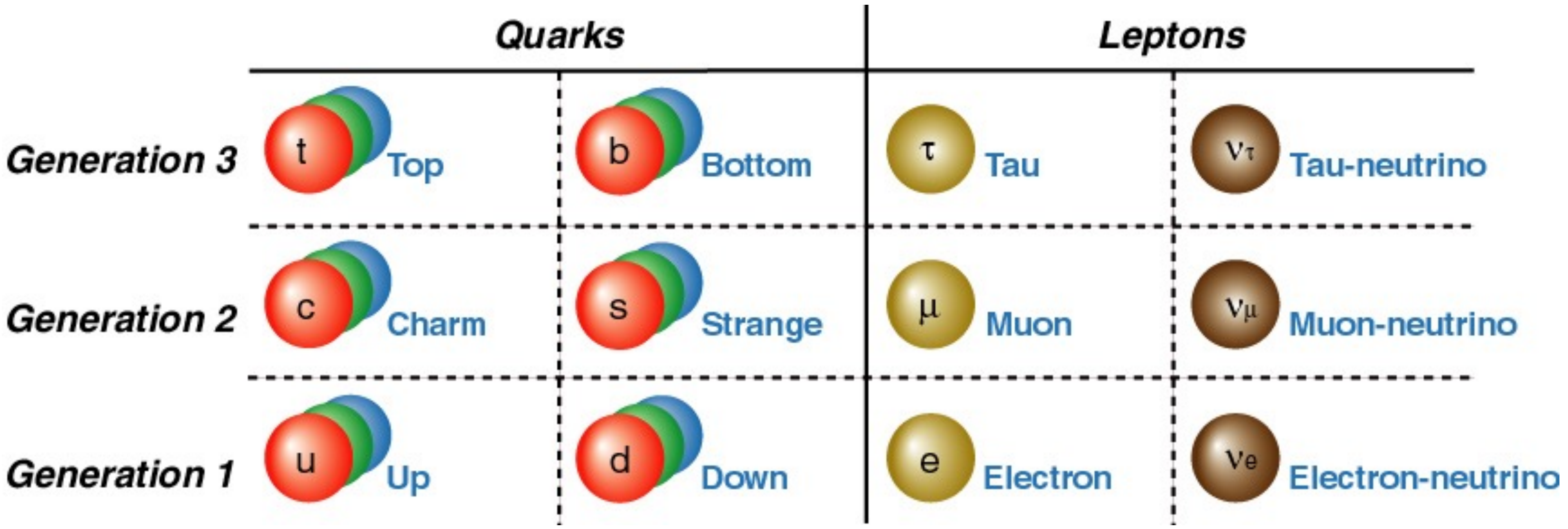
Week 11 Particle Physics Tutorial

Fundamental Particles & Forces

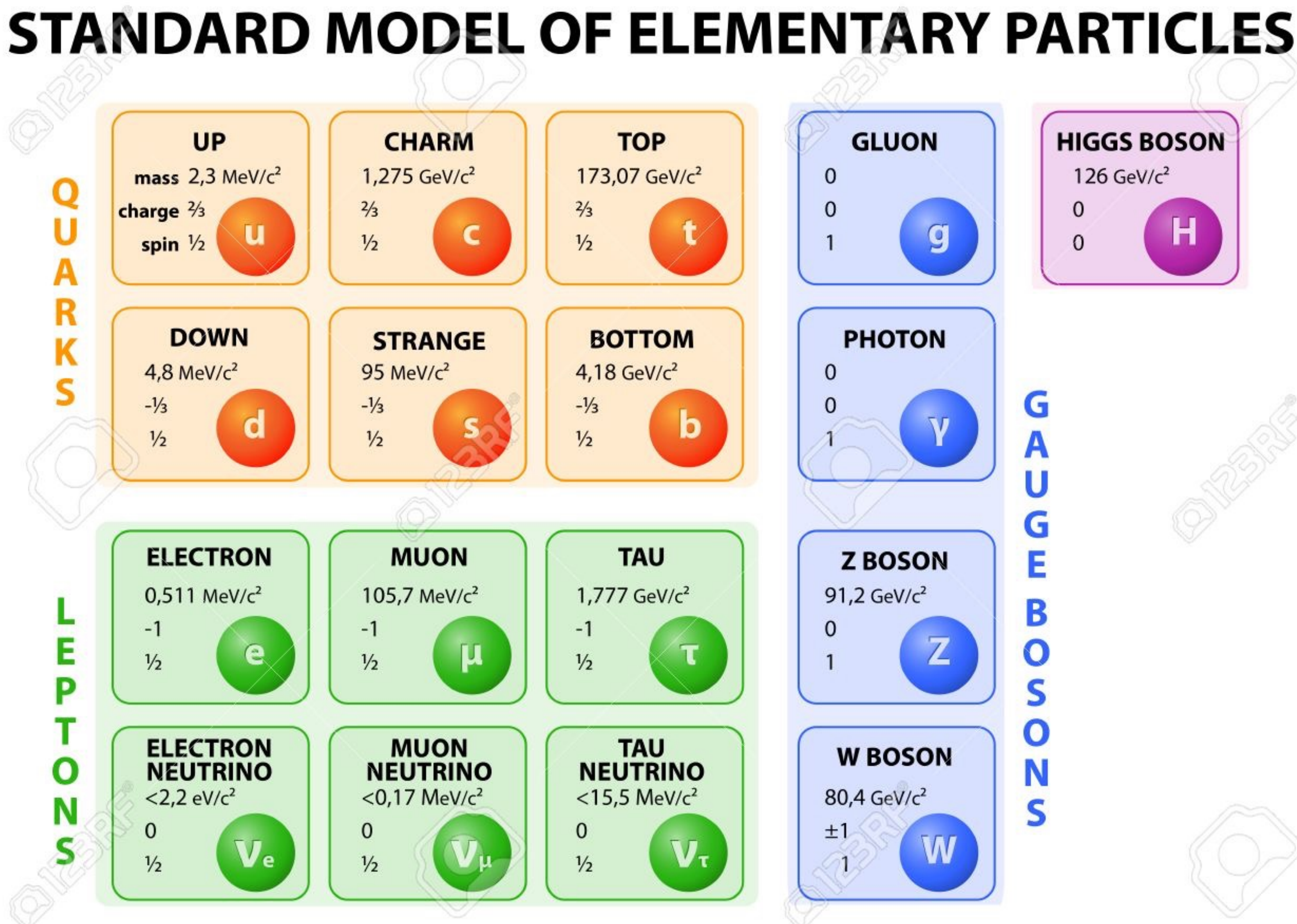
- This week's Class Prep
- Concept review of fundamental particles & forces
- Example calculations



The Particle Zoo:

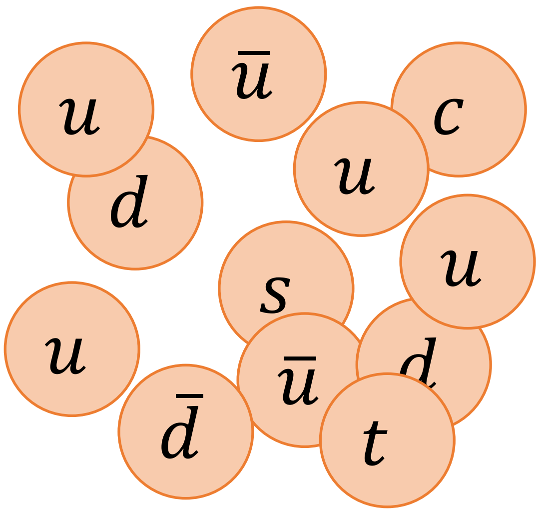
Concepts & Examples

Concepts of the Particle Zoo



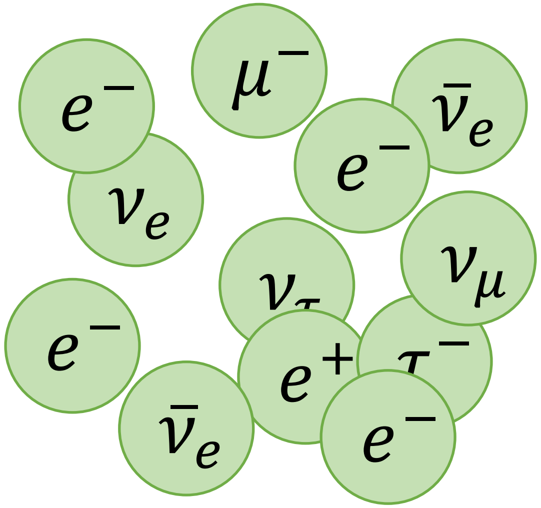
Concepts of the Particle Zoo

THE QUARKS!



- Six flavours (u, d, c, s, t, b)
- Fractional charges!
- Never observed singly / confined in hadrons
- Strong force interactions

THE LEPTONS!

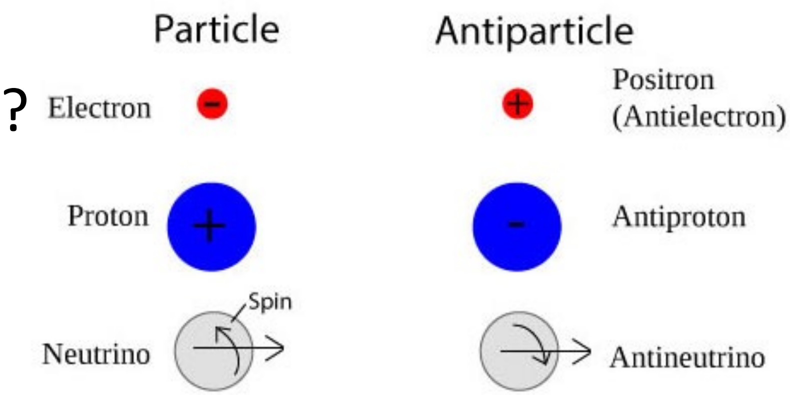


- 3 charged (e^-, μ^-, τ^-)
- 3 neutral $(\nu_e, \nu_\mu, \nu_\tau)$ and almost massless
- Do not feel strong force

Concepts of the Particle Zoo

What is meant by an **anti-particle**?

A particle with the opposite charge, but the same mass



Particles & Antiparticles

Quarks combine to form **hadrons**

u u d

3 quarks = baryon

$\bar{u}$ $\bar{u}$ $\bar{d}$

3 antiquarks = antibaryon

u $\bar{d}$

Quark-antiquark pair = meson

Why are these the allowed combinations?

The Particle Zoo Example 1

Quarks have fractional charges which are either $+\frac{2}{3}$ or $-\frac{1}{3}$ (in units of the elementary charge). Hadrons are composed of either 3 quarks, 3 anti-quarks, or a quark-antiquark pair. Show that hadrons always have integral total charge, regardless of their quark composition.

Possible combinations for **baryons** are $\frac{2}{3}+\frac{2}{3}+\frac{2}{3}=2$, $\frac{2}{3}+\frac{2}{3}-\frac{1}{3}=1$, $\frac{2}{3}-\frac{1}{3}-\frac{1}{3}=0$, $-\frac{1}{3}-\frac{1}{3}-\frac{1}{3}=-1$ for 3 quarks, or the negative of these values for 3 anti-quarks. **(Total $= -2, -1, 0, +1, +2$)**

Possible combinations for **mesons** are $\frac{2}{3}+\frac{1}{3}=1$, $-\frac{2}{3}-\frac{1}{3}=-1$, or $-\frac{1}{3}+\frac{1}{3}=-\frac{2}{3}+\frac{2}{3}=0$. **(Total $= -1, 0, +1$)**

All of these combinations produce integral total charge.

The Particle Zoo Example 2

Why is the neutrino its own anti-particle, but the anti-neutron is a different particle to the neutron?

The anti-neutron is made up of 3 anti-quarks, which are different elementary particles to the 3 quarks which make up the neutron. The neutrino is an neutral elementary particle, so its anti-particle is also a neutrino.

Concepts of the Particle Zoo

- There are hundreds of different hadrons, which correspond to different combinations of quarks

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Mesons $q\bar{q}$

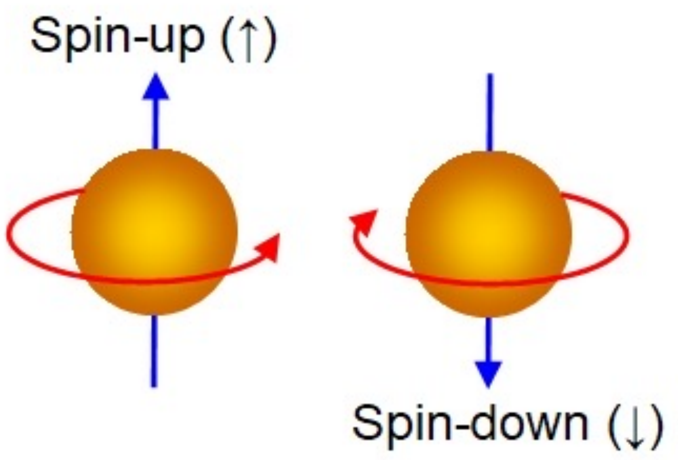
Mesons are bosonic hadrons.
There are about 140 types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

Concepts of the Particle Zoo

What is the difference between a **fermion** and a **boson**?

- Particles have a special quantum property called **spin**
- *Analogy: a spinning ball of charge, pointing up or down*



This is a spin-$\frac{1}{2}$ particle   Angular momentum $= \pm\frac{1}{2}\hbar$

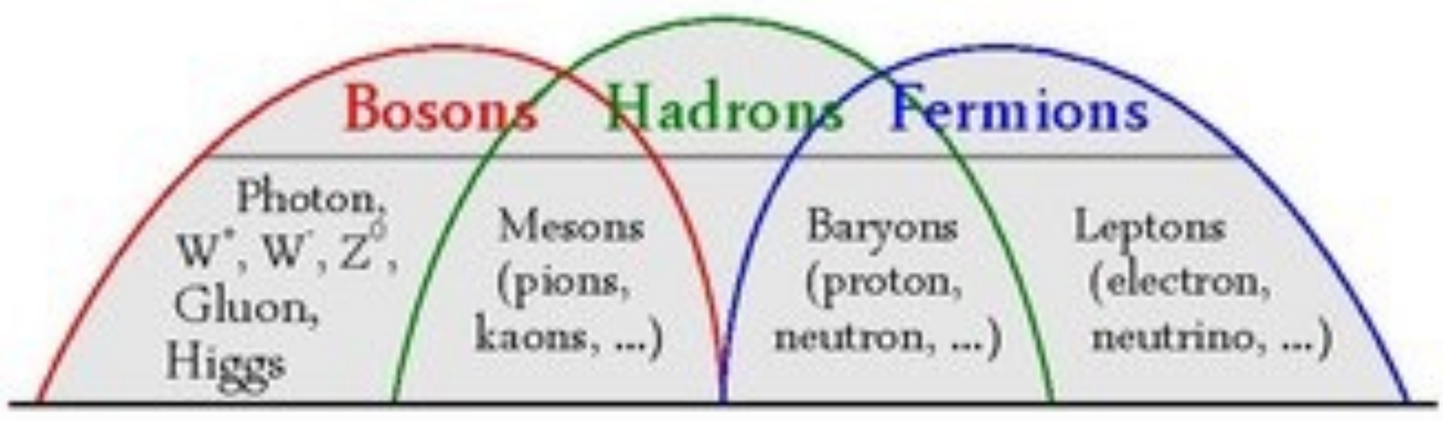
Fermions have half-integer spin values and **bosons** have integer spin values

Fermions satisfy the **Pauli exclusion principle**

Two fermions cannot exist in the same location in the same quantum state

Concepts of the Particle Zoo

- The **quarks** and the **leptons** are all **spin-$\frac{1}{2}$ fermions**
- The **force-carrier** particles (more on these soon) are all **spin-1 bosons**
- **2 particles** with half-integer spin combine to give a particle with integer spin (→ **mesons are bosons**)
- **3 particles** with half-integer spin combine to give a particle with half-integer spin (→ **baryons are fermions**)



The Particle Zoo Example 3

Classify the following particles into fermions and bosons:

$$e^-, p, \gamma, \nu_e, \pi^0, K^-, \Lambda^0, Z, \Sigma^+$$

Is the nucleus of an atom a fermion or a boson?

e^- = electron
p = proton
γ = photon
ν_e = electron neutrino
π^0 = neutral pion = $u\bar{u}$ or $d\bar{d}$
K^- = negative kaon = $s\bar{u}$
Λ^0 = Lambda particle = uds
Z = carrier for weak interaction
Σ^+ = Sigma particle = uus

Fermions: $e^-, p, \nu_e, \Lambda, \Sigma^+$
Bosons: γ, π^0, K^-, Z

The nucleus can be either a fermion or a boson, depending on whether the total number of protons and neutrons is odd or even, respectively. This is because the individual nucleons are fermions, and an odd/even number of fermions produces a fermion/boson!

The Particle Zoo Example 4

Here are six particle descriptors:

lepton, hadron, meson, baryon, fermion, boson

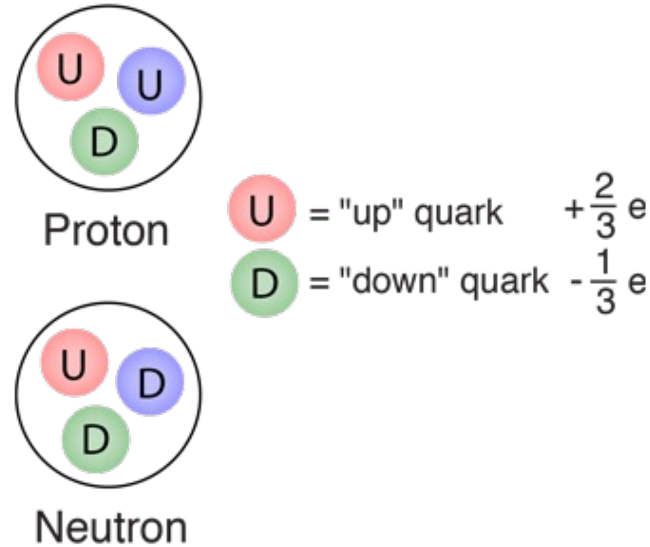
Which of these six words may be correctly applied to the following particles?

a) The Ω^{-} particle, which is composed of 3 strange quarks
b) The tau particle, τ^{-}
c) The photon, γ
d) The muon neutrino, ν_{μ}
e) The π^{+} pion, which is composed of an up quark and a down anti-quark

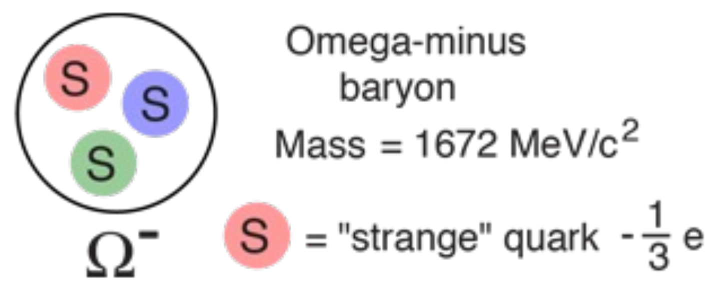
a) Hadron, baryon, fermion
b) Lepton, fermion
c) Boson
d) Lepton, fermion
e) Hadron, meson, boson

Concepts of the Particle Zoo

- Given that quarks are fermions which obey the Pauli exclusion principle, it seems that protons and neutrons cannot exist?
- Quarks come in 3 colours (blue, red, green) – which is how they avoid violating the Pauli exclusion principle
- All hadrons have **net zero colour** (i.e. all 3 colours are present in equal amounts)



The Ω^- particle is made up of three strange quarks!

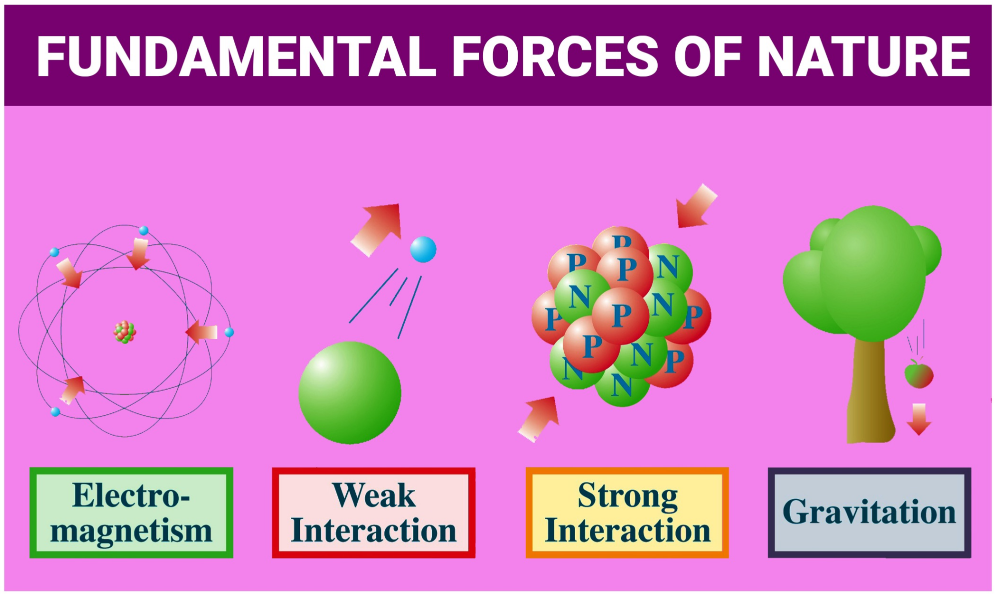


Fundamental Forces:

Concepts & Examples

Concepts of Fundamental Forces

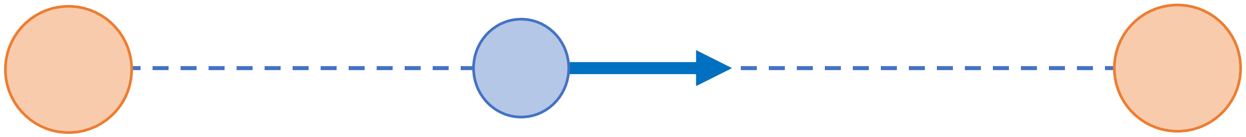
*Note: We will often refer to "forces" as "interactions" because the Newtonian idea of an action-and-reaction pair of forces does **not** clearly apply in sub-atomic cases*



Type of Force	Acts between …
Electromagnetic interaction	Charged particles
Strong interaction	Quarks, hence hadrons
Weak interaction	All particles, but generally negligible

What are some processes in Nature that can only exist because of the electromagnetic interaction, the strong interaction and the weak interaction?

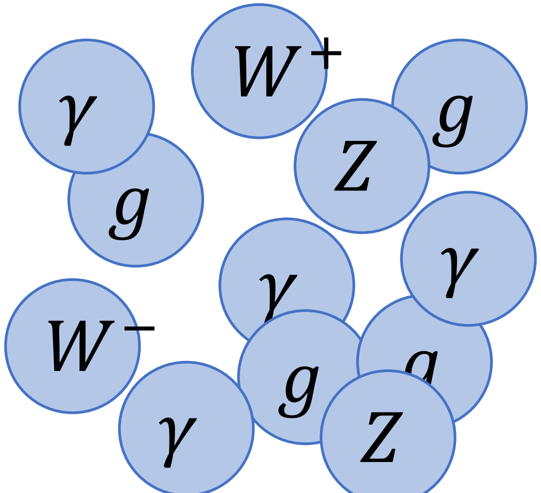
Concepts of Fundamental Forces



In modern particle physics, particles interact by **exchanging other particles known as force carriers**

The “force” is the net result of all the particle exchanges

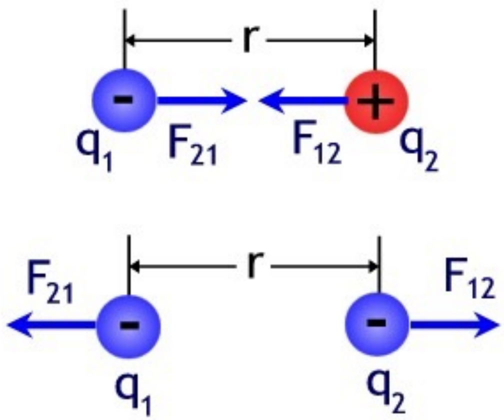
THE GAUGE BOSONS!

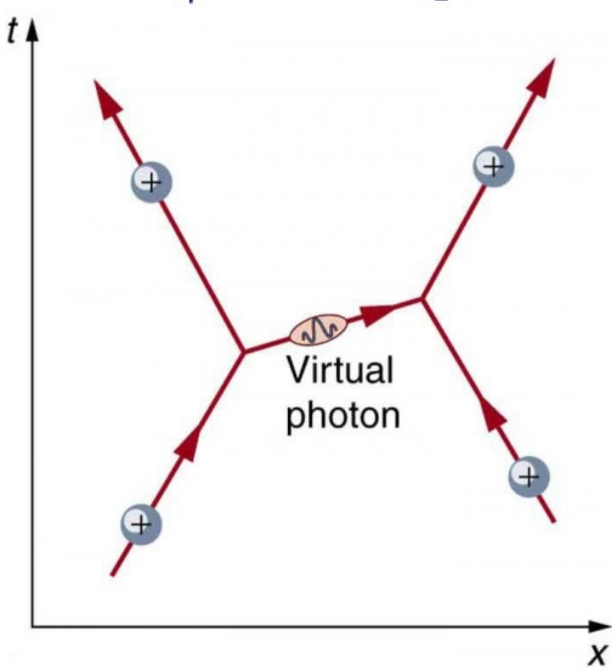


Force	Carrier particle	Charge $[e]$	Mass $[\frac{GeV}{c^2}]$
Electromagnetism	Photon γ	0	0
Weak	W^+	$+1$	80.4
	W^-	-1	80.4
	Z^0	0	91.2
Strong	Gluon	0	0

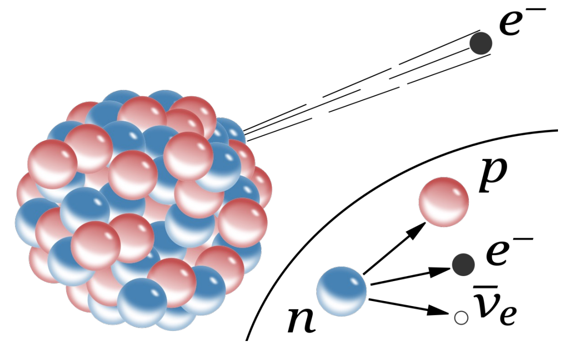
Concepts of Fundamental Forces

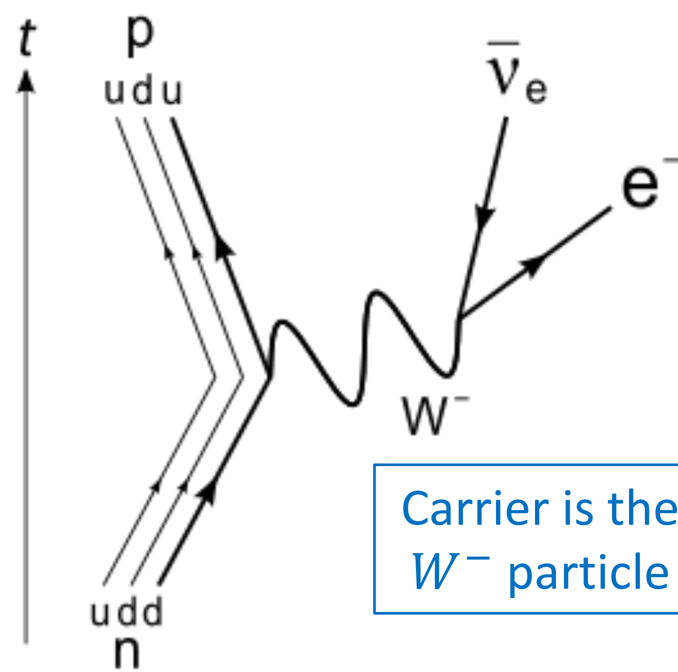
Electromagnetism





Weak force (β decay)

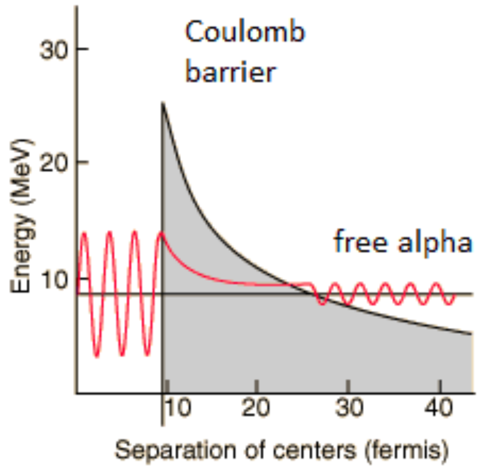




Carrier is the W^- particle

Concepts of Fundamental Forces

- The process of producing a carrier particle **violates energy and momentum conservation**. However, this is permissible for a short time owing to the **uncertainty principle** $\Delta E\ \Delta t \sim \hbar$



This is the same uncertainty principle that's related to quantum tunnelling, that helped us with nuclear fusion, α decay, etc.!

- So, force carriers are known as **"virtual particles"** and do not need to satisfy the usual relation, $E^2 = p^2c^2 + m^2c^4$

- To make a real process, two virtual processes are combined such that *energy conservation is only violated for a short time*

Concepts of Fundamental Forces

We can use the uncertainty principle to estimate the **range** of an interaction

Uncertainty principle gives us the time
$\Delta E \, \Delta t \sim \hbar$

Carrier particle mass gives us the energy fluctuation
$\Delta E \sim mc^2$

Assuming carrier particle is travelling at or near speed-of-light gives us the range: $R \sim c \, \Delta t$

Combining these equations: $$R \sim \frac{\hbar}{mc}$$

Predictions of our very simple calculation:

- **Electromagnetism** has infinite range since photon has $m = 0$ – correct!
- **Weak force** has finite range using mass of W and Z bosons – correct!
- **Strong force** has infinite range since gluon has $m = 0$ – incorrect!

Fundamental Forces Example 1

Photons are quantum energy packets of light, and are also carrier particles for the electromagnetic interaction.

Are these types of photon the same elementary particle? In what way do they differ?

These types of photon are the same elementary particle, but the carrier particle for the electromagnetic force can only exist for a finite, short time governed by the uncertainty principle, whereas the particle of light can exist forever, in principle.

Fundamental Forces Example 2

The weak interaction is carried by a Z boson, which has mass $91.2\ \mathrm{GeV}/c^2$. What is the approximate range of the weak interaction?

By the uncertainty principle, the Z boson can exist for a time $\Delta t = \frac{\hbar}{\Delta E} = \frac{1.05\times10^{-34}}{91.2\times1.6\times10^{-10}} = 7.2\times10^{-27}\ \mathrm{s}.$

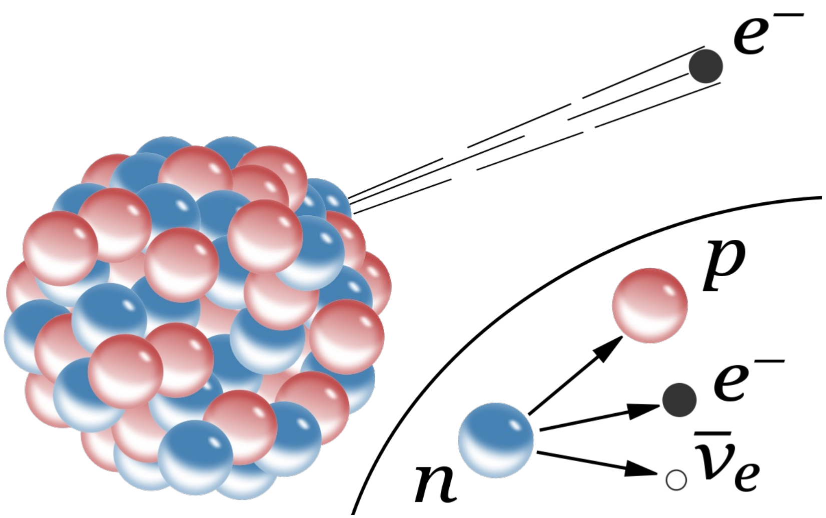
The maximum range of the weak interaction is then $c\ \Delta t = 3\times10^{8}\times7.2\times10^{-27} \approx 2\times10^{-18}\ \mathrm{m}.$

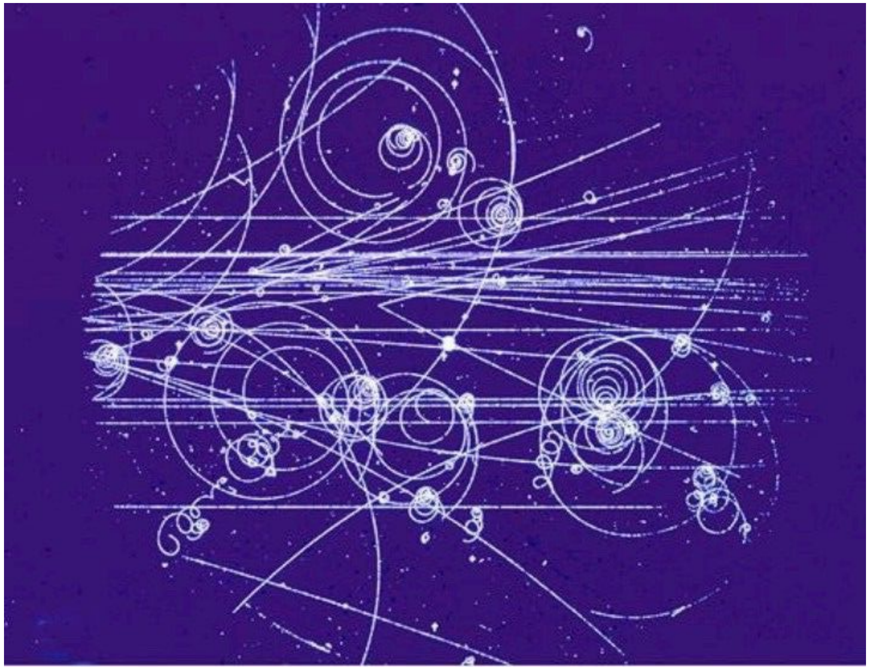
Break time!

Conservation Laws:

Concepts & Examples

Concepts of Conservation Laws



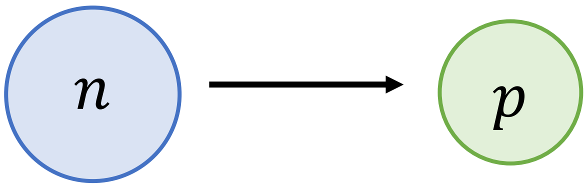


- Very few sub-atomic particles can live forever!
- Most exist in an unstable state and spontaneously decay, or can be "encouraged" to react and re-configure by bombardment
- Conservation laws determine which transformations are allowed

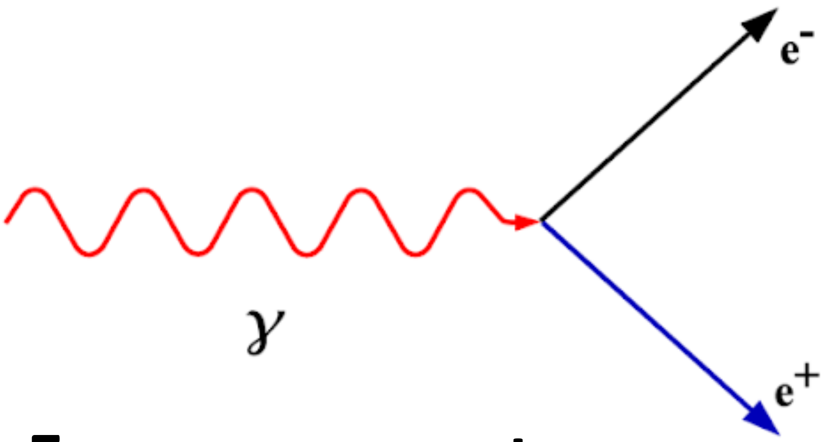
Concepts of Conservation Laws

Which quantities must be conserved??

(no other particles)



Charge



Energy, momentum

What is wrong with:

This decay is not possible because it violates **conservation of charge** – how can we fix it?

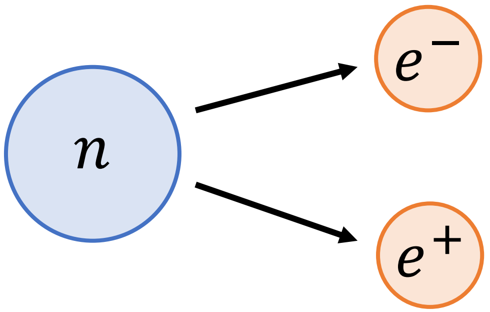
This decay is not possible because it violates **conservation of momentum** (to see why, imagine viewing it from the centre-of-mass frame of the electron and positron)

How can we fix it?

Concepts of Conservation Laws

Which quantities must be conserved??

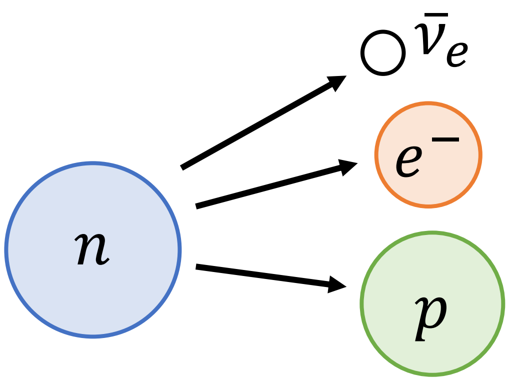
What is wrong with:



Baryon number

This decay is not possible because it violates **conservation of baryon number**

Baryon number simply means a count of baryons (and subtracting anti-baryons)



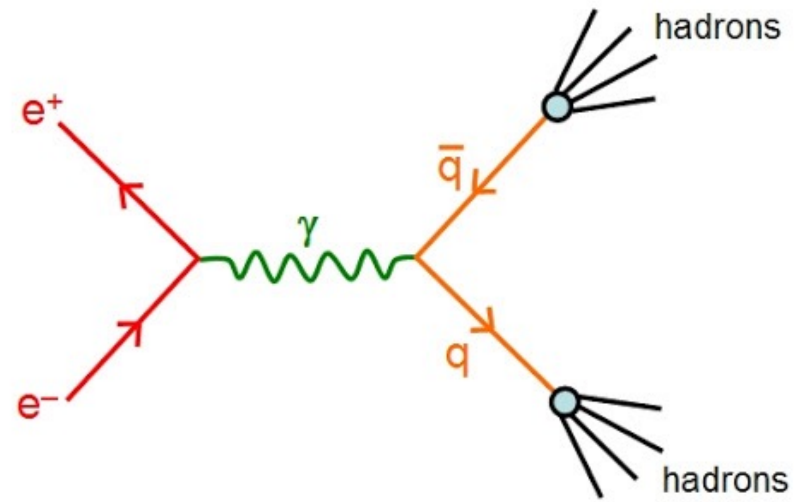
Lepton number

This decay is not possible because it violates **conservation of lepton number**

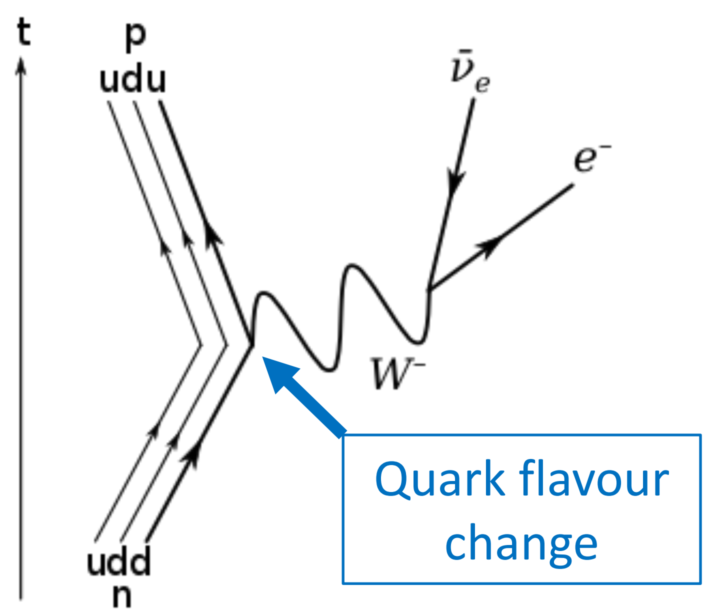
Lepton number simply means a count of each lepton generation (e.g., e^-, ν_e) *subtracting off any anti-leptons*

Concepts of Conservation Laws

- In **strong and electromagnetic interactions**, *the numbers of each quark flavour are separately conserved* (i.e. quarks & anti-quarks are created/destroyed in pairs)



- In **weak interactions**, *quark flavour can change and only baryon number is conserved* (an example of this is β-decay, where a down quark becomes an up quark)

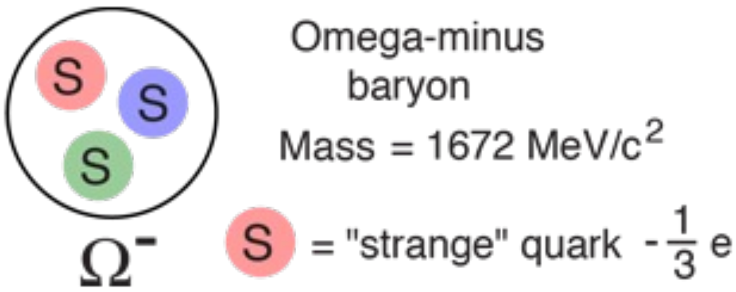


Concepts of Conservation Laws

- An example of tracking quark numbers is the property of **strangeness** *(we can do the same for other other flavours too)*

Particle	*Strangeness*
Each strange quark	-1
Each strange antiquark	$+1$
All other particles	0

- E.g. the Ω^{-} baryon contains 3 strange quarks so has a strangeness of -3 !



We will focus on checking conservation of charge, baryon number, lepton number and strangeness to determine whether a reaction is allowed, and what type of interaction it represents

Conservation Laws Example 1

State the total charge, baryon number, lepton number(s) and strangeness of the following particles:

a) The positron (e^+)
b) The lambda particle (Λ^0) – quark composition uds
c) The kaon (K^0) – quark composition $d\bar{s}$
d) The muon neutrino (ν_μ)

a) e^+: charge $= +1$, baryon number $= 0$, electron lepton number $= -1$, strangeness $= 0$

b) Λ^0: $0, 1, 0, -1$

c) K^0: $0, 0, 0, +1$

d) ν_μ: $0, 0$, muon lepton number $= 1$, 0

Conservation Laws Example 2

The follow decays of a neutron are all forbidden. Which conservation laws make this so?

a) $n \rightarrow p + e^{-}$
b) $n \rightarrow \pi^{+} + e^{-}$
c) $n \rightarrow p + \pi^{-}$
d) $n \rightarrow p + \gamma$

a) Violates conservation of lepton number

b) Violates conservation of baryon number and lepton number

c) Violates conservation of energy

d) Violates conservation of electric charge

Conservation Laws Example 3

Classify the following as strong, electromagnetic or weak reactions:

a) $p + \bar{p} \rightarrow \pi^+ + \pi^-$
b) $\Sigma^0 \rightarrow \Lambda^0 + \gamma$
c) $\Xi^- \rightarrow \Lambda^0 + \pi^-$
d) $\Delta^+ \rightarrow p + \pi^0$

Quark composition:

$p = uud$
$\pi^+ = u\bar{d}$
$\pi^0 = u\bar{u}$ or $d\bar{d}$
$\pi^- = d\bar{u}$
$\Sigma^0 = uds$
$\Lambda^0 = uds$
$\Xi^- = dss$
$\Delta^+ = uud$

a) Conserve individual quark numbers → strong interaction

b) Conserves strangeness and involves a photon → electromagnetic interaction

c) Violates strangeness → weak interaction

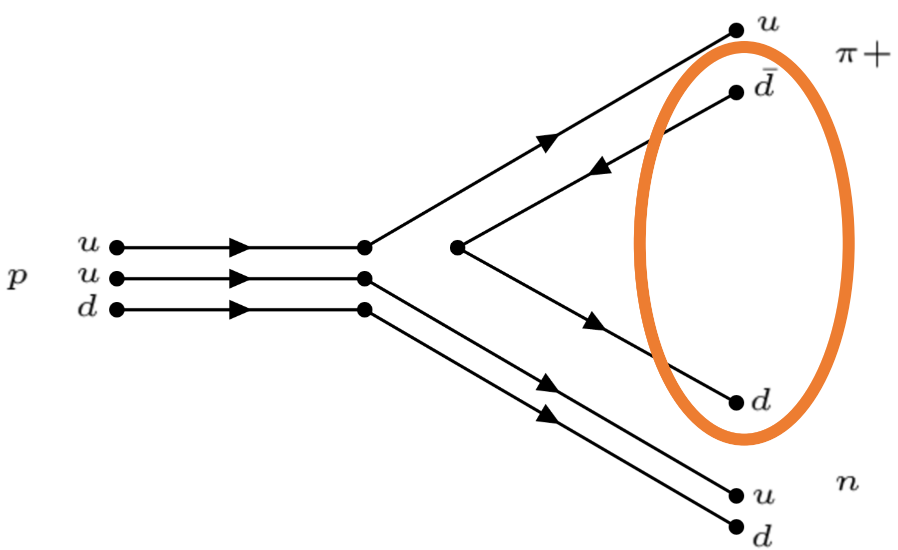
d) Conserve individual quark numbers → strong interaction

Concepts of Conservation Laws

- Transformations like these may be represented by **quark flow diagrams**

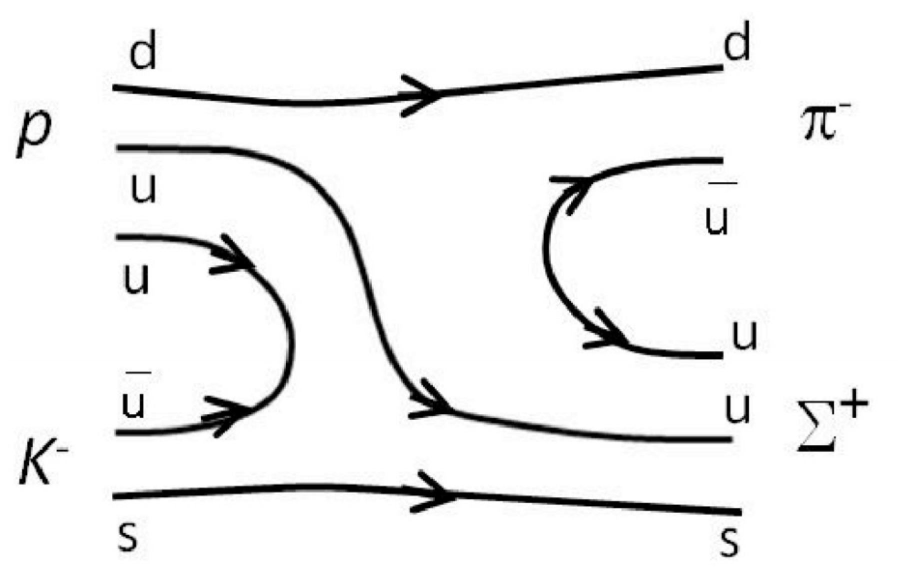
Proton (with energy) becomes a neutron and pion

$$p \rightarrow n + \pi^{+}$$



Proton and kaon becomes a hyperon and pion

$$p + K^{-} \rightarrow \Sigma^{+} + \pi^{-}$$



Conservation Laws Example 4

Draw a quark flow diagram for the process:

$$\pi^- + p \rightarrow \Delta^0 \rightarrow \pi^0 + n$$

Quark composition:

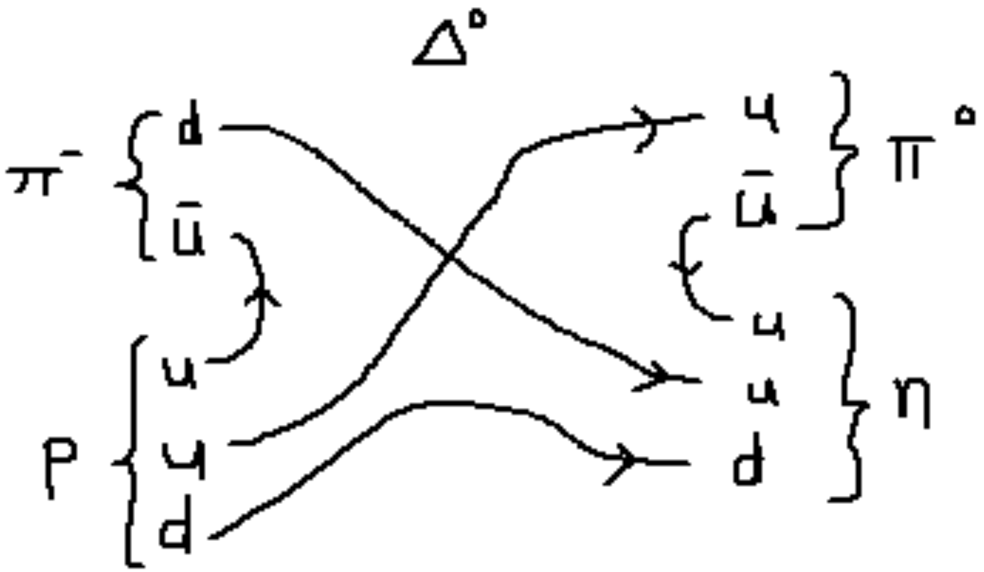
$\pi^- = d\bar{u}$

$p = uud$

$\Delta^0 = udd$

$\pi^0 = u\bar{u}$

$n = udd$



That’s all for today!