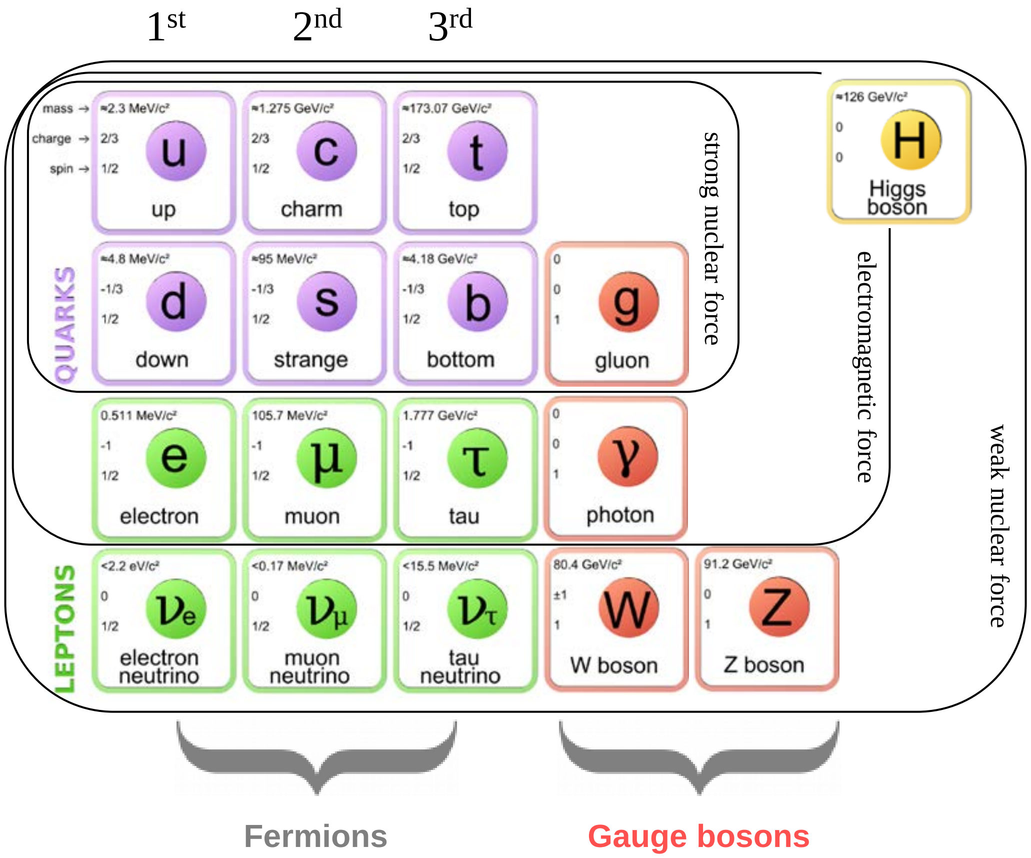
The Standard Model

- ❖ Describes 3 of the 4 known fundamental forces.
  Separates particle into categories

- ❖ ***Bosons*** (force carriers)
- Photon, W, Z, gluon, Higgs

- ❖ ***Fermions*** (matter particles)
- 3 generations
- Quarks (up and down type)
- Leptons (charged and uncharged)



Leptons

Charged leptons
Electrically charged (-1e)

Electron (e)
Mass = 511 keV/c^2
Stable

Muon (μ)
Mass = 105.7 MeV/c^2
Lifetime = 2.2 μs

Tau (τ)
Mass = 1.777 GeV/c^2
Lifetime = 0.29 ps

Uncharged leptons

Electron neutrino (ν_e)
Muon neutrino (ν_μ)
Tau neutrino (ν_τ)

In the SM:

- neutrinos are massless
- neutrinos are stable

experimentally this is wrong

Empirical properties:

The total number of leptons is conserved
I = #leptons - #antileptons

The total number of each generation of leptons is conserved

$I_e = \#e^- + \#\nu_e - \#e^+ - \#\overline{\nu}_e$
$I_\mu = \#\mu^- + \#\nu_\mu - \#\mu^+ - \#\overline{\nu_\mu}$
$I_\tau = \#\tau^- + \#\nu_\tau - \#\tau^+ - \#\overline{\nu}_\tau$

Quarks

Each quark carries a color charge, like electric charge (+, -), but three types

Red, anti-red

Green, anti-green

Blue, anti-blue

Up type

Electric charge +2/3

Up (u)

Mass = 2.3 MeV/c^2

Charm (c)

Mass = 1.27 GeV/c^2

Top (t)

Mass = 173.1 GeV/c^2

Down type

Electrical charge -1/3

Down (d)

Mass = 4.8 MeV/c^2

Strange (s)

Mass = 95 MeV/c^2

Bottom (b)

Mass = 4.2 GeV/c^2

Empirical properties:

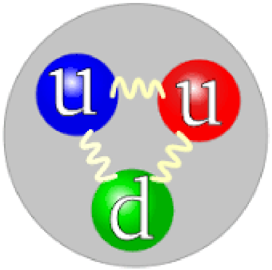
- No bare color charge has ever been observed
- Quarks (and gluons) are contained in composite objects that are color neutral called **Hadrons**
- ***Mesons***: 1 quark + 1 anti-quark
- ***Baryons***: 3 quarks

Bound States: Baryons

Baryons are color neutral objects with 3 quarks
(anti-baryons have 3 anti-quarks)

Electric charge can be -1, 0, 1, 2

Examples: proton (uud), neutron (udd), Σ^- (dds) Σ_c^{++} (uuc)

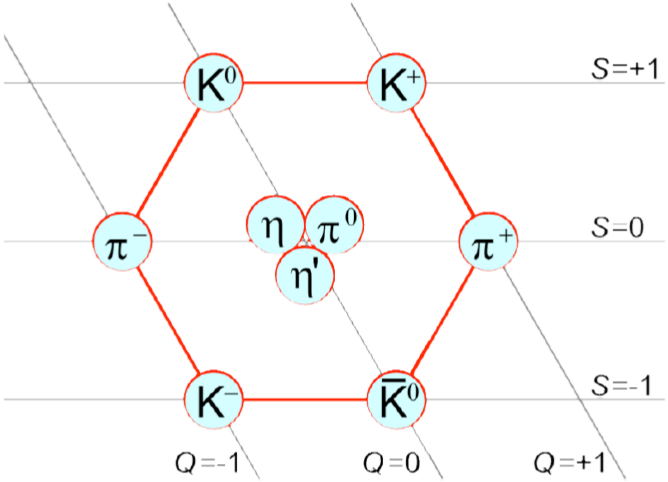


Only the lightest baryon (proton) is stable
Free neutrons, for example, decay to protons.
The total number of baryons is conserved!

$$B = \frac{1}{3}(n_q - n_{\bar{q}})$$

This poses constraints on possible decays

Bound States: Mesons



Mesons are composed of one quark and one anti-quark.

The quark/anti-quark pair contain the same color/anti-color (e.g. red – anti-red) → color neutral.

No conservation law for mesons → all mesons decay

Hadrons (both mesons and baryons) are found in patters, derivable from group theory.

This was used to predict many, many bound states of quarks, what we call the particle zoo.

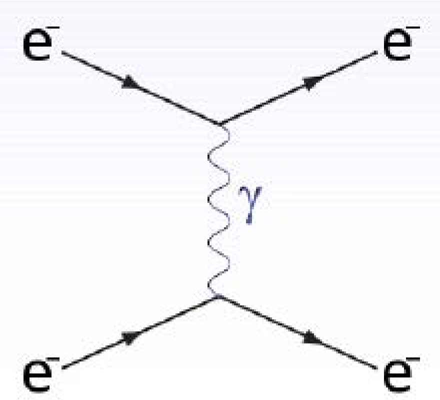
The Photon

- Massless boson (γ)
- Transmits electromagnetic force
- Couples to electric charge but **does not carry** charge
- Spin 1 particle
  - Naively, there should be 3 spin projection states $m_z = -1, 0, 1$
  - It turns out, $m_z = 0$ is not allowed because of special relativity (transverse nature of E&M waves)
  - 2 spin states → 2 polarizations

- Long range force:

Because the photon is massless, it can propagate indefinitely.

Two charged particles can communicate from across the universe



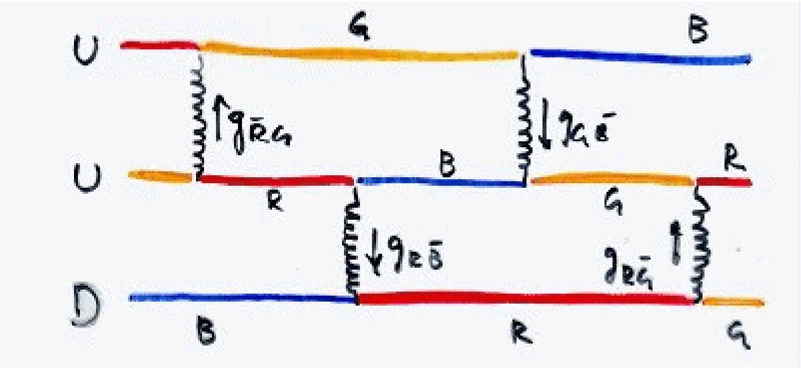
Coupling strength (or strength of force) is electric charge

$$\alpha = \frac{e^2}{4\pi\varepsilon_0\hbar c} \approx \frac{1}{137}$$

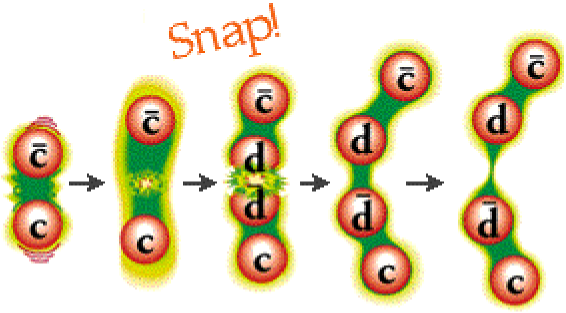
EM interaction always possible between charged particles, never for neutral particles

Gluons

- The ***gluon (g)*** transmit the strong interaction
- The spin is 1, but only two polarization states (like the photon)
- Unlike the photon, the gluon carries color charge
- Quarks carry color, antiquarks carry anti-color
- Gluons carry both color and anti-color
- 8 color – anti-color states

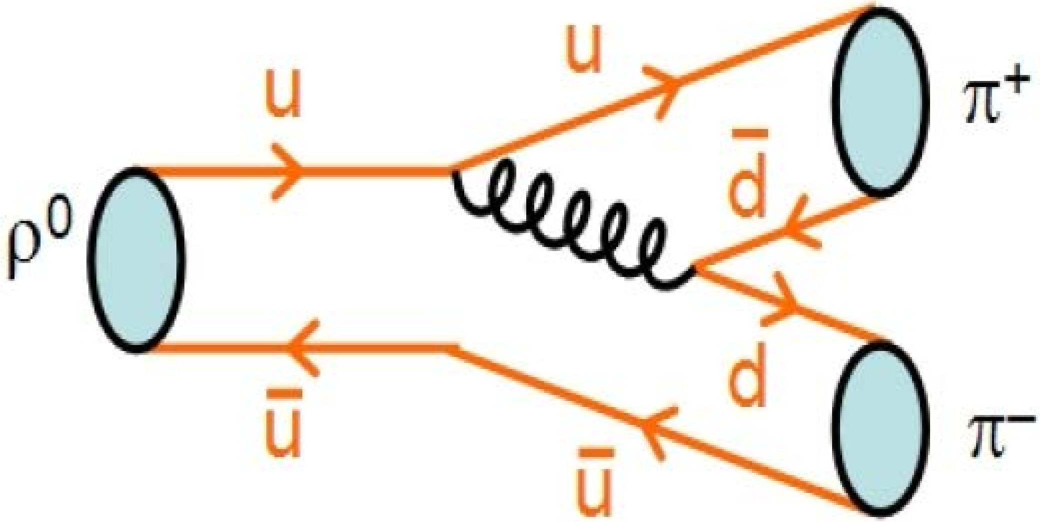


The strong interaction gets stronger as the range increases. If you try to pull a quark free, more energy is pumped into gluons. New quark – anti-quark pair is produced.

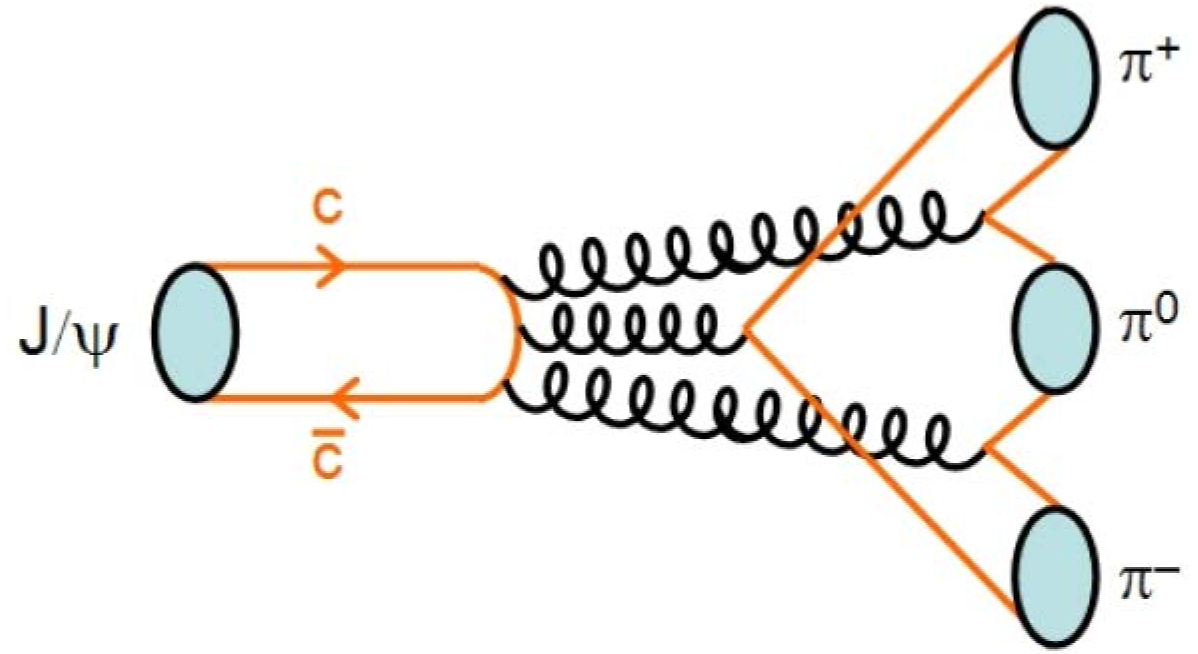


- The timescale for the strong interaction is very short ~ 10^{-22} s
- Thus, lifetimes of strongly interacting particles are short
- However, the strong interaction preserves quark generations!
- Example: # of t + b quarks is unchanged in strong interactions
- We need the weak interaction to break this rule

Example: Rho decay

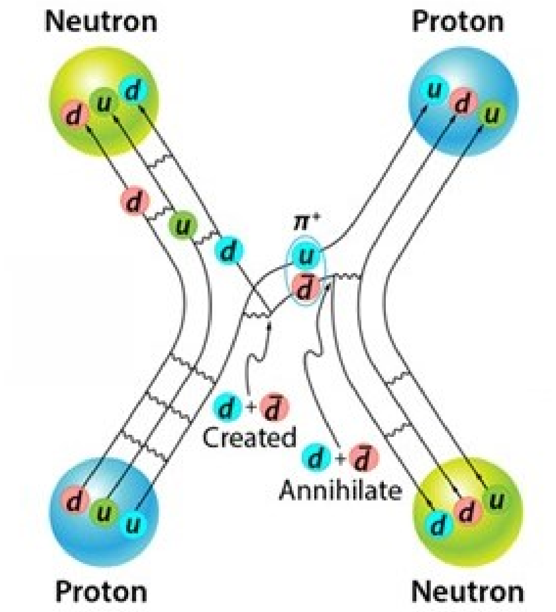


Example: J/Ψ decay



Note this is a higher order diagram, one closed loop

Example: Pion exchange



- The force that holds the nucleus together is a special case of strong interactions
- Protons and neutrons interact by exchanging π mesons (pions)

Weak Interaction

- The ***W*** and ***Z bosons*** that transmit the weak interaction need careful discussion
- They are **massive** $m_W = 80.4\ \mathrm{GeV}/c^2$ $m_Z = 91.2\ \mathrm{GeV}/c^2$
- Spin 1 particles, but also each with only 2 spin projection states (same as photon)
- Slower interaction than Strong $10^{-8} – 10^{-13}$ s

Two important features of the weak interaction:

- *The **W** carries electric charge*
  - W^+, W^-
  - W interactions change particle type
  - Underlying processes like radioactive decay
  - Only the W changes quark/lepton flavor
- *The **Z** is electrically neutral*
  - Coupling/timescale the same as W

Massive bosons = short range force

- These heavy bosons are not long lived
- They do not propagate freely
- Interactions can only happen over a distance ~ 10^{-16} m or less
- This makes the force effectively very weak

Why is the Weak Force weak?

In E&M, the photon didn’t require any mass energy.
But in weak interactions, the W and Z bosons do require mass energy

How does that happen for low energy particles?

The uncertainty principle!

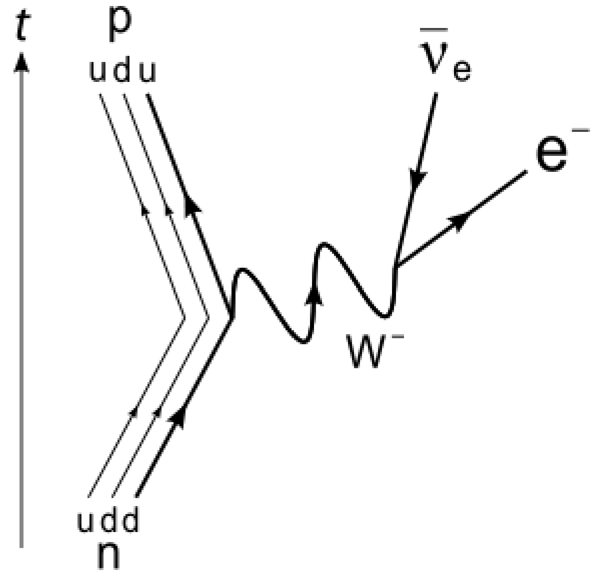
$$\Delta E \cdot \Delta t \geq \hbar/2$$

I can borrow an elephant if I give it back on time

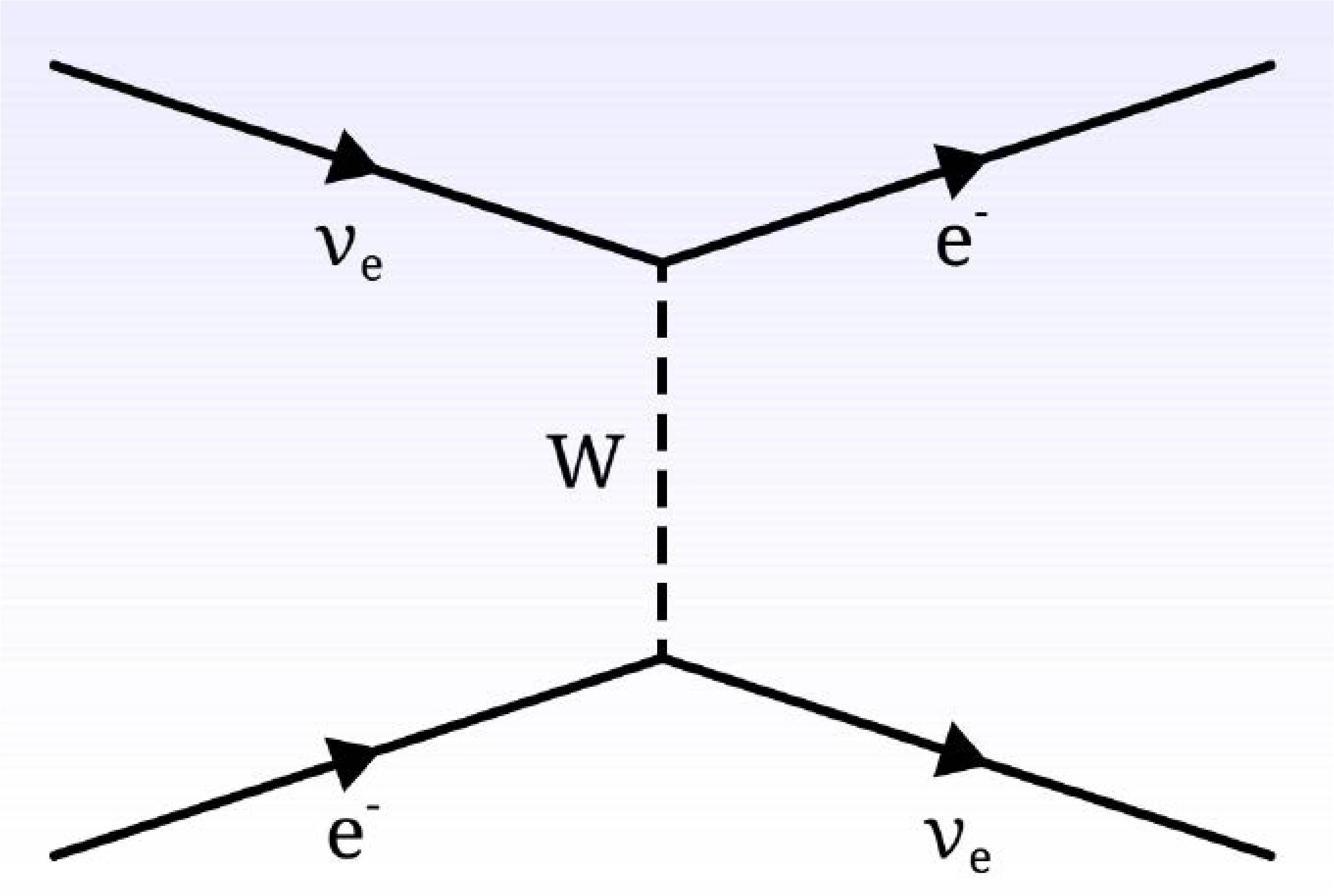
If two particles are close enough, they can “borrow” energy to create a Z or W boson just long enough to transmit the force

Example: Beta Decay

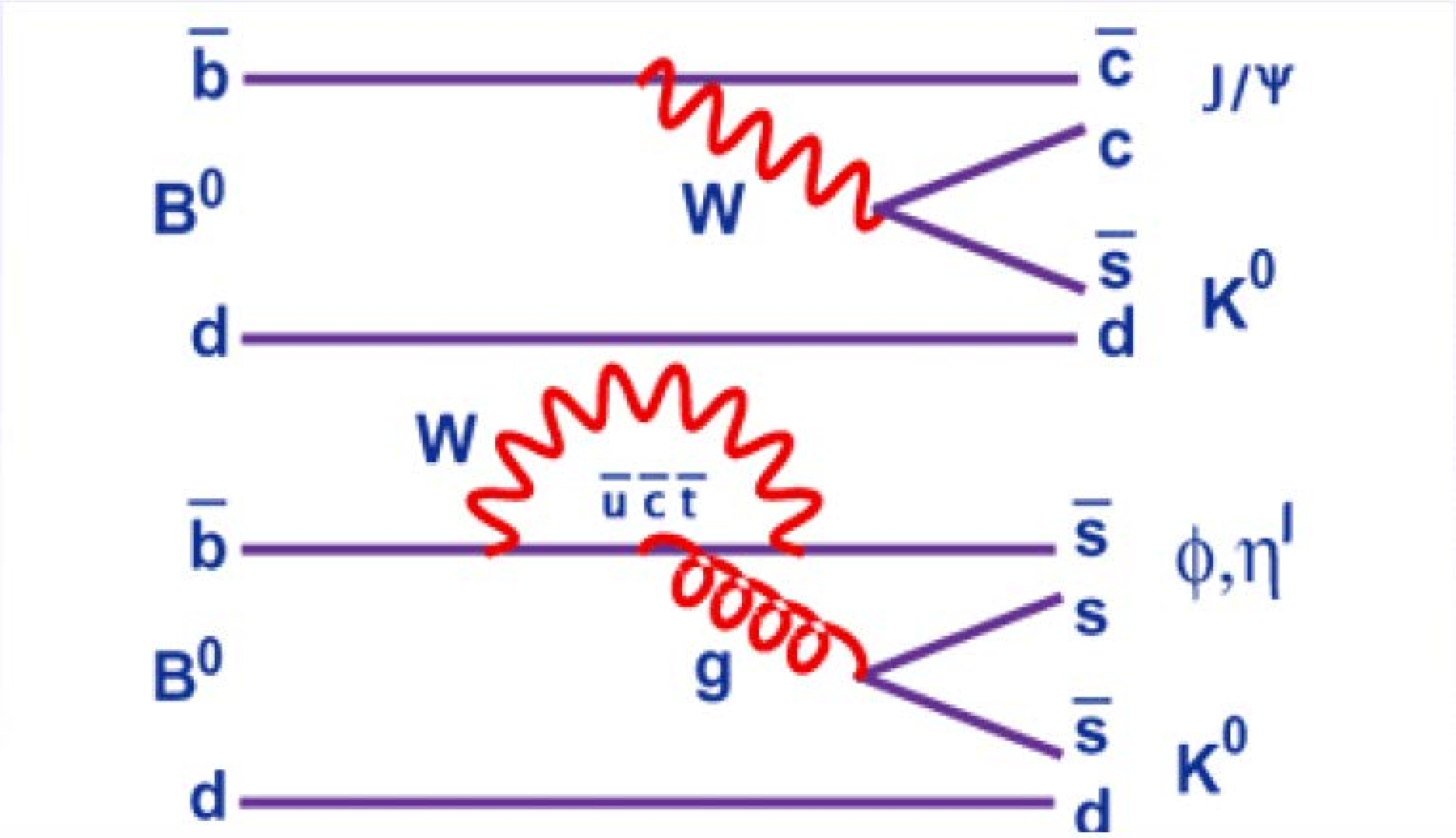
A neutron (udd) changes to a proton (uud) by emitting a W- boson, which decays into an electron and an anti-neutrino



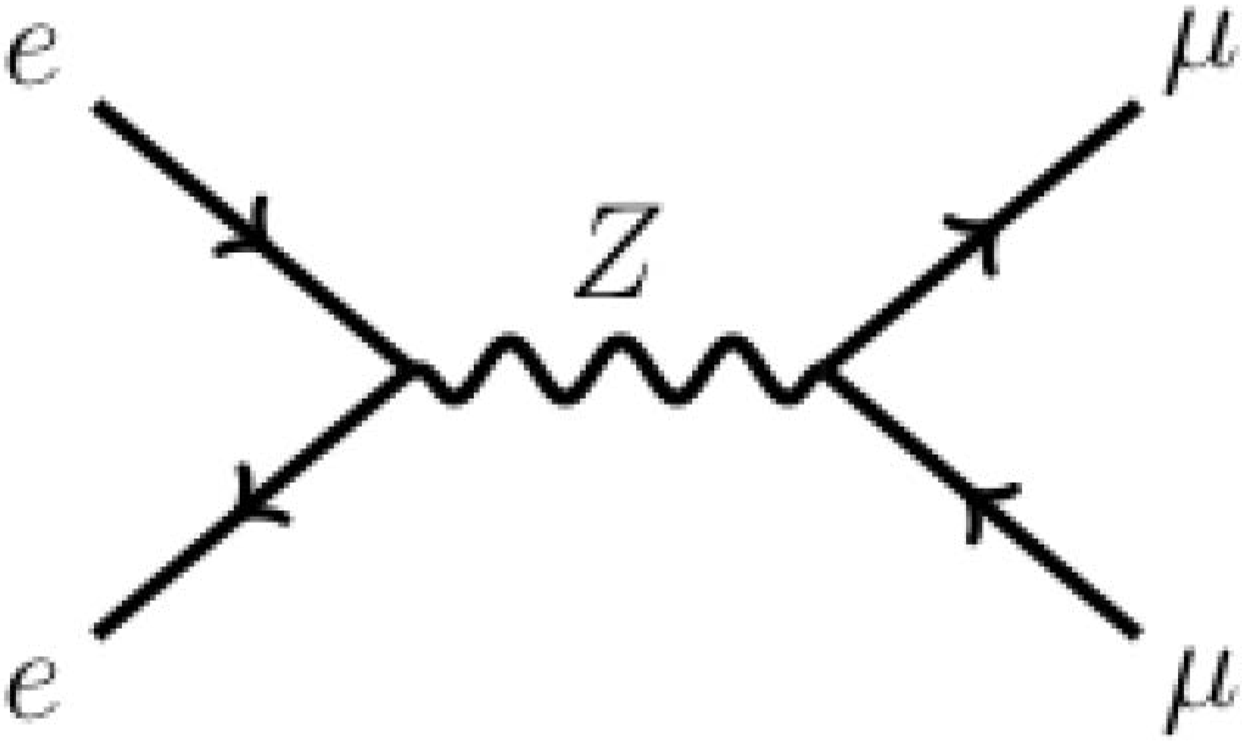
Example: Neutrino – Electron Scattering



Example: B-Meson Decay



Example: Electron – Positron Scattering



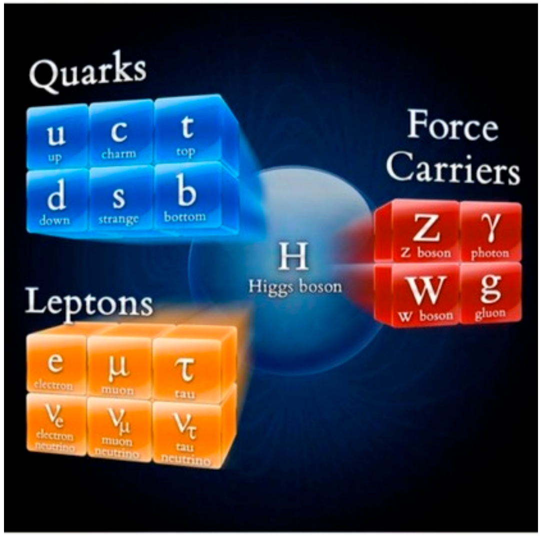
Summary

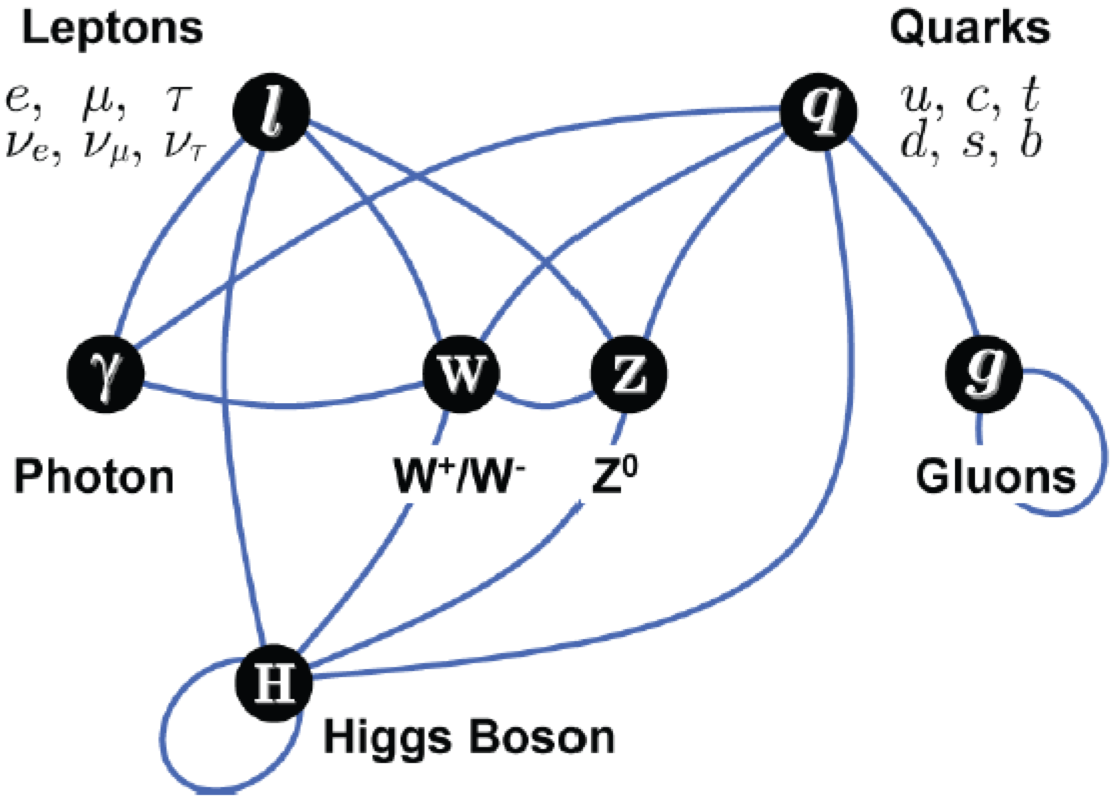
The three forces described by the standard model:

- Include all the known fundamental fermions
- Leptons
- Quarks
- Interactions governed by boson exchange
  - Photons
    - Long range, coupled to electric charge
  - Gluons
    - Couple to and carry color charge
    - Force gets stronger as quarks are pulled apart
    - Only color neutral composite objects
  - W/Z
    - W is electrically charged
- Charge flavor (quark and lepton generations)

- The Higgs boson
  - Related to unification of the electromagnetic and weak interactions
  - Responsible for particle masses

The Standard Model of Elementary Particles





Open Questions

- Why are the masses of the particles what they are?
- Why are there 3 generations of fermions?
- Are quarks and leptons truly fundamental?
- Why is the charge of the electron *exactly* opposite to that of the proton.
  Or: why is the total charge of leptons and quarks exactly equal to 0?
- Is a neutrino its own anti-particle?
- Can all forces be described in a single theory (unification)?
- Why is there no anti-matter in the universe?
- What is the source of dark matter?
- What is the source of dark energy?