

Outline

■ Relativistic Kinematics

- ▶ (4-momentum)² invariance, invariant mass
- ▶ Hypothesis testing, production thresholds
- ▶ Cross-sections, flux and luminosity, accelerators
- ▶ Particle lifetime, decay length, width

Today

■ Classification of particles

- ▶ Fermions and bosons
- ▶ Leptons, hadrons, quarks
- ▶ Mesons, baryons

- [Lecture 14 \(4 slides/page\)](#) CKM matrix, heavy flavour production and decay
 - Griffiths, pp. 74-77, 324-329.

■ Quark Model

- ▶ Meson and baryon multiplets
- ▶ Isospin, strangeness, c, b, t quarks

■ Particle Interactions

- ▶ Colour charge, QCD, gluons, fragmentation, running couplings
- ▶ **Strong and weak decays, conservation rules**
- ▶ Virtual particles and range of forces
- ▶ Parity, charge conjugation, CP
- ▶ **Weak decays of quarks**
- ▶ Charmonium and upsilon systems

Previous
lecture

- [Lecture 13 \(4 slides/page\)](#) - Quark flavour conservation, CKM matrix
 - Griffiths, pp. 74-77, 324-329.
 - Williams not the best for this topic

■ Electroweak Interactions

- ▶ Charged and neutral currents
- ▶ W, Z, LEP experiments
- ▶ Higgs and the future

■ LHC Experiments

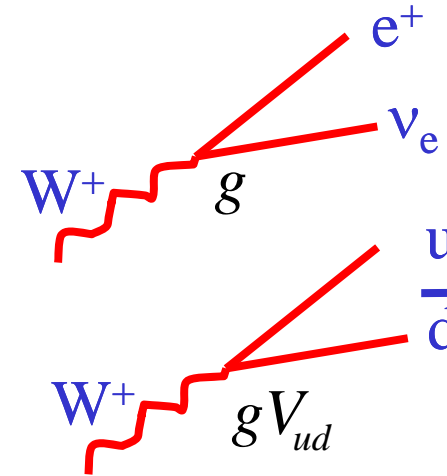
■ Future - introduction to accelerator physics

W coupling to quarks

- Cabibbo theory
 - ▶ W boson couples to lepton/neutrinos with universal coupling, g
 - ▶ W boson couples to **u** quark and a **d** quark with coupling $g \cdot V_{ud}$

- W does not couple directly to physical/mass states of u and d quarks
 - ▶ Actually couples to a **u-type** and a **linear combination** of d-type quarks in all 3 generations
 - ▶ Without this, would be no decay of lightest strange mesons, etc.!

- Effectively, a "**rotation**" of mass eigenstates to the weak eigenstates



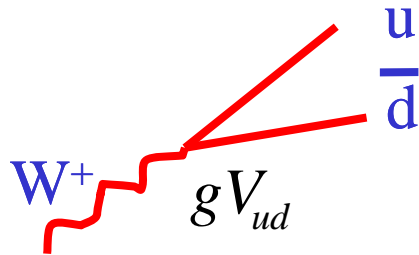
$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{vmatrix} V_{ud} & V_{us} \\ V_{cd} & V_{cs} \end{vmatrix} \begin{pmatrix} d \\ s \end{pmatrix} = \begin{pmatrix} \cos \theta_C & \sin \theta_C \\ -\sin \theta_C & \cos \theta_C \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

$$\begin{aligned} \text{i.e. } d' &= d \cos \theta_C + s \sin \theta_C \\ s' &= -d \sin \theta_C + s \cos \theta_C \end{aligned}$$

$$\theta_C \approx 13.1^\circ$$

Cabibbo Theory and Golden Rule

- Convention to "rotate" d type quarks, but could equally well rotate u type quarks



- Cabibbo theory is historical name when dealing with 1st and 2nd generations only

$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{vmatrix} V_{ud} & V_{us} \\ V_{cd} & V_{cs} \end{vmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

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

$$= \begin{pmatrix} 0.974 & 0.225 \\ 0.225 & 0.974 \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

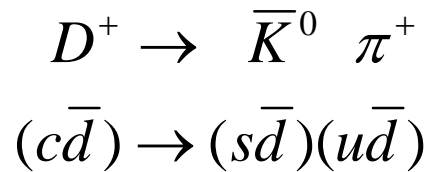
- "Fermi Golden Rule" for decay/scattering rates - see QM text
- Rate is product of two terms

$$Rate = \frac{2\pi}{\hbar} |M_{fi}|^2 \rho(E)$$

$\rho(E)$ is phase space factor, dN / dE

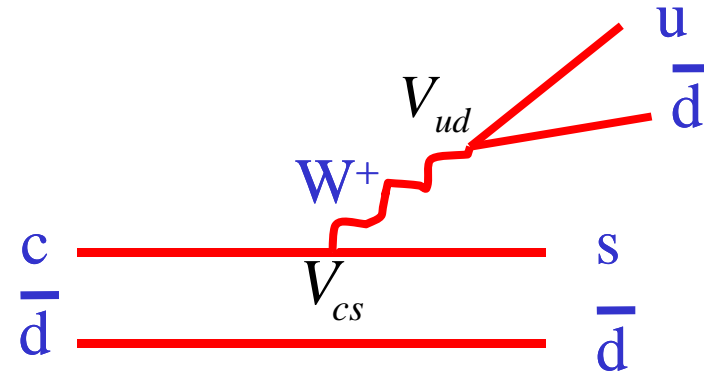
- A dynamical term, derived from Feynman diagrams.
 - Enters as the $|QM \text{ amplitude}|^2$, (sometimes called "matrix element"²)
 - For our case, amplitude is proportional to the product of couplings present in diagram
- A kinematical term, purely depending on energy/momenta/masses
 - Independent of particle types
 - Variouly called "phase space factor" or "density of states"
 - More energy available in final state (apart from masses) increases this statistical counting factor: number of states possible with energy E available

Example: Cabibbo Suppression



Amplitude

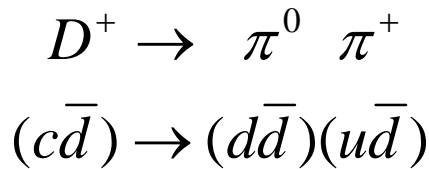
$$\propto V_{ud} V_{cs}$$



Rate

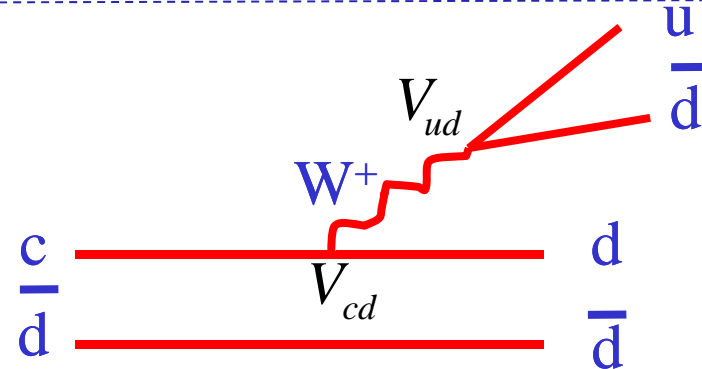
$$\propto |V_{ud} V_{cs}|^2 = |\cos \theta_C \cos \theta_C|^2$$

“Cabibbo favoured” decay



Amplitude

$$\propto V_{ud} V_{cd}$$



Rate

$$\propto |V_{ud} V_{cd}|^2 = |\cos \theta_C \sin \theta_C|^2$$

“Cabibbo suppressed” decay

Relative rates

$$\frac{D^+ \rightarrow \bar{K}^0 \pi^+}{D^+ \rightarrow \pi^0 \pi^+} \propto |V_{ud} V_{cs}|^2 / |V_{ud} V_{cd}|^2 = |1 / \tan \theta_C|^2 \sim 1 / 20$$

3 Flavour case: CKM Matrix

- Generalisation to 3 generations: CKM (Cabibbo-Kobayashi-Maskawa) Matrix
- Rotation of mass to weak eigenstates
- 2x2 Cabibbo matrix is merely the upper left part of the full 3x3 CKM matrix
- $\lambda = \sin\theta_C$

Cabibbo

$$\begin{vmatrix} V_{ud} & V_{us} \\ V_{cd} & V_{cs} \end{vmatrix} = \begin{pmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{pmatrix}$$

CKM (magnitudes only)

$$\begin{vmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{vmatrix} \approx \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

$$\begin{vmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{vmatrix} \approx \begin{pmatrix} 0.974 & 0.225 & 0.003 \\ 0.225 & 0.973 & 0.041 \\ 0.008 & 0.040 & 0.999 \end{pmatrix}$$

- Note: small size of

▶ V_{ub}, V_{cb}, V_{td}

▶ Observations?? Impact on lifetimes of b, c decays?

Strange Particle Production

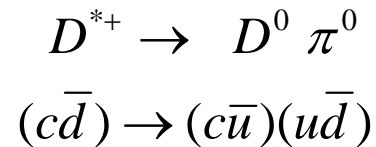
- Properties of **SI**, **WI** important in **production/decay** of strange and heavier quarks
- **Production** requires **strong** (or EM) to give large cross-section. Requires $s\bar{s}$ production to conserve strangeness
 - ▶ Strange hadrons created in pairs - so-called "associated production"
 - ▶ Examples of **production** (on board): p (π^+ , π^- , K^-)
- **SI** decays **13 orders magnitude** faster than **WI**, so **WI** decays only observed when **SI/EM** forbidden by (e.g.) flavour conservation rules.
- Heavy strange hadrons (i.e. excited states) decay to lighter strange hadrons by **SI**
 - ▶ Examples of **SI decays** (on board): p (π^+ , π^- , K^-)
 - ▶ **Conserves flavour** and other quantum numbers
 - ▶ Typical lifetime of strong decays $\sim 10^{-22}$ - 10^{-23} s, called resonances
- Process continues until arrive at **lightest** strange hadrons (kaons), which are **stable** under **SI** because of **strangeness conservation**
- **WI** decays only observed when **SI** and **EM** forbidden by, e.g. flavour conservation.

Light Strange Particle Decays

- Lightest strange particles
- Mesons
 - ▶ $K^+ = u\bar{s}, K^0 = d\bar{s}, \bar{K}^0 = \bar{d}s, K^- = \bar{u}s$
 $\Rightarrow S = \pm 1$
- Baryons
 - ▶ $\Lambda^0 = uds$
 $\Rightarrow S = -1$
 - ▶ $\Sigma^+ = uus, \Sigma^- = dds,$
 $\Rightarrow S = -1$
 \Rightarrow [not $\Sigma^0 = uds$ - not lightest uds : $m_{\Sigma^0} - m_{\Lambda} = (76.959 \pm 0.023) \text{ MeV}$]
 - ▶ $\Xi^0 = uss, \Xi^- = dss$
 $\Rightarrow S = -2$
 - ▶ $\Omega^- = sss$
 $\Rightarrow S = -3$
 - ▶ Feynman diagrams on board
- These can only decay with change in strangeness, so must be weak decays.
- Typical lifetimes $\sim 10^{-8} - 10^{-11} \text{ s}$

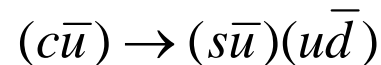
Heavy Quark (c, b, t) Decays

- Same pattern as in strange hadrons
- SI, EM and weak neutral current (Z^0) also conserve flavour for C, B, T
 - ▶ Each flavour number can change by 1 unit in a single W mediated reaction
- Heavy particles decay to lighter by SI, conserving flavours
 - ▶ e.g. $\tau \sim 10^{-23} \text{s}$, Feynman diagram on board



- Lightest particle of each flavour decays by WI, changing flavour

▶ e.g. $D^0 \rightarrow K^- \pi^+$ $\tau \sim 4.1 \times 10^{-13} \text{s}$, diagram on board



▶ e.g. $B^+ \rightarrow \bar{D}^0 \pi^+$ $\tau \sim 1.6 \times 10^{-12} \text{s}$, diagram on board

