Subatomic Physics:

Particle Physics

Lecture 7: Introduction to the Weak Force

November 24th 2009

- Weak interactions
- Charged and neutral current
- Feynman Rules for weak force

Introduction to the Weak Force

The weak force is responsible for some of the most important phenomena:

- Decays of the muon and tau leptons
- Neutrino interactions
- Decays of the lightest mesons and baryons
- Radioactivity, nuclear fission and fusion

Characteristics of Weak Processes:

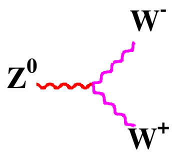
- Long lifetimes 10^{-13} - 10^{3} s
- Small cross sections 10^{-13} mb

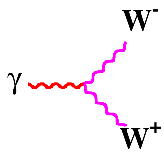
Boson	$W^{\pm}$	Z^0
Mass GeV/c^2	80.4	91.2
charge, e	±1	0
spin	$1\hbar$	$1\hbar$

Weak Force is propagated by massive W^+, W^- and Z^0 bosons

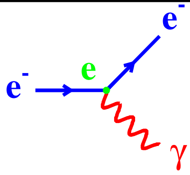
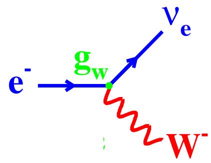
- The interactions of $W^{\pm}$ and Z^0 are different (related by symmetry of the weak interaction)

- $W^{\pm}$ and Z^0 can interact with each other
- $W^{\pm}$ and γ can interact (as $W^{\pm}$ bosons are charged)





Weak Vertices

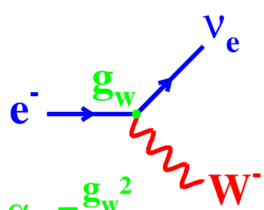
QED	W-boson
mediated by the exchange of virtual photons	mediated by the exchange of W boson
acts on all charged particles	acts on all quark and leptons
coupling strength $\propto e \propto \sqrt{\alpha}$	coupling strength $\propto g_W \propto \sqrt{\alpha_W}$
propagator term: $1/(q^2-m_\gamma^2) = 1/q^2$	propagator term: $1/(q^2-m_W^2)$
For many processes: $\mathcal{M} \propto e^2/q^2$	For many processes: $\mathcal{M} \propto g_W^2/(q^2-m_W^2)$
	

Recall: matrix element, $\mathcal{M}$, is the amplitude of a process.
Scattering cross section, $\sigma \propto \mathcal{M}^2$. Decay width, $\Gamma \propto \mathcal{M}^2$

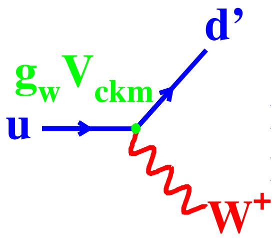
Interactions of the $W^{\pm}$ boson

- Known as "charged current interactions"
- $W^{\pm}$ boson interacts with **all** fermions (all quarks and leptons)
- Charged current **changes the flavour of the fermion**:
  - *e.g.* electron emitting an W-boson can't remain an electron - violates conservation of charge!
    - an electron turns into a electron neutrino
    - an up quark turns into a down quark

      and vice versa!
- Coupling strength at every vertex $\propto g_W$
- Propagator term describing the W-boson $\propto \dfrac{1}{(\underline{q}^2 - m_W^2)}$
  - $\underline{q}$ is the four-momentum transferred by the W-boson



$\alpha_w = \dfrac{g_w^2}{4\pi}$

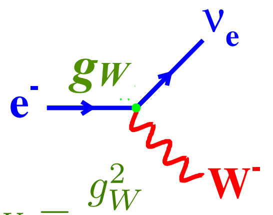


Allowed Flavour Changes

At a W-boson vertex:

- Lepton numbers: L_e, L_μ and L_τ, is conserved:

  Allowed lepton flavour changes: $e^- \leftrightarrow \nu_e \quad \mu^- \leftrightarrow \nu_\mu \quad \tau^- \leftrightarrow \nu_\tau$



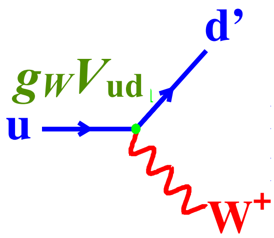
$$\alpha_W = \frac{g_W^2}{4\pi}$$

- Total Quark Number, N_q, is conserved
- Individual quark flavour numbers: $N_u, N_d, N_s, N_c, N_b, N_t$ are **not** conserved

  Allowed quark flavour changes:

  (Q=+2/3 *e* quark) ↔ (Q=−1/3 *e* quark)

  (d s b) ↔ (u c t)

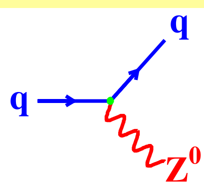


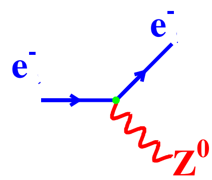
- Each of the nine possible quark flavour changes has a different coupling strength: e.g. $g_W V_{ud}$ for **u** to **d** quarks (Vs are terms in **CKM** matrix V_{CKM} - more next lecture)
- Main quark flavour changes are within a generation:

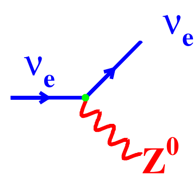
  d ↔ u   s ↔ c   b ↔ t

Interactions of the Z^0 boson

- Known as "neutral current interactions"
- Acts on **all** fermions - (all quarks and leptons)
- Neutral current **conserves** flavour of the fermion
- No allowed fermion flavour changes
- Propagator term $\propto \dfrac{1}{(q^2 - m_Z^2)}$
- Coupling strength depends on fermion flavour - we won't consider this in this course







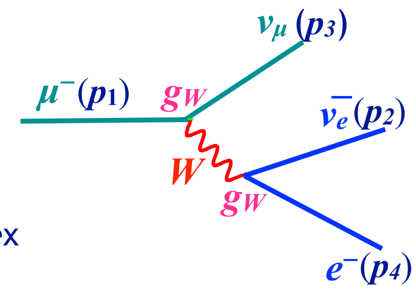
Anywhere a photon could be exchanged a Z^0 boson can be exchanged.
(Almost vice-versa, except Z^0 boson also has neutrino interactions too!)

Electromagnetic and weak neutral current interactions are linked!

Feynman Rules for Weak Interaction

How to calculate the matrix element, $\mathcal{M}$, for a weak decay or scattering

***e.g.* decay of a muon** $\mu^- \to e^- \nu_\mu \bar{\nu}_e$



- Draw the Feynman diagram for the process
  - give a four momentum for each particle
- Check quantum numbers conservation at every vertex
  - For both W and Z: L_e, L_μ and L_τ, N_q, Q
  - For Z only: no change of quark or lepton flavour
- Is energy and momentum conserved? For decay: $\sum m_{\text{initial}} > \sum m_{\text{final}}$
- Write down the **coupling at each vertex**: g_W (for W)
- Work out four-momentum transferred by boson: $\underline{q} = (\underline{p}_3 - \underline{p}_1) = (\underline{p}_4 + \underline{p}_2)$
- Write down the **propagator term** for each boson: $1/(\underline{q}^2 - m^2_{\text{boson}})$
- $\mathcal{M}$ is proportional to **product** of **vertex** and **propagator terms**: $\mathcal{M} \propto \dfrac{g_w^2}{(\underline{q}^2 - m_W^2)}$

Summary

The weak force acts on **all** quarks and leptons. Two **massive** bosons propagate the weak interaction: $W^\pm$ and Z^0.	Weak interactions are characterised by: • Long lifetimes 10^{-13} - 10^3 s • Small cross sections 10^{-13} mb
$W^\pm$**-boson** interactions **changes** fermion flavour $e^- \leftrightarrow \nu_e$ $\mu^- \leftrightarrow \nu_\mu$ $\tau^- \leftrightarrow \nu_\tau$ (Q=+2/3 e quark) $\leftrightarrow$ (Q=−1/3 e quark) • quark coupling at $W^\pm$ vertex: $g_W V_{\text{CKM}}$ • lepton coupling at $W^\pm$ vertex: g_W • $W^\pm$ propagator term: $\dfrac{1}{(\underline{q}^2 - m_W^2)}$	Z^0**-boson** interactions **conserve** the flavour of the fermion • Z^0-boson propagator term: $\dfrac{1}{(\underline{q}^2 - m_Z^2)}$ Z^0-boson interactions are **strongly** linked to the electromagnetic interaction