Particle physics: what is the world made of?

From our experience from chemistry has told us about:

Decreasing mass

Name	Mass (kg)	Mass (atomic mass units)
Neutron	1.674×10^{-27} kg	1.008 amu
Proton	1.672×10^{-27} kg	1.007 amu
Electron	9.11×10^{-31} kg	0.0005 amu

Previous lecture on stellar evolution claimed we needed other particles:

- "positive electron"
- (anti-)neutrino (hard to see)

Particle physics: and how do they interact?

1) Electricity : ancient Greeks – electron (jade)

2) Magnetism: magnetic rocks in ancient Greece, Volta – frog legs in storm

3) Electro-magnetism (E&M): **Unified Electricity and Magnetism** James Maxwell 1876

4) Relativity theory: Einstein 1905

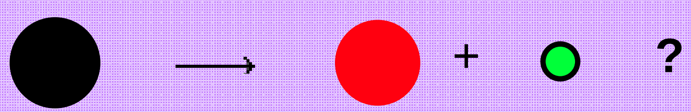
5) Quantum mechanics: Schroedinger, Heisenberg: 1925

6) Quantum Electro Dynamics (QED): **Unified quantum mechanics, relativity and E&M** Dirac 1926

   Verified spectacularly by observation and explanation of Lamb shift, a small shift of the Schroedinger energy levels in hydrogen 1947

Central theme: Unification! Weak interactions?

Weak interaction: responsible for
- neutron transforming into proton (radioactive β decay), and
- proton transforming into neutron inside stars



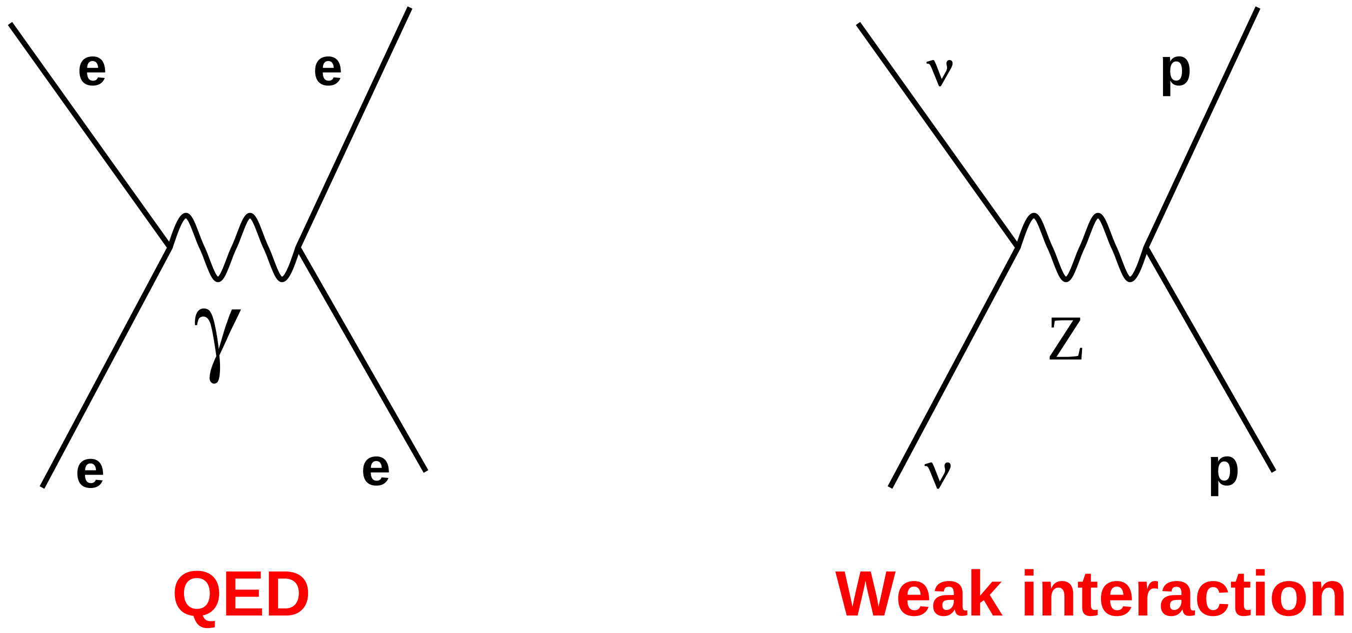
$n \longrightarrow p + e$?

(Free) neutrons turn into protons and electrons in about 15 minutes

Can this be unified with QED? Yes

Weak interaction: Theory

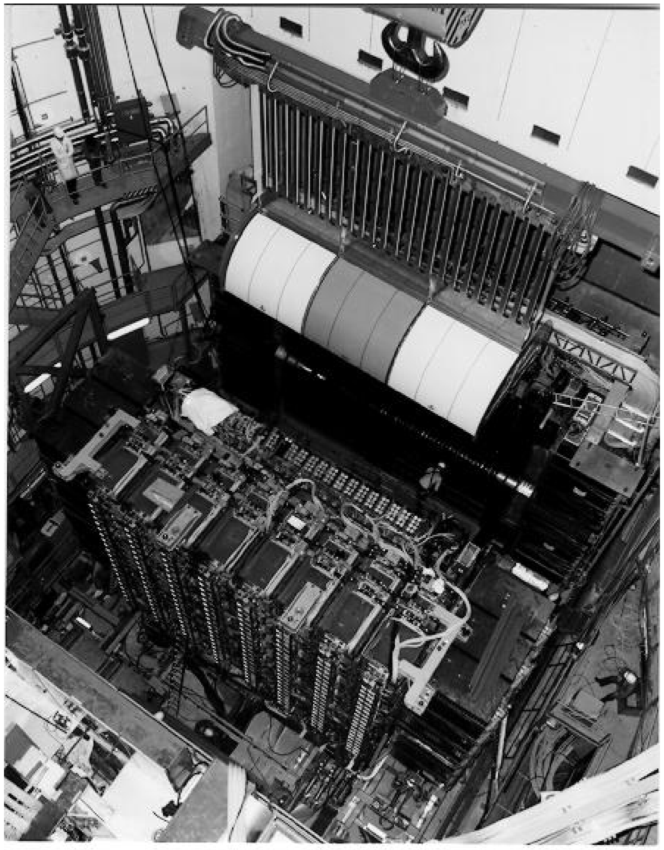
The E&M interaction is mediated by photons
Maybe the weak interaction is also mediated by particles
Glashow, Weinberg, Salam Nobel 1979

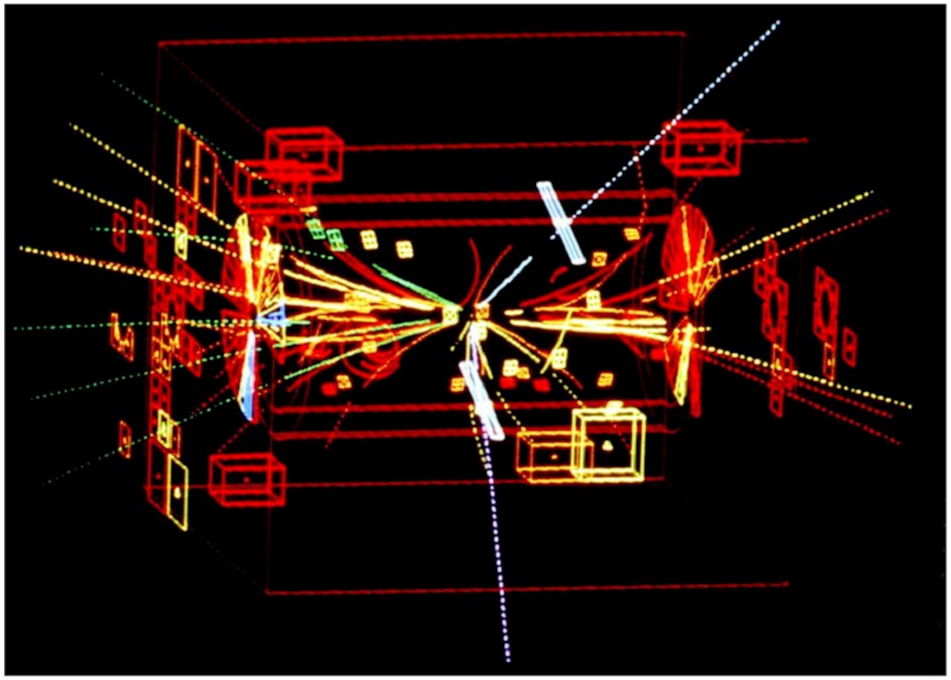


Weak interaction: Experiment

Rubbia: observed 3 W particles

Eventually there are 3 such particles: W+, W- and Z Nobel 1984





Strong Interaction

What keeps the nucleus together?
Nucleons (p, n) attract each other when close

Particles in 1932: Baryon (Greek for heavy) — proton, neutron; Lepton (light) — electron neutrino

Yukawa, the first Japanese Nobelist: **in QED the particles interact by exchanging a particle, the photon. Maybe here again particles will be exchanged**

We need to "borrow" energy to make the pion:

$$\Delta E = m_\pi c^2$$

The furthest this particle could travel before it had to reabsorbed (i.e. "paid back") was estimated by the speed of light.

$$\Delta t \sim \frac{\hbar}{\Delta E}, \quad \Delta d = c\Delta t = \frac{\hbar}{m_\pi c}$$

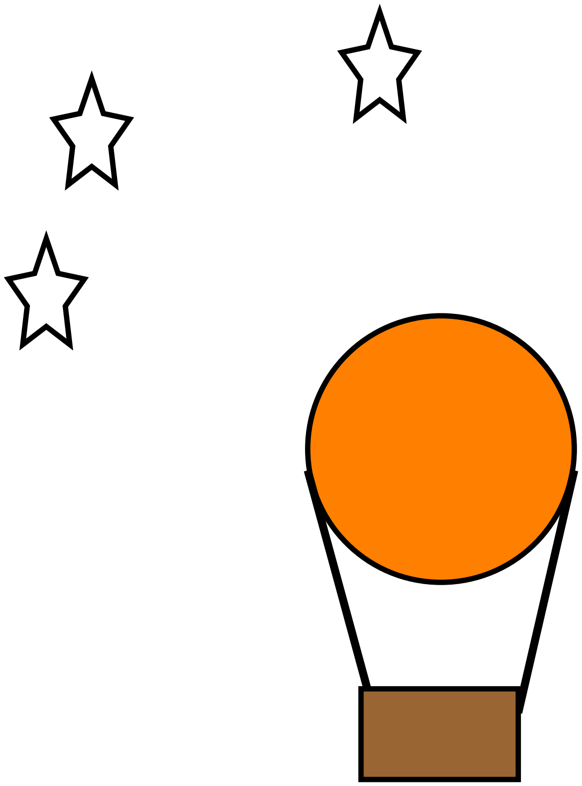
Plug in size of nucleus for distance and we get

$$m_\pi = \frac{\hbar}{rc} \sim 200 \text{ MeV}/\text{c}^2$$

Mass of the observed pions: 140 MeV/c^2.
Could they be the particles that hold the nucleus together?

Observation of Yukawa’s particle

Balloon experiments detected particles in photographic plates in the upper atmosphere.



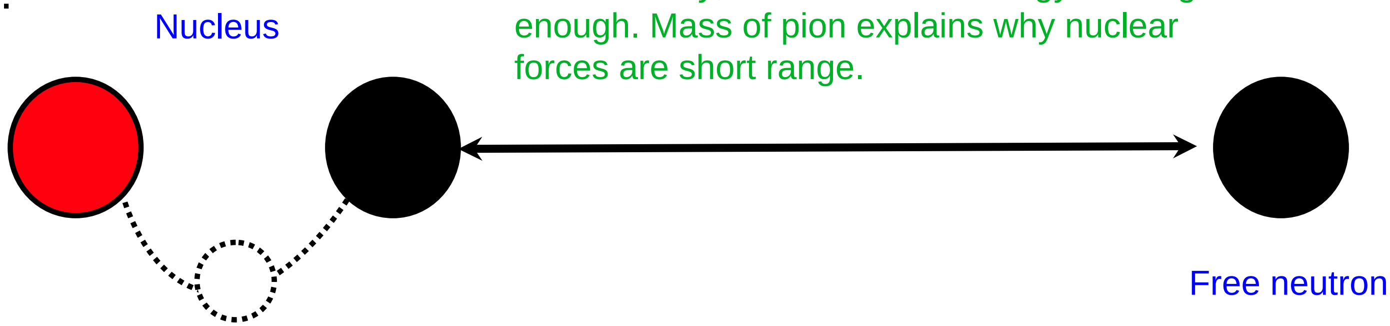
Comes in three varieties:

positive (π^+), negative (π^-) and neutral (π^0)

Pions and the nucleus

In pictures:

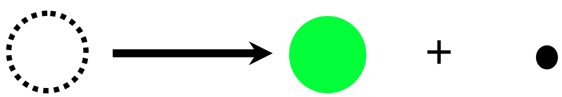
Too far away, cannot borrow energy for long enough. Mass of pion explains why nuclear forces are short range.



“Borrowed” energy makes pion, pion glues nucleons together.

Observed pions have the right mass, and interact with nucleons. Explained how the (positive) nucleus could stay together against electromagnetic repulsion.

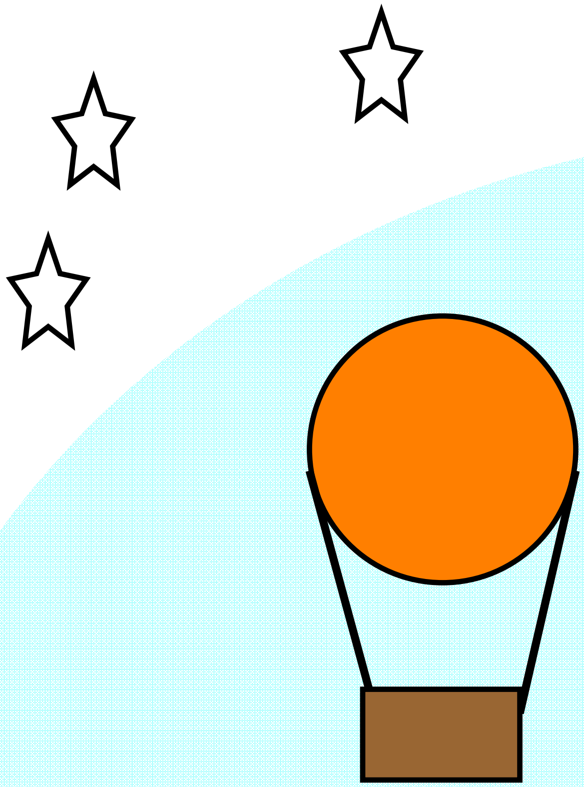
Free pions decay into muons and neutrinos.



$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

wait a second - what is a muon?

This was only the start for many other particles

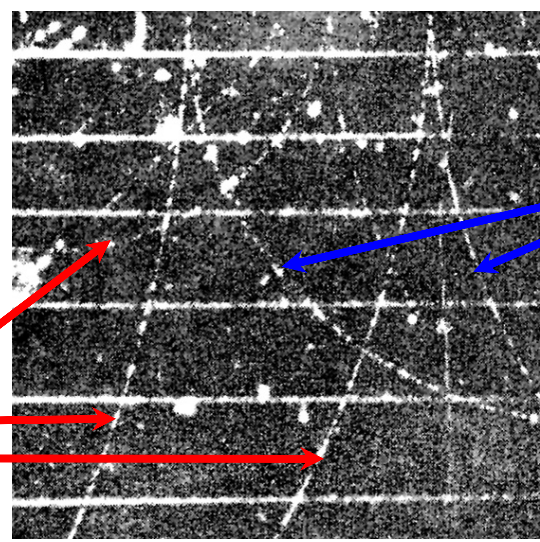


Balloon experiments detect additional weird particles in the upper atmosphere.

Detected in “cloud chambers”.
Water vapour is “supercooled” meaning that a slight disturbance turns vapour into liquid.
Particles travelling through leave a trail of mist behind them

If we have a magnetic field applied then the amount the path bends tells us about the charge and mass of the particle.

Cosmic rays!



These two have opposite charge to the “red” tracks

Tracks bend more if they have

- smaller momentum (i.e small m or small v)
- greater charge

Direction of bending tells us about the sign of charge

Who ordered that?

A muon is almost exactly the same as an electron

- ☑ Spin 1/2 (i.e. fermion)
- ☑ Charge same as electron
- ☑ Interacts the same way

One major difference: muon is 200x heavier!

What could we do with a heavier version of the electron?

"Who ordered that?" -- Isidor Rabi.

i.e. "Reasons" for other particles:
- electrons (chemistry)
- protons (trap neutrons)
- neutrons (help bind nucleus)
- pions (strong force mediator)

But a particle that is "just" an electron but heavier seems unnecessary and redundant.

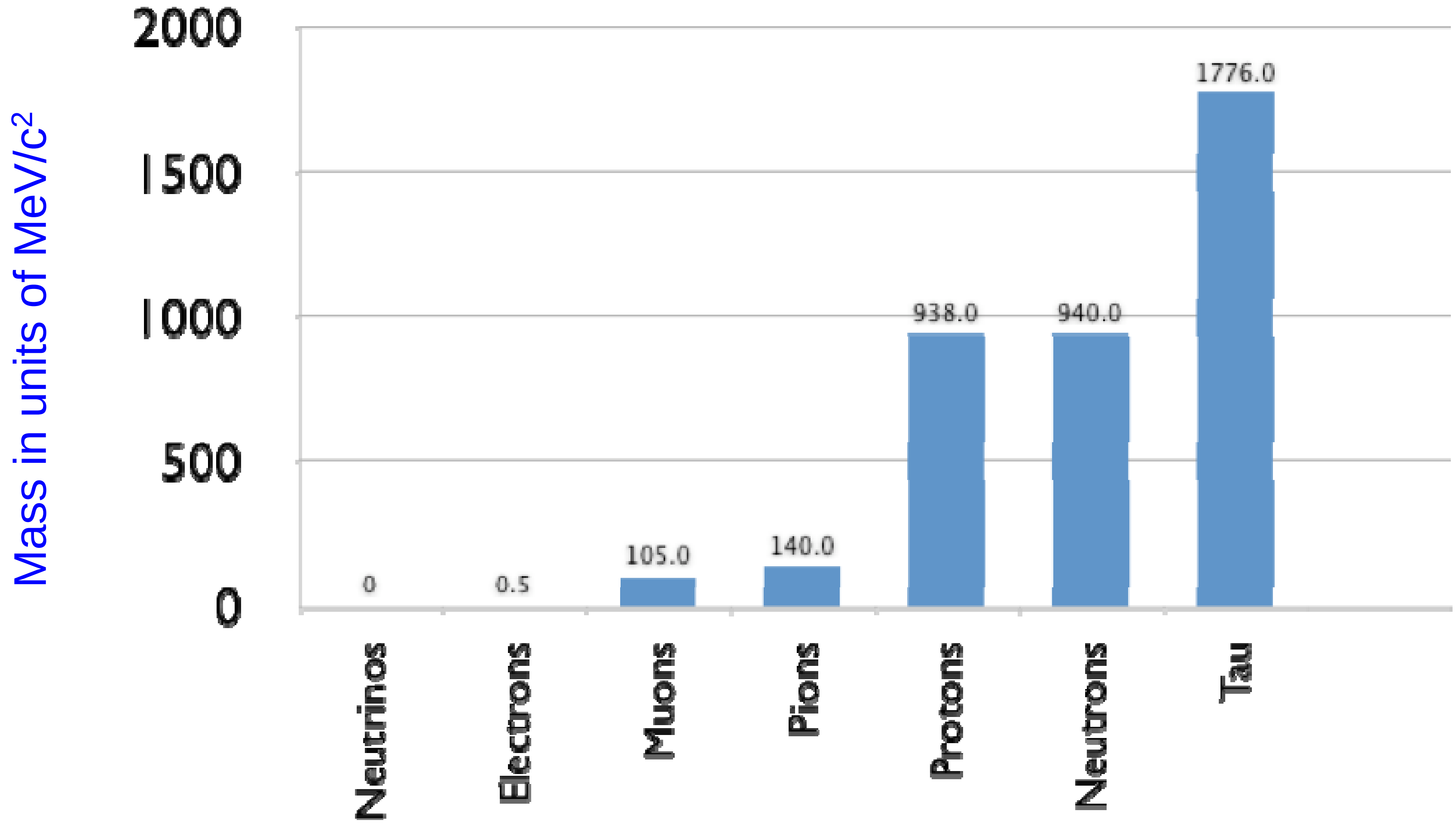
Not liked by physicists, but found in nature. Nature "wins"

Muon also deays!

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

Even worse -- there is an even "heavier" version of the electron-- the tau

Masses of the particles



There is an even heavier version of the electron called the "tau"
M. Perl, Nobel 1995

Welcome to the particle zoo

Versions of the electron: Electrons, muons, tau

Three types of neutrino: electron neutrino, muon neutrino, tau neutrino

Protons, neutrons

Pions (positive, negative and neutral)

Baryons

$$\Lambda^0, \Lambda_c^-, \Lambda_b^-, \Sigma^+, \Sigma^0, \Sigma^-, \Sigma_c^{++}, \ldots,$$
$$\Xi^0, \Xi^-, \Xi_c^+, \ldots, \Omega_c^0, \Omega_b^0, \ldots$$

Mesons

$$\eta, \eta', \eta_c, \eta_b, K^+, K^-, K^0, D^+, D^0, D_s^+,$$
$$B^+, B^0, B_c^+, \rho^+, \rho^0 \omega, \phi. J/\psi, \Upsilon, \ldots$$

Turn on accelerators, HUGE mess of particles!

All these new particles are strongly interacting (like protons and neutrons)

(You don't need to memorize this list - just to emphasize it is a mess!)

Young man, if I could remember the names of these particles, I would have been a botanist!

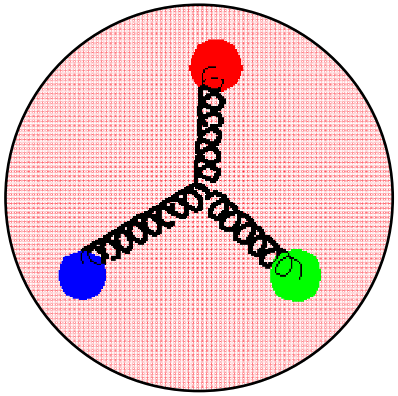
Fermi

The finder of a new elementary particle used to be rewarded by a Nobel Prize, but such a discovery now ought to be punished by a $10,000 fine

Lamb, nobel lecture

Quarks to the rescue

We have seen this problem before: hundreds of elements which can be explained by three particles (+ “magic” to hold the nucleus together)



Proton
Made of 3 quarks: up, up, down

Can these “strongly interacting” particles be made of something themselves? Gell-Mann and Zweig suggested quarks. Quarks are weird:

- Want shells - need Pauli! Quarks are fermions
- Need an additional quantum number (like spin) called color
- Never seen a free quark! – need confinement
- Quarks have **fractions** of an electron’s charge!

Quarks started like the periodic table -- a phenomenological description of strongly interacting particles. Just like chemists had to wait for the Bohr model, we had to wait for years for **Quantum Chromodynamics**

Quarks, quarks, quarks

Quark "flavour"	Charge
Up	+2/3
Down	-1/3
Strange	-1/3
Charm	+2/3
Bottom	-1/3
Top	+2/3

We can explain all of these strongly interacting particles by considering bound states of the six "types" of quarks

Electric charge has "one" type: positive and negative.
(negative really "anti-positive")
Strong charge comes in three types: red, green and blue.

Anything made of quarks interact strongly!

Our theory of strong interactions tell us we can only have colourless particles, which we can get in two different ways:

Mesons: **Two quarks:** red/anti-red, blue/anti-blue, green/anti-green

Hadrons: **Three quarks:** red/green/blue, (all colours but anti)

All particles are mesons, hadrons or do not contain quarks (e.g. electrons)

Where to from here?

Is particle physics done? Have we described the universe at the most fundamental level?

No!

Our "standard model" describes quark/strong interactions, electromagnetic interactions and weak interactions.

Does not describe gravity, does not treat these interactions as related to one another, has many adjustable parameters that seem arbitrary...... And one important particle called the Higgs is still MIA

Perhaps there are more beautiful theories that really tie these forces together (Grand Unified Theories -- GUTs)

Theories that include gravity at a quantum level also desirable as (potential) Theories of Everything (TOEs).

Summary

- **The theory of particles advanced by unifying the seemingly separate theories: electricity – magnetism- relativity – quantum mechanics => QED**

- **Key understanding: Interaction mediated by an intermediary particle:**

- **QED: γ**

- **Weak interaction: W,Z**

- **Strong Interaction:**
  first version: pions between nucleons
  modern version: gluons between quarks

- **Nucleons are made of quarks**