The Standard Model

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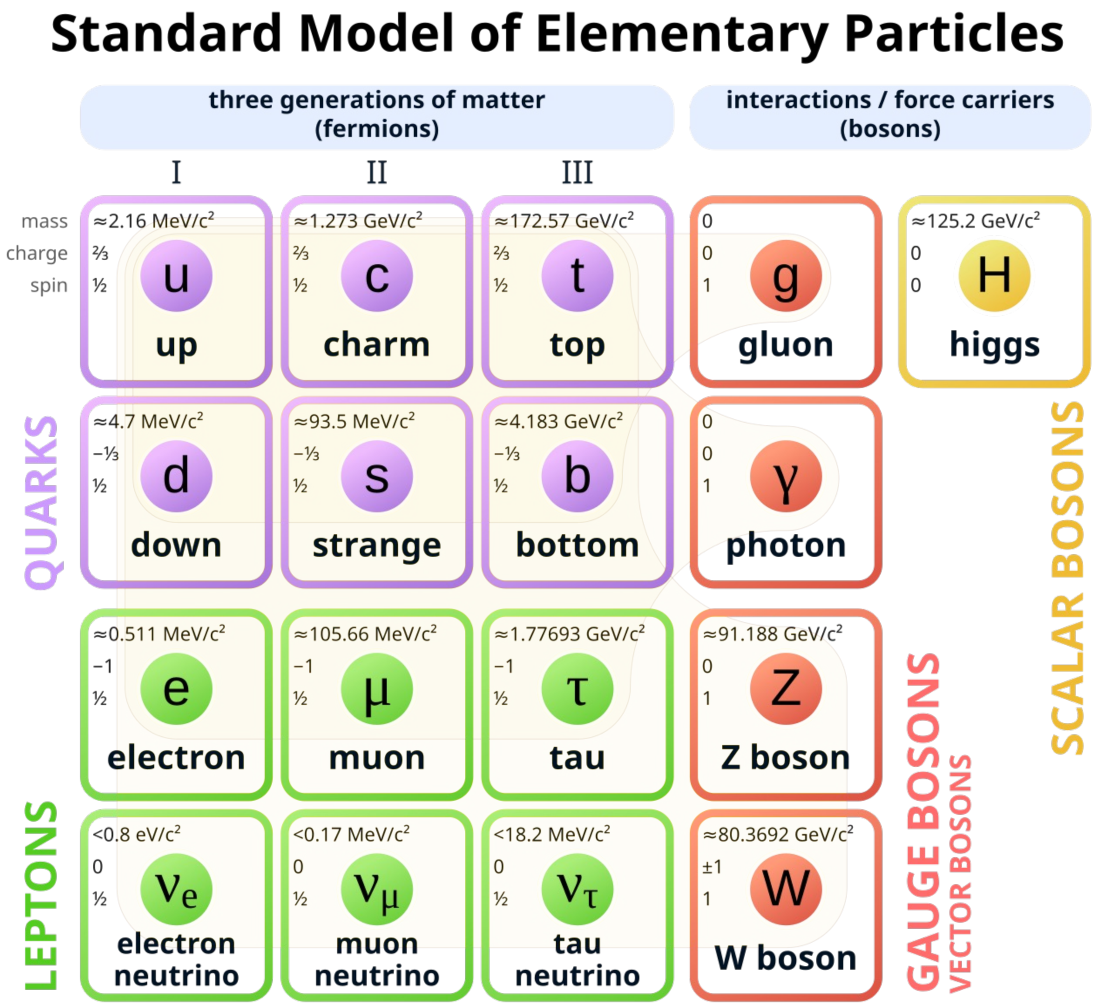
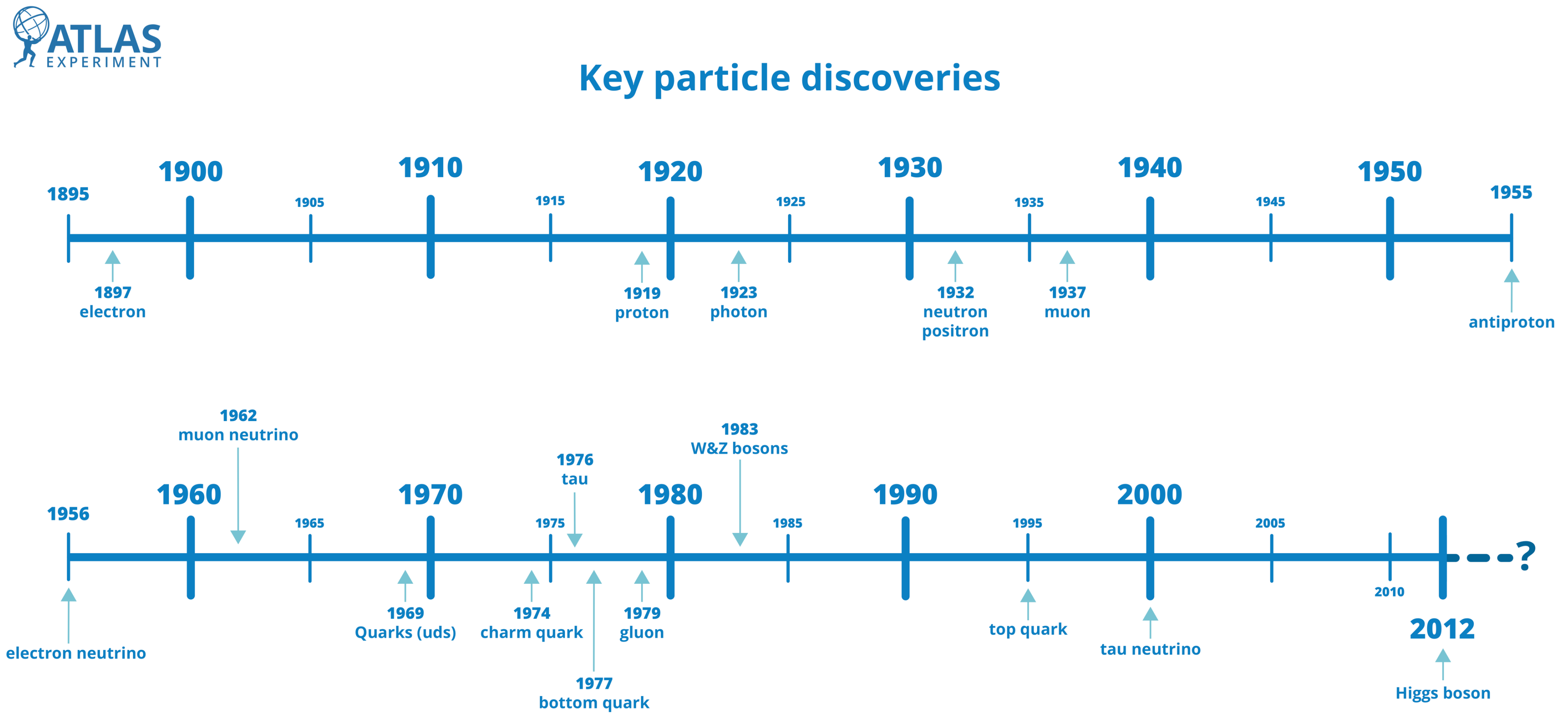
What is the Standard Model?

- The Standard Model is the theory that describes the **fundamental** particles that make up the Universe and how they interact with one another.
- Fundamental means that these particles are the smallest known building blocks of nature, they cannot be broken down into smaller pieces.
- This lecture will cover a bit of about what these particles are and how they interact.
- Do you recognise any particles from the table?



Timeline

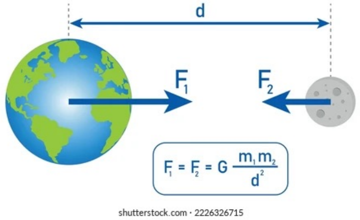

ATLAS
EXPERIMENT
Key particle discoveries
1895
1900
1905
1910
1915
1920
1925
1930
1935
1940
1945
1950
1955
1897
electron
1919
proton
1923
photon
1932
neutron
positron
1937
muon
antiproton
1962
muon neutrino
1983
W&Z bosons
1976
tau
1956
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
?
electron neutrino
1969
Quarks (uds)
1974
charm quark
1977
bottom quark
1979
gluon
top quark
tau neutrino
2012
Higgs boson

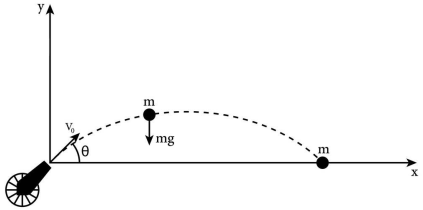
Building the framework

Classical Mechanics (Newton)

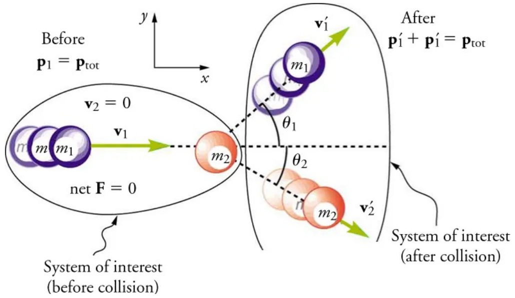
Newton

- Objects move according to forces (change in momentum)





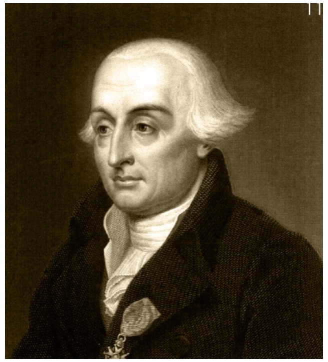
- Energy and momentum of a system is conserved



- So, if we want to describe a system we care about the: Forces, momentum (mass and velocity) and energy

Classical Mechanics (Lagrangian)

There is a more complicated why to get the equation of motion using something called the Lagrangian



Lagrange

Lagrangian

$$L = T - V$$

T: Kinetic Energy; V: Potential Energy

Equation of motion

Euler-Lagrange equation

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}}\right) - \frac{\partial L}{\partial q} = 0$$

$\frac{\partial L}{\partial \dot{q}}$: Momentum; $\frac{\partial L}{\partial q}$: How Energy Changes with Location; q: Generalized Coordinates

Euler

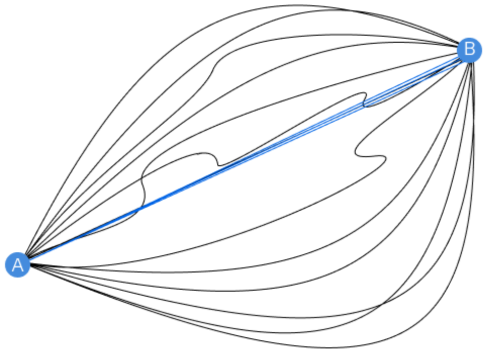
Principle of least action,

A moving object naturally follows a path which minimises the action. $\delta S = 0$

$$S = \int_{t_i}^{t_f} L dt$$

Action

Blue lines -Least action and paths closeby



Using a Lagrangian is more useful for more complex problems due to it being invariant under symmetries.

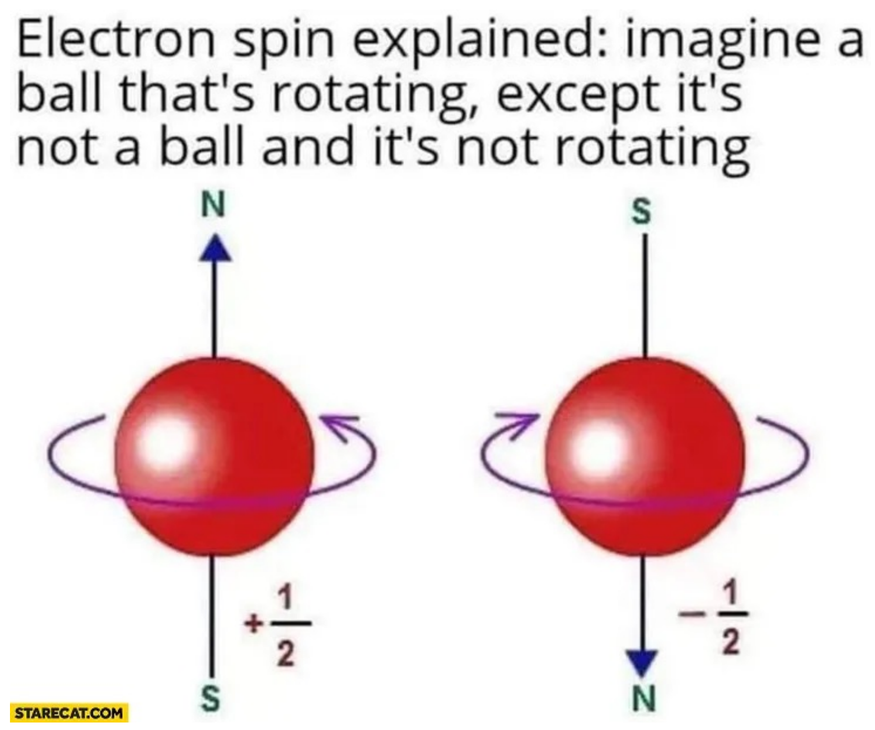
Quantum Mechanics

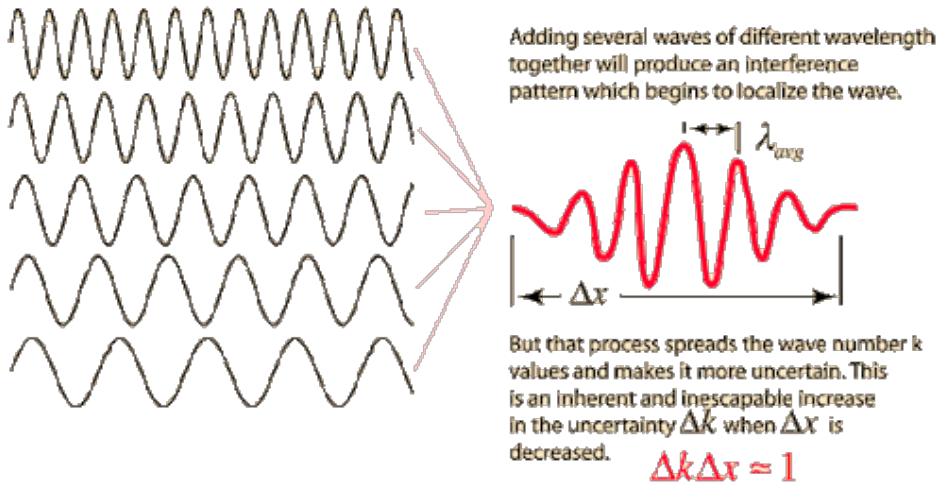
- Particles are quantum objects.
  - They have intrinsic properties (charge, mass, spin)
  - Behave both like particles and waves

- Outcomes are probabilistic

- Uncertainty Principle
  - Some pairs of properties cannot both be known at the same time

$$\Delta t \Delta E \geq \frac{\hbar}{2} \qquad \Delta x \, \Delta p \geq \frac{\hbar}{2}$$



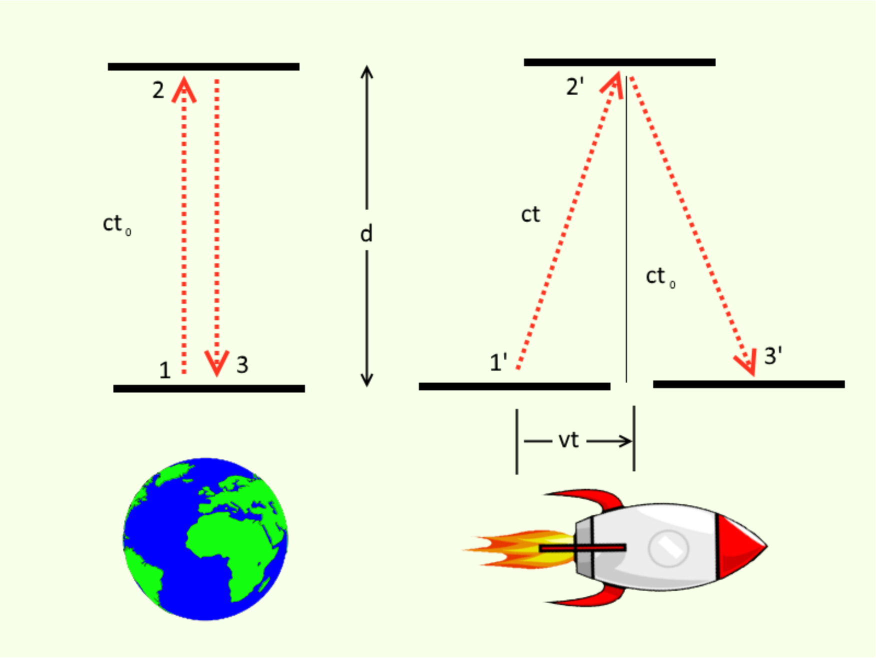


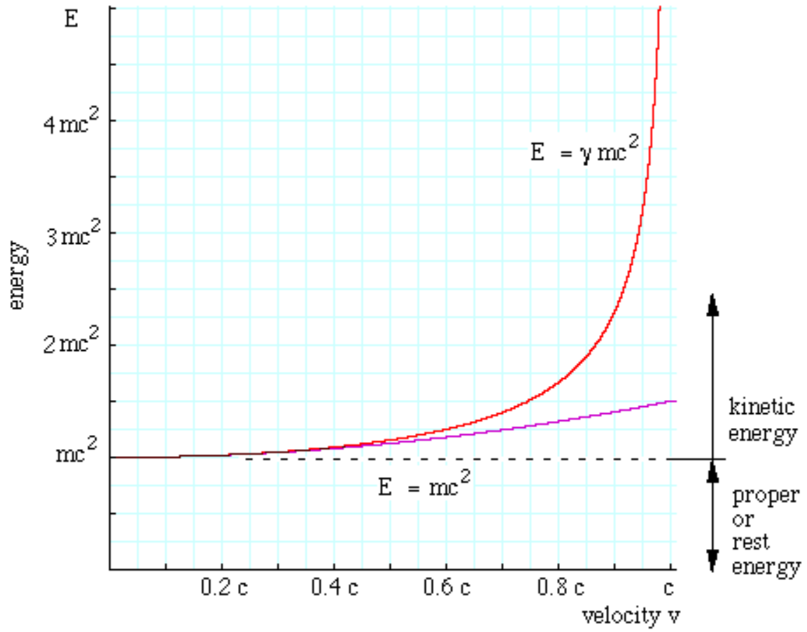
Special Relativity

- Speed of light is a constant
- Time and distance and relative
  - Moving clocks run slower
- You can change reference frames
- Mass is a form of energy

energy, mass, speed of light, momentum

$$E^2 = (mc^2)^2 + (pc)^2$$





Quantum Field Theory

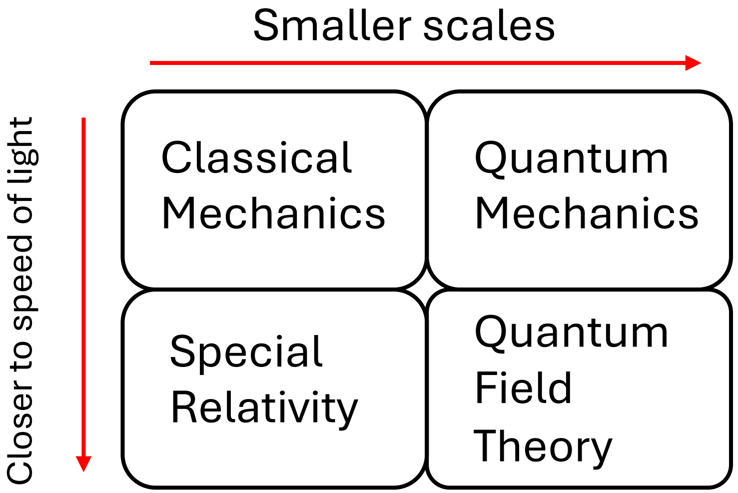
- Quantum Field Theory is the framework which describes the Standard Model
- It is the combination of classical mechanics, quantum mechanics and special relativity.
- Lagrangians are used to describe the system

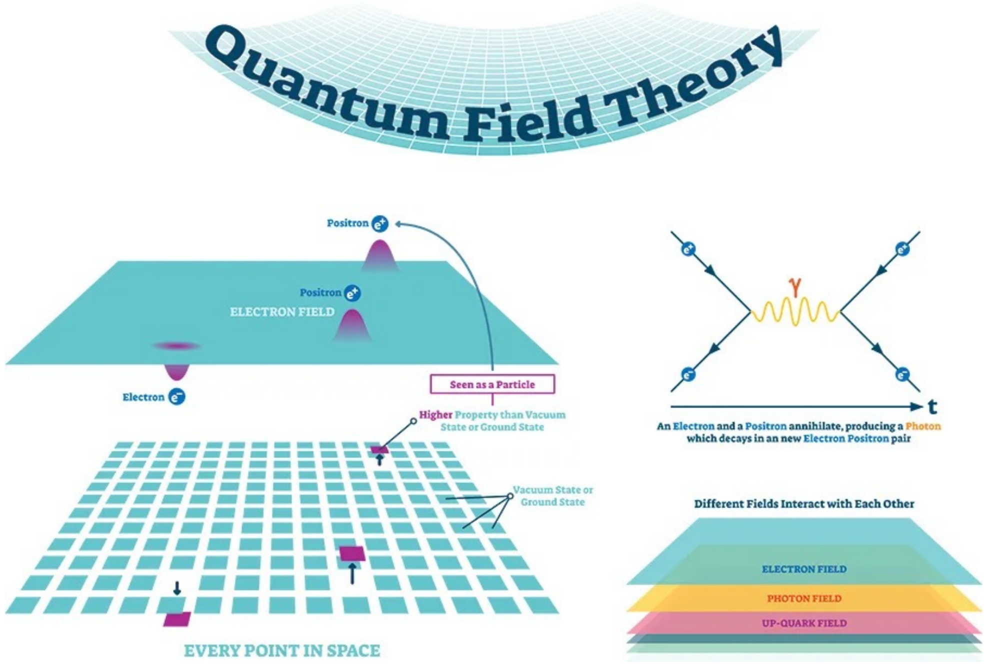
$$\mathcal{L} = \frac{1}{2}\partial_\mu \phi \partial^\mu \phi \; - \frac{1}{2} m^2 \phi^2 \; - V(\phi)$$

Kinetic mass potential

Main Ideas:

- The Universe is filled with quantum fields
- Every fundamental particle has its own field
- Particles are tiny excitations in these fields
- Forces arise from interactions between the fields





Leptons and QED

Leptons

Leptons are fermions

- Spin = ½
- Follow the Pauli exclusion principle
    - No two particles with the same quantum numbers can be in the same place

Charged (electron) and neutral (neutrino) leptons

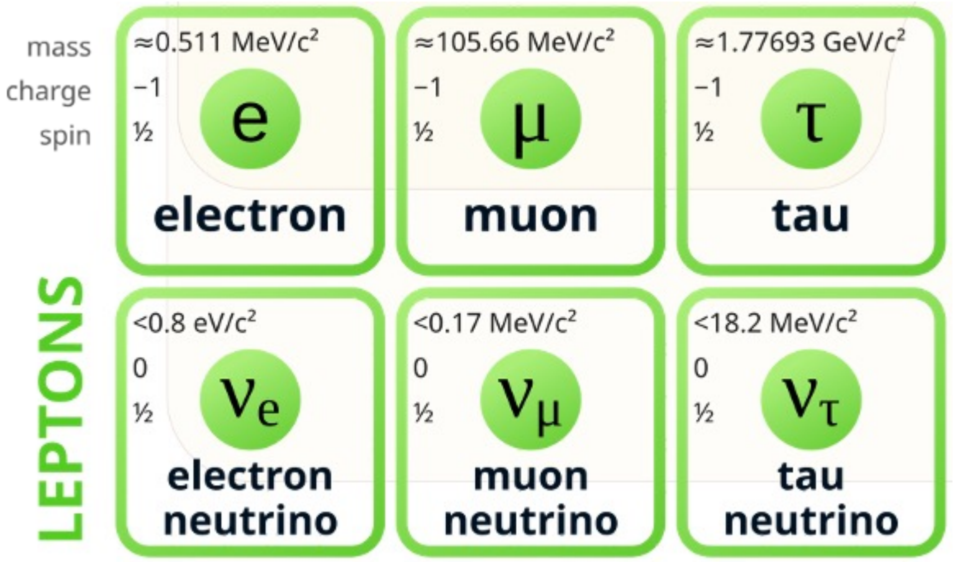
Each lepton has an antiparticle

- Electron -> Positron
- Muon -> anti-muon
- Tau -> anti-tau

There are three generations of leptons

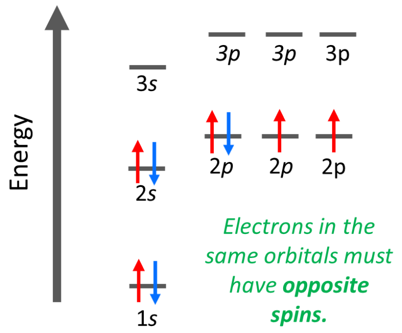
- Electron – Muon – Tau
- Each generation has higher mass

Neutrinos have very small mass, origin for the mass unknown



Pauli's Exclusion Principle

No two electrons in an atom can have the **same *four* quantum numbers.**



This is because when they are in the **same orbital, the values of *n*, *l*, and m_l are the same**. Therefore, they **must have opposite spins** (**different m_s**) so that they do not have all four quantum numbers the same.

Anti-Matter

So, in 1928 when Dirac was trying to merge quantum mechanics with special relativity.

He ran into a problem of there being four solutions. 2 for the electron (spin up/down) and 2 more for opposite charge electrons (positron)

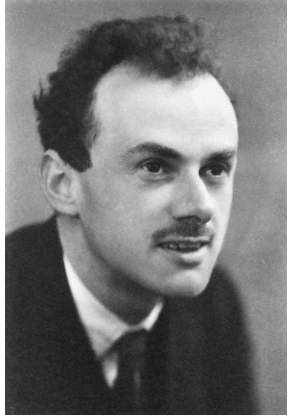
In 1932, Anderson discovered a mysterious particle track with positive charge but less mass than a proton, a positron.

For every particle there exists an antiparticle,

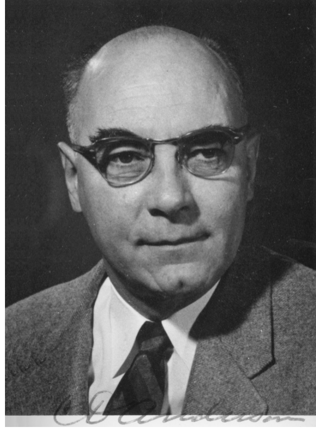
- The same mass
- The same lifetime
- Opposite electric charge and quantum numbers

When a particle meets its anti-particle, they both turn into energy

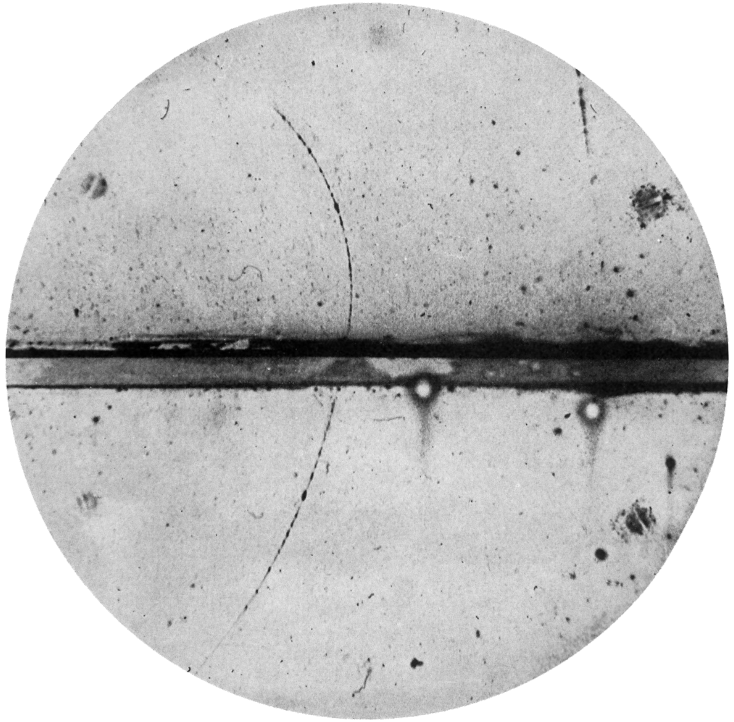
And energy can turn back into particle anti-particle pair.



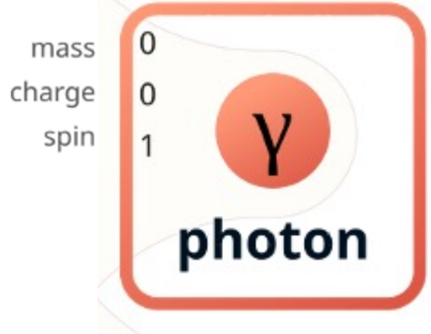
Dirac



Anderson

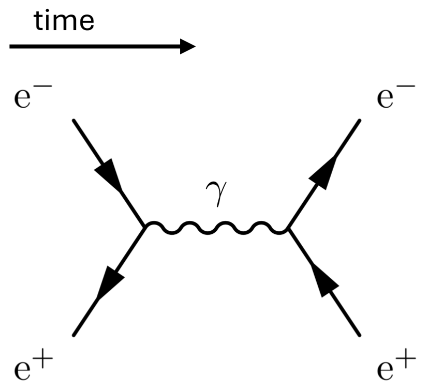


Electromagnetic Force - QED



Quantum Electro-Dynamics describes how electrically charged particles interact through the exchange of photons.

The photon is the **force carrier**
- It is a boson with Spin = 1
- No electric charge
- Zero rest mass (infinite range)
- Travels at speed of light

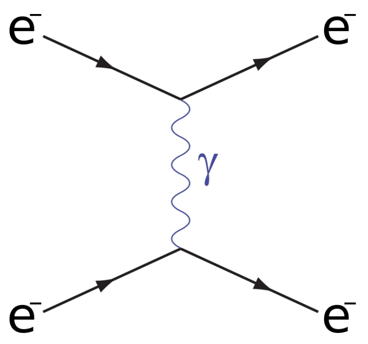


Anti-particles move backwards in time

Electric charge is a conserved quantity

The photon transfers energy and momentum between charged particles, kind of like a messenger.

Telling whether the charged particles should be attracted or repelled.



Feynman Diagrams

Feynman

Feynman diagrams are not pictures of what literally happens.

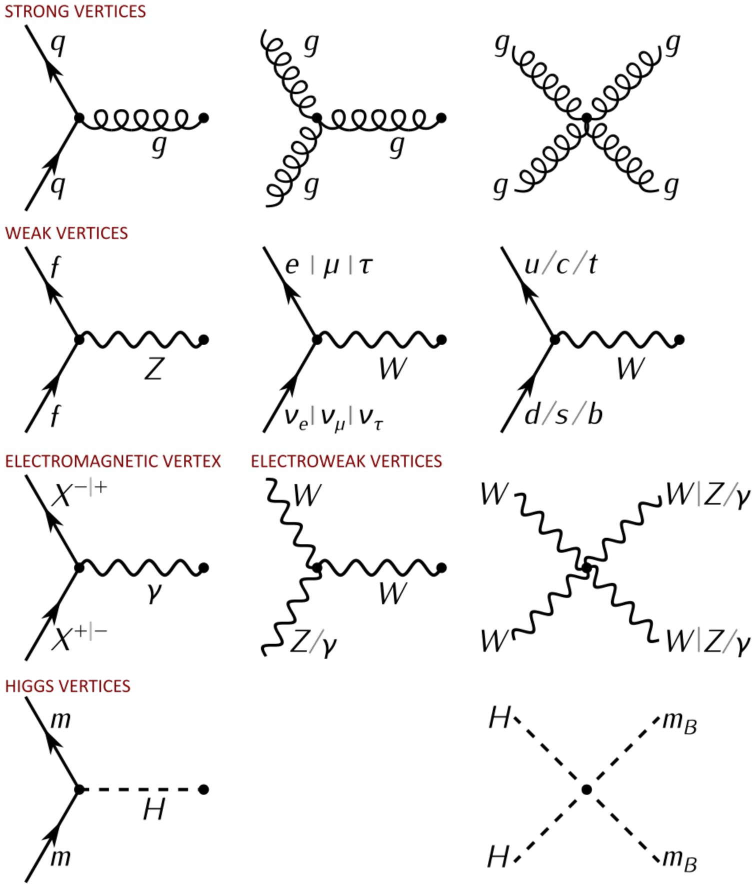
But actually, a visual language for calculating particle interactions.

This is very useful as the maths is very complicated.

Similar, to how circuit diagrams are used.

To allow the maths to work there are certain rules which must be followed when creating a diagram.

Such as the different allowed vertices for the different forces.



Feynman Diagrams QED

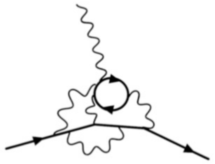
There is more than one possible way to have the same process.

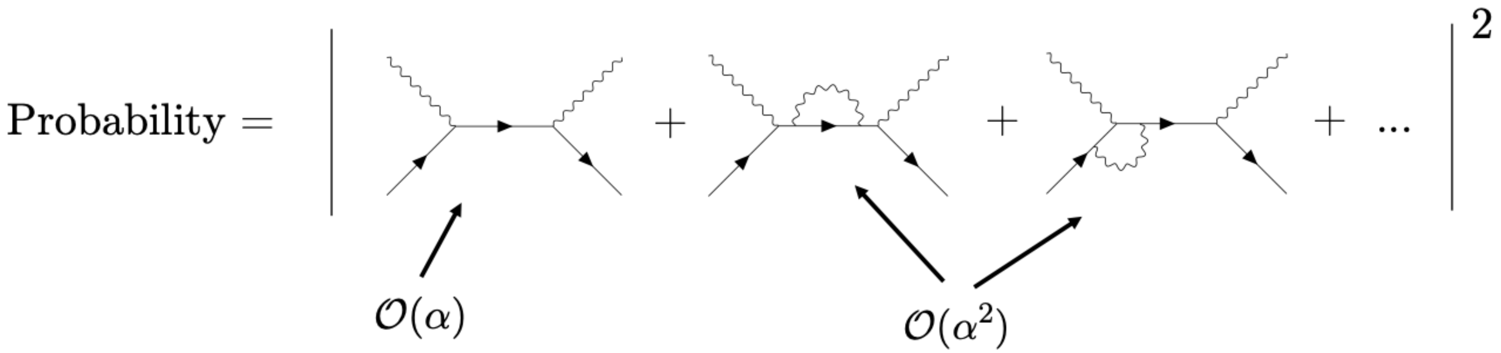
There can be an infinite way of having the same process with increasingly complicated diagrams.

The contribution of each diagram is dependent on how many vertices.

For QED each vertex contributes $\sqrt{\alpha}$. Where α is the coupling constant $\approx \frac{1}{137}$

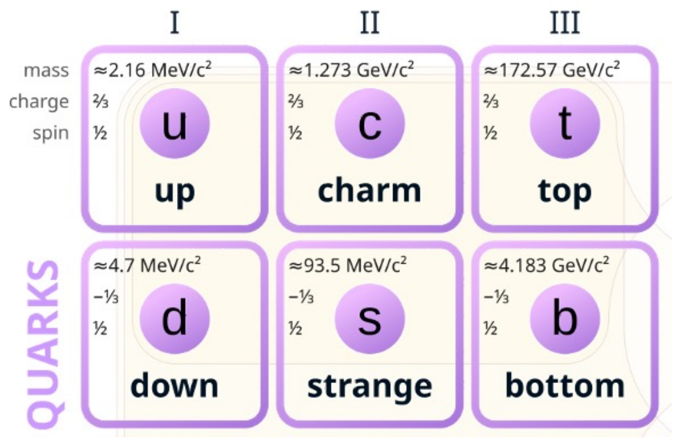
Therefore, more complicated diagrams contribute less and less. So can be ignored.





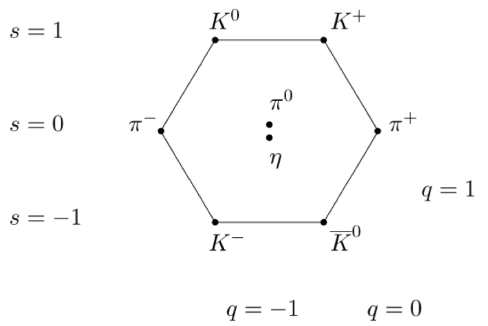
Quarks and QCD

Quarks



Similar to leptons, quarks have:

- Spin ½, Fermions (follow Pauli exclusion principle)
- 3 generations
- Each generation has a higher mass
- Each have an anti-particle

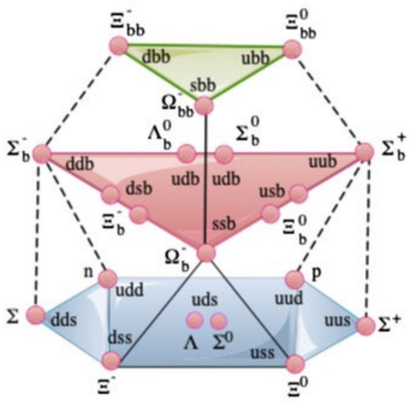


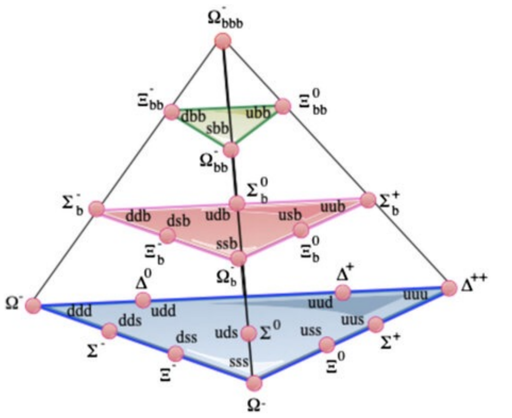
However,

- They have an electric charge of $\frac{2}{3}$ or $-\frac{1}{3}$
- Colour charge

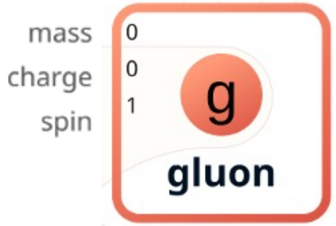
Quarks are combined into hadrons being either baryons (3 quarks) or mesons (2 quarks).

With a proton being a baryon made up of (uud) and neutron made of (udd).





Strong Nuclear Force - QCD

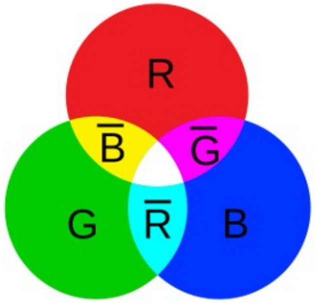


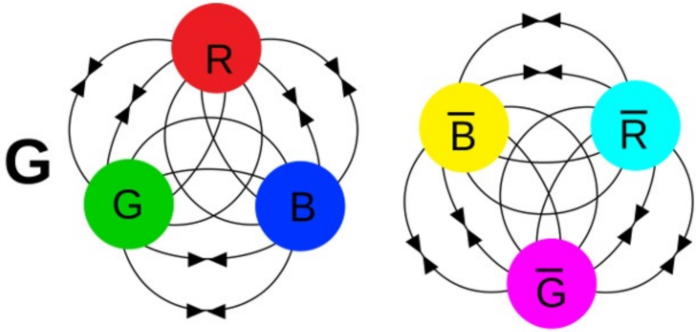
Quantum Chromo-dynamics describes how colour charged particles interact through the exchange of gluons.

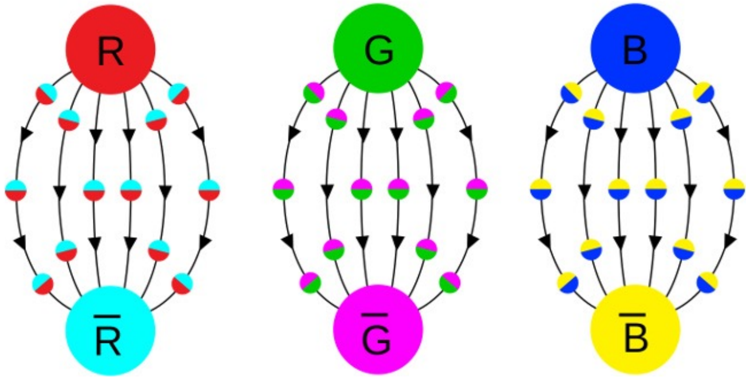
Gluon is a **force carrier**

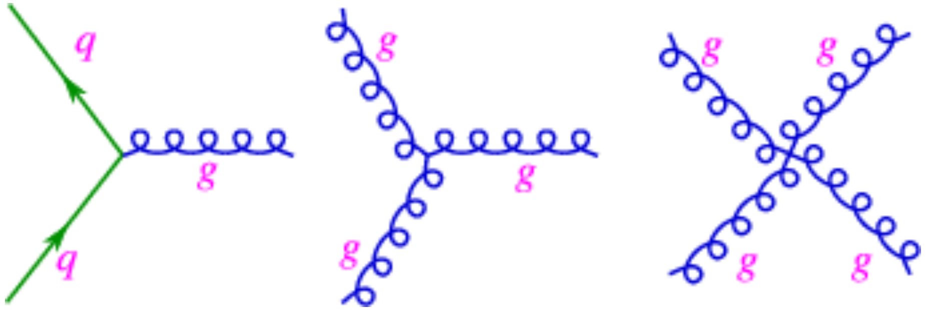
- Is a boson with Spin 1
- Has a colour charge (it can interact with itself)
- No rest mass

Quarks have one of three colours (red, green or blue)
And need to form a colourless pair.

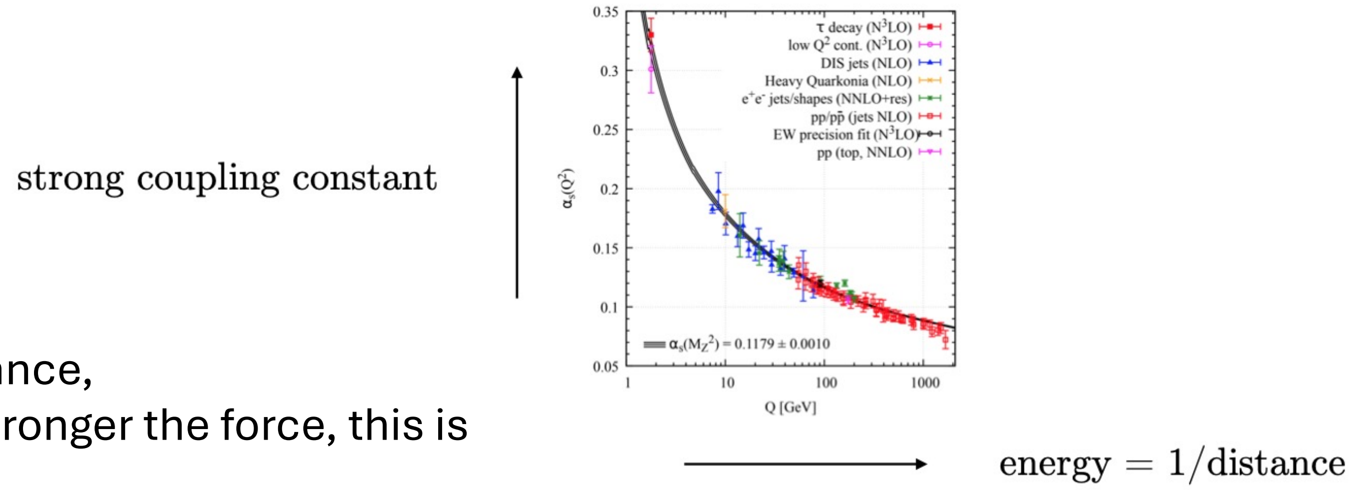








Confinement



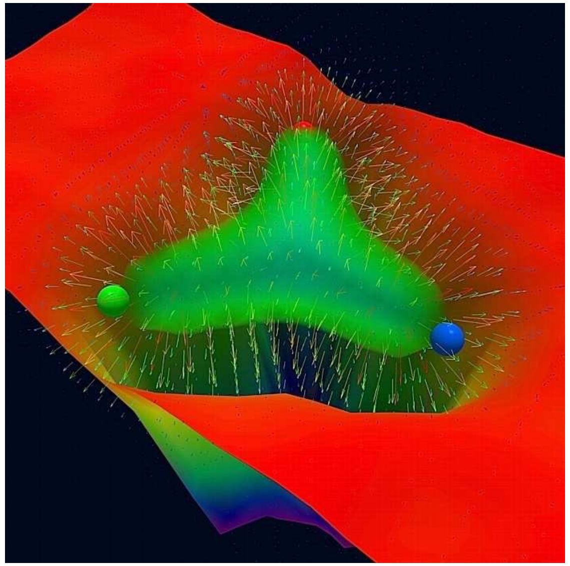
The strong coupling constant (α_S) changes with distance,
the closer the weaker the force and the further the stronger the force, this is called "Asymptotic freedom"

So, this means that α_S can be larger than 1.
Therefore, at low energies more complicated Feynman Diagrams become more probable.

Creating challenges understanding QCD at low energies.

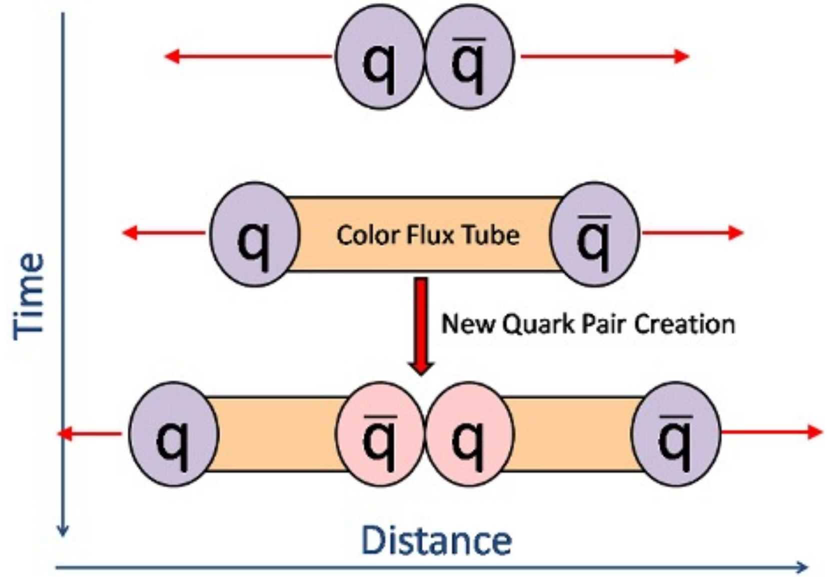
Quarks cannot be free and must be in a hadron, this is called "confinement".

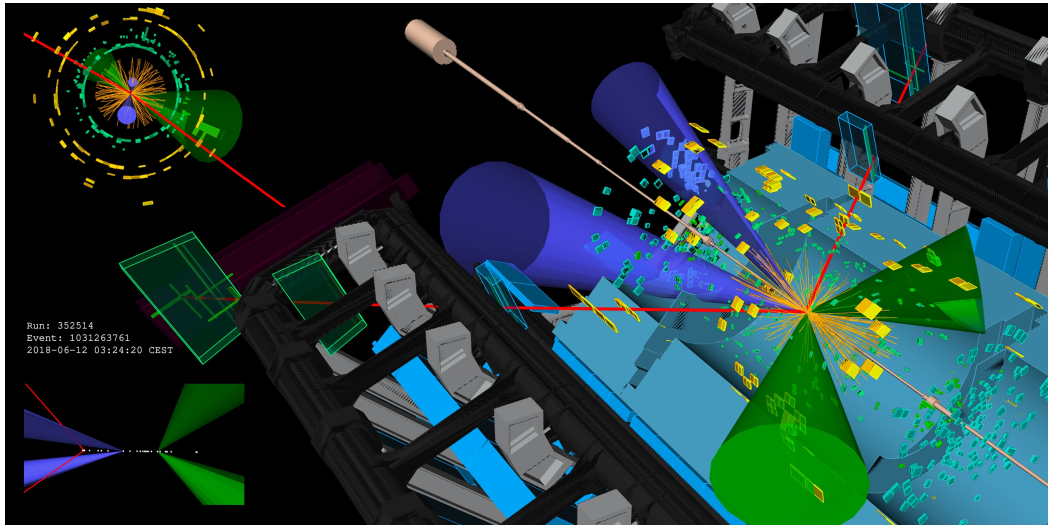
Hadrons are held together by "colour flux tubes"



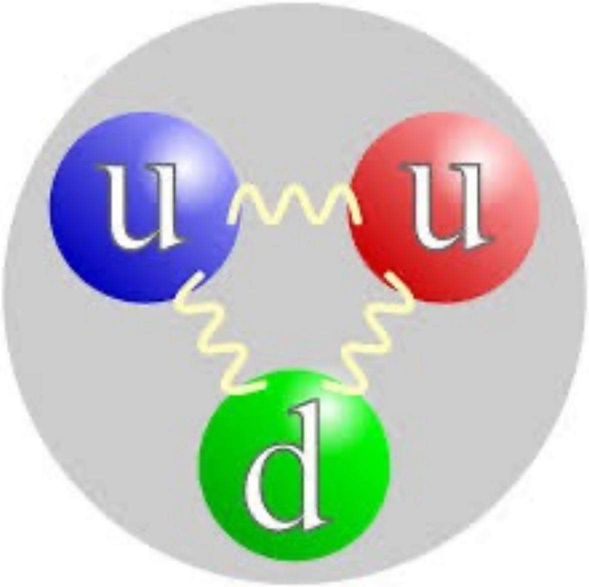
Making jets of particles

- As you pull apart these "colour flux tubes".
- More and more energy is put into the bound.
- Eventually enough to make new quark anti-quark pair.
- When we collide protons at high energies and they break apart.
- This creates lots of hadrons that spray into the detector we call jets.
- So, the detector see lots of jets





Mass of baryons



Earlier we said that a proton is made up of three quarks (uud)

Now if the proton's mass is 938 MeV,

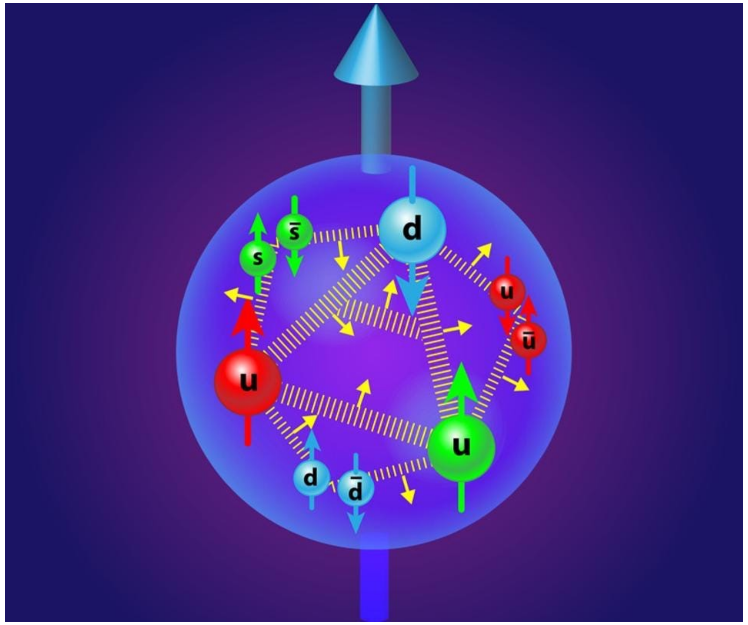
The mass of up and down quark are 2.2 and 4.7 MeV.

The proton mass must be coming from somewhere else other than these three quarks.

Now these three quarks determine the proton's identity but are not the whole story.

Really in the proton there are a sea of quark antiquark pairs and gluons. Where these quark anti quark pairs are constantly annihilating into gluons which can turn back into quark anti quark pairs.

So, most of the mass of everything around us is coming from the kinetic energy of all these quarks and the energy stored in the gluon's bonds



Symmetries and Weak Force

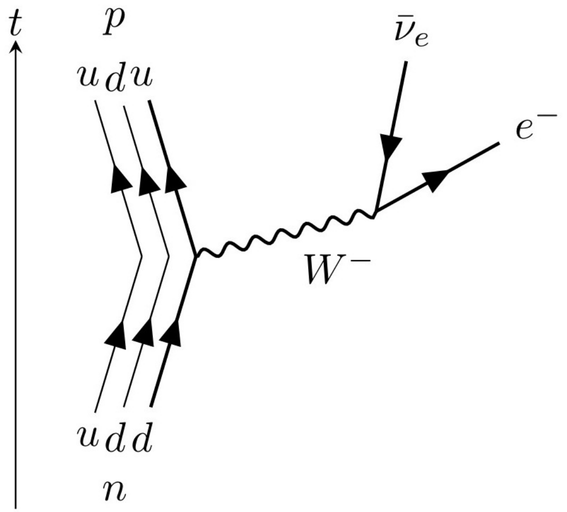
Weak Force

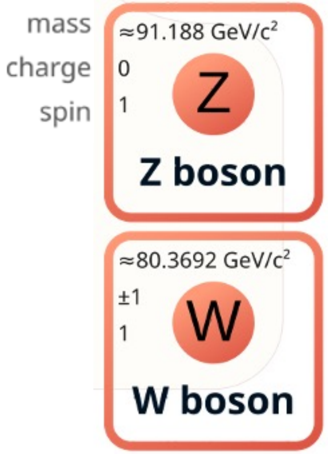
The weak interaction allows particles to change type.
And is responsible for beta decay.

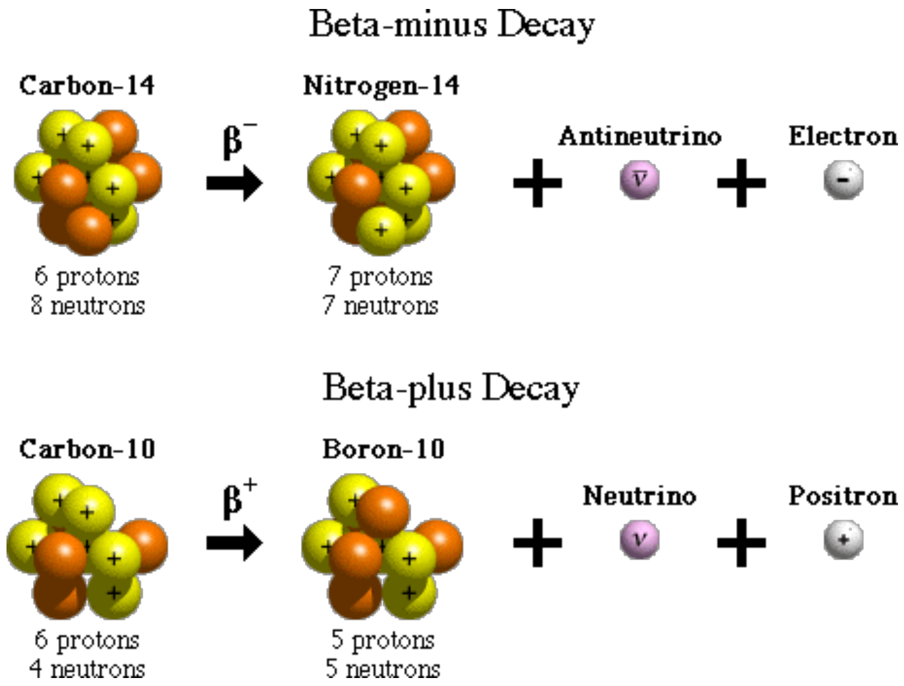
Both quarks and leptons interact with the weak force
So, neutrinos can only interact via the weak force.

The weak force is mediated by: W^+, W^-, Z^0
Properties:

- Spin 1 (bosons)
- Very massive (80 to 90 GeV)
- Therefore, have short range







Symmetries

An important part of the Standard Model is symmetries.

A symmetry means a transformation can be made without changing the laws of physics

So spatial symmetry would mean we would get the same result if we moved our experiment,

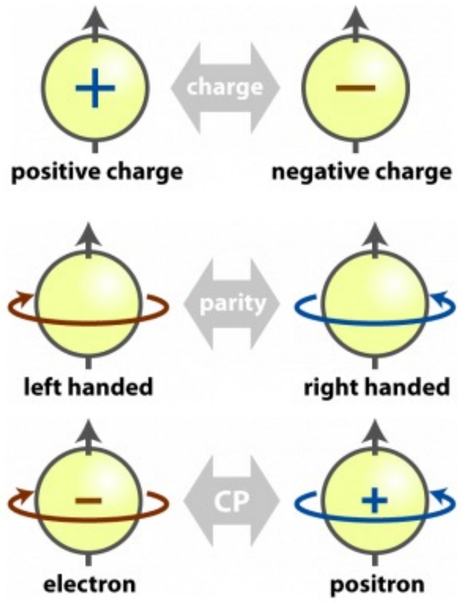
Or a time symmetry would mean we get the same result today and if we did an experiment tomorrow.

And these symmetries are closely connected to conservation laws Noethers Theorem.

With time symmetry giving energy conservation

Spatial symmetry giving momentum conservation

Noether



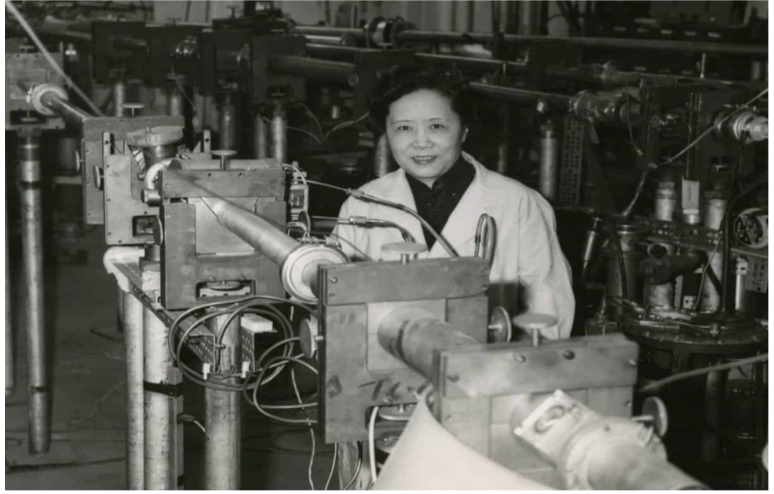
Parity

Parity symmetry is like if the universe behaves the same way in a mirror

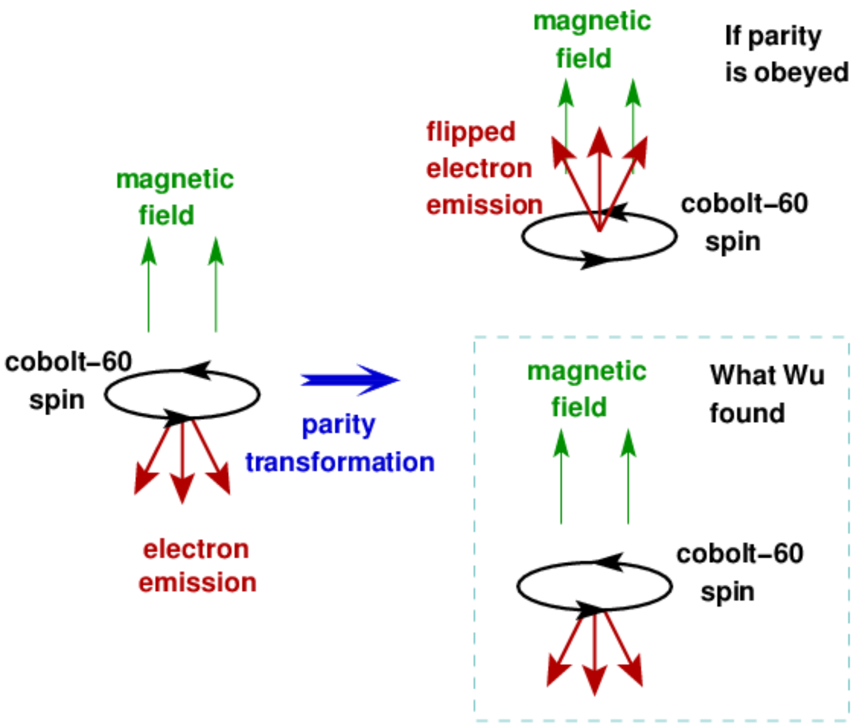
Wu measured beta decay of Cobalt 60 and measured the spin direction of the emitted electron.

And found the spin of the electron is emitted preferentially in a certain direction

Therefore, the Weak interaction violates parity symmetry.



Wu



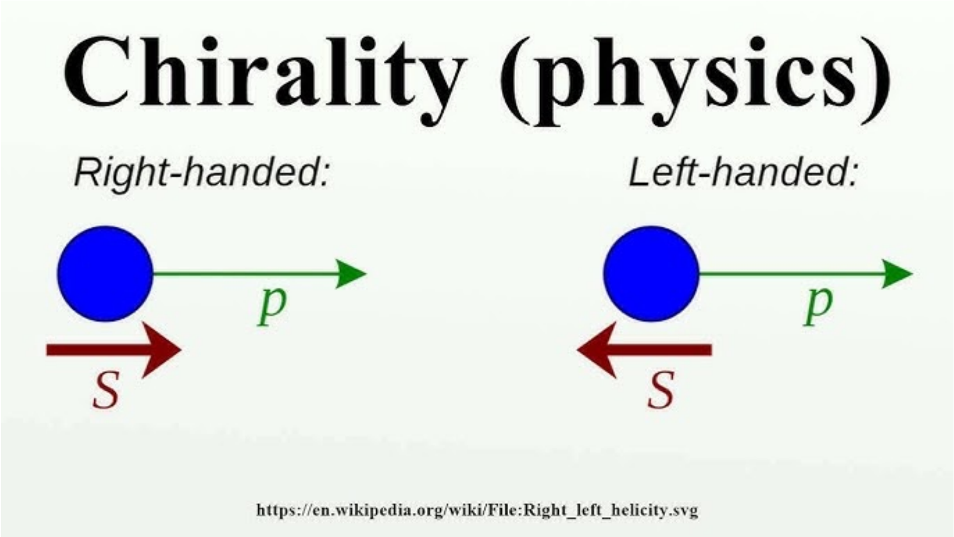
Chirality

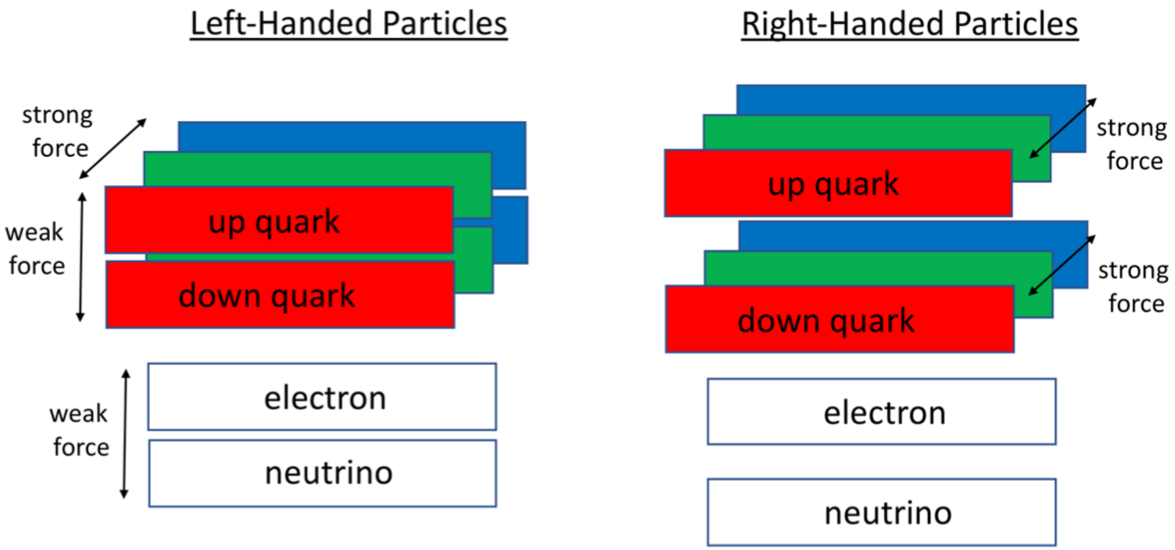
So, the weak force has a preferred handedness
Left-handed ≠ Right-handed

With the weak force only interacts with left-handed particles and right-handed anti-particles

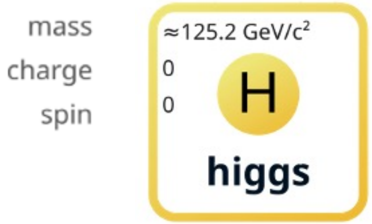
This leaves right-handed neutrinos and left-handed anti-neutrinos all alone

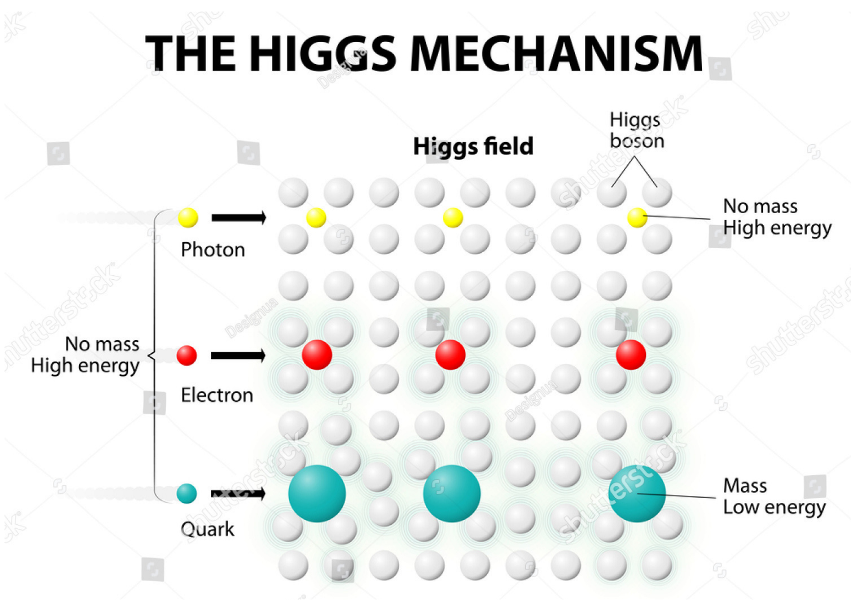
And we don't know if they exist





Higgs Field





The Higgs field interacts with the fundamental particles with different strength. And that strength is what gives the particles their mass.

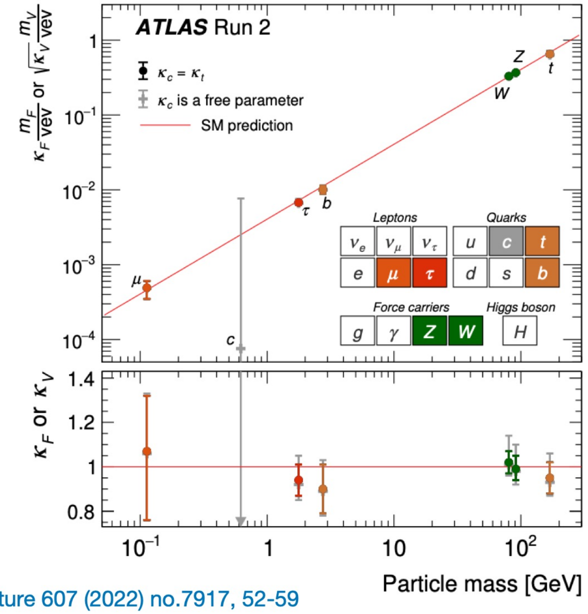
Where the Higgs boson is an excitation of this Higgs field, so the force carrier.

It is kind of similar to moving through syrup where a larger object would be slowed down more.

Except a more massive particle bumps into more Higgs bosons than a lighter one as it moves slowing it down.

And a photon doesn't bump into any allowing it to move at the speed of light.

The Higgs boson is different to the other bosons we have seen as its spin is 0.



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Spontaneous Symmetry Breaking

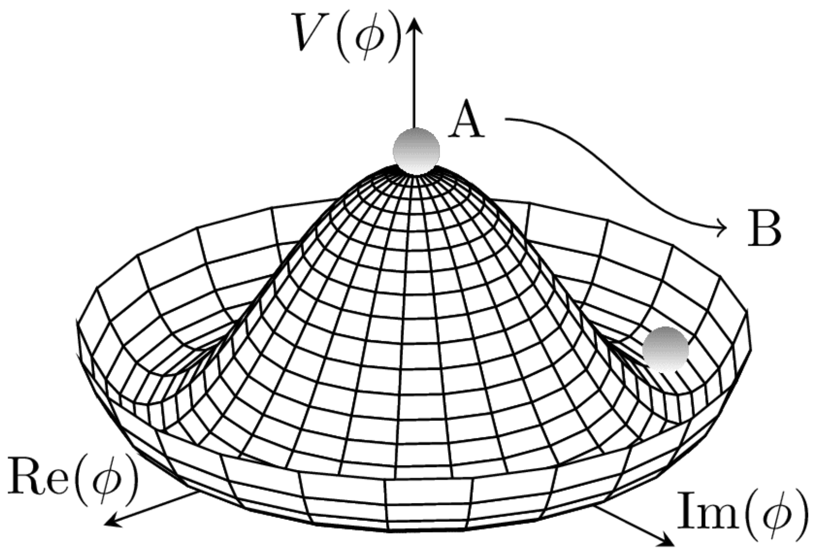
The Higgs potential has a strange "Mexican hat" shape, where the lowest energy state is not at zero.

In the early universe, the Higgs field was in a symmetric state with a value of zero.

At this point all the fundamental particles were massless, meaning the weak force would have had infinite range.

As the universe cooled, the Higgs field moved to the lowest energy state, where it had a non-zero value.
This gave particles mass through their interactions with the Higgs field.
This process is called **spontaneous symmetry breaking**.

Without the Higgs mechanism, all fundamental particles would be massless.



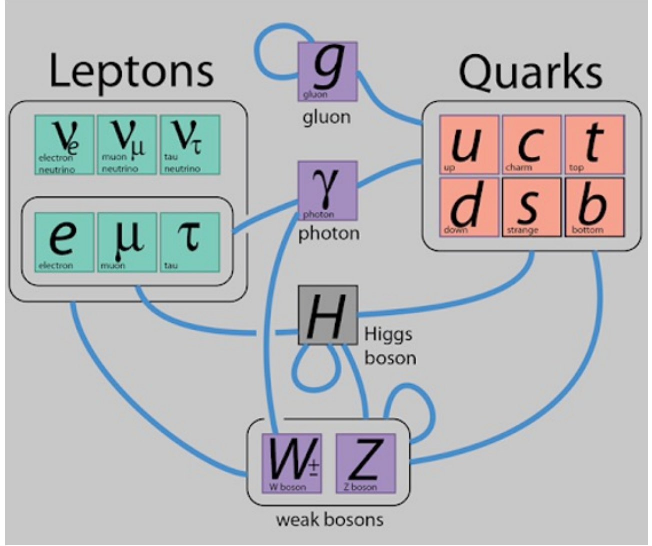
Completed the Standard Model

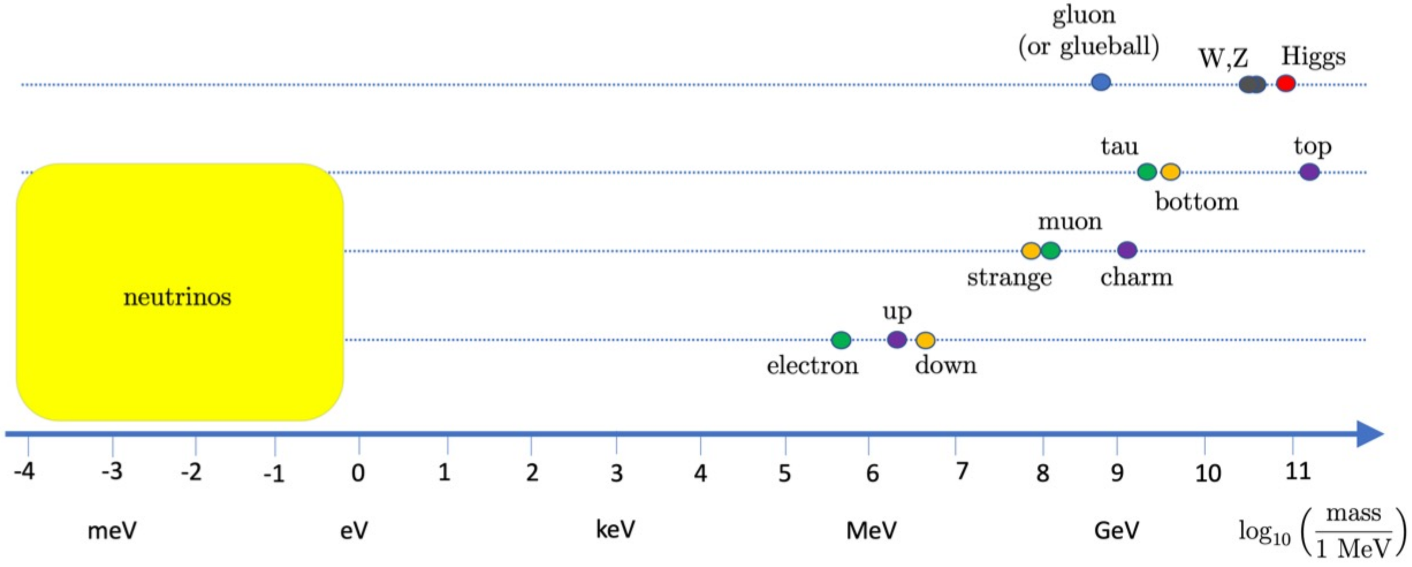
12 Matter particles (Fermions)

- 6 leptons in 3 generations
  - Electric charge of 1 or 0
  - No colour charge
- 6 quarks in 3 generations
  - Electric charge of $\frac{2}{3}$ or $-\frac{1}{3}$
  - Colour charge

5 Force carriers (Bosons)

- Spin 1
  - Photon (Quantum Electro-dynamics)
  - Gluon (Quantum Chromo-dynamics)
  - W and Z boson (Weak force)
- Spin 0
  - Higgs boson (Higgs field)





Beyond Standard Model

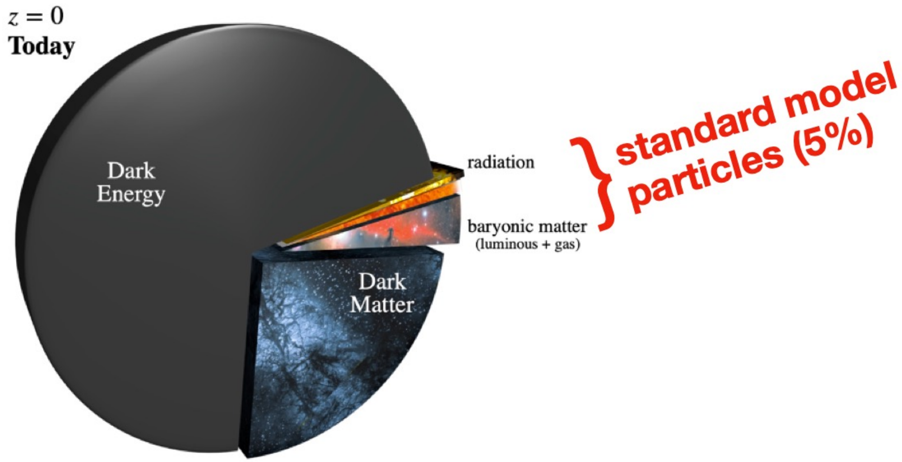
The Standard Model is not finished there is some things not explained:

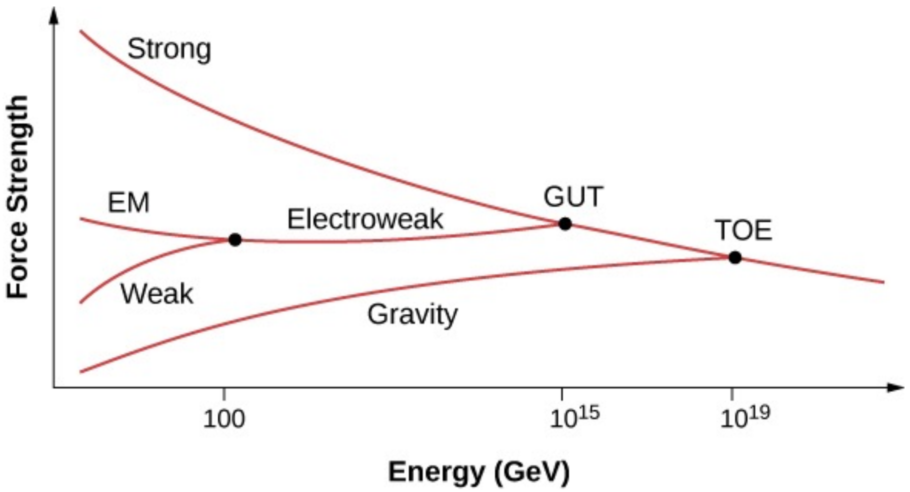
- What is dark matter?
- What is dark energy?
- Why do neutrinos have mass?
- Why is there more matter than anti-matter?
- How does gravity fit into the Standard Model?

So, there must be extensions to answer these questions,

Or maybe the Standard Model only works up to what we have seen so far.

And a new model might be needed for higher energy or smaller scales.





How can we answer these questions

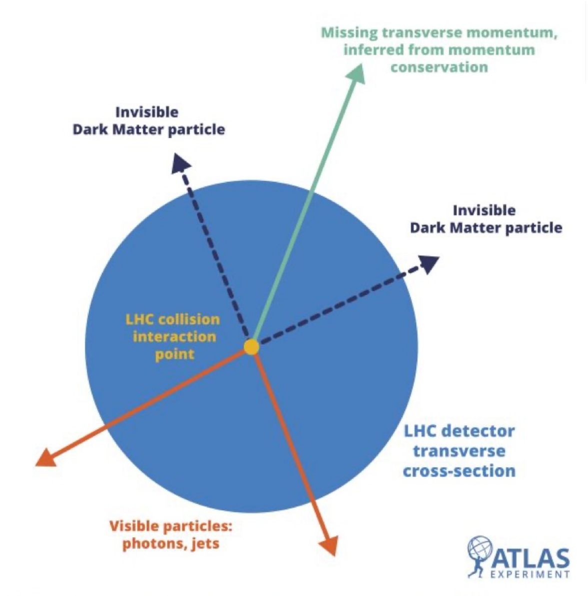
What I look for is the possibility of a Higgs being a portal to dark matter.

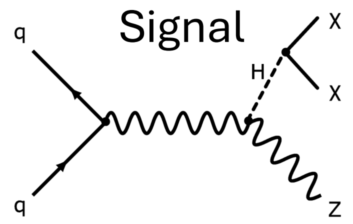
This makes logical sense as the Higgs gives the fundamental particles mass and dark matter has mass.

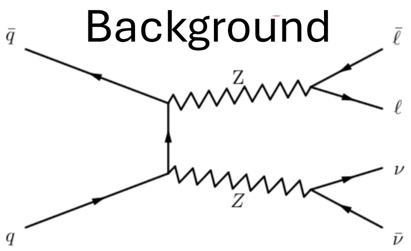
So, we collide lots of high energy protons to make lots of Higgs bosons.

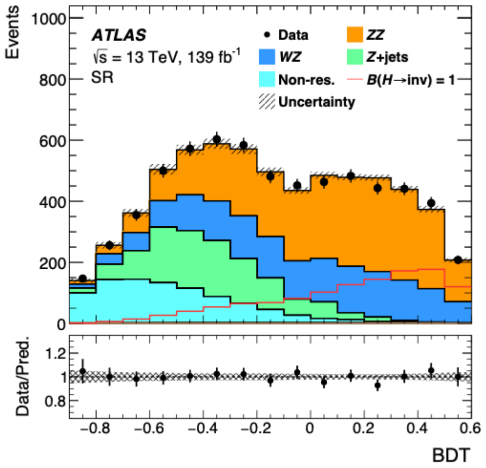
We find an optimal place where we could see this and simulate the Standard Model, then we simulate the scenario where the Higgs is a portal to dark matter.

And then check compare the simulations to data to see which scenario is more likely.





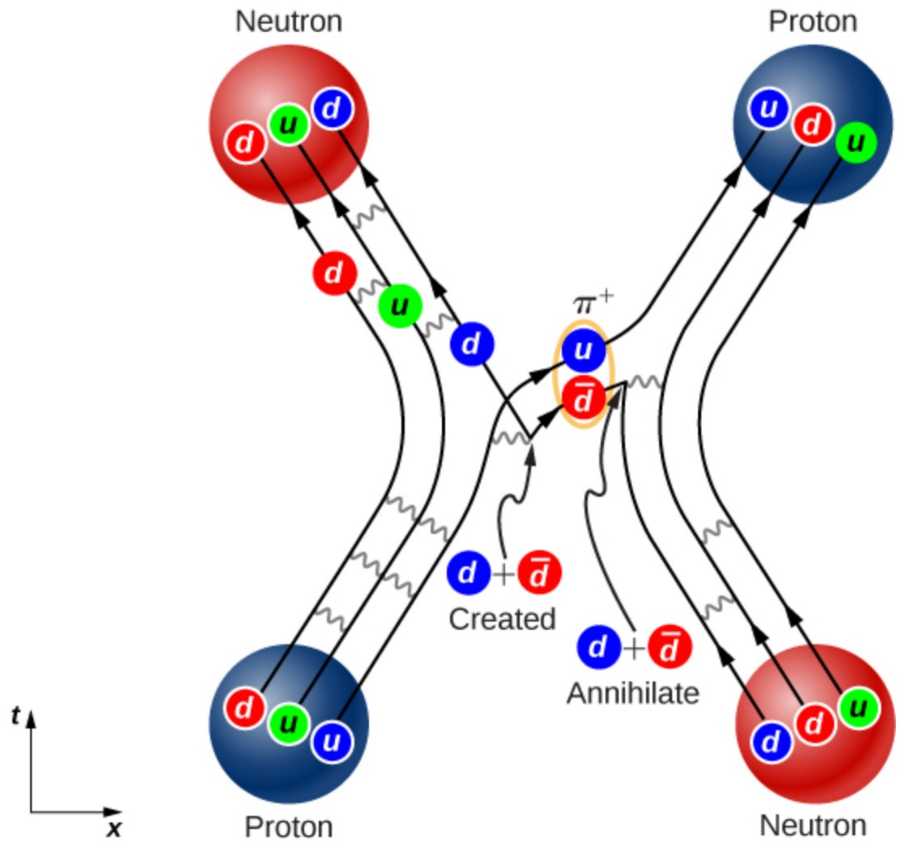




Questions?

Extra Material

Pion Exchange holding nucleus together



Electroweak Unification

Electromagnetism and the Weak force are two manifestations of a single Electroweak force.

They become unified at high energies (>100 GeV) due to the W and Z bosons being massive.

The photon and Z are mixtures of the original electroweak field.

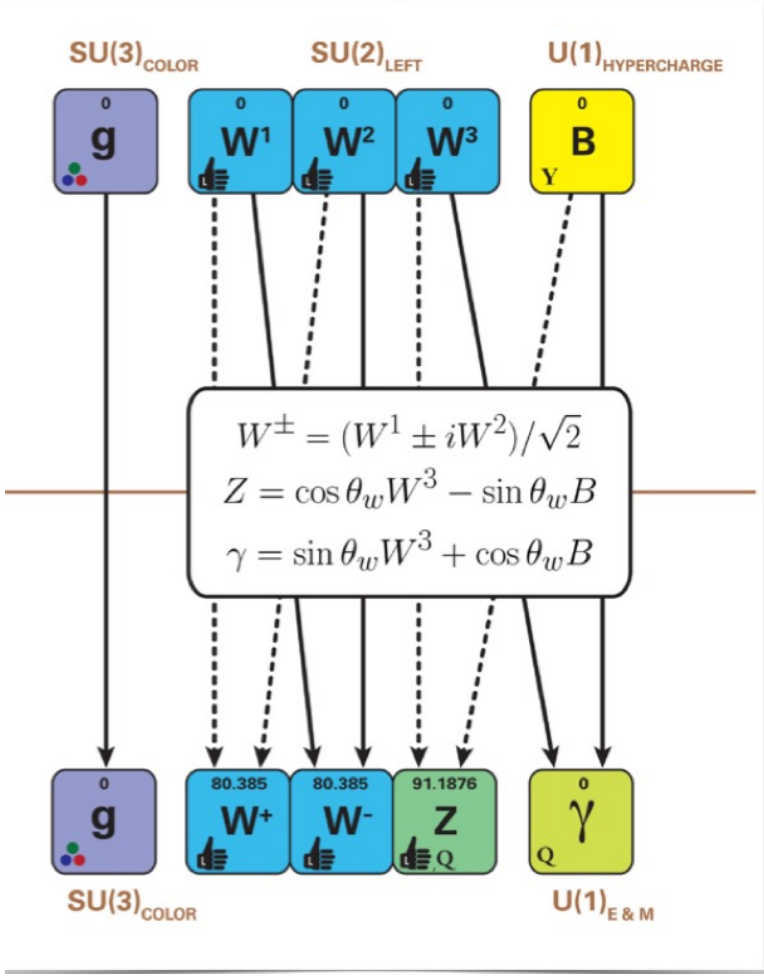
Electric charge is a mixture of hypercharge and weak isospin

$$Q = T_3 + \frac{1}{2} Y_W$$

$$G = SU(3) \times SU(2) \times U(1)$$

strong — weak — hypercharge

Fermion family	Left-chiral fermions				Right-chiral fermions			
		Electric charge Q	Weak isospin T_3	Weak hyper-charge Y_W		Electric charge Q	Weak isospin T_3	Weak hyper-charge Y_W
Leptons	ν_e, ν_μ, ν_τ	0	$+\frac{1}{2}$	−1	ν_R May not exist	0	0	0
	e^-, μ^-, τ^-	−1	$-\frac{1}{2}$	−1	e_R^-, μ_R^-, τ_R^-	−1	0	−2
Quarks	u, c, t	$+\frac{2}{3}$	$+\frac{1}{2}$	$+\frac{1}{3}$	u_R, c_R, t_R	$+\frac{2}{3}$	0	$+\frac{4}{3}$
	d, s, b	$-\frac{1}{3}$	$-\frac{1}{2}$	$+\frac{1}{3}$	d_R, s_R, b_R	$-\frac{1}{3}$	0	$-\frac{2}{3}$



Quark Mixing – CKM Matrix

- The weak force allows quark mixing, for example if we have a decay:

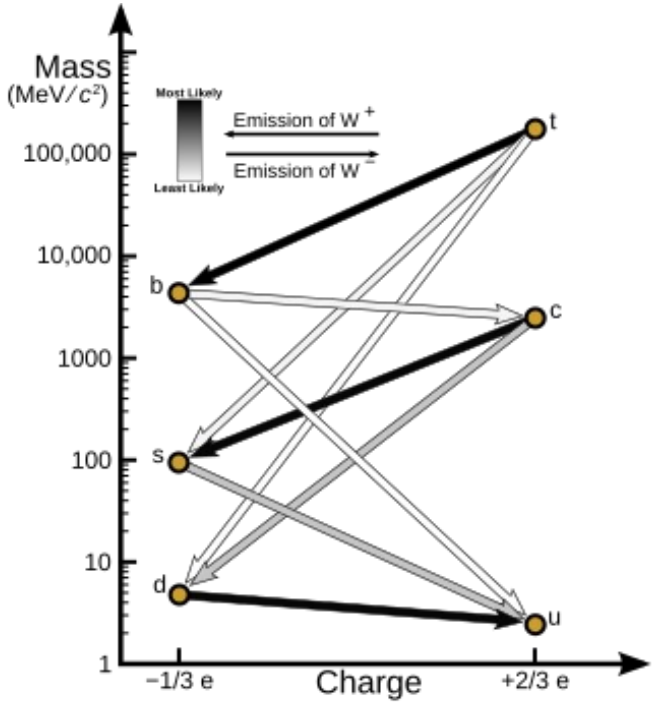
$$t \rightarrow W^+ \, b' = W^+(V_{tb})b + W^+(V_{ts})s + W^+(V_{td})d$$

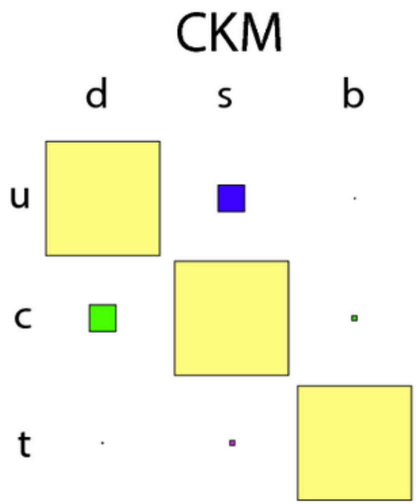
- This is due to weak force being misaligned with the masses which come from the Higgs.
- So, the state which interacts with the weak force is a composition of the mass states.
- This mixing can explain matter antimatter asymmetry due to the CKM having a complex phase.

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

These particles interact with weak force

These particles interact with Higgs, and so definite mass.





Neutrino Mixing - PMNS

- The neutrino states which interact with the weak interaction don’t align with their mass states

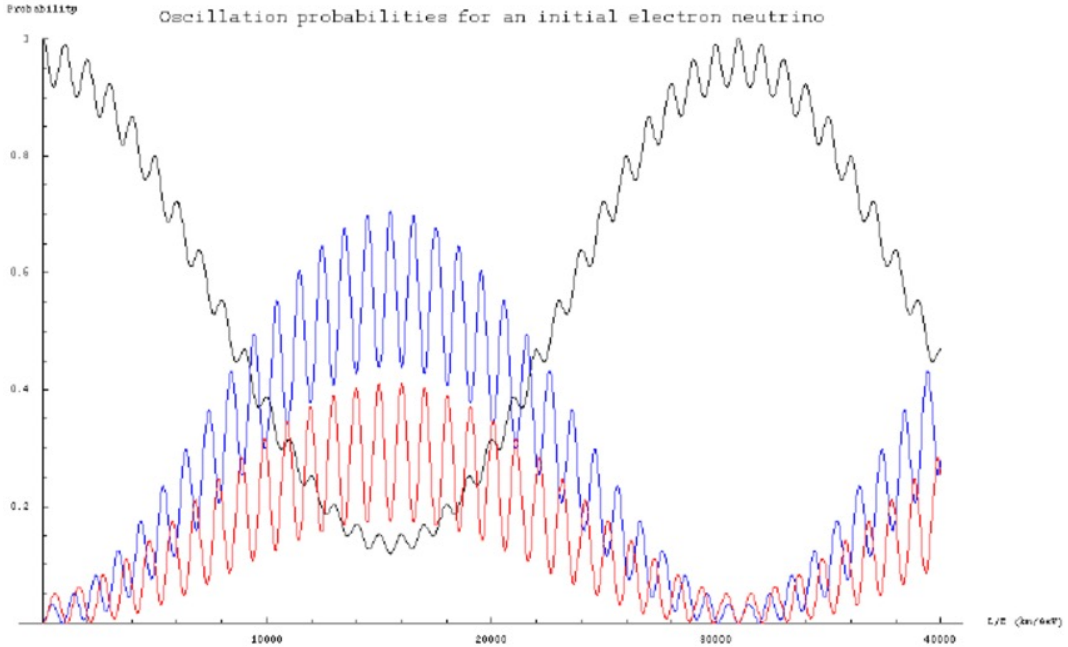
$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

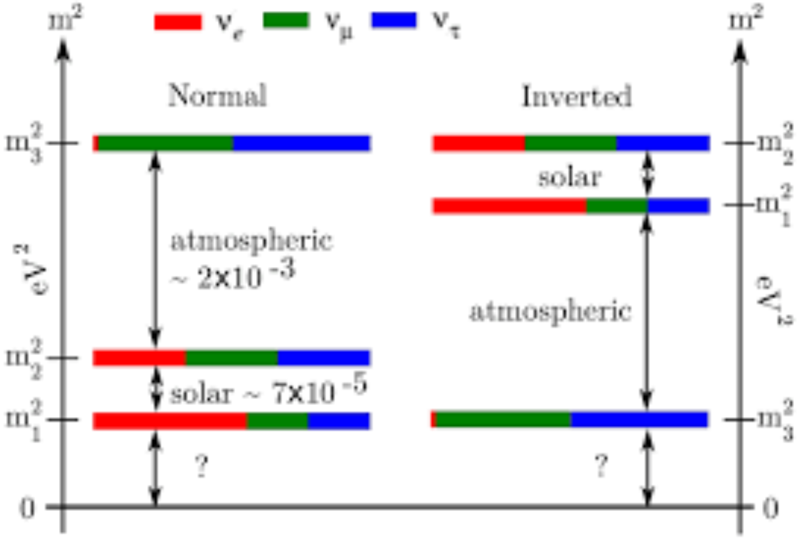
- This means the flavour states are a mix of the mass states.

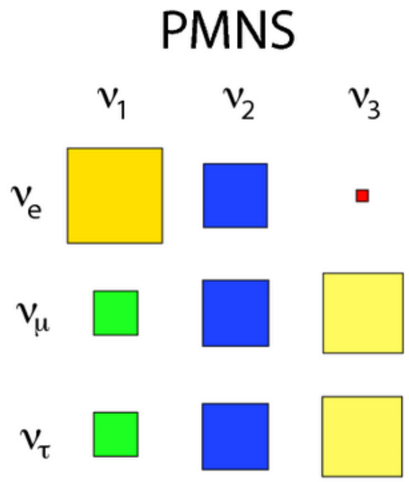
- As they made up of different masses, these states waves propagate differently over time.

- Changing how they interfere causing oscillations between flavour states.

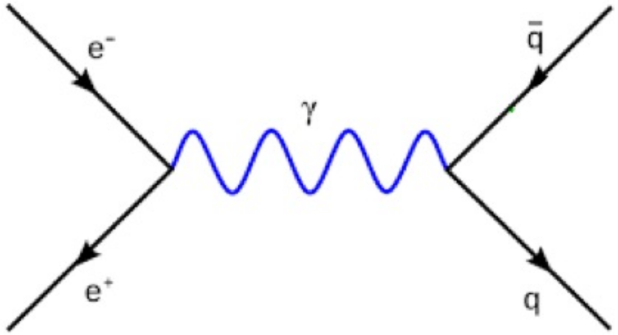
- This proves they have mass.







How do we know there is 3 colours



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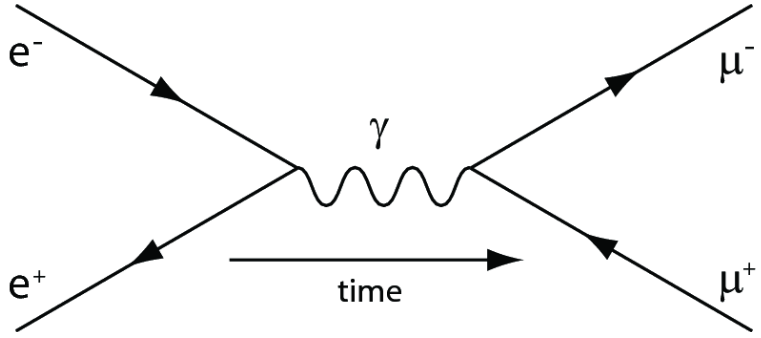

because there are 3 colors

$SU(3)_c$

q_u q_d q_s

$$R(E=1GeV)=3\times\left(\left(\frac{2}{3}\right)^2+\left(-\frac{1}{3}\right)^2+\left(-\frac{1}{3}\right)^2\right)=2$$

q_c

$$R(1.2<E<4.6)=3\times\left(\left(\frac{2}{3}\right)^2+\left(-\frac{1}{3}\right)^2+\left(-\frac{1}{3}\right)^2+\left(\frac{2}{3}\right)^2\right)=10/3\approx 3.33$$

q_b

$$R(E>4.7GeV)=3\times\left(\left(\frac{2}{3}\right)^2+\left(-\frac{1}{3}\right)^2+\left(-\frac{1}{3}\right)^2+\left(\frac{2}{3}\right)^2+\left(-\frac{1}{3}\right)^2\right)=11/3$$