Nuclear and Particle Physics
Lecture 7: Fundamental Particles and the Quark Model

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Particles and Antiparticles

The relativistic expression for the energy of a particle is:

$$E^2 = p^2c^2 + m^2c^4$$

This means that the energy of a particle can be one of two values:

$$E = \pm\sqrt{p^2c^2 + m^2c^4}$$

What does the negative energy solution mean?

In his relativistic quantum theory of 1928, Paul Dirac suggested that the negative energy state is a "hole" in a sea of full negative energy states.

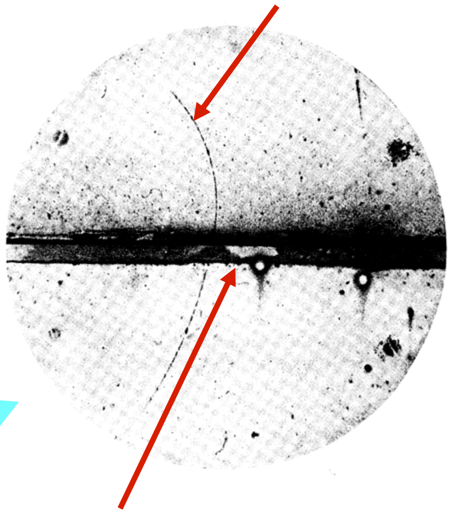
In 1933, the positron was discovered – with the same mass as the electron, but with a positive charge +e.

The positron e^+

The positron was discovered in 1932 in experiments using a cloud chamber.
How that works ?

- Charged particles leave trails of "clouds" in the super-saturated air.
- A magnetic field bends the trajectories of the charged particles
- A photograph is timed to capture the image

In this image a positron can be identified by:
* The direction of curvature (positive charge)
* The range of the track (i.e. it is not a proton)



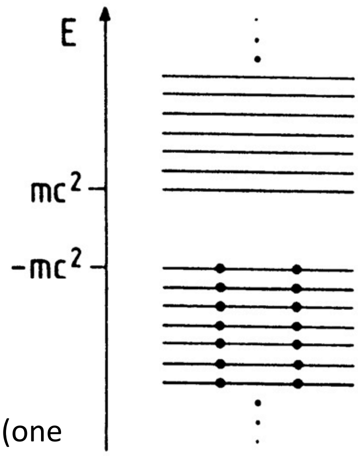
Carl D. Anderson was awarded the 1936 Nobel Prize for Physics for the discovery of the positron.

Image: C.D. Anderson, Physical Review 43 (1933) 491

Hole Theory

Properties of a vacuum state:

Energy:	$E_V = 0$
Momentum:	$\vec{p}_V = 0$
Charge:	$Q = 0$
Spin (angular momentum)	$S_V = 0$



Dirac's concept of the vacuum:

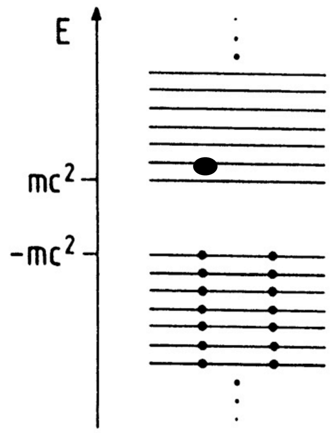
• Vacuum is a "sea" of negative energy states

• Each positive energy state can contain two electrons (one with spin 1/2, the other with spin -1/2)

• <u>All negative energy states are occupied</u>

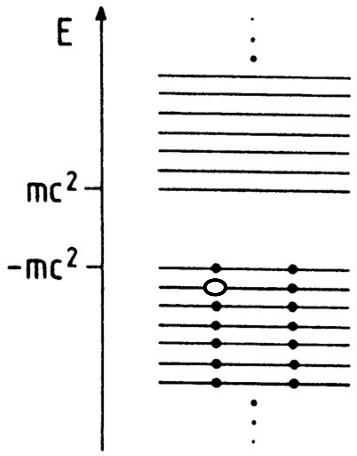
• If an electron loses energy e.g. by emitting photons it would be forbidden from dropping below zero energy.

Adding or removing electrons from the vacuum



Adding an electron to the vacuum

- All negative energy states are full.
- Only positive energy states are available



Removing an electron from a negative energy state

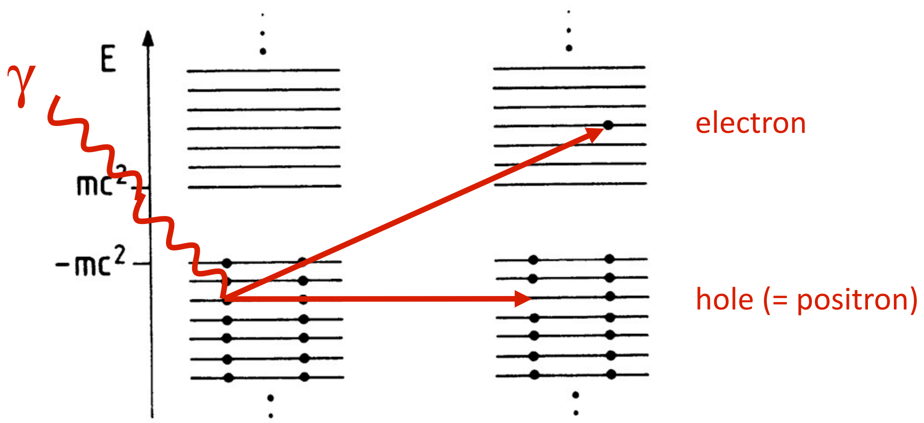
- Electron has energy $E = -E_p < 0$, momentum $-\boldsymbol{p}$ and charge $-e$.
- Same as adding a hole with energy

$E = +E_p > 0$, momentum $+\boldsymbol{p}$ and charge $+e$

Pair Production

A real process can occur when a photon of sufficient energy (calculate this!) moves an electron from a negative energy state to a positive energy state.

This is equivalent to creating both an electron and a positron: $\gamma \rightarrow e^- + e^+$



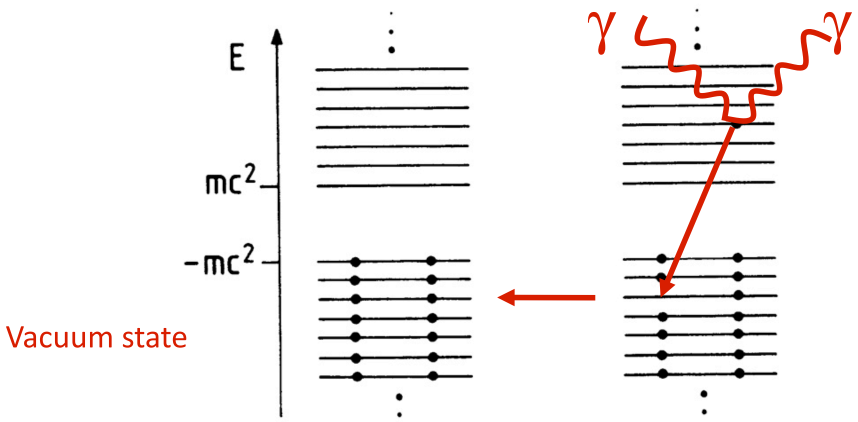
Pair production by a single photon cannot occur in empty space - a nucleus (or another particle) is needed to conserve both momentum and energy.

e⁺e⁻ annihilation

The process opposite to pair production can occur, when an electron jumps into a negative energy hole, with the release of energy.

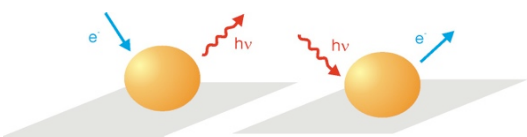
Since this is equivalent to removing both an electron and a positron, it is called annihilation.

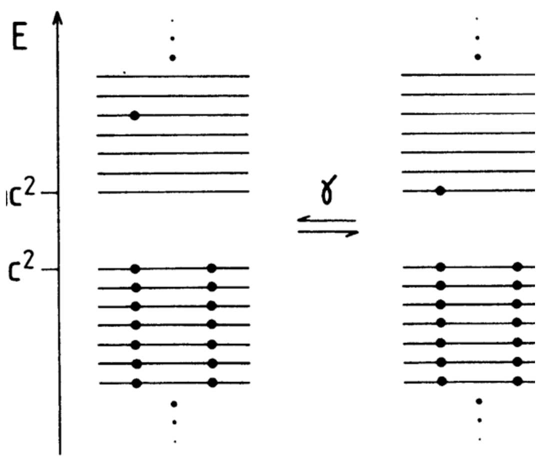
To conserve momentum, two or more photons must be created (why?).



Interactions of photons and electrons

Electrons can either absorb photons and climb to a higher energy state, or emit photons to reduce their energy.





Antimatter

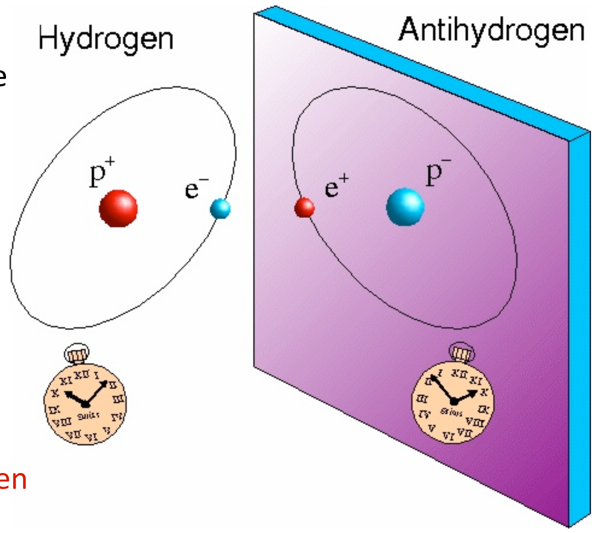
• Hole theory applies to *all* fermions – there is a sea of negative energy states for each type of particle (electron, proton, etc.).

• For Bosons, relativistic quantum field theory (QFT) shows that for every boson there is an anti-boson

• Anti-particles have exactly the same characteristics as particles except for having <u>opposite charge</u>.

• In the case of *neutral* particles, some have distinct antiparticles (e.g. neutron and anti-neutron), while others do not (e.g. photon).

• Why there is an apparent asymmetry between the observed matter and anti-matter in the universe remains an open question ...

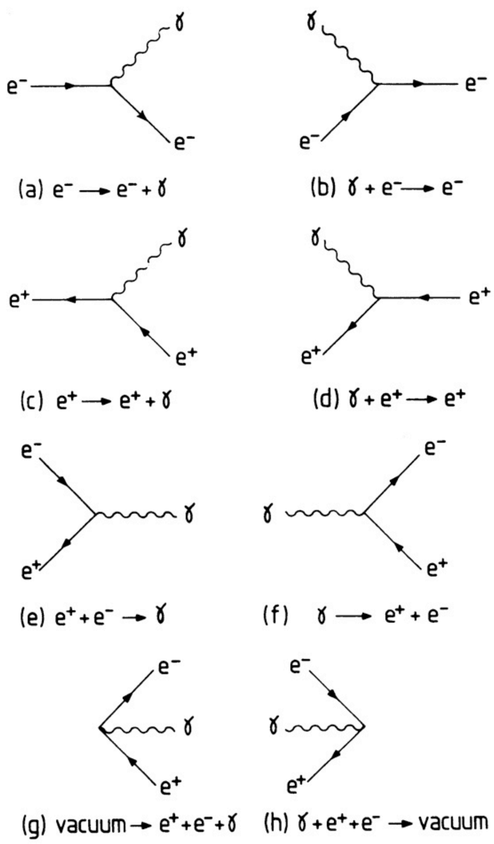


Feynman Diagrams

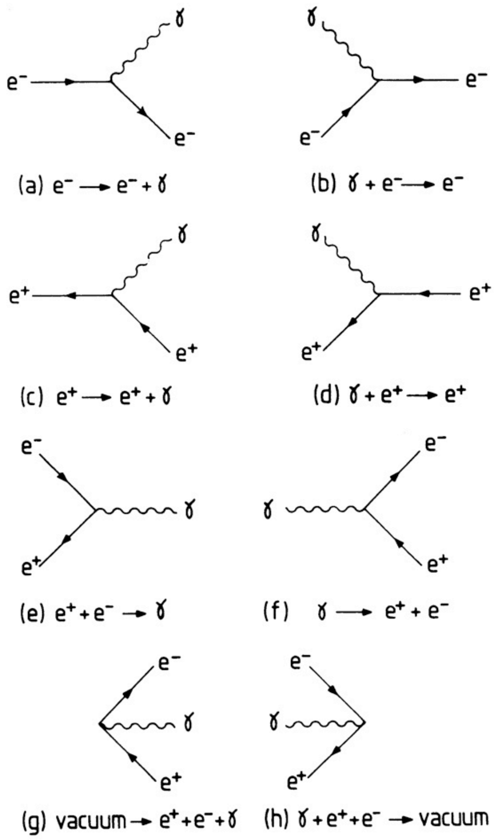
In the 1940s, Richard Feynman invented a pictorial technique to aid the calculations of processes involving photons and electrons.

The theory of interactions between photons and electrons is called Quantum Electrodynamics (QED), and remains the most precise physical theory we know of.

The idea is to represent particles by "world lines" in time and space



Feynman Diagrams

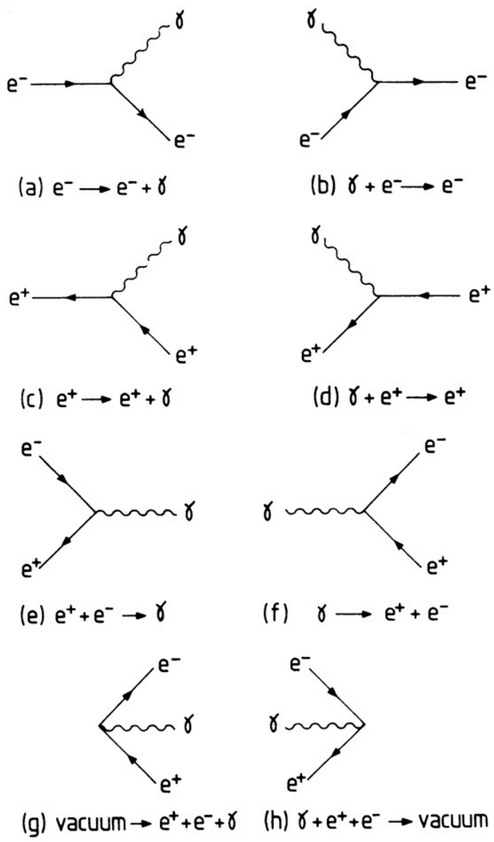


We will use the following convention (others are commonly used):

- Time flows along the horizontal axis from left to right.
- Space is represented in the vertical direction (all 3 spatial dimensions!).
- Electrons are represented by lines with arrows pointing from **left to right.**
- Positrons are represented by lines with arrows pointing from **right to left.**

i.e. a positron going forward in time is equivalent to a (positive energy) electron going backwards in time!

Feynman Diagrams



Bosons are represented by wiggly lines and fermions by solid lines.

Photons are represented by wiggly lines with no arrow (recall that there is no "anti-photon").

The use of the arrows indicate that at the vertices (where the photon joins the two electron lines), charge must be conserved.

In QED, there is only one basic vertex, which has eight different configurations as shown.

Each of the eight basic diagrams can be obtained from any other by continuously deforming the lines without the need to cut a line

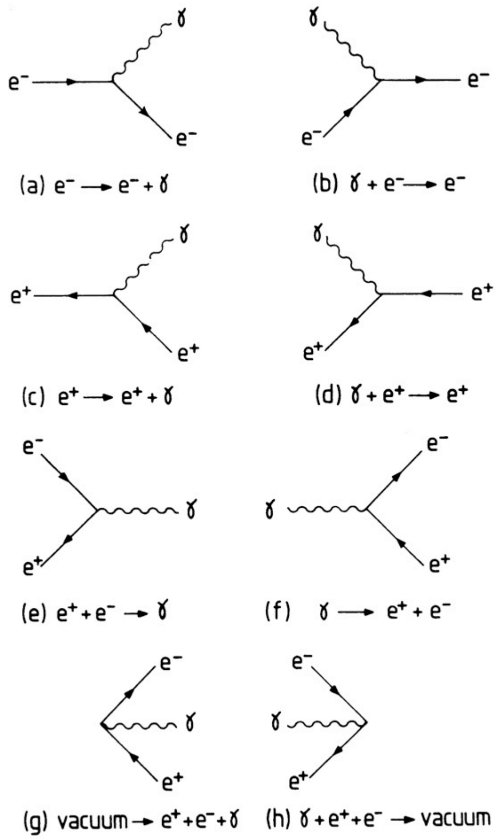
Feynman Diagrams

At every vertex, momentum, angular momentum and charge are all conserved.

Single diagrams, however, can not conserve energy. They are referred to as **virtual processes**.

Real, physical processes require two or more virtual processes to combine, and energy conservation can be violated for a time allowed by the uncertainty principle:

$$t\Delta E \sim \hbar$$



Example: electron-electron scattering

Combining two of the eight basic processes (which ones?) gives the diagrams for e^--e^- scattering.

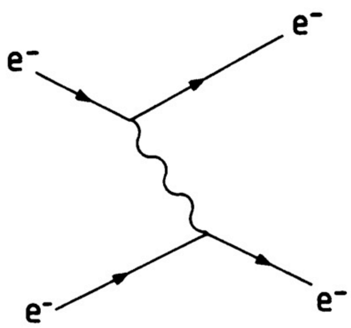
Energy in the distant past ($t \to -\infty$) = energy in the far future ($t \to \infty$)

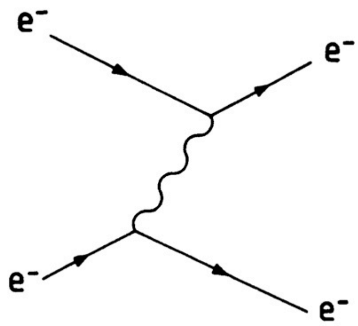
Particles joining two vertices internally are referred to as virtual particles, i.e. they cannot be observed.

Note that the two diagrams correspond to two different time orderings of the processes.

Often only one is drawn, with the different time orderings implied.

In calculations each diagram represents an amplitude (c.f. optics).



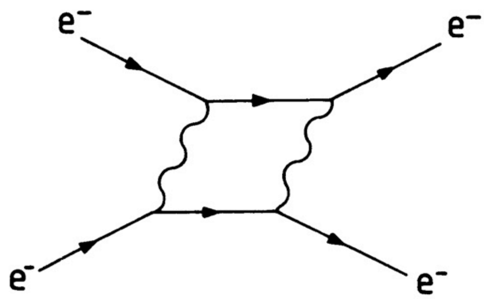


Example: electron-electron scattering

In QED, each diagram has a number of vertices, called its order.

Each vertex carries a factor of $\alpha(\approx 1/137)$ which determines the rate of the process corresponding to that diagram.

The probability of each diagram is related to its order.



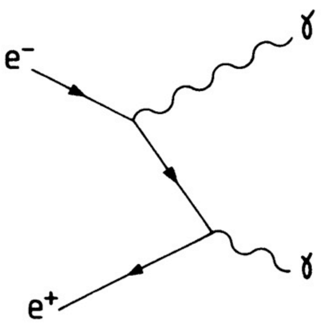
e.g. in e^--e^- scattering, one possibility is two-photon exchange. How much less likely is this to happen that one-photon exchange?

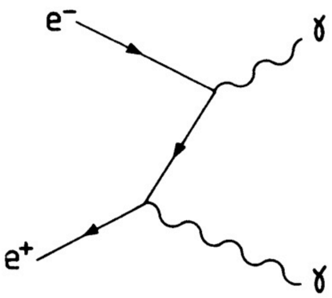
Example: e^+e^- annihilation

The two diagrams shown below both correspond to electron-positron annihilation:

$$e^- + e^+ \rightarrow 2\gamma$$

As before, the two different time orderings are shown, i.e. one diagram can be continuously deformed into the other.





Can e^+e^- annihilation occur with the emission of three photons?

Example: Pair production

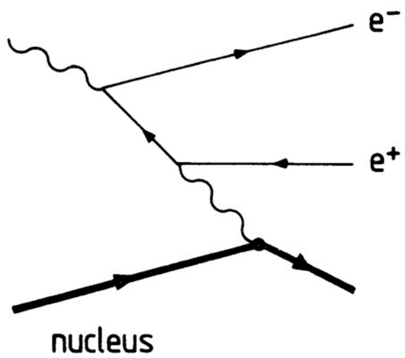
The pair production process

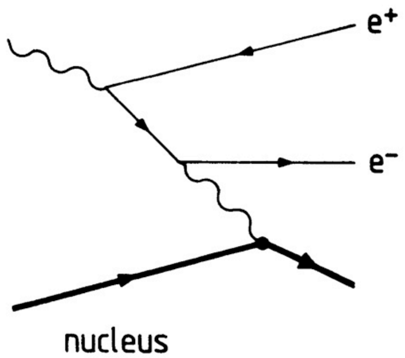
$$\gamma \rightarrow e^{+} + e^{-}$$

can not conserve both energy and momentum.

However, it is possible in the presence of a nucleus.

Two different diagrams are shown below. They are **not** different time orderings, since one can not be continuously deformed into the other (try drawing the time orderings!). They are topologically distinct.





Diagrams for the proton-neutron interaction

Protons and neutrons are collectively known as nucleons.

They can interact via exchange of mesons (as shown below, with time orderings).

As with QED, energy and momentum are conserved before and after process.

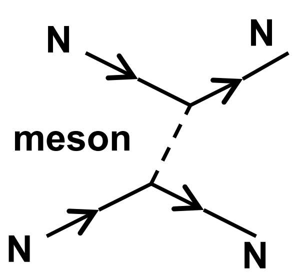
During the process we can "borrow" energy

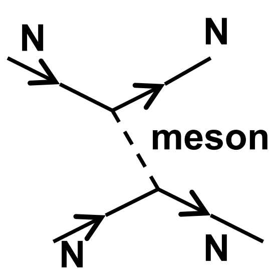
$$\Delta E \Delta t \sim \hbar$$

So for a meson of mass m, the time it may exist will be

$$mc^2 \Delta t \approx \hbar$$

$$\Rightarrow \Delta t \approx \frac{\hbar}{mc^2}$$





Diagrams for the weak interaction

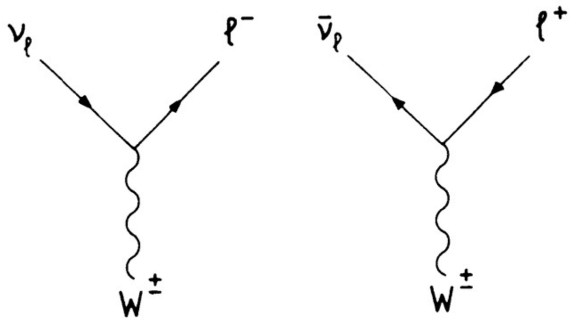
The basic vertices are shown below for W mesons.

A weak coupling constant α_W is associated with each vertex.

Here, l stands for lepton, and refers to the three generations: electron, muon and tau

As with QED, vertices must be combined to conserve both energy and momentum.

In this case the arrows indicate that the "**lepton number**" is conserved

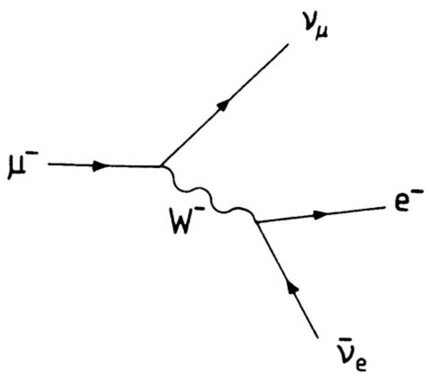


Example: muon decay

A muon is observed to decay in the process

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

i.e. a muon neutrino, an electron anti-neutrino and an electron

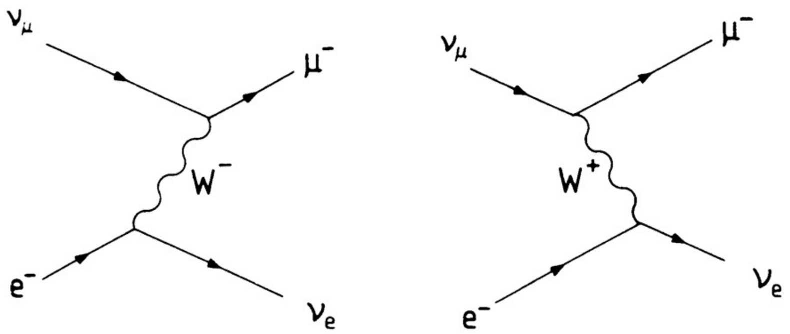


Note that the diagram indicates charge and lepton number conservation.

Other examples of weak interaction processes …

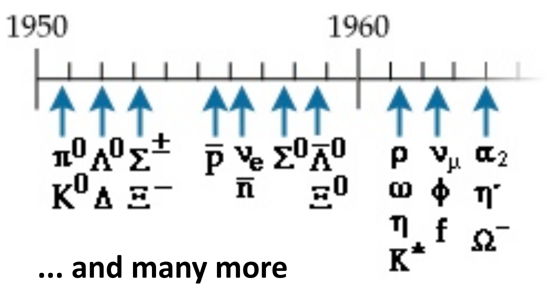
Another example: the inverse muon decay

$$\nu_\mu + e^- \rightarrow \mu^- + \nu_e$$

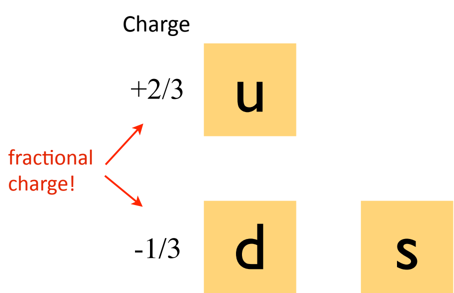


The Quark Model

By the middle of the 1960s, more than 200 'elementary' particles had been discovered. Some particles seemed to have almost the same mass.



The problem was solved by postulating the existence of <u>quarks</u>*, which (at that time) came in three "flavours", up (u), down (d) and strange (s).



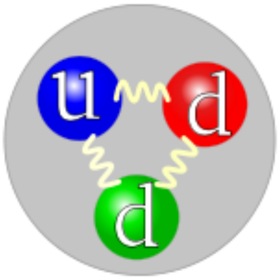
Various combinations of the quarks could produce the observed particle zoo.

M. Gell-Mann was awarded the 1969 Nobel Prize for this.

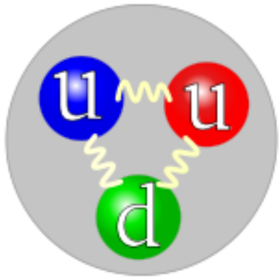
* the name quarks is taken from James Joyce's 'Finnegan's Wake'

The proton and neutron

- Baryons are made of 3 quarks or three anti-quarks
- A proton consists of two *u*-quarks and one *d*-quark, while a neutron consists of two *d*-quarks and one *u*-quark:



NEUTRON
Quark structure

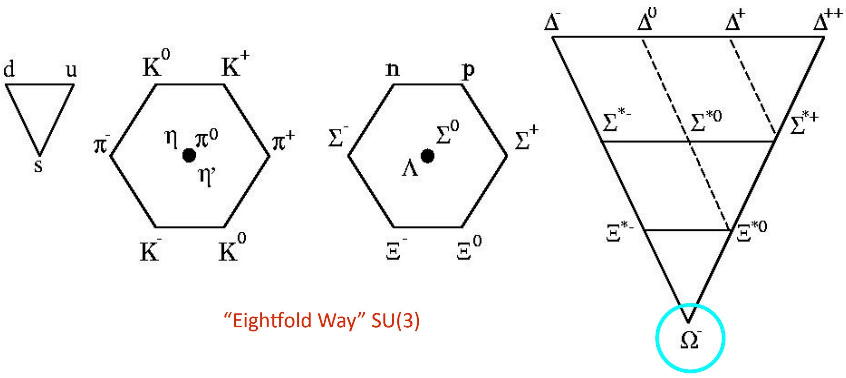


PROTON
Quark structure

$$Q_{neutron} = \frac{2}{3} - \frac{1}{3} - \frac{1}{3} = 0 \qquad Q_{proton} = \frac{2}{3} + \frac{2}{3} - \frac{1}{3} = +1$$

Symmetry groups

- Many of the detected particles could now be classified based on symmetry groups



"Eightfold Way" SU(3)

Baryons (strongly interacting fermions) consist of three quarks.

Mesons (strongly interacting bosons) consist of a quark and an anti-quark.

The prediction of the Ω^- hyperon and its properties before its subsequent discovery in 1964 was a major success for the model.

The Ω^- Hyperon

The bubble chamber picture of the first omega-minus. An incoming K^- meson interacts with a proton in the liquid hydrogen of the bubble chamber and produces an omega-minus, a K° and a K^+ meson which all decay into other particles. Neutral particles which produce no tracks in the chamber are shown by dashed lines. The presence and properties of the neutral particles are established by analysis of the tracks of their charged decay products and application of the laws of conservation of mass and energy.

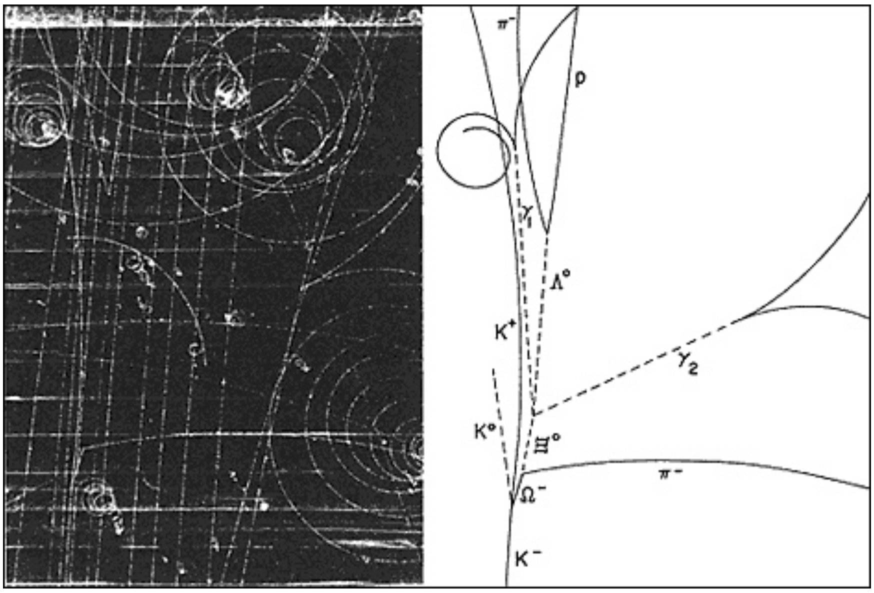
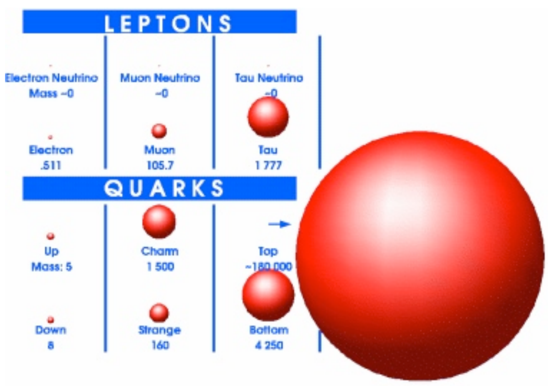


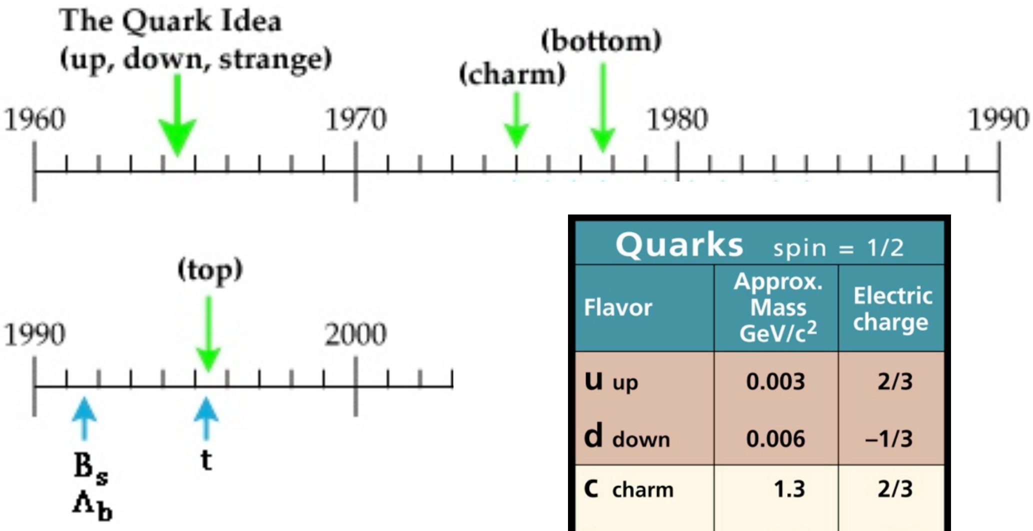
Image and text credits: bnl.gov

The Quark Model

- Generalisations to higher symmetry groups required the introduction of other three quarks in the theory.
- **charm (c) -** predicted in 1964 by S.Glashow and J. Bjoerken, was first observed in Nov 1974, at SLAC (B. Richter et al.) and BNL (S. Ting et al.)
- **bottom (b)** - was discovered in 1977 at Fermilab (L. Ledermann et al.) in the form of the Y-meson consisting of a *b* and an anti-*b*. The discovery of this 5th quark made it very likely that its partner the *t*-quark exists
- **top (t)** - was detected in 1995 by the Tevatron experiments CDF and D0 at Fermilab. The top is very heavy - about the weight of a tungsten (W) atom.



Quarks discovery timeline



Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b bottom	4.3	−1/3

Six flavours of quark have been identified by now

Baryons review

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

Image credits: PDG

Mesons review

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 credits: PDG

The Quark Model

Quarks spin = 1/2		
Flavor	**Approx. Mass GeV/c^2**	**Electric charge**
u up		
d down		
c charm		
s strange		
t top		
b bottom		

Six flavours of quark have now been identified

Baryons (strongly interacting fermions) consist of three quarks.

Mesons (strongly interacting bosons) consist of

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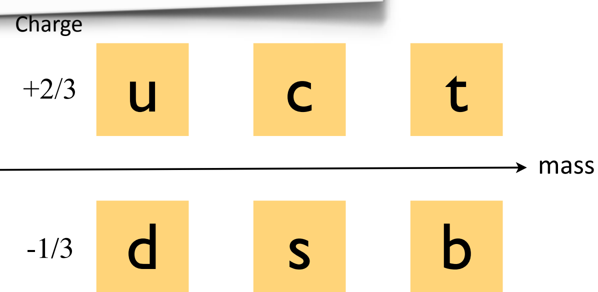
Two problems with the model:

1. No quarks have ever been observed in isolation (this puzzle is referred to as confinement)
2. As fermions, the quarks do not obey the Pauli Exclusion principle

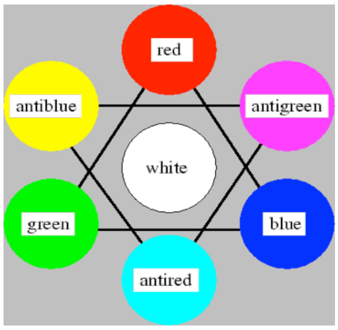


Color

- In the quark model, the Δ^{++} particle (detected in 1951 by Fermi) has with charge +2 consists of three *u* quarks.

- It has spin 3/2, which means that the three spins 1/2 of the *u* quarks are aligned:

$$u\uparrow u\uparrow u\uparrow$$



- This, however, violates the Pauli exclusion principle, which states that *no two fermions can be in exactly the same state.*

- To resolve this problem, in 1964 it was suggested (by O. Greenberg) that quarks carry also a **color charge.**

Quantum Chromodynamics (QCD)

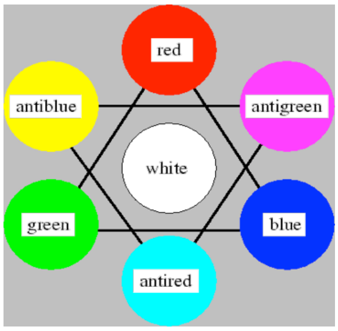
So, in addition to electric charge, quarks carry "colour" charge in three colours: red, blue and green.

There are also *anti-colours* for the anti-quarks.

All physical particles contain a combination of quark colours which are "white".

Quarks interact with each other via the exchange of **gluons.**

Gluons must also carry colour/anti-color charge - and therefore they could interact with other gluons.



Direct experimental evidence for gluons was found in 1979 by the PETRA experiments at DESY.

Quantum Numbers of the Quarks

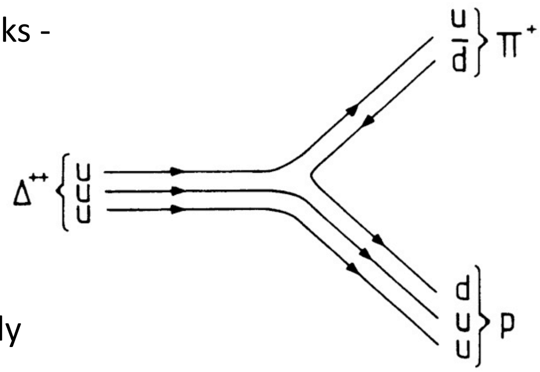
Summary table

Property \ Quark	d	u	s	c	b	t
Q – electric charge	$-\frac{1}{3}$	$+\frac{2}{3}$	$-\frac{1}{3}$	$+\frac{2}{3}$	$-\frac{1}{3}$	$+\frac{2}{3}$
I – isospin	$\frac{1}{2}$	$\frac{1}{2}$	0	0	0	0
I_z – isospin z-component	$-\frac{1}{2}$	$+\frac{1}{2}$	0	0	0	0
S – strangeness	0	0	−1	0	0	0
C – charm	0	0	0	+1	0	0
B – bottomness	0	0	0	0	−1	0
T – topness	0	0	0	0	0	+1

The Quark Model and decay processes

Strong decays of particles can be now understood in terms of individual quarks - e.g. the decay

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



can be viewed as shown.

Interaction times (~ lifetimes of strongly decaying particles) **~ 10^{-23}s**

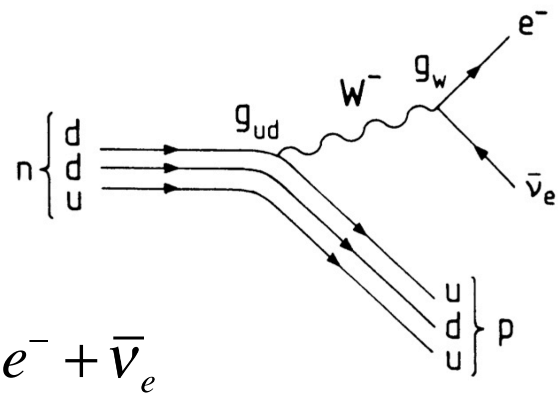
Compare this with the electromagnetic decay of the neutral pion

$$\pi^{0} \rightarrow \gamma + \gamma$$

Where the typical timescale is **~ 10^{-16}s**

Example: neutron decay

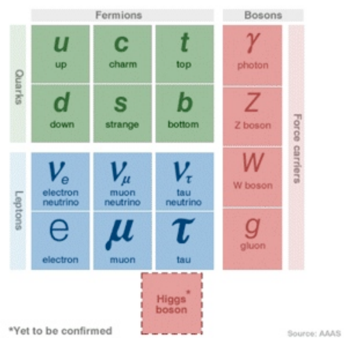
The weak decay of the neutron can now be represented in terms of quarks as



$$n \rightarrow p + e^- + \bar{\nu}_e$$

The Standard Model

- The combination of QCD and electroweak theories are collectively known as the **standard model** (of particle physics).
- The standard model represents our current complete knowledge of matter.
- To include gravity in the theory is a challenge (and is presently not possible consistently).
- There must be physics "beyond the standard model" to complete a "theory of everything".



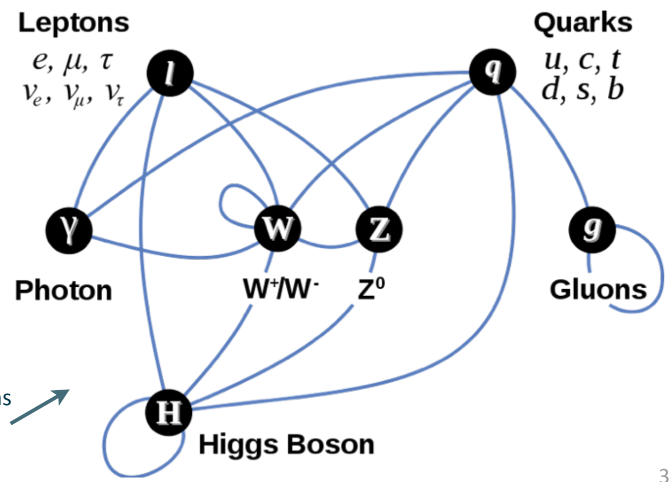
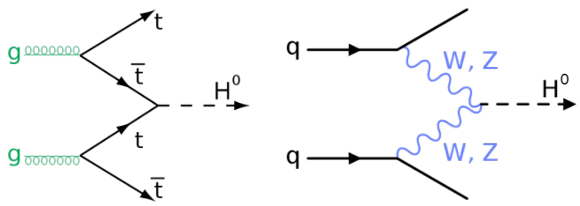


Diagram summarising the tree-level interactions between elementary particles described in the Standard Model

The Higgs Boson

- Predicted by the Standard Model (Higgs mechanism incorporated into the Standard Model by A. Salam and S. Weinberg). Named after Peter Higgs of Edinburgh University
- The Higgs mechanism is the process that gives mass to elementary particles: simply put, particles gain mass by interacting with the Higgs field that permeates all space
- Ongoing experiments at CERN and Fermilab are trying to detect the Higgs boson



Feynman diagrams showing two ways the Higgs boson might be produced at the LHC.

- ATLAS and CMS at CERN have reported a possible find with mass within 115-127 GeV/c^2
- As of March 2012 the D0 and CDF Collaborations announced finds that could be interpreted as a Higgs boson with a mass of 115-135 GeV/c^2. The significance of the result is 2.2σ, not enough to rule out a statistical fluctuation.

the search continues ...

ATLAS and the Higgs

The red lines show four muon tracks in ATLAS. They could have been the byproducts of a short-lived Higgs boson - or they could have been more banal events.