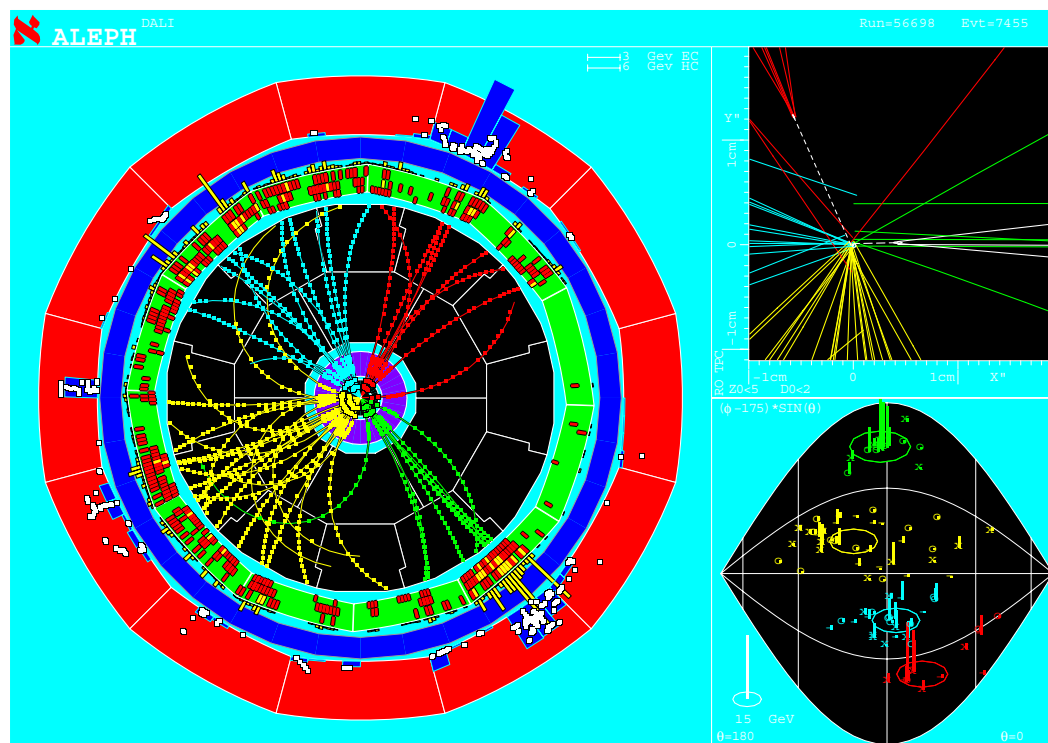


An Introduction to Modern Particle Physics

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Science Summer School: 30th July - 1st August 2007

Course Synopsis

- ★ **Introduction : Particles and Forces**
 - what are the fundamental particles
 - what is a force
- ★ **The Electromagnetic Interaction**
 - QED and e^+e^- annihilation
 - the Large Electron-Positron collider
- ★ **The Crazy world of the Strong Interaction**
 - QCD, colour and gluons
 - the quarks
- ★ **The Weak interaction**
 - W bosons
 - Neutrinos and Neutrino Oscillations
 - The MINOS Experiment
- ★ **The Standard Model (what we know) and beyond**
 - Electroweak Unification
 - the Z boson
 - the Higgs Boson
 - Dark matter and supersymmetry
 - Unanswered questions

Format and goals

Each Session :

- ★ ~30 minute mini-lecture
- ★ ~15 discussion
- ★ ~30 minute mini-lecture
- ★ ~15 discussion

The discussion is important some of the ideas will be very new to you ... there are no foolish questions !

COURSE GOALS: develop a good qualitative understanding of the main ideas in MODERN particle physics.

A few words about me:

D.Phil Oxford in 1991 : particle-astrophysics
CERN 1992-2000 : working on the LEP accelerator
studying the Z and W bosons
Cambridge 2000- : mainly working on the MINOS
neutrino experiment and the
ILC

Introduction to the Standard Model of Particle Physics

Particle Physics is the study of

- ★ **MATTER** : the fundamental constituents which make up the universe
- ★ **FORCE** : the basic forces in nature, i.e. the forces between the fundamental particles

Try to categorise **PARTICLES** and **FORCES** in a simple and fundamental manner

Current understanding is embodied in the **STANDARD MODEL** of particle physics :

- Explains all current experimental observations !
- Beautiful and simple !
- Forces explained by particle exchange
- It is not the ultimate theory – many mysteries

What is Matter ?

The Greek View

- ★ **c. 400 B.C.** : Democritus – concept of matter being composed of indivisible “atoms”
- ★ “Fundamental elements” : **air, earth, water, fire**
- not a hugely useful model

Newton's Definition

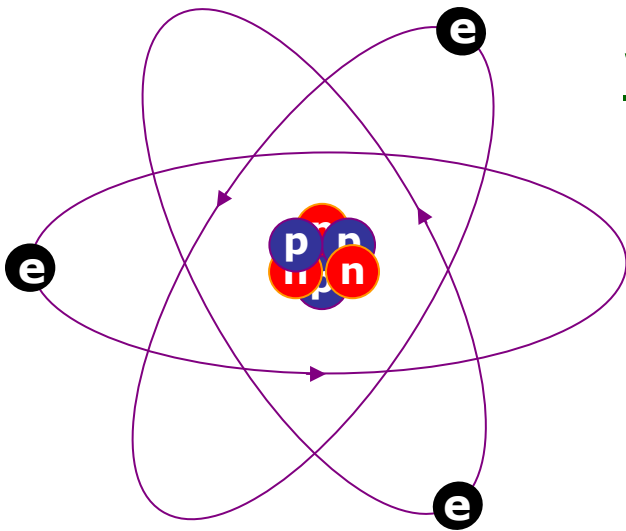
- ★ **1704** : matter comprised of “primitive particles ... incomparably harder than any other porous bodies compounded of them, even so very hard, as never to wear out or break in pieces.”
- ★ Newton was thinking along the lines of `tiny pool balls' bouncing off each other..... **a rather good model for many of the properties of gases !**

Chemistry

- ★ **Fundamental particles** : “elements”
- ★ **1869** : patterns emerged, Mendeleev's Periodic Table
➡ **patterns suggest SUB-STRUCTURE**

Atomic/Nuclear Physics:

- ★ **Periodic Table** : explained by atomic shell model
- ★ -ve charged electrons orbit a +ve charged nucleus
- ★ “Fundamental particles” : **electron** (e^-), **proton** (p), and **neutron** (n)



What forces are involved ?

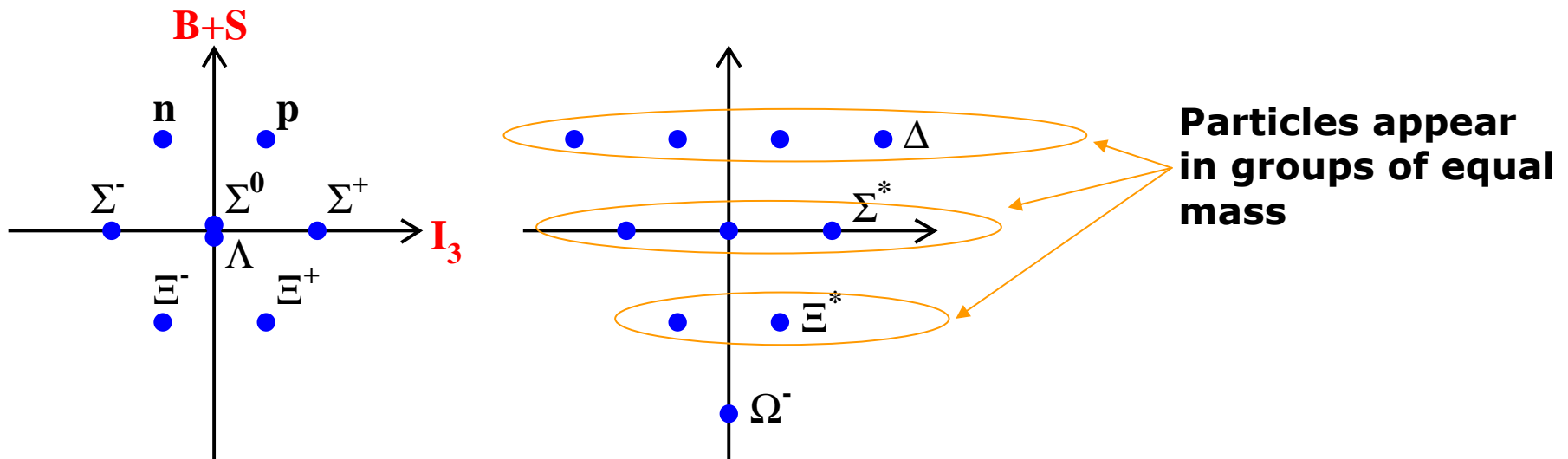
ELECTROMAGNETISM electrons attracted to positively charged nucleus – **unlike** charges attract !

STRONG (NUCLEAR FORCE) holds the neutrons and protons together in the nucleus

Very simple model – with only a few “fundamental particles” !

1960s Particle Physics:

- ★ **Hadronic particles (particles which feel strong interaction i.e. n , p) discovered almost daily !**
 $\{n, p, \pi^0, \pi^\pm, \Sigma^\pm, \Lambda, \eta, \eta', K^0, K^\pm, \rho, \omega, \Omega, \Delta, \dots\}$
- ★ **Far too many – couldn't all be fundamental !**
- ★ **Again Patterns emerged :**



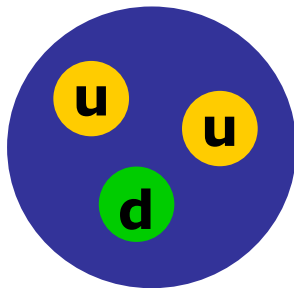
- ★ **Suggestive of sub-structure – QUARKS**
- ★ **many of these new particles were just different arrangements of two quarks : UP and DOWN**

Matter : the 1st Generation

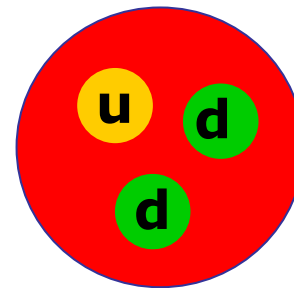
- ★ All (?) phenomena encountered in everyday life can be described in terms of **THREE** particles: the **electron**, and the **up** and **down** quarks

Particle	Symbol	Type	Charge	Mass
Electron	e^-	lepton	-1	10^{-31} kg
UP	u	Quark	+2/3	10^{-30} kg
DOWN	d	Quark	-1/3	10^{-30} kg

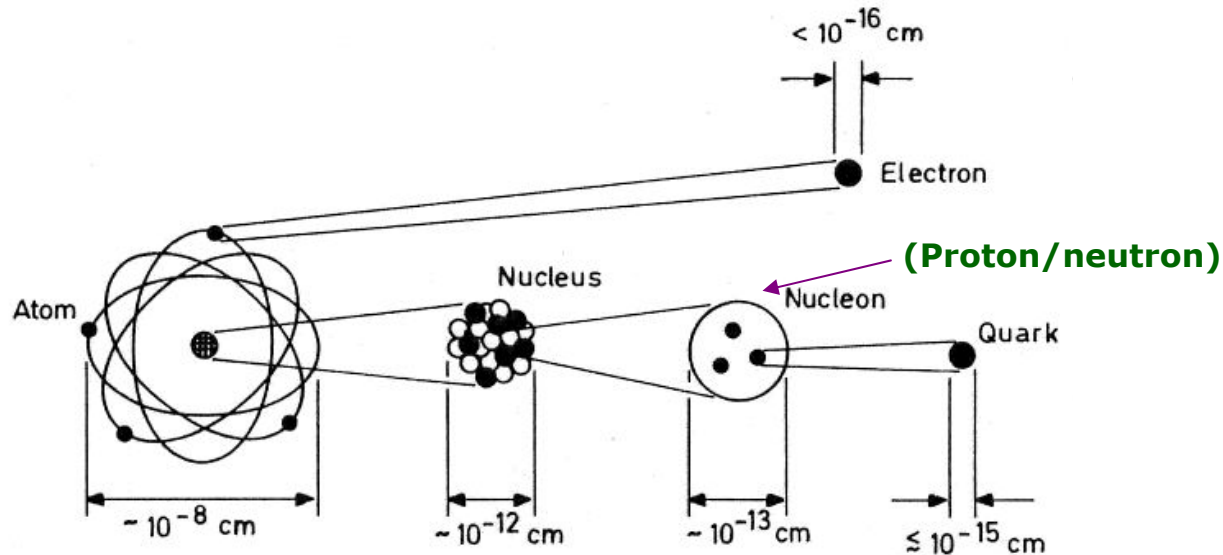
Proton (**uud**) ➡ charge **+1**



Neutron (**udd**) ➡ charge 0



★ How large are these fundamental particles ?



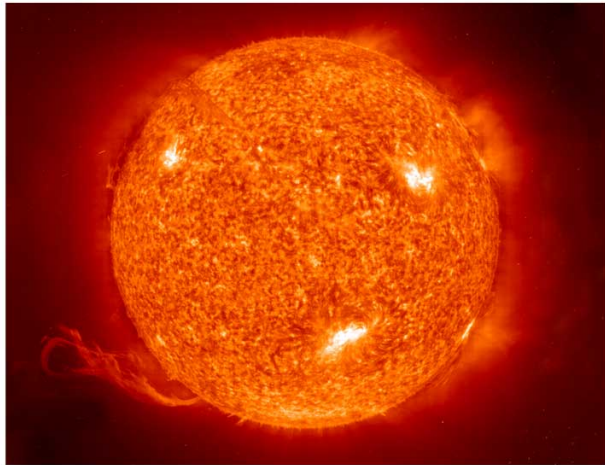
(recall : $10^{-10} = 0.0000000001$ and $10^{10} = 10000000000$)

NOTE:

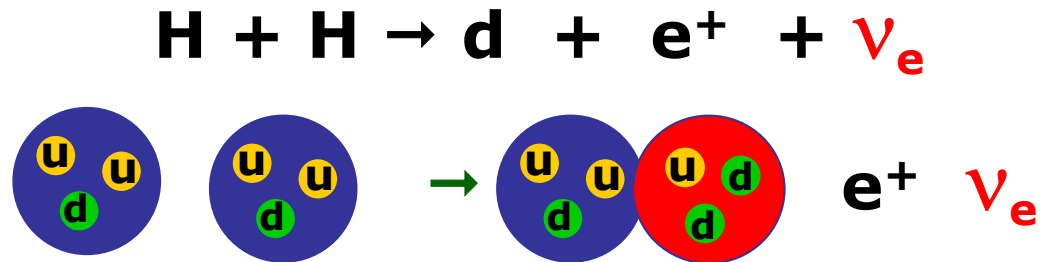
- ★ If the nucleus were the size of a football the electrons would be ~ 2.5 km away ! **ATOMS** are mainly empty space !
- ★ The nucleus behaves as if it were a close packed structure of nucleons (neutrons/protons)
- ★ In fact we believe all fundamental particles are pointlike – i.e. have zero size !

Neutrinos

- ★ So far have 3 particles (e^- , u , d) and 3 forces (electromagnetism, strong nuclear and gravity)
- ★ Can explain nearly all everyday phenomena in terms of these 3 particles and 3 forces (even George Bush ?)
- ★ There is one exception – the sun.



1st stage of nuclear fusion involves another force, the **WEAK force**, and another particle, the **neutrino**



- ★ The weak force is so weak that it plays no role in normal life, however, without it, the sun wouldn't shine.
- ★ The weak force is also rather different – it changes one fundamental particle into another e.g. $u \rightarrow d$

The first generation....

Particle	Symbol	Type	Charge	Mass
Electron	e^-	lepton	-1	10^{-31} kg
Neutrino	ν	lepton	0	$<10^{-40}$ kg
UP	u	Quark	+2/3	10^{-30} kg
DOWN	d	Quark	-1/3	10^{-30} kg

- ★ BUT there are already some questions ?
- ★ The **e,u,d** masses are all rather similar...
.... so why is the neutrino mass so small – less than 1 billionth the mass of the electron !


down

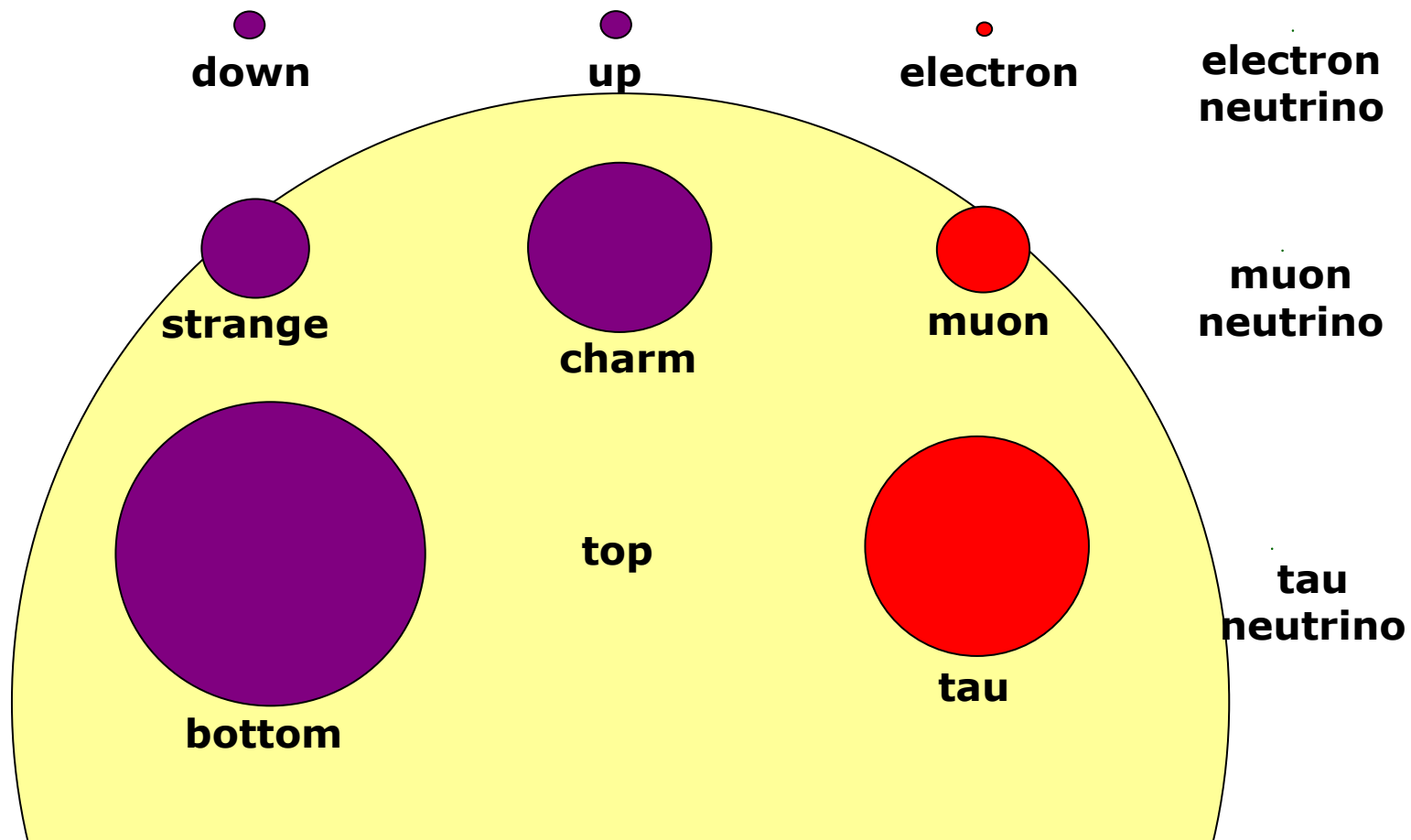

up


electron


electron
neutrino

- ★ There is very little in the universe that cannot be described by these **4** fundamental particles – a very simple picture

- ★ Nature isn't quite that simple in addition to the first generation (d, u, e^-, ν_e) there is an almost exact copy of each of these 4 particles.
- ★ The only difference is that the 'copies' are more massive
- ★ In fact there are two copies of each of (d, u, e^-, ν_e) !



Generations

First generation	Second Generation	Third Generation
Electron (e^-)	Muon (μ^-)	Tau (τ^-)
Electron Neutrino (ν_e)	Muon Neutrino (ν_μ)	Tau Neutrino (ν_τ)
Up Quark (u)	Charm Quark (c)	Top Quark (t)
Down Quark (d)	Strange Quark (s)	Bottom Quark (b)

- ★ We believe that there are only 3 generations
- ★ Just **12** fundamental particles !
- ★ Clear symmetry – the corresponding particles in the different generations have exactly the same properties except for being more massive
 - why there are three generations is not understood
- ★ The fundamental particles fall into two distinct categories – **LEPTONS** and **QUARKS**

The LEPTONS

LEPTONS : Fundamental particles which **do not** experience the **STRONG** force.

★ **3 charged LEPTONS** (e^- , μ^- , τ^-)

- muon (μ^-) just heavier version of the electron

★ **3 neutral LEPTONS** (ν_e , ν_μ , ν_τ) - the **neutrinos**.

Gen	Flavour		Q	Mass
1 st	Electron	e^-	-1	0.0005 GeV/c ²
1 st	Electron Neutrino	ν_e	0	~ 0
2 nd	Muon	μ^-	-1	0.106 GeV/c ²
2 nd	Muon Neutrino	ν_μ	0	~ 0
3 rd	Tau	τ^-	0	1.777 GeV/c ²
3 rd	Tau Neutrino	ν_τ	0	~ 0

NOTE: **kg** fine for everyday objects, e.g.

1 Widdecombe = 200 **kg**, but a little clumsy for particles, $m_e = 3 \times 10^{-31}$ **kg**.

From now will quote particle masses in **GeV/c²**.

1 GeV/c² = 1.7x10⁻²⁷ kg
 \sim mass of proton

★ Charged Leptons feel : **ELECTROMAGNETIC**, and **WEAK** forces

★ Neutrinos only feel the **WEAK** force

The Quarks

QUARKS : Fundamental particles which **DO** experience the **STRONG** force.

★ **6** distinct **FLAVOURS** of **QUARKS**

★ Fractionally charged !

Gen	Flavour		Q	Mass
1 st	Down	d	-1/3	0.3 GeV/c ²
1 st	Up	u	+2/3	0.3 GeV/c ²
2 nd	Strange	s	-1/3	0.5 GeV/c ²
2 nd	Charm	c	+2/3	1.5 GeV/c ²
3 rd	Bottom	b	-1/3	4.5 GeV/c ²
3 rd	Top	t	+2/3	175 GeV/c ²

★ Quarks feel all forces : **STRONG**, **ELECTROMAGNETIC**, **WEAK** (and **GRAVITY**)

★ Quarks never directly observed always **CONFINED** within **HADRONS**

HADRONS

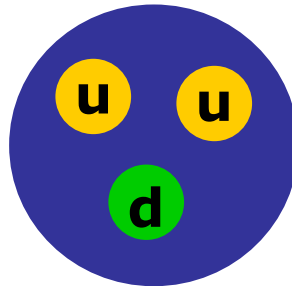
HADRONS : All other 'matter' particles are bound states of quarks (e.g. proton, neutron).

These are not fundamental particles !

★ quarks always confined within **HADRONS**:
- only see bound states of ($q\bar{q}$) or (qqq)

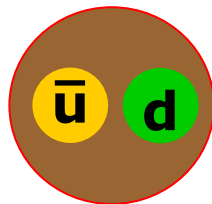
★ **HADRONS** = {MESONS, BARYONS}

BARYONS:



Bound states of **3 quarks**,
e.g. proton (**uud**)

MESONS:



Bound states of a **quark**
and an **anti-quark**
e.g. pion (**$\bar{u}d$**)

Aside : Stable Particles

★ Of the **3** charged leptons only the e^- is stable

★ Muon decay: (lifetime 10^{-6} s)

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

★ Tau decay: (lifetime 10^{-12} s)

$$\tau^- \rightarrow e^- \nu_\tau \bar{\nu}_e \quad \tau^- \rightarrow \mu^- \nu_\tau \bar{\nu}_\mu \quad (+ \text{ hadronic decays})$$

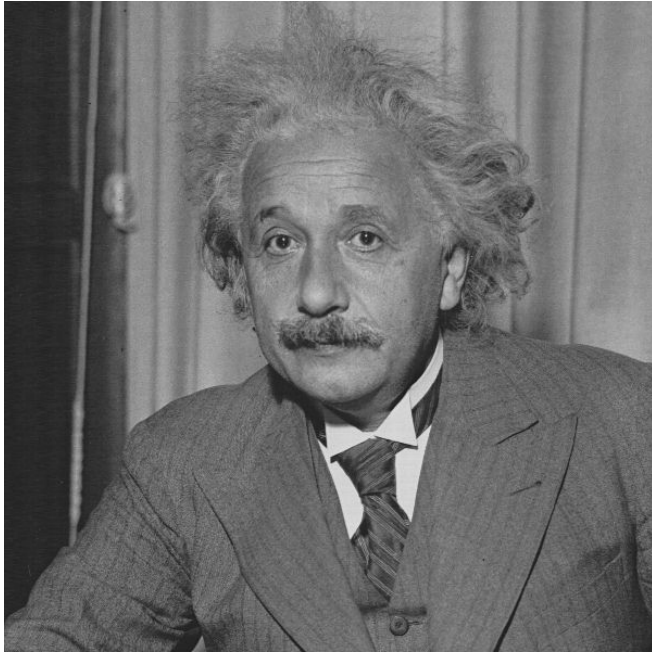
★ Believe the **3** neutrinos are stable

★ Of the hadrons, **ONLY** the proton is stable !

★ STABLE PARTICLES:

- e^- , ν_e , ν_μ , ν_τ , $p(\text{uud})$

$E=mc^2$ and Anti-Matter



EINSTEIN:

- ★ Nothing can travel faster than the speed of light (**c**)
- ★ **c** = $3 \times 10^8 \text{ ms}^{-1}$ (or 186,000 miles/sec)
- ★ particle physics perhaps the most important result is :

$$E = mc^2$$

- ★ Energy of an object at rest equals mass times speed of light squared



1 Widdicombe = 4000 Megaton TNT
= 300000 x Hiroshima !

For an object in motion – two forms of energy, kinetic and rest mass:

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

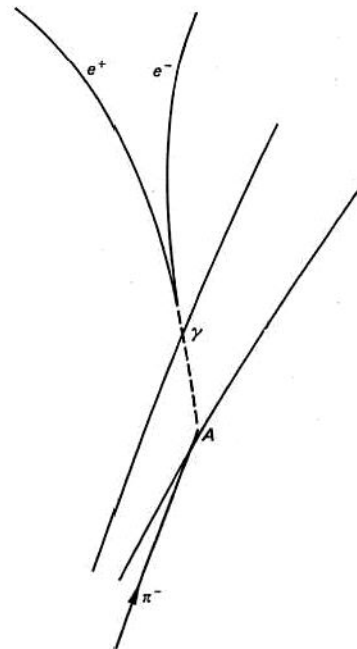
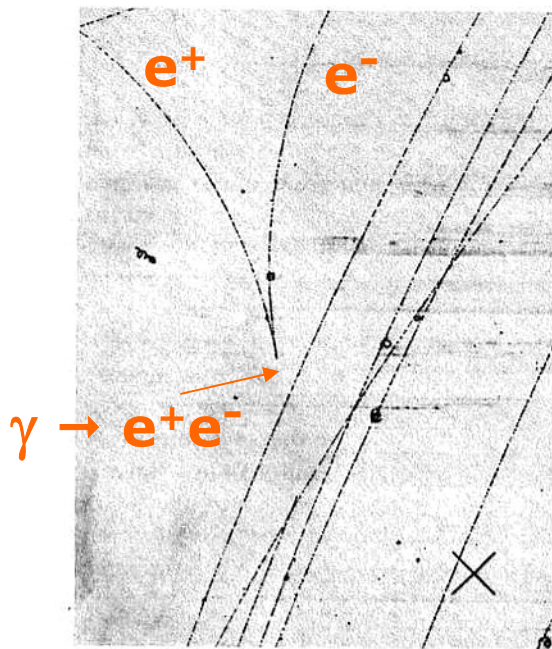
Taking square root suggest +ve and -ve energies possible



★ In 1931 Dirac brought together **relativity** and **quantum mechanics** and predicted the existence of anti-matter; discovered shortly after.

★ For each particle there exists an anti-particle of **equal mass** but **opposite charge**.

e.g. the anti-electron, called the **positron**, looks just like an electron but has positive charge e^+



- ★ a particle and its anti-particle can annihilate producing $2mc^2$ of energy, e.g. $e^+e^- \rightarrow \text{energy}$
- ★ similarly particles and anti-particles can be produced from 'energy', $\text{energy} \rightarrow e^+e^-$
- ★ what is this energy ?
- ★ ultimately all energy is in the form of particles (**rest mass** and **kinetic energy**)
- ★ **WHEN particles annihilate they produce other particles !**

In our detectors anti-matter behaves very much like matter – it can/will annihilate but not immediately

What is a Force ?

So far:

12 particles : $\{e^-, \mu^-, \tau^-, \nu_e, \nu_\mu, \nu_\tau, d, u, s, c, b, t\}$

12 anti-particles : $\{e^+, \mu^+, \tau^+, \bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau, \bar{d}, \bar{u}, \bar{s}, \bar{c}, \bar{b}, \bar{t}\}$

★ Now need to describe the interactions between the particles – **how do forces arise ?**

What is a force ?

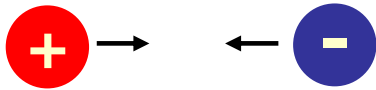
Newton's Laws:

- ★ N1 : “a body will remain at rest or in a state of constant motion unless acted upon by an external **force**”
- ★ N2 : “the rate of change of motion (i.e. momentum **mv**) is proportional to the external **force** (**$F=ma$**)”
- ★ N3 : “for every **action** there is an equal and opposite **reaction**”

High School Forces

Two familiar forces:

★ Electrostatic Force



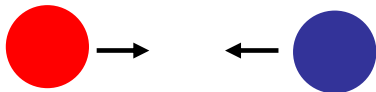
unlike charges attract



like charges repel

$$F = \frac{Q_1 Q_2}{4\pi\epsilon_0 r^2}$$

★ Gravitational Force



always attractive

$$F = \frac{G m_1 m_2}{r^2}$$

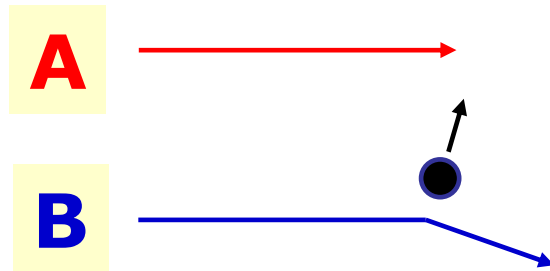
Newton: “....that one body can act upon another at a distance, through a vacuum, without mediation of anything else, ..., is to me a great absurdity.”

★ How do forces arise ?

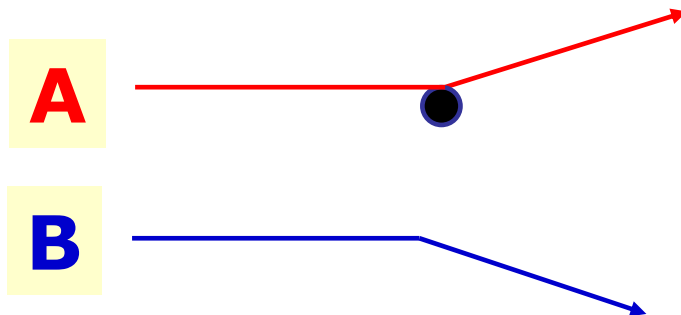
Imagine : two people, **A and **B**, sliding on an ice rink**



★ **No forces acting so continue in state of constant motion (N1)**



★ **B throws a heavy ball towards A. B exerts force on ball – ball exerts an equal and opposite force on B (N3) and B recoils (N2)**



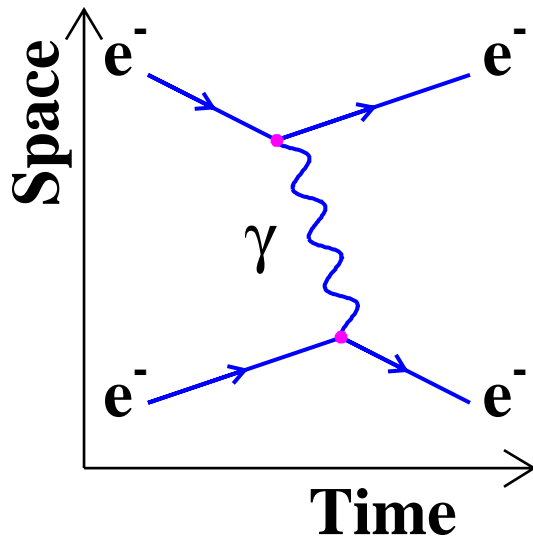
★ **A catches the ball and is knocked back.**



A and B have “repelled” each other by exchanging a particle (ball). No mysterious action at a distance.

Particle Exchange

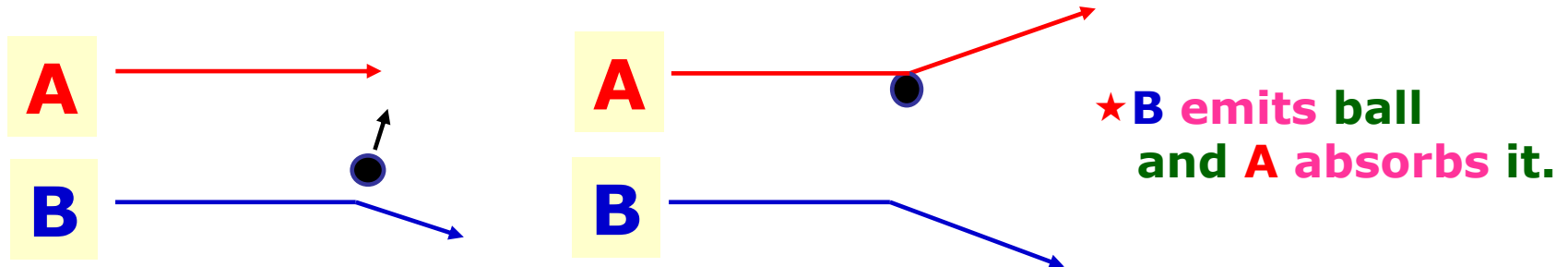
★ Particle interactions are described in a similar manner



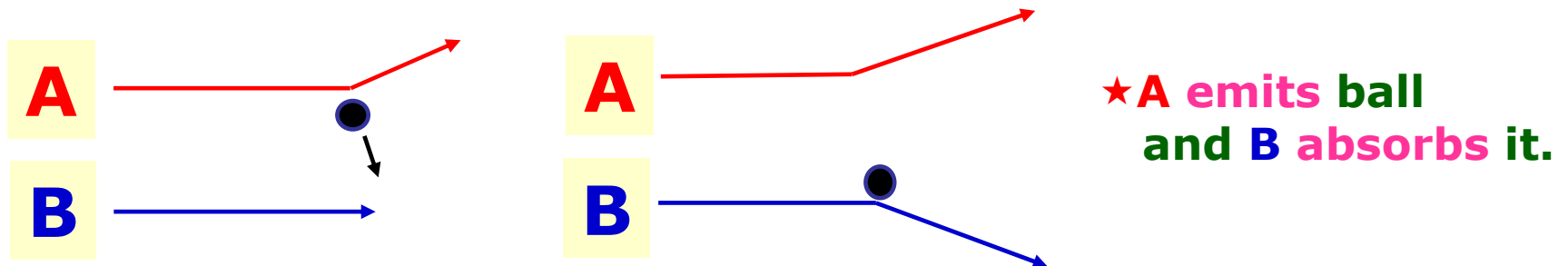
- For example, the **electromagnetic interaction** occurs via the exchange of a **VIRTUAL photon** (the photon, denoted γ , is the particle of light).

The word **VIRTUAL** is important....

Recall : two people, A and B, sliding on an ice rink



★ the interaction could have occurred differently !

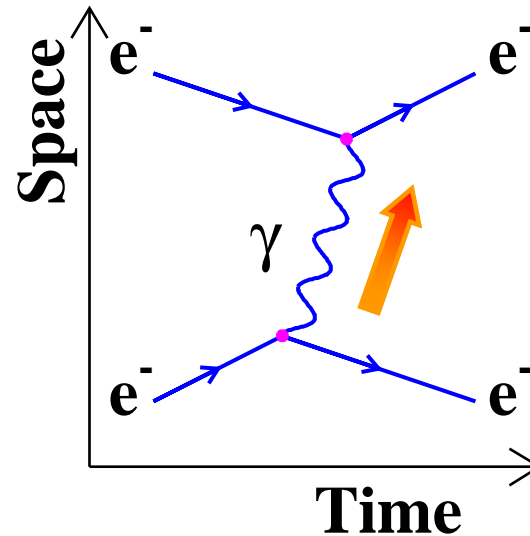
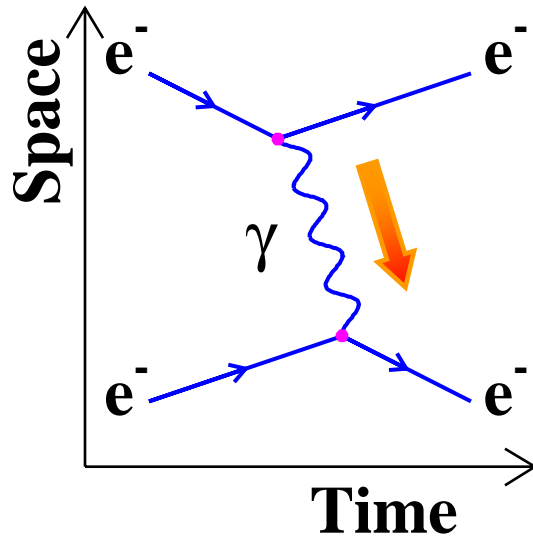


★ Unless you see the “exchanged particle” you can’t tell the two TIME ORDERINGS apart.

★ in the above example you see the ball by shining light on it – this light doesn’t change the ball’s path.

Particle Exchange and Quantum Mechanics

- ★ In particle physics have two possible time orderings.

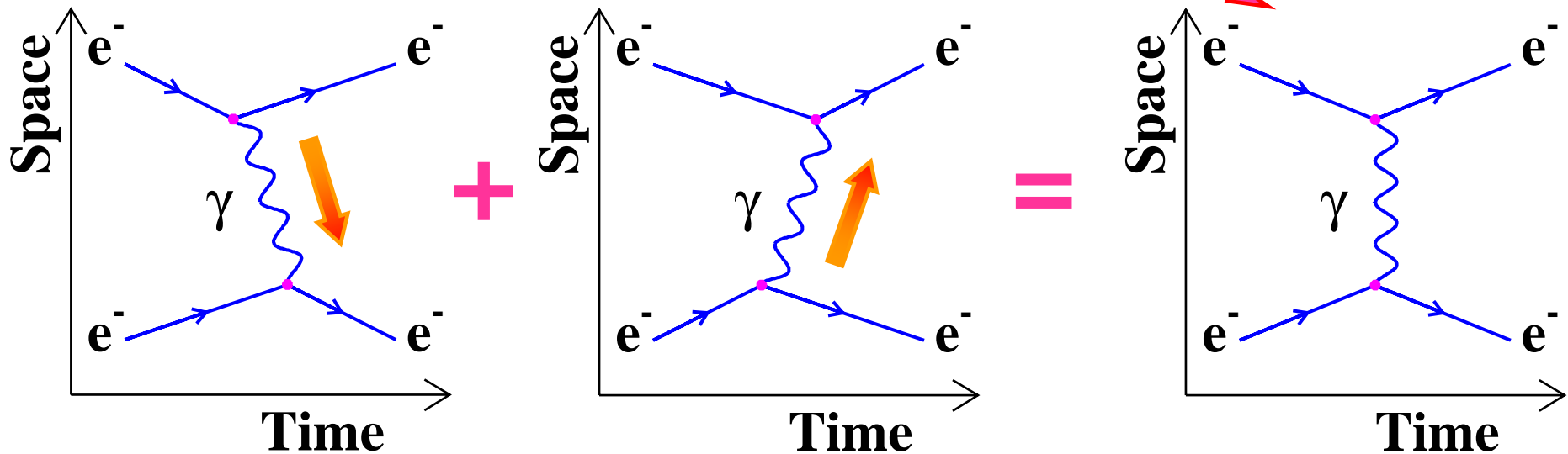


- ★ However, we are now dealing with single particles.
- ★ It is no longer possible to observe which way the photon is going – if we observe the photon we no longer have the above interaction !
- ★ CAN NOT DISTINGUISH THE TWO CASES !

Feynman Diagrams

★ To determine what happens in an interaction, must sum over all possible time orderings.

★ Represented by a **FEYNMAN** diagram



★ A subtle, but vital point, this summing over time orderings is absolutely necessary, as in relativity time is not absolute...

★ **NOTE** : forces between particles due to particles !
No mysterious action at a distance

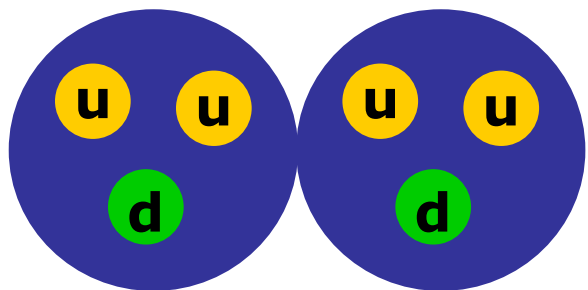
The Forces

- ★ All (known) particle interactions can be explained by 4 fundamental forces:

Electromagnetic	Weak
Strong	Gravity

Relative Strengths of the forces :

- ★ Consider two protons, just touching, i.e separated by 10^{-15}m



Strong	1
Electromagnetic	
Weak	
Gravity	10^{-39}

The Gauge Bosons

- ★ Each force is mediated by a different particle
 - a **GAUGE BOSON**
- ★ The properties of these gauge bosons **and** the manner in which they interact with the matter particles determines the nature of the fundamental force !

Force	Boson	Symbol	Mass	Range
Electromagnetic	photon	γ	0	∞
Strong	Gluon	g	0	10^{-15} m
Weak	W/Z Bosons	W^{\pm}, Z	$\sim 80 \text{ GeV}/c^2$	10^{-17} m



These **3** different forces will be discussed in the next **3** lectures

Summary

The particle world is rather simple :

★ There are **12** fundamental particles + **12** anti-particles

Electron (e^-)	Muon (μ^-)	Tau (τ^-)
Electron Neutrino (ν_e)	Muon Neutrino (ν_μ)	Tau Neutrino (ν_τ)
Up Quark (u)	Charm Quark (c)	Top Quark (t)
Down Quark (d)	Strange Quark (s)	Bottom Quark (b)

★ and 4 fundamental forces

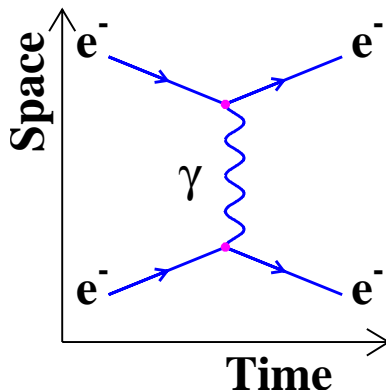
Strong

Weak

Electromagnetic

Gravity

★ and the forces are due to the exchange of particles:



i.e. forces described by particles !