cdot (-1)^{L_2} = -1$$

$$C(\pi^+ \pi^- \pi^0) = +1 \cdot C(\pi^+ \pi^-) = P(\pi^+ \pi^-) = (-1)^{L_1}$$

Hence: $CP(\pi^+ \pi^- \pi^0) = -1 \cdot (-1)^{L_1}$



- The small amount of energy available in the decay, $m(K) - 3m(\pi) \approx 70 \text{ MeV}$ means that the $L > 0$ decays are strongly suppressed by the angular momentum barrier effects (recall QM tunnelling in alpha decay)

Neutral kaon decays to three pions occur in CP odd (i.e. -1) eigenstates

- ★ **If CP were conserved in the Weak decays of neutral kaons, would expect decays to pions to occur from states of definite CP (i.e. the CP eigenstates K_1, K_2)**

$ K_1\rangle = \frac{1}{\sqrt{2}}(K^0\rangle - \bar{K}^0\rangle)$	$\hat{C}\hat{P} K_1\rangle = + K_1\rangle$	$K_1 \rightarrow \pi\pi$	CP EVEN
$ K_2\rangle = \frac{1}{\sqrt{2}}(K^0\rangle + \bar{K}^0\rangle)$	$\hat{C}\hat{P} K_2\rangle = - K_2\rangle$	$K_2 \rightarrow \pi\pi\pi$	CP ODD

- ★ **Expect lifetimes of CP eigenstates to be very different**

- For two pion decay energy available: $m_K - 2m_\pi \approx 220\text{MeV}$
- For three pion decay energy available: $m_K - 3m_\pi \approx 80\text{MeV}$

- ★ **Expect decays to two pions to be more rapid than decays to three pions due to increased phase space**

- ★ **This is exactly what is observed: a short-lived state “K-short” which decays to (mainly) to two pions and a long-lived state “K-long” which decays to three pions**

- ★ **In the absence of CP violation we can identify**

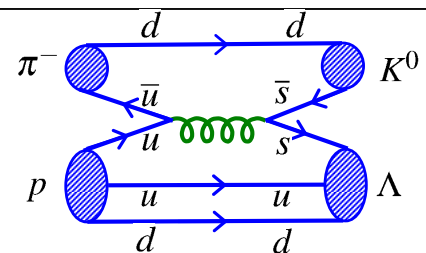
$$|K_S\rangle = |K_1\rangle \equiv \frac{1}{\sqrt{2}}(|K^0\rangle - |\bar{K}^0\rangle) \quad \text{with decays: } K_S \rightarrow \pi\pi$$

$$|K_L\rangle = |K_2\rangle \equiv \frac{1}{\sqrt{2}}(|K^0\rangle + |\bar{K}^0\rangle) \quad \text{with decays: } K_L \rightarrow \pi\pi\pi$$

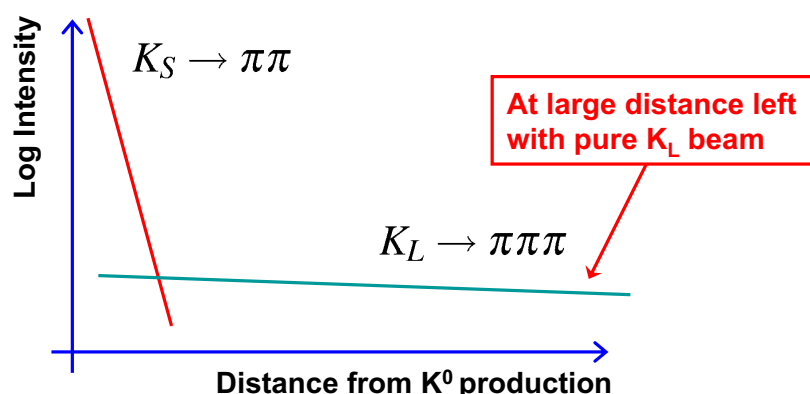
Neutral Kaon Decays to pions

- Consider the decays of a beam of K^0
- The decays to pions occur in states of definite CP
- If CP is conserved in the decay, need to express K^0 in terms of K_S and K_L

$$|K^0\rangle = \frac{1}{\sqrt{2}}(|K_S\rangle + |K_L\rangle)$$



- Hence from the point of view of decays to pions, a K^0 beam is a linear combination of CP eigenstates:
a rapidly decaying CP-even component and a long-lived CP-odd component
- Therefore, expect to see predominantly two-pion decays near start of beam and predominantly three pion decays further downstream



★ To see how this works algebraically:

- Suppose at time $t=0$ make a beam of pure K^0

$$|\psi(t=0)\rangle = \frac{1}{\sqrt{2}}(|K_S\rangle + |K_L\rangle)$$

- Put in the time dependence of wave-function

$$|K_S(t)\rangle = |K_S\rangle e^{-im_S t - \Gamma_S t/2}$$

$$\begin{array}{ll} K_S \text{ mass:} & m_S \\ K_S \text{ decay rate:} & \Gamma_S = 1/\tau_S \end{array}$$

NOTE the term $e^{-\Gamma_S t/2}$ ensures the K_S probability density decays exponentially

i.e. $|\psi_S|^2 = \langle K_S(t)|K_S(t)\rangle = e^{-\Gamma_S t} = e^{-t/\tau_S}$

- Hence wave-function evolves as

$$|\psi(t)\rangle = \frac{1}{\sqrt{2}} \left[|K_S\rangle e^{-(im_S + \frac{\Gamma_S}{2})t} + |K_L\rangle e^{-(im_L + \frac{\Gamma_L}{2})t} \right]$$

- Writing $\theta_S(t) = e^{-(im_S + \frac{\Gamma_S}{2})t}$ and $\theta_L(t) = e^{-(im_L + \frac{\Gamma_L}{2})t}$

$$|\psi(t)\rangle = \frac{1}{\sqrt{2}}(\theta_S(t)|K_S\rangle + \theta_L(t)|K_L\rangle)$$

- The decay rate to two pions for a state which was produced as K^0 :

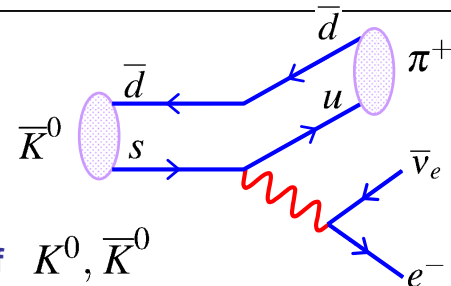
$$\Gamma(K_{t=0}^0 \rightarrow \pi\pi) \propto |\langle K_S|\psi(t)\rangle|^2 \propto |\theta_S(t)|^2 = e^{-\Gamma_S t} = e^{-t/\tau_S}$$

which is as anticipated, i.e. decays of the short lifetime component K_S

Neutral Kaon Decays to Leptons

- Neutral kaons can also decay to leptons

$$\begin{array}{ll} \bar{K}^0 \rightarrow \pi^+ e^- \bar{\nu}_e & \bar{K}^0 \rightarrow \pi^+ \mu^- \bar{\nu}_\mu \\ K^0 \rightarrow \pi^- e^+ \nu_e & K^0 \rightarrow \pi^- \mu^+ \nu_\mu \end{array}$$



- **Note:** the final states are not CP eigenstates

which is why we express these decays in terms of K^0, \bar{K}^0

- Neutral kaons propagate as combined eigenstates of weak + strong interaction i.e. the K_S, K_L . The **main** decay modes/branching fractions are:

$K_S \rightarrow \pi^+ \pi^-$	$BR = 69.2\%$
$\rightarrow \pi^0 \pi^0$	$BR = 30.7\%$
$\rightarrow \pi^- e^+ \nu_e$	$BR = 0.03\%$
$\rightarrow \pi^+ e^- \bar{\nu}_e$	$BR = 0.03\%$
$\rightarrow \pi^- \mu^+ \nu_\mu$	$BR = 0.02\%$
$\rightarrow \pi^+ \mu^- \bar{\nu}_\mu$	$BR = 0.02\%$

$K_L \rightarrow \pi^+ \pi^- \pi^0$	$BR = 12.6\%$
$\rightarrow \pi^0 \pi^0 \pi^0$	$BR = 19.6\%$
$\rightarrow \pi^- e^+ \nu_e$	$BR = 20.2\%$
$\rightarrow \pi^+ e^- \bar{\nu}_e$	$BR = 20.2\%$
$\rightarrow \pi^- \mu^+ \nu_\mu$	$BR = 13.5\%$
$\rightarrow \pi^+ \mu^- \bar{\nu}_\mu$	$BR = 13.5\%$

- Leptonic decays are more likely for the K-long because the three pion decay modes have a lower decay rate than the two pion modes of the K-short

Strangeness Oscillations (neglecting CP violation)

- The “semi-leptonic” decay rate to $\pi^- e^+ \nu_e$ occurs from the K^0 state. Hence to calculate the expected decay rate, need to know the K^0 component of the wave-function. For example, for a beam which was initially K^0 we have (1)

$$|\psi(t)\rangle = \frac{1}{\sqrt{2}}(\theta_S(t)|K_S\rangle + \theta_L(t)|K_L\rangle)$$

- Writing K_S, K_L in terms of K^0, \bar{K}^0

$$\begin{aligned} |\psi(t)\rangle &= \frac{1}{2} \left[\theta_S(t)(|K^0\rangle - |\bar{K}^0\rangle) + \theta_L(t)(|K^0\rangle + |\bar{K}^0\rangle) \right] \\ &= \frac{1}{2}(\theta_S + \theta_L)|K^0\rangle + \frac{1}{2}(\theta_L - \theta_S)|\bar{K}^0\rangle \end{aligned}$$

- Because $\theta_S(t) \neq \theta_L(t)$ a state that was initially a K^0 evolves with time into a mixture of K^0 and \bar{K}^0 - “strangeness oscillations”

- The K^0 intensity (i.e. K^0 fraction):

$$\Gamma(K_{t=0}^0 \rightarrow K^0) = |\langle K^0 | \psi(t) \rangle|^2 = \frac{1}{4} |\theta_S + \theta_L|^2 \quad (2)$$

- Similarly $\Gamma(K_{t=0}^0 \rightarrow \bar{K}^0) = |\langle \bar{K}^0 | \psi(t) \rangle|^2 = \frac{1}{4} |\theta_S - \theta_L|^2 \quad (3)$

- Using the identity $|z_1 \pm z_2|^2 = |z_1|^2 + |z_2|^2 \pm 2\Re(z_1 z_2^*)$

$$\begin{aligned} |\theta_S \pm \theta_L|^2 &= |e^{-(im_S + \frac{1}{2}\Gamma_S)t} \pm e^{-(im_L + \frac{1}{2}\Gamma_L)t}|^2 \\ &= e^{-\Gamma_S t} + e^{-\Gamma_L t} \pm 2\Re\{e^{-im_S t} e^{-\frac{1}{2}\Gamma_S t} \cdot e^{+im_L t} e^{-\frac{1}{2}\Gamma_L t}\} \\ &= e^{-\Gamma_S t} + e^{-\Gamma_L t} \pm 2e^{-\frac{\Gamma_S + \Gamma_L}{2}t} \Re\{e^{-i(m_S - m_L)t}\} \\ &= e^{-\Gamma_S t} + e^{-\Gamma_L t} \pm 2e^{-\frac{\Gamma_S + \Gamma_L}{2}t} \cos(m_S - m_L)t \\ &= e^{-\Gamma_S t} + e^{-\Gamma_L t} \pm 2e^{-\frac{\Gamma_S + \Gamma_L}{2}t} \cos \Delta m t \end{aligned}$$

- Oscillations between neutral kaon states with frequency given by the mass splitting

$$\Delta m = m(K_L) - m(K_S)$$

- Reminiscent of neutrino oscillations ! Only this time we have **decaying states**.

- Using equations (2) and (3):

$$\Gamma(K_{t=0}^0 \rightarrow K^0) = \frac{1}{4} \left[e^{-\Gamma_S t} + e^{-\Gamma_L t} + 2e^{-(\Gamma_S + \Gamma_L)t/2} \cos \Delta m t \right] \quad (4)$$

$$\Gamma(K_{t=0}^0 \rightarrow \bar{K}^0) = \frac{1}{4} \left[e^{-\Gamma_S t} + e^{-\Gamma_L t} - 2e^{-(\Gamma_S + \Gamma_L)t/2} \cos \Delta m t \right] \quad (5)$$

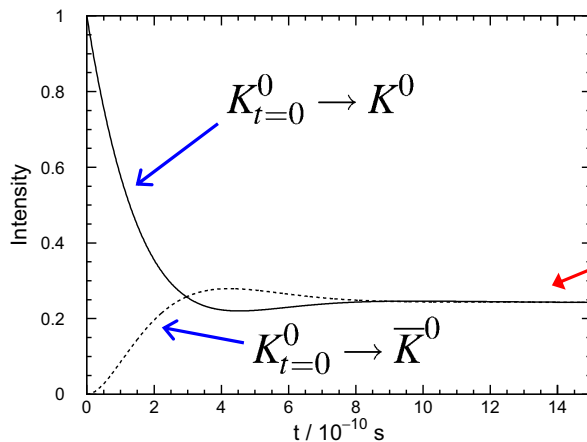
- Experimentally we find: $\tau(K_S) = 0.9 \times 10^{-10} \text{ s}$ $\tau(K_L) = 0.5 \times 10^{-7} \text{ s}$
and $\Delta m = (3.506 \pm 0.006) \times 10^{-15} \text{ GeV}$

i.e. the K-long mass is greater than the K-short by 1 part in 10^{16}

- The mass difference corresponds to an oscillation period of

$$T_{osc} = \frac{2\pi\hbar}{\Delta m} \approx 1.2 \times 10^{-9} \text{ s}$$

- The oscillation period is relatively long compared to the K_S lifetime and consequently, do not observe very pronounced oscillations

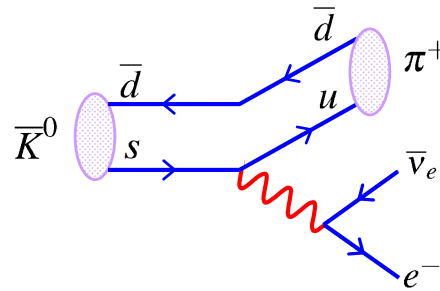
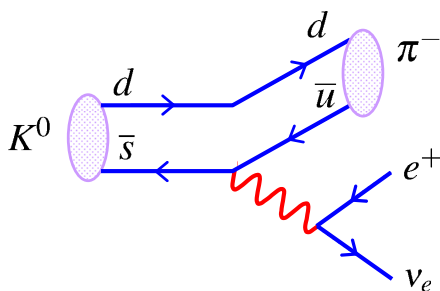


$$\Gamma(K_{t=0}^0 \rightarrow K^0) = \frac{1}{4} \left[e^{-\Gamma_S t} + e^{-\Gamma_L t} + 2e^{-(\Gamma_S + \Gamma_L)t/2} \cos \Delta m t \right]$$

$$\Gamma(K_{t=0}^0 \rightarrow \bar{K}^0) = \frac{1}{4} \left[e^{-\Gamma_S t} + e^{-\Gamma_L t} - 2e^{-(\Gamma_S + \Gamma_L)t/2} \cos \Delta m t \right]$$

After a few K_S lifetimes, left with a pure K_L beam which is half K^0 and half \bar{K}^0

- ★ Strangeness oscillations can be studied by looking at semi-leptonic decays



- ★ The charge of the observed pion (or lepton) tags the decay as from either a \bar{K}^0 or K^0 because

$$K^0 \rightarrow \pi^- e^+ \nu_e$$

$$\bar{K}^0 \rightarrow \pi^+ e^- \bar{\nu}_e$$

but

$$\left. \begin{aligned} \bar{K}^0 &\nrightarrow \pi^- e^+ \nu_e \\ K^0 &\nrightarrow \pi^+ e^- \bar{\nu}_e \end{aligned} \right\}$$

NOT ALLOWED

(see Question 23)

- So for an initial K^0 beam, observe the decays to both charge combinations:

$$K_{t=0}^0 \rightarrow K^0 \rightarrow \pi^- e^+ \nu_e$$

$$K_{t=0}^0 \rightarrow \bar{K}^0 \rightarrow \pi^+ e^- \bar{\nu}_e$$

which provides a way of measuring strangeness oscillations

The CPLEAR Experiment



- CERN : 1990-1996
- Used a low energy **anti-proton** beam
- Neutral kaons produced in reactions

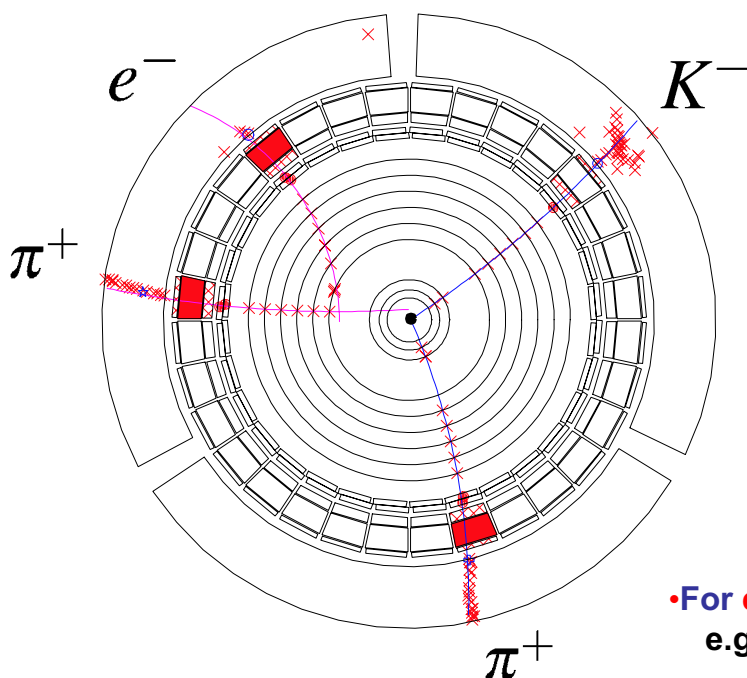
$$\bar{p}p \rightarrow K^- \pi^+ K^0$$

$$\bar{p}p \rightarrow K^+ \pi^- \bar{K}^0 \quad (\text{Question 24})$$

- Low energy, so particles produced almost at rest
- Observe production process and decay in the same detector
- Charge of $K^\pm \pi^\mp$ in the production process tags the initial neutral kaon as either K^0 or \bar{K}^0

- Charge of decay products tags the decay as being either K^0 or \bar{K}^0
- Provides a direct probe of strangeness oscillations

An example of a CPLEAR event



$$\begin{array}{l} K^- (s\bar{u}) \\ K^0 (d\bar{s}) \\ \bar{K}^0 (s\bar{d}) \end{array}$$

Production:

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

Decay:

$$\bar{K}^0 \rightarrow \pi^+ e^- \bar{\nu}_e$$

Mixing

- For each event know initial wave-function, e.g. here: $|\psi(t=0)\rangle = |K^0\rangle$

- Can measure decay rates as a function of time for all combinations:

e.g. $R^+ = \Gamma(K_{t=0}^0 \rightarrow \pi^- e^+ \bar{\nu}_e) \propto \Gamma(K_{t=0}^0 \rightarrow K^0)$

- From equations (4), (5) and similar relations:

$$R_+ \equiv \Gamma(K_{t=0}^0 \rightarrow \pi^- e^+ \nu_e) = N_{\pi e \nu} \frac{1}{4} \left[e^{-\Gamma_S t} + e^{-\Gamma_L t} + 2e^{-(\Gamma_S + \Gamma_L)t/2} \cos \Delta m t \right]$$

$$R_- \equiv \Gamma(K_{t=0}^0 \rightarrow \pi^+ e^- \bar{\nu}_e) = N_{\pi e \nu} \frac{1}{4} \left[e^{-\Gamma_S t} + e^{-\Gamma_L t} - 2e^{-(\Gamma_S + \Gamma_L)t/2} \cos \Delta m t \right]$$

$$\bar{R}_- \equiv \Gamma(\bar{K}_{t=0}^0 \rightarrow \pi^+ e^- \bar{\nu}_e) = N_{\pi e \nu} \frac{1}{4} \left[e^{-\Gamma_S t} + e^{-\Gamma_L t} + 2e^{-(\Gamma_S + \Gamma_L)t/2} \cos \Delta m t \right]$$

$$\bar{R}_+ \equiv \Gamma(\bar{K}_{t=0}^0 \rightarrow \pi^- e^+ \nu_e) = N_{\pi e \nu} \frac{1}{4} \left[e^{-\Gamma_S t} + e^{-\Gamma_L t} - 2e^{-(\Gamma_S + \Gamma_L)t/2} \cos \Delta m t \right]$$

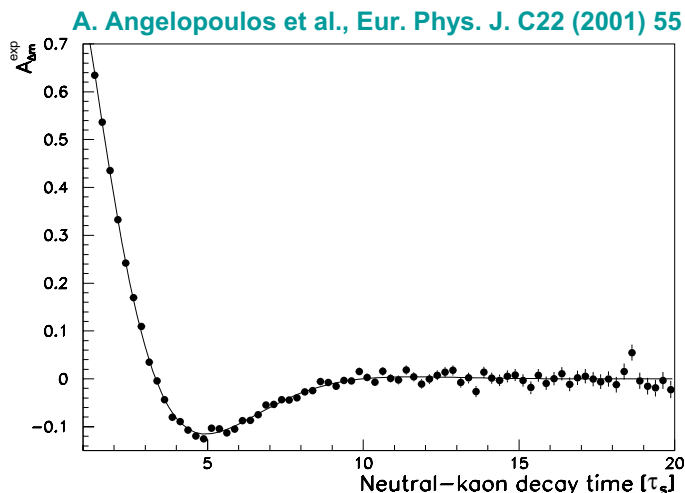
where $N_{\pi e \nu}$ is some overall normalisation factor

- Express measurements as an “asymmetry” to remove dependence on $N_{\pi e \nu}$

$$A_{\Delta m} = \frac{(R_+ + \bar{R}_-) - (R_- + \bar{R}_+)}{(R_+ + \bar{R}_-) + (R_- + \bar{R}_+)}$$

- Using the above expressions for R_+ etc., obtain

$$A_{\Delta m} = \frac{2e^{-(\Gamma_S + \Gamma_L)t/2} \cos \Delta m t}{e^{-\Gamma_S t} + e^{-\Gamma_L t}}$$



- ★ Points show the data
- ★ The line shows the theoretical prediction for the value of Δm most consistent with the CPLEAR data:

$$\Delta m = 3.485 \times 10^{-15} \text{ GeV}$$

- The sign of Δm is not determined here but is known from other experiments
- When the CPLEAR results are combined with experiments at FermiLab obtain:

$$\Delta m = m(K_L) - m(K_S) = (3.506 \pm 0.006) \times 10^{-15} \text{ GeV}$$

CP Violation in the Kaon System

- ★ So far we have ignored CP violation in the neutral kaon system
- ★ Identified the K-short as the CP-even state and the K-long as the CP-odd state

$$|K_S\rangle = |K_1\rangle \equiv \frac{1}{\sqrt{2}}(|K^0\rangle - |\bar{K}^0\rangle) \quad \text{with decays: } K_S \rightarrow \pi\pi \quad \boxed{CP = +1}$$

$$|K_L\rangle = |K_2\rangle \equiv \frac{1}{\sqrt{2}}(|K^0\rangle + |\bar{K}^0\rangle) \quad \text{with decays: } K_L \rightarrow \pi\pi\pi \quad \boxed{CP = -1}$$

- ★ At a long distance from the production point a beam of neutral kaons will be 100% K-long (the K-short component will have decayed away). Hence, if CP is conserved, would expect to see only three-pion decays.
- ★ In 1964 Fitch & Cronin (joint Nobel prize) observed 45 $K_L \rightarrow \pi^+\pi^-$ decays in a sample of 22700 kaon decays a long distance from the production point



Weak interactions violate CP

- CP is violated in hadronic weak interactions, but only at the level of 2 parts in 1000

K_L to pion BRs:

$K_L \rightarrow \pi^+\pi^-\pi^0$	BR = 12.6%	CP = -1
$\rightarrow \pi^0\pi^0\pi^0$	BR = 19.6%	CP = -1
$\rightarrow \pi^+\pi^-$	BR = 0.20%	CP = +1
$\rightarrow \pi^0\pi^0$	BR = 0.08%	CP = +1

★ Two possible explanations of CP violation in the kaon system:

- i) The K_S and K_L do not correspond exactly to the CP eigenstates K_1 and K_2

$$|K_S\rangle = \frac{1}{\sqrt{1+|\varepsilon|^2}} [|K_1\rangle + \varepsilon|K_2\rangle] \quad |K_L\rangle = \frac{1}{\sqrt{1+|\varepsilon|^2}} [|K_2\rangle + \varepsilon|K_1\rangle]$$

with $|\varepsilon| \sim 2 \times 10^{-3}$

- In this case the observation of $K_L \rightarrow \pi\pi$ is accounted for by:

$$|K_L\rangle = \frac{1}{\sqrt{1+|\varepsilon|^2}} [|K_2\rangle + \varepsilon|K_1\rangle]$$

\swarrow $\pi\pi$ **CP = +1**
 \searrow $\pi\pi\pi$ **CP = -1**

- ii) and/or CP is violated in the decay

$$|K_L\rangle = |K_2\rangle \quad \boxed{CP = -1}$$

Parameterised by ε'

\swarrow $\pi\pi\pi$ **CP = -1**
 \searrow $\pi\pi$ **CP = +1**

- ★ Experimentally both known to contribute to the mechanism for CP violation in the kaon system but i dominates: $\varepsilon'/\varepsilon = (1.7 \pm 0.3) \times 10^{-3}$ { NA48 (CERN)
KTeV (FermiLab)
- ★ The dominant mechanism is discussed in examinable **Appendix III**

CP Violation in Semi-leptonic decays

- ★ If observe a neutral kaon beam a long time after production (i.e. a large distances) it will consist of a pure K_L component

$$|K_L\rangle = \frac{1}{\sqrt{2}} \frac{1}{\sqrt{1+|\varepsilon|^2}} \left[(1+\varepsilon)|K_0\rangle + (1-\varepsilon)|\bar{K}^0\rangle \right]$$

$$\begin{array}{ccc} & \swarrow & \searrow \\ & \pi^+ e^- \bar{\nu}_e & \pi^- e^+ \nu_e \end{array}$$

- ★ Decays to $\pi^- e^+ \nu_e$ must come from the \bar{K}^0 component, and decays to $\pi^+ e^- \bar{\nu}_e$ must come from the K^0 component

$$\Gamma(K_L \rightarrow \pi^+ e^- \bar{\nu}_e) \propto |\langle \bar{K}^0 | K_L \rangle|^2 \propto |1 - \varepsilon|^2 \approx 1 - 2\Re\{\varepsilon\}$$

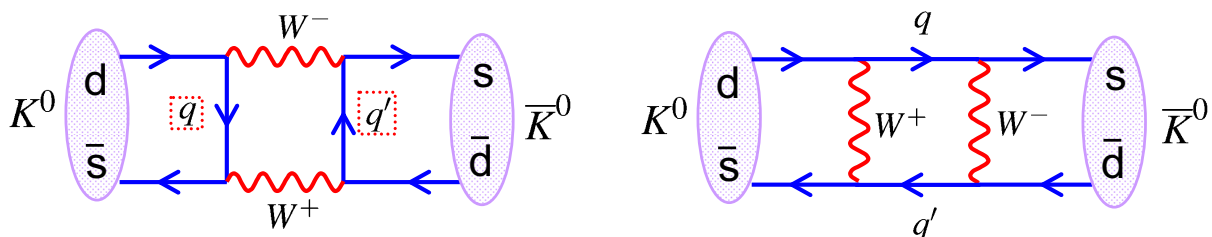
$$\Gamma(K_L \rightarrow \pi^- e^+ \nu_e) \propto |\langle K^0 | K_L \rangle|^2 \propto |1 + \varepsilon|^2 \approx 1 + 2\Re\{\varepsilon\}$$

- ★ Results in a small difference in decay rates: the decay to $\pi^- e^+ \nu_e$ is **0.7 % more likely** than the decay to $\pi^+ e^- \bar{\nu}_e$
- This difference has been observed and thus provides the first direct evidence for an absolute difference between matter and anti-matter.
- ★ It also provides an unambiguous definition of matter which could, for example, be transmitted to aliens in a distant galaxy

“The electrons in our atoms have the same charge as those emitted least often in the decays of the long-lived neutral kaon”

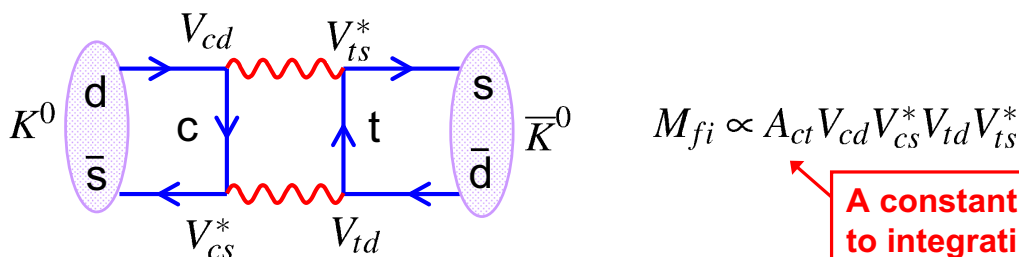
CP Violation and the CKM Matrix

- ★ How can we explain $\Gamma(\bar{K}_{t=0}^0 \rightarrow K^0) \neq \Gamma(K_{t=0}^0 \rightarrow \bar{K}^0)$ in terms of the CKM matrix ?
- ★ Consider the box diagrams responsible for mixing, i.e.



where $q = \{u, c, t\}$, $q' = \{u, c, t\}$

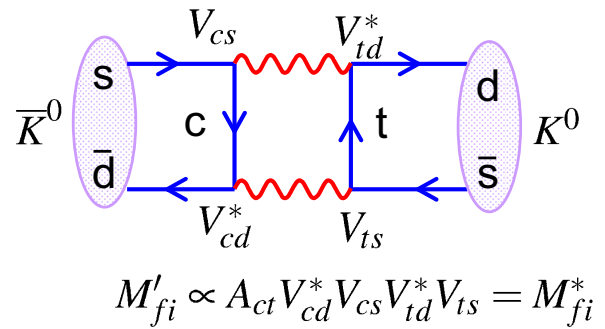
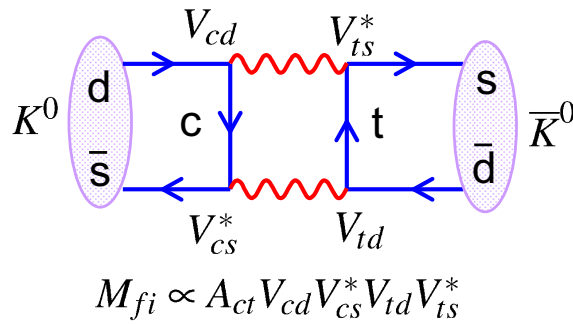
- ★ Have to sum over all possible quark exchanges in the box. For simplicity consider just one diagram



$$M_{fi} \propto A_{ct} V_{cd} V_{cs}^* V_{td} V_{ts}^*$$

A constant related to integrating over virtual momenta

- ★ Compare the equivalent box diagrams for $K^0 \rightarrow \bar{K}^0$ and $\bar{K}^0 \rightarrow K^0$



- ★ Therefore difference in rates

$$\Gamma(K^0 \rightarrow \bar{K}^0) - \Gamma(\bar{K}^0 \rightarrow K^0) \propto M_{fi} - M_{fi}^* = 2\Im\{M_{fi}\}$$

- ★ Hence the rates can only be different if the CKM matrix has imaginary component

$$|\epsilon| \propto \Im\{M_{fi}\}$$

- ★ A more formal derivation is given in Appendix IV

- ★ In the kaon system we can show (question 25)

$$|\epsilon| \propto A_{ut} \cdot \Im\{V_{ud} V_{us}^* V_{td} V_{ts}^*\} + A_{ct} \cdot \Im\{V_{cd} V_{cs}^* V_{td} V_{ts}^*\} + A_{tt} \cdot \Im\{V_{td} V_{ts}^* V_{td} V_{ts}^*\}$$

Shows that CP violation is related to the imaginary parts of the CKM matrix

Summary

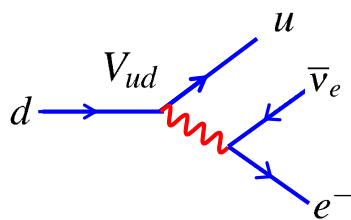
- ★ The weak interactions of quarks are described by the **CKM** matrix
- ★ Similar structure to the lepton sector, although unlike the **PMNS** matrix, the **CKM** matrix is nearly diagonal
- ★ CP violation enters through via a complex phase in the **CKM** matrix
- ★ A great deal of experimental evidence for CP violation in the weak interactions of quarks
- ★ CP violation is needed to explain matter – anti-matter asymmetry in the Universe
- ★ **HOWEVER**, CP violation in the SM is **not** sufficient to explain the matter – anti-matter asymmetry. There is probably another mechanism.

Appendix I: Determination of the CKM Matrix

Non-examinable

- The experimental determination of the **CKM matrix** elements comes mainly from measurements of leptonic decays (the leptonic part is well understood).
- It is easy to produce/observe meson decays, however theoretical uncertainties associated with the decays of bound states often limits the precision
- Contrast this with the measurements of the **PMNS matrix**, where there are few theoretical uncertainties and the experimental difficulties in dealing with neutrinos limits the precision.

① **$|V_{ud}|$** from nuclear beta decay $\begin{pmatrix} \times & \dots \\ \cdot & \cdot \\ \cdot & \cdot \end{pmatrix}$

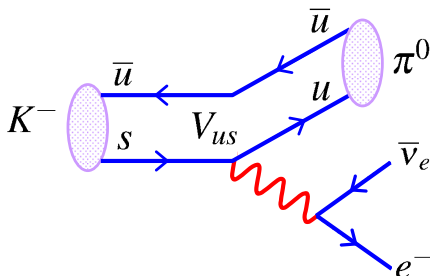


Super-allowed $0^+ \rightarrow 0^+$ beta decays are relatively free from theoretical uncertainties

$$\Gamma \propto |V_{ud}|^2$$

$$|V_{ud}| = 0.97377 \pm 0.00027 \quad (\approx \cos \theta_c)$$

② **$|V_{us}|$** from semi-leptonic kaon decays $\begin{pmatrix} \cdot & \times & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \end{pmatrix}$

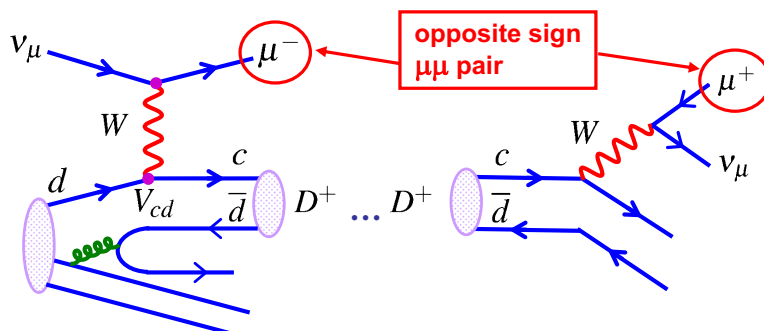


$$\Gamma \propto |V_{us}|^2$$

$$|V_{us}| = 0.2257 \pm 0.0021 \quad (\approx \sin \theta_c)$$

③ **$|V_{cd}|$** from neutrino scattering $\nu_\mu + N \rightarrow \mu^+ \mu^- X$ $\begin{pmatrix} \cdot & \cdot & \cdot \\ \times & \cdot & \cdot \\ \cdot & \cdot & \cdot \end{pmatrix}$

Look for opposite charge di-muon events in ν_μ scattering from production and decay of a $D^+(c\bar{d})$ meson



$$\text{Rate} \propto |V_{cd}|^2 \text{Br}(D^+ \rightarrow X \mu^+ \nu_\mu)$$

Measured in various collider experiments

$$|V_{cd}| = 0.230 \pm 0.011$$

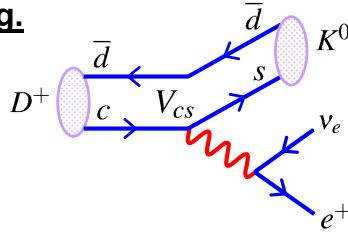
4

$$|V_{cs}|$$

from semi-leptonic charmed meson decays

$$\begin{pmatrix} \cdot & \cdot & \cdot \\ & \times & \\ \cdot & \cdot & \cdot \end{pmatrix}$$

e.g.



$$\Gamma \propto |V_{cs}|^2$$

• Precision limited by theoretical uncertainties

$$|V_{cs}| = 0.957 \pm 0.017 \pm 0.093$$

experimental error

theory uncertainty

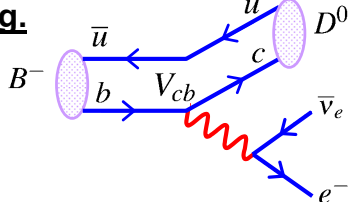
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$$|V_{cb}|$$

from semi-leptonic B hadron decays

$$\begin{pmatrix} \cdot & \cdot & \cdot \\ & \times & \\ \cdot & \cdot & \cdot \end{pmatrix}$$

e.g.



$$\Gamma \propto |V_{cb}|^2$$

$$|V_{cb}| = 0.0416 \pm 0.0006$$

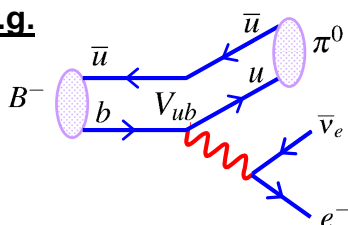
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$$|V_{ub}|$$

from semi-leptonic B hadron decays

$$\begin{pmatrix} \cdot & \cdot & \times \\ & \cdot & \\ \cdot & \cdot & \cdot \end{pmatrix}$$

e.g.



$$\Gamma \propto |V_{ub}|^2$$

$$|V_{ub}| = 0.0043 \pm 0.0003$$

Appendix II: Particle – Anti-Particle Mixing

Non-examinable

• The wave-function for a single particle with lifetime $\tau = 1/\Gamma$ evolves with time as:

$$\psi(t) = N e^{-\Gamma t/2} e^{-iMt}$$

which gives the appropriate exponential decay of

$$\langle \psi(t) | \psi(t) \rangle = \langle \psi(0) | \psi(0) \rangle e^{-t/\tau}$$

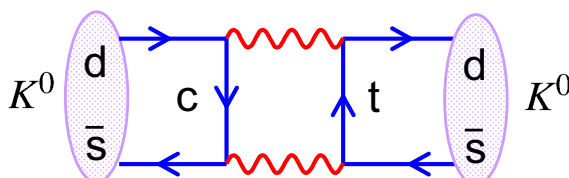
• The wave-function satisfies the time-dependent wave equation:

$$\hat{H}|\psi(t)\rangle = (M - \frac{1}{2}i\Gamma)|\psi(t)\rangle = i\frac{\partial}{\partial t}|\psi(t)\rangle \quad (\text{A1})$$

• For a bound state such as a K^0 the mass term includes the “mass” from the weak interaction “potential” \hat{H}_{weak}

$$M = m_{K^0} + \langle K^0 | \hat{H}_{\text{weak}} | K^0 \rangle + \sum_j \frac{|\langle K^0 | \hat{H}_{\text{weak}} | j \rangle|^2}{m_{K^0} - E_j}$$

Sum over intermediate states j



The third term is the 2nd order term in the perturbation expansion corresponding to box diagrams resulting in $K^0 \rightarrow K^0$

- The total decay rate is the sum over all possible decays $K^0 \rightarrow f$

$$\Gamma = 2\pi \sum_f |\langle f | \hat{H}_{weak} | K^0 \rangle|^2 \rho_F \quad \leftarrow \text{Density of final states}$$

- ★ Because there are also diagrams which allow $K^0 \leftrightarrow \bar{K}^0$ mixing need to consider the time evolution of a mixed state

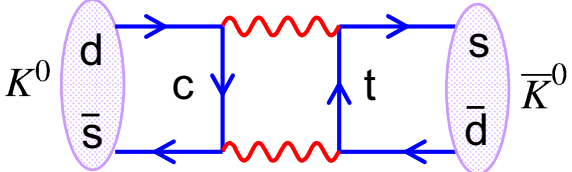
$$\psi(t) = a(t)K^0 + b(t)\bar{K}^0 \quad (\text{A2})$$

- ★ The time dependent wave-equation of (A1) becomes

$$\begin{pmatrix} M_{11} - \frac{1}{2}i\Gamma_{11} & M_{12} - \frac{1}{2}i\Gamma_{12} \\ M_{21} - \frac{1}{2}i\Gamma_{21} & M_{22} - \frac{1}{2}i\Gamma_{22} \end{pmatrix} \begin{pmatrix} |K^0(t)\rangle \\ |\bar{K}^0(t)\rangle \end{pmatrix} = i \frac{\partial}{\partial t} \begin{pmatrix} |K^0(t)\rangle \\ |\bar{K}^0(t)\rangle \end{pmatrix} \quad (\text{A3})$$

the diagonal terms are as before, and the off-diagonal terms are due to mixing.

$$M_{11} = m_{K^0} + \langle K^0 | \hat{H}_{weak} | K^0 \rangle + \sum_n \frac{|\langle K^0 | \hat{H}_{weak} | K^0 \rangle|^2}{m_{K^0} - E_n}$$

$$M_{12} = \sum_j \frac{\langle K^0 | \hat{H}_{weak} | j \rangle^* \langle j | \hat{H}_{weak} | \bar{K}^0 \rangle}{m_{K^0} - E_j}$$


- The off-diagonal decay terms include the effects of interference between decays to a common final state

$$\Gamma_{12} = 2\pi \sum_f \langle f | \hat{H}_{weak} | K^0 \rangle^* \langle f | \hat{H}_{weak} | \bar{K}^0 \rangle \rho_F$$

- In terms of the time dependent coefficients for the kaon states, (A3) becomes

$$[\mathbf{M} - i\frac{1}{2}\Gamma] \begin{pmatrix} a \\ b \end{pmatrix} = i \frac{\partial}{\partial t} \begin{pmatrix} a \\ b \end{pmatrix}$$

where the Hamiltonian can be written:

$$\mathbf{H} = \mathbf{M} - i\frac{1}{2}\Gamma = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} - \frac{1}{2} \begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{21} & \Gamma_{22} \end{pmatrix}$$

- Both the mass and decay matrices represent observable quantities and are Hermitian

$$M_{11} = M_{11}^*, \quad M_{22} = M_{22}^*, \quad M_{12} = M_{21}^*$$

$$\Gamma_{11} = \Gamma_{11}^*, \quad \Gamma_{22} = \Gamma_{22}^*, \quad \Gamma_{12} = \Gamma_{21}^*$$

- Furthermore, if CPT is conserved then the masses and decay rates of the K^0 and \bar{K}^0 are identical:

$$M_{11} = M_{22} = M; \quad \Gamma_{11} = \Gamma_{22} = \Gamma$$

- Hence the time evolution of the system can be written:

$$\begin{pmatrix} M - \frac{1}{2}i\Gamma & M_{12} - \frac{1}{2}i\Gamma_{12} \\ M_{12}^* - \frac{1}{2}i\Gamma_{12}^* & M - \frac{1}{2}i\Gamma \end{pmatrix} \begin{pmatrix} a \\ b \end{pmatrix} = i\frac{\partial}{\partial t} \begin{pmatrix} a \\ b \end{pmatrix} \quad (\text{A4})$$

- To solve the coupled differential equations for $a(t)$ and $b(t)$, first find the eigenstates of the Hamiltonian (the K_L and K_S) and then transform into this basis. The eigenvalue equation is:

$$\begin{pmatrix} M - \frac{1}{2}i\Gamma & M_{12} - \frac{1}{2}i\Gamma_{12} \\ M_{12}^* - \frac{1}{2}i\Gamma_{12}^* & M - \frac{1}{2}i\Gamma \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} = \lambda \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} \quad (\text{A5})$$

- Which has non-trivial solutions for

$$|\mathbf{H} - \lambda I| = 0$$

$$\Rightarrow (M - \frac{1}{2}i\Gamma - \lambda)^2 - (M_{12}^* - \frac{1}{2}i\Gamma_{12}^*)(M_{12} - \frac{1}{2}i\Gamma_{12}) = 0$$

with eigenvalues

$$\lambda = M - \frac{1}{2}i\Gamma \pm \sqrt{(M_{12}^* - \frac{1}{2}i\Gamma_{12}^*)(M_{12} - \frac{1}{2}i\Gamma_{12})}$$

- The eigenstates can be obtained by substituting back into (A5)

$$(M - \frac{1}{2}i\Gamma)x_1 + (M_{12} - \frac{1}{2}i\Gamma_{12})x_2 = (M - \frac{1}{2}i\Gamma \pm \sqrt{(M_{12}^* - \frac{1}{2}i\Gamma_{12}^*)(M_{12} - \frac{1}{2}i\Gamma_{12})})x_1$$

$$\Rightarrow \frac{x_2}{x_1} = \pm \sqrt{\frac{M_{12}^* - \frac{1}{2}i\Gamma_{12}^*}{M_{12} - \frac{1}{2}i\Gamma_{12}}}$$

- ★ Define

$$\eta = \sqrt{\frac{M_{12}^* - \frac{1}{2}i\Gamma_{12}^*}{M_{12} - \frac{1}{2}i\Gamma_{12}}}$$

- ★ Hence the normalised eigenstates are

$$|K_{\pm}\rangle = \frac{1}{\sqrt{1+|\eta|^2}} \begin{pmatrix} 1 \\ \pm\eta \end{pmatrix} = \frac{1}{\sqrt{1+|\eta|^2}} (|K^0\rangle \pm \eta |\bar{K}^0\rangle)$$

- ★ Note, in the limit where M_{12}, Γ_{12} are real, the eigenstates correspond to the CP eigenstates K_1 and K_2 . Hence we can identify the general eigenstates as the long and short lived neutral kaons:

$$|K_L\rangle = \frac{1}{\sqrt{1+|\eta|^2}} (|K^0\rangle + \eta |\bar{K}^0\rangle) \quad |K_S\rangle = \frac{1}{\sqrt{1+|\eta|^2}} (|K^0\rangle - \eta |\bar{K}^0\rangle)$$

★ Substituting these states back into (A2):

$$\begin{aligned}
 |\psi(t)\rangle &= a(t)|K^0\rangle + b(t)|\bar{K}^0\rangle \\
 &= \sqrt{1+|\eta|^2} \left[\frac{a(t)}{2}(K_L + K_S) + \frac{b(t)}{2\eta}(K_L - K_S) \right] \\
 &= \sqrt{1+|\eta|^2} \left[\left(\frac{a(t)}{2} + \frac{b(t)}{2\eta} \right) K_L + \left(\frac{a(t)}{2} - \frac{b(t)}{2\eta} \right) K_S \right] \\
 &= \frac{\sqrt{1+|\eta|^2}}{2} [a_L(t)K_L + a_S(t)K_S]
 \end{aligned}$$

with

$$a_L(t) \equiv a(t) + \frac{b(t)}{\eta} \quad a_S(t) \equiv a(t) - \frac{b(t)}{\eta}$$

★ Now consider the time evolution of $a_L(t)$

$$i \frac{\partial a_L}{\partial t} = i \frac{\partial a}{\partial t} + \frac{i}{\eta} \frac{\partial b}{\partial t}$$

★ Which can be evaluated using (A4) for the time evolution of $a(t)$ and $b(t)$:

$$\begin{aligned}
 i \frac{\partial a_L}{\partial t} &= [(M - \tfrac{1}{2}i\Gamma_{12})a + (M_{12} - \tfrac{1}{2}i\Gamma_{12})b] + \frac{1}{\eta} [(M_{12}^* - \tfrac{1}{2}i\Gamma_{12}^*)a + (M - \tfrac{1}{2}i\Gamma)b] \\
 &= (M - \tfrac{1}{2}i\Gamma) \left(a + \frac{b}{\eta} \right) + (M_{12} - \tfrac{1}{2}i\Gamma_{12})b + \frac{1}{\eta} (M_{12}^* - \tfrac{1}{2}i\Gamma_{12}^*)a \\
 &= (M - \tfrac{1}{2}i\Gamma)a_L + (M_{12} - \tfrac{1}{2}i\Gamma_{12})b + \left(\sqrt{(M_{12}^* - \tfrac{1}{2}i\Gamma_{12}^*)(M_{12} - \tfrac{1}{2}i\Gamma_{12})} \right) a \\
 &= (M - \tfrac{1}{2}i\Gamma)a_L + \left(\sqrt{(M_{12}^* - \tfrac{1}{2}i\Gamma_{12}^*)(M_{12} - \tfrac{1}{2}i\Gamma_{12})} \right) \left(a + \frac{b}{\eta} \right) \\
 &= (M - \tfrac{1}{2}i\Gamma)a_L + \left(\sqrt{(M_{12}^* - \tfrac{1}{2}i\Gamma_{12}^*)(M_{12} - \tfrac{1}{2}i\Gamma_{12})} \right) a_L \\
 &= (m_L - \tfrac{1}{2}i\Gamma_L)a_L
 \end{aligned}$$

★ Hence:

$$i \frac{\partial a_L}{\partial t} = (m_L - \tfrac{1}{2}i\Gamma_L)a_L$$

with $m_L = M + \Re \left\{ \sqrt{(M_{12}^* - \tfrac{1}{2}i\Gamma_{12}^*)(M_{12} - \tfrac{1}{2}i\Gamma_{12})} \right\}$

and $\Gamma_L = \Gamma - 2\Im \left\{ \sqrt{(M_{12}^* - \tfrac{1}{2}i\Gamma_{12}^*)(M_{12} - \tfrac{1}{2}i\Gamma_{12})} \right\}$

★ Following the same procedure obtain:

$$i\frac{\partial a_S}{\partial t} = (m_S - \frac{1}{2}i\Gamma_S)a_S$$

with $m_S = M - \Re \left\{ \sqrt{(M_{12}^* - \frac{1}{2}i\Gamma_{12}^*)(M_{12} - \frac{1}{2}i\Gamma_{12})} \right\}$

and $\Gamma_S = \Gamma + 2\Im \left\{ \sqrt{(M_{12}^* - \frac{1}{2}i\Gamma_{12}^*)(M_{12} - \frac{1}{2}i\Gamma_{12})} \right\}$

★ In matrix notation we have

$$\begin{pmatrix} M_L - \frac{1}{2}i\Gamma_L & 0 \\ 0 & M_S - \frac{1}{2}i\Gamma_S \end{pmatrix} \begin{pmatrix} a_L \\ a_S \end{pmatrix} = i\frac{\partial}{\partial t} \begin{pmatrix} a_L \\ a_S \end{pmatrix}$$

★ Solving we obtain

$$a_L(t) \propto e^{-im_L t - \Gamma_L t/2} \quad a_S(t) \propto e^{-im_S t - \Gamma_S t/2}$$

★ Hence in terms of the K_L and K_S basis the states propagate as independent particles with definite masses and lifetimes (the mass eigenstates). The time evolution of the neutral kaon system can be written

$$|\psi(t)\rangle = A_L e^{-im_L t - \Gamma_L t/2} |K_L\rangle + A_S e^{-im_S t - \Gamma_S t/2} |K_S\rangle$$

where A_L and A_S are constants

Appendix III: CP Violation : $\pi\pi$ decays

Non-examinable

- ★ Consider the development of the $K^0 - \bar{K}^0$ system now including CP violation
- ★ Repeat previous derivation using

$$|K_S\rangle = \frac{1}{\sqrt{1+|\epsilon|^2}} [|K_1\rangle + \epsilon |K_2\rangle] \quad |K_L\rangle = \frac{1}{\sqrt{1+|\epsilon|^2}} [|K_2\rangle + \epsilon |K_1\rangle]$$

- Writing the CP eigenstates in terms of K^0, \bar{K}^0

$$|K_L\rangle = \frac{1}{\sqrt{2}} \frac{1}{\sqrt{1+|\epsilon|^2}} [(1+\epsilon)|K_0\rangle + (1-\epsilon)|\bar{K}^0\rangle]$$

$$|K_S\rangle = \frac{1}{\sqrt{2}} \frac{1}{\sqrt{1+|\epsilon|^2}} [(1+\epsilon)|K_0\rangle - (1-\epsilon)|\bar{K}^0\rangle]$$

- Inverting these expressions obtain

$$|K^0\rangle = \sqrt{\frac{1+|\epsilon|^2}{2}} \frac{1}{1+\epsilon} (|K_L\rangle + |K_S\rangle)$$

$$|\bar{K}^0\rangle = \sqrt{\frac{1+|\epsilon|^2}{2}} \frac{1}{1-\epsilon} (|K_L\rangle - |K_S\rangle)$$

- Hence a state that was produced as a K^0 evolves with time as:

$$|\psi(t)\rangle = \sqrt{\frac{1+|\epsilon|^2}{2}} \frac{1}{1+\epsilon} (\theta_L(t)|K_L\rangle + \theta_S(t)|K_S\rangle)$$

where as before $\theta_S(t) = e^{-(im_S + \frac{\Gamma_S}{2})t}$ and $\theta_L(t) = e^{-(im_L + \frac{\Gamma_L}{2})t}$

- If we are considering the decay rate to $\pi\pi$ need to express the wave-function in terms of the CP eigenstates (remember we are neglecting CP violation in the decay)

$$\begin{aligned} |\psi(t)\rangle &= \frac{1}{\sqrt{2}} \frac{1}{1+\varepsilon} [(|K_2\rangle + \varepsilon|K_1\rangle)\theta_L(t) + (|K_1\rangle + \varepsilon|K_2\rangle)\theta_S(t)] \\ &= \frac{1}{\sqrt{2}} \frac{1}{1+\varepsilon} [(\theta_S + \varepsilon\theta_L)|K_1\rangle + (\theta_L + \varepsilon\theta_S)|K_2\rangle] \end{aligned}$$

CP Eigenstates

- Two pion decays occur with CP = +1 and therefore arise from decay of the CP = +1 kaon eigenstate, i.e. K_1

$$\Gamma(K_{t=0}^0 \rightarrow \pi\pi) \propto |\langle K_1 | \psi(t) \rangle|^2 = \frac{1}{2} \left| \frac{1}{1+\varepsilon} \right|^2 |\theta_S + \varepsilon\theta_L|^2$$

- Since $|\varepsilon| \ll 1$

$$\left| \frac{1}{1+\varepsilon} \right|^2 = \frac{1}{(1+\varepsilon^*)(1+\varepsilon)} \approx \frac{1}{1+2\Re\{\varepsilon\}} \approx 1 - 2\Re\{\varepsilon\}$$

- Now evaluate the $|\theta_S + \varepsilon\theta_L|^2$ term again using

$$|z_1 \pm z_2|^2 = |z_1|^2 + |z_2|^2 \pm 2\Re(z_1 z_2^*)$$

$$\begin{aligned} |\theta_S + \varepsilon\theta_L|^2 &= |e^{-im_S t - \frac{\Gamma_S}{2}t} + \varepsilon e^{-im_L t - \frac{\Gamma_L}{2}t}|^2 \\ &= e^{-\Gamma_S t} + |\varepsilon|^2 e^{-\Gamma_L t} + 2\Re\{e^{-im_S t - \frac{\Gamma_S}{2}t} \cdot \varepsilon^* e^{+im_L t - \frac{\Gamma_L}{2}t}\} \end{aligned}$$

- Writing $\varepsilon = |\varepsilon|e^{i\phi}$

$$\begin{aligned} |\theta_S + \varepsilon\theta_L|^2 &= e^{-\Gamma_S t} + |\varepsilon|^2 e^{-\Gamma_L t} + 2|\varepsilon|e^{-(\Gamma_S + \Gamma_L)t/2} \Re\{e^{i(m_L - m_S)t - \phi}\} \\ &= e^{-\Gamma_S t} + |\varepsilon|^2 e^{-\Gamma_L t} + 2|\varepsilon|e^{-(\Gamma_S + \Gamma_L)t/2} \cos(\Delta m \cdot t - \phi) \end{aligned}$$

- Putting this together we obtain:

$$\Gamma(K_{t=0}^0 \rightarrow \pi\pi) = \frac{1}{2} (1 - 2\Re\{\varepsilon\}) N_{\pi\pi} \left[e^{-\Gamma_S t} + |\varepsilon|^2 e^{-\Gamma_L t} + 2|\varepsilon|e^{-(\Gamma_S + \Gamma_L)t/2} \cos(\Delta m \cdot t - \phi) \right]$$

Short lifetime component
 $K_S \rightarrow \pi\pi$

CP violating long lifetime component
 $K_L \rightarrow \pi\pi$

Interference term

- In exactly the same manner obtain for a beam which was produced as \bar{K}^0

$$\Gamma(\bar{K}_{t=0}^0 \rightarrow \pi\pi) = \frac{1}{2} (1 + 2\Re\{\varepsilon\}) N_{\pi\pi} \left[e^{-\Gamma_S t} + |\varepsilon|^2 e^{-\Gamma_L t} - 2|\varepsilon|e^{-(\Gamma_S + \Gamma_L)t/2} \cos(\Delta m \cdot t - \phi) \right]$$

Interference term changes sign

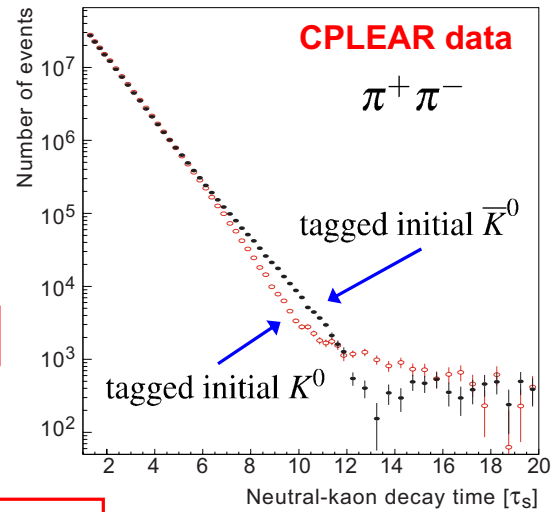
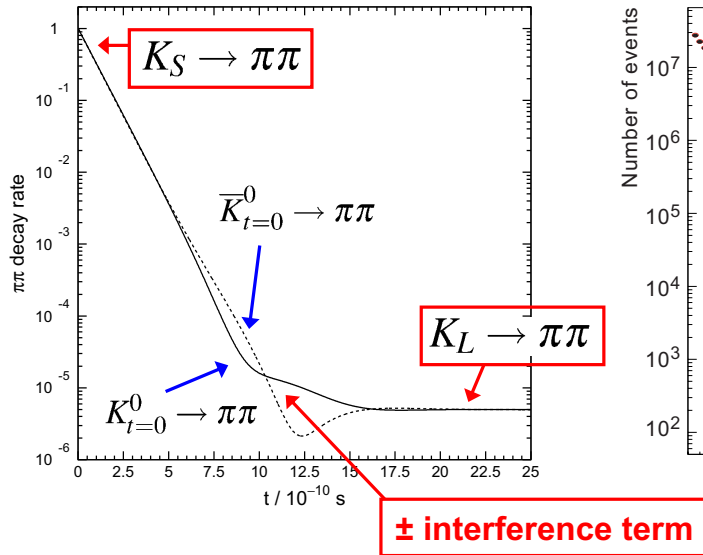
- ★ At large proper times only the long lifetime component remains :

$$\Gamma(K_{t=0}^0 \rightarrow \pi\pi) \rightarrow \frac{1}{2}(1 - 2\Re\{\varepsilon\})N_{\pi\pi}|\varepsilon|^2 e^{-\Gamma_L t}$$

i.e. CP violating $K_L \rightarrow \pi\pi$ decays

- ★ Since CPLEAR can identify whether a K^0 or \bar{K}^0 was produced, able to measure $\Gamma(K_{t=0}^0 \rightarrow \pi\pi)$ and $\Gamma(\bar{K}_{t=0}^0 \rightarrow \pi\pi)$

Prediction with CP violation



- ★ The CPLEAR data shown previously can be used to measure $\varepsilon = |\varepsilon|e^{i\phi}$

- Define the asymmetry:

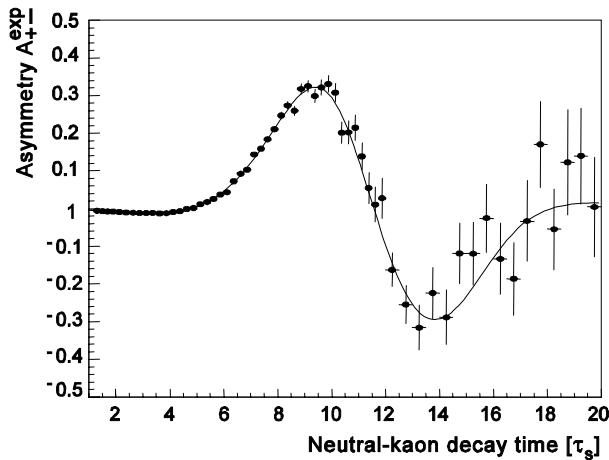
$$A_{+-} = \frac{\Gamma(\bar{K}_{t=0}^0 \rightarrow \pi\pi) - \Gamma(K_{t=0}^0 \rightarrow \pi\pi)}{\Gamma(\bar{K}_{t=0}^0 \rightarrow \pi\pi) + \Gamma(K_{t=0}^0 \rightarrow \pi\pi)}$$

- Using expressions on page 443

$$A_{+-} = \frac{4\Re\{\varepsilon\} [e^{-\Gamma_S t} + |\varepsilon|^2 e^{-\Gamma_L t}] - 4|\varepsilon| e^{-(\Gamma_L + \Gamma_S)t/2} \cos(\Delta m \cdot t - \phi)}{2[e^{-\Gamma_S t} + |\varepsilon|^2 e^{-\Gamma_L t}] - 8\Re\{\varepsilon\} |\varepsilon| e^{-(\Gamma_L + \Gamma_S)t/2} \cos(\Delta m \cdot t - \phi)}$$

$\propto |\varepsilon|\Re\{\varepsilon\}$ i.e. two small quantities and can safely be neglected

$$\begin{aligned} A_{+-} &\approx \frac{2\Re\{\varepsilon\} [e^{-\Gamma_S t} + |\varepsilon|^2 e^{-\Gamma_L t}] - 2|\varepsilon| e^{-(\Gamma_L + \Gamma_S)t/2} \cos(\Delta m \cdot t - \phi)}{e^{-\Gamma_S t} + |\varepsilon|^2 e^{-\Gamma_L t}} \\ &= 2\Re\{\varepsilon\} - \frac{2|\varepsilon| e^{-(\Gamma_L + \Gamma_S)t/2} \cos(\Delta m \cdot t - \phi)}{e^{-\Gamma_S t} + |\varepsilon|^2 e^{-\Gamma_L t}} \\ &= 2\Re\{\varepsilon\} - \frac{2|\varepsilon| e^{(\Gamma_S - \Gamma_L)t/2} \cos(\Delta m \cdot t - \phi)}{1 + |\varepsilon|^2 e^{(\Gamma_S - \Gamma_L)t}} \end{aligned}$$



Best fit to the data:

$$|\varepsilon| = (2.264 \pm 0.035) \times 10^{-3}$$

$$\phi = (43.19 \pm 0.73)^\circ$$

Appendix IV: CP Violation via Mixing

Non-examinable

★ A full description of the SM origin of CP violation in the kaon system is beyond the level of this course, nevertheless, the relation to the box diagrams is illustrated below

★ The K-long and K-short wave-functions depend on η

$$|K_L\rangle = \frac{1}{\sqrt{1+|\eta|^2}}(|K^0\rangle + \eta|\bar{K}^0\rangle) \quad |K_S\rangle = \frac{1}{\sqrt{1+|\eta|^2}}(|K^0\rangle - \eta|\bar{K}^0\rangle)$$

with

$$\eta = \sqrt{\frac{M_{12}^* - \frac{1}{2}i\Gamma_{12}^*}{M_{12} - \frac{1}{2}i\Gamma_{12}}}$$

★ If $M_{12}^* = M_{12}$; $\Gamma_{12}^* = \Gamma_{12}$ then the K-long and K-short correspond to the CP eigenstates K_1 and K_2

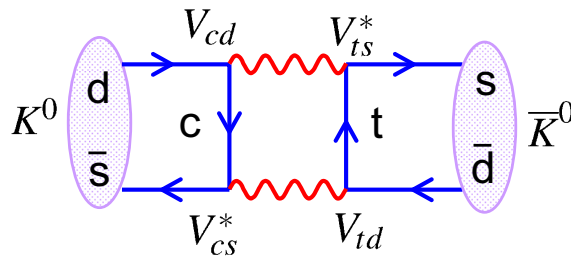
• CP violation is therefore associated with imaginary off-diagonal mass and decay elements for the neutral kaon system

• Experimentally, CP violation is small and $\eta \approx 1$

• Define: $\varepsilon = \frac{1-\eta}{1+\eta} \Rightarrow \eta = \frac{1-\varepsilon}{1+\varepsilon}$

- Consider the mixing term M_{12} which arises from the sum over all possible intermediate states in the mixing box diagrams

e.g.



$$M_{12} = A_{ct} V_{cd} V_{cs}^* V_{ts}^* V_{td} + \dots$$

- Therefore it can be seen that, in the Standard Model, CP violation is associated with the imaginary components of the CKM matrix
- It can be shown that mixing leads to CP violation with

$$|\varepsilon| \propto \Im\{M_{12}\}$$

- The differences in masses of the mass eigenstates can be shown to be:

$$\Delta m_K = m_{K_L} - m_{K_S} \approx \sum_{q,q'} \frac{G_F^2}{3\pi^2} f_K^2 m_K |V_{qd} V_{qs}^* V_{q'd} V_{q's}^*| m_q m_{q'}$$

where q and q' are the quarks in the loops and f_K is a constant

- In terms of the small parameter ε

$$|K_L\rangle = \frac{1}{2\sqrt{1+|\varepsilon|^2}} \left[(1+\varepsilon)|K^0\rangle + (1-\varepsilon)|\bar{K}^0\rangle \right]$$

$$|K_S\rangle = \frac{1}{2\sqrt{1+|\varepsilon|^2}} \left[(1-\varepsilon)|K^0\rangle + (1+\varepsilon)|\bar{K}^0\rangle \right]$$

- ★ If epsilon is non-zero we have CP violation in the neutral kaon system

Writing $\eta = \sqrt{\frac{M_{12}^* - \frac{1}{2}i\Gamma_{12}^*}{M_{12} - \frac{1}{2}i\Gamma_{12}}} = \sqrt{\frac{z^*}{z}}$ and $z = ae^{i\phi}$

gives

$$\eta = e^{-i\phi}$$

- ★ From which we can find an expression for ε

$$\varepsilon \cdot \varepsilon^* = \frac{1 - e^{-i\phi}}{1 + e^{-i\phi}} \cdot \frac{1 - e^{+i\phi}}{1 + e^{+i\phi}} = \frac{2 - \cos\phi}{2 + \cos\phi} = \tan^2 \frac{\phi}{2}$$

$$|\varepsilon| = \left| \tan \frac{\phi}{2} \right|$$

- ★ Experimentally we know ε is small, hence ϕ is small

$$|\varepsilon| \approx \frac{1}{2}\phi = \frac{1}{2} \arg z \approx \frac{1}{2} \frac{\Im\{M_{12} - \frac{1}{2}i\Gamma_{12}\}}{|M_{12} - \frac{1}{2}i\Gamma_{12}|}$$

Appendix V: Time Reversal Violation

- Previously, equations (4) and (5), obtained expressions for strangeness oscillations in the absence of CP violation, e.g.

$$\Gamma(K_{t=0}^0 \rightarrow K^0) = \frac{1}{4} \left[e^{-\Gamma_S t} + e^{-\Gamma_L t} + 2e^{-(\Gamma_S + \Gamma_L)t/2} \cos \Delta m t \right]$$

- This analysis can be extended to include the effects of CP violation to give the following rates (see question 24):

$$\Gamma(K_{t=0}^0 \rightarrow K^0) \propto \frac{1}{4} \left[e^{-\Gamma_S t} + e^{-\Gamma_L t} + 2e^{-(\Gamma_S + \Gamma_L)t/2} \cos \Delta m t \right]$$

$$\Gamma(\bar{K}_{t=0}^0 \rightarrow \bar{K}^0) \propto \frac{1}{4} \left[e^{-\Gamma_S t} + e^{-\Gamma_L t} + 2e^{-(\Gamma_S + \Gamma_L)t/2} \cos \Delta m t \right]$$

$$\Gamma(\bar{K}_{t=0}^0 \rightarrow K^0) \propto \frac{1}{4} (1 + 4\Re\{\epsilon\}) \left[e^{-\Gamma_S t} + e^{-\Gamma_L t} - 2e^{-(\Gamma_S + \Gamma_L)t/2} \cos \Delta m t \right]$$

$$\Gamma(K_{t=0}^0 \rightarrow \bar{K}^0) \propto \frac{1}{4} (1 - 4\Re\{\epsilon\}) \left[e^{-\Gamma_S t} + e^{-\Gamma_L t} - 2e^{-(\Gamma_S + \Gamma_L)t/2} \cos \Delta m t \right]$$

- ★ Including the effects of CP violation find that

$$\Gamma(\bar{K}_{t=0}^0 \rightarrow K^0) \neq \Gamma(K_{t=0}^0 \rightarrow \bar{K}^0)$$

Violation of time reversal symmetry !

- ★ No surprise, as CPT is conserved, CP violation implies T violation