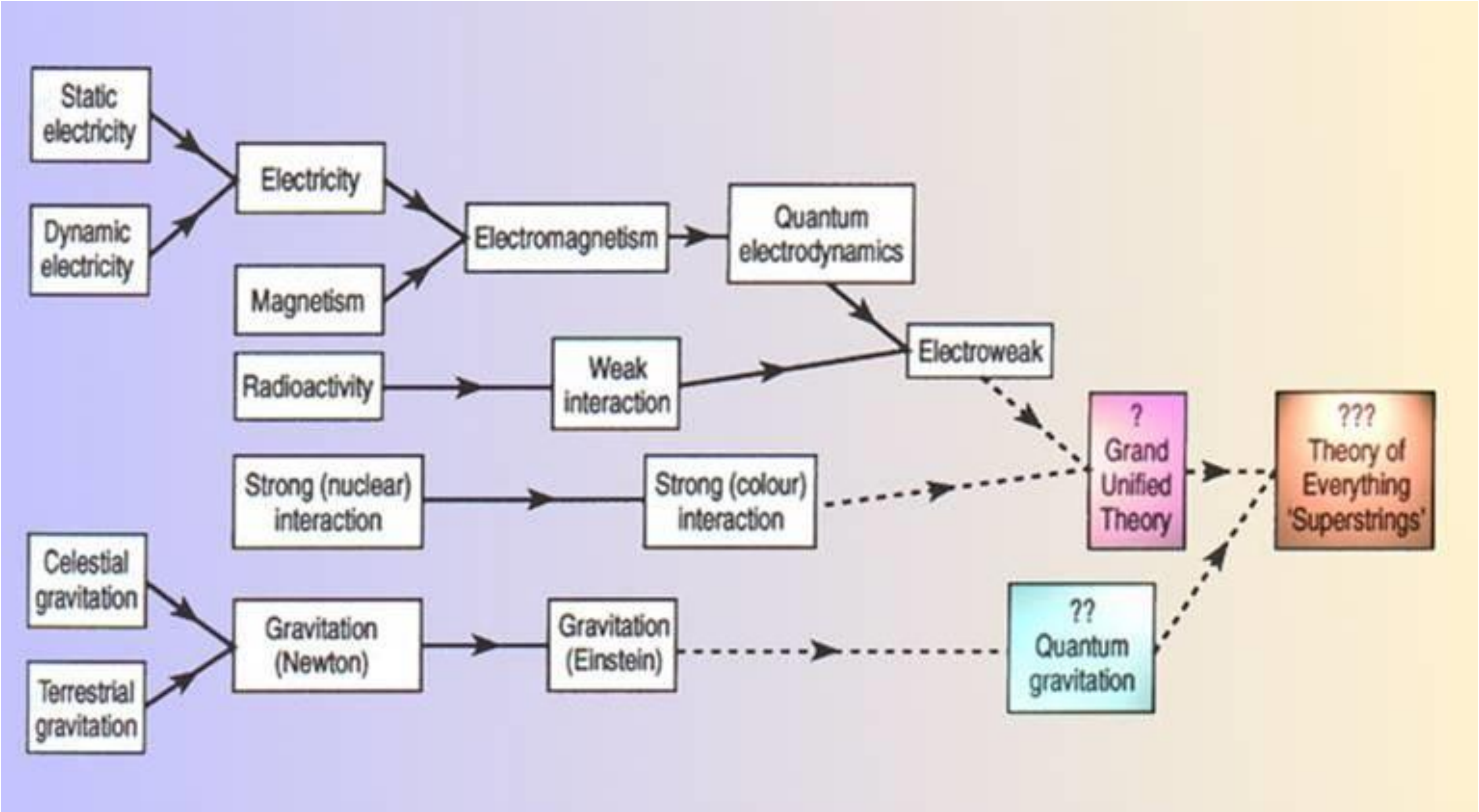
Concepts in Theoretical Physics

Lecture 8: Elementary Particles

John D Barrow

‘Nothing is real’
John Lennon & Paul McCartney

The Story of Physics – laws and unifications

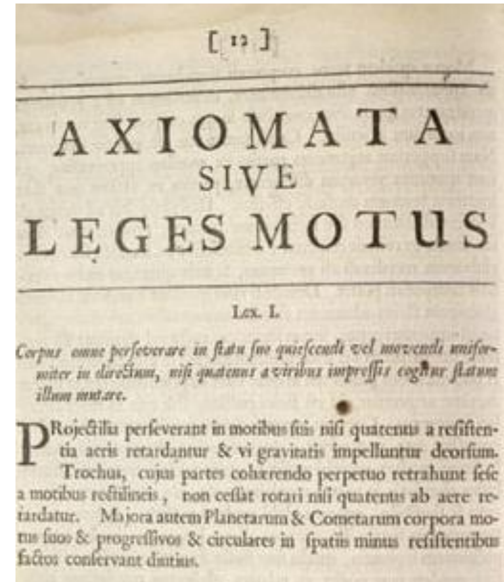


New types of law of nature

Newton's First Law of Motion

Every body persists in its state of being at rest or of moving uniformly straight forward, except insofar as it is compelled to change its state by force impressed.

Isaac Newton 1687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AXIOMATA
SIVE
LEGES MOTUS

Lex. I.

Corpus omne perſeverare in ſtatu ſuo quieſcendi vel movendi uniformiter in directum, niſi quatenus a viribus impreſſis cogitur ſtatum illum mutare.

Projectilia perſeverant in motibus ſuis niſi quatenus a reſiſtentia aeris retardantur & vi gravitatis impelluntur deorſum. Trochus, cujus partes cohærendo perpetuo retrahunt ſeſe a motibus rectilineis, non ceſſat rotari niſi quatenus ab aere retardatur. Majora autem Planetarum & Cometarum corpora motus ſuos & progreſſivos & circulares in ſpatiis minus reſiſtentibus factos conſervant diutius.

Notice that this law applies to <u>all</u> bodies

Therefore it cannot tell you about the nature of those bodies

Laws of particle physics apply to populations of identical elementary particles

So they can constrain the existence and interactions of those particles if a global (constant) or local (space dependent) symmetry must be maintained

GAUGE THEORIES

Four fundamental forces

- The particles interact with each other through four forces:
  - Electromagnetism (QED)
  - Strong Nuclear Force (QCD)
  - Weak Nuclear Force
  - Gravity
- Each of these comes with an associated particle which transmits the force

photon | gluons | W and Z boson | graviton

Force range = h/mc

Gravitational waves

Number of generators of the group symmetry determines the number of carrier particles:

$U(1) = 1$ photon, $SU(2) = 2^2 - 1 = 3$ W^+, W^-, Z^0 bosons,

$SU(3) = 3^2 - 1 = 8$ gluons, and in general $SU(N)$ has N^2-1 generators

A New Periodic Table of Quarks and Leptons

Electric charge		Mass				
-1	electron	1	muon	~200	tau	~3000
0	neutrino	$\sim 10^{-6}$	muon neutrino	$\sim 10^{-6}$	tau neutrino	$\sim 10^{-6}$
-1/3	down quark	~8	strange quark	~200	bottom quark	~8000
2/3	up quark	~4	charm quark	~2000	top quark	~340,000

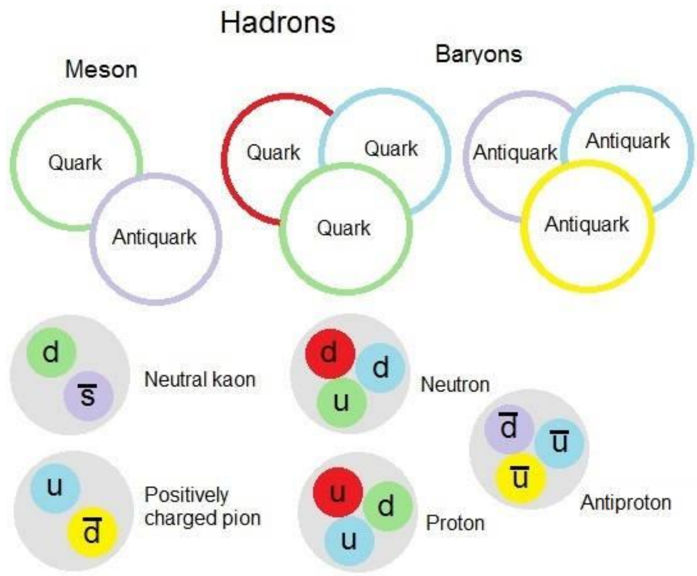
electron mass = $9.10938188 \times 10^{-31}$ kilograms

These are 'elementary' particles in the sense that they are believed to have no internal structure and behave as though they are point-like.

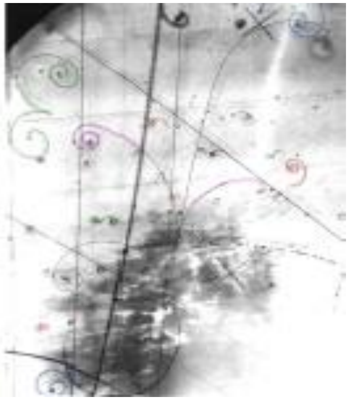
6 types ('flavours') of quark. Linked to lepton pairs in 3 'generations' or 'families'

The Particle-Antiparticle Zoo

The proton is made from 2 u quarks and 1 d quark
The neutron is made from 2 d quarks and 1 u quark
Baryons are made of 3 quarks
Mesons (kaons, pions,..) made of quark-antiquark pairs

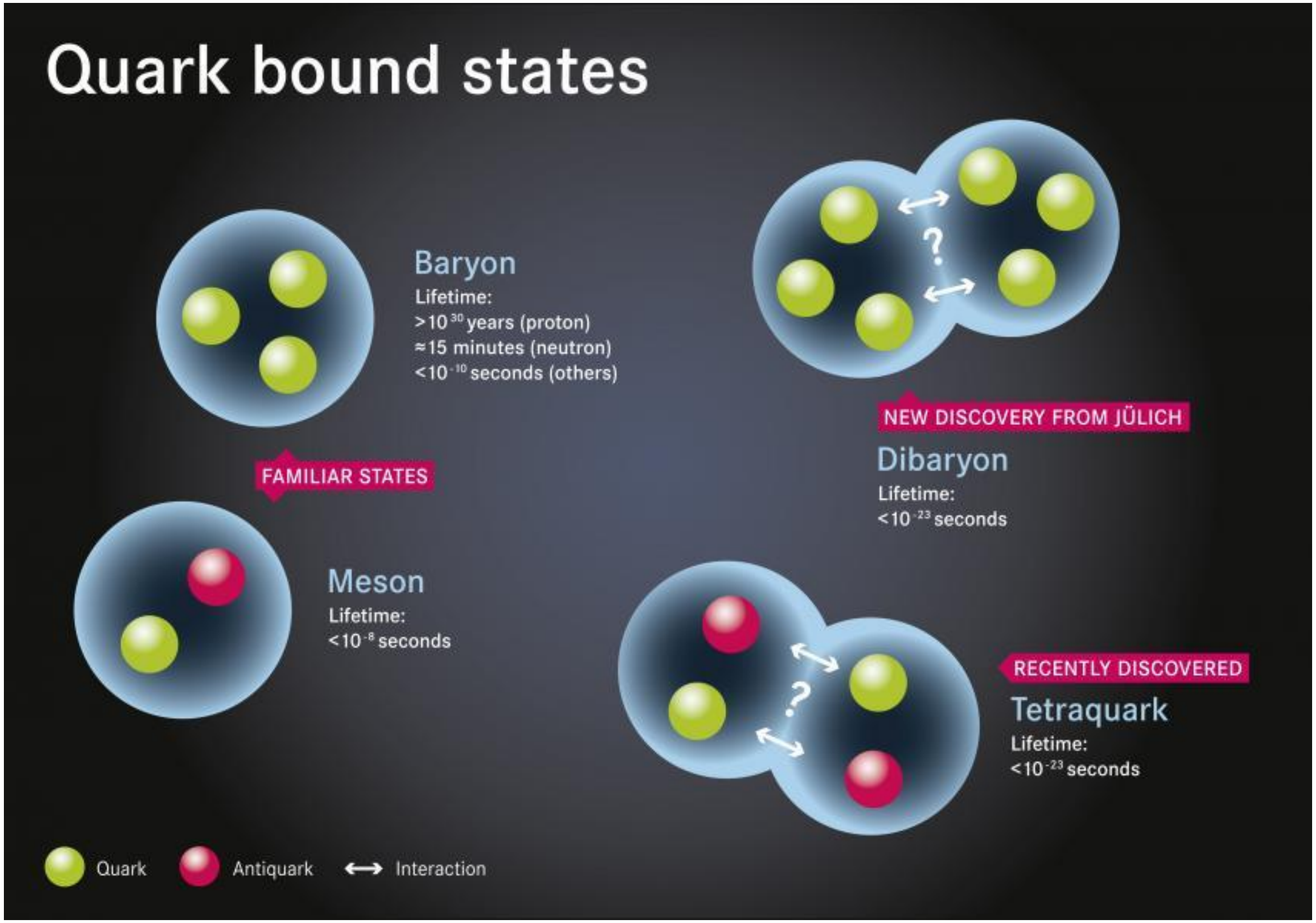


All particles possess an antiparticle with the same mass and lifetime, but opposite charge.
Particles annihilate with their antiparticles into photons.
The photon is its own antiparticle – so you can't tell a star from an anti-star by its light alone.
The observable universe is made of matter not matter and antimatter!
There are about 2 billion photons per proton which suggests originally there were a billion+1 protons for every billion antiprotons !



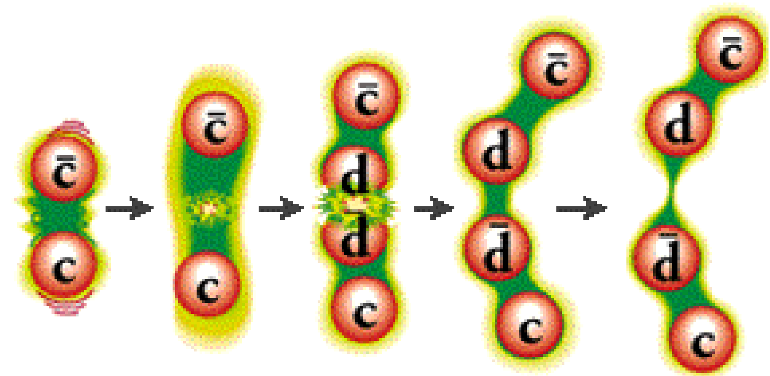
Paul Dirac predicted the existence of antiparticles in 1930. The 'positron' (anti-electron) was discovered 2 years later by Carl Anderson.

Quarks band together

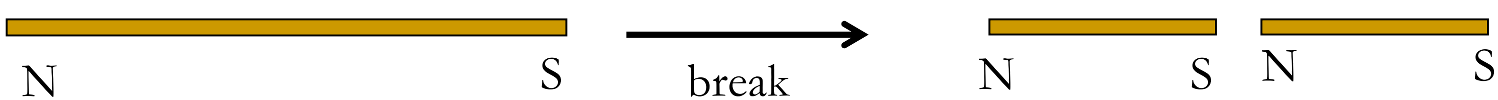


Quarks are confined

- A free quark has never been observed
- They are confined inside baryons and mesons. Prove it!
- Splitting one of these states is like cutting a bar magnet to create a single N or S magnetic pole – you just create two magnets

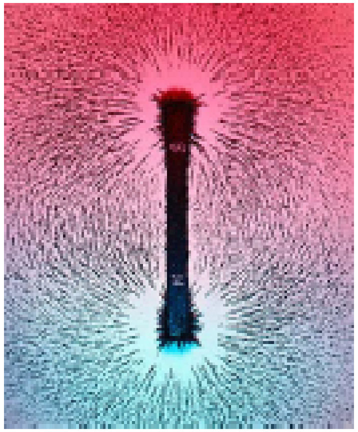


Binding energy released is enough to create a new quark-antiquark pair
Force $\propto$ separation



Electromagnetic fields, waves and particles

- The electromagnetic force is described in terms of electric and magnetic fields. Each of these is a 3-vector



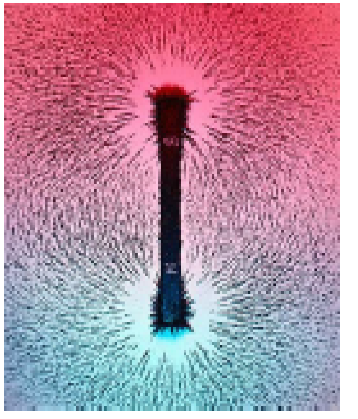
$$\vec{E} = \begin{pmatrix} E_x \\ E_y \\ E_z \end{pmatrix} \qquad \vec{B} = \begin{pmatrix} B_x \\ B_y \\ B_z \end{pmatrix}$$

- Electric charges and magnets set up electric and magnetic fields
- Light waves arise as ripples of these fields
- These light waves are actually made of particles: these are photons

Weak and strong forces, matrices and groups

- The two nuclear forces work in the same way. There are again analogs of electric and magnetic fields.

$$\vec{E} = \begin{pmatrix} E_x \\ E_y \\ E_z \end{pmatrix} \qquad \vec{B} = \begin{pmatrix} B_x \\ B_y \\ B_z \end{pmatrix}$$



- Except now, each component of the vectors is itself a Hermitian matrix
    - 2x2 matrix for the weak force
    - 3x3 matrix for the strong force
- The three forces are associated to matrix groups: U(1), SU(2) and SU(3)

Quantum chromodynamics (QCD)

- The strong force (QCD) acts only on the quarks. So how does it stick them together? It's like electromagnetism, but with matrices for the fields.

- Going from numbers to matrices shouldn't make too much difference. Right?! In fact it makes the problem completely intractable!!

- It's because the world is quantum, not classical. Recall the path integral from the first lecture. You should integrate over all possible paths that a particle takes. In particle physics, this translates to the fact that you should integrate over all possible configurations of the electric and magnetic fields.

$$Prob \sim \sum_{\text{all fields}} \exp\left(iS/\hbar\right) \qquad S = \int d^4x \, \mathrm{Tr}\left(\vec{E}^2 - \vec{B}^2\right)$$

- We can do this sum when the fields are normal vectors...but not when the elements of the vectors are matrices!

Unification – how is it possible?

- Physicists have long dreamt of unifying the 4 forces in 1 theory
- Finding an overarching group symmetry
- Needs to be a 'simple' group – no proper subgroups – so all particles 'talk' to one another. Simplest is SU(5) with 5^2-1 = 24 carrier particles (1 photon + 3 W,Z + 8 gluons + 12 new super-heavy 'leptoquarks' (X,Y bosons and anti-X and anti-Y's) to mediate quark-lepton interactions
- BUT – the 4 forces have very different strengths and act on different particles?(gravitational pp force/e-mag pp force ≈ 10^{-39})

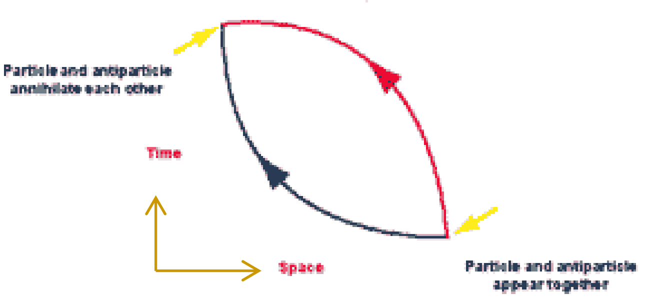
The trick is that the quantum vacuum makes the effective strengths of the forces change with energy

The vacuum is busy

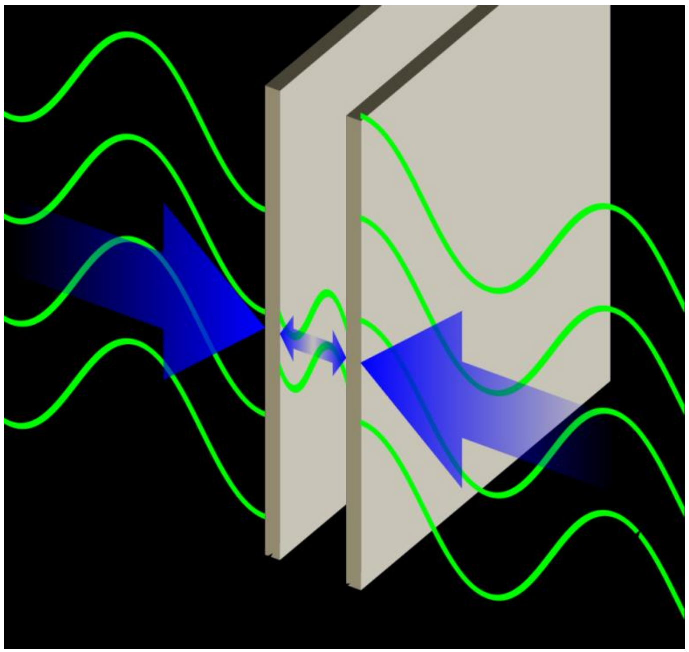
- The quantum vacuum is full of 'virtual' particle-antiparticle pairs (needing energy $\Delta E = 2mc^2$) appearing and annihilating in a time Δt so that

$$\Delta E \Delta t < \hbar/2$$

- If a force acts on them they can become 'real' and observable. This is why black holes can evaporate by the Hawking effect.



The vacuum is real: the Casimir Effect



Fewer zero-point energy standing waves between the plates than outside where they don't need to fit the boundary conditions at both plates so extra pressure pushes the plates together.

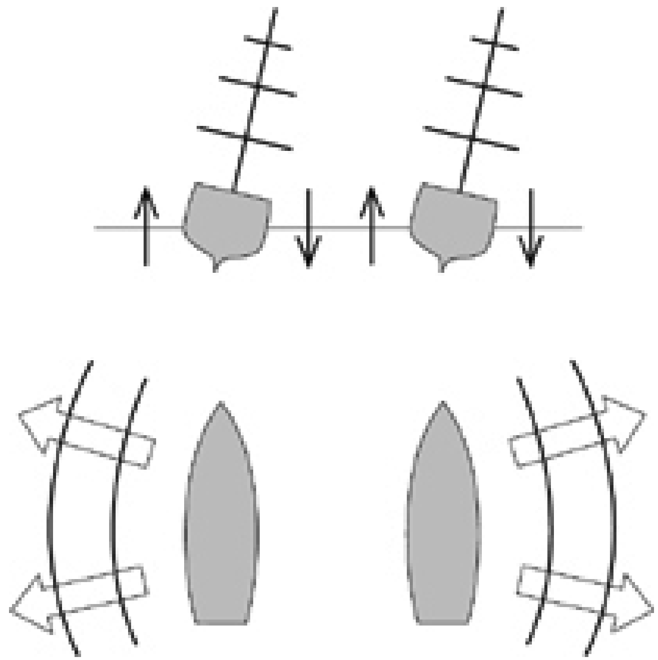
(Hendrik Casimir 1948)

L = plate separation

Pressure = Force/Area = $-hc\pi/480L^4$

Attractive force

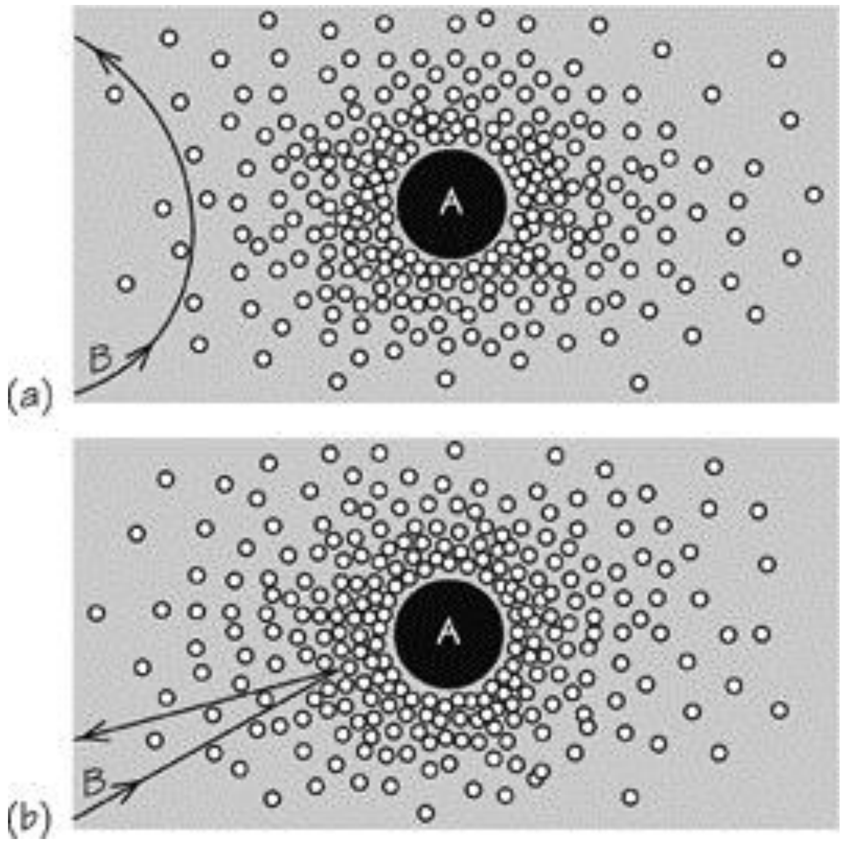
A Nautical Analogy (*L'Album du Marin*,1836)



Attractive Force = 2000 N
If ship mass = 700 tons
Oscillation period = 8 s

French sailors told to avoid allowing two large ships to be parallel in low winds and large swell because 'une certaine force attractive' will draw the ships together and Their riggings will collide. They were to use small boats and lines to separate them. Calculations show that rolling ships attract due higher wave pressure on their outer hulls.

Vacuum polarisation -- electrons



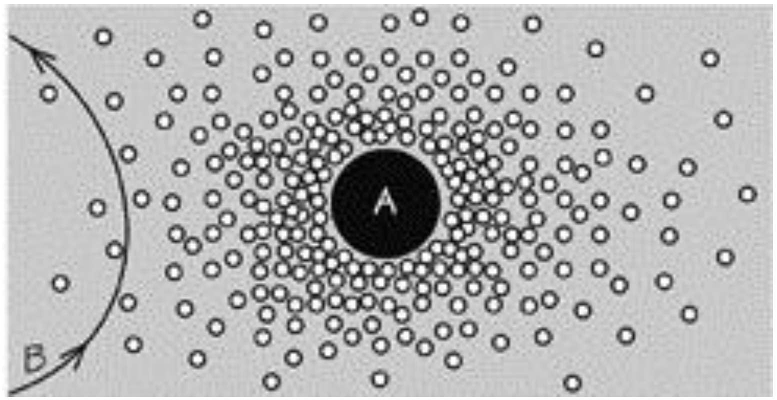
Electron B with low energy hardly penetrates the cloud of virtual positrons and scatters weakly from electron A

Electron B with high energy deeply penetrates the cloud of virtual positrons and scatters strongly from electron A

Photons do not carry electric charge

Effective strength of electromagnetic interactions increases with energy

Vacuum polarisation – quarks and gluons



A quark at A is surrounded by q and anti-q pairs and gluons. But gluons carry the colour charge which they mediate (non-Abelian group) whereas photons do not carry the electric charge they mediate (Abelian group) . A battle between two effects: the q and anti-q effect is just like with the electrons-positrons and makes the force stronger at high energies. But the gluons smear out the central colour charge and weaken it at high energy.

The gluon smearing wins out and the strong colour force gets weaker at higher energies. This is called Asymptotic Freedom. It makes very high energy physics tractable, especially in the study of the early stages of the Universe.

Asymptotic freedom

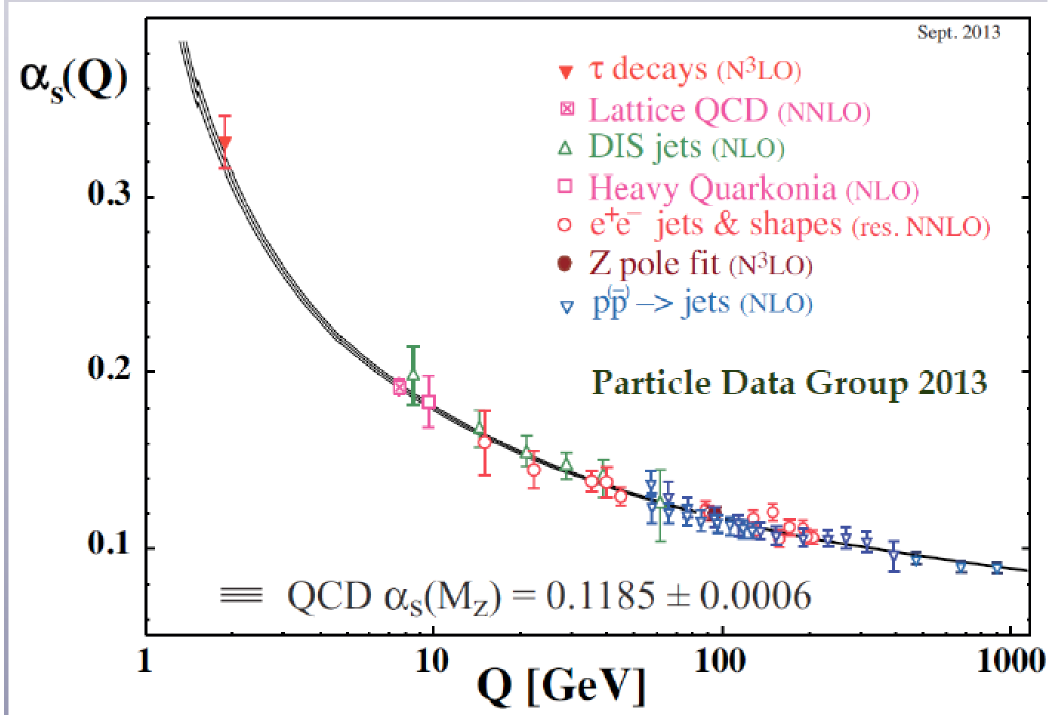
$$\alpha_{\rm ren}(\mu^2) = \frac{1}{b_0 \log \mu^2/\Lambda^2}$$

$$b_0 = \frac{33 - 2n_f}{12\pi}$$

$$b_0^{\rm QED} = -\frac{4n_f}{12\pi}$$

From gluon self-interactions

From gluon(photon)/quark interaction

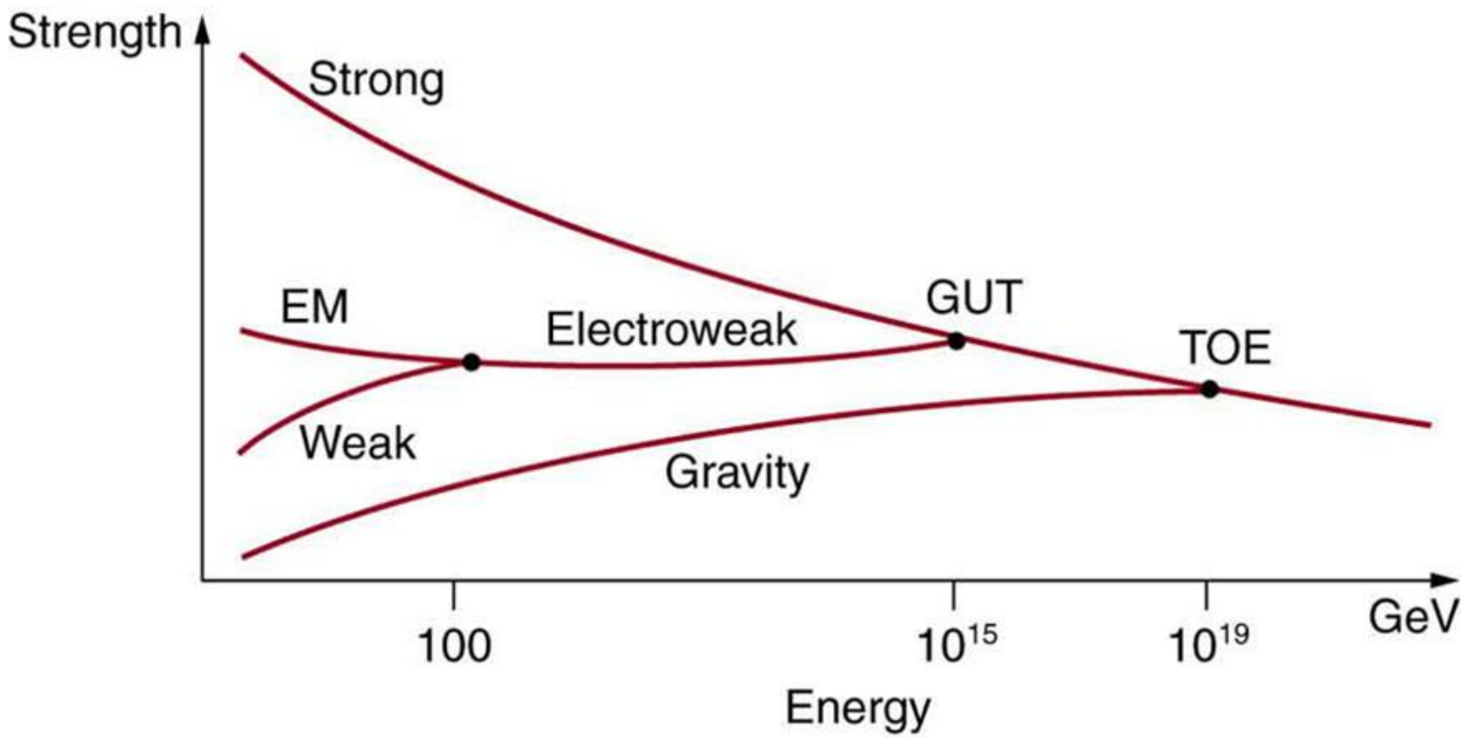


$\alpha_{em} \uparrow$ as energy $\uparrow$

$\alpha_s \downarrow$ as energy $\uparrow$

Asymptotic freedom requires $n_f < 17$ so the number of neutrino types must be $\leq n_f/2 = 8$

Unification of forces now looks possible

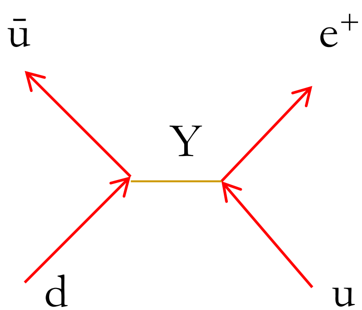


At high energies near 10^{15} GeV, new 'lepto-quark' particles with colour and electric charges can appear which can mediate interactions between quarks and leptons. This allows 'grand unification' (GUT) to be possible.

A further unification with gravity is needed to create a 'Theory of Everything' (TOE)

Proton decay: diamonds are not forever

- Unification of strong and electroweak forces means that quarks must be able to interact with leptons
- This require exchange particles (X, Y bosons) that couple to leptons and quark colour charge
- So the proton will decay (d,u,u) → (e^+,u,u) → (e^+,π^0)



Expt. bound > 1.7 × 10^{34} yrs

$e^+ + 2\gamma$

Proton lifetime ≈ 10^{34} yrs × $(M_Y/10^{14}\ \mathrm{GeV})^4$

10^{30} yrs half-life is approx one atom in your body per human lifetime

Cosmic Matter-Antimatter Asymmetry

- Universe is overwhelmingly made of matter not antimatter no evidence for any primary antimatter – just $p^-/p \sim 10^{-4}$ from secondary production in cosmic ray showers. No anti-atoms seen.
- About 2×10^9 photons per proton in the universe on average
- This would result from an imbalance of $1 + 10^9$ protons for every 10^9 antiprotons in the very early universe since $p^- + p \rightarrow 2\gamma$
- What is the origin of this asymmetry?
- In Grand Unified Theories (GUTs) this asymmetry is not fixed (baryon number, $p - p^-$, or $q - q^-$, is not conserved). A non-zero asymmetry can be generated if interactions violate baryon number, CP, and are out of thermal equilibrium: the maximum value that can be generated is

$$n(\text{protons})/n(\text{photons}) \approx 10^{-2} \times (\text{CP\#})$$

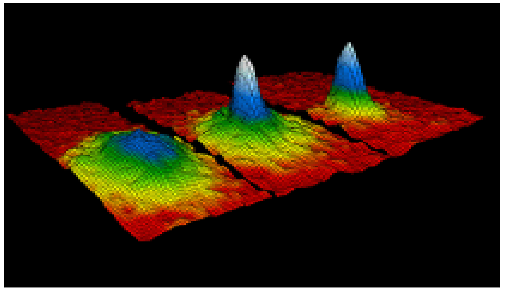
The Higgs Boson

- The W and Z bosons are the carriers of the weak force. They are like the photon – the quanta of light. But they are massive.

- The reason they are massive is the same reason all the other fundamental particles are massive: the Higgs

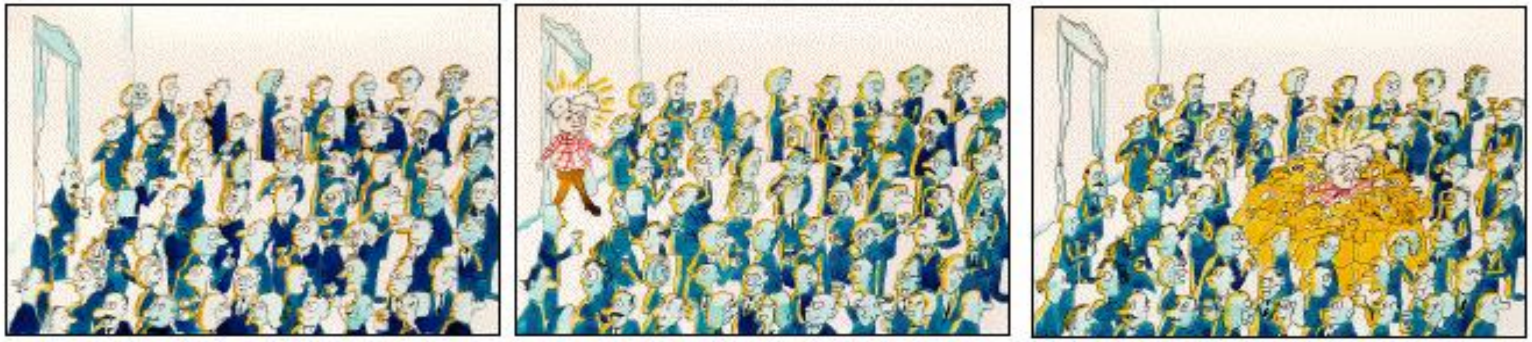
- The Higgs condensate fills the vacuum of space, rather like the Bose-Einstein condensate shown below

- The Higgs condensate acts like treacle through which other particles must move. In fact, all particles are actually massless. But their interaction with the Higgs condensate gives them mass.



The Higgs Condensate

- A common analogy used is that of a famous person moving through a crowded room



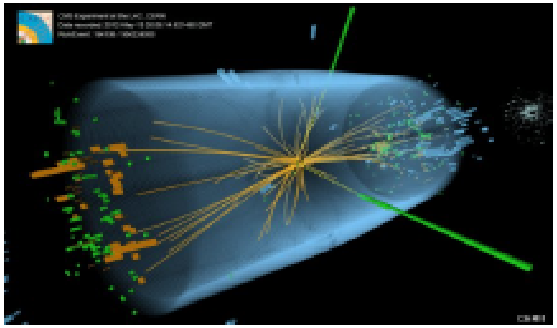
- Different particles get stuck in the condensate by different amounts. But why? What gives rise to the vast difference in masses of the particles? We don't know…

The Discovery of the Higgs Boson

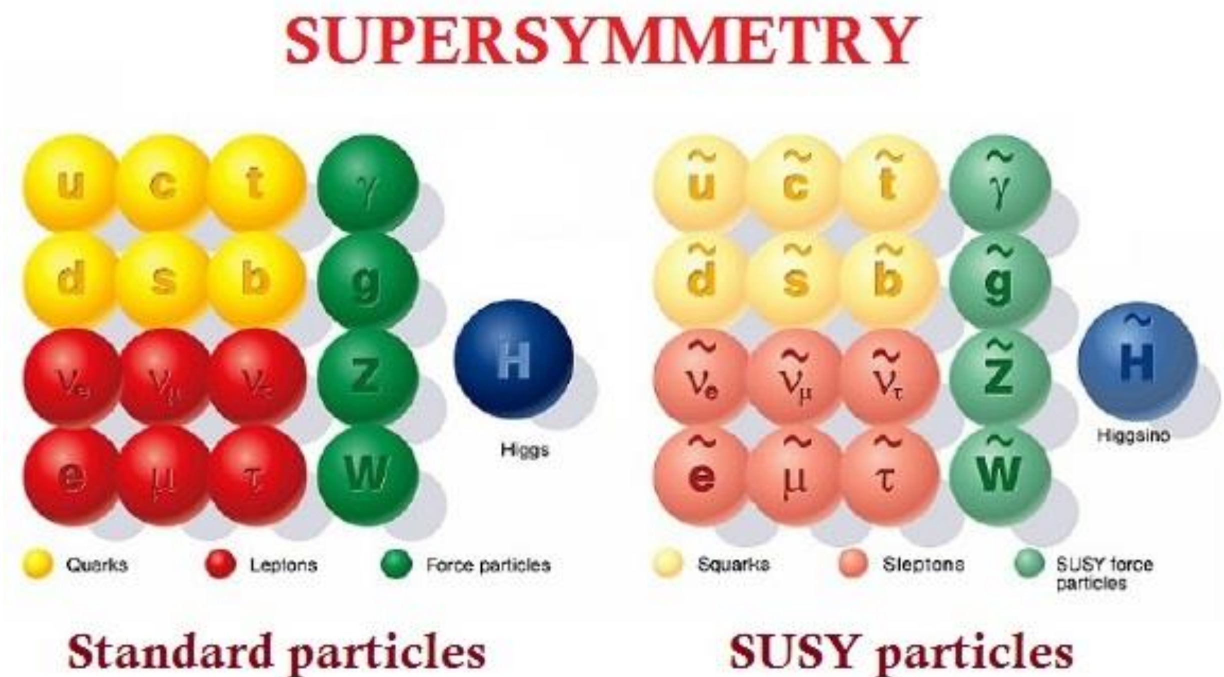
- The Higgs boson is a particle. It can be thought of as a ripple of the condensate, or a splash in the treacle which fills all of space.

- The Higgs boson was finally discovered in July 2012. It weighs around 125 to 126 *GeV*.

- The next step is to check the various properties of the Higgs to see if they agree with our theoretical understanding



Supersymmetric particles (‘sparticles’)



CERN & IES de SAR

If there is a symmetry between fermions and bosons:

All known fermions have bosonic superpartners (selectron, sneutrinos, squarks etc)

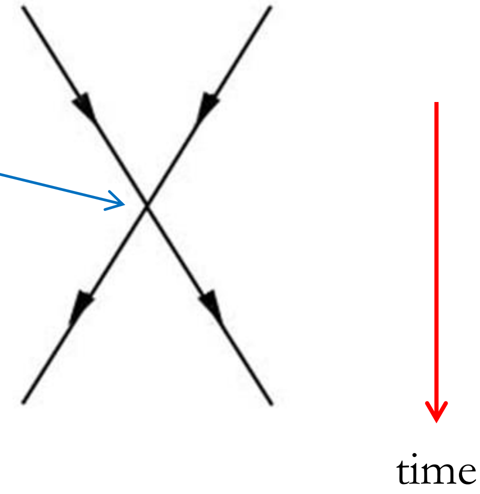
All known bosons have fermionic superpartners (photinos, gluinos)

Sneutrinos are prime candidates for dark matter

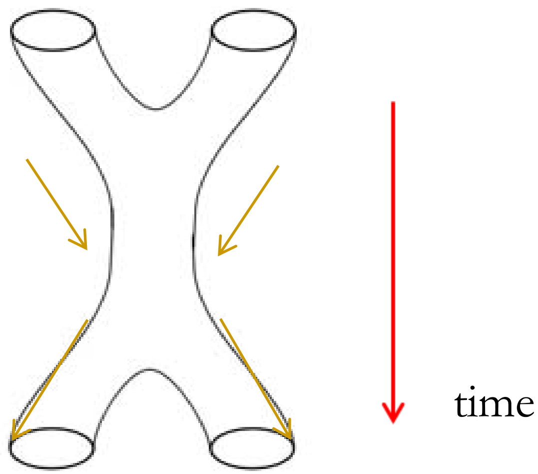
Current search with the LHC at CERN (> 13 TeV) – none seen so far

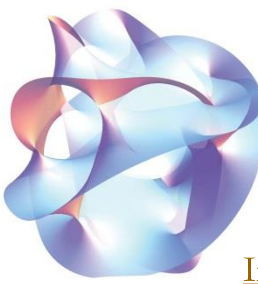
Superstring Theory

Point particles follow lines in spacetime – infinities!



Loops (trace out tubes with finite smooth interactions





2d hypersurface of the quintic Calabi-Yau 3-fold

Image; Jbourjai

String loops have tensions which increase as energy falls → become like points
Tension falls as energy increases → become string-like near the Planck energ,y 10^{19} GeV

Is this a Theory of Everything?? There are over 10^{500} different vacuum states!
Only finite in 10d (superstring) or 11d (M-theory)spacetime
so we have to believe that only 3 dimensions of space grew large to 10^{60} L_{pl}

Further reading

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