An Introduction to Modern Particle Physics

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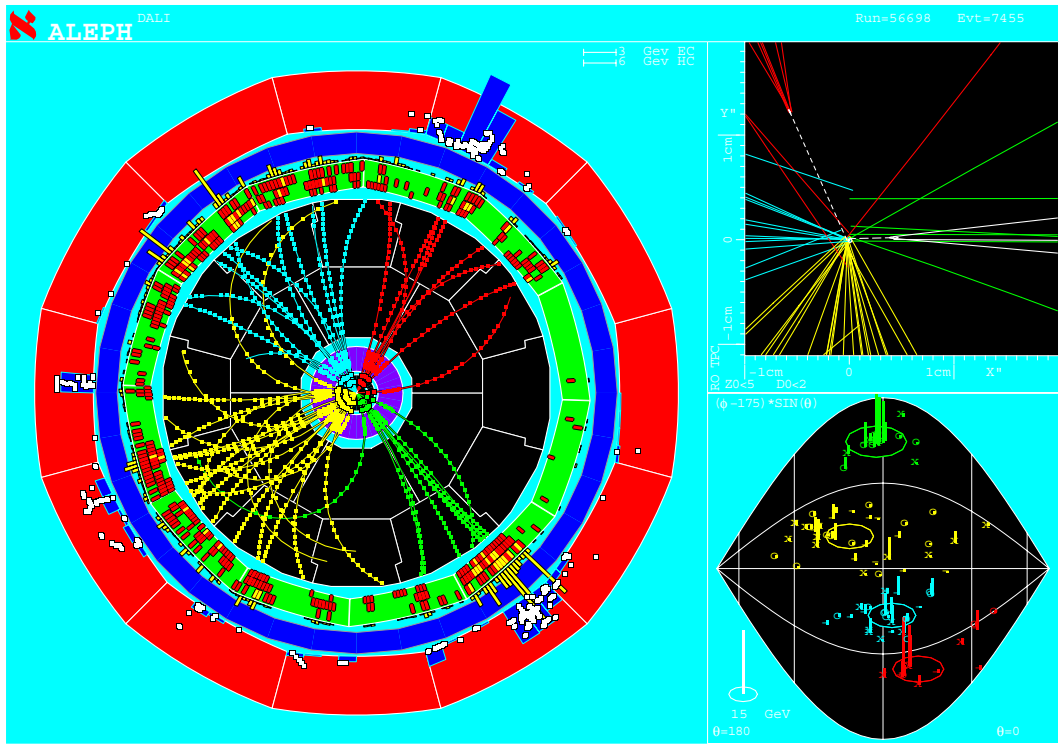


Science Summer School: 30th July - 1st August 2007

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

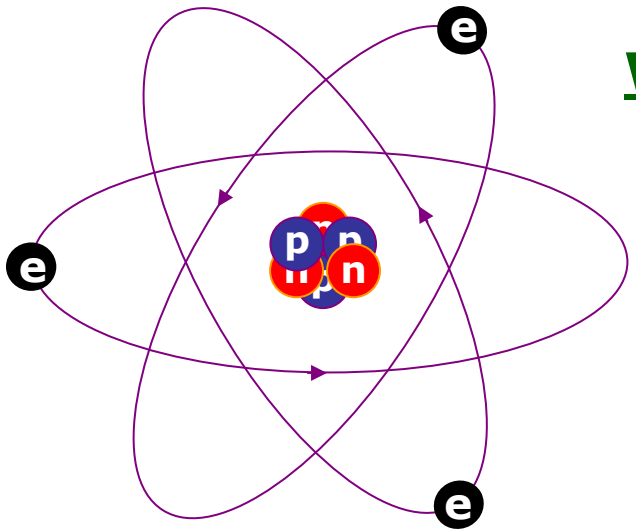
- ★ Fundamental particles : "elements"
- ★ 1869 : patterns emerged, Mendeleev's Periodic Table
  - ➡ patterns suggest SUB-STRUCTURE

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 !

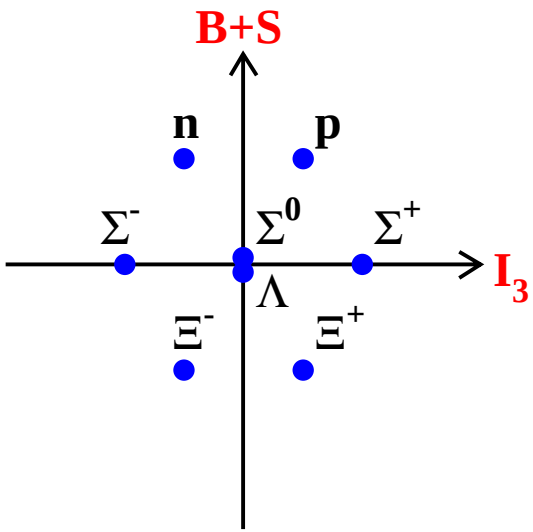
STRONG (NUCLEAR FORCE) holds the neutrons and protons together in the nucleus

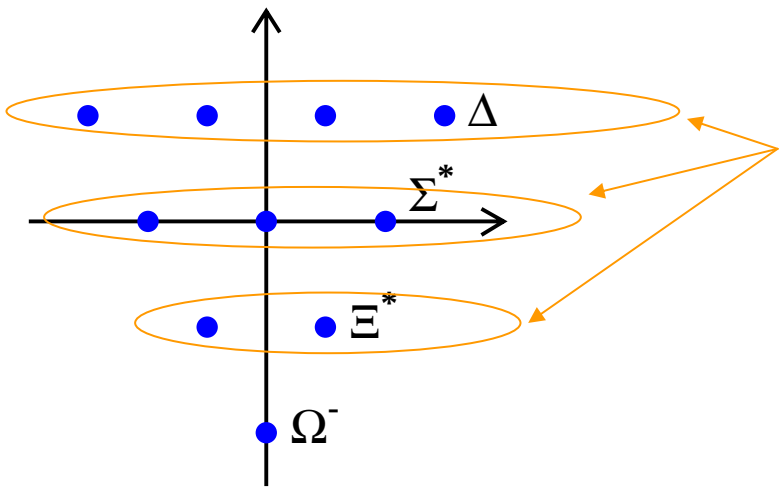
Very simple model – with only a few "fundamental particles" !

1960s Particle Physics:

- ★ **Hadronic particles (particles which feel strong interaction i.e. n, p) discovered almost daily !**

  {n, p, π^0, $\pi^\pm$, $\Sigma^\pm$, Λ, η, η', K^0, $K^\pm$, ρ, ω, Ω, Δ..... }
- ★ **Far too many – couldn't all be fundamental !**
- ★ **Again Patterns emerged :**





Particles appear in groups of equal mass

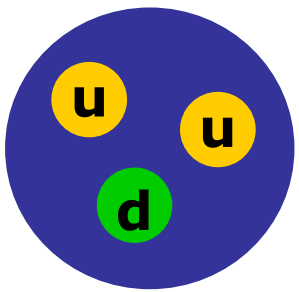
- ★ **Suggestive of sub-structure – QUARKS**
- ★ **many of these new particles were just different arrangements of two quarks : UP and DOWN**

Matter : the 1st Generation

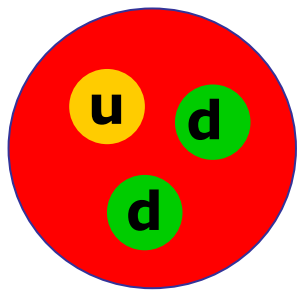
★ All (?) phenomena encountered in everyday life can be described in terms of THREE particles: the electron, and the up and down quarks

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

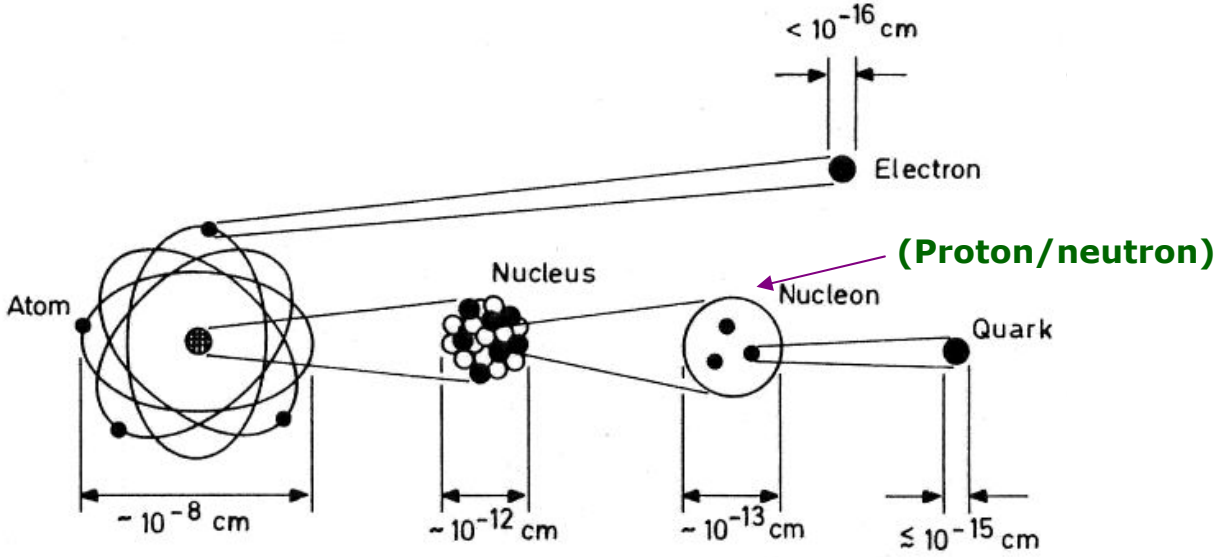
Proton (uud) ➡ charge +1



Neutron (udd) ➡ charge 0



★How large are these fundamental particles ?



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

NOTE:

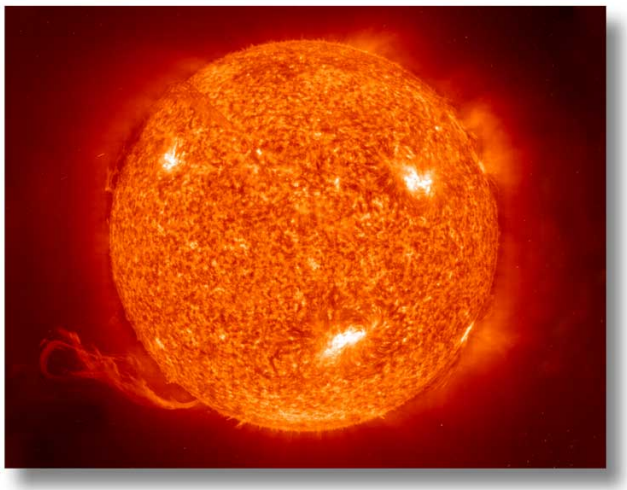
- ★ **If the nucleus were the size of a football the electrons would be ~2.5 km away ! ATOMS are mainly empty space !**
- ★ **The nucleus behaves as if it were a close packed structure of nucleons (neutrons/protons)**
- ★ **In fact we believe all fundamental particles are pointlike – i.e. have zero size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

Neutrinos

★So far have 3 particles (e^-,u,d) and 3 forces (electromagnetism, strong nuclear and gravity)

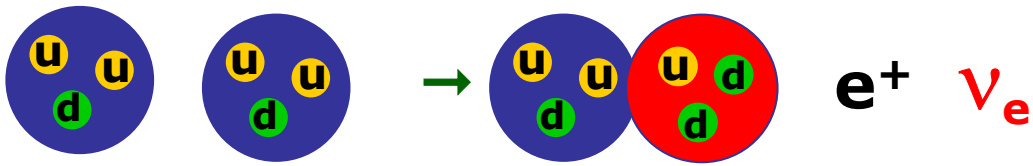
★Can explain nearly all everyday phenomena in terms of these 3 particles and 3 forces (even George Bush ?)

★There is one exception – the sun.



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

$$H + H \rightarrow d + e^+ + \nu_e$$



★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 → 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 ?

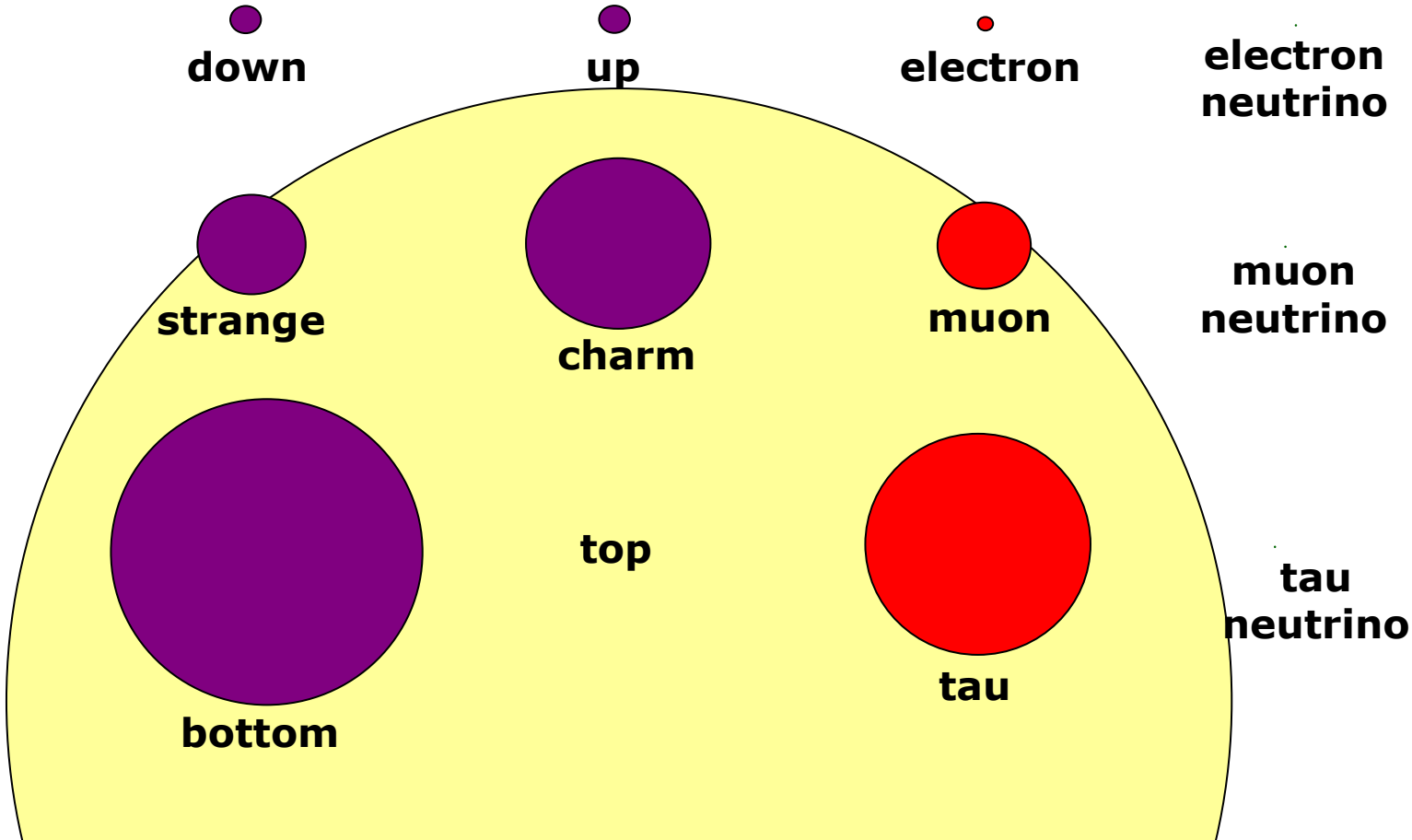
★ The e,u,d masses are all rather similar…
…. so why is the neutrino mass so small – less than 1 billionth the mass of the electron !

★ 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 <u>two</u> 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 (d)	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
1st	Electron	e^-	-1	0.0005 GeV/c^2
1st	Electron Neutrino	ν_e	0	~ 0
2nd	Muon	μ^-	-1	0.106 GeV/c^2
2nd	Muon Neutrino	ν_μ	0	~ 0
3rd	Tau	τ^-	0	1.777 GeV/c^2
3rd	Tau Neutrino	ν_μ	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/c^2.

1 GeV/c^2 = 1.7×10^{-27} kg ~ 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
1st	Down	d	-1/3	0.3 GeV/c^2
1st	Up	u	+2/3	0.3 GeV/c^2
2nd	Strange	s	-1/3	0.5 GeV/c^2
2nd	Charm	c	+2/3	1.5 GeV/c^2
3rd	Bottom	b	-1/3	4.5 GeV/c^2
3rd	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

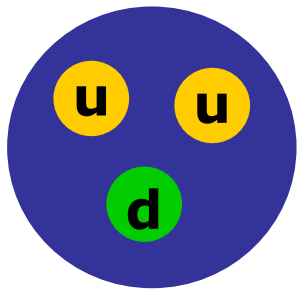
HADRONS

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)

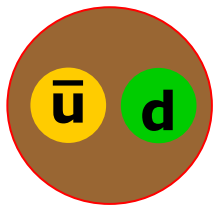
★ HADRONS = {MESONS, BARYONS}

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)

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

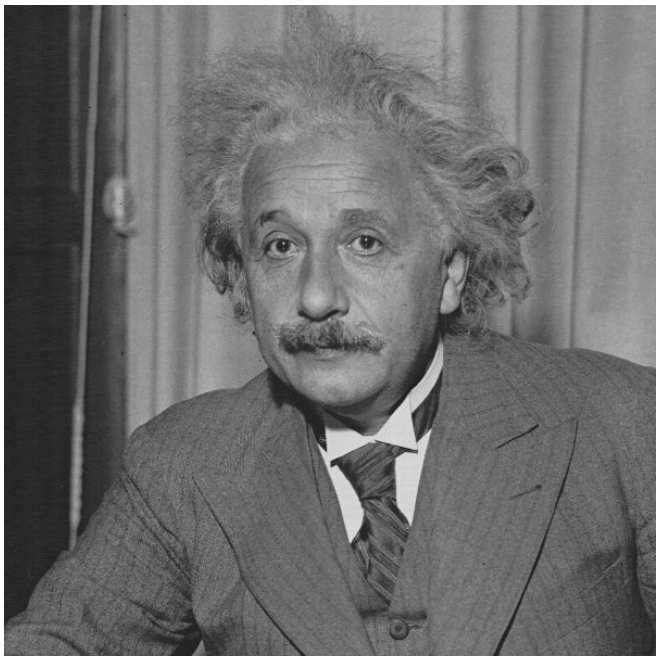
★ Believe the 3 neutrinos are stable

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

★ **STABLE PARTICLES:**

- e^-, ν_e, ν_μ, ν_τ, p(uud)

$E=mc^2$ and Anti-Matter



EINSTEIN:

★ Nothing can travel faster than the speed of light (c)

★ $c = 3x10^8\ ms^{-1}$ (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 Widdecombe = 4000 Megaton TNT
= 300000 x Hiroshima !

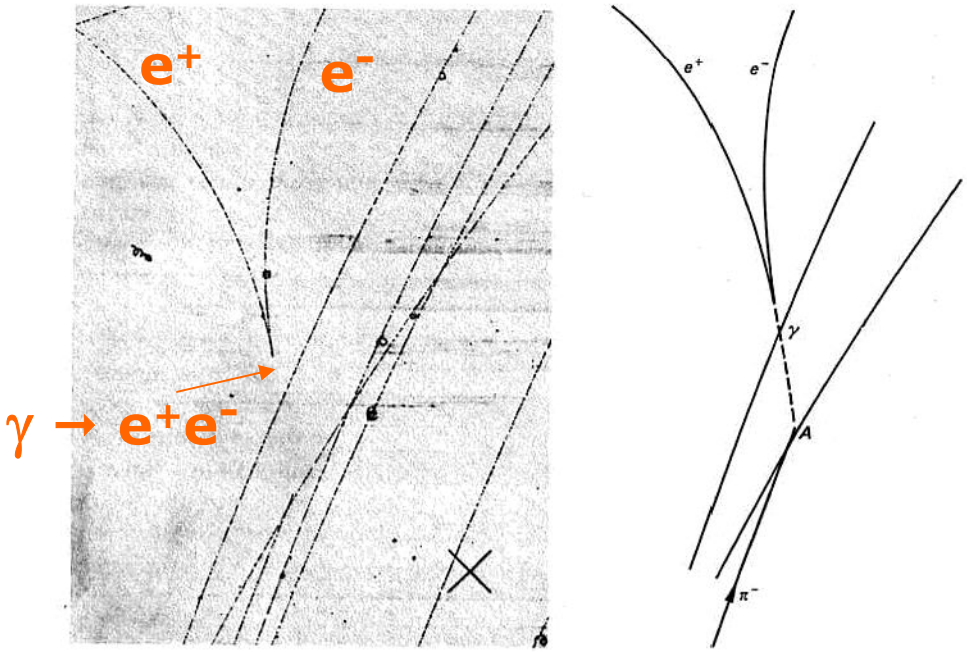
For an object in motion – two forms of energy, kinetic and rest mass:

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

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. $e^+e^- \rightarrow$ energy
- similarly particles and anti-particles can be produced from `energy', energy → 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^-, μ^-, τ^-, ν_e, ν_μ, ν_τ, d, u, s, c, b, t}

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

★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"

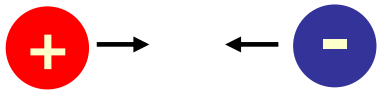
★**N2** : "the rate of change of motion (i.e. momentum mv) is proportional to the external force (F=ma)"

★**N3** : "for every action there is an equal and opposite reaction"

High School Forces

Two familiar forces:

★ **Electrostatic Force**

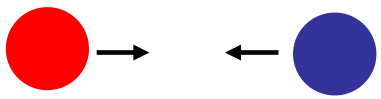


unlike charges attract

like charges repel

$$F = \frac{Q_1 Q_2}{4\pi\varepsilon_0 r^2}$$

★ **Gravitational Force**



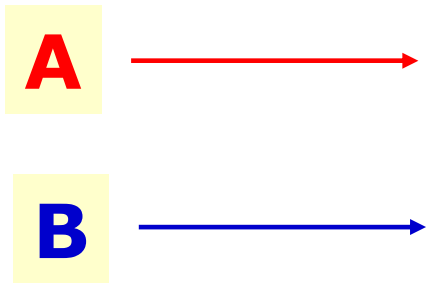
always attractive

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

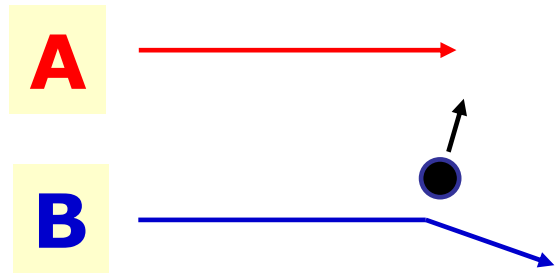
Newton: "....that one body can act upon another at a distance, through a vacuum, without mediation of anything else, ..., is to me a great absurdity."

★ How do forces arise ?

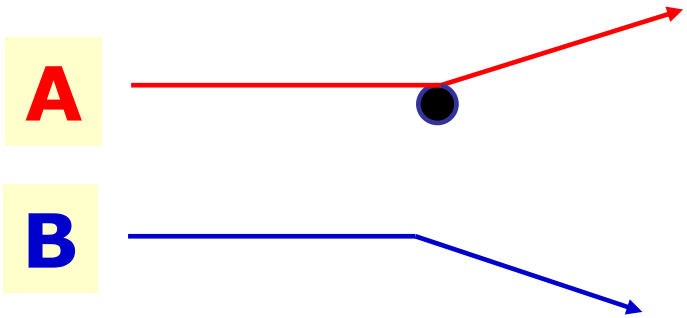
Imagine : two people, A and B, sliding on an ice rink



★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)

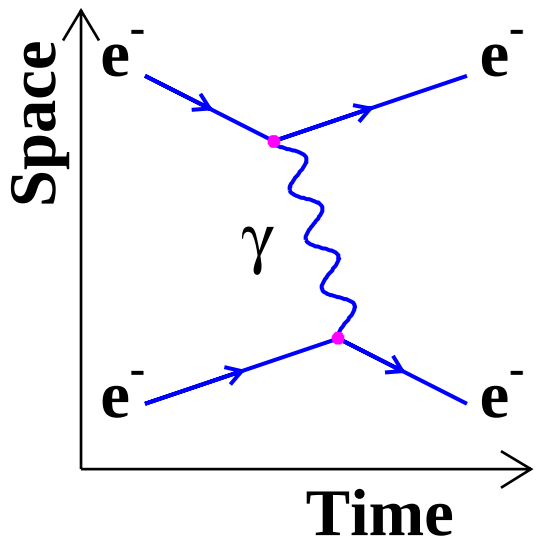


★A catches the ball and is knocked back.

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

Particle Exchange

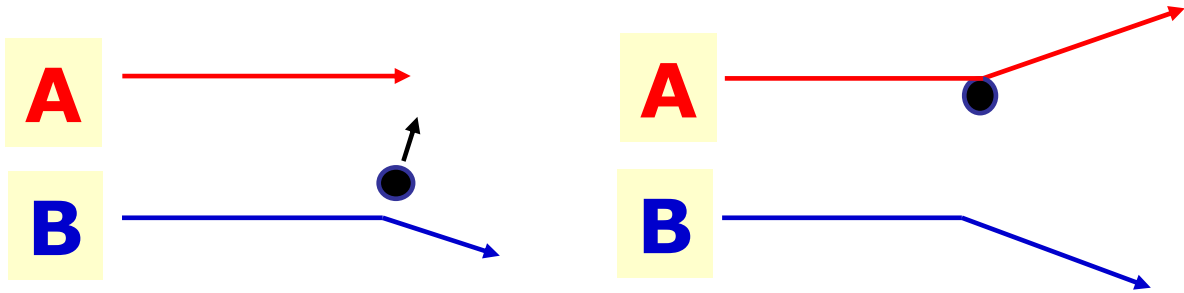
★ **Particle interactions are described in a similar manner**



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

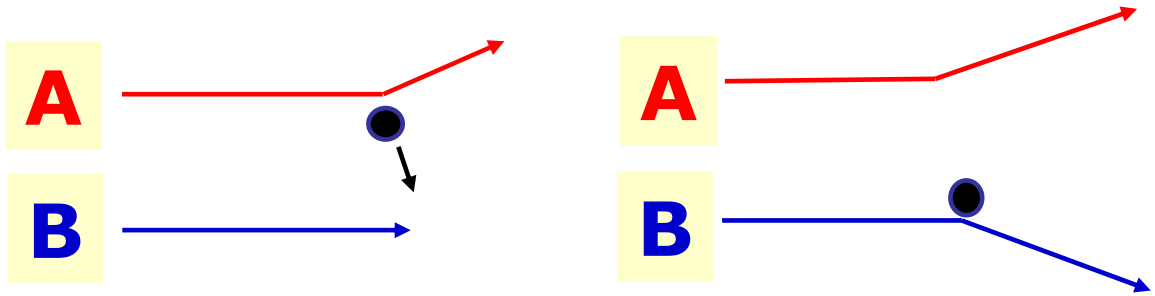
The word VIRTUAL is important….

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



★B emits ball and A absorbs it.

★the interaction could have occurred differently !



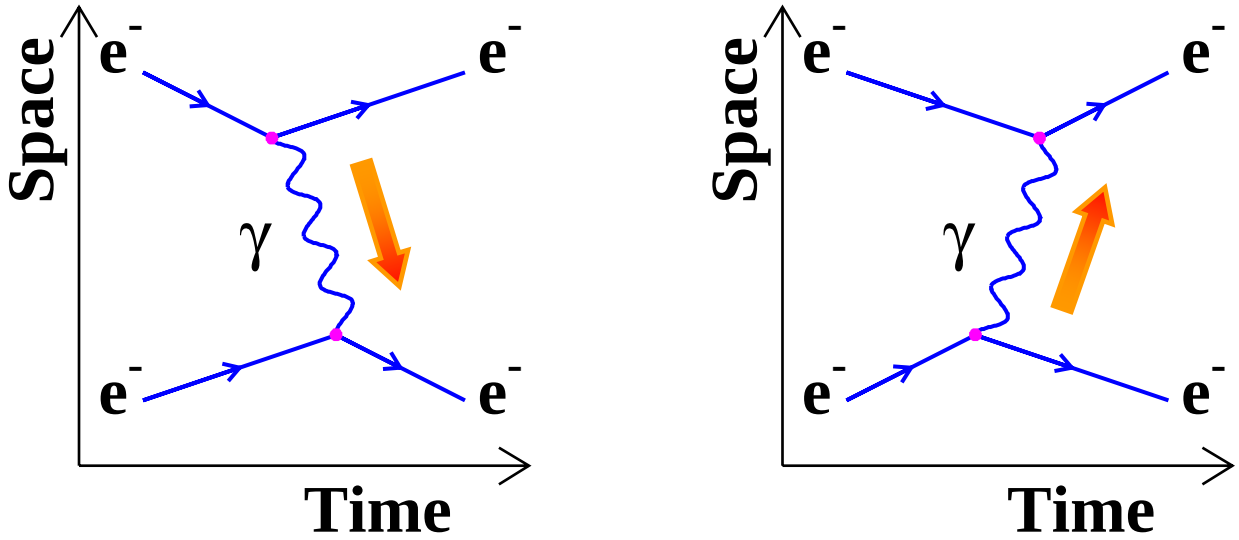
★A emits ball and B absorbs it.

★ 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.

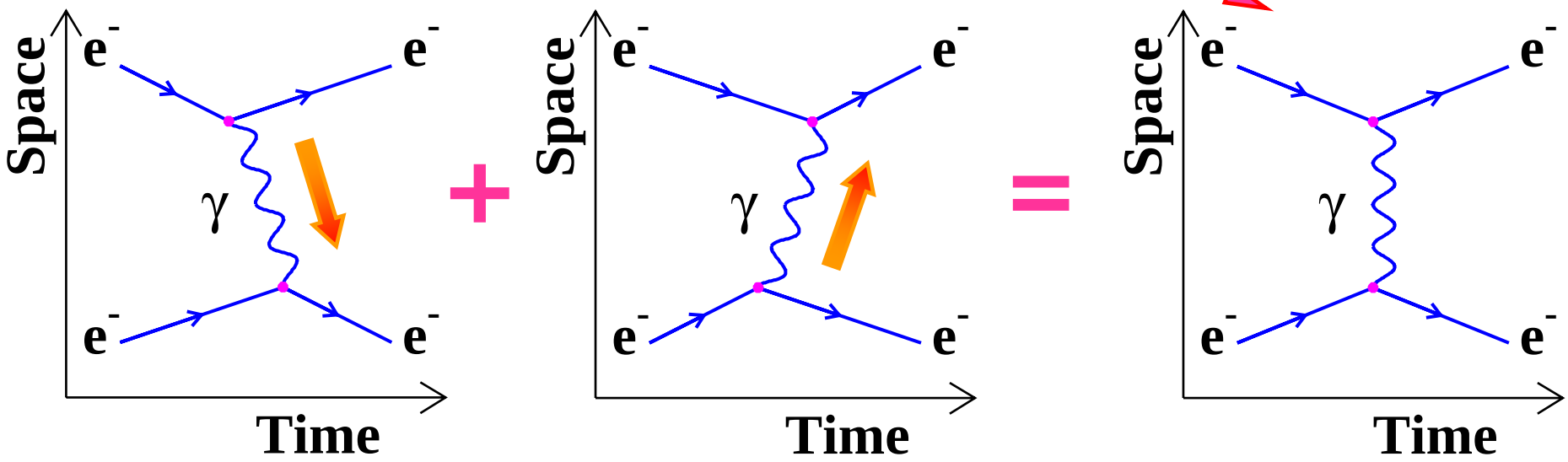
★ It is no longer possible to observe which way the photon is going – if we observe the photon we no longer have the above interaction !

★ 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

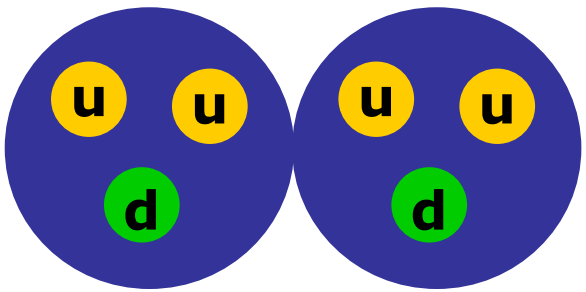
The Forces

★ 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	~80 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 :

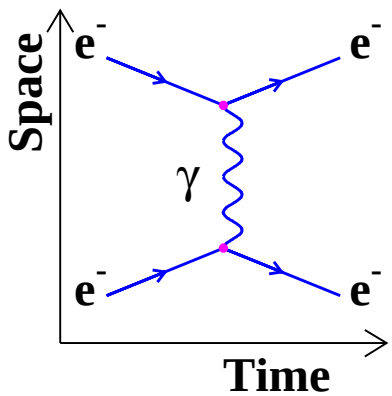
- There are 12 fundamental particles + 12 anti-particles

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 (d)	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 !