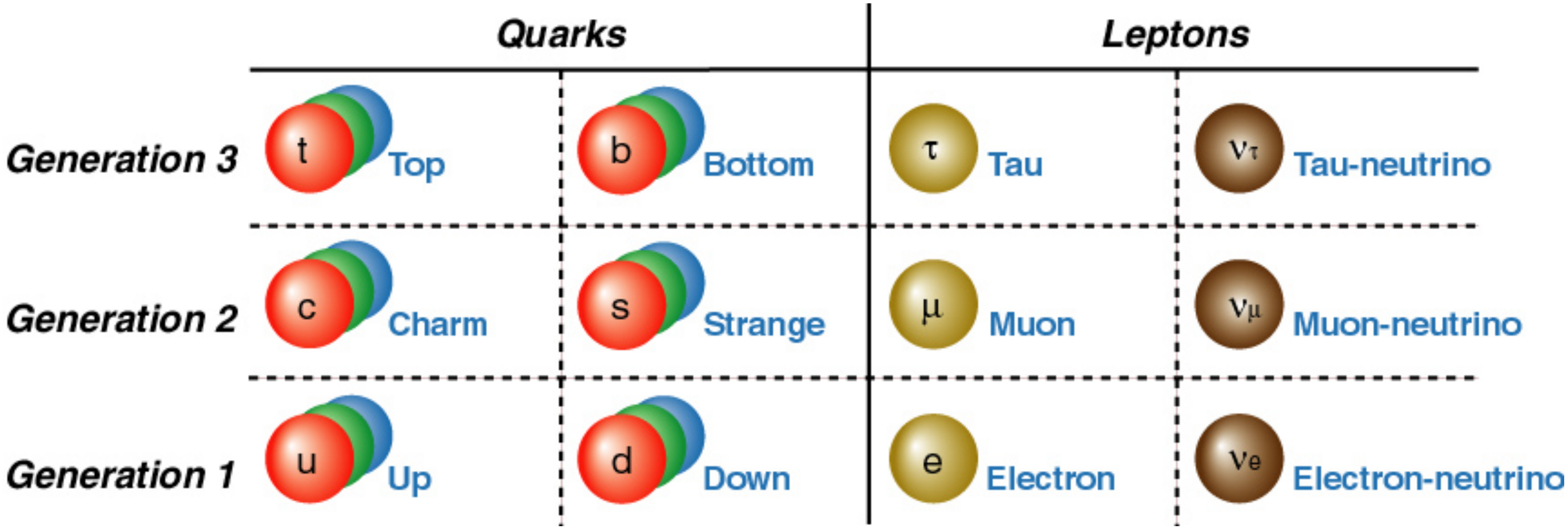
PHY20004 Particle Physics Class 1:

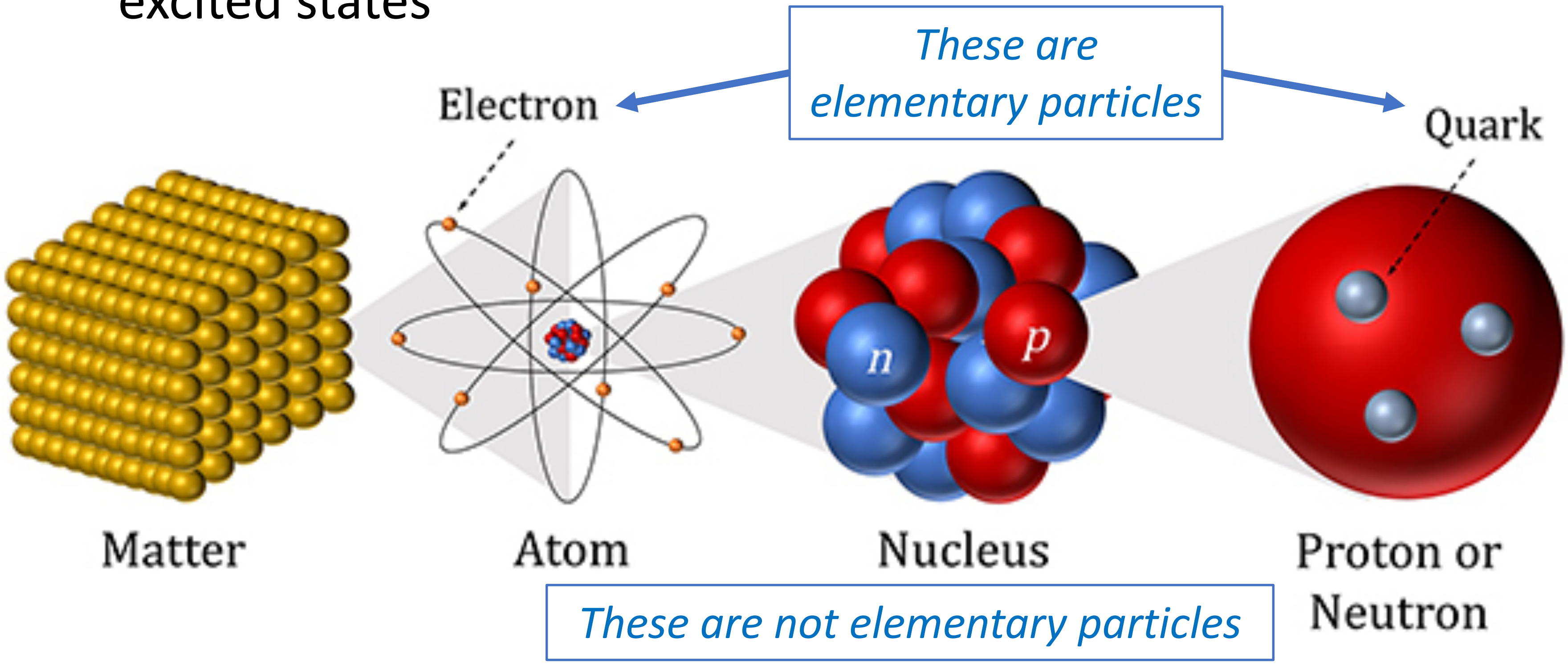
The Particle Zoo

In this class we will introduce the elementary particles – the leptons and quarks – and their key properties



What are elementary particles?

- **Elementary particles** are the fundamental constituents, or basic building blocks, of matter
- They are **point-like** particles with no internal structure or excited states



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Introducing leptons and quarks

- There are two types of elementary particles which constitute matter – **leptons** and **quarks**
- Almost all everyday phenomena can be described by the interactions of ***just four*** of these particles: the **electron**, the **neutrino**, the **"up" quark** and the **"down" quark**

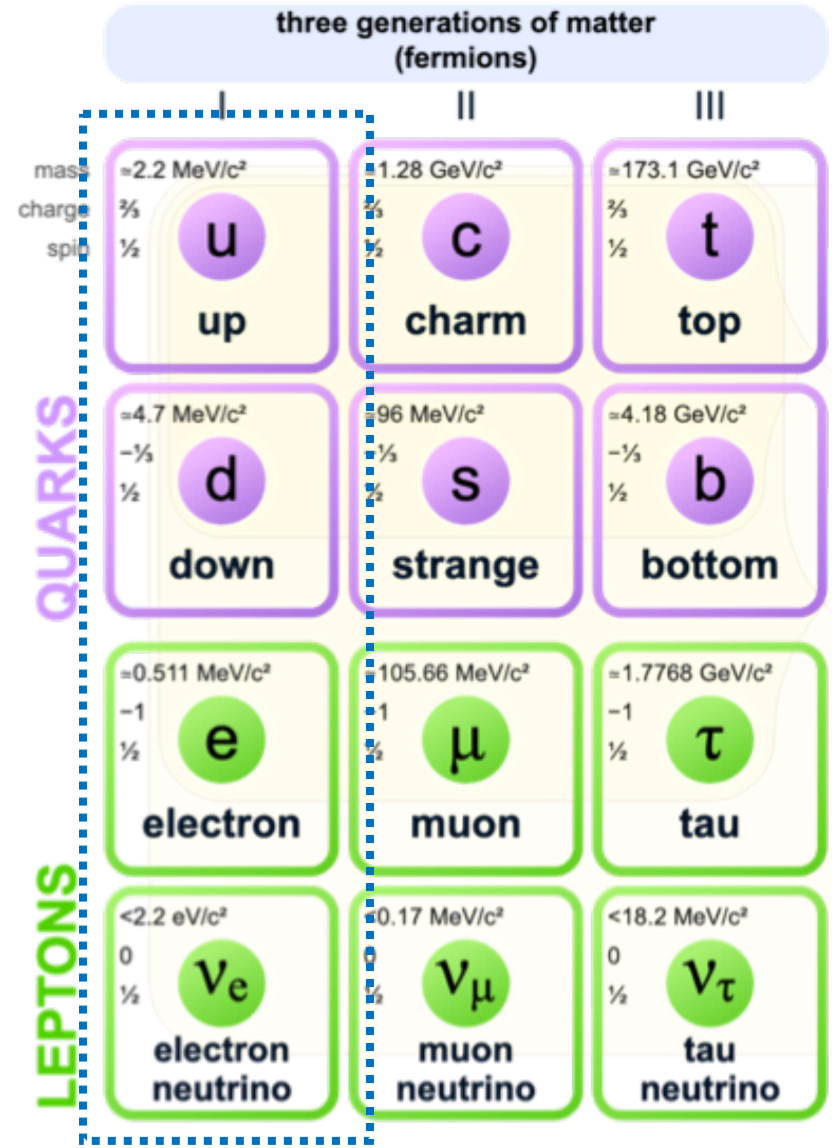
Particle	Symbol	Type	Charge $[e]$	Mass $[\mathrm{MeV}/c^2]$
electron	e^-	lepton	-1	0.511
neutrino	ν_e	lepton	0	≈ 0
up quark	u	quark	${}^2/_3$	≈ 2.2
down quark	d	quark	$-{}^1/_3$	≈ 4.7

Difficult to measure since no free quarks!

- The **proton** (uud) and **neutron** (udd) are the lowest energy states of combinations of three quarks

Particles: the next generation

- Unfortunately, the Universe is not that simple!
- We have discovered a total of **three generations** of leptons and quarks
- Each generation is a replica of these first four particles, featuring new particles of **increasing mass**
- The origin of these three generations is still a mystery



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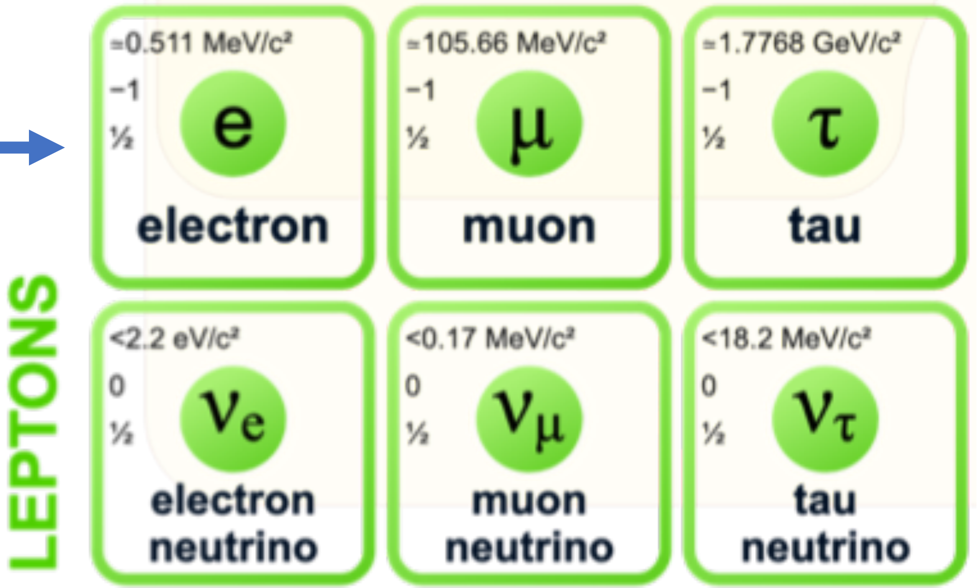
Leptons and their properties

- **Leptons** are point-like particles which do not undergo strong interactions *(we'll find out more about this soon!)*
- The **electron**, **muon** and **tau** particles are the *charged leptons*
- Their corresponding **neutrinos** are *neutral leptons*, which are (almost) massless and only interact weakly

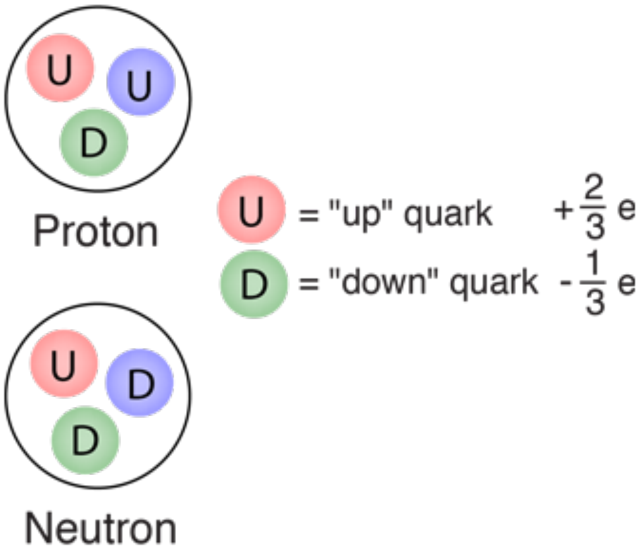
The particle mass increases significantly with each generation



Quarks and their properties

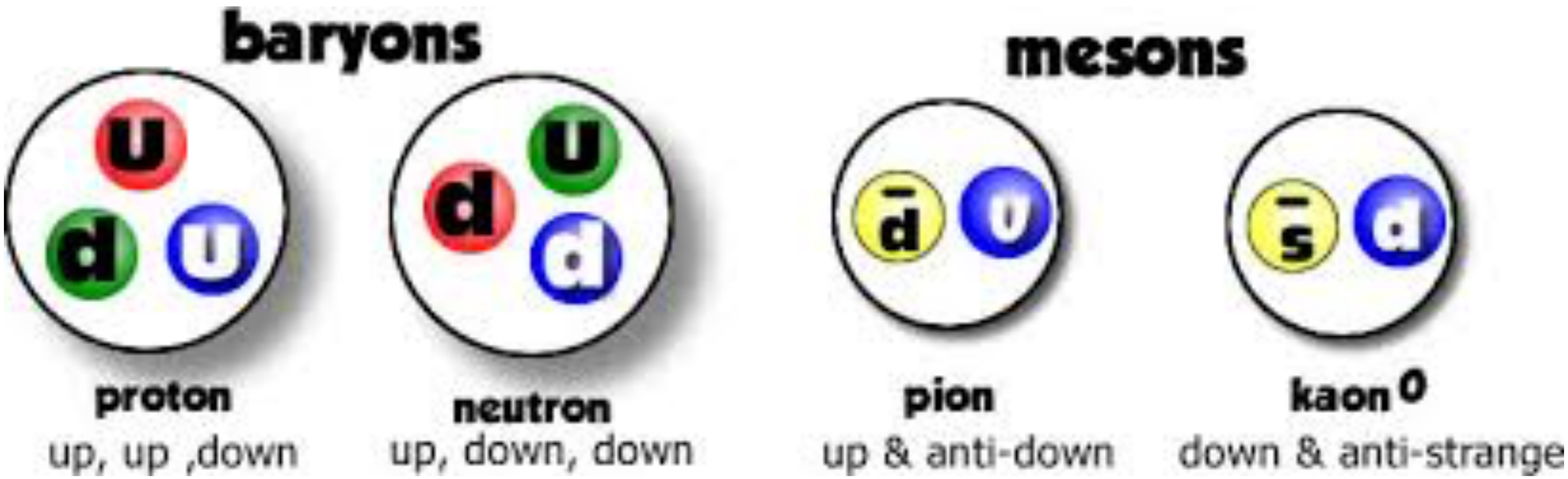
- Let's look more closely at the key properties of **quarks**:
  - There are **six quark flavours** (up, down, charm, strange, top, bottom)
  - Quarks have **fractional charge** (which is weird) however…
  - Quarks are **never observed singly** (apart from in the early Universe)
  - Quarks are confined in **composite particles called hadrons**

Arrange in composite particles



The hadron family

- Hadrons are composite particles made up of quarks. They come in two types: **baryons** and **mesons**



- Baryons are bound systems of three quarks or three anti-quarks (examples are protons and neutrons)

- Mesons are bound systems of a quark and anti-quark (examples are pions and kaons)

The hadron family

- There are hundreds of different hadrons, for example:

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.

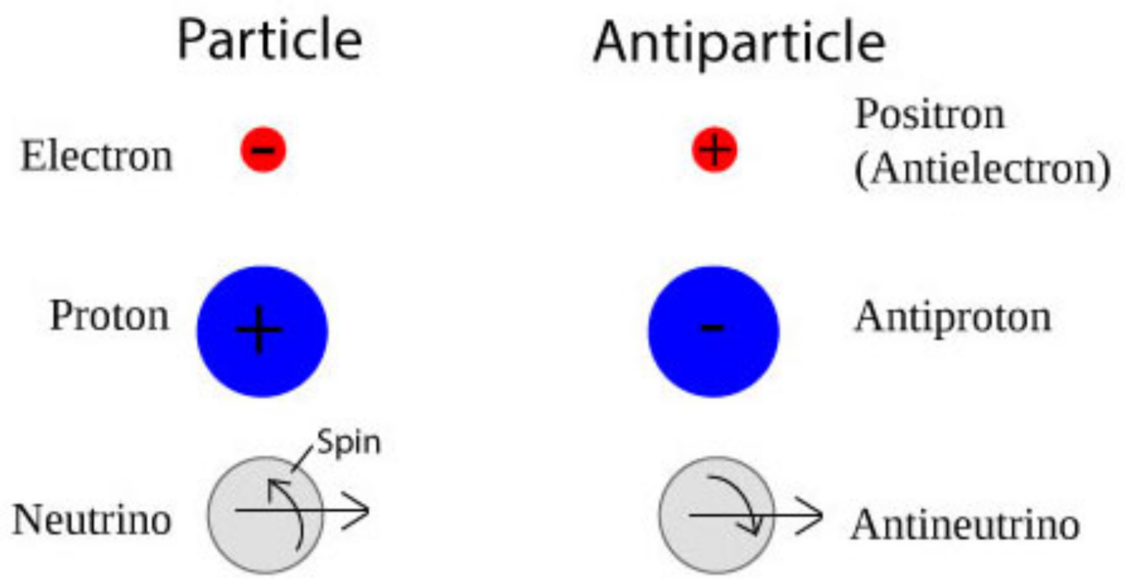
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

Image credit: fden-2.phys.uaf.edu

- The LHC has now discovered **tetraquarks** and **pentaquarks**!

Particles and anti-particles

- Each type of particle has an associated **anti-particle** with **opposite charge** but otherwise identical properties, e.g., the anti-particle of the electron (e^-) is the positron (e^+)



- Anti-particles are a consequence of **relativity** and **quantum mechanics**

Fermions and bosons

- In addition to properties such as mass and charge, particles also have a quantum-mechanical property known as **spin**

- Spin can either have **integer values** (like $0, 1, 2, \ldots$) or **half-integer values** (like $^{1}/_{2}\,, ^{3}/_{2}\,, ^{5}/_{2}\,, \ldots$)

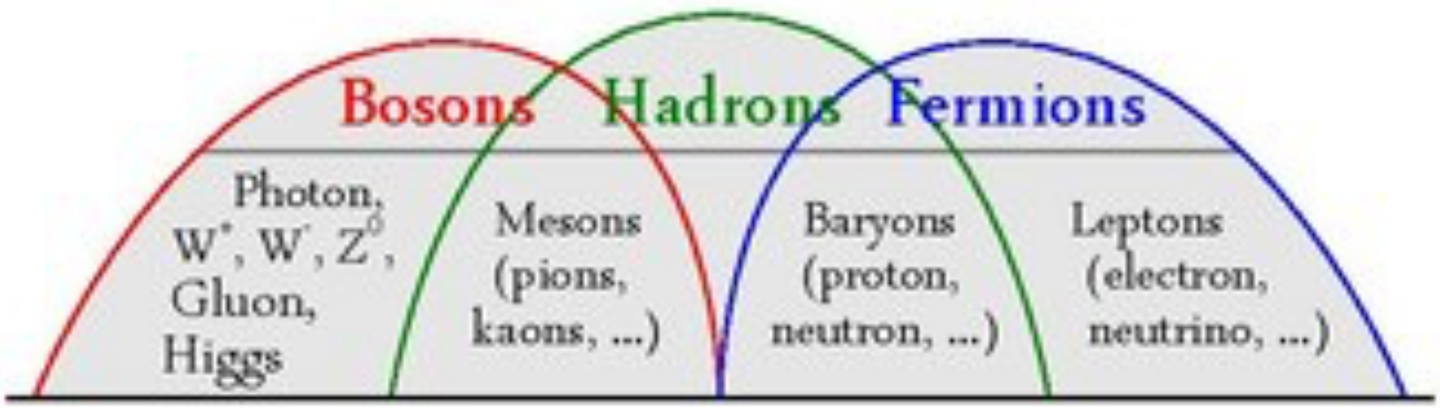
- Particles with half-integer spin values are called **fermions** and particles with integer spin values are called **bosons**

- The key difference between fermions and bosons is that **fermions obey the Pauli exclusion principle:**

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

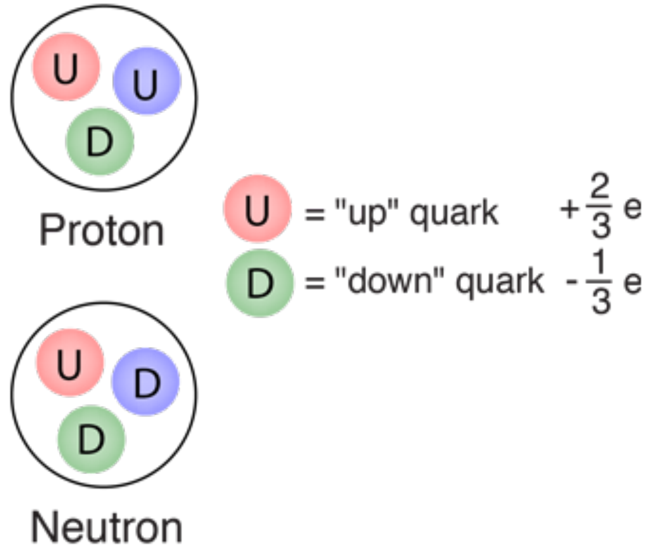
Fermions and bosons

- The elementary particles of matter (leptons & quarks) are all **spin-$\frac{1}{2}$ fermions**
- For composites of elementary particles, spins combine such that **baryons are fermions** (3 spin-$\frac{1}{2}$ quarks → half-integer spin), and **mesons are bosons** (2 spin-$\frac{1}{2}$ quarks → integer spin)
- The carrier particles of the fundamental interactions *(we'll meet those in the next class!)* are all **spin-1 bosons**

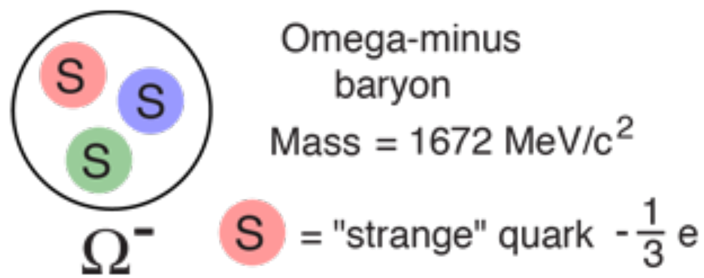


Quark colour

- Given that quarks are fermions, it seems that protons and neutrons cannot exist! – the presence of 2 identical quarks would violate the Pauli exclusion principle?
- 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!

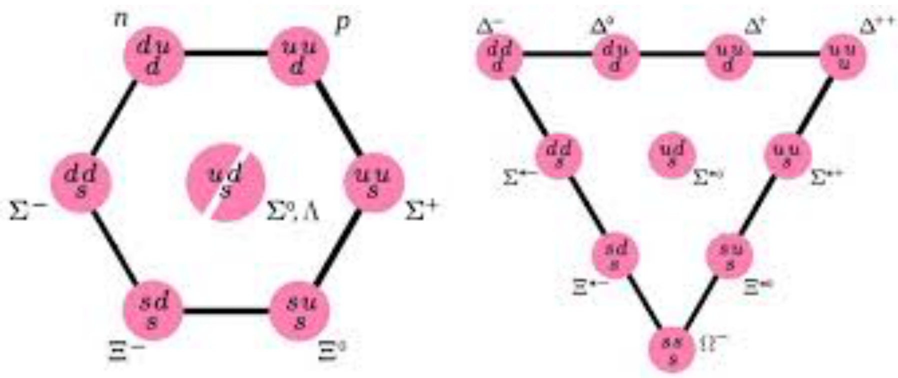


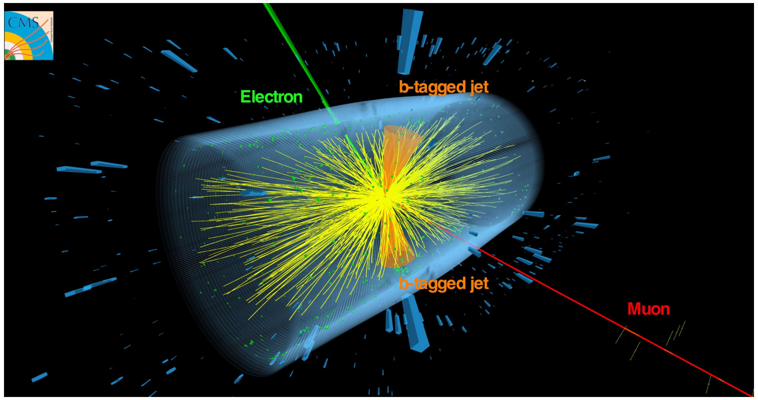
Experimental evidence for quarks

- There are many pieces of experimental evidence for quarks, which we'll discuss in more detail later …

The regularities in the properties of the lightest hadrons

Hadron jets produced by electron-positron and proton-proton collisions





The proton & neutron are not point-like (magnetic moment, scattering)

Observations of quark-antiquark bound states after electron-positron collisions (e.g. charmonium)

Key take-aways

- The fundamental constituents of matter are three generations of **leptons** and **quarks**
- Quarks are confined in **hadrons**: groups of 3 quarks (**baryons**) or quark-antiquark pairs (**mesons**)
- Particles are classified as **fermions** or **bosons** depending on a quantum property called spin. Fermions obey the **Pauli exclusion principle**
- All particles have **anti-particles**, with the same properties but opposite charge
- Quarks come in 3 different **colours**, arranged such that all hadrons have net zero colour