Particle Zoo and Feynman Diagrams

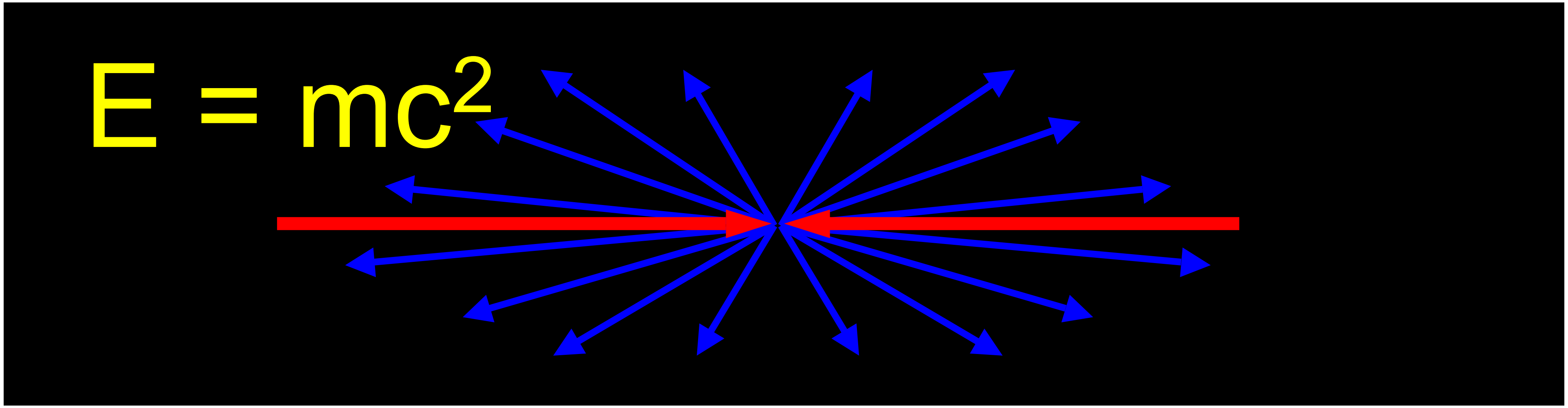
Cristina Lazzeroni
Professor in Particle Physics
STFC Public Engagement Fellow

ASE Conference 2016
University of Birmingham
Muirhead 118
7th January 2016, 10:00-12:00

Science & Technology Facilities Council

European Research Council
Established by the European Commission

Particles accelerated to speed of light :



Energy and mass are related, in general

$$E^2 = p^2 + m_0^2 \quad , c=1$$

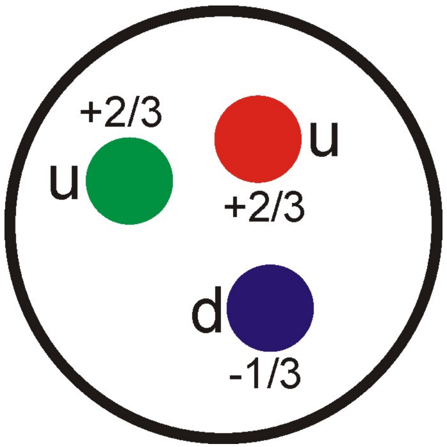
$$(\text{Invariant mass})^2 = E^2 - (p_x^2 + p_y^2 + p_z^2)$$

Protons smashing together can produce all sorts of particles, seen in the earliest moments of the universe

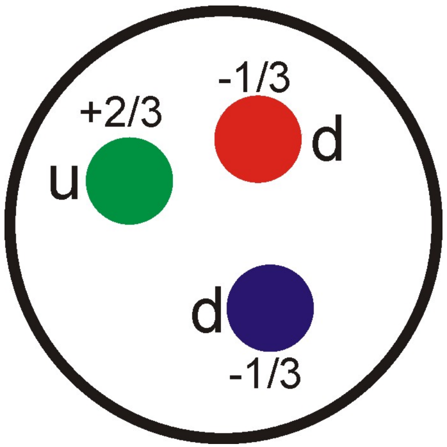
The Modern Picture of Protons and Neutrons

In 1969, an experiment at SLAC using a 2-mile long 20 billion eV electron accelerator showed that protons have structure → "quarks"

- Protons and neutrons made from Up (u) and Down (d) quarks.
- u-quarks have +2/3 of electron charge, d-quarks have –1/3



Proton



Neutron

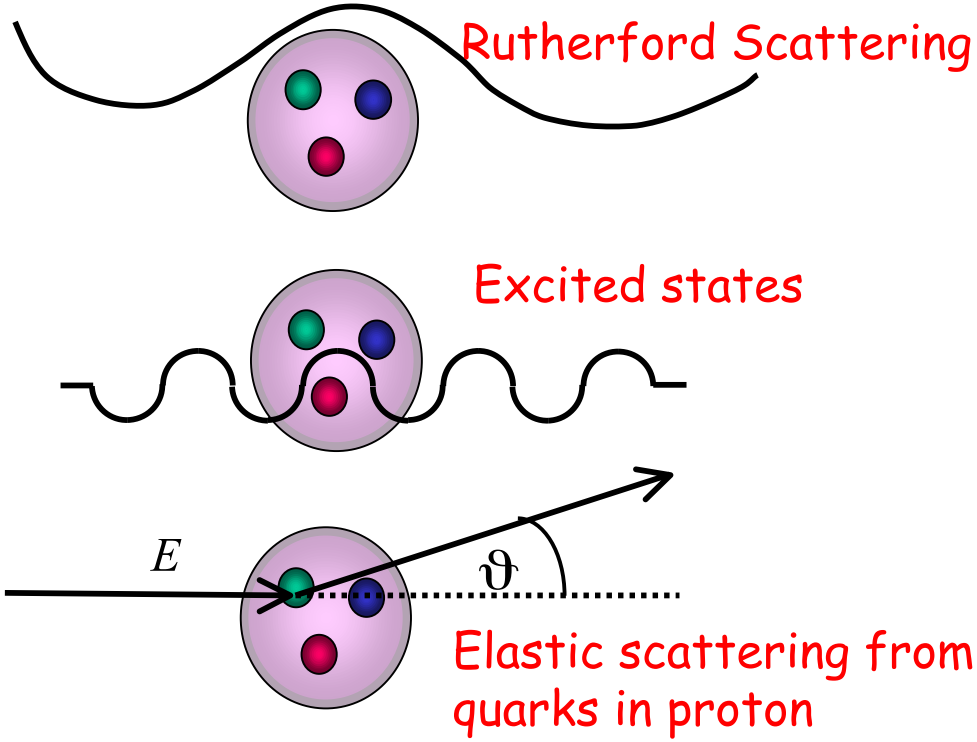
Discovery of Quarks

γ carries momentum

Large $\vec{p}$, small λ $\quad \vec{p} = \hbar / \lambda$

Large E, large ω $\quad E = \hbar\omega$

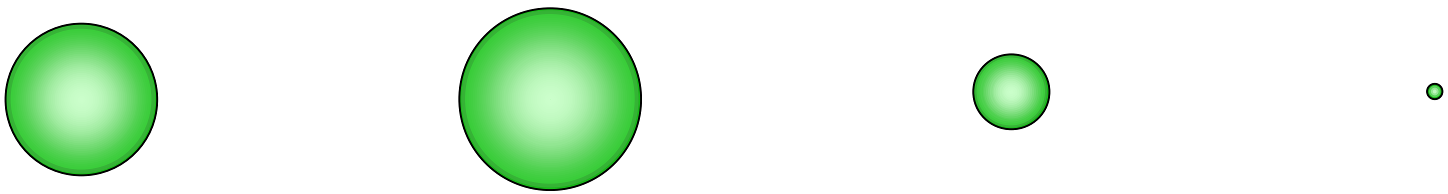
Wave-function oscillates rapidly in space and time $\Rightarrow$ probes short distances and short time.



$\lambda <<$ size of proton

A Nice Happy Family of Particles

Up quark (u)	Down quark (d)	Electron (e^-)	Electron neutrino (ν_e)
Mass ~ 0.003	~ 0.006	~0.0005	~ 10^{-8} ?



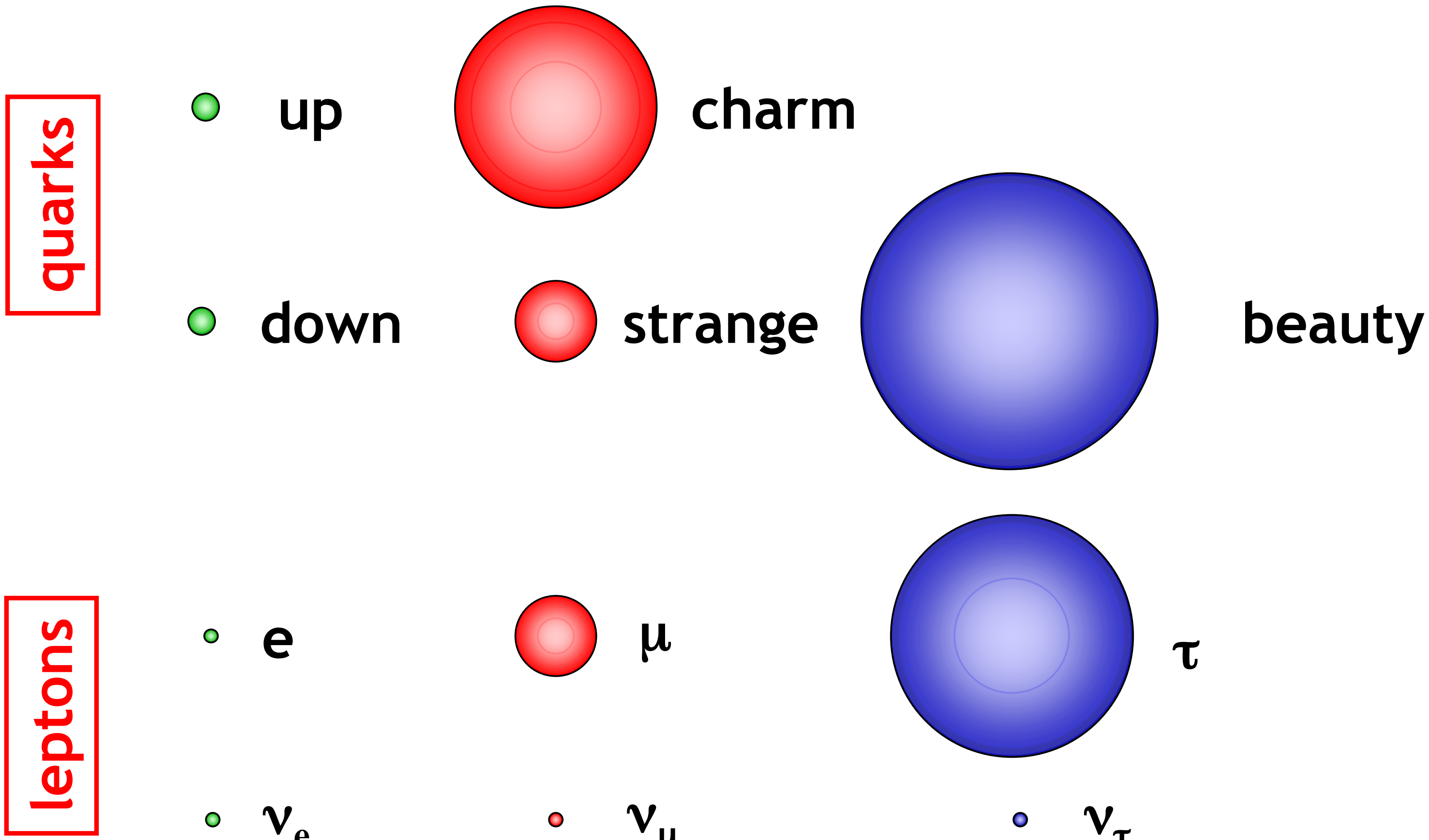
(relative to the mass of a single proton)

Everything around us (the whole Periodic Table) is made of up quarks, down quarks and electrons.
But the masses don’t add up….

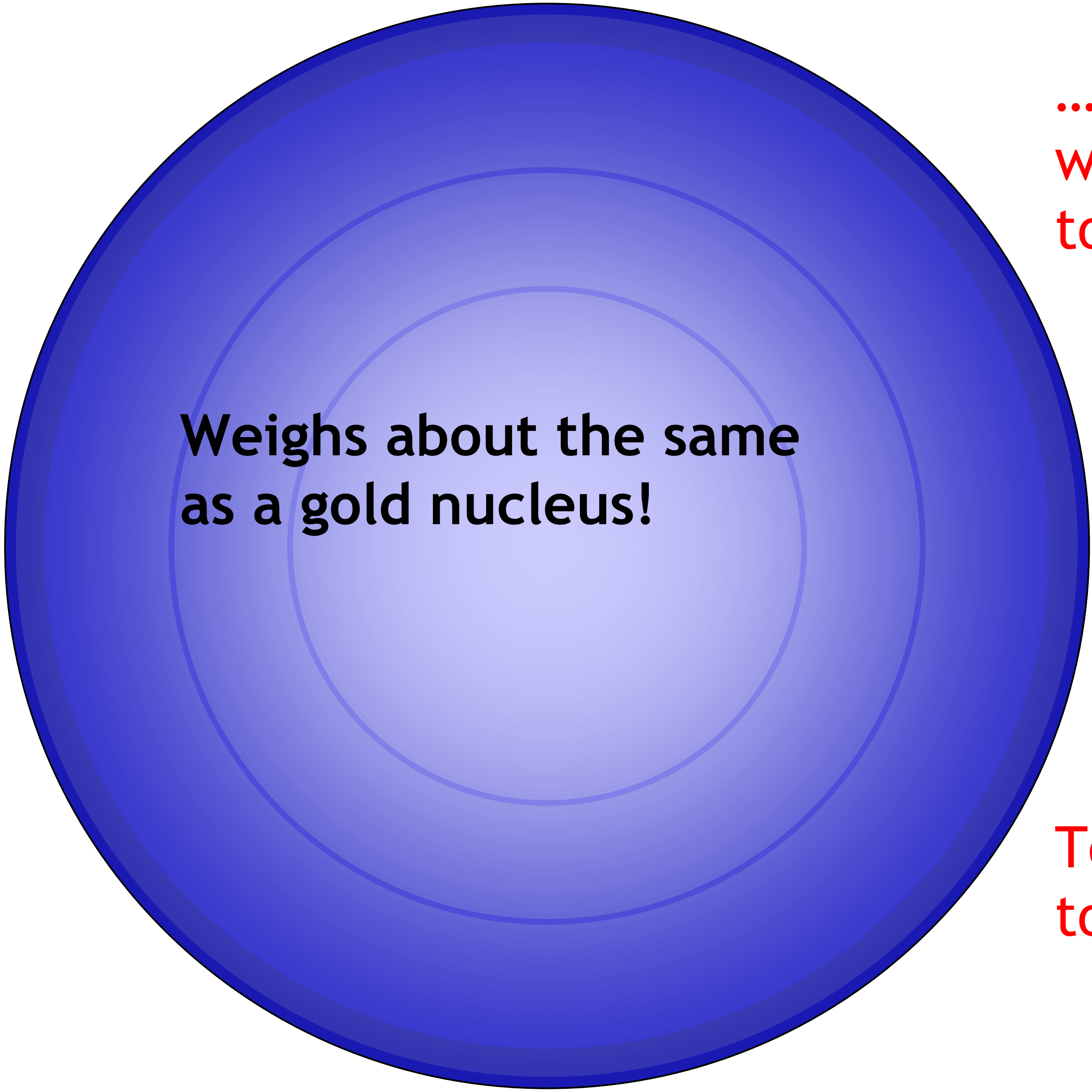
… for some reason, there is more …

Nature supplies us with a copy of the family but heavier …

… and another copy of the family but even heavier …



The Top Quark



… and that is where it seems to stop

Top has no time to hadronize

Antimatter

1928: Paul Dirac put together Relativity with Quantum Mechanics into the theory of the electron …
it also predicted anti-electrons (`positrons')

Every fundamental fermion particle has an antiparticle, with the same mass, but opposite charge.

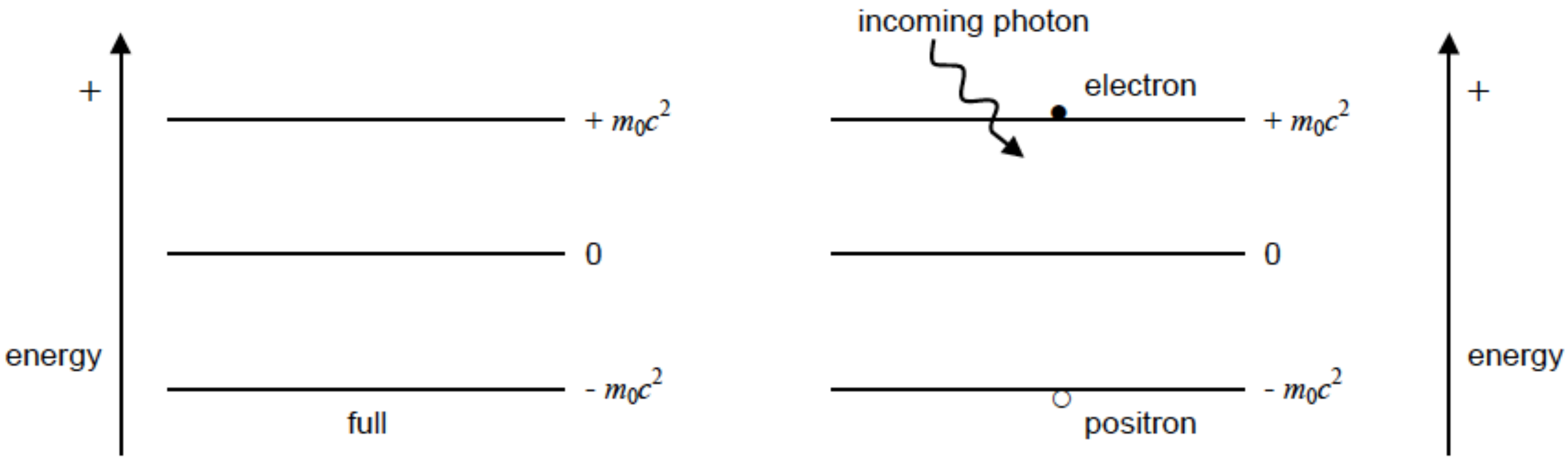
electron e^- e^+ positron

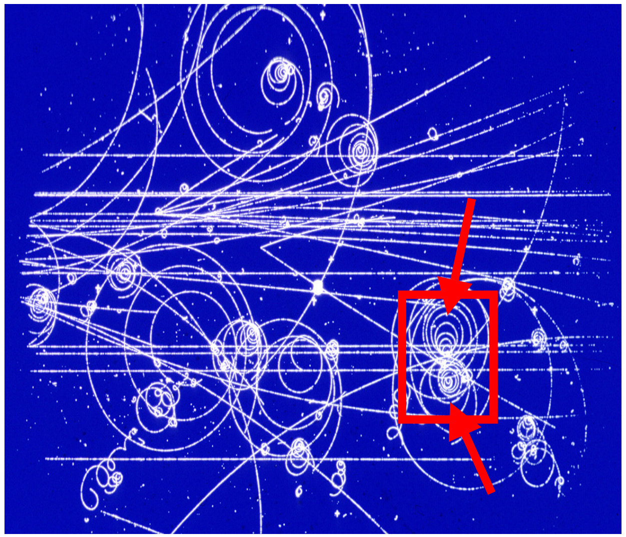
up quark $u^{+2/3}$ $\bar{u}^{-2/3}$ up anti-quark

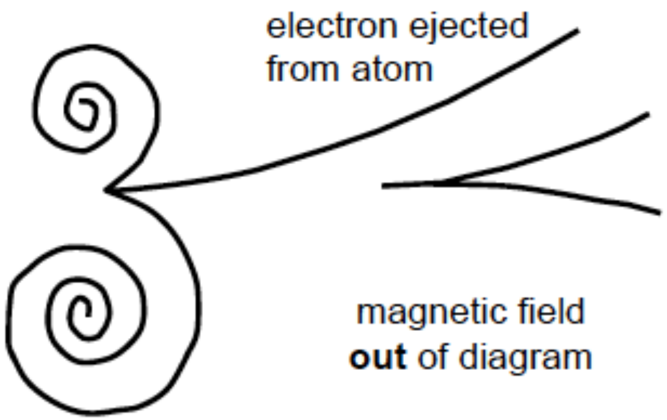
etc etc …

Antimatter

In unifying QM and Relativity, there is the need of negative-energy particles: antimatter

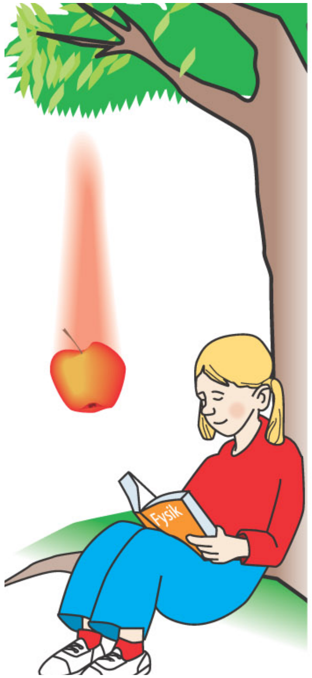


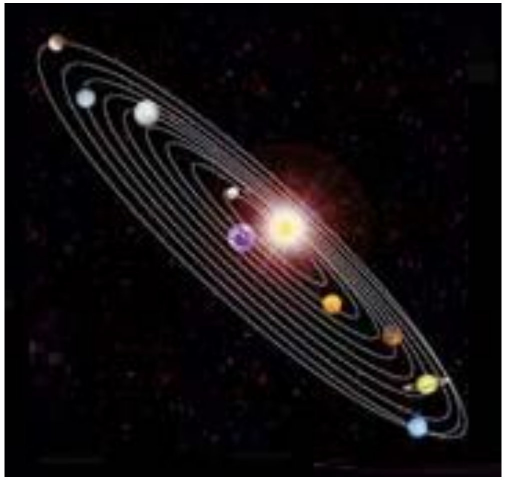




Gravitational Force

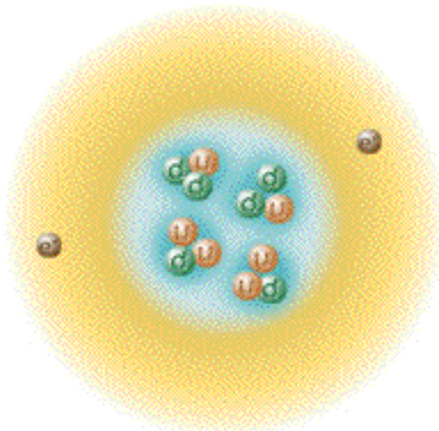
Isaac Newton
(1642 - 1727)

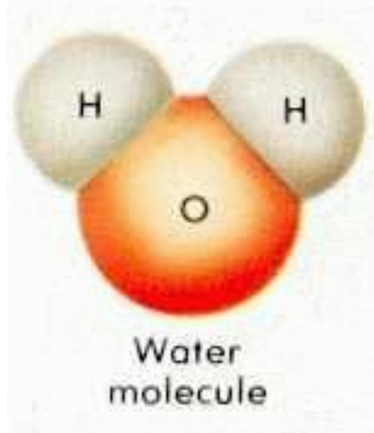




Electromagnetic Force

James Clerk Maxwell
(1831 - 1879)





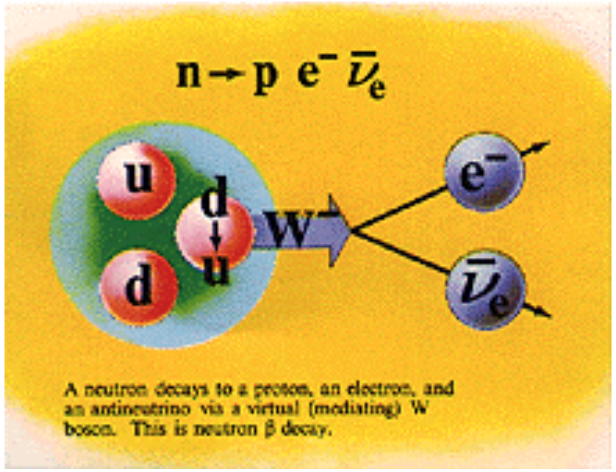
Size of atoms is set by strength of EM force

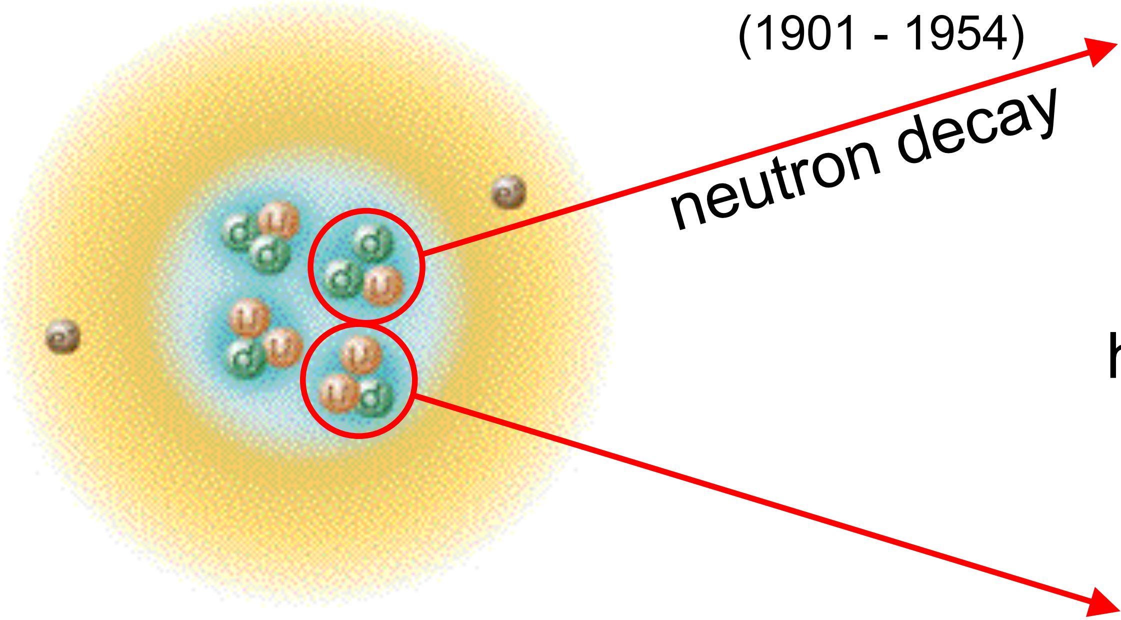
How stars generate energy

Weak Force

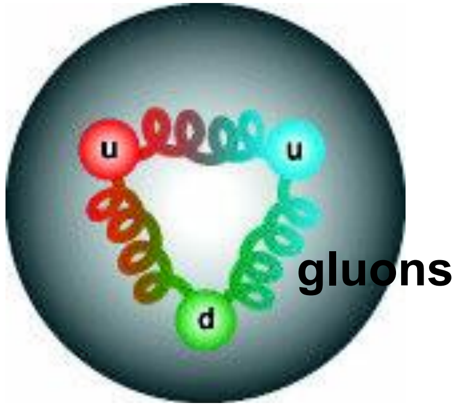
Enrico Fermi
(1901 - 1954)

radioactive decays





holding proton, nucleus



Strong Force

Size of nuclei is set by strength of strong force

	LEPTONS			QUARKS		
		q	m/GeV		q	m/GeV
First Generation	e^-	–1	0.0005	d	–1/3	0.3
	ν_1	0	≈0	u	+2/3	0.3
Second Generation	μ^-	–1	0.106	s	–1/3	0.5
	ν_2	0	≈0	c	+2/3	1.5
Third Generation	τ^-	–1	1.77	b	–1/3	4.5
	ν_3	0	≈0	t	+2/3	175

Leptons:
integer charge,
DON'T feel STRONG

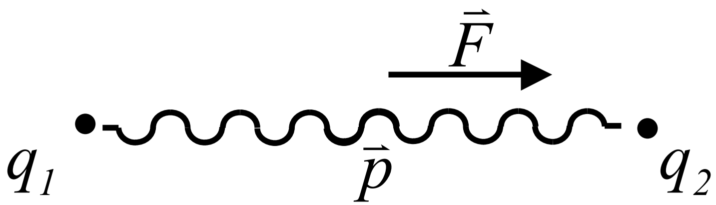
Quarks:
fractional charge
feel ALL forces

Force	Boson(s)	m/GeV
EM (QED)	Photon γ	0
Weak	$W^{\pm}$ / Z	80 / 91
Strong (QCD)	8 Gluons g	0
Gravity (?)	Graviton?	0

Bosons:
Force carriers
integer charge

Forces

Quantum Mechanically: Forces arise due to exchange of VIRTUAL FIELD QUANTA



$$\begin{array}{lcll} Q_1 & \rightarrow & Q_1 & \gamma \\ 0 & \rightarrow & -\Delta E & \Delta E \\ m & \rightarrow & \sqrt{m^2 + \Delta E^2} & \Delta E \end{array}$$

Force	Boson		Strength	Mass (GeV/c^2)
Strong	Gluon	g	1	Massless
Electromagnetic	Photon	γ	10^{-2}	Massless
Weak	W and Z	$W^{\pm}$, Z^0	10^{-7}	80, 91
Gravity	Graviton	?	10^{-39}	Massless

Range of Forces

The range of a force is directly related to the mass of the exchanged bosons

$$\Delta E \Delta t \sim \hbar \qquad E = mc^2$$

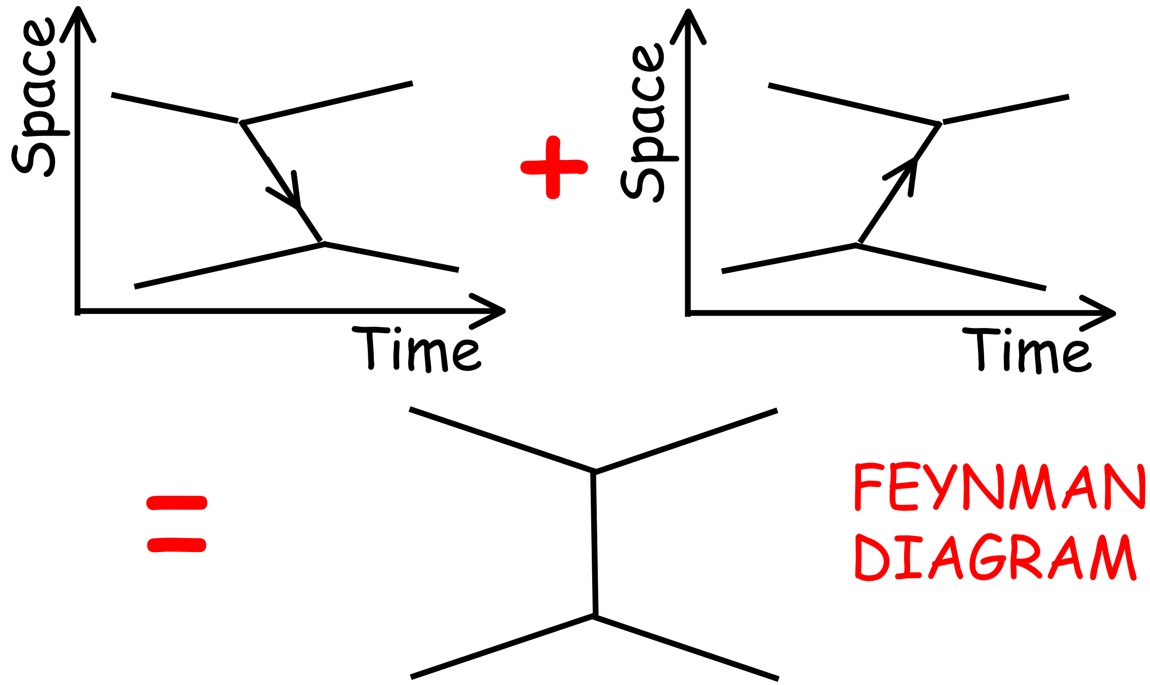
$$mc^2 \sim \hbar / \Delta t \sim \hbar c / r$$

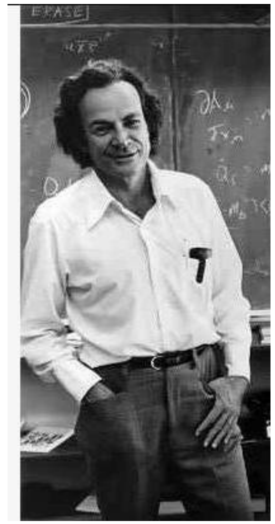
$$r \sim \hbar / mc \qquad \hbar = c = 1 \text{ natural units}$$

Force	Range (m)
Strong Strong (Nuclear)	∞ 10^{-15}
Electromagnetic	∞
Weak	10^{-18}
Gravity	∞

1 fm distance at speed c means 3 10^{-23} s
Uncertainty principle: E ~ 200 MeV i.e. pion
Predicted in 1935; discovered in cosmic ray interactions in 1947

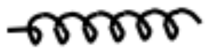
Feynman diagrams





Feynman devised a pictorial method to evaluate probability of interaction between fundamental particles

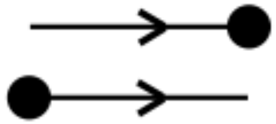
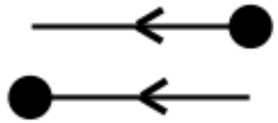
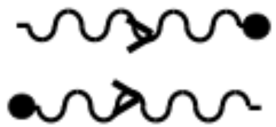
Represent particles (and antiparticles):

Spin $\frac{1}{2}$	Quarks and Leptons	———
Spin 1	γ, $W^{\pm}$ and Z^0	
	g	

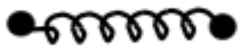
and their interaction point (vertex) with a "●".

Each vertex gives a factor of the coupling constant, g.

External Lines (visible particles)

Spin $\frac{1}{2}$	Particle		Incoming Outgoing
	Antiparticle		Incoming Outgoing
Spin 1	Particle		Incoming Outgoing

Internal lines (propagators)

Spin $\frac{1}{2}$	Particle (antiparticle)	
Spin 1	γ, $W^{\pm}$ and Z^0	
	g	

Virtual particles

Forces arise due to the exchange of unobservable VIRTUAL particles.

- The mass of the virtual particle, q^2, is given by

$$q^2 = E^2 - |\vec{p}|^2$$

and is not the physical mass m, i.e. it is OFF MASS-SHELL.

- The mass of a virtual particle can by +ve, -ve or imaginary.

- A virtual particle which is off-mass shell by amount Δm can only exist for time and range

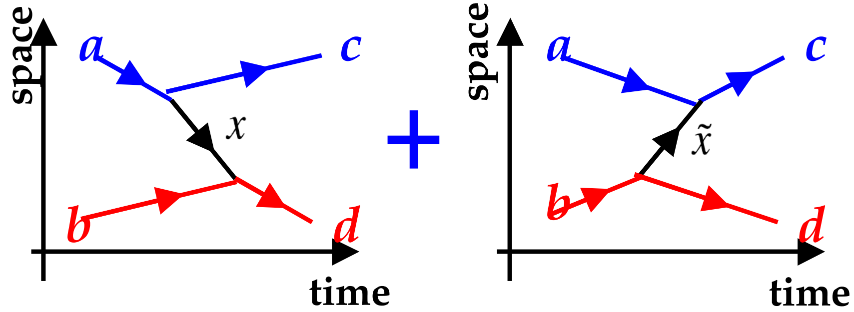
$$t \sim \frac{\hbar}{\Delta mc^2} = \frac{1}{\Delta m}, \quad range = \frac{\hbar}{\Delta mc} = \frac{1}{\Delta m}$$

$\hbar$ =c=1 natural units

- If $q^2 = m^2$, then the particle is real and can be observed.

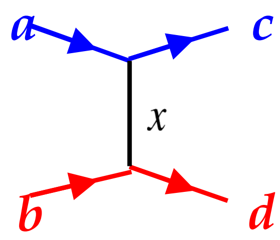
Virtual Particles

"Time-ordered QM"



=

Feynman diagram



- **Momentum conserved at vertices**
- **Energy not conserved at vertices**
- **Exchanged particle "on mass shell"**

$$E_x^2 - |\vec{p}_x|^2 = m_x^2$$

- **Momentum AND energy conserved at interaction vertices**
- **Exchanged particle "off mass shell"**

$$E_x^2 - |\vec{p}_x|^2 = q^2 \neq m_x^2$$

VIRTUAL PARTICLE

- **Can think of observable "on mass shell" particles as propagating waves and unobservable virtual particles as normal modes between the source particles**

Conservations

Energy, momentum, charge

Baryon number, lepton number

Strangeness (and Colour) in Strong interactions

$$\mathrm{p} + \mathrm{p} \rightarrow \bar{\mathrm{p}} + \mathrm{p} + \mathrm{p} + \mathrm{p}$$

$$p \rightarrow \pi^0 e^+$$

$$\Lambda p \rightarrow K^- p p$$

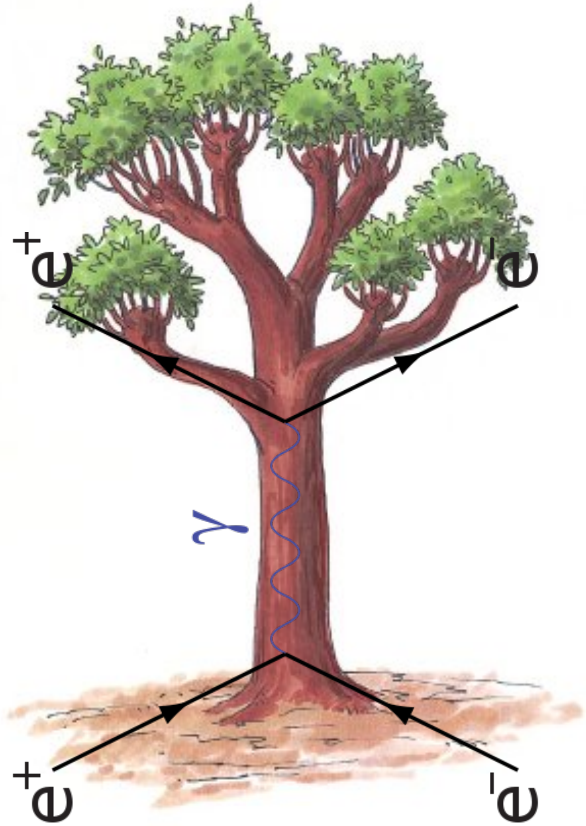
$$n \rightarrow p e^- \gamma$$

$$\Lambda \rightarrow \pi^+ \pi^-$$

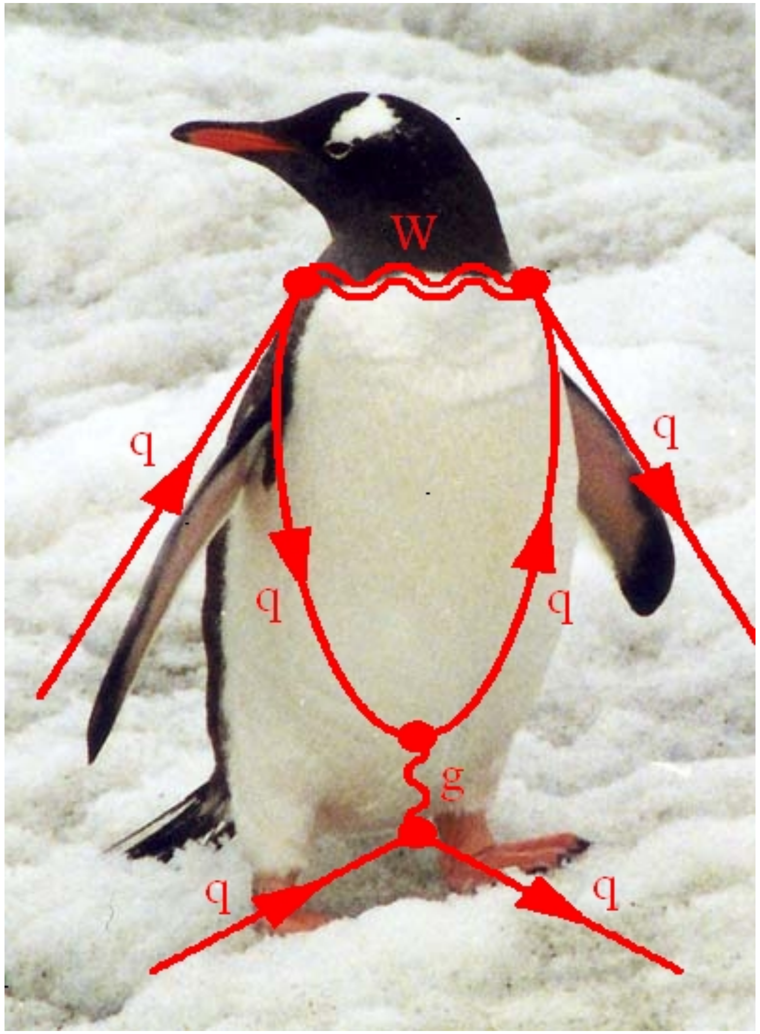
$$n \rightarrow p e^- \nu_e$$

$$\nu_\mu n \rightarrow e^- p$$

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



Trees



Penguins

The story of penguin diagrams

Particle Spin

Introduced by Pauli in 1924 as new quantum degree of freedom which allowed formulation of Pauli exclusion principle.

In 1925, it was suggested that it relates to self-rotation, but heavily criticised… only useful as a picture.

In 1927 Pauli formulated theory of spin as a fully quantum object (non-relativistic). In 1928 Dirac described the relativistic electron as a spin object.

In 1940 Pauli proved the spin-statistic theorem: fermions have half-integer spin and bosons have integer spin.

Particle Spin

Quantum mechanical, intrinsic angular momentum.

Particles are observed to possess angular momentum that cannot be accounted for by orbital angular momentum.
Although the direction of its spin can be changed, an elementary particle cannot be made to spin faster or slower.

Spin cannot be explained by postulating that they are made up of even smaller particles rotating about a common centre of mass. Truly intrinsic property.

Same behavior as angular momentum, quantised.

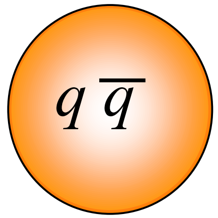
Integer and half-integer values: fermions (Pauli exclusion principle) and bosons (Bose-Einstein condensation).

Hadrons = massive

Single free quarks are NEVER observed, but are always CONFINED in bound states, called HADRONS. Macroscopically hadrons behave as point-like COMPOSITE particles. Hadrons are of two types:

MESONS (qq)

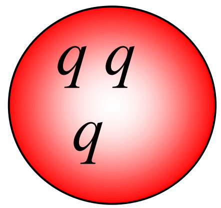
- Bound states of a QUARK and an ANTIQUARK
- All have INTEGER spin, Bosons



$$\pi^- \equiv (\bar{u}d) \qquad \pi^+ \equiv (u\bar{d})$$

BARYONS (qqq)

- Bound states of 3 QUARKS
- All have HALF-INTEGER spin, Fermions



$$p \equiv (uud) \qquad n \equiv (udd)$$

PLUS ANTIBARYONS

$$(\bar{q}\bar{q}\bar{q}) \qquad \bar{p} \equiv (\bar{u}\bar{u}\bar{d}) \quad \bar{n} \equiv (\bar{u}\bar{d}\bar{d})$$

Isospin

Heisenberg in 1932 suggested that neutron and proton are treated as different charge states of one particle, the nucleon.
Idea originally introduced in nuclear physics to explain observed symmetry between protons and neutrons: e.g. mirror nuclei have similar strong interaction properties

A nucleon is given a number ISOSPIN I and then there are 2 states with I_3 with value +1/2 or -1/2:

$I = 1/2$, $I_3 = +1/2, -1/2$

$$\begin{pmatrix} p \\ n \end{pmatrix}$$

Mesons were firstly postulated as the carrier of the strong force.
In 1947, the charged pion was discovered by a group of scientists in Bristol, looking at photographic emulsions exposed to cosmic rays.

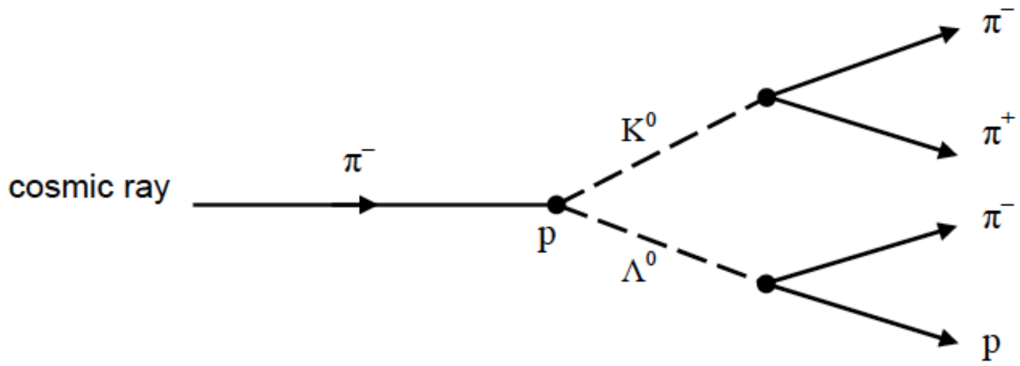
For ISOSPIN, one can put pions in a set of 3
They are formed by u and d quarks

$$\begin{pmatrix} \pi^+ \\ \pi^0 \\ \pi^- \end{pmatrix}$$

Charge $Q = I_3 + B/2$ B=baryon number

Relevance of ISOSPIN now understood as a consequence of very similar masses of u and d quarks, and conservation of isospin in strong interactions.

About at the same time, scientists from Manchester found another new particle in interactions of cosmic rays in a cloud chamber.



More and more were seen, and their rate of production in pion-proton reaction was measured and their lifetimes were also measured.

This new kind of particle was STRANGE in the sense that they decay very very slowly but the reaction production proceed very fast. Besides, they are always produced in at least 2 of them. So they were called STRANGE particles !

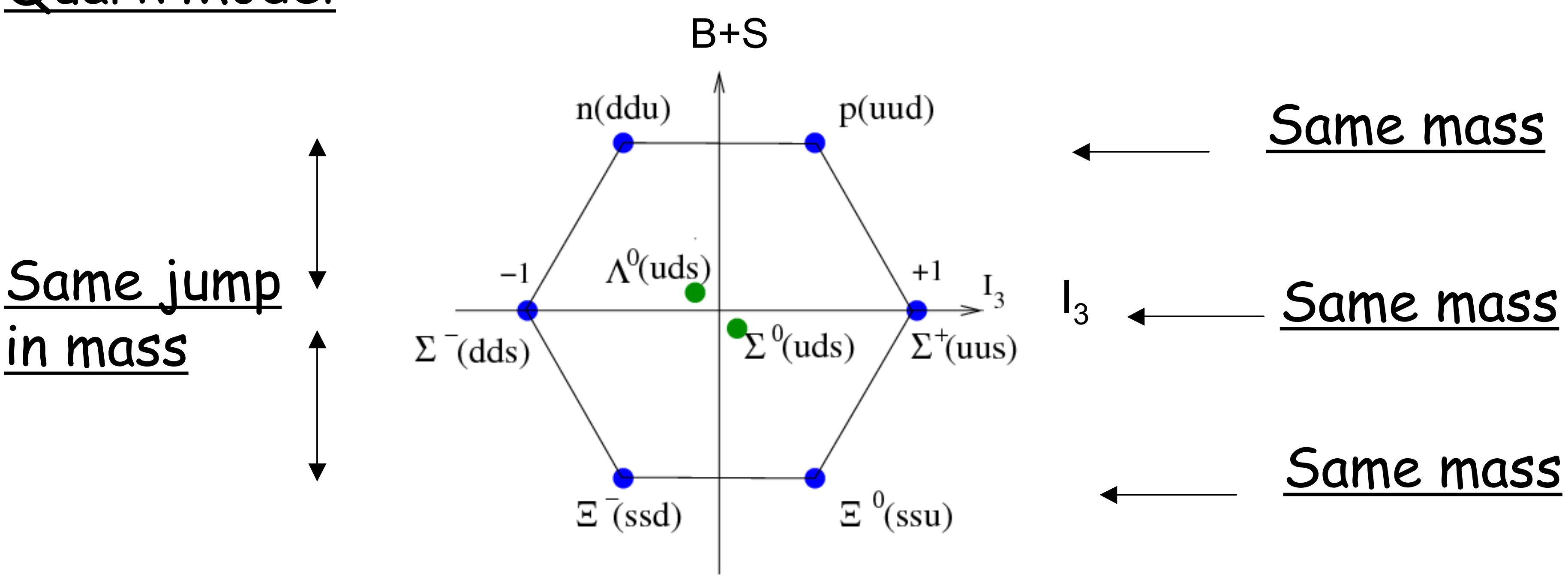
Produced in pairs $\pi^- + p \rightarrow K^0 + \Lambda^0$

Now understood in terms of s quark and the fact the strong interaction conserve any quark type, so conserve also strangeness.

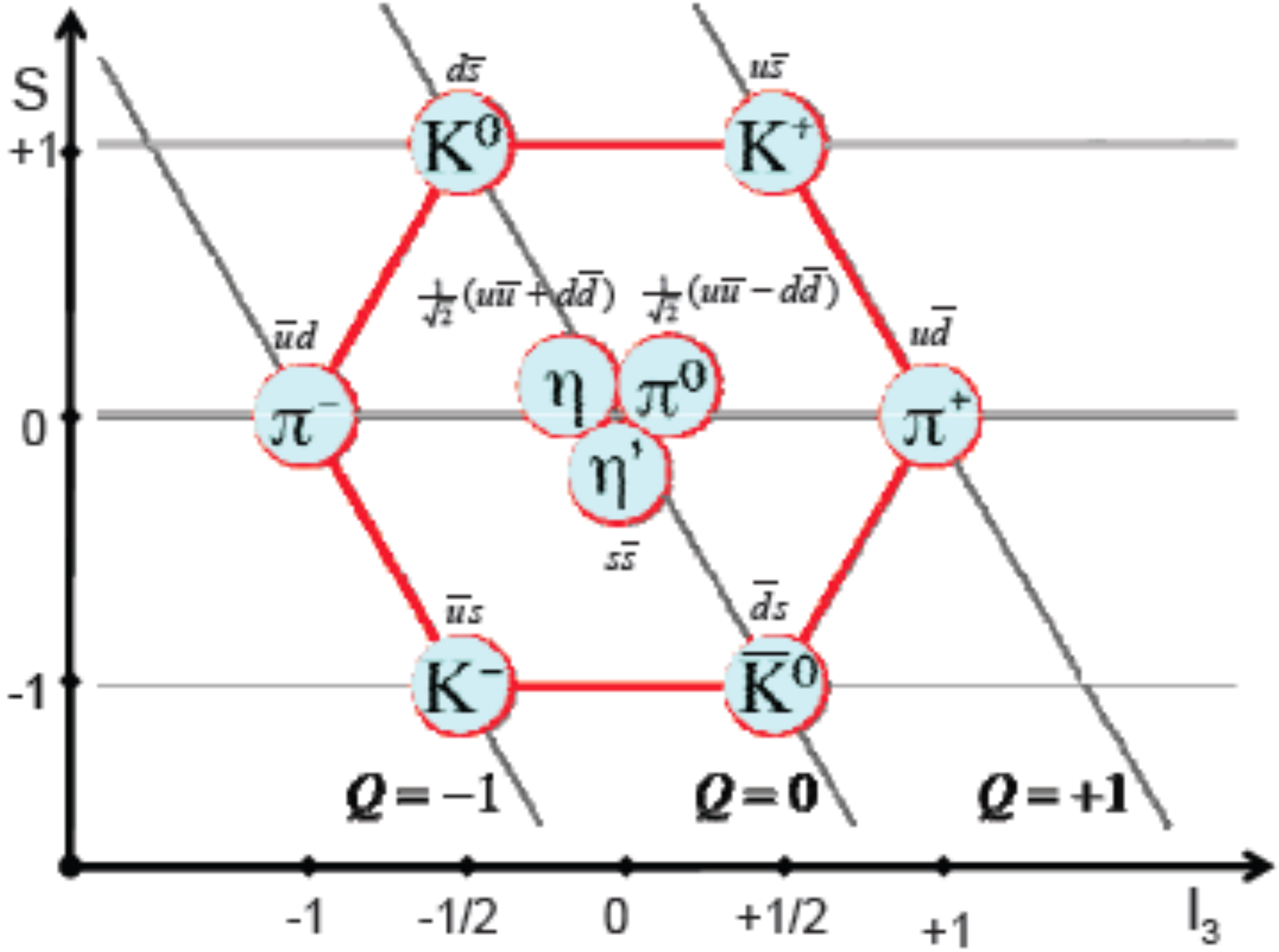
$Q = I_3 + (B+S)/2$ B=baryon number

<u>This is purely because s quark is not so much heavier</u>

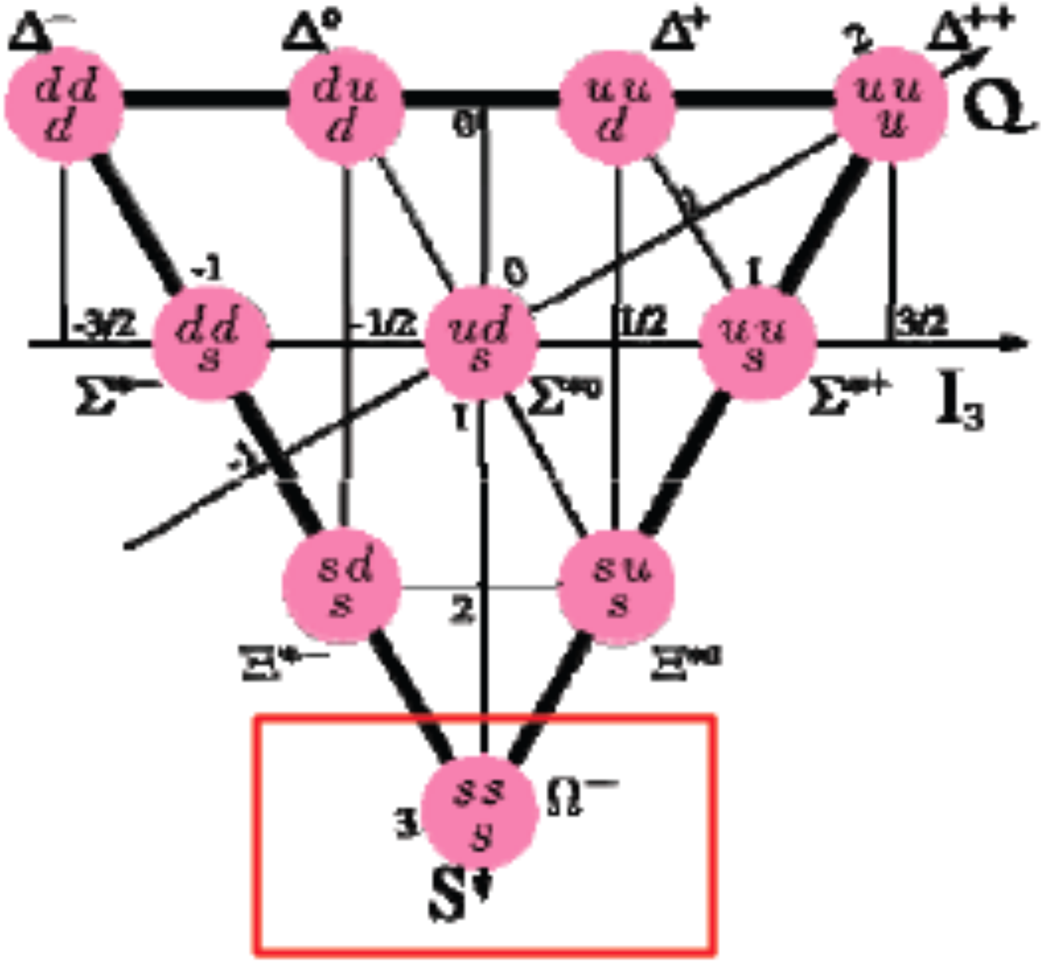
<u>Now classify mesons and baryons on basis of I_3 and B+S: Quark Model</u>



Spin=0 mesons

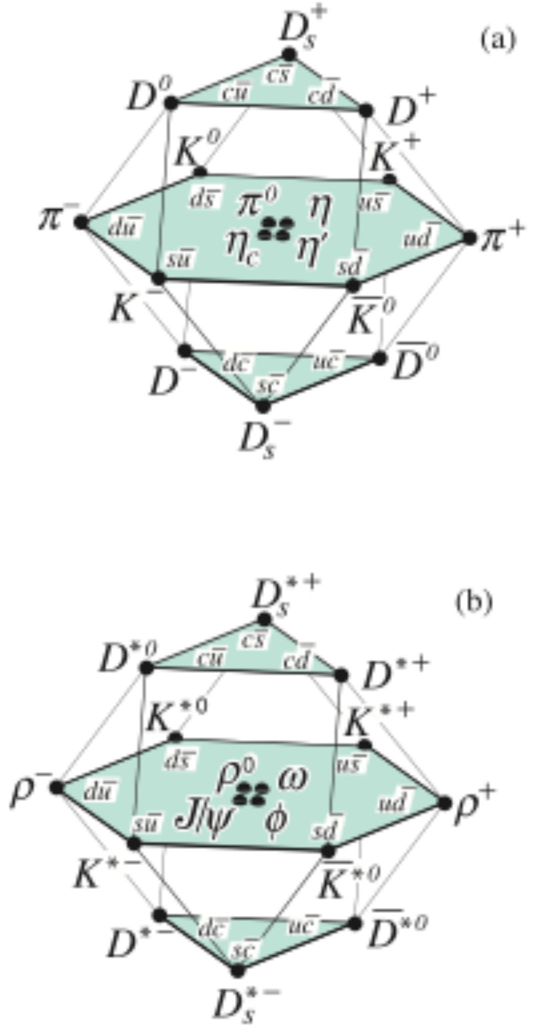


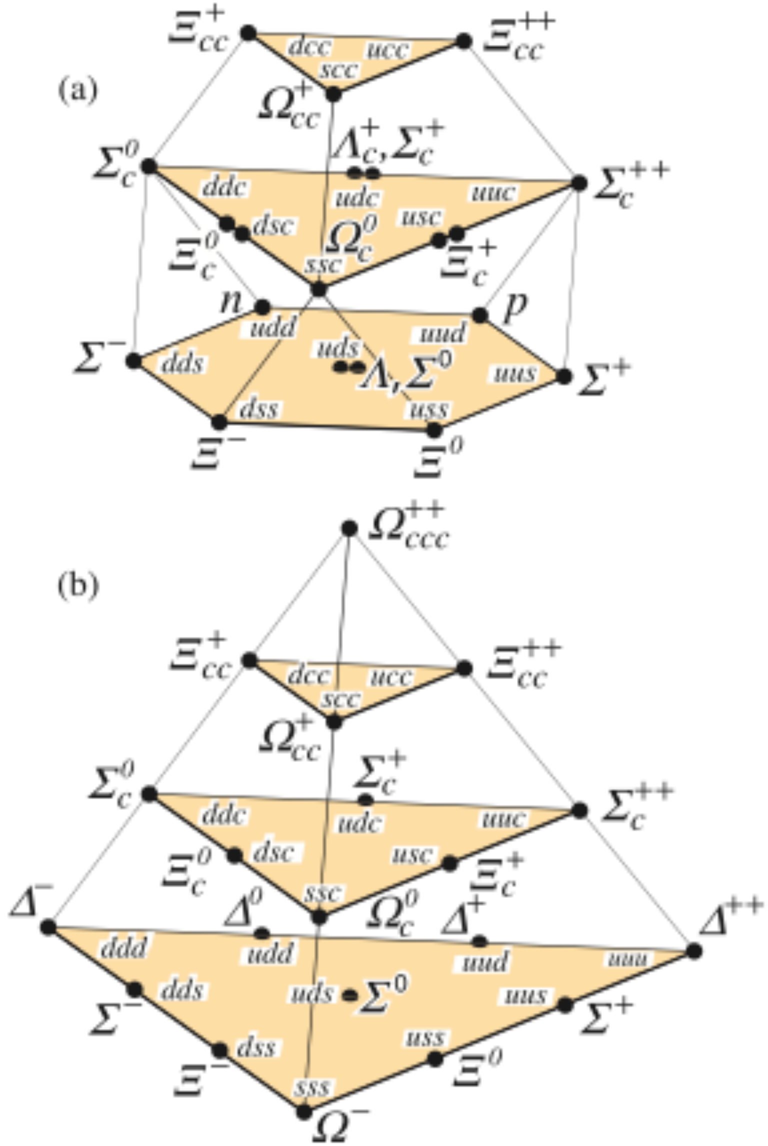
Spin=3/2 baryons



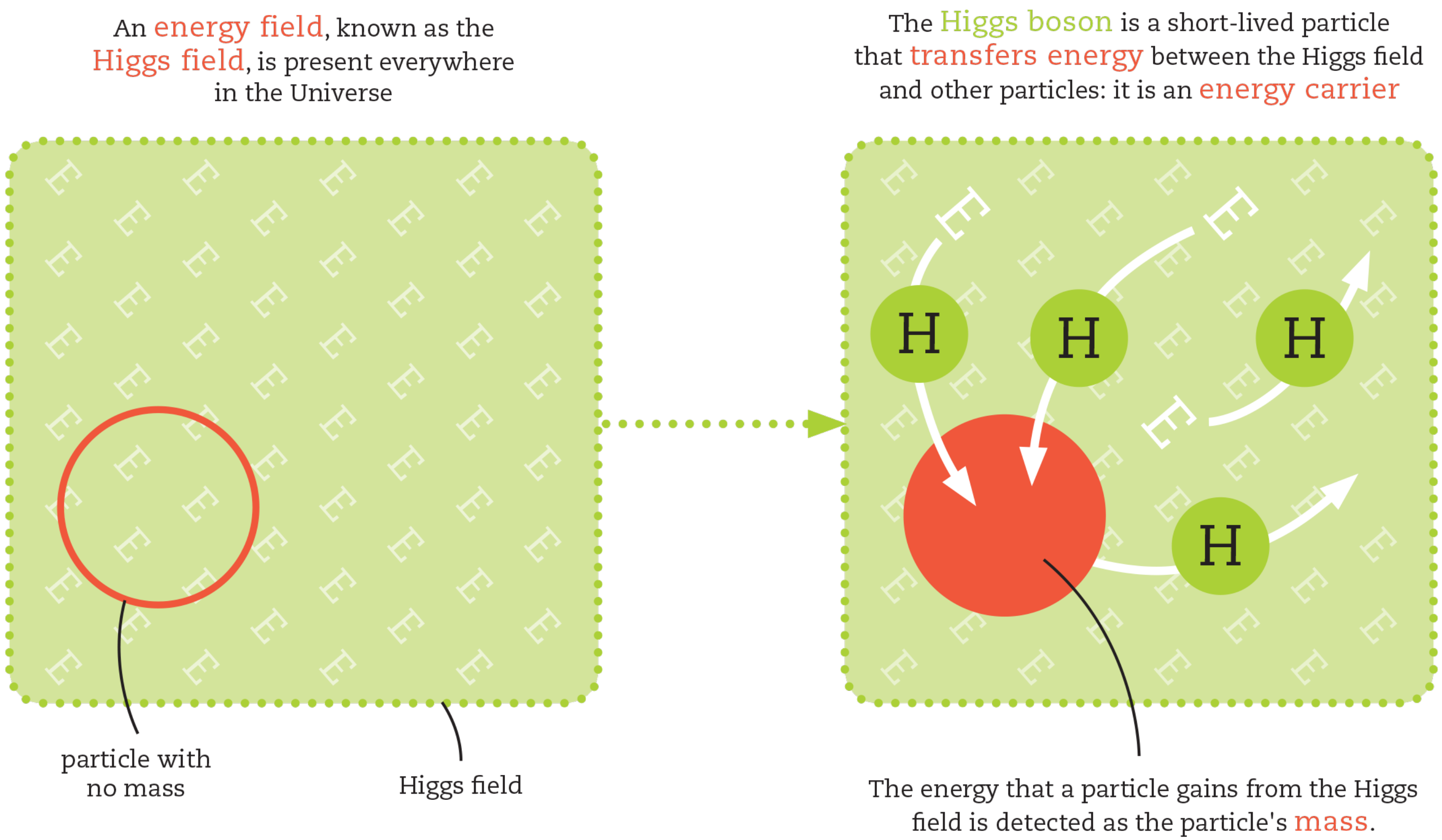
- Ω^- not observed initially but predicted from pattern in quark model.
- Existence of the S=-3 (sss) baryon at at mass ~1680 MeV/c^2
- Identified based on a single event in bubble chamber (1964)
  - 3 very characteristic weak decays
  - 1st successful prediction of quark model!

Possible to extend to include charm and beauty but less and less precise the more the quark is heavier

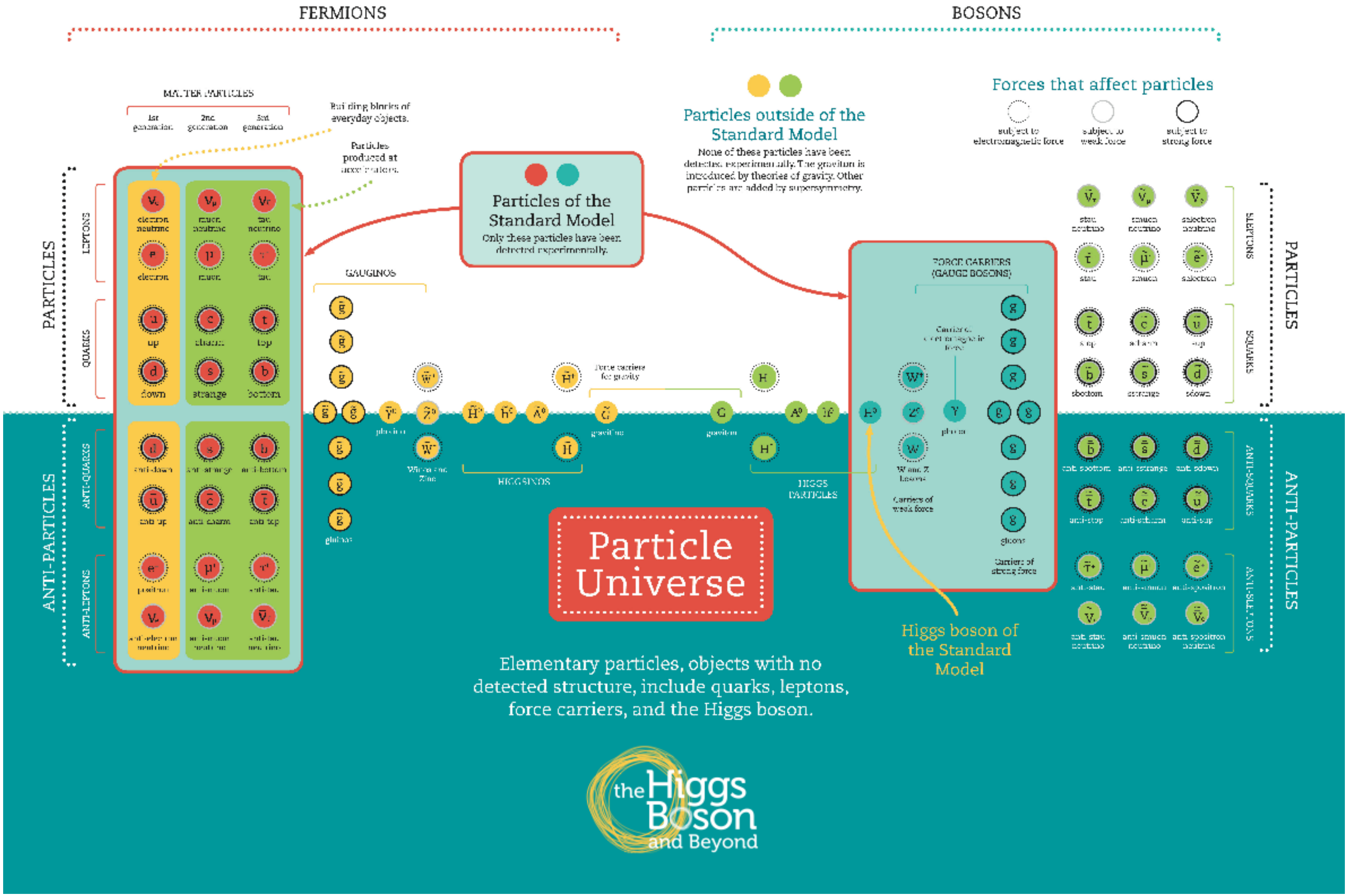




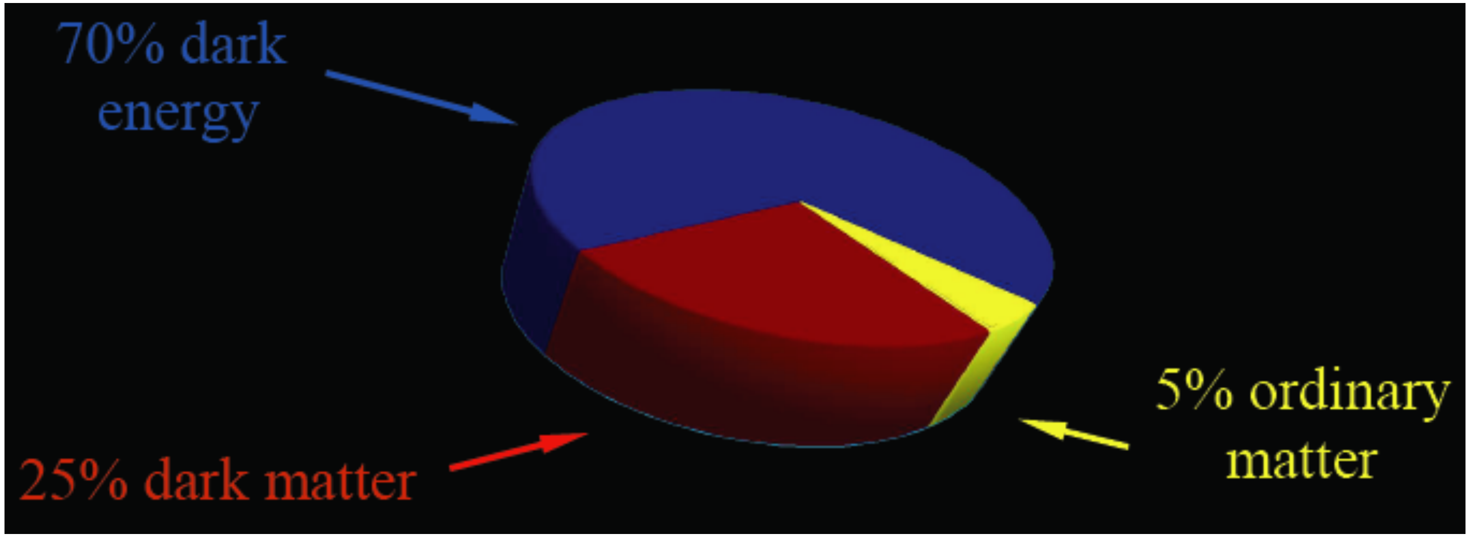
Higgs mechanism

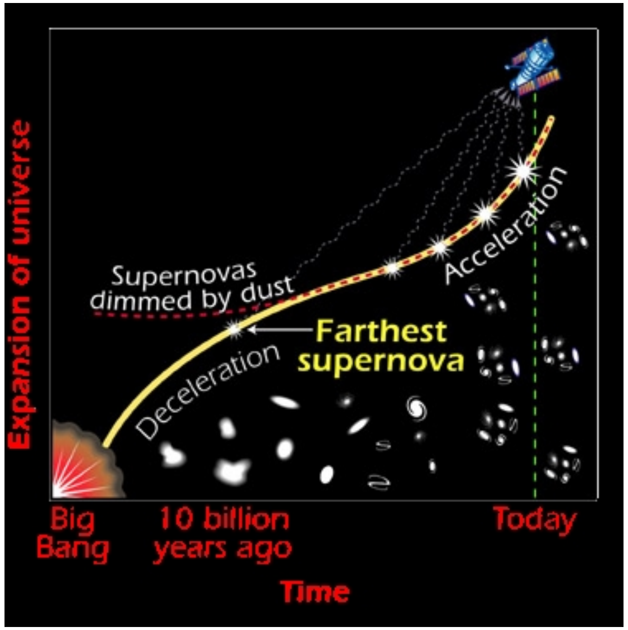


Supersymmetry



Only a small fraction of the total is ordinary matter that we know !





Resources:

Quark game
Top-trump card game

Plus various others from websites:

http://www.the-higgs-boson-and-beyond.org/

http://www.ep.ph.bham.ac.uk/DiscoveringParticles/

http://www.understanding-the-higgs-boson.org/

http://www.ep.ph.bham.ac.uk/user/lazzeroni/outreach/harry_card_game

Particle Zoo: http://www.particlezoo.net/

Other Particle Physics Sessions:

Particle Zoo and Feynman Diagrams
Muirhead 118
7th January 2016, 10:00-12:00

ASE Frontier Science Lecture: The Mystery of Antimatter
Poynting Physics S02
7th January 2016, 14:30-15:30

Schools' STEM exhibitions: HiSPARC project
Aston Webb Great Hall
8th January 2016, 9:00-12:30

Particle Teaching Resources: LHC Minerva
Learning Centre LG13
8th January 2016, 9:30-11:30

Particle World for Primary
Arts LR8
8th January 2016, 13:45-15:45

Please don't forget to complete the on-line evaluation for this session

http://bit.ly/AC2016FF