Flavour physics – Lecture 1

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Outline

- What is flavour physics?
- Some theory and history
- CKM matrix

What is flavour physics?

Fermions ("matter")	Bosons ("forces")
$\left\{ \begin{array}{ccc} & \text{Quarks} & \\ uuu & ccc & ttt \\ ddd & sss & bbb \\ & & \\ & \text{Leptons} & \\ e & \mu & \tau \\ \nu_e & \nu_\mu & \nu_\tau \end{array} \right\} \times \left\{ \begin{array}{c} \text{MATTER} \\ \text{ANTIMATTER} \end{array} \right\}$	$gggggggg$ γ W^+ W^- Z H

SM parameters

- 3 gauge couplings
- 2 Higgs parameters
- 6 quark masses
- 3 quark mixing angles and 1 phase
- 3 + [3] lepton masses
- [3 lepton mixing angles and 1 phase]

[with massive neutrinos]

SM parameters

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- 2 Higgs parameters
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FLAVOUR PARAMETERS

[with massive neutrinos]

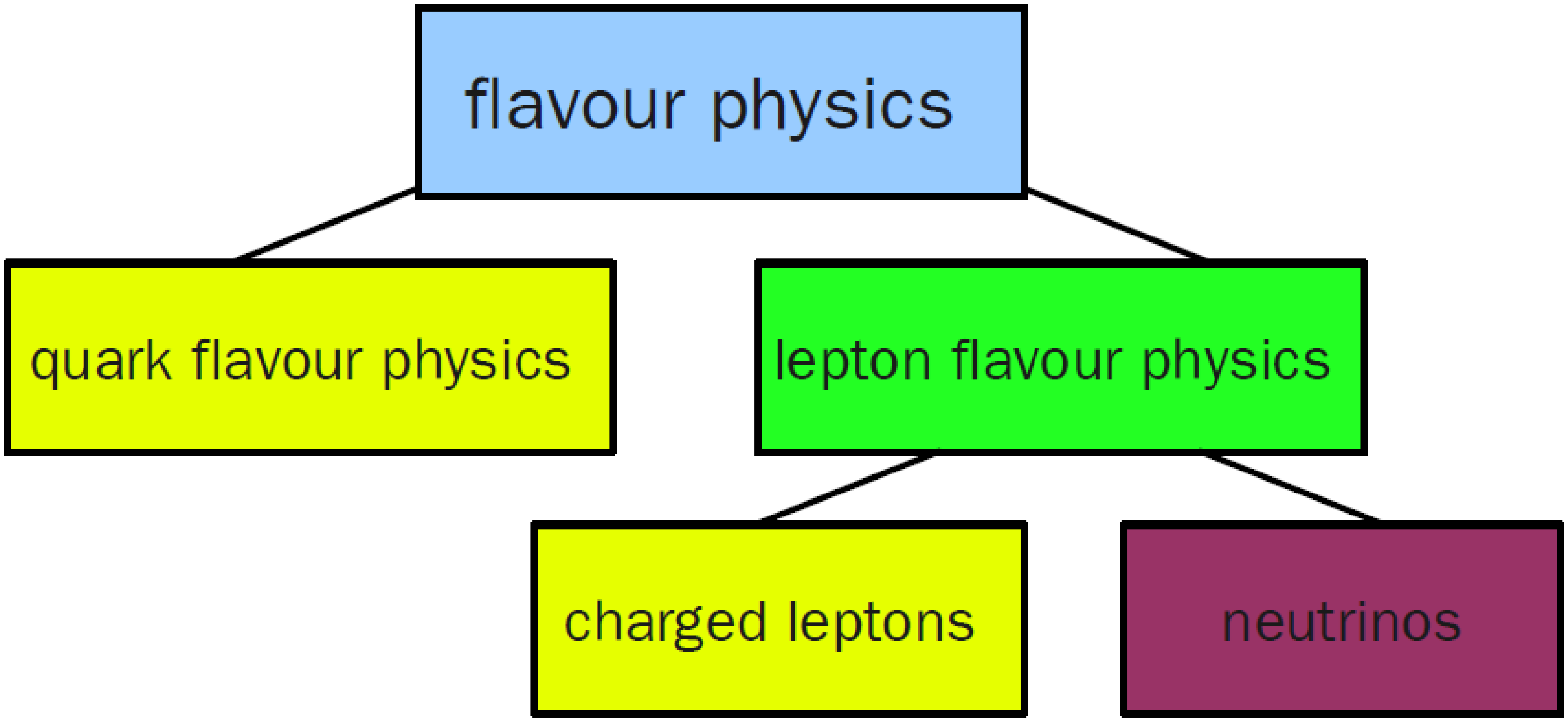
What is not flavour physics?

- QCD
  - But important for interpretation of flavour variables
- Electroweak physics
  - But linked to weak couplings and absence of flavour changing neutral currents
  - Higgs mechanism generates quark masses and mixings
- High-p_t – searches for new heavy particles
  - Complementary effects in virtual processes in flavour physics

Puzzles in flavour physics

- Why three generations of quarks and leptons
- Mass hierarchies of quarks and leptons
- Hierarchy of weak mixing of quarks
  - What about leptons?
- Charged lepton coupling universality
- Absence of flavour changing neutral currents
- Symmetry principles and their violation
  - P and C
  - CP and T
  - Baryon and anti-baryon asymmetry in the universe
  - Lepton flavour violation?

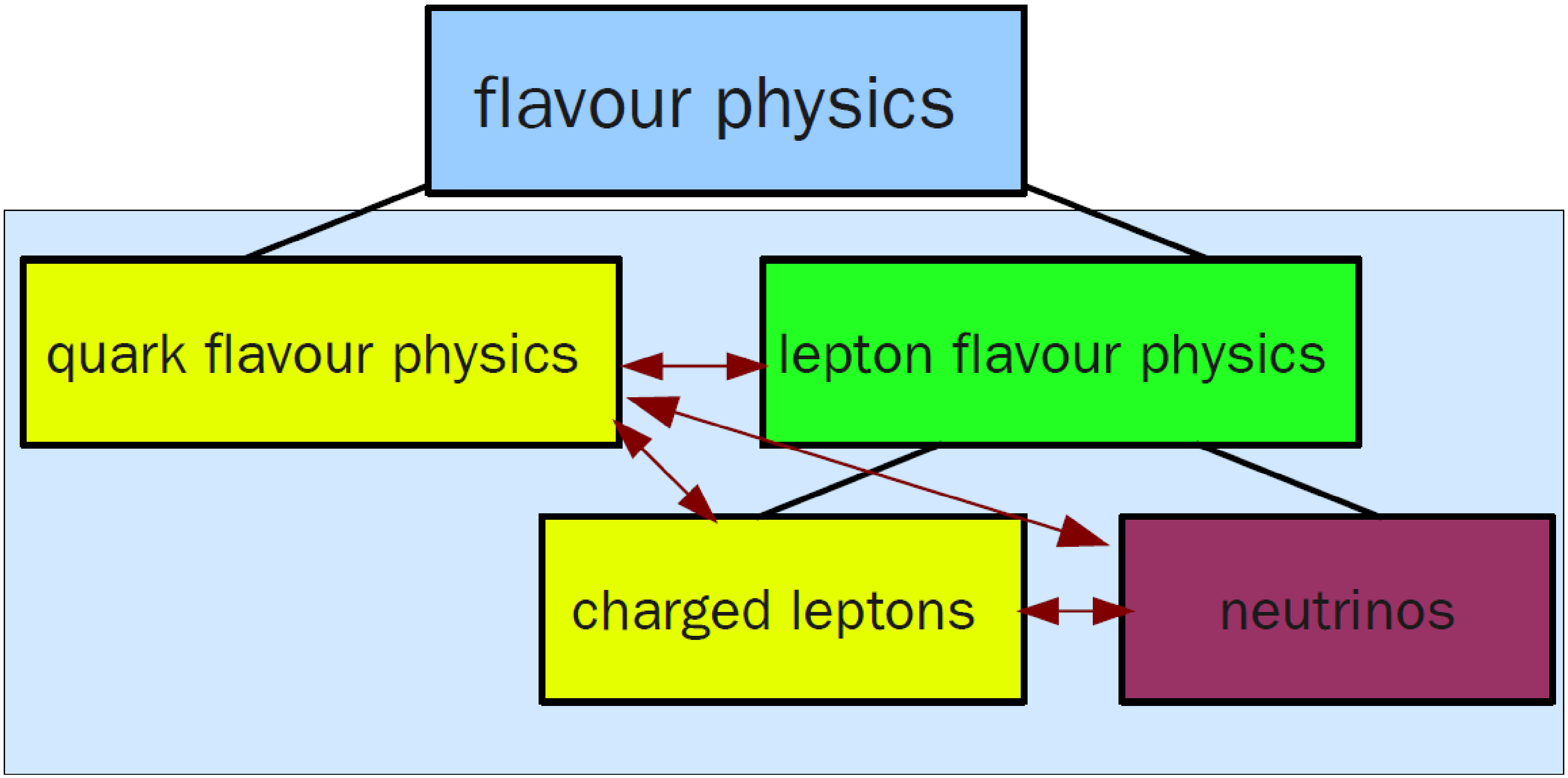
Flavour organigram



A few words about neutrinos…

- Parity violation
  - Neutrinos are left handed (chiral) states
    - Antineutrinos are righthanded
  - But not massless
    - So where are right handed neutrinos?
- Massive field with many intriguing questions
  - ….but this topic will not be covered in depth here as we will deal with more traditional discussion of flavour in the hadronic weak sector

Ultimate goal – unified description of interplay between the different divisions



Alternatively can think about a division

1. Flavour changing physics
   - Decays and couplings
   - Lifetimes
   - Mixing
   - CP violation
2. Flavour conserving physics
   - Masses
   - Dipole moments

A historical review

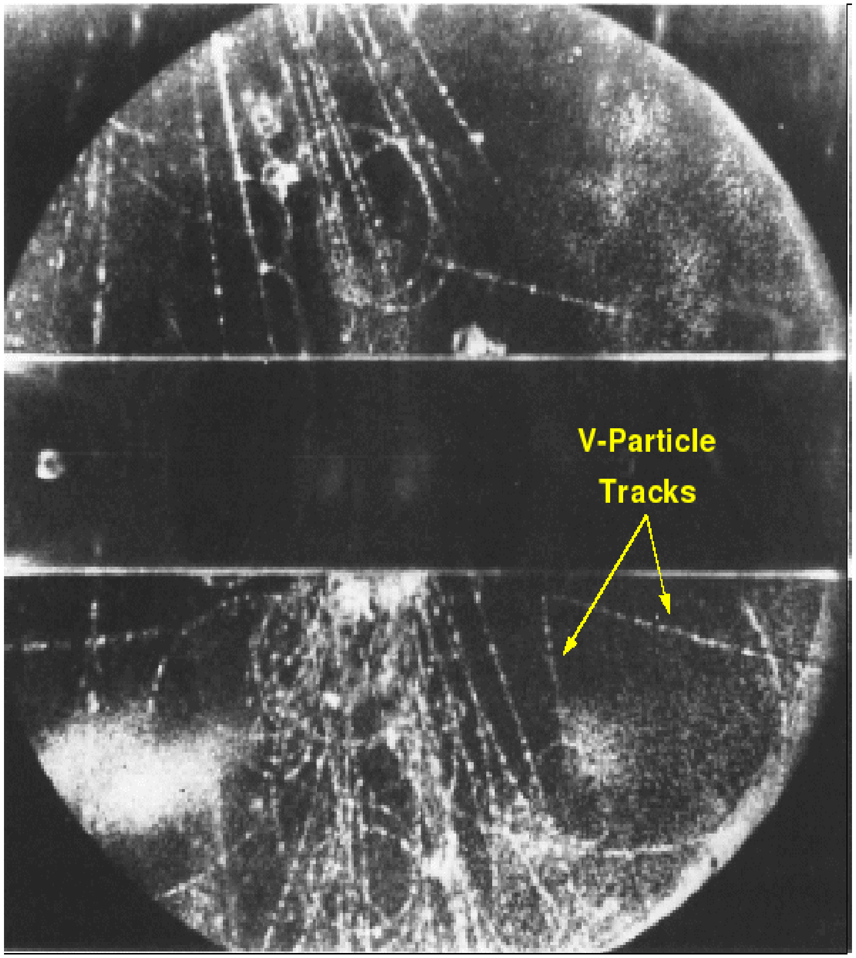
- Isospin
- Strangeness
- Quark model
- τ-θ puzzle
- P and C violation
- Mixing and GIM mechanism
- CP violation
- Sakaharov and the link to cosmology

Isospin

- Proton and neutron different charge but
  - Near identical mass
  - Strong couplings
- Heisenberg proposed new quantum number isospin (I) of which n and p form a doublet I=1/2,
  - $I_3(p)=1/2$, and $I_3(n)=-1/2$
- Later observed that pions form a triplet I=1
  - $I_3(\pi^-)=-1$, $I_3(\pi^0)=0$, and $I_3(\pi^+)=+1$
- Link between symmetry and invariance
  - n and p strong interactions invariant under SU(2) rotation
  - Works because u and d almost degenerate in mass
- Isospin is a way of saying the strong interaction is flavour blind and the third component counts upness and downness flavour

Strangeness

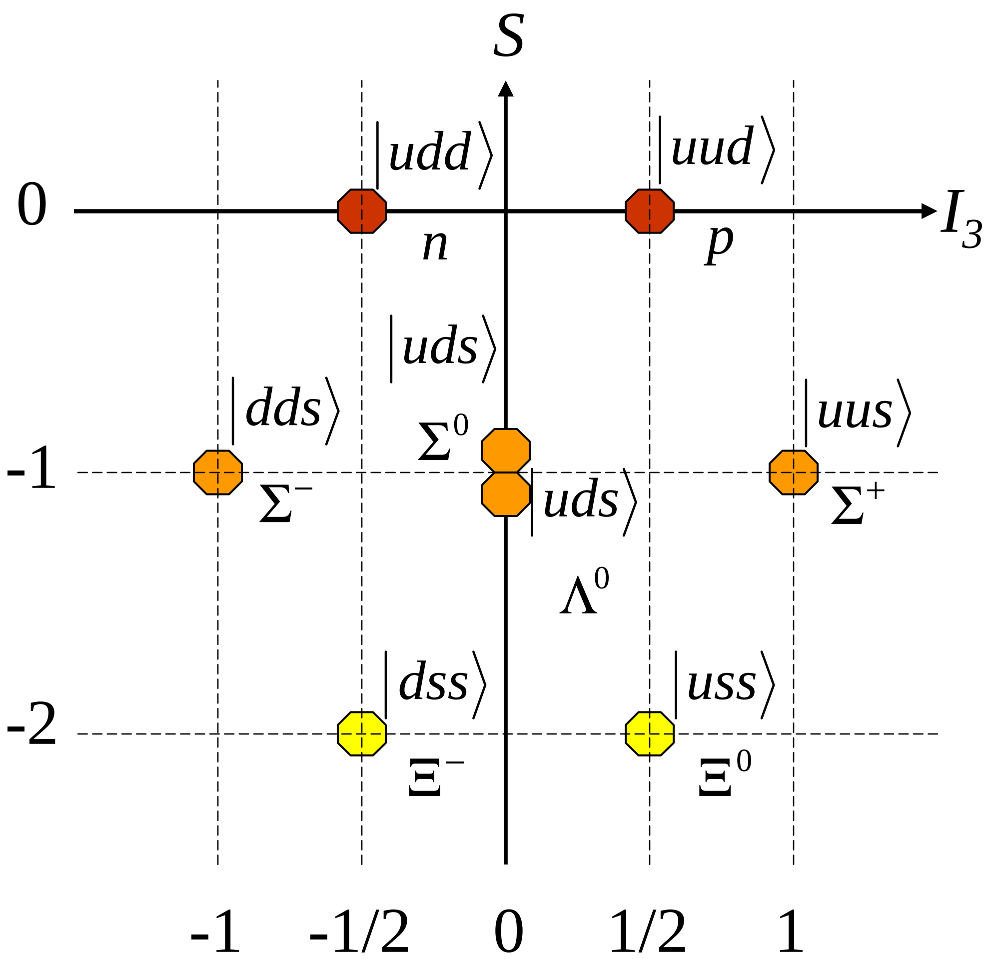
- Rochester and Butler (1947)
  - Neutral particle in cosmic rays decay to two charged pions
    - forms a V
  - Long-lifetime - strange
  - Also, saw evidence of charged particle that decayed to a pion and something else
- Pais (1952) introduced new quantum number strangeness
  - Conserved in strong interactions
  - Violated in weak interactions
    - **Flavour change**



Quark model – Gell-Mann (1961-1964)

- All very comfortable with quarks now but only accepted after discovery of charm in 1974
  - More later
- Neatly explained the zoo of particles discovered in 1950s and 1960s
- The SU(3) flavour symmetry – eightfold way - gave rise to groupings
  - Baryon octet and decuplet
  - Meson nonet

Baryon octet



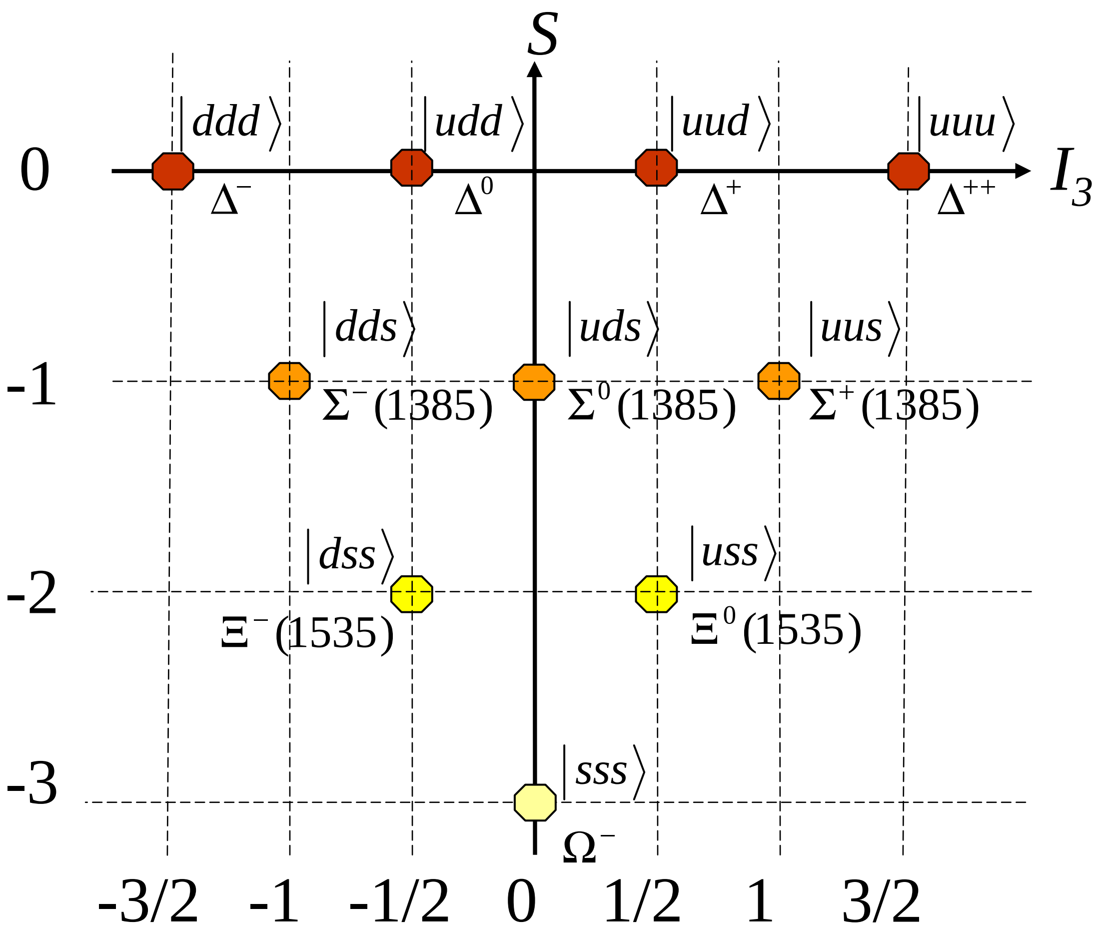
Spin-parity $J^P=\frac{1}{2}^+$

- Two quark spins aligned the third antiparallel
- Parity from +ve intrinsic parity of quarks

***S* and I_3 are additive quantum numbers**

- S=strangeness ($S=-1$ for a strange quark and +1 for an anti-strange quark)
- I_3= third component of isospin ($I_3=+\frac{1}{2}$ for up quarks and $-\frac{1}{2}$ for down quarks)

Baryon decuplet



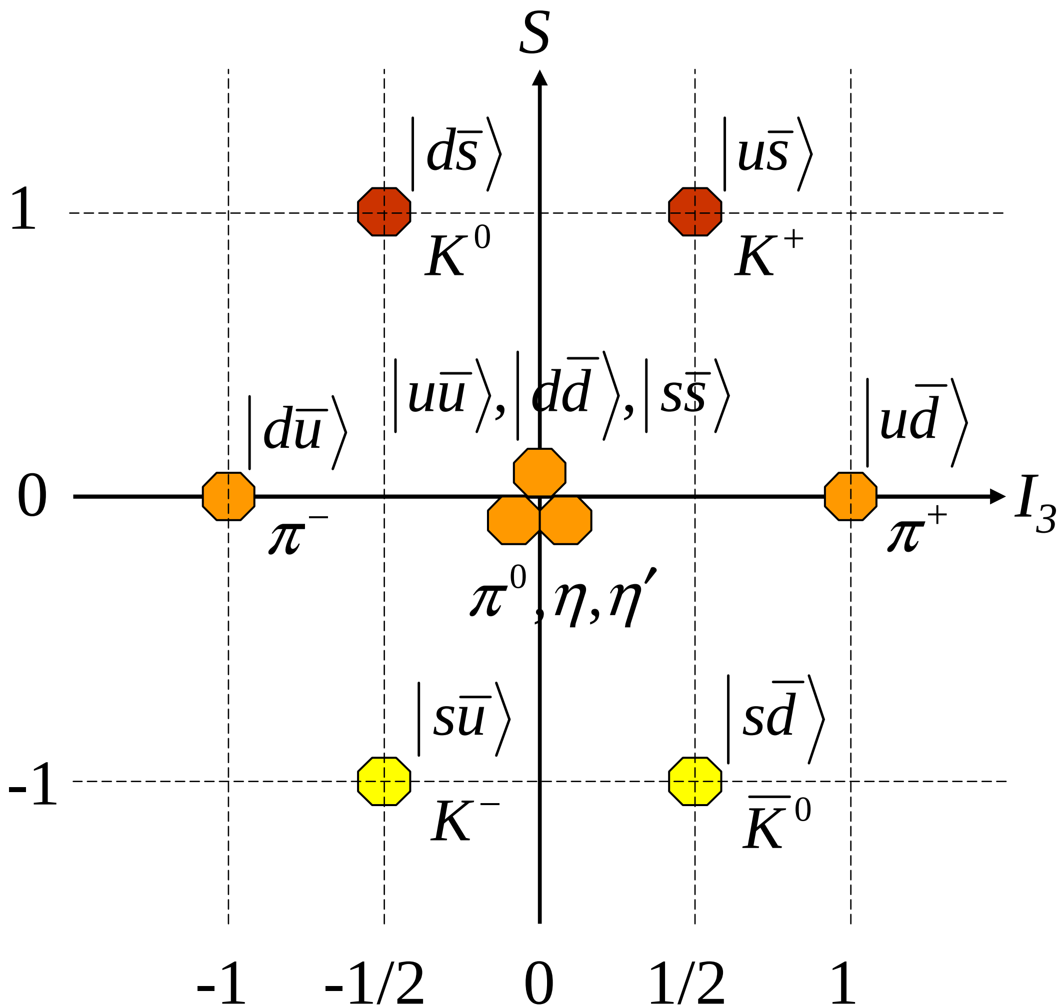
Spin-parity $J^P=3/2^+$

All quark spins aligned

Quark compositions |qq′q″> are not the same as quark wavefunctions

The discovery of 1964 of Ω^- predicted by the model first vindication

Meson nonet: $J^P=0^-$



Spin-parity $J^P=0^-$
Quark spins antiparallel

Pseudoscalars: zero spin (scalar quantity) but antisymmetric under parity operation

The three $S=I_3=0$ states quark wavefunctions are different admixtures of $|u\bar{u}\rangle, |d\bar{d}\rangle$ and $|s\bar{s}\rangle$

The θ - τ problem

- Spin 0 θ particle decayed to $\pi^+\pi^0$
  - Even parity final state
- Spin 0 τ particle decayed to $\pi^+\pi^-\pi^+$
  - Odd parity final state
- But masses the and lifetimes the same
- Parity violation discovered in 1957
  - Wu (after Lee and Yang's suggestion)
- θ and τ the same – K^+
  - Parity violated maximally in flavour changing weak decays

P, C and CP

- P maximal violation in weak processes
  - All neutrinos lefthanded
- But C also violated in weak decays
  - No righthanded neutrinos
- But product CP assumed to be a conserved quantity (Landau 1957)
  - So CP distinguishes matter from antimatter
- Note that CP and T combined is conserved in all Lorentz invariant gauge field theories (i.e. SM)
  - Will return to this when CP violation is discussed

Weak couplings - Cabibbo (1963)

- When corrected for phase space it was found that $s \rightarrow u$ weak transition rates suppressed by a factor of ~ 20 compared to $d \rightarrow u$
  - $K^+ \rightarrow \mu^+ \nu$ compared to $\pi^+ \rightarrow \mu^+ \nu$
- Also, small differences in G_F measured in $d \rightarrow u$ transitions compared to muon decay
- Above could be explained if flavour eigenstates and weak eigenstates different

$$\begin{pmatrix} d \\ s \end{pmatrix}_{weak} = \begin{bmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{bmatrix} \begin{pmatrix} d \\ s \end{pmatrix}_{flavour} \qquad \sin\theta_C \approx 0.22 \quad \cos\theta_C \approx 0.98$$

Neutral kaon mixing

- Consequence of strangeness and weak states not being the same is that the physical states of neutral kaons are almost equal admixtures of the strangeness eigenstates
  - $$K_S^0 \approx \frac{1}{\sqrt{2}}\left(K^0 + \overline{K^0}\right) \qquad K_L^0 \approx \frac{1}{\sqrt{2}}\left(K^0 - \overline{K^0}\right)$$
- K_S is CP-even (decays to two pions)
- K_L is CP-odd (decays to three pions and semileptonically)

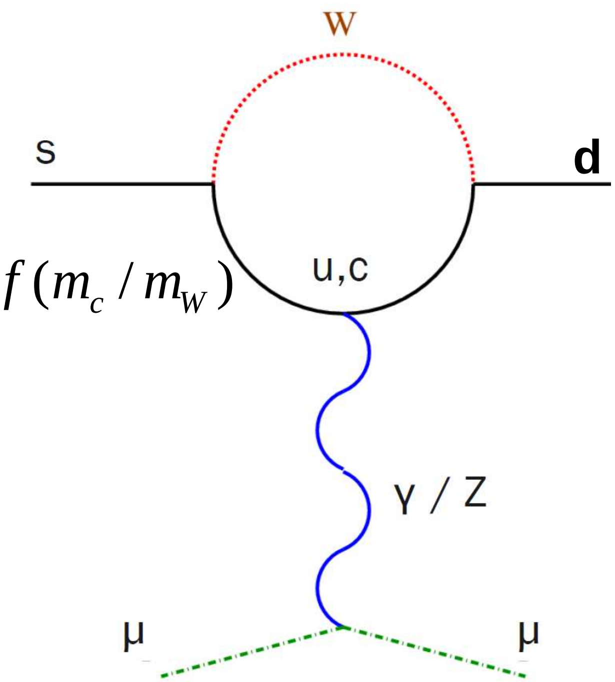
GIM mechanism

- There was a puzzle
  - $K^+ \rightarrow \mu^+ \nu$ so why not $K^0 \rightarrow \mu^+ \mu^-$
  - $K^+ \rightarrow \pi^0 \mu^+ \nu$ so why not $K^0 \rightarrow \pi^0 \mu^+ \mu^-$
- GIM (Glashow, Iliopoulos and Maiani) mechanism (1970)
  - Leads to no flavour changing neutral currents (FCNC)
  - Suppression via loops
  - Requires that quarks come in doublets
    - Predicted a fourth quark - charm

GIM continued

$$\begin{pmatrix} u & c \end{pmatrix}_{flavour} \begin{bmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{bmatrix} \begin{pmatrix} d \\ s \end{pmatrix}_{flavour}$$

$$A(s \rightarrow d\mu^+\mu^-) = \cos\theta_C \sin\theta_C f(m_u/m_W) - \cos\theta_C \sin\theta_C f(m_c/m_W)$$

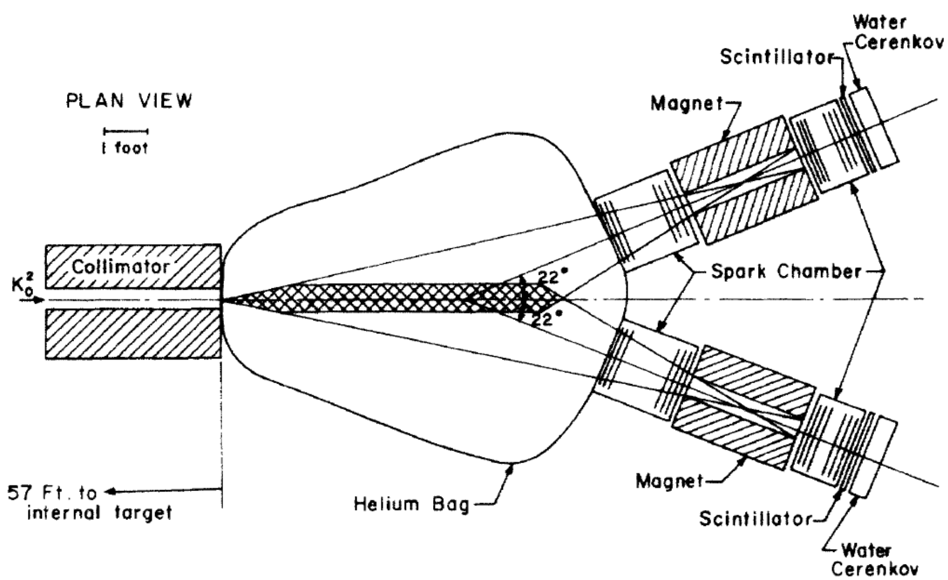


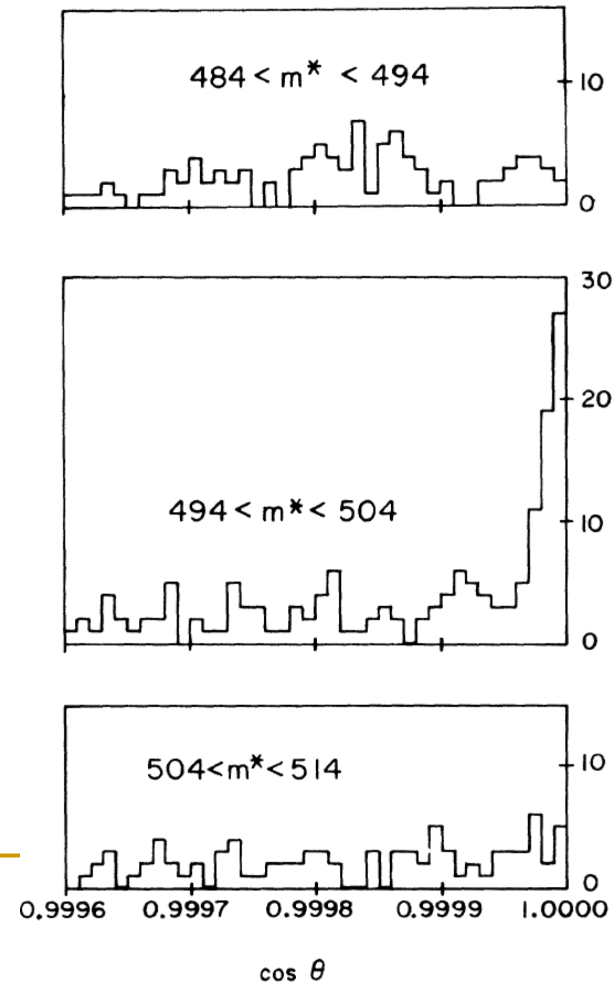
As $m_u << m_W$ and $m_c << m_W$
A~0

The small rate at which these processes occur allowed value of charm mass to be predicted

CP violation

- Another puzzle was the observation in 1964 of $K_L \rightarrow \pi\pi$ by Cronin, Fitch et al.
- This violates CP!





Sakharov conditions – CP and cosmology

- Proposed by A. Sakharov (1967)
- N_B observed a billion times bigger than expected
- No antimatter observed
- Three conditions for evolution of matter dominated universe from symmetric initial state
  1. Baryon number violation
  2. C and CP violation
  3. Lack of thermal equilibrium

CKM matrix

Predicted 3rd generation even before charm had been observed

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CP-Violation in the Renormalizable Theory of Weak Interaction

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(Received September 1, 1972)

In a framework of the renormalizable theory of weak interaction, problems of *CP*-violation are studied. It is concluded that no realistic models of *CP*-violation exist in the quartet scheme without introducing any other new fields. Some possible models of *CP*-violation are also discussed.

CKM matrix

- Extension of Cabibbo's two by two mixing matrix
- Unitary complex matrix
  - 18 parameters
- Unitary constraints ($VV^{+}=I$)
  - 9 parameters
- Quark fields can absorb five unobservable phases
  - 4 parameters
  - 3 mixing angle and 1 phase

$$\begin{pmatrix} u & c & t \end{pmatrix} \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Responsible for CP violation

Summary of lecture 1

- Flavour physics integral to development of SM
  - Mixing
  - FCNC
  - CP violation and CKM
- Led to prediction, and as we shall see, properties of the charm, bottom and top quark
  - Low energy probe of high energy scales