Fundamentals of Particle Physics

Particle Physics Masterclass

Emmanuel Olaiya

The Universe

- The universe is 15 billion years old
- Around 150 billion galaxies (150,000,000,000)
- Each galaxy has around 300 billion stars (300,000,000,000)
- 150 billion x 300 billion stars (that is a lot of stars!)
  - That is a huge amount of material
  - That is an unimaginable amount of particles
- How do we even begin to understand all of matter?

How many elementary particles does it take to describe the matter around us?

3

We can describe the material around us using just 3 particles .

Matter Particles

Quarks

+2/3 u

-1/3 d

Point like elementary particles that protons and neutrons are made from. Hence we can construct all nuclei using these two particles

Leptons

-1 e

Electrons orbit the nuclei and are help to form molecules. These are also point like elementary particles

We can build the world around us with these 3 particles. But how do they interact. To understand their interactions we have to introduce forces!

Force carriers

g^1 g^2 g^3 g^4 g^5 g^6 g^7 g^8

The gluon, of which there are 8 is the force carrier for nuclear forces

Consider 2 forces: nuclear forces, and electromagnetism

The photon, ie light is the force carrier when experiencing forces such and electricity and magnetism

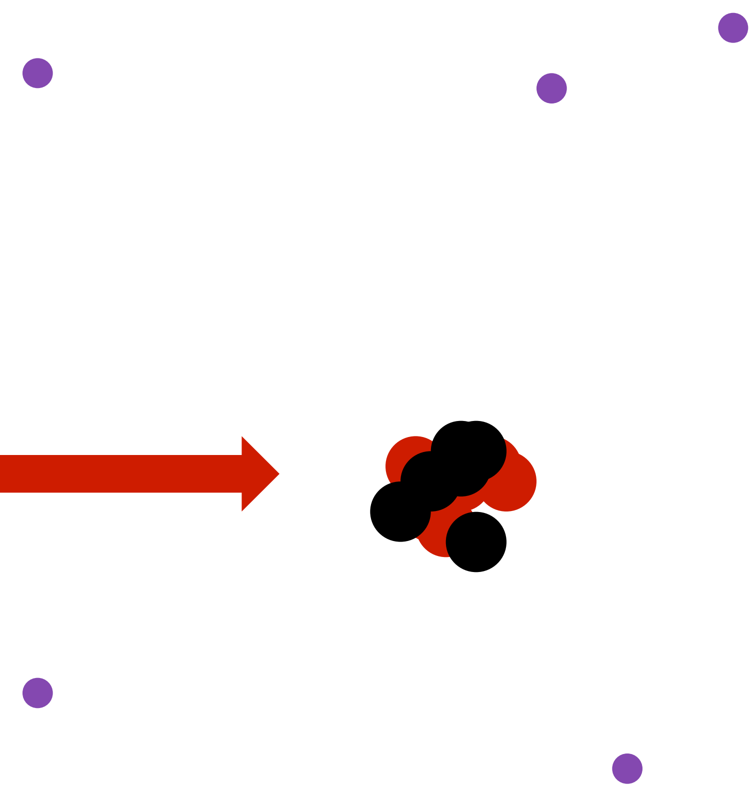
γ

SOME FAMILAR PARTICLES

THE ATOM ≈10^{-10}m

- **electron (-) 0.511 MeV**
  A Fundamental ("pointlike") Particle

THE NUCLEUS →



- **proton (+) 938.3 MeV**
- **neutron (0) 939.6 MeV**

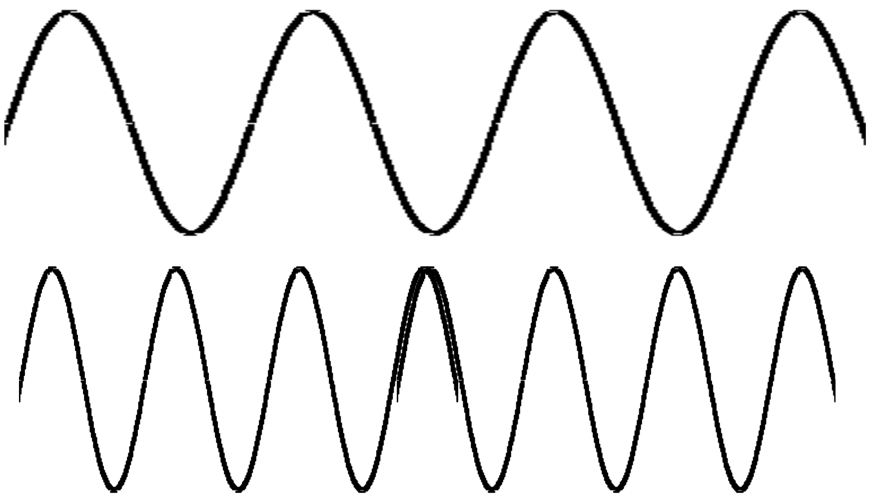
$E=mc^2$. Einstein's equation tells us mass and energy are equivalent

Wave/Particle Duality (Quantum Mechanics)

Einstein $E = h f$ $f =$ frequency (in time)

De Broglie $p = h k$ $k =$ frequency in space!

($k = 1/\lambda$ λ = wavelength)



"low" momentum

"high" momentum

Heisenberg's Uncertainty Principle

$\Delta p \; \Delta x \geq h$ → $\Delta p \geq \dfrac{h}{\Delta x}$

$\Delta x \approx 10^{-15}$ m

⇓

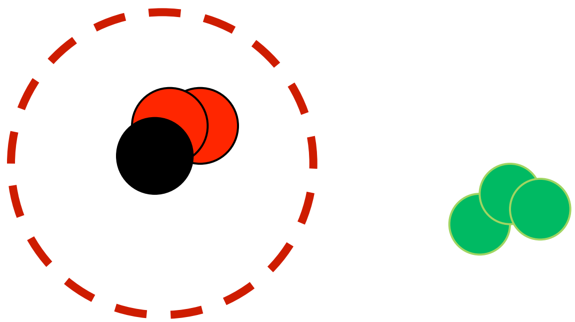
$\Delta p \approx 1$ GeV

The "nucleons" are **composite**:

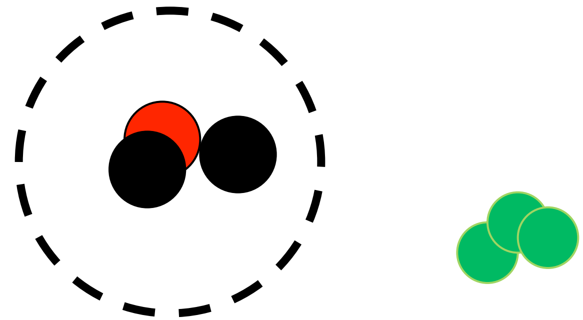
≈10^{-15} m

≈ 1 GeV

proton



neutron



"up" quark (+2/3)

"down" quark (-1/3)

"gluon" (0) 0 MeV

FUNDAMENTAL
("pointlike")
PARTICLES !!!

Quantum Field Theory

(The Standard Model)

- Sounds complicated but there are some simple points
  - Interactions are described by underlying fields
  - The “Quantum” means that the interaction takes place in discrete amounts. The interaction is not continuous, all values are not allowed
  - The field “communicates” via particles
  - Therefore for every field there is a particle!
    - Important when we talk about the Higgs Boson
  - When we consider forces between particles as the interaction, there must be a particle associated with the field that transmits the force
  - We would like to have a quantum field theory for the 4 fundamental forces
    - Strong
    - Weak
    - Electromagnetism
    - Gravity
  - The Standard Model doesn’t describe gravity

Matter Particles (Fermions)

	Charge			
Quarks	+2/3	u ~1 MeV	c ~2000 MeV	t ~175000MeV
	-1/3	d ~2 MeV	s ~100 MeV	b ~5000 MeV
Leptons	-1	e 0.511 MeV	μ 106 MeV	τ 1777 MeV
	0	ν_e ~0 MeV	ν_μ >0 MeV	ν_τ >0 MeV

Force carriers (Bosons)

Strong force carrier

g^1 g^2 g^3 g^4 g^5 g^6 g^7 g^8

Massless

Weak force carrier

W^+	Z^0	W^-
80385 MeV	91187 MeV	80385 MeV

Electromagnetic force carrier

γ

Massless

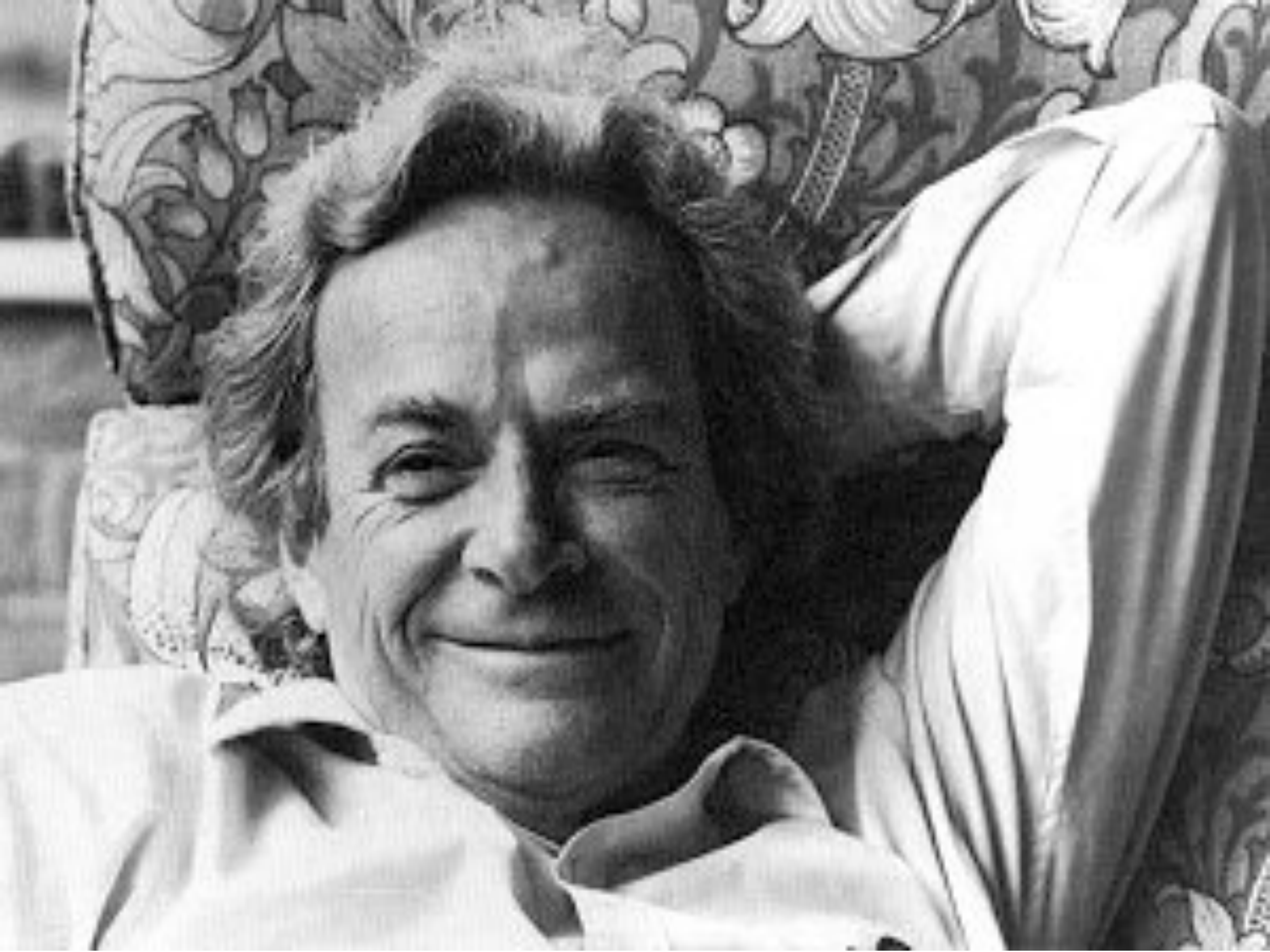
These are Bosons, particles with whole number spin

Particle properties

- Particles are described by their properties
- They have:
  - Mass
  - Charge
  - Intrinsic spin (0,1,2,3.. are called bosons), (1/2, 3/2, .. Are fermions)
  - Interact with specific forces
  - etc.
  - Instead of talking about matter and forces, on a quantum level we talk about fermions and bosons!

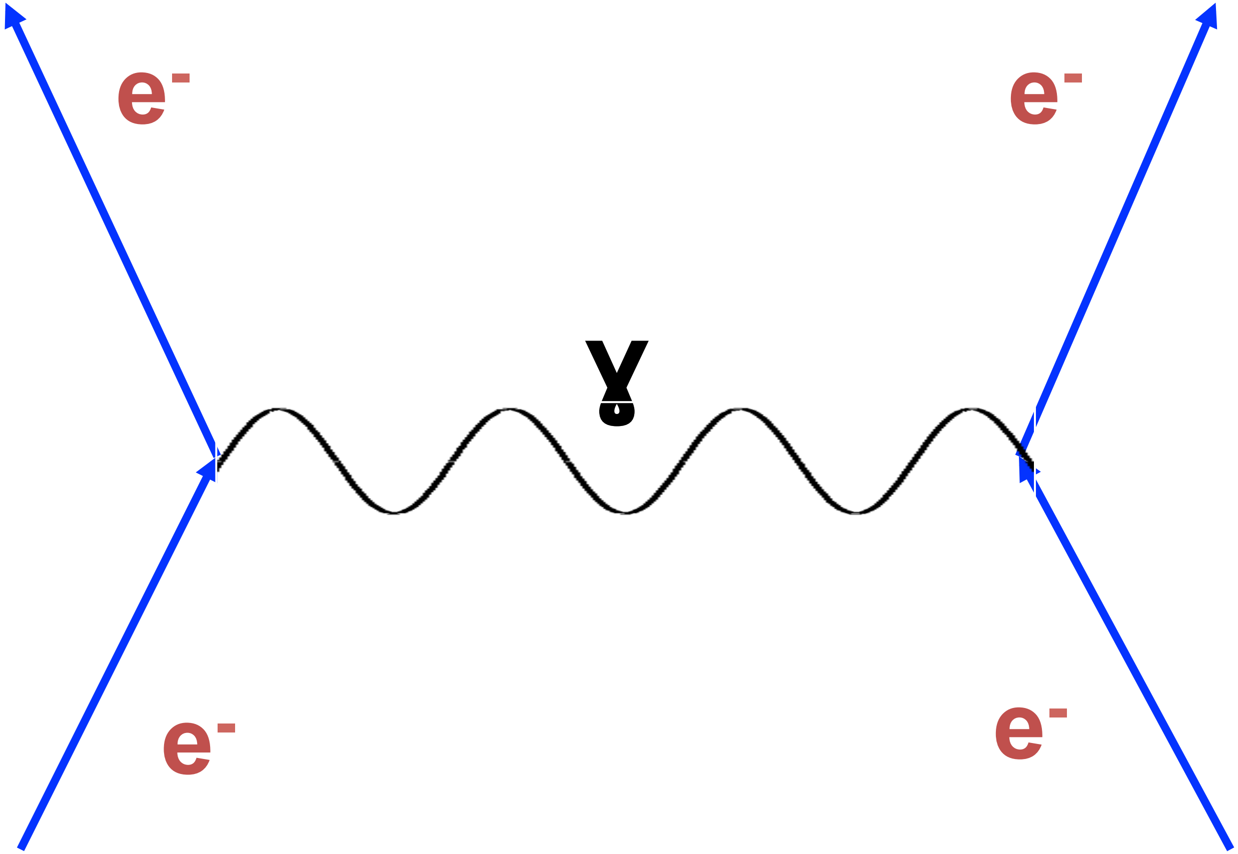
Particle Creation

- How do we create particles?
  - From energy
  - However we must not violate conservation laws, charge, momentum, etc
- Energy has no charge and angular momentum
- So if I create an electron with negative charge and positive angular momentum, I must also create a particle with positive charge and negative angular momentum (positron) for conservation's sake
- Consequently, when you create a particle from energy you also create an antiparticle



Quantum Electro-Dynamics (QED)

Feynman Diagram:



Repulsion of two electrons via the exchange of a photon

"A photon is a particle of light"

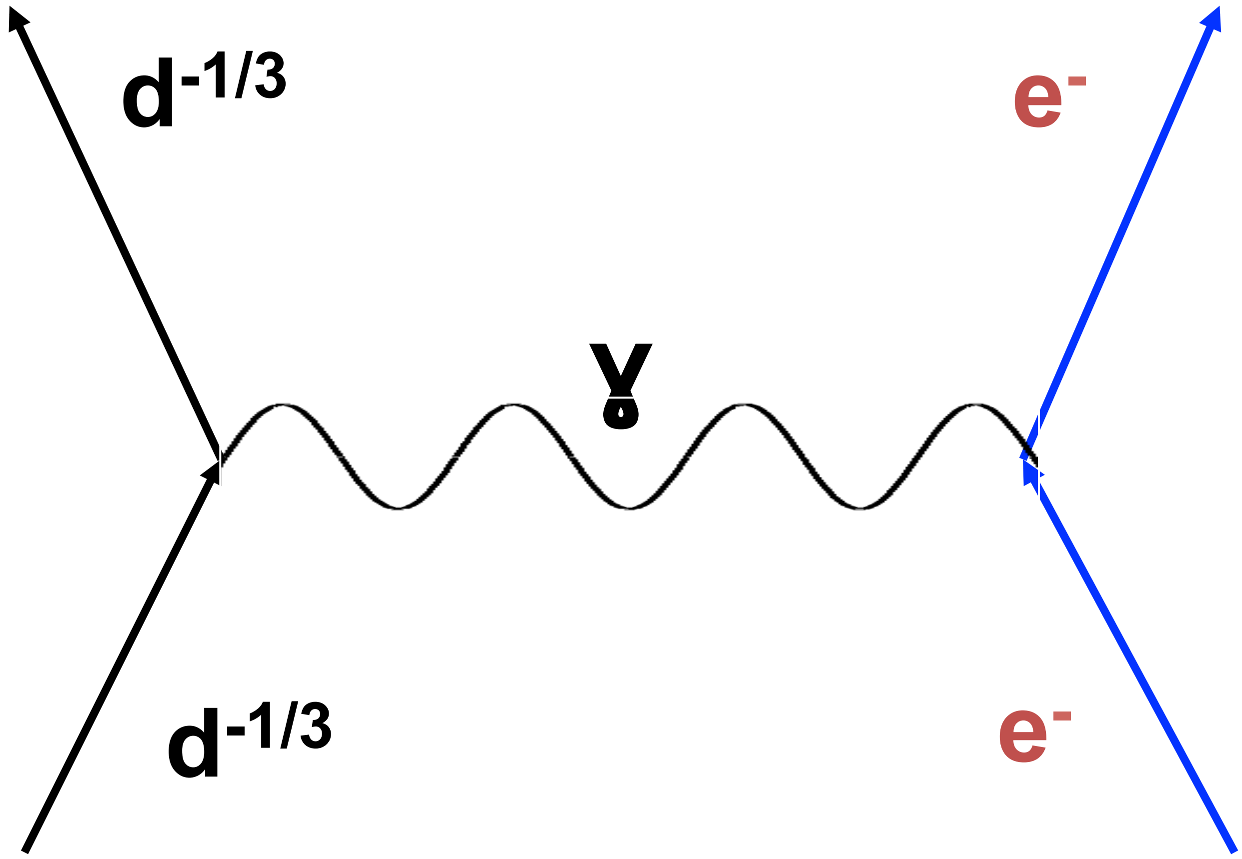
photon (0) 0 MeV

Electrical (and Magnetic) Forces explained by photon exchange!!

How do we know there are quarks inside the nucleons?

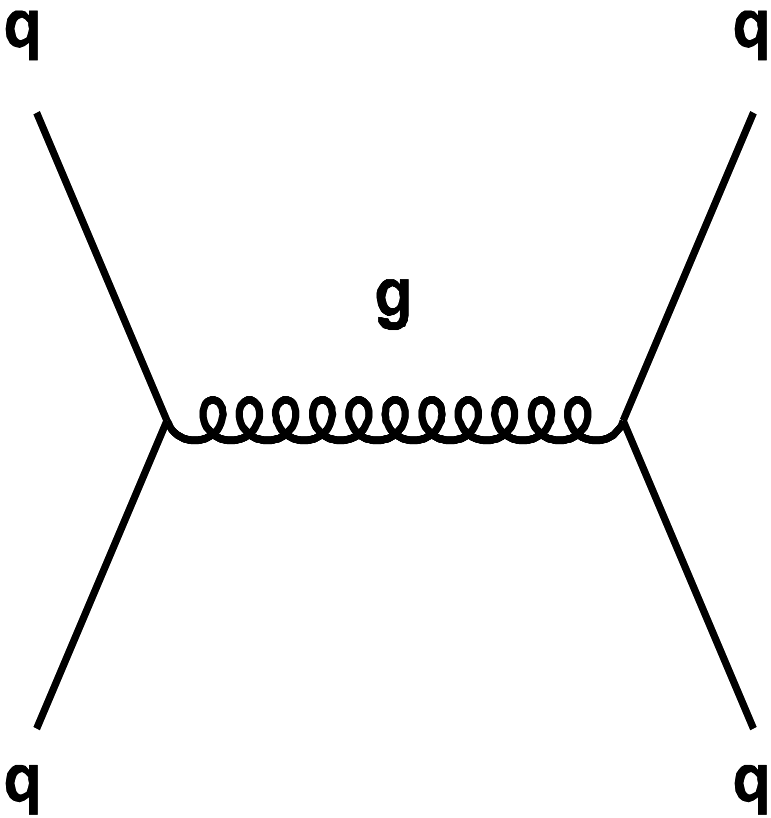
Ans: We can do electron-quark "scattering" and see

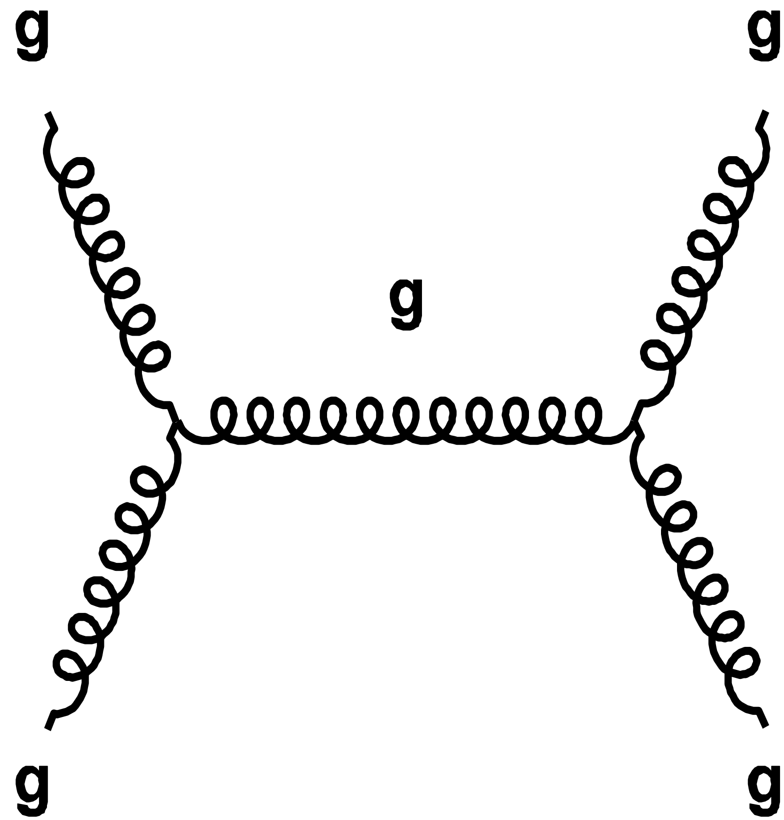
(e.g. at the HERA electron-proton collider)



Quantum "Chromo"-Dynamics (QCD)

(more Feynman diagrams)





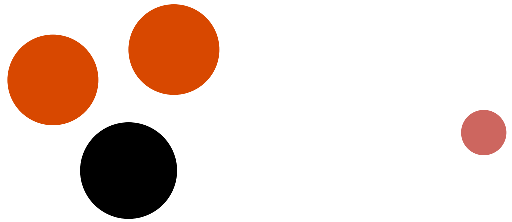
quarks come in 3 "colours"

gluons come in 8 "colours"

Struck quark forms “jet” of “mesons”

meson = quark + anti-quark
composite particle (“hadron”)

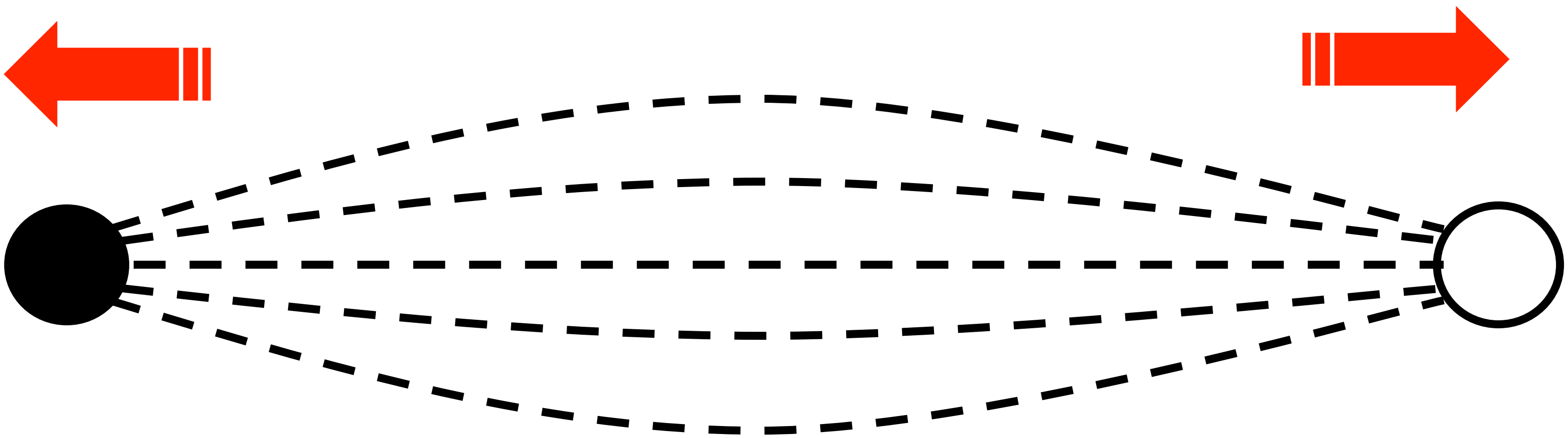
proton



quarks and gluons said to be “confined” in hadrons

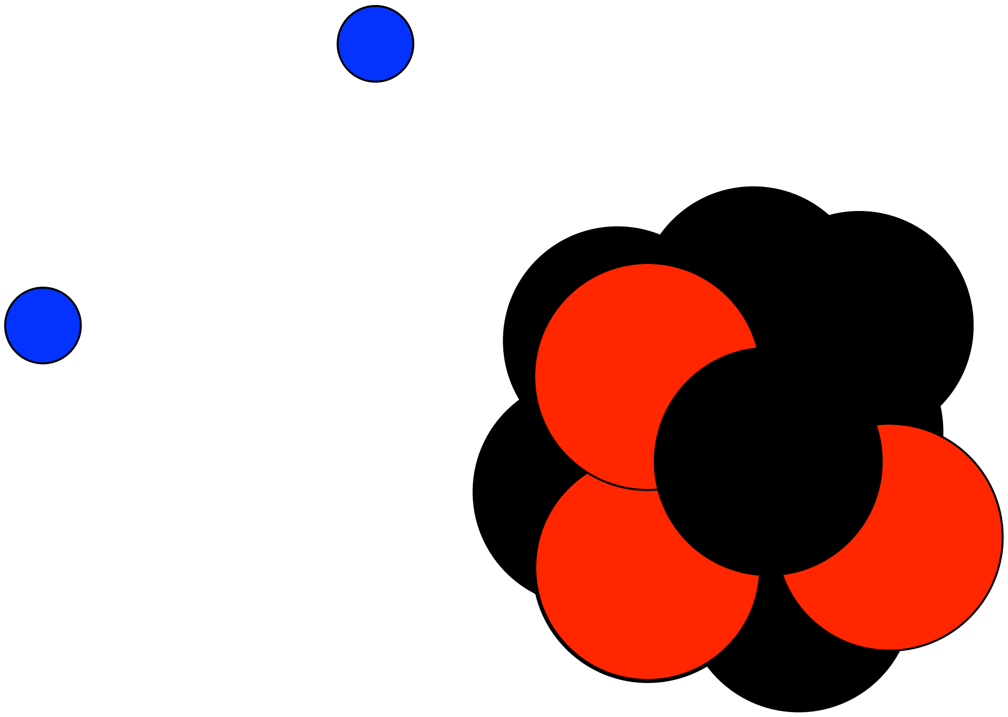
Confinement

Confinement is a property of the strong force.
The strong force works by gluon exchange
but at "large" distance the self-interaction of the gluons
breaks the inverse square-law forming "flux tubes":



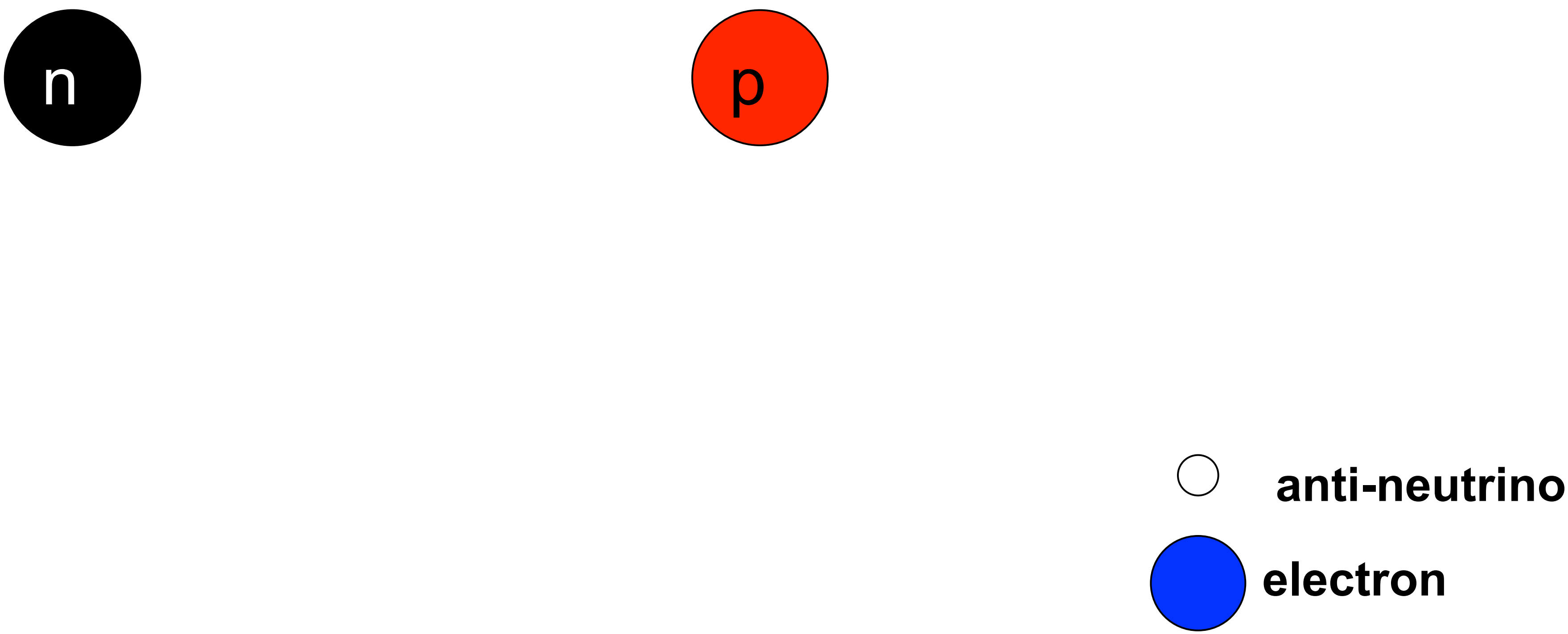
Quarks and gluons carry "colour " quantum numbers
analogous to electric charge –
but only "colourless" objects like baryons (3-quark states)
and mesons (quark-antiquark states) escape confinement.

The “weak” force: β decay

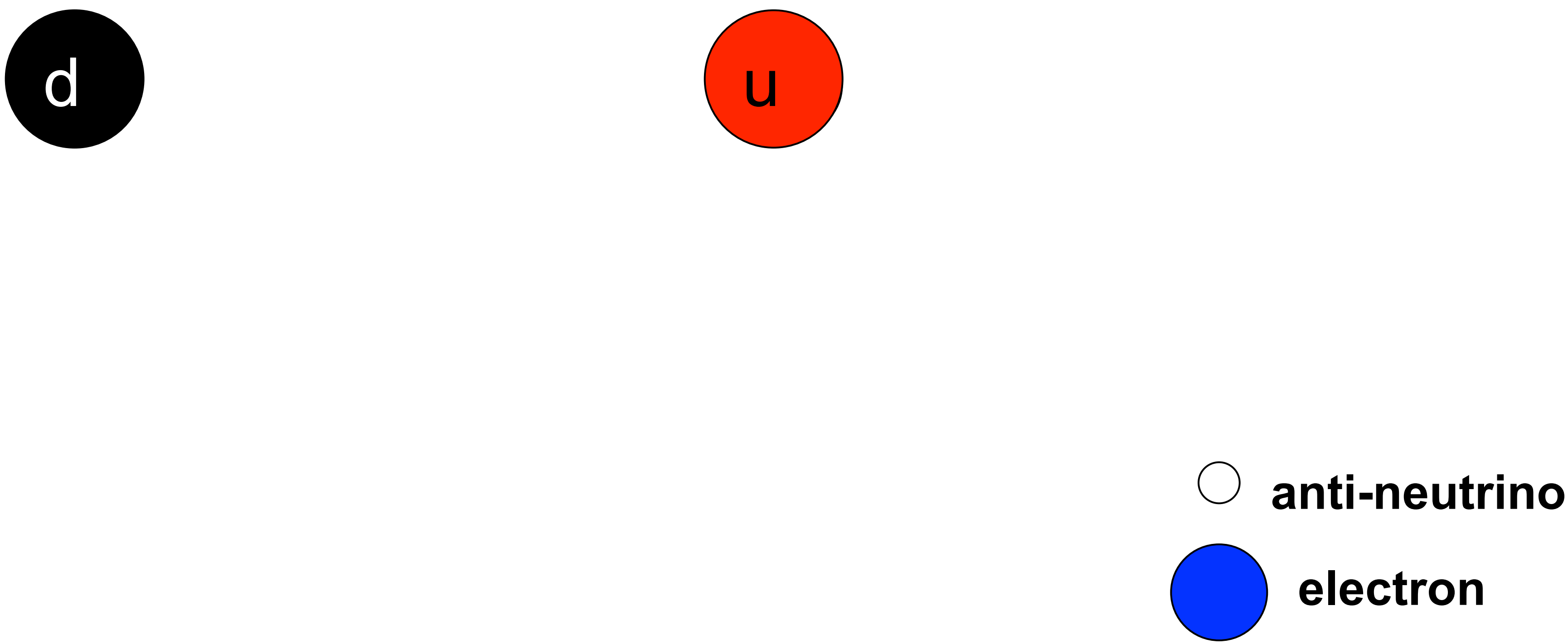


Radioactive β-decay $n \rightarrow p\ e^-\ \bar{\nu}$ is an example of the “weak force” in action!

The free neutron is an unstable particle: ≈15 mins
It beta-decays to a proton with the emission of an electron (e^-) and an (anti-)neutrino

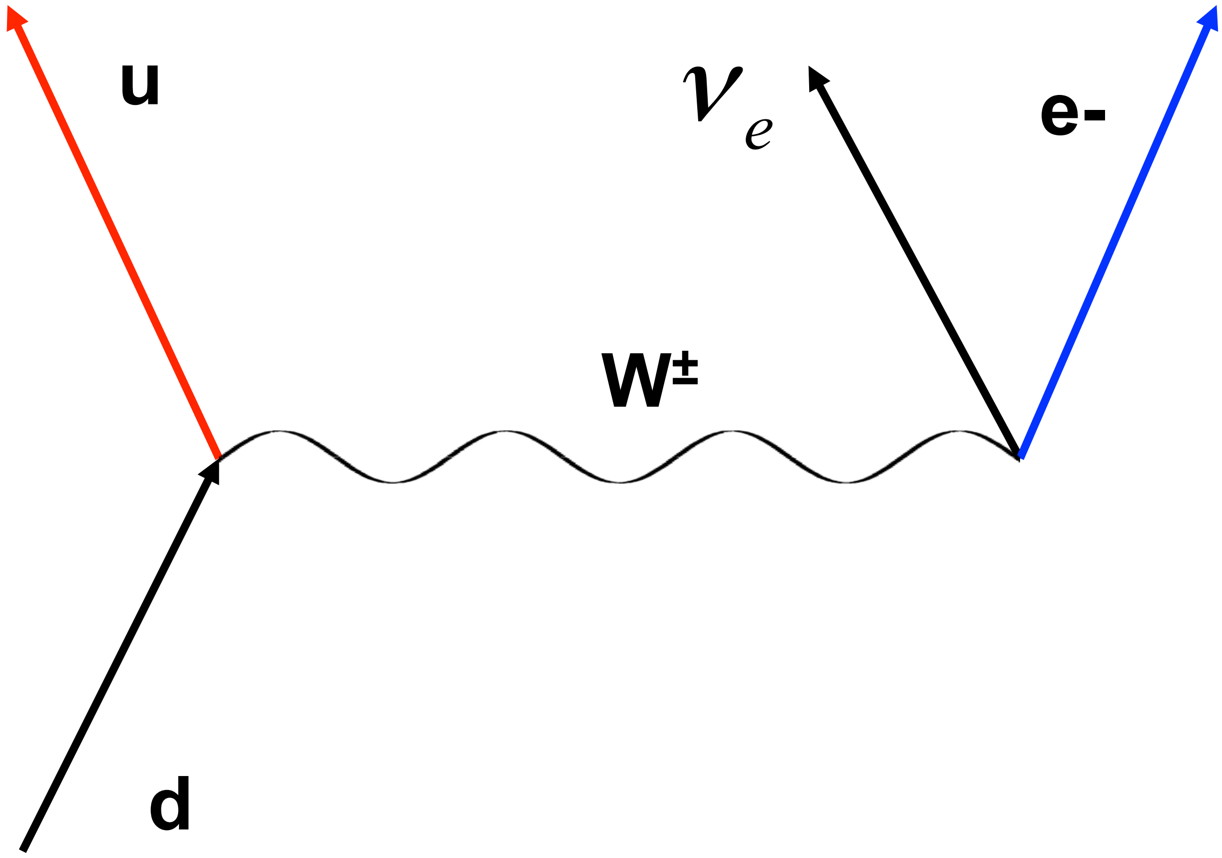


At the level of the quarks, a d-quark in the neutron is changing into an u-quark giving a proton instead:



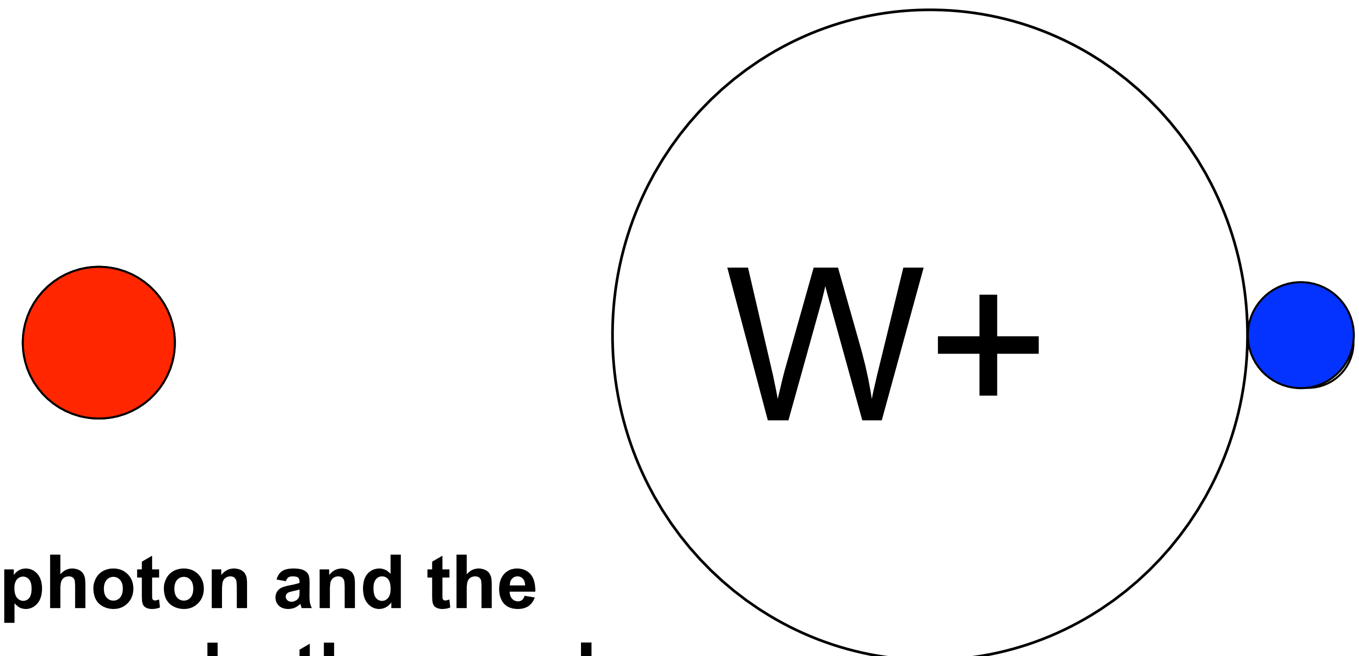
Feynman diagram for beta decay:

(at the quark level)



The weak force is here mediated by W exchange

The weak force only *looks* weak because the W is such a *heavy* particle ≈ 80 GeV (1983)



The photon and the gluon are both massless.

Why are the W and Z bosons not massless also?

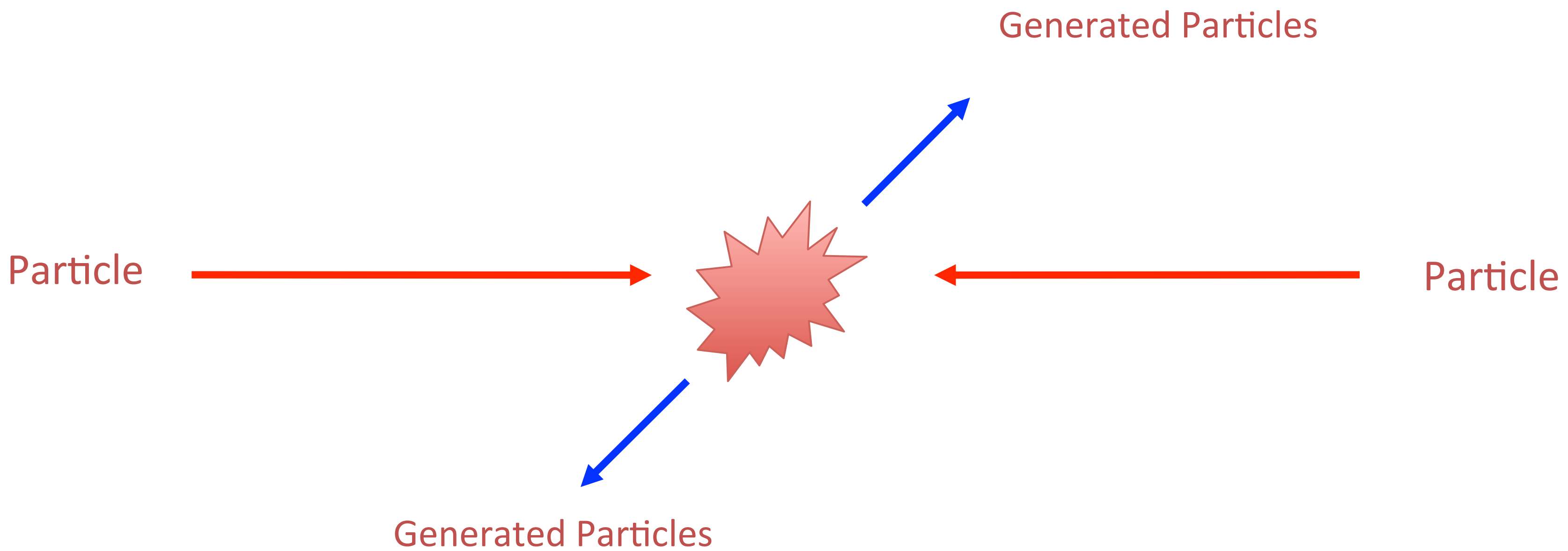
Ans: the W and Z bosons get their masses in the theory via their interaction with the Higgs field!!!

Matter Particles

	Charge			
Quarks	+2/3	u	c	t
	-1/3	d	s	b
Leptons	-1	e	μ	τ
	0	ν_e	ν_μ	ν_τ

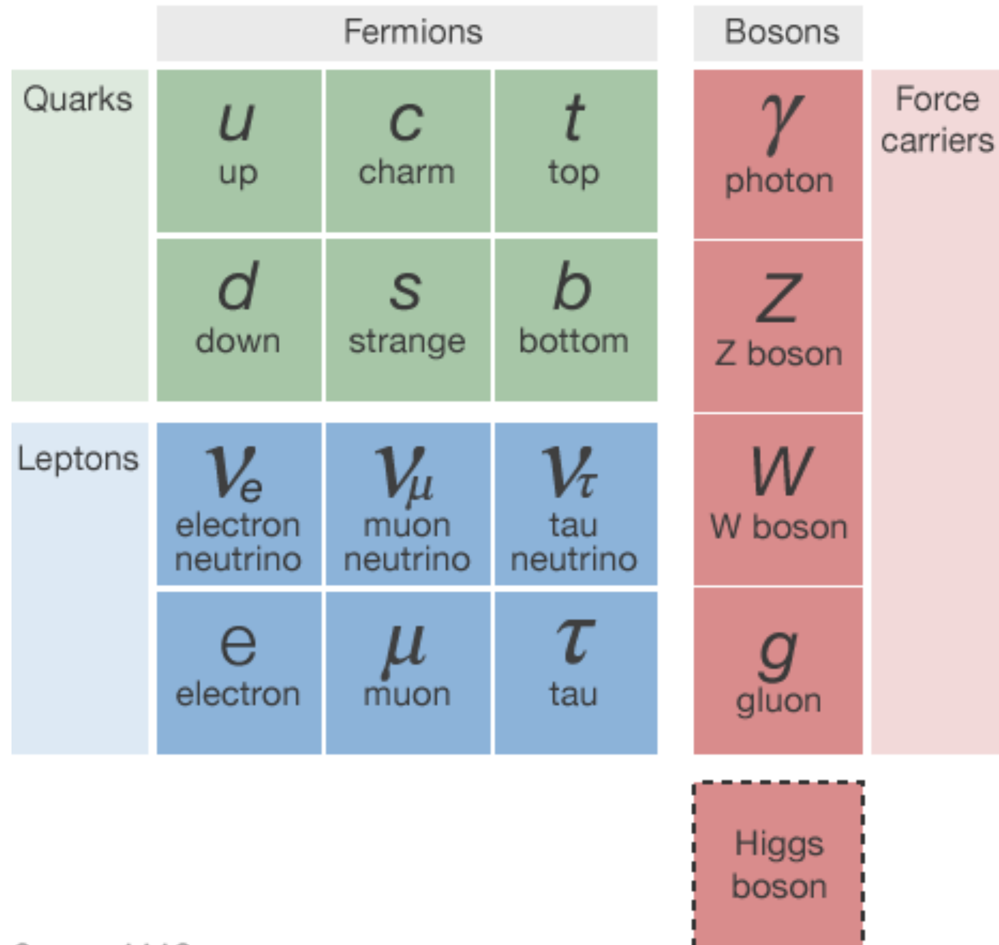
Particle Particle collisions

- How do know about these elementary particle?
- Collide particles together to generate new particles
- The heavier particles are unstable and eventually decay to lighter particles
- From Einstein's equation $E= mc^2$, mass and energy are interchangeable. So we talk about a particles energy and not its mass
- We need to collide particles with sufficient energy to create new particles
- We identify these new generated particles using particle detectors



The Standard Model

- Combining all of these elementary particles we have all the particles that form the Standard Model
- There is just one particle I have not yet mentioned
- The Higgs Boson!



Source: AAAS

The Higgs Boson

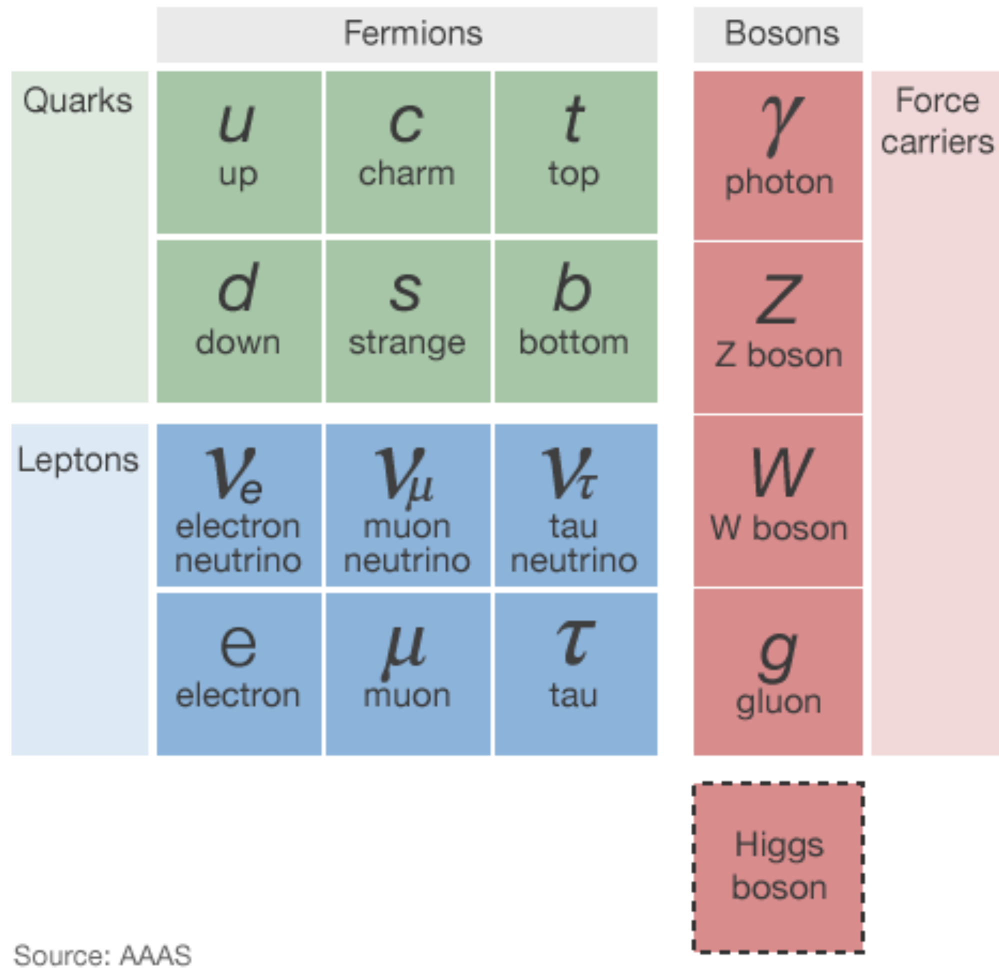
- We have seen that the standard model particles have different masses.
- How do they acquire that mass (think W boson!)
- The standard model particles acquire their mass by interacting with a field that acts over all space. This field is the Higgs field.
- Therefore there must be a particle associated with the field. The Higgs Boson
- If you provide enough energy to the field then you will be able to generate the Higgs Boson from the field. This is how physicists look for the Higgs boson

Higgs Boson Analogy

- Imagine pulling a light object. Then imagine pulling the same object through water. In water the object seems “heavier” when you pull it. The analogy is that the water is the Higgs field and in water the object acquires mass (“feels heavier”)

The Standard Model

- The Standard model describes particle interactions to a very high precision
- But there are some problems
- I'll mention a few. Can you see a problem?



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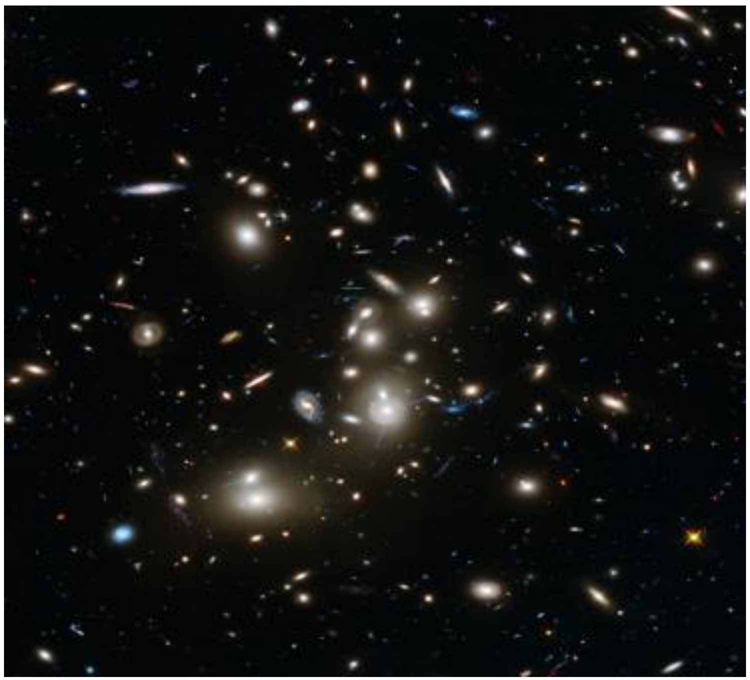
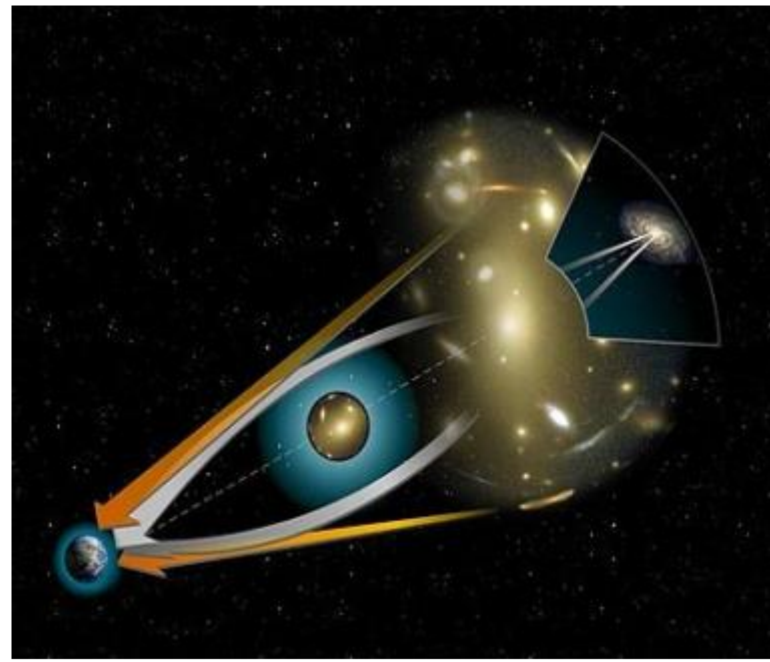
Gravity

- Our understanding of gravity is impressive
- Using Einstein's theory of general relativity we can describe the behaviour of gravity very well
- For example

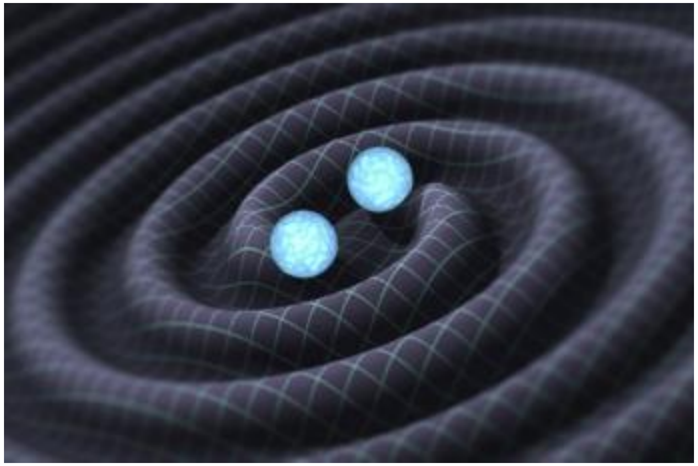




We can explain the duplication of galaxies via gravitational lensing

Gravitational Waves

- Gravitational waves were also predicted by Einstein and their discovery by the LIGO experiment is further evidence to supporting the theory
- Gravitational waves are distortions of space-time caused by some of the most energetic processes in the universe
- LIGO detected two black holes each around 30 times the mass of our sun orbiting each other with a frequency rising up to 250 times a second until they eventually collided



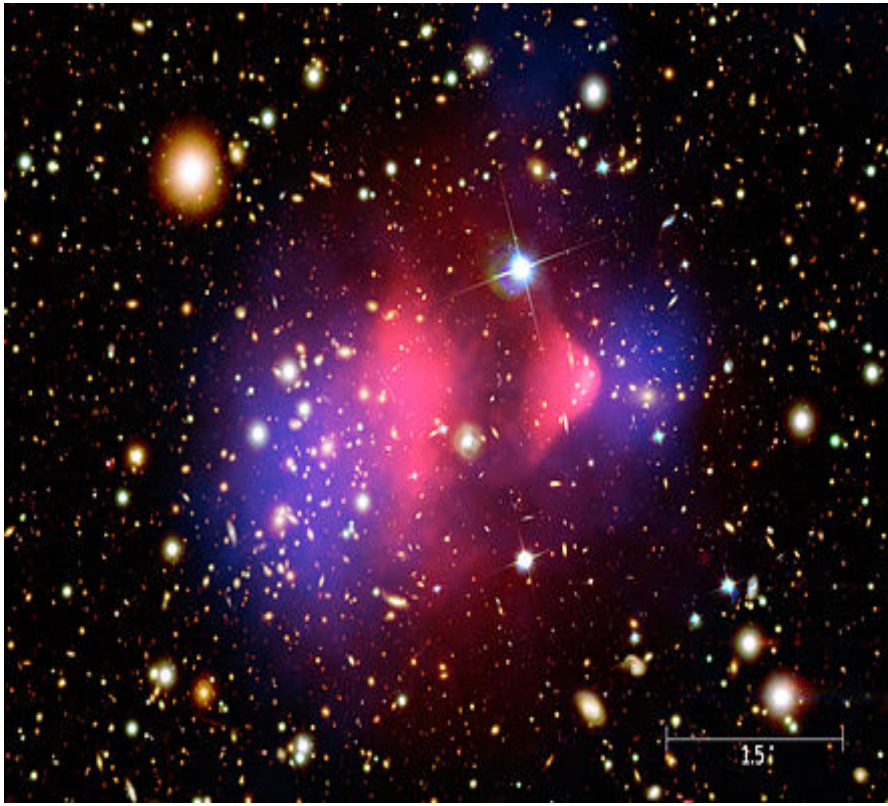
- LIGO detected how this event 1.3 billion light years away distorted space time here on earth.
- They measured how the wavelength of a laser beam they generated was distorted by the gravitational waves
- We can explain how gravitational waves distort space-time

Gravity

- However we cannot explain gravity as a quantum field theory
- The force carrier for gravity (graviton) has not been found and is not a part of the standard model
- We know so much but yet so little!

Missing matter

- Still, our understand of gravity is very good. It helps point out another problem with the Standard Model
- From the orbits of galaxies and other bodies we can calculate the mass of the central body. In space we see that the mass calculated is much greater than what we can detect. There is missing matter out there that we cannot detect
- A famous illustration of this is the Bullet Cluster
  - The aftermath of two galaxy clusters colliding
  - The red shows that matter detected by x-rays (standard model particles). They collide and progress no further
  - The blue shows the matter detected by gravitational lensing. They pass right through each other uninterrupted and continue to the ends of the picture



The Stand Model cannot explain this!

Conclusions

- We have a great understanding of fundamental physics
- Our understanding has grown with the discovery of the Higgs Boson
- Though there are some interesting questions still to be answered
- What is Dark matter?
- What is Dark energy?
- What about gravity?
- The LHC is now taking data again at much higher energy.

Hopefully some of these questions will be answered there!