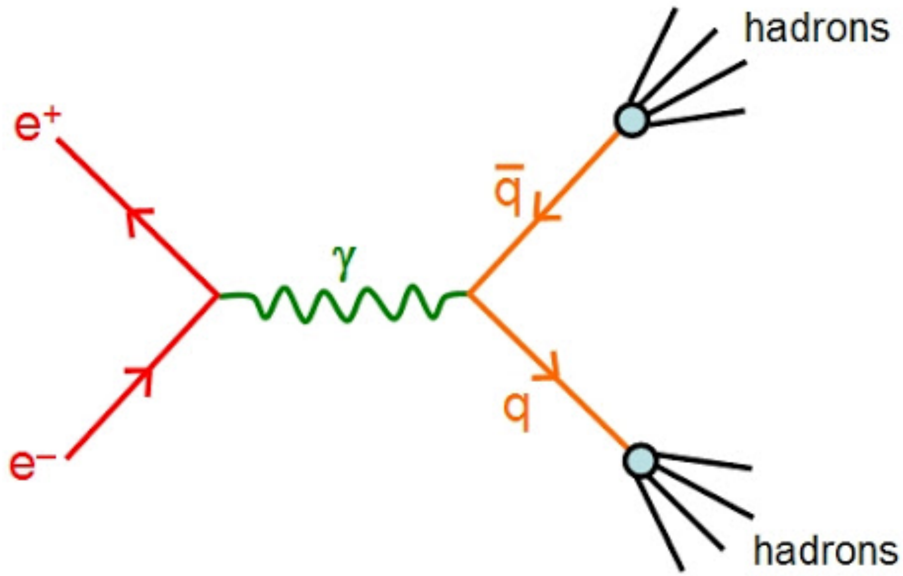
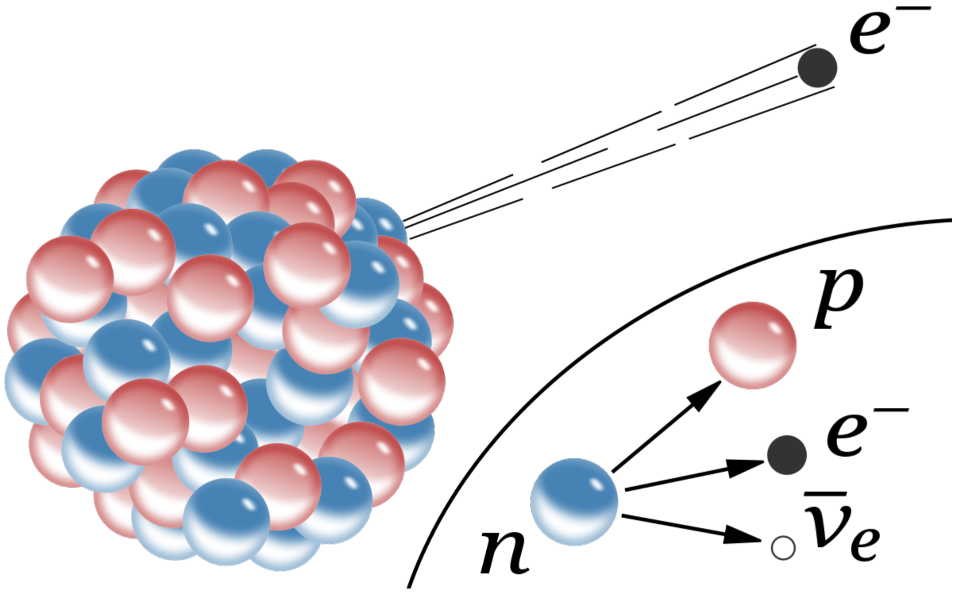
PHY20004 Particle Physics Class 3:
Conservation Laws

In this class we will study the conservation laws that determine which types of particle decays and reactions are allowed, and which are forbidden



Spontaneous particle decay

- Although a few sub-atomic particles can live forever (e.g. electron, proton), most exist in an **unstable state**
- Unstable particles **decay spontaneously** into related configurations of particles in a lower energy state



A canonical example is β-decay, in which a neutron transforms into a proton, electron and anti-neutrino

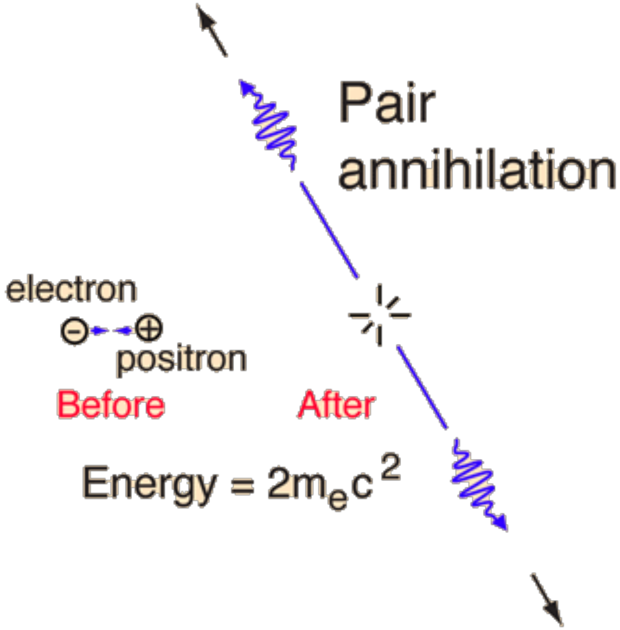
Credit: https://en.wikipedia.org/wiki/Beta_decay

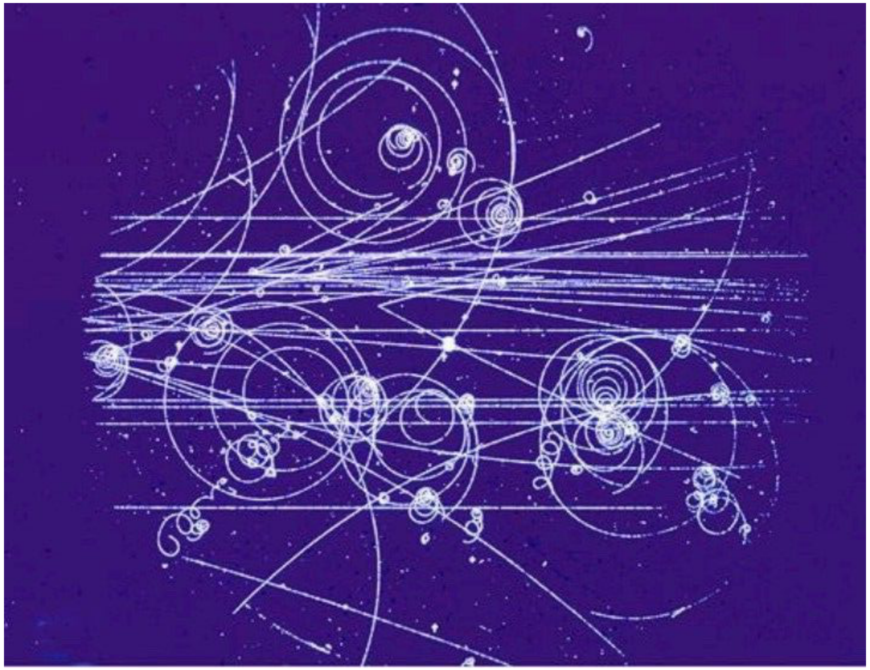
Particle reactions/collisions

- Likewise, when two particles **"collide"** or **react** they can re-configure into combinations of other particles

Example: particles and anti-particles can "annihilate" into photons

Example: when hydrogen atoms are bombarded by a beam of energetic particles, many new particles are created!



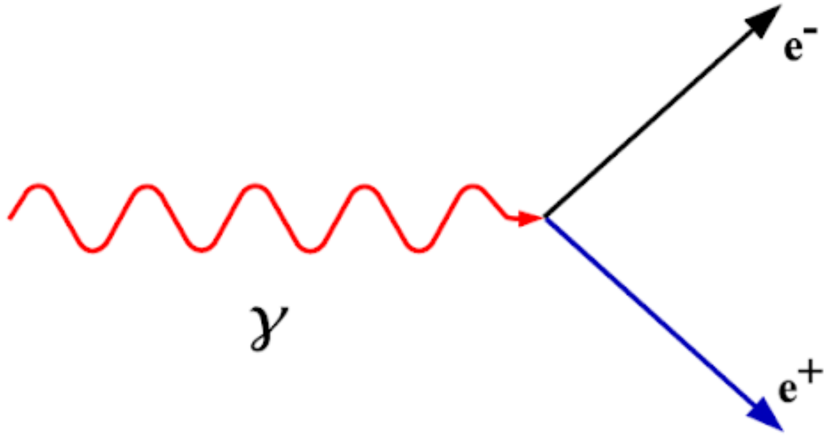


Energy and momentum conservation

- Particle decays or reactions must satisfy certain **conservation laws** – some transformations are allowed, and others are not

- To start with, decays must **conserve energy, momentum and charge** – e.g. a particle cannot decay to a higher-energy state (unless energy is taken from somewhere else)

- For example, a single (free) photon cannot transform into an electron and positron, since momentum cannot be conserved

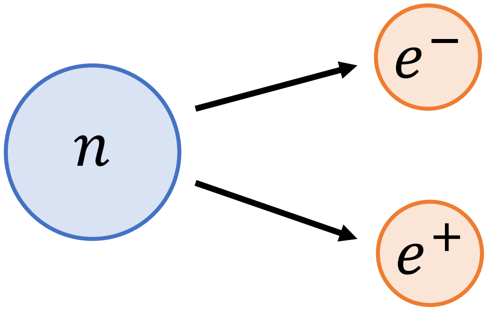


(This decay is not possible because it violates conservation of momentum: to see why, imagine viewing it from the centre-of-mass frame of the electron and positron)

Baryon number conservation

- What are some other conservation laws? A neutron can decay into a proton, but a neutron never decays into an electron and positron:

NOT ALLOWED!



This reaction would satisfy energy, momentum and charge conservation, but it never happens … why not?

- This reaction violates **conservation of baryon number**

Particle	***Baryon number***
Baryons	$+1$
Anti-baryons	-1
Other particles	0

The baryon number before the above reaction is $+1$, and the baryon number afterwards is 0, which breaks baryon number conservation

Lepton number conservation

- Each generation of lepton (electron, muon, tau) also has an **associated lepton number** which is conserved

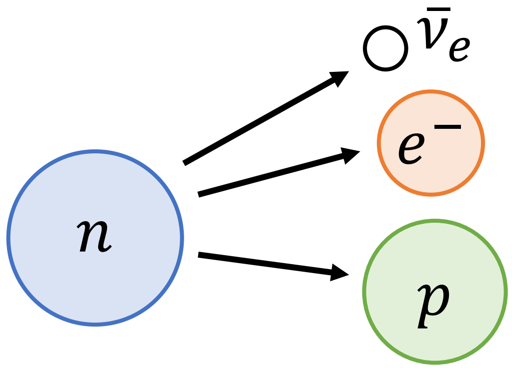
Particle	Symbol	Electron lepton number	Muon lepton number	Tau lepton number
Electron	e^-	$+1$	0	0
Electron neutrino	ν_e	$+1$	0	0
Positron	e^+	-1	0	0
Electron anti-neutrino	$\bar{\nu}_e$	-1	0	0
Muon	μ^-	0	$+1$	0
Muon neutrino	ν_μ	0	$+1$	0
Tau	τ^-	0	0	$+1$
Tau neutrino	ν_τ	0	0	$+1$
Quarks / hadrons		0	0	0

(Muons and taus have anti-particles which have negative muon/tau number)

Lepton number conservation

- For example, β^--decay $n \rightarrow p + e^- + \bar{\nu}_e$ produces an **electron anti-neutrino** in order to conserve electron lepton number

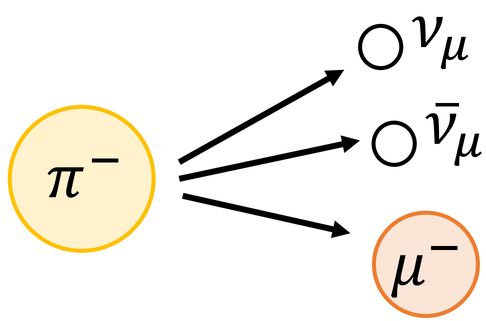
ALLOWED!



The electron lepton number is 0 before, and $+1$ (e^-) -1 ($\bar{\nu}_e$) $+0$ (p) $= 0$ afterwards, so this decay is allowed

- However, the hypothetical decay of the negatively-charged pion $\pi^- \rightarrow \mu^- + \nu_\mu + \bar{\nu}_\mu$ cannot occur

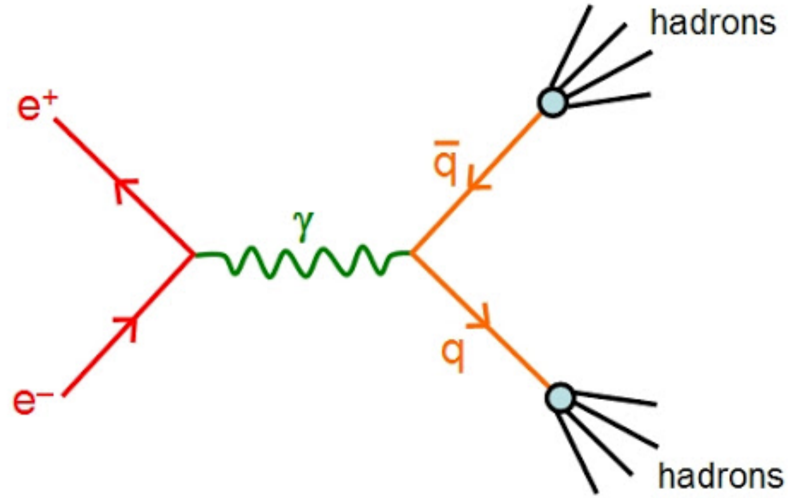
NOT ALLOWED!



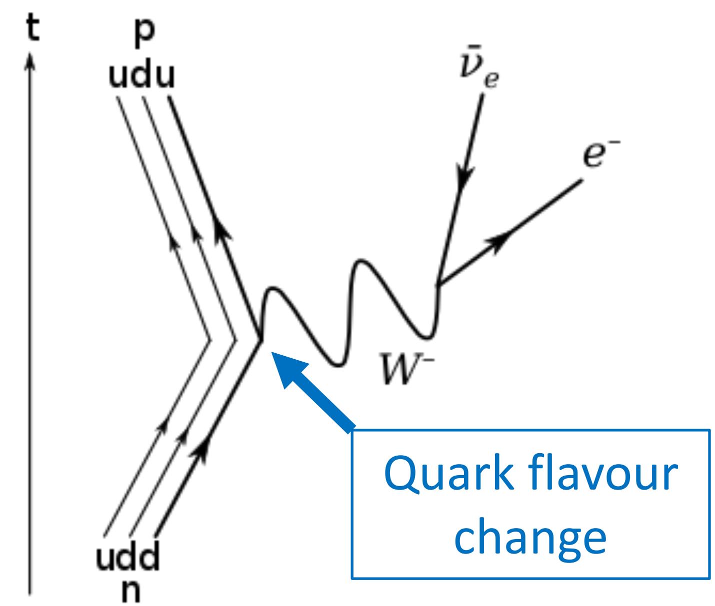
The muon lepton number is 0 before, and $+1$ (μ^-) -1 ($\bar{\nu}_\mu$) $+1$ (ν_μ) $= +1$ afterwards, so this decay is not allowed

Quark number conservation

- 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)

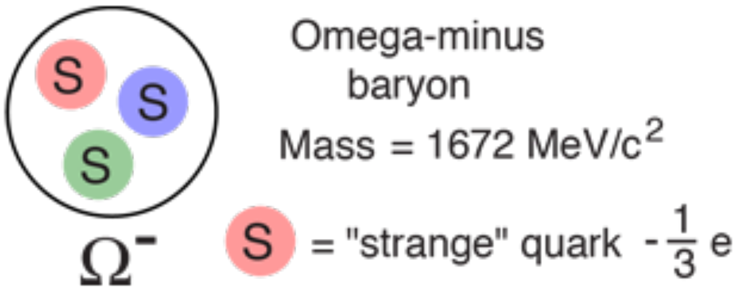


Strangeness

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

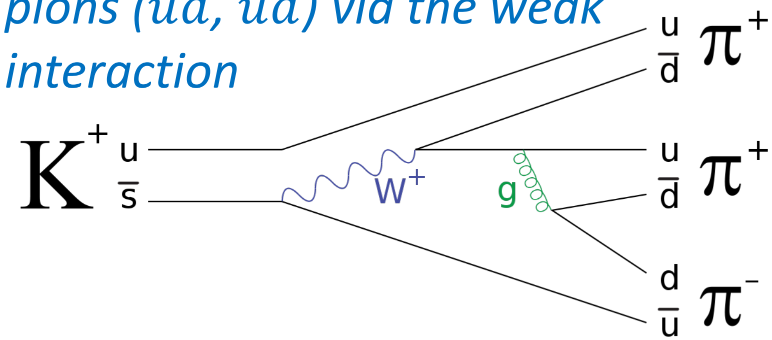
Particle	*Strangeness*
Each strange quark	-1
Each strange antiquark	$+1$
All other particles	0

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



- The strangeness can change in a weak interaction, but not in a strong or electromagnetic interaction

The decay of a kaon ($u\bar{s}$) into pions ($u\bar{d}$, $\bar{u}d$) via the weak interaction

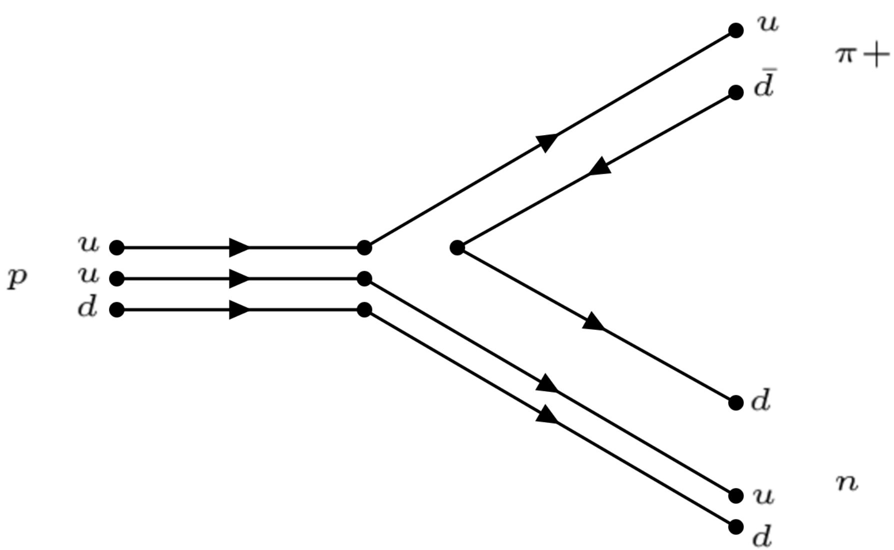


Quark flow diagrams

- Transformations like these may be represented by **quark flow diagrams** (simpler version of a Feynman diagram)

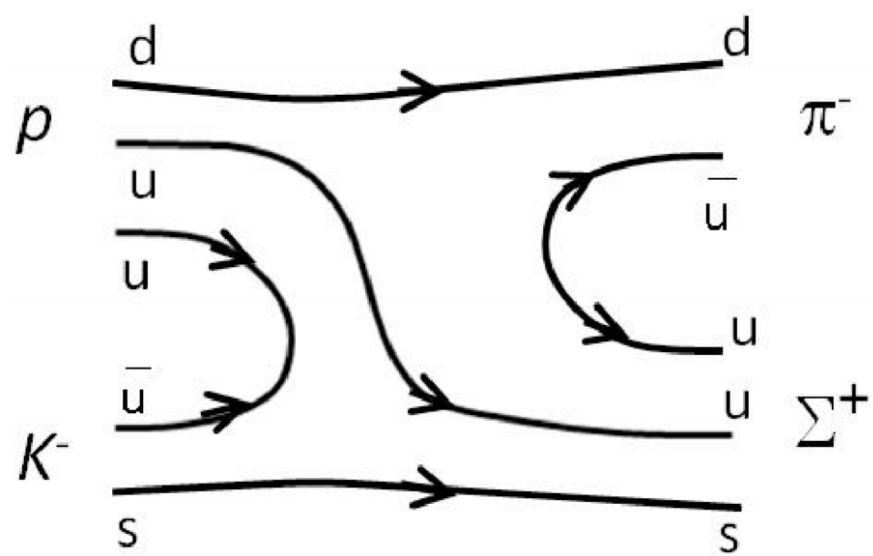
Proton (with energy) becomes a neutron and pion

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



Proton and kaon becomes a hyperon and pion

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



Key take-aways

- Particles may undergo transformations into other particles through **spontaneous decays** or **reactions/collisions**
- These processes must satisfy various **conservation laws**
- **Energy**, **momentum**, **charge**, **baryon number** and **lepton numbers** are always conserved
- **Quark numbers** (e.g. strangeness) are conserved in electromagnetic and strong interactions, but not necessarily in weak interactions
- Reactions may be represented by **quark flow diagrams**