

Outline

- Relativistic Kinematics
 - (4-momentum)² invariance, invariant mass
 - Hypothesis testing, production thresholds
 - Cross-sections, flux and luminosity, accelerators
 - Particle lifetime, decay length, width
- Classification of particles
 - Fermions and bosons
 - Leptons, hadrons, quarks
 - Mesons, baryons
- 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
- Electroweak Interactions
 - Charged and neutral currents
 - W, Z, LEP experiments
 - Higgs and the future
- LHC Experiments
- Future - introduction to accelerator physics

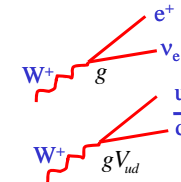
Today

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

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 gV_{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

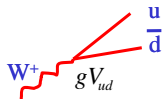


$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{vmatrix} V_{ud} & V_{us} \\ V_{cd} & V_{cs} \end{vmatrix} \begin{pmatrix} d \\ s \end{pmatrix} = \begin{pmatrix} \cos \theta_C & \sin \theta_C \\ -\sin \theta_C & \cos \theta_C \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

i.e. $d' = d \cos \theta_C + s \sin \theta_C$
 $s' = -d \sin \theta_C + s \cos \theta_C$
 $\theta_C \approx 13.1^\circ$

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

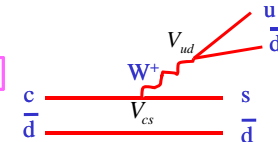
$$\text{Rate} = \frac{2\pi}{\hbar} |M_{fi}|^2 \rho(E)$$

$\rho(E)$ 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

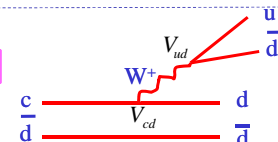
$$D^+ \rightarrow \bar{K}^0 \pi^+ \quad \text{Amplitude} \propto V_{ud} V_{cs}$$



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

"Cabibbo favoured" decay

$$D^+ \rightarrow \pi^0 \pi^+ \quad \text{Amplitude} \propto V_{ud} V_{cd}$$



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

"Cabibbo suppressed" decay

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

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

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

CKM (magnitudes only)

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

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

- 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): $p(\pi^+, \pi^-, K^-)$
- 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): $p(\pi^+, \pi^-, K^-)$
 - 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} 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. $D^{*+} \rightarrow D^0 \pi^+$ $\tau \sim 10^{-23}$ s, Feynman diagram on board
 - $(c\bar{u}) \rightarrow (c\bar{u})(u\bar{d})$
- Lightest particle of each flavour decays by WI, changing flavour
 - e.g. $D^0 \rightarrow K^- \pi^+$ $\tau \sim 4.1 \times 10^{-13}$ s, diagram on board
 - $(c\bar{u}) \rightarrow (s\bar{u})(u\bar{d})$
 - e.g. $B^+ \rightarrow \bar{D}^0 \pi^+$ $\tau \sim 1.6 \times 10^{-12}$ s, diagram on board
 - $(u\bar{b}) \rightarrow (u\bar{c})(u\bar{d})$