Elementary particles, forces and Feynman diagrams
### Particles & Forces

<table>
<thead>
<tr>
<th></th>
<th>quarks</th>
<th>Charged leptons ((e, \mu, \tau))</th>
<th>Neutral leptons ((\nu))</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Strong</strong></td>
<td>Y</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td><strong>Electro-Magnetic</strong></td>
<td>Y</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td><strong>Weak</strong></td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
</tbody>
</table>

Quarks carry strong, weak & EM charge !!!!!!
The electromagnetic force
The Photon ($\gamma$)

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>0</td>
</tr>
<tr>
<td>Charge</td>
<td>0</td>
</tr>
</tbody>
</table>

- The photon is the “mediator” of the electromagnetic interaction
- The photon can only interact with objects which have electric charge
Feynman Diagrams (Electron Scattering)

Electron-Positron Annihilation

Compton Scattering

Position

time
Photon Conversion and Emission

Photon Conversion

Photon Emission
More Feynman Diagrams

- **Quark Pair Production**

  - "q" can be **any quark**, as long as there is enough energy to create 2 of 'em!

- **Quark Antiquark Annihilation**
Summary of EM Interactions

1. The **Photon** is the *mediator* of the **EM Interaction**.
   - This means that EM interactions occur via photons.

2. The **photon** is **massless** and has no **electrical charge**.

3. Photon can **convert** into pairs of **oppositely-charged, like-type leptons or quarks**.
   \[ \gamma \rightarrow e^+e^-, \mu^+\mu^-, \tau^+\tau^- \]
   \[ \gamma \rightarrow uu, dd, ss, cc, bb, tt \]

4. Feynman diagrams are a pictorial method for expressing a type of interaction.
The weak force
The weak force

- Like the Electromagnetic & Strong forces, the Weak force is also mediated by “force carriers”.
- For the weak force, there are actually 3 force carriers:

\[ W^+, \ W^-, \ Z^0 \]

These “weak force” carriers carry electric charge also!
This “weak force” carrier is electrically neutral

The “charge” of the weak interaction is called “weak charge”
The weak force

Both quarks & leptons carry weak charge

- Both quarks & leptons “couple to” the W and Z force carriers
- Since the W’s have a charge of +1 and –1 they cause a “charge-changing” interaction. That is when they are emitted or absorbed, to conserve charge, the “emitting” or “absorbing” particle changes charge by +1 or –1 unit.
- The emitting or absorbing particle changes into a different particle. Alternately, when the W decays, it decays into 2 particles which:
  • Carry weak charge
  • The sum of their charges equals the charge of the W
- I will mainly talk about the W in the context of decays…
Feynman diagram for weak decay

\[ d \rightarrow u + e^- + \bar{\nu}_e \]

Spectator quark(s): Those quarks which do not directly participate in the interaction or decay.
Since the spectator quarks do not directly participate in the decay, we can just omit them…
This yields the “quark-level” Feynman diagram!

Is charge conserved?

Is \( L_e \) conserved?
Decays of “heavy” quarks

The heavy quarks decay to the lighter ones by “cascading down”

- $t$: $Q=+2/3$
- $b$: $Q=-1/3$
- $c$: $Q=+2/3$ (cascades to $s$)
- $s$: $Q=-1/3$ (cascades to $u$)
- $u$: $Q=+2/3$ (cascades to $d$)
- $d$: $Q=-1/3$

The quark charges are indicated as follows:

- $t$: Top quark, $Q=+2/3$
- $b$: Bottom quark, $Q=-1/3$
- $c$: Charm quark, $Q=+2/3$ (decays to $s$ with $Q=-1/3$)
- $s$: Strange quark, $Q=-1/3$ (decays to $u$ with $Q=+2/3$)
- $u$: Up quark, $Q=+2/3$ (decays to $d$ with $Q=-1/3$)
- $d$: Down quark, $Q=-1/3$
What about the decay of a b-quark?

\[ b \rightarrow c + \mu^- + \bar{\nu}_\mu \]

Is charge conserved?

Notice: Here, the \( W^- \) decays to a \( \mu^- \) and \( \nu_\mu \)

Is \( L_\mu \) conserved?
What about the decay of a $c$-quark?

$c \rightarrow s + \mu^+ + \nu_\mu$

Is charge conserved?

Notice: Here, I have the $W^+$ decaying to a $\mu^+$ and $\nu_\mu$ (could have been an $e^+$ and $\nu_e$ as well).

Is $L_\mu$ conserved?
What about the decay of a b-quark?

\[ s \to u + e^- + \bar{\nu}_e \]

Is charge conserved?

Is \( L_e \) conserved?
Decays of heavy quarks to u & d

- A quark can only decay to a lighter quark.
- The W charge has the same sign as the parent quark.

- $t \rightarrow b \ W^+ (100\%)$
- $b \rightarrow c \ W^- (\sim 90\%)$
- $b \rightarrow u \ W^- (\sim 10\%)$
- $c \rightarrow s \ W^+ (\sim 95\%)$
- $c \rightarrow d \ W^+ (\sim 5\%)$
- $s \rightarrow u \ W^- (\sim 100\%)$
- $d \rightarrow u \ W^+ (\sim 100\%)$

**Quark Charge**

<table>
<thead>
<tr>
<th>Quark</th>
<th>Charge</th>
<th>Mass [GeV/c²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>top</td>
<td>$+2/3$</td>
<td>$\sim 175$</td>
</tr>
<tr>
<td>bottom</td>
<td>$-1/3$</td>
<td>$\sim 4.5$</td>
</tr>
<tr>
<td>charm</td>
<td>$+2/3$</td>
<td>$\sim 1.5$</td>
</tr>
<tr>
<td>strange</td>
<td>$-1/3$</td>
<td>$\sim 0.2$</td>
</tr>
<tr>
<td>up</td>
<td>$+2/3$</td>
<td>$\sim 0.005$</td>
</tr>
<tr>
<td>down</td>
<td>$-1/3$</td>
<td>$\sim 0.010$</td>
</tr>
</tbody>
</table>
“Leptonic” Decay of W

Once the W is produced, it must decay

<table>
<thead>
<tr>
<th>W⁻ → e⁻ (\bar{\nu}_e)</th>
<th>W⁺ → e⁺ (\nu_e)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W⁻ → (\mu^- \bar{\nu}_\mu)</td>
<td>W⁺ → (\mu^+ \nu_\mu)</td>
</tr>
<tr>
<td>W⁻ → τ⁻ (\bar{\nu}_\tau)</td>
<td>W⁺ → τ⁺ (\nu_\tau)</td>
</tr>
</tbody>
</table>

It’s call “leptonic decay” because the W is decaying to leptons!

The W **can** decay to leptons because leptons **carry weak charge**

But so do quarks …
“Hadronic” Decay of W

Since quarks also carry weak charge, we can also get:

\[ W^- \rightarrow \bar{u} \, d \quad \text{W}^+ \rightarrow u \, \bar{d} \]

It’s call “hadronic decay” because the \[ W \text{ is decaying to quarks, which will will form hadrons!} \]

Check charge:
\[ (-2/3 + -1/3 = -1) \]

But quarks are bound to one another by the strong force, and are not observed as “free” particle. That is, they are bound up inside hadrons…

What happens next?
One possibility…

Can, in fact, form a $\pi^-$

$B^- \rightarrow D^0 \pi^-$
W Decays

W → e⁻ \bar{\nu}_e

W → \mu⁻ \bar{\nu}_\mu

W → \tau⁻ \bar{\nu}_\tau

W → hadrons

W⁺ follows in an analogous way... see previous slides
There are LOTS of ways the $B^+$ can decay (here’s a small fraction of em)!

Semileptonic and leptonic modes

- $\ell^+ \nu_\ell$ anything
- $D^0 \ell^+ \nu_\ell$
- $D^*(2007)^0 \ell^+ \nu_\ell$
- $D_1(2420)^0 \ell^+ \nu_\ell$
- $D_s^*(2460)^0 \ell^+ \nu_\ell$
- $\pi^0 e^+ \nu_e$
- $\omega \ell^+ \nu_\ell$
- $\omega \mu^+ \nu_\mu$
- $\mu^0 \ell^+ \nu_\ell$
- $e^+ \nu_e$
- $\mu^+ \nu_\mu$
- $\gamma^+ \nu_\gamma$
- $\mu^+ \nu_\mu \gamma$

$[a] \ (10.2 \pm 0.9) \%$

$[a] \ (2.15 \pm 0.22) \%$

$[a] \ (5.3 \pm 0.8) \%$

$[a] \ (< 8 \times 10^{-3})$

$[a] \ (< 5.6 \pm 1.5 \times 10^{-3})$

$[a] \ (< 9.0 \pm 2.8 \times 10^{-5})$

$[a] \ (< 2.1 \times 10^{-4})$

$[a] \ (1.34^{+0.32}_{-0.35} \times 10^{-4})$

$[a] \ (< 1.5 \times 10^{-5})$

$[a] \ (< 2.1 \times 10^{-5})$

$[a] \ (< 5.7 \times 10^{-4})$

$[a] \ (< 2.0 \times 10^{-4})$

$[a] \ (< 5.2 \times 10^{-5})$

$D$, $D^*$, or $D_s$ modes

- $D^0 \pi^+$
- $D^0 \rho^+$
- $D^0 K^+$
- $D^{0+} \pi^+ \pi^+ \pi^-$ nonresonant
- $D^{0+} \pi^+ \pi^0$
- $D^0 a_1(1260)^+$
- $D^*(2010)^+ \pi^+ \pi^+$
- $D^{*-} \pi^+ \pi^+$
- $D^{*}(2007)^0 \pi^+$
- $D^*(2010)^+ \pi^0$

$[a] \ (5.3 \pm 0.5) \times 10^{-3}$

$[a] \ (1.34 \pm 0.18) \%$

$[a] \ (2.9 \pm 0.8) \times 10^{-4}$

$[a] \ (1.1 \pm 0.4) \%$

$[a] \ (5 \pm 4) \times 10^{-3}$

$[a] \ (4.2 \pm 3.0) \times 10^{-3}$

$[a] \ (5 \pm 4) \times 10^{-3}$

$[a] \ (2.1 \pm 0.5) \times 10^{-3}$

$[a] \ (< 1.4 \times 10^{-3})$

$[a] \ (< 4.6 \pm 0.4 \times 10^{-3})$

$[a] \ (< 1.7 \times 10^{-4})$

Observed decays where the $W$ decays to a lepton and neutrino

Observed decays where the $W$ decays to quarks $\rightarrow$ hadrons
Interactions involving $W$’s

Here is one… Don’t worry about these types of interactions…

I want to emphasize the role of $W$’s in decays of quarks

$$e^+ + e^- \rightarrow v_e + \overline{v}_e$$

Check lepton number, charge conservation…
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 GeV/c².

- 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.
The strong force
What does it really mean for a particle to have electric charge?

It means the particle has an attribute which allows it to talk to (or ‘couple to’) the photon, the mediator of the electromagnetic interaction.

The ‘strength’ of the interaction depends on the amount of charge.

Which of these might you expect experiences a larger electrical repulsion?

- Electric charge $u = +2/3$ e
- Electric charge $e = -1$ e

Diagram:
- $u$ and $e$ interact with each other.
We hypothesize that in addition to the attribute of ‘electric charge’, quarks have another attribute known as ‘color charge’, or just ‘color’ for short. The attribute’s name, color, is just by convention. It’s easy to visualize this attribute and how colors combine…(coming up)

The property of color allows quarks to talk to the mediator of the strong interaction, the **gluon** (g).

Unlike electric charge, we find (experimentally) that there are 3 values for color:

We assign these possible values of color to be: **red, green, blue**

Also, unlike Electromagnetism, we find that the carrier of the strong force carries ‘color charge’. Recall the photon is electrically neutral!
## Comparison
Strong and EM force

<table>
<thead>
<tr>
<th>Property</th>
<th>EM</th>
<th>Strong</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force Carrier</td>
<td>Photon (γ)</td>
<td>Gluon (g)</td>
</tr>
<tr>
<td>Mass</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Charge ?</td>
<td>None</td>
<td>Yes, color charge</td>
</tr>
<tr>
<td>Charge types</td>
<td>+, -</td>
<td>red, green, blue</td>
</tr>
<tr>
<td>Mediates interaction between:</td>
<td>All objects with electrical charge</td>
<td>All objects with color charge</td>
</tr>
<tr>
<td>Range</td>
<td>Infinite (∼ 1/d²)</td>
<td>∼10⁻¹⁴ [m] (inside hadrons)</td>
</tr>
</tbody>
</table>
Color of Hadrons

BARYONS

RED + BLUE + GREEN = “WHITE”
or “COLORLESS”

MESONS

GREEN + ANTIGREEN = “COLORLESS”
RED + ANTIREDD = “COLORLESS”
BLUE + ANTIBLUE = “COLORLESS”

A meson can be any one of these combinations!

Hadrons observed in nature are colorless
(but there constituents are not)
Color Exchange

- Quarks interact by the exchange of a gluon.
- Since gluons carry color charge, it is fair to say that the interaction between quarks results in the exchange of color (or color charge, if you prefer)!
Gluons – Important Points

- **Gluons** are the “force carrier” of the strong force.

- They **only interact** with objects which have color, or color charge.

- Therefore, **gluons cannot interact with leptons** because leptons do not have color charge!

This cannot happen, because the gluon does not interact with objects unless they have color charge!

Leptons do not have color charge!
As before, we can draw *Feynman diagrams* to represent the strong interactions between quarks.

The method is more or less analogous to the case of EM interactions.

When drawing Feynman diagrams, we *don’t show the flow of color charge* (oh goody). It’s understood to be occurring though.

Let’s look at a few Feynman diagrams...
Feynman Diagrams (Quark Scattering)

Quark-antiquark Annihilation

Quark-quark Scattering
Could also be Quark-antiquark Scattering
or Antiquark-antiquark Scattering
Flashback to EM Interactions

Recall that photons do not interact with each other.

Why?

Because photons only interact with objects which have electric charge, and photons do not have electric charge!

This can’t happen because the photon only interacts with electrically charged objects!
BUT GLUONS HAVE COLOR CHARGE !!!

Gluons carry the “charge” of the strong force, which is “color charge”, or just “color”!
Ok, so here’s where it gets hairy!

Since gluons carry “color charge”, they can interact with each other! (Photons can’t do that)

Gluon-gluon Scattering

Gluon-gluon Fusion
And quark-gluon interactions as well!

Since both quarks and gluons have color, they can interact with each other !!!
The property which gives rise to the strong force is "color charge".

There are 3 types of colors, RED, GREEN and BLUE.

Quarks have color charge, and interact via the mediator of the strong force, the gluon.

The gluon is massless like the photon, but differs dramatically in that:
- It has color charge
- It’s force acts over a very short range (inside the nucleus)
Because **gluons carry color charge**, they can **interact among themselves**.

**Quarks and gluons are confined inside hadrons** because of the nature of the strong force.

Only ~**50% of a proton’s energy is carried by the quarks**. The remaining **50% is carried by gluons**.

We learn about the strong force by **hadron-hadron scattering experiments**.