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Quark flavour physics

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- Plan
  - Kaon physics and SM construction (bit of history)
  - Establishing SM experimentally
  - Looking for breakdown of SM
- Hard to cover everything in details in three lectures, some details are offloaded to exercises

Outline – lecture 1

- What is flavour physics and what is not
- Kaon physics – understand its importance for development of standard model of particle physics
  - Weak decays – quark mixing
  - FCNC kaon decays – GIM mechanism
  - Neutral kaon mixing
  - CP violation in neutral kaons
  - How to accommodate CP violation to model

Content of standard model

Fermions ("matter")		Bosons ("forces")
Quarks: $uuu \quad ccc \quad ttt$; $ddd \quad sss \quad bbb$		$gggggggg$
		γ
		W^+
		W^-
		Z
Leptons: $e \quad \mu \quad \tau$; $\nu_e \quad \nu_\mu \quad \nu_\tau$		H

$$\left\{ \begin{array}{ccc} & \text{Quarks} & \\ uuu & ccc & ttt \\ ddd & sss & bbb \\ & & \\ & \text{Leptons} & \\ e & \mu & \tau \\ \nu_e & \nu_\mu & \nu_\tau \end{array} \right\} \times \left\{ \begin{array}{c} \text{MATTER} \\ \text{ANTIMATTER} \end{array} \right\}$$

Parameters of standard model

- 3 gauge couplings
- 2 Higgs parameters
- 6 quark masses
- 3 quark mixing angles + 1 phase
- 3 (+3) lepton masses
- (3 lepton mixing angles + 1 phase)
- Why 3 generations (are we sure about it)?
- Why hierarchy in mass?
- Why hierarchy in mixing?
- Why do we have only matter in current Universe?

Flavour parameters

What is not flavour physics

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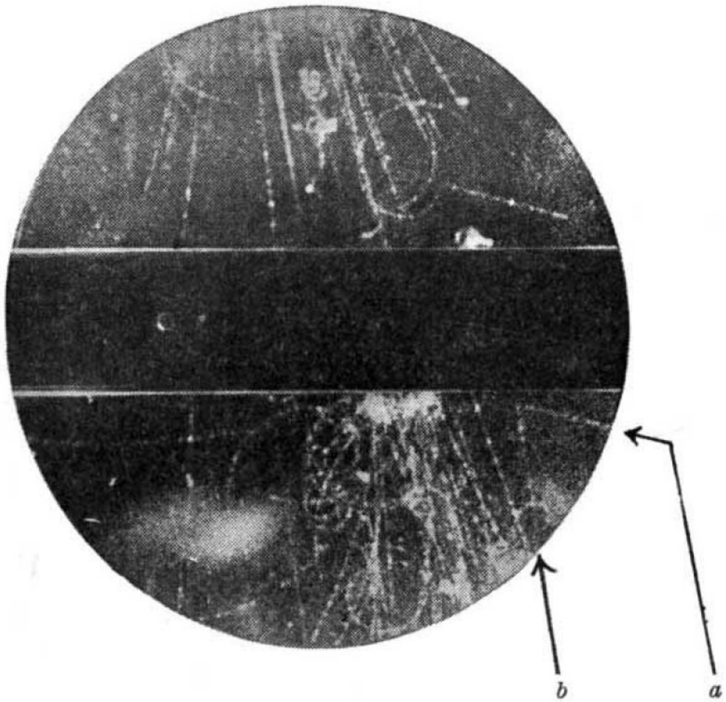
- QCD: Strong interactions
  - Any details of QCD including studies of different “exciting” states
- Electroweak physics
  - There is some relation, but questions do not overlap
- Energy frontier
  - Search for new particles in production (on-shell)

Going to
history

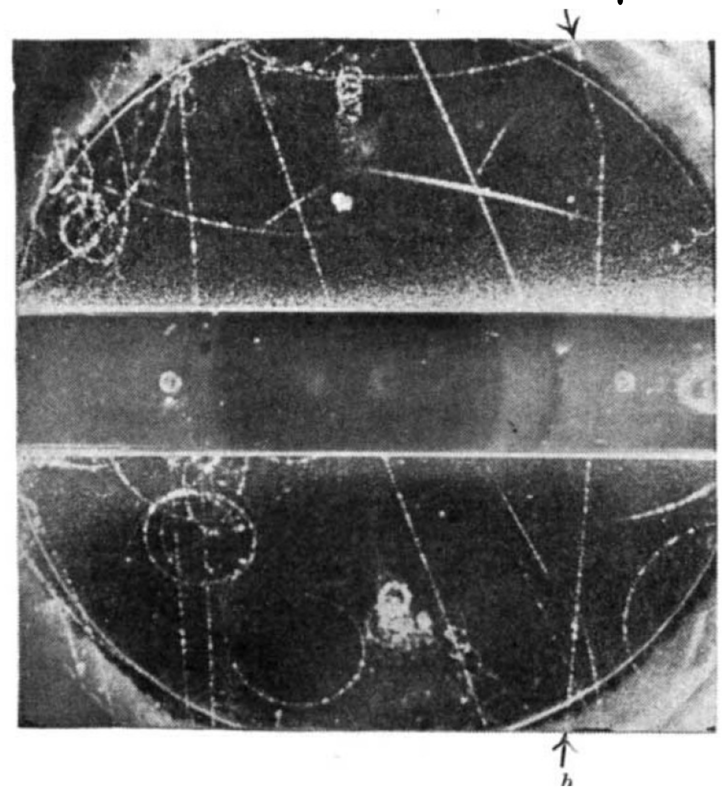
Kaon discovery

- 1947, G. D. Rochester and C. C. Butler
- Using fancy detector called cloud chamber



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

$K^+ \to \mu^+\nu$



- Produced in strong interaction
- Decay rather slow, lifetime of $10^{-8} - 10^{-10}$ s

Quark mixing - Cabibbo

- Quark content of kaon is $u\bar{s}$ (K^+) and $d\bar{s}$ (K^0)
- Main decays are
  - $K^+ \rightarrow \mu^+ \nu_\mu$, $K^+ \rightarrow \pi^0 e^+ \nu_e$, $K^0 \rightarrow \pi\pi$
  - Weak interaction has to allow transition $s \rightarrow u$
- There are good reasons why W (weak interaction) couples only to left-handed doublets
  - How to construct doublets to allow $s \rightarrow u$ and $d \rightarrow u$?
- Cabibbo provided solution in terms of quark mixing
- Doublet of weak interaction is $(u,d')=(u,d^*\cos(\theta)+s^*\sin(\theta))$
- θ is quark mixing angle, which was determined experimentally
- Actually solved difference in G between nuclear and muon decay

GIM

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- Next piece of puzzle comes from FCNC kaon decays
- Cabibbo fixed one issue ($s \to u$ transition), but introduced another one
- If doublet of weak interaction is (u,d'), than also Z^0 can couple to $d'\bar{d}'$
- What does it mean in terms of original quarks?

$$u\bar{u} + d\bar{d}\cos^2\theta + s\bar{s}\sin^2\theta + (s\bar{d} + \bar{s}d)\sin\theta\cos\theta$$

- First three terms are fine, but last part causes problem
- It would allow flavour changing neutral current decays at tree-level
  - $K^+ \to \pi^+ e^+ e^-$ would be approximately 5% of $K^+ \to \pi^0 e^+ \nu_e$
  - But in experiment it was known to be < 10^{-5}

GIM

- Is Cabibbo wrong, or can we find some way to fix it?
- Not quite with three quarks known at the time, but
- In 1970 Glashow, Iliopoulos, Maiani suggested way
- To existing doublet (u,d')=(u,d*cos(θ)+s*sin(θ)) add second one (c,s')=(c,d*cos(θ)-s*sin(θ))
- Now Z^0 would also couple to $s'\bar{s}'$ which would give us term like $-(s\bar{d}+\bar{s}d)\sin\theta\cos\theta$ which approximately cancel contribution from other doublet
  - Approximately comes from other factors contributing
- So in 1970 charm quark was predicted, despite that not everybody accepted existence of the quarks

Neutral Kaon Oscillation

- Now we come to next puzzle about neutral kaon lifetimes
- Originally two particles were seen with same mass, but very different lifetimes $9 \cdot 10^{-11}$ s and $5 \cdot 10^{-8}$
- They not only have very different lifetimes, but first one decays to 2π while other to 3π
- Both were produced in same type of interaction in association with other strange particles
- Is this just strange coincidence or is there something more behind it?
- Different decays suggest that lifetimes have something to do with CP symmetry

Neutral kaon mixing

- To explain different lifetimes, lets look to CP properties
  - CP | 2π > = + | 2π >
  - CP | 3π > = - | 3π >
- Shorter lived kaon (call it $|K_1\rangle$) decays to 2π and is CP-even
- Longer lived kaon (call it $|K_2\rangle$) decays to 3π and is CP-odd
- Difference in the lifetimes come from different phase space available in two decays
  - m(2π)=279 MeV, m(3π)=419 MeV and $M(K^0)$=497 MeV

$$d\Gamma = \frac{(2\pi)^4}{2M}|M|^2 d\Phi_n \qquad d\Phi_n = \delta^4(P - \sum p_i)\prod \frac{d^3 p_i}{(2\pi)^3 2E_i}$$

Neutral kaon mixing

- Now we have to put together fact that in strong interaction we produce K^0 or $\overline{K}^0$, while in weak interaction (decay) we have K_1 and K_2
- But we already know from quark mixing, that quarks entering strong and weak interaction are not exactly same
- So we can connect kaons from strong interaction to those in weak interaction via mixing
- We can define those as
  - $K_1=1/2(K^0+\overline{K}^0)$
  - $K_2=1/2(K^0-\overline{K}^0)$
  - With CP | K^0 > = + $\overline{K}^0$ and CP | $\overline{K}^0$ > = + K^0 all fits together

Time evolution

- Now we can start to look to time evolution
- Definitely one set of states will behave like $e^{(\Gamma/2+im)t}$
- Question is which one?
- After deciding above question, it is easy to calculate what to expect at given time for all four states
- There is interesting effect called kaon regeneration which we will discuss during exercises

Blackboard is my friend here

$K^0 - \bar{K}^0$ oscillation

$$|K_1\rangle = |K_1(0)\rangle\, e^{\left(-\frac{\Gamma_1}{2} + i m_1\right)t}$$

$$|K_2\rangle = |K_2(0)\rangle\, e^{\left(-\frac{\Gamma_2}{2} + i m_2\right)t}$$

$|K_1(0)\rangle =$

$$|K_0\rangle = \frac{1}{\sqrt{2}}\left(|K_1\rangle + |K_2\rangle\right)$$

$t:\ \langle K^0(t)|K^0(t)\rangle$

$$\frac{1}{2}\Big(\langle K_1^*|K_1\rangle + \langle K_2^*|K_2\rangle + \langle K_1^*|K_2\rangle + \langle K_2^*|K_1\rangle$$

$$e^{-\Gamma_1 t} + e^{-\Gamma_2 t} + e^{\left(-\frac{\Gamma_1}{2} - i m_1\right)t} e^{\left(-\frac{\Gamma_2}{2} + i m_2\right)t}$$

$$e^{\left(-\frac{\Gamma_2}{2} - i m_2\right)t} e^{\left(-\frac{\Gamma_1}{2} + i m_1\right)t}$$

$$e^{-\frac{\Gamma_1 + \Gamma_2}{2}t}\underbrace{\left[e^{-i(m_1 - m_2)t} + e^{-i(m_2 - m_1)t}\right]}_{\cos(m_2 - m_1)t}$$

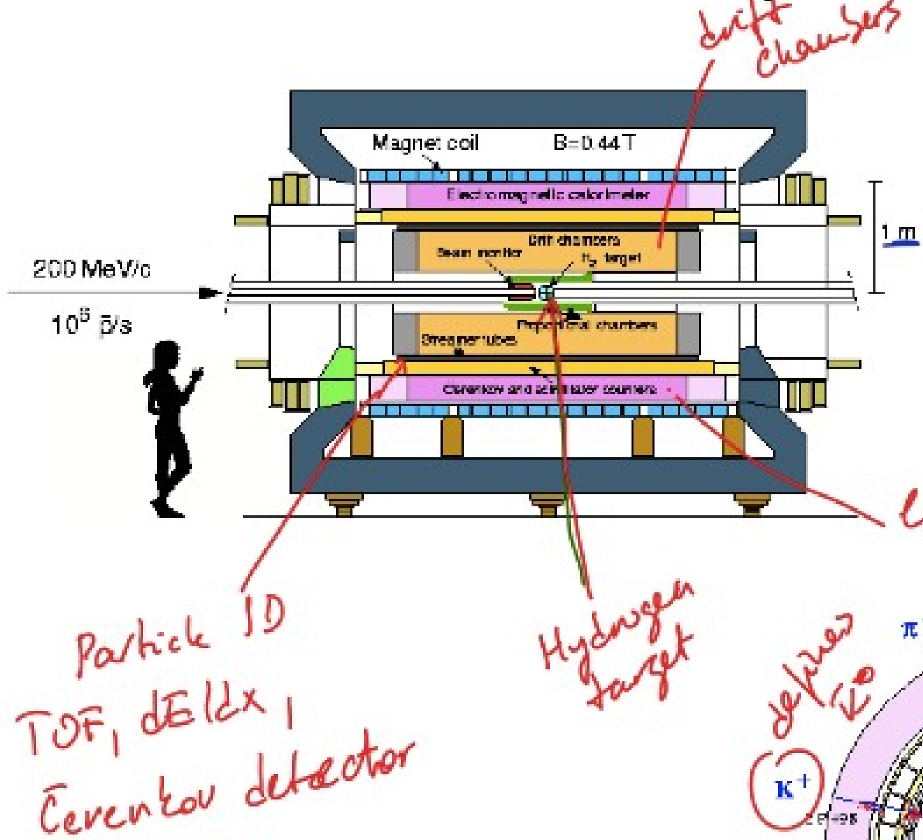
$$\bar{K}^0:\ e^{-\Gamma_1 t} + e^{-\Gamma_2 t} - \cos(m_2 - m_1)t\, e^{-\frac{\Gamma_1+\Gamma_2}{2}t}$$

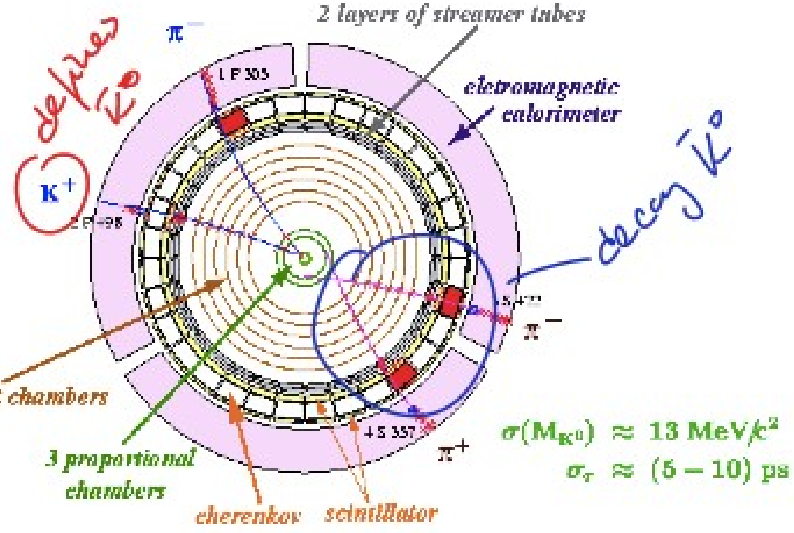
8

CPLEAR experiment at CERN

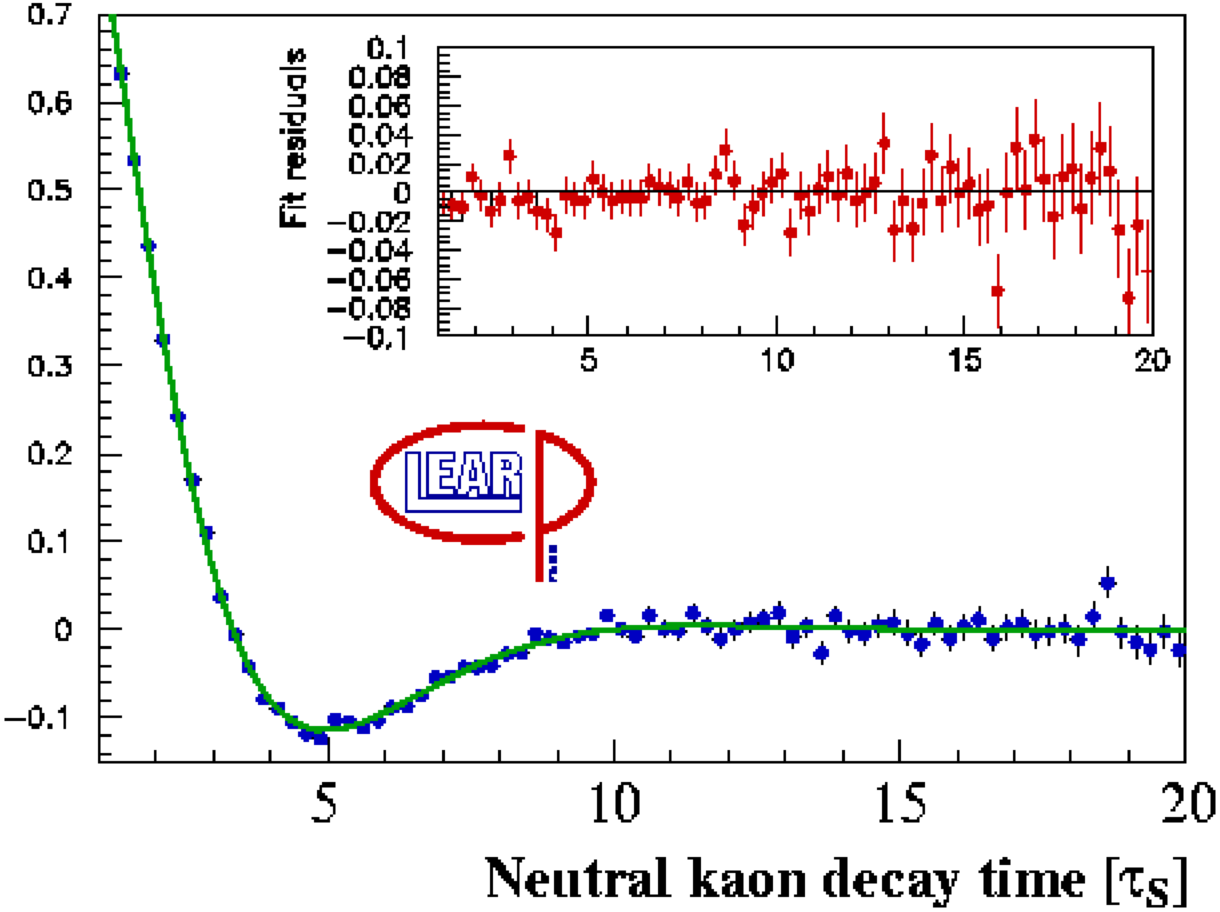
cplear.web.cern.ch

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





Kaon mixing in experiment



- Gives $\Delta M = 529 \cdot 10^{-7}\ s^{-1}$

Explain details on blackboard

CP Violation

- We defined K_1 to be CP-even and K_2 CP-odd
- If CP is conserved, than
  - K_1 decays only to 2π
  - K_2 decays only to 3π
- What happens when CP is violated?
- Could we experimentally test CP violation?

CPV Discovery

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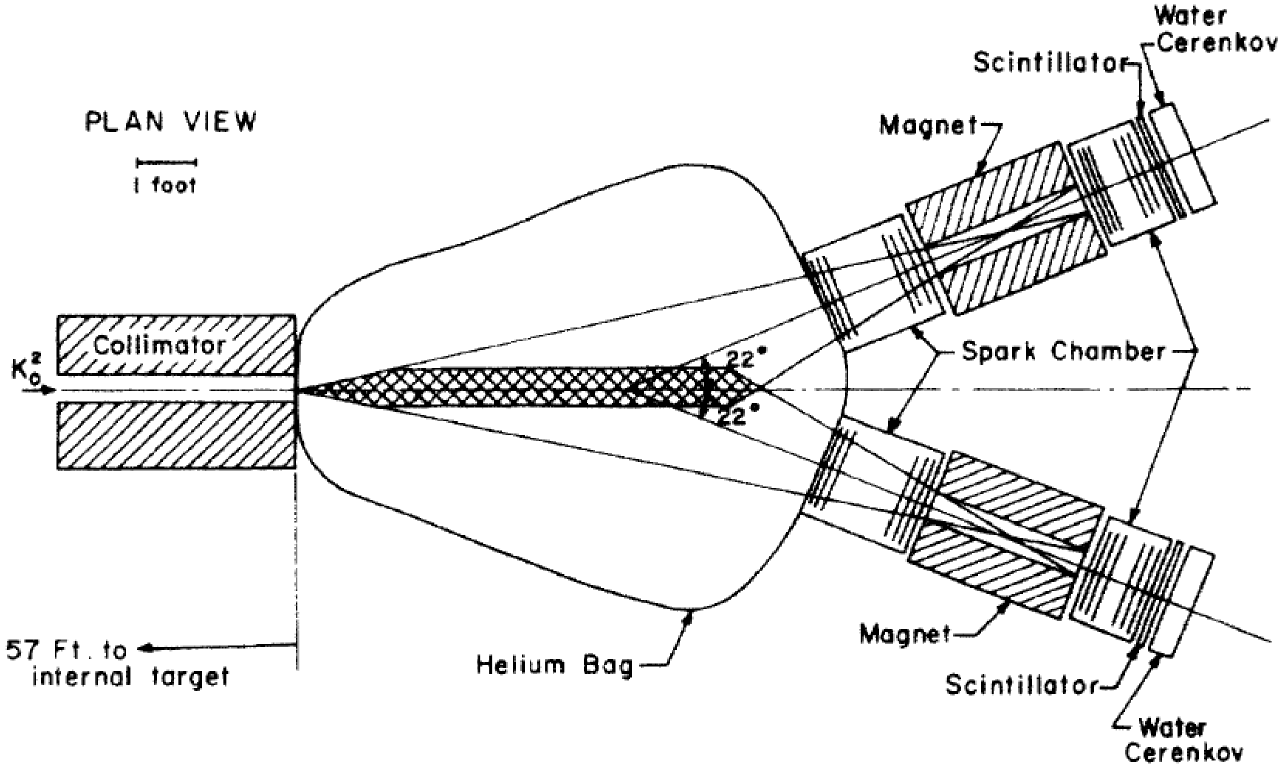
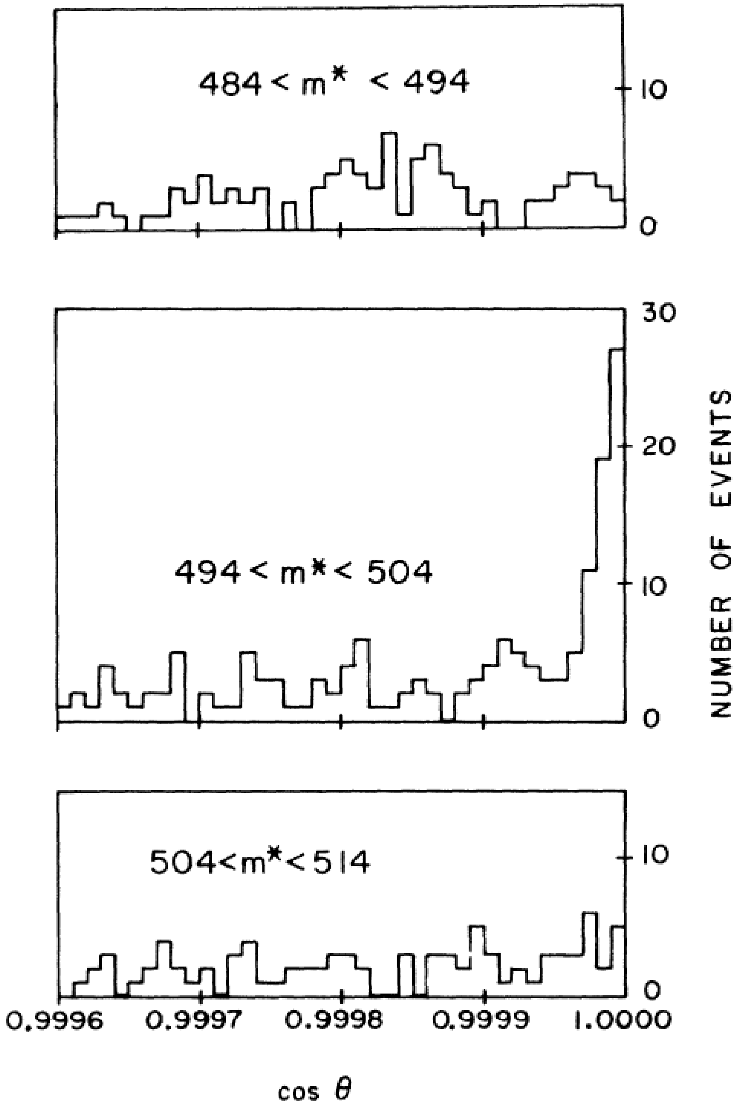


Christenson, Cronin, Fitch, Turley

Discovery of CPV



- If CP is violated, should see $K_2 \to 2\pi$
- Angle between sum of the momenta of 2π and beam should be zero
- Experiment measured

$$R = \frac{N(K_2 \to \pi^+\pi^-)}{N(K_2 \to \text{all charged})} = (2 \pm 0.4)10^{-3}$$

How to make sense out of it?

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→ K_1, K_2 are not eigenstates of weak inter.

$$K_S = \frac{1}{\sqrt{1+|\varepsilon|^2}}\left(K_1 + \varepsilon K_2\right) = \frac{1}{\sqrt{2(1+|\varepsilon|^2)}}\left[(1+\varepsilon)K^0 + (1-\varepsilon)\bar{K}^0\right]$$

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

$$\Gamma(K_1 \to 2\pi) \sim \frac{1}{\tau_1}$$

$$\Gamma(K_L \to 2\pi) \approx \varepsilon^2 A^2(K_1 \to 2\pi) \sim \varepsilon^2 \frac{1}{\tau_1}$$

$$\varepsilon^2 = R_\pm \frac{\tau_1}{\tau_2}$$

$$\Gamma(K_L \to 2\pi) \sim \underbrace{\frac{\Gamma(K_L \to 2\pi)}{\Gamma(K_L \to all)}}_{R} \cdot \underbrace{\Gamma(K_L \to all)}_{\frac{1}{\tau_2}}$$

$$R_\pm = \frac{3}{2} R$$

$$\varepsilon = 2.3 \times 10^{-3}$$

Example of $K_L \to e^+\pi^-\nu$

$$\Delta = \frac{N(K_L \to e^+\pi^-\nu) - N(K_L \to e^-\pi^+\nu)}{N(K_L \to e^+\pi^-\nu) + N(K_L \to e^-\pi^+\nu)} \quad \leftarrow \text{Num}$$

$$\text{Num} = \cancel{(1+\varepsilon)[K^0} \to \pi^+ e^- \bar{\nu}] + (1-\varepsilon)[\bar{K}^0 \to \pi^+ e^- \bar{\nu}] - (1+\varepsilon)[K^0 \to \pi^- e^+ \nu) - \cancel{(1-\varepsilon)[\bar{K}^0 \to \pi^- e^+ \nu]}$$

assume $\bar{K}^0 \to \pi^+ e^- \bar{\nu} = K^0 \to \pi^- e^+ \nu$

$$\text{Num} = -2\varepsilon\, R(K^0 \to \pi^- e^+ \nu)$$

$$\Delta = 2\,\mathrm{Re}(\varepsilon)$$

Experiment $\Delta_e = 3.34 \times 10^{-3}$

$\Delta_\mu = 3.04 \times 10^{-3}$

Indirect CPV

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$|\psi\rangle = p|K^0\rangle + q|\bar{K}^0\rangle$ $\quad$ p, q – complex numbers

$|p|^2 + |q|^2 = 1$

$\begin{pmatrix} p \\ q \end{pmatrix}$

schrödinger type eq.

$$i\frac{d}{dt}|\psi\rangle = \left[\begin{pmatrix} M_{11} & M_{12} \\ M_{12}^* & M_{22} \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_{22} \end{pmatrix}\right]|\psi\rangle$$

M, Γ are hermitian matrices

mass matrix $\Rightarrow$ oscillation

decay matrix $\Rightarrow$ decay

$\swarrow$ eigenstates, eigenvalues

$$\left(\frac{q}{p}\right)^2 = \frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}$$

if $|q| = |p|$ $\Rightarrow$ $M_{12}^* - \frac{i}{2}\Gamma_{12}^* = M_{12} - \frac{i}{2}\Gamma_{12}$ $\Rightarrow$ zero phase between M_{12} and Γ_{12}

Standard model

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

Kobayashi Maskawa

proposed third generation of quarks

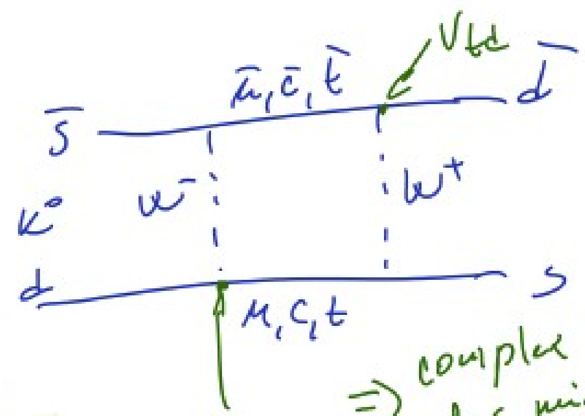
$\Rightarrow$ parametrised by 3 rotations and 1 complex phase

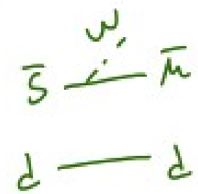
Wolfenstein parametrization

complex

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

$\lambda = \sin\theta_c \simeq 0.22$





$\Rightarrow$ complex phase for mixing M_{12}

$\Rightarrow$ decay itself is real

Γ_{12} real

10

Note on CKM matrix

- CKM matrix is unitary matrix
- It has only four parameters
- Product of any two rows or two columns is equal to zero
  - It can be visualized as triangle in complex plain (called unitarity triangle)
- All unitarity triangles have same area given by Jarlskog invariant
- Jarlskog invariant is measure of CP violation in quark sector
- The CKM matrix is hierarchical

Some questions for thinking

- What are implications of observation of CP violation?
- What you would do to confirm Kobayashi-Maskawa mechanism
- If you have answers in terms of experiment, what capabilities experiment has to have?
- How would you determine CKM matrix elements?