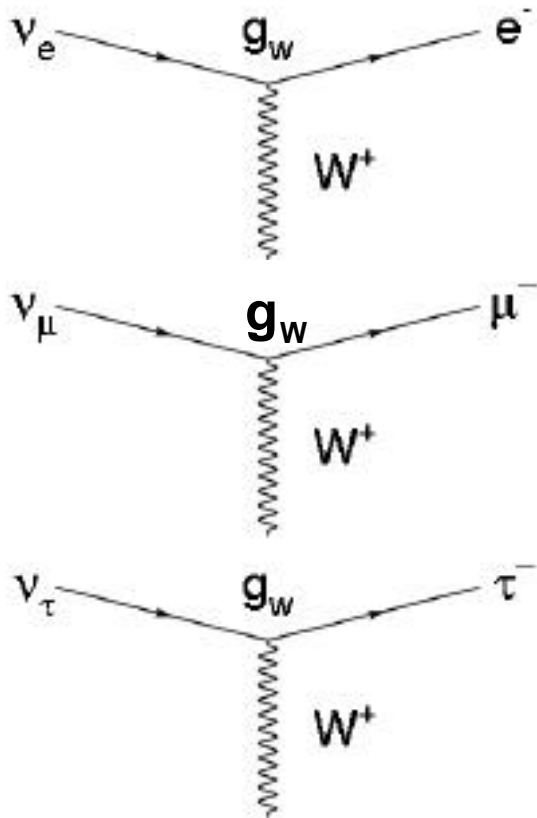


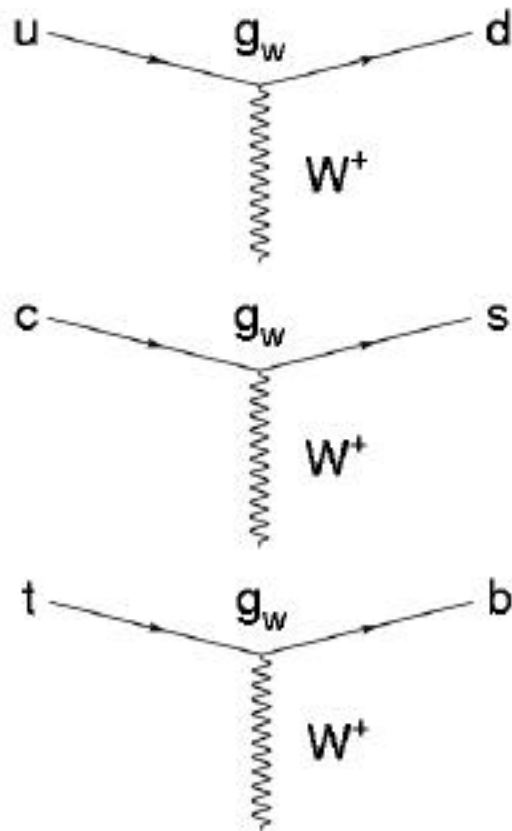
Leptonic Charged-Current Interactions



- The basic weak charged-current vertex couples a neutrino to its corresponding charged lepton.
- The coupling strength is the same in each case, g_w .
- Unlike the photon and the gluon, the W-boson has non-zero mass. In fact, the mass of the W-boson is large, about $80 \text{ GeV}/c^2$.
- Because the mass of the W-boson is large, the matrix elements have propagators proportional to

$$\frac{1}{q^2 - M_W^2}$$

Hadronic Charged-Current Interactions (the first approximation)

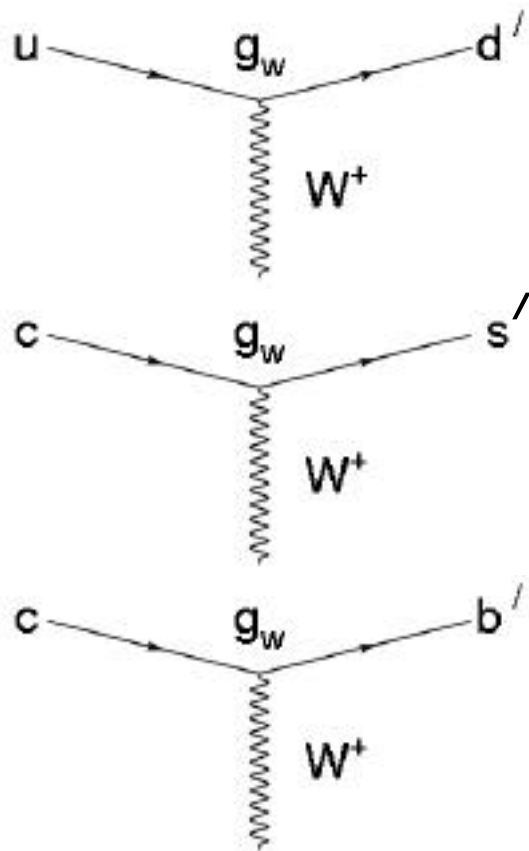


- As a first approximation, the weak charged current interactions of the quarks parallel those of the leptons.
- Charge $+2/3$ quarks couple to charge $-1/3$ quarks: up to down, charm to strange, and top to bottom, each with coupling strength g_w .
- The nature of the weak interaction is exactly the same as for the leptons, so the propagator remains proportional to

$$\frac{1}{q^2 - M_W^2}$$

More generally, the dynamics is the same.

Introducing the Cabibbo- Kobayashi- Maskawa (CKM) Mixing Matrix



- The weak charged-current interaction couples each up-type (charge $+2/3$) quark to a linear superposition of down-type (charge $-1/3$) quarks with coupling strength g_w .

- The coefficients are the Cabibbo-Kobayashi-Maskawa matrix elements:

$$\begin{array}{l}
 d \\
 s \\
 b
 \end{array}
 =
 \begin{array}{ccc}
 V_{ud} & V_{us} & V_{ub} \\
 V_{cd} & V_{cs} & V_{cb} \\
 V_{td} & V_{ts} & V_{tb}
 \end{array}
 \begin{array}{l}
 d \\
 s \\
 b
 \end{array}$$

- This matrix V_{ij} is unitary.
- The matrix elements are complex numbers and the matrix is approximately diagonal.

An Example of a CKM Superposition

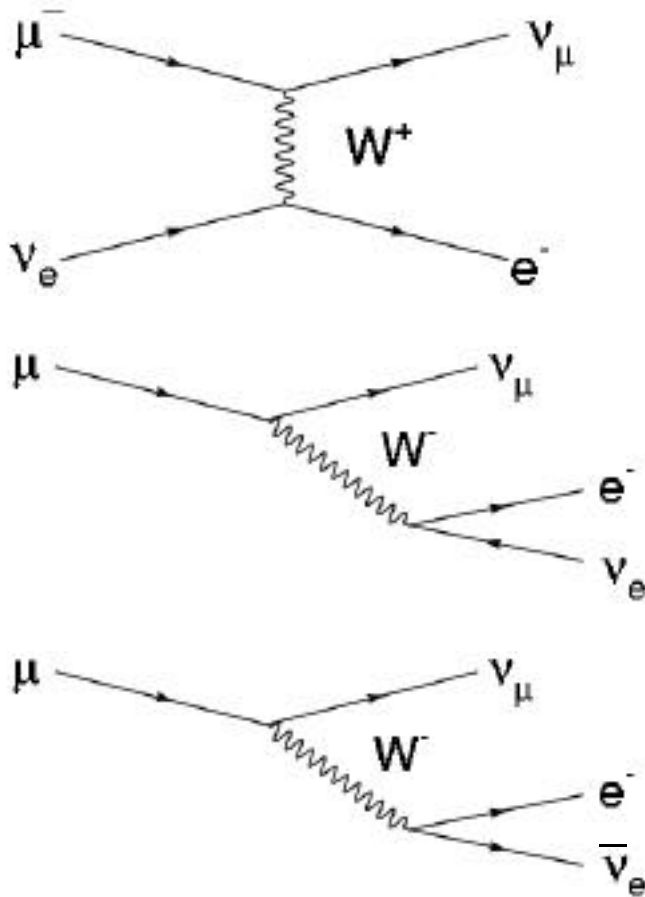
The diagram illustrates the CKM superposition for a charm quark transition. It shows four Feynman diagrams arranged in a sum:

- Top-left: A charm quark (c) transitions to a strange quark (s') via a W^+ boson. The vertex is labeled g_w .
- Top-right: A charm quark (c) transitions to a down quark (d) via a W^+ boson. The vertex is labeled g_w .
- Bottom-left: A charm quark (c) transitions to a strange quark (s) via a W^+ boson. The vertex is labeled g_w .
- Bottom-right: A charm quark (c) transitions to a bottom quark (b) via a W^+ boson. The vertex is labeled g_w .

The diagrams are summed as follows:

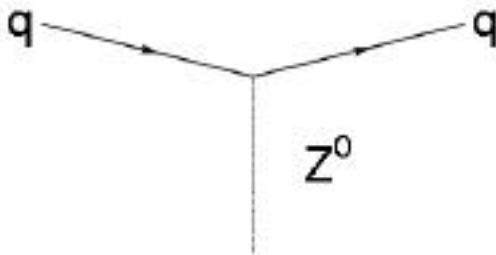
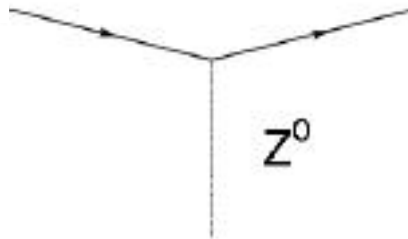
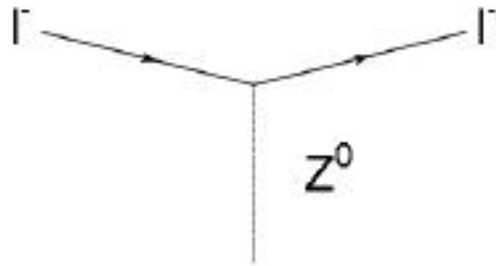
$$c \rightarrow s' \text{ via } W^+ = V_{cd} \times c \rightarrow d \text{ via } W^+ + V_{cs} \times c \rightarrow s \text{ via } W^+ + V_{cb} \times c \rightarrow b \text{ via } W^+$$

Muon Decay



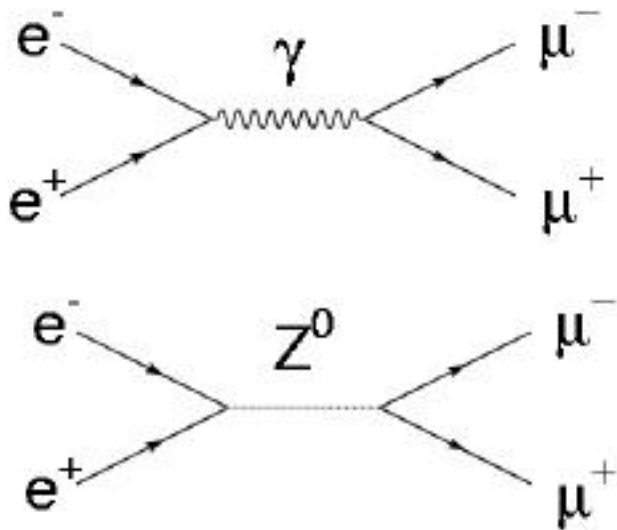
- These three Feynman diagrams have precisely the same structure.
- The first represents the charged-current scattering of muons by electron neutrinos (unlikely to occur in the current universe, but not uncommon in the very early universe).
- The second two represent muon decay into a muon neutrino, an electron, and an electron anti-neutrino (shown as an electron neutrino travelling backward in time in the middle diagram and as an electron anti-neutrino travelling forward in time in the bottom diagram).

Weak Neutral-Current Interactions



- In addition to the weak charged-current interaction, there is a weak neutral-current interaction mediated by the Z -boson whose mass is about $90 \text{ GeV}/c^2$.
- The weak neutral-current interaction conserves flavor; it does not change up into charm or strange; it does not change down into strange or bottom; etc.
- The weak neutral-current interaction is intimately related to both the weak charged-current interaction and to the electromagnetic interaction. The unified description of these interactions is known as the **electro-weak interaction**.

Electro-weak Interference



- The two amplitudes represented by these Feynman diagrams share initial and final states. Therefore, the amplitudes one calculates for these diagrams, following the Feynman rules, must be added together to determine the total transition rate.
- The propagator for photon exchange is proportional to

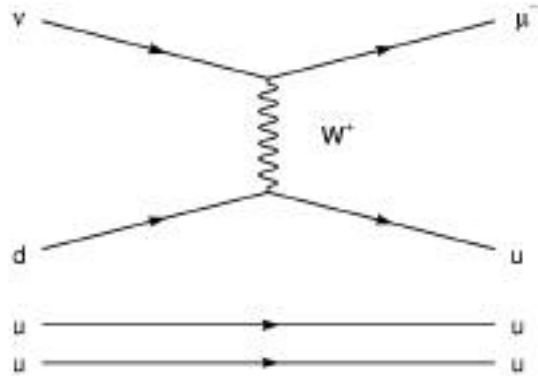
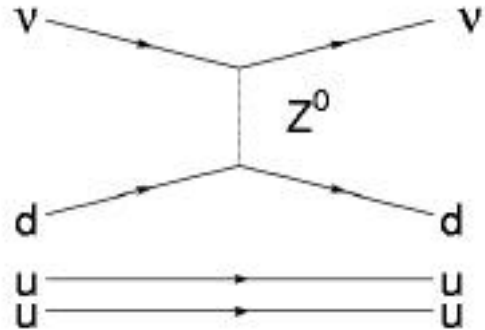
$$\frac{1}{q^2}$$

while that for Z exchange is proportional to

$$\frac{1}{q^2 - M_Z^2}$$

At low q^2 photon exchange is dominant; near $q^2=M_Z^2$, Z-boson exchange is dominant.

Neutral-Current Deep Inelastic Scattering



- The Feynman diagram for neutral-current deep inelastic scattering looks almost the same as that for charged-current deep inelastic scattering.
- The effective coupling strength (coupling strength at the vertex times the propagator) is somewhat less.
- The process by which final state quarks turn into collections of hadrons is the the same.

Confinement in QCD

- $\alpha_s(Q^2)$ increases at small Q^2 confinement.
- As an example, $q\bar{q} = u\bar{d}$ is a color-singlet, $c\bar{c}$.
- Less obviously, $qqq = uud$ is also a color-singlet, **rgb**.

