Concepts in Theoretical Physics

Lecture 6: Particle Physics

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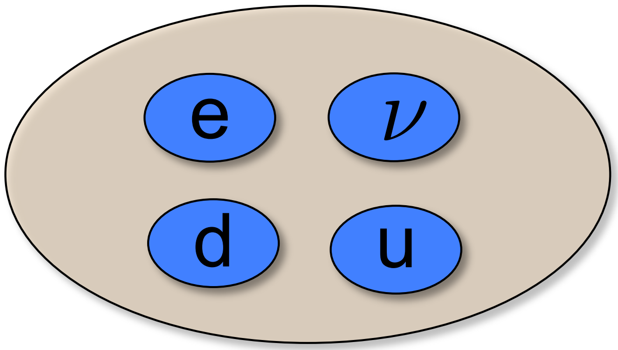
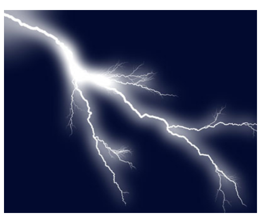
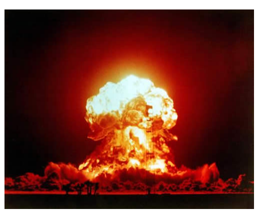
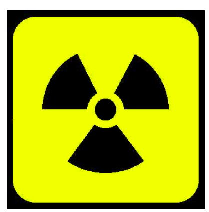
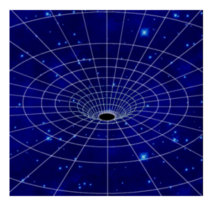
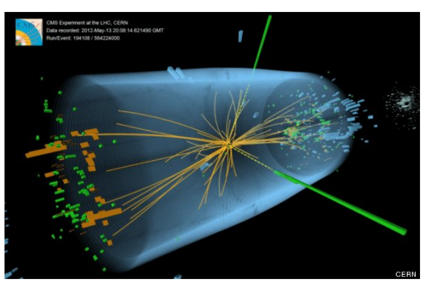
The Structure of Things



- Four fundamental particles
- Repeated twice!

- Four fundamental forces
- All based on symmetry…
  …which means group theory



- The Higgs boson

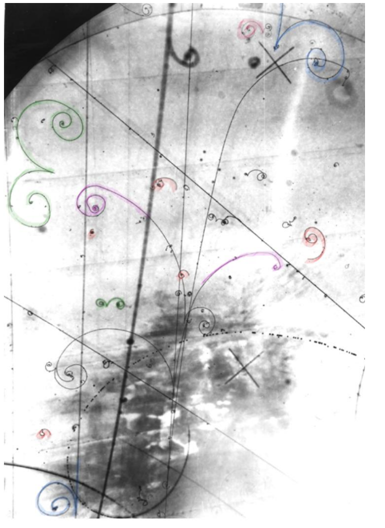
+ stuff we don’t know + stuff that we don’t even know we don’t know

The New Periodic Table

Electric charge		Mass				
-1	electron	1	muon	~200	tau	~3000
0	neutrino	~10^{-6}	muon neutrino	~10^{-6}	tau neutrino	~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 × 10^{-31} kilograms

+ Anti-Particles

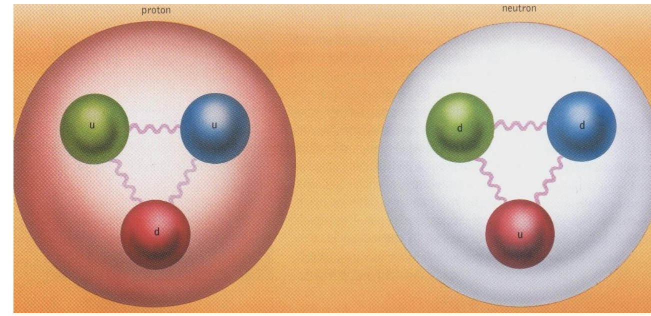


- Each type of particle has an *anti-particle*
- This has the same mass, but opposite charge
- If a particle and anti-particle come across each other, they annihilate.
- Anti-particles were predicted in 1930 by Dirac, and discovered 2 years later

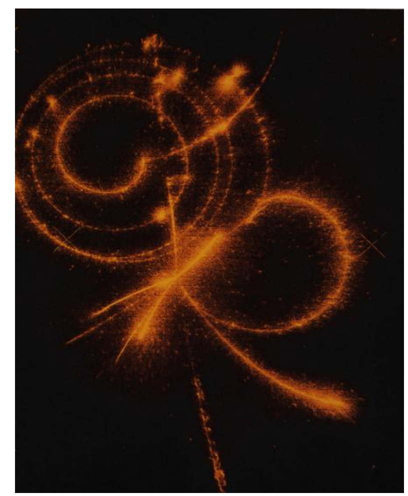
$$(i\gamma_\mu \mathcal{D}^\mu - m)\,\psi = 0$$

The Zoo of Particles

- The proton is made of two up quarks and a down quark
- The neutron is made of two down quarks and an up quark



- In the 1960's, physicists discovered hundreds upon hundreds of further particles.
- Each contains either three quarks, or a quark and an anti-quark
  - There are pions and kaons and vector rho mesons. There's the Delta ++ baryon and the omega, lambda, sigma, eta, nu, upsilon. After running out of greek letters, they were named simply a, b, f…



How to Make Stuff

Why do the quarks stick together in this way?
It's because the quarks are the only particles to feel the strong nuclear force. To understand this better, we next need to look at the forces.

Four Forces

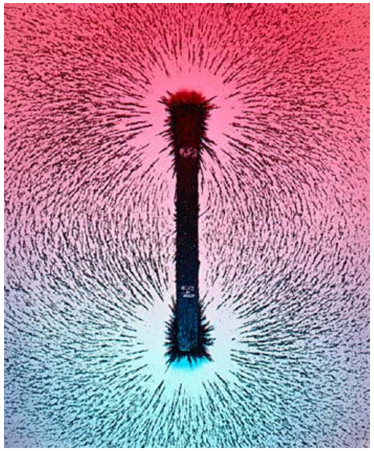
- The particles interact with each other through four forces:
  - Electromagnetism (QED)
  - Strong Nuclear Force (QCD)
  - Weak Nuclear Force
  - Gravity
    - We don't understand gravity as well the others…see the next lecture
- Each of these comes with an associated particle which transmits the force

photon	gluons	W and Z boson	graviton

Not discovered, although there is strong evidence for gravity waves

Fields to Waves to Particles

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

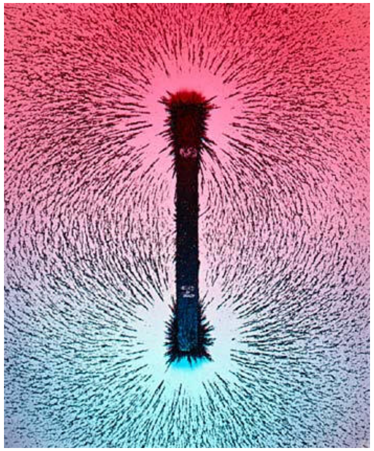


$$\vec{E} = \begin{pmatrix} E_x \\ E_y \\ E_z \end{pmatrix} \qquad \vec{B} = \begin{pmatrix} B_x \\ B_y \\ B_z \end{pmatrix}$$

- 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

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)

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.

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

- We can do this sum when the fields are normal vectors...

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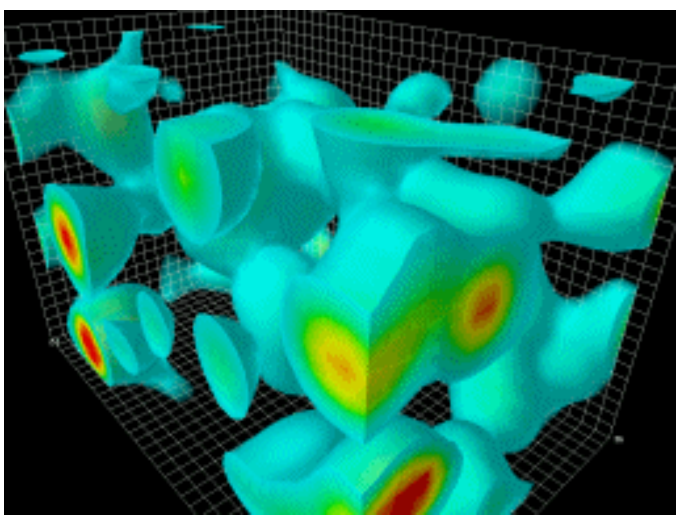
$$Prob \sim \sum_{\text{all fields}} \exp\left(iS/\hbar\right) \qquad S = \int d^4x \, \mathrm{Tr}\left(\vec{E}^2 - \vec{B}^2\right)$$

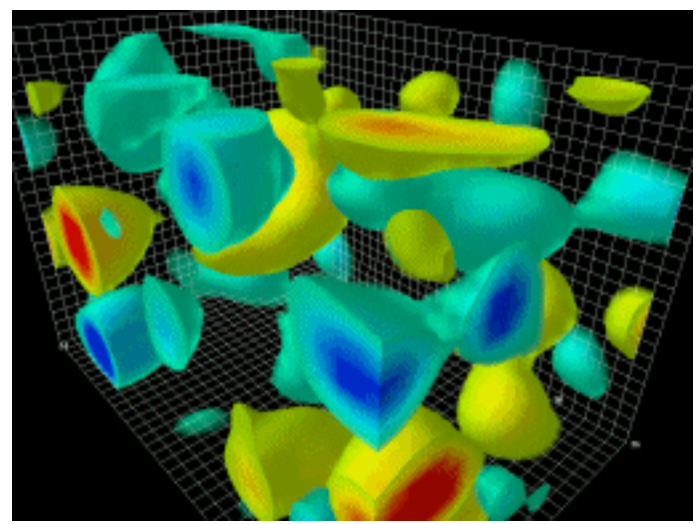
- We can do this sum when the fields are normal vectors...but not when the elements of the vectors are matrices!

QCD is Hard!

- Clay Mathematics problem: $1 million
- Serious Supercomputers

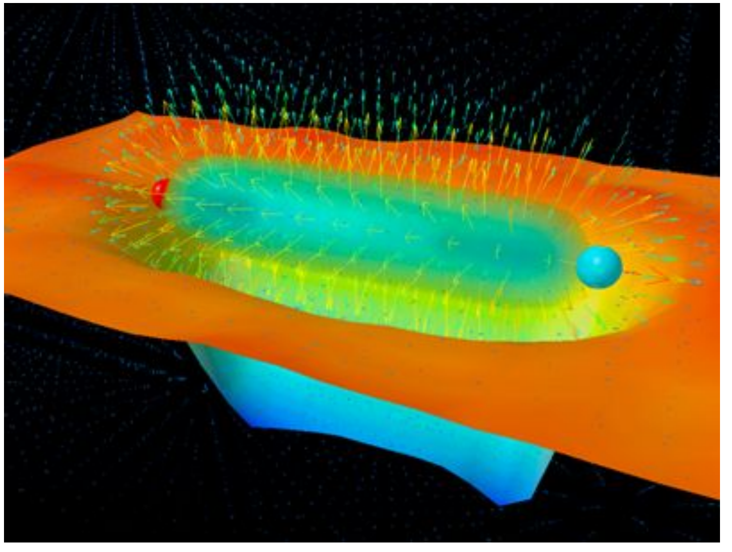
- Even the simplest question is immensely difficult: what does empty space look like?





Confinement

- The quarks can never escape the proton or neutron.
- If you try to pull a quark away, a long string forms pulling it back in. The force between two quarks is linear: $F \sim r$. This is called "confinement"

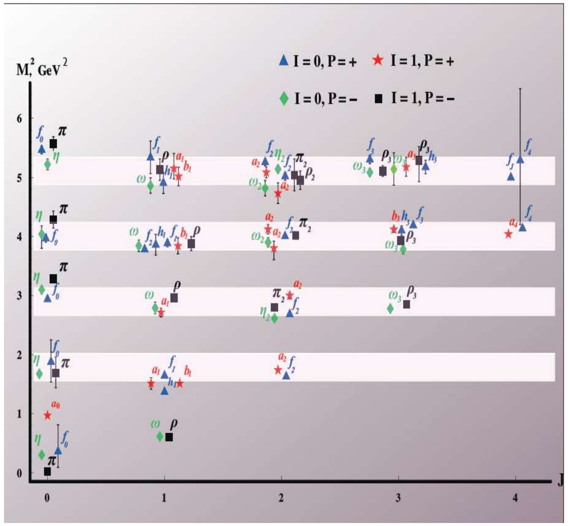


- This is why quarks stick together in so many ways.
- To prove confinement from the equations of QCD is one of the most important open problems in theoretical physics.

An Aside: Strings in QCD

- Homework exercise: consider two *relativistic* particles with separation r, and an attractive force *F=r*.
- Show that when the angular momentum, *J*, is large, the energy of a the spinning particles, attached by a string, scales as

$$E \sim \sqrt{J}$$

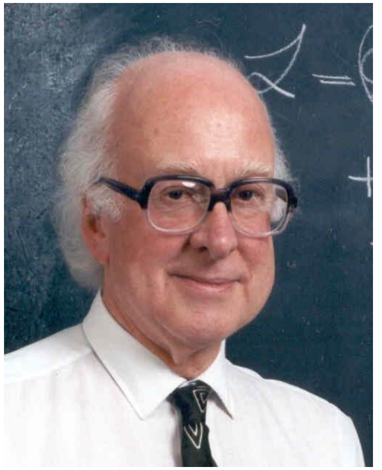


- But since $E=mc^2$, this gives a relationship between mass and angular momentum of particles.
- This was the beginning of string theory…trying to understand the string that appears between two quarks. It later led to connections between QCD and quantum gravity that we still don't fully understand.

The Weak Force and the Higgs Boson

- The properties of the weak force are intimately tied with the Higgs boson.

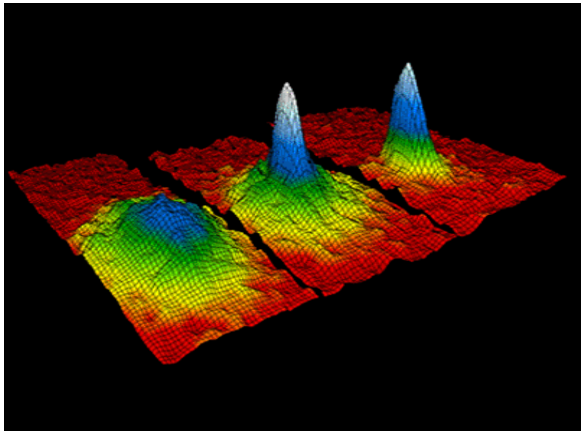
The Higgs Boson



- 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

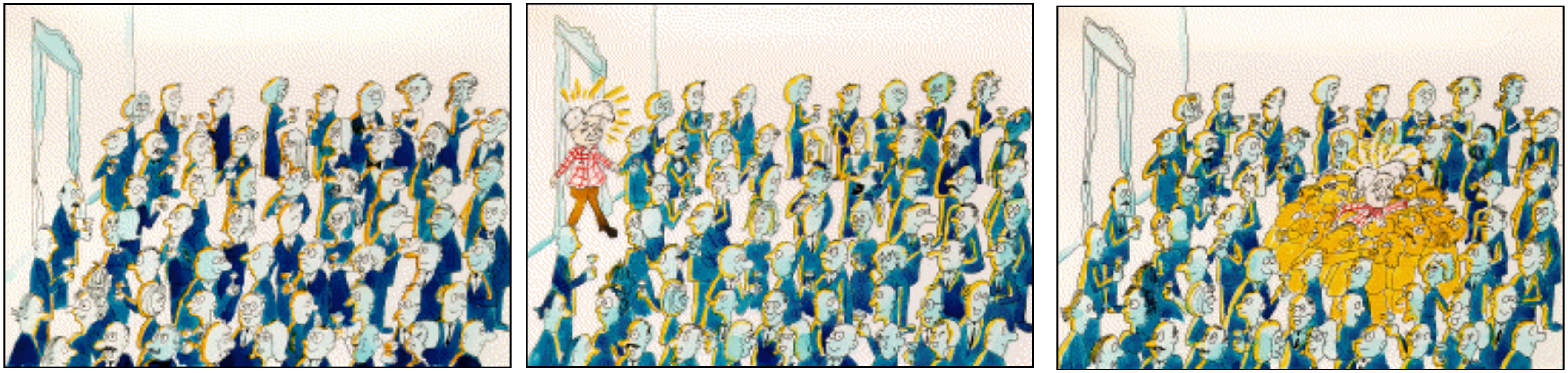
The Higgs Condensate

- 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

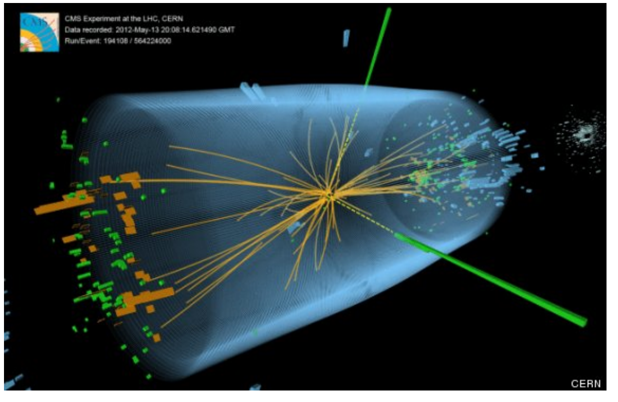
- A common analogy used is that of a famous person moving through a crowded room



- 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 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

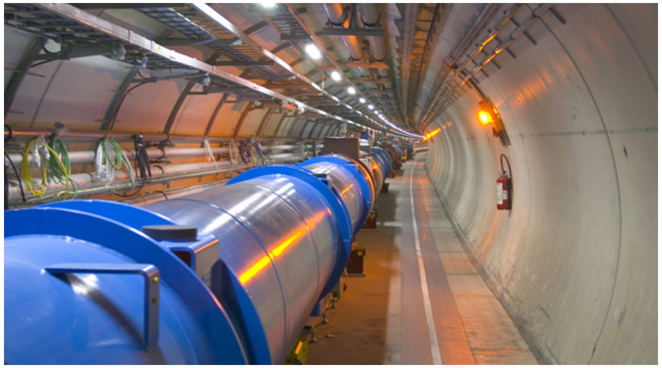


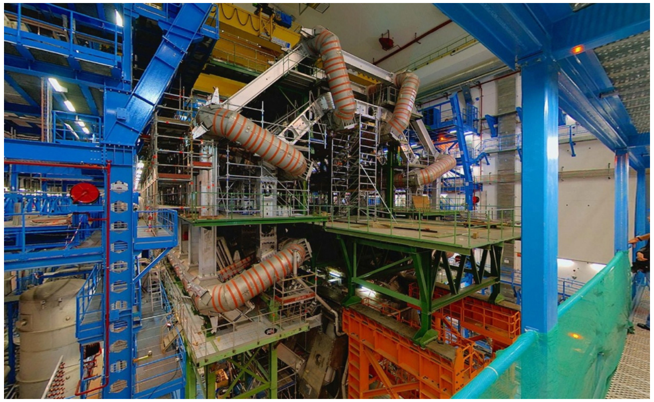
LHC @ CERN

- Ring: 27 km circumference and 100 m underground.
- 1232, 34 ton superconducting magnets for beam
- 36,000 tons of coolant below 2K.

LHC

- Protons collide at 8 TeV centre of mass energy
- Two multi-purpose detectors: ATLAS and CMS
  - Track particles, measure energy
- 600 million collisions per second
- 10 Petabytes of data a year (= 20 km high stack of CDs!)





New Physics?

- The LHC has discovered the Higgs. But what next?

- For various reasons (known as the Hierarchy Problem) we think (hope) that the Higgs will have companion particles. This will be the first physics beyond the Standard Model.
  - (See http://www.damtp.cam.ac.uk/user/tong/talks/tss.pdf for a presentation on this subject, albeit one with more pictures than words)

- This is the next goal for the LHC…find new physics.