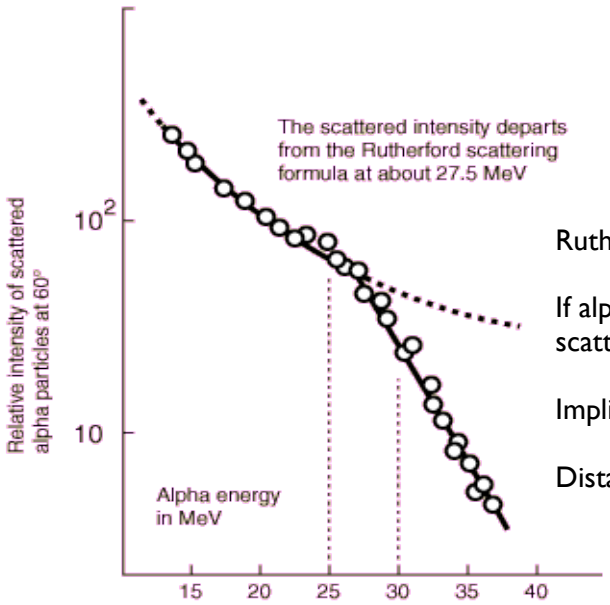
PHY-302

Dr. E. Rizvi

Lecture 25
Particle Physics

Queen Mary
University of London



Rutherford scattering formula based on EM force alone

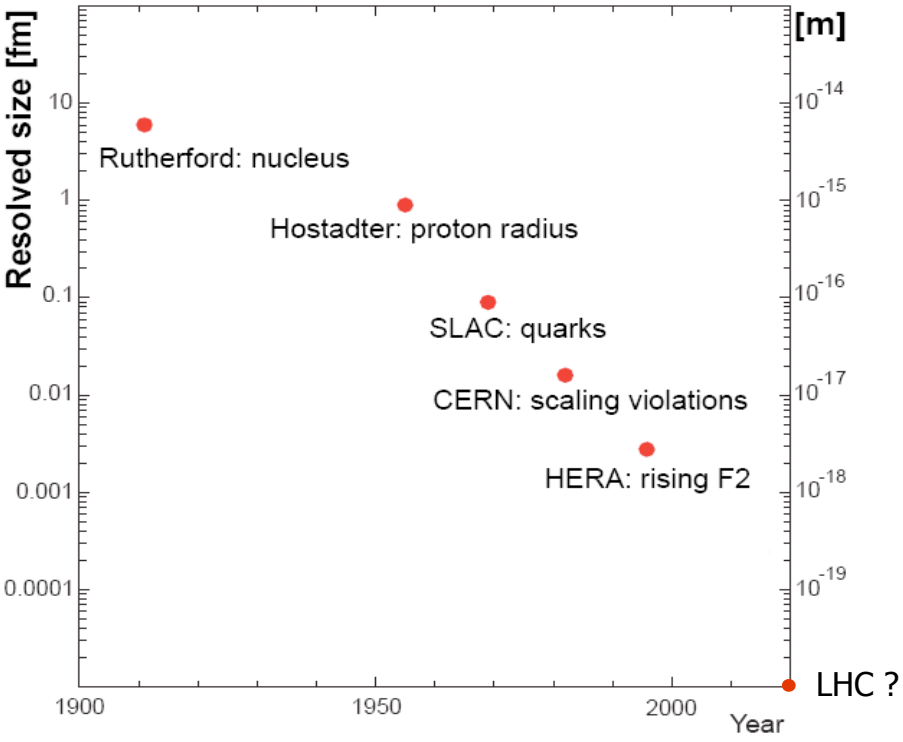
If alpha energy ~30 MeV simple Rutherford scattering fails to describe the data.

Implies another "interaction" is taking place

Distances of ~3 fm

In 1967 at SLAC (Stanford Linear Accelerator):
electron beam used to probe proton (hydrogen target)
beam energy was 10,000 - 20,000 MeV !!!

Data indicated existence of small charged particles within proton: quarks



The Standard Model

Worlds most successful theory to date - Describes fundamental constituents of matter

Three generations of increasing mass

u	d	s	c	b	t	quarks: strong, weak, electromagnetic
e		μ		τ		charged leptons: weak, electromagnetic
ν_e		ν_μ		ν_τ		neutral leptons: neutrinos: weak

All matter made up of these 12 fermions (spin ½ particles) - 1st generation only!

All are point-like particles (as far as we know!)

All forces of nature propagated by these 4 bosons (spin 1 particles)

gluons	~~~~~~~~	Strong: holds atomic nucleus together
photons	∿∿∿∿∿∿∿∿	Electromagnetic: binds atom together
W and Z bosons	.....	Weak: radioactive decay processes

Standard Model also requires existence of Higgs boson - discovered July 2012

quark	symbol	mass(MeV/c^2)	charge (e)
up	u	2	+2/3
down	d	5	-1/3
strange	s	100	-1/3
charm	c	1300	+2/3
bottom	b	4300	-1/3
top	t	175000	+2/3

← Flavour →

All have spin ½
Each has an anti-particle

lepton	symbol	mass(MeV/c^2)	charge (e)
electron	e	0.5	-1
elec. neutrino	υ_e	$<10^{-5}$	0
muon	μ	106	-1
muon neutrino	υ_μ	$<10^{-1}$	0
tau	τ	1780	-1
tau neutrino	υ_τ	<0.3	0

← Flavour →

- Leptons never form bound states (unlike quarks forming hadrons)
- Leptons interact via: EM & weak forces only

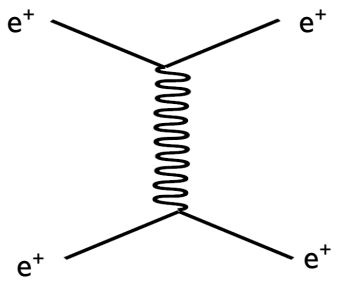
Bosons are force carrier particles: integer spin 0,1,2

Particle	mass	Range	Interacts with
Photon:	0	infinite range	all charged particles
Z^0:	91,000 MeV/c^2	very short range	all fermions + Z^0+ $W^\pm$
$W^\pm$:	80,000 MeV/c^2	very short range	all fermions + Z^0+ $W^\pm$
gluon:	0	short range (~1fm)	quarks + itself
Higgs:	125,000 MeV/c^2	generates mass	

Electromagnetism: Quantum Electrodynamics

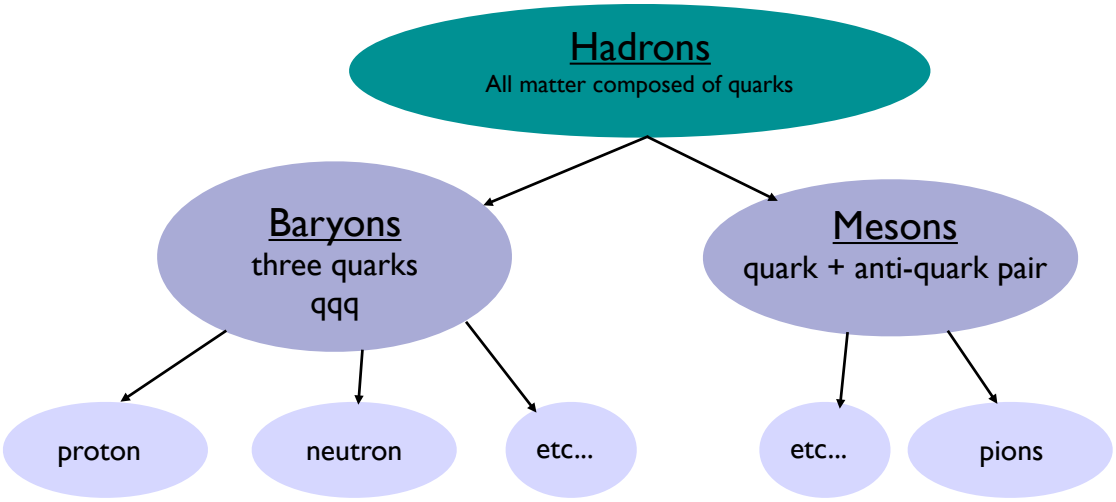
All charged particles interact via photon exchange
Coulomb interaction!

Feynman diagram of two positrons scattering



Led to theory of Quantum Electrodynamics
The most precise theory humanity has ever achieved!

- Only quarks (and therefore hadrons) feel strong force
- Quarks can never be isolated....
- Quarks also feel electromagnetic and weak forces



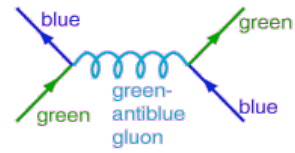
Strong Force: Quantum chromodynamics (QCD)

All quarks, anti-quarks and gluons carry new quantum number: colour charge
Analogous to electric charge: particles with electric charge interact electromagnetically

quarks carry one of three colours: red green blue
anti-quarks carry anti-colours: anti-red anti-green anti-blue
gluons carry colour & anti-colour (e.g. green & anti-red)
All hadrons are colourless: RGB or $\bar{R}\bar{G}\bar{B}$

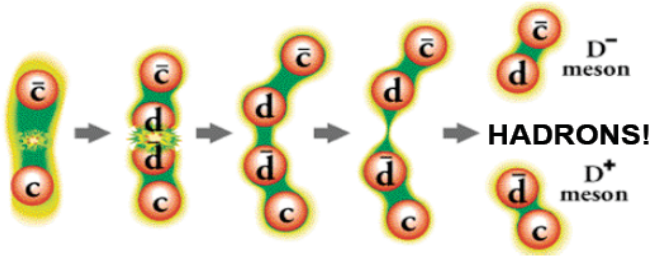
Note: colour charge has nothing to do with colours of EM spectrum!

since gluons have colour - they can interact with themselves
unlike photon - photon has no electric charge



Feynman diagram for an interaction between quarks generated by a gluon.

This unique property leads to bound nature of quarks: cannot be isolated!



If you pull 2 quarks apart - force increases
i.e. like a spring

when energy in "spring" exceeds mass of two quarks, then a quark / anti-quark pair are created!

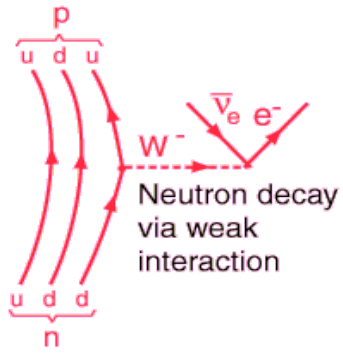
Weak Force

Mediated by 3 very massive particles: $W^{\pm}$ and the Z^0
masses similar to a heavy atom!

All particles (leptons & quarks) carry a weak charge

Large mass means very short lifetime ~ 10^{-25} s ⇒ short range < 10^{-3} fm !

Weak force violates parity

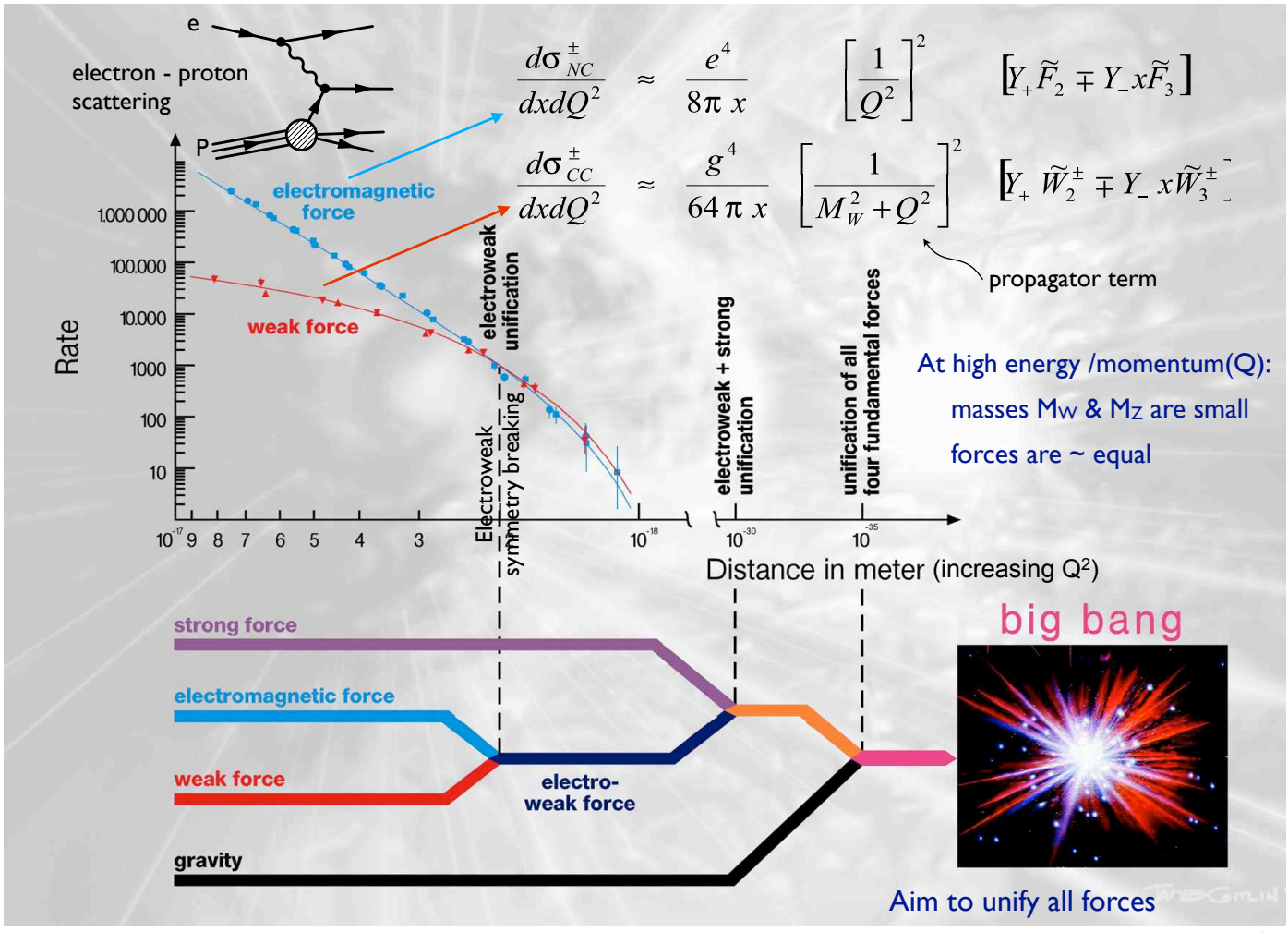


Strictly, weak force involves exchange of charged bosons
In 1960s weak and electromagnetism were unified:
electromagnetism and weak are low energy manifestations of the electro-weak force

just like Maxwell unified electricity and magnetism

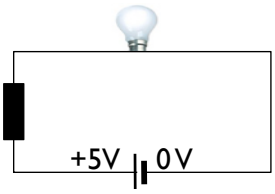
unification predicted the existence of a heavy neutral boson: Z^0

It's discovery led to 1984 Nobel Prize (Rubbia)
QM group members were involved in the discovery!

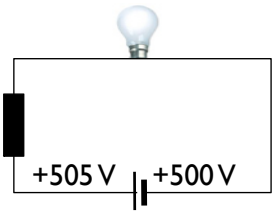


Gauge Theories

Standard Model composed of QCD + Electro-Weak theory + Higgs mechanism
The are all examples of relativistic gauge quantum field theories



A gauge transformation is one in which a symmetry transformation leaves the physics unchanged



Both circuits behave identically
Circuit is only sensitive to potential differences
Change the ground potential of the earth and see no difference!
Leads to concept of charge conservation

In electromagnetism we are insensitive to phase α of EM radiation
Could globally change the phase at all points in universe: no difference
global gauge transformation
What happens if we demand local phase transformations? $\alpha \rightarrow \alpha(x,t)$

Gauge Theories

If we demand local phase invariance AND consistent physics then
we must alter Maxwells equations

The alterations required to accommodate these changes introduce a new field
- interaction of charged particle with an EM field - the photon!

This can be applied to many situations:
local gauge invariance introduces new fields & particles:

Electromagnetism	photon
Quantum chromodynamics	gluons
Electro-Weak force	$W^{\pm}$ and Z^0

Intimately related to symmetries and conservation laws

The Standard Model

Based on perturbation theory & relativistic quantum mechanics
given us the language of Feynman diagrams to calc cross sections

Potential = V + V'

V gives rise to stationary stable, time independent states

V' is a weak additional potential leading to transitions between states $\psi_i \rightarrow \psi_f$

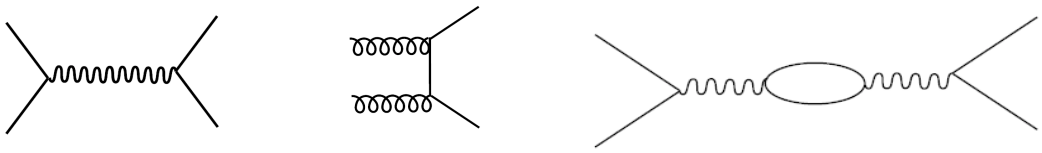
$$\sigma = \frac{2\pi}{\hbar}|V_{fi}|^2\rho(E_f)$$

$\rho(E_f)$ density of final states and flux factors

$V_{fi} = \int \psi_f^* V_i \psi_i' \, \mathrm{d}v$ is known as the matrix element for the scattering process

V_{fi} contains the standard model Lagrangian describes the dynamics of all interactions

Series expansion in powers of couplings α between particles for each force



The Standard Model

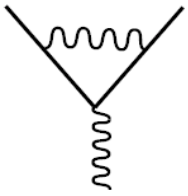
Quantum mechanics predicts the gyromagnetic ratio of the electron g=2
(ratio of magnetic dipole moment to it's spin)

Experiment measures g_{exp}=2.0023193043738 ± 0.0000000000082

Discrepancy of g-2 due to radiative corrections

Electron emits and reabsorbs additional photons

Corresponds to higher terms in perturbative series expansion



$$\frac{g_{theory} - 2}{2} = 1159652140(28) \times 10^{-12}$$

$$\frac{g_{exp} - 2}{2} = 1159652186.9(4.1) \times 10^{-12}$$

Phenomenal agreement between theory and experiment! 4 parts in 10^8
QED (quantum electrodynamics) is humanity's most successful theory
Demonstrates understanding of our universe to unprecedented precision

Equivalent to measuring distance from me to centre of moon
and asking if we should measure from top of head or my waist!

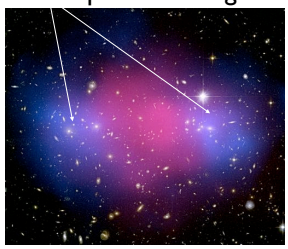
... but all is not well...

The Problematic Standard Model

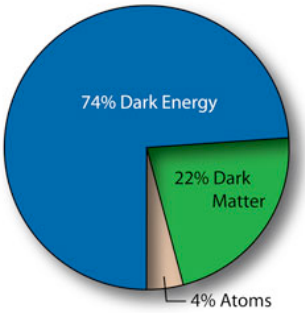
22 Parameters of the SM to be measured
- 6 quark masses
- 3 charged leptons masses
- 3 coupling constants
- 4 quark mixing parameters
- 4 neutrino mixing parameters
- 1 weak boson mass (1 predicted from other EW params)
- 1 Higgs mass

(better than 105 params of supersymmetry)

Two gas clouds collide
Clouds slow down
Dark matter passes through



We have no idea what 96% of the universe is!
unknown form of dark energy
unknown form of dark matter



No treatment of gravity in the Standard Model...
In a symmetric theory gauge bosons are massless
Higgs mechanism explains EW symmetry breaking
→ EW bosons acquire mass

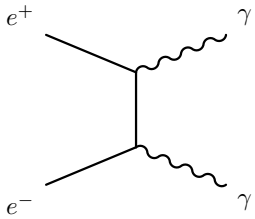
...but there must be a deeper relationship
between Higgs / mass / gravity / dark energy

We know quantum gravity effects must play a role at the Planck scale i.e. energy ~ 10^{19} GeV

The Problematic Standard Model

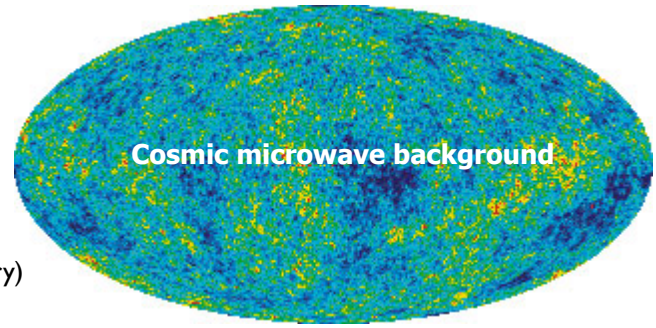
Standard Model is lacking:
- why 3 generations of particles?
- why do particles have the masses they do?
- no consideration of gravity on quantum level...

e^+ e^- annihilation



In the Standard Model matter and anti-matter produced in equal quantities
- In the Big Bang: for every quark, one anti-quark is also produced
- As universe cools expect all particles and anti-particles to annihilate
- ⇒ soon after big bang all matter will have annihilated to photons

We should not exist!
For every proton/neutron/electron in universe there are 10^9 photons (CMB - cosmic microwave background)
Thus matter/anti-matter asymmetry must be 1:10^9
We cannot see where this asymmetry lies...



(Actually SM can account for only 1000th of this asymmetry)