Unravelling the Mysteries of Matter with the CERN Large Hadron Collider
An Introduction/Overview of Particle Physics

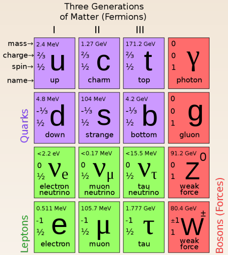
Introductory Lecture August 1st 2016

Bobby Samir Acharya
International Centre for Theoretical Physics and King's College London

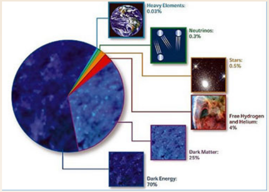
African School of Fundamental Physics and Applications 2016, ICTP-East African Institute for Fundamental Research, U. of Rwanda

Welcome Everyone to the 4th African School in Fundamental Physics and its Applications!!
Especially welcome to the students who have travelled from all over Africa and beyond and for whom this school has been developed.
Also welcome to the lecturers and the LOC and URwanda and MINEDUC for making this possible
Finally: thank you to the numerous international institutes and universities for their support.

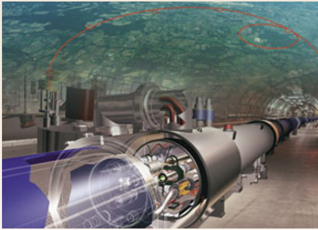
Particles, the Universe and the LHC



All known elementary particles



Energy of the Universe



Large Hadron Collider

An introduction and overview of particle physics. Also: why and what the LHC is for. Two Mysteries: Dark Matter and the Higgs Boson

Atoms and the Periodic Table

hydrogen 1 **H** 1.0079																		helium 2 **He** 4.0026
lithium 3 **Li** 6.941	beryllium 4 **Be** 9.0122												boron 5 **B** 10.811	carbon 6 **C** 12.011	nitrogen 7 **N** 14.007	oxygen 8 **O** 15.999	fluorine 9 **F** 18.998	neon 10 **Ne** 20.180
sodium 11 **Na** 22.990	magnesium 12 **Mg** 24.305												aluminium 13 **Al** 26.982	silicon 14 **Si** 28.086	phosphorus 15 **P** 30.974	sulfur 16 **S** 32.065	chlorine 17 **Cl** 35.453	argon 18 **Ar** 39.948
potassium 19 **K** 39.098	calcium 20 **Ca** 40.078		scandium 21 **Sc** 44.956	titanium 22 **Ti** 47.867	vanadium 23 **V** 50.942	chromium 24 **Cr** 51.996	manganese 25 **Mn** 54.938	iron 26 **Fe** 55.845	cobalt 27 **Co** 58.933	nickel 28 **Ni** 58.693	copper 29 **Cu** 63.546	zinc 30 **Zn** 65.39	gallium 31 **Ga** 69.723	germanium 32 **Ge** 72.61	arsenic 33 **As** 74.922	selenium 34 **Se** 78.96	bromine 35 **Br** 79.904	krypton 36 **Kr** 83.80
rubidium 37 **Rb** 85.468	strontium 38 **Sr** 87.62		yttrium 39 **Y** 88.906	zirconium 40 **Zr** 91.224	niobium 41 **Nb** 92.906	molybdenum 42 **Mo** 95.94	technetium 43 **Tc** [98]	ruthenium 44 **Ru** 101.07	rhodium 45 **Rh** 102.91	palladium 46 **Pd** 106.42	silver 47 **Ag** 107.87	cadmium 48 **Cd** 112.41	indium 49 **In** 114.82	tin 50 **Sn** 118.71	antimony 51 **Sb** 121.76	tellurium 52 **Te** 127.60	iodine 53 **I** 126.90	xenon 54 **Xe** 131.29
caesium 55 **Cs** 132.91	barium 56 **Ba** 137.33	57-70 *	lutetium 71 **Lu** 174.97	hafnium 72 **Hf** 178.49	tantalum 73 **Ta** 180.95	tungsten 74 **W** 183.84	rhenium 75 **Re** 186.21	osmium 76 **Os** 190.23	iridium 77 **Ir** 192.22	platinum 78 **Pt** 195.08	gold 79 **Au** 196.97	mercury 80 **Hg** 200.59	thallium 81 **Tl** 204.38	lead 82 **Pb** 207.2	bismuth 83 **Bi** 208.98	polonium 84 **Po** [209]	astatine 85 **At** [210]	radon 86 **Rn** [222]
francium 87 **Fr** [223]	radium 88 **Ra** [226]	89-102 * *	lawrencium 103 **Lr** [262]	rutherfordium 104 **Rf** [261]	dubnium 105 **Db** [262]	seaborgium 106 **Sg** [266]	bohrium 107 **Bh** [264]	hassium 108 **Hs** [269]	meitnerium 109 **Mt** [268]	ununnilium 110 **Uun** [271]	unununium 111 **Uuu** [272]	ununbium 112 **Uub** [277]		ununquadium 114 **Uuq** [289]				

*Lanthanide series	lanthanum 57 **La** 138.91	cerium 58 **Ce** 140.12	praseodymium 59 **Pr** 140.91	neodymium 60 **Nd** 144.24	promethium 61 **Pm** [145]	samarium 62 **Sm** 150.36	europium 63 **Eu** 151.96	gadolinium 64 **Gd** 157.25	terbium 65 **Tb** 158.93	dysprosium 66 **Dy** 162.50	holmium 67 **Ho** 164.93	erbium 68 **Er** 167.26	thulium 69 **Tm** 168.93	ytterbium 70 **Yb** 173.04
* *Actinide series	actinium 89 **Ac** [227]	thorium 90 **Th** 232.04	protactinium 91 **Pa** 231.04	uranium 92 **U** 238.03	neptunium 93 **Np** [237]	plutonium 94 **Pu** [244]	americium 95 **Am** [243]	curium 96 **Cm** [247]	berkelium 97 **Bk** [247]	californium 98 **Cf** [251]	einsteinium 99 **Es** [252]	fermium 100 **Fm** [257]	mendelevium 101 **Md** [258]	nobelium 102 **No** [259]

All the matter that we know about on and in the Earth has this simple classification. Simple enough to fit on a t-shirt!

Particles, Matter and the Universe

We, and the matter which makes up all of the Earth is made of atoms

The planets and stars also ALL seem to be made of atoms

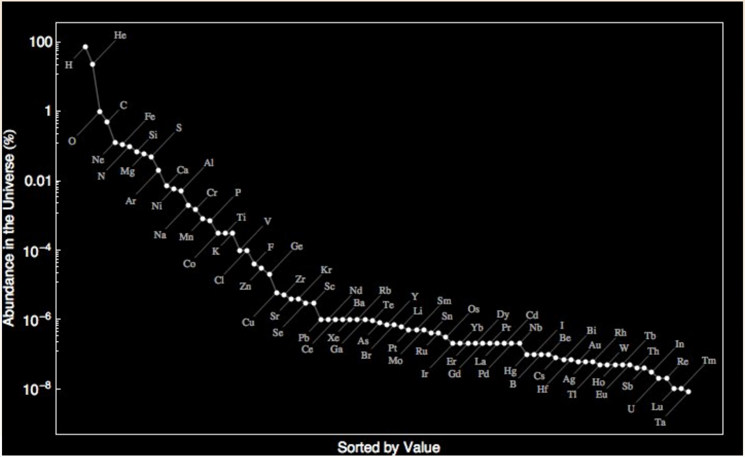
The galaxy contains hundreds of billions (i.e. $\sim 10^{11}$) of stars which are basically alike: so much of the galaxy is also be made of atoms.

Remarkably, all of the galaxies (and there are $\sim 10^{11}$ of them) also look quite similar!

Hence, we learn that much of the matter of the entire Universe is made of atoms

We will ADD some very important details to this picture later.

Abundance of Elements in the Universe



The heavier the atom, the less of it there is

Simpler atoms are easier to make!

The Structure of Atoms

The structure and regularity of the periodic table suggests that atoms are made of even simpler objects

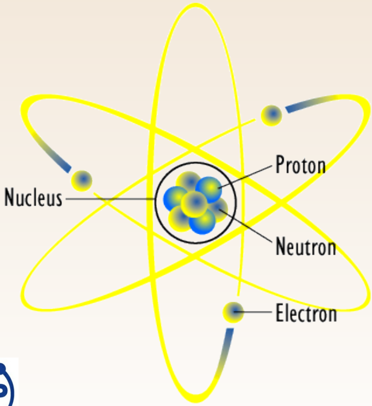
Electrons were discovered by Thompson in so-called cathode ray tubes around 1897.A wire filament with a current passing through was seen to emit particles with negative charge. This showed that atoms contained "electrons".
α-particles (now known to be Helium nuclei) were discovered as radiation emitted by various radioactive elements and compounds

Rutherford used beams of α-particles scattered off Gold to prove that atoms "must" contain a very dense nucleus

The α-particles were deflected at large angles, proving that atoms had "structure" - dense nucleus.

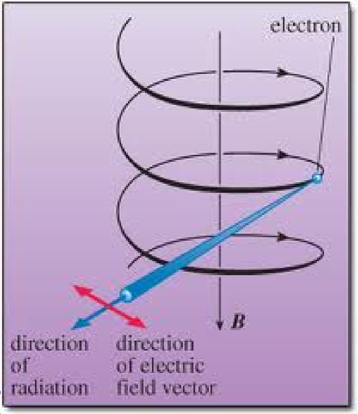
Shortly after this, the Bohr model of the atom (protons and neutrons in a dense nucleus, surrounded by a cloud of electrons) was "established".

The Atom



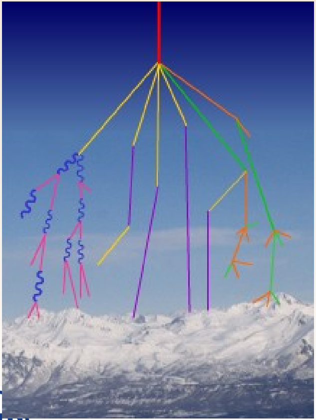
- The atom consists of a very dense nucleus surrounded by a "cloud of electrons"
- Atoms have sizes of order 10^{-11} to 10^{-10} m.
- Nucleus is 10^{-4} times smaller!
- Protons are positively charged. Neutrons are neutral.
- Electrons have *minus* the charge of protons but are *much* lighter ($m_e \sim m_p/2000$)
- **But are protons, neutrons and electrons fundamental?**

Charged particles in Electric and Magnetic Fields



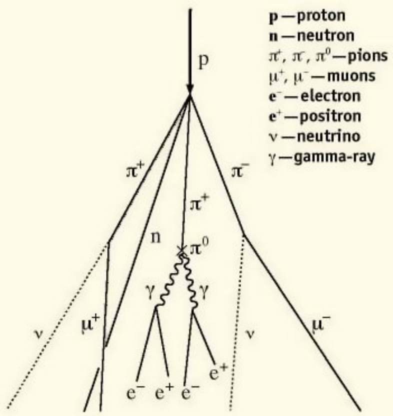
- Electric current is just moving charge
- You can create a magnetic field by coiling a current carrying wire
- By the same token, a magnetic field exerts a force on charged particles
- Strong electric and magnetic fields can be used to accelerate charged particles to high energies!
- This is how particle accelerators work: you will learn this in week 3!

The galaxy is a particle collider!



- The galaxy has a strong magnetic field and charged particles!
- A high energy particle is created in a star and brought to Earth by the galactic magnetic field
- It strikes the upper atmosphere of Earth
- Multiple interactions occur between the particle and the atoms in the atmosphere
- Creates a cosmic ray "shower"

The galaxy as a particle collider!

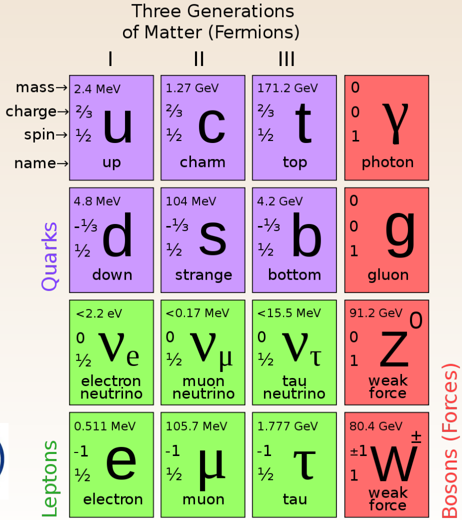


- This is a particular example when the original particle is a proton
- This example produces pions, photons, muons, electrons and neutrinos!
- A muon from a cosmic ray like this just passed through your body!
- In fact, muons and pions were discovered in cosmic rays

The Particle Zoo

- As a result of cosmic ray and ground-based particle collider experiments we now know that protons and neutrons are actually made of more fundamental particles called quarks and gluons
- We also know that protons and neutrons have many ‘cousins’ which are also made of quarks and gluons. Hundreds of these have been discovered over the past six decades.
- Neutrons, when not bound inside atoms, actually decay into a proton, an electron and a neutral (almost massless) particle called a neutrino.
- The most remarkable fact, though, is that *all of these hundreds of particles and their properties are* **precisely** *described by a very simple model.*

The Standard Model of Particle Physics



The *entire* periodic table can be explained by just the first and last columns!

Last column are the force carrying particles

There are three "families" of quarks and leptons.Why not just one?

Why these particular masses?

Are there more than just these particles?

Mass and The Higgs Boson.

- There is one additional particle predicted by the Standard Model which was not yet mentioned.
- This is the so-called Higgs boson, after Peter Higgs who made significant contributions to this part of the Standard Model in 1964
- According to the model, it is the Higgs boson which is responsible for giving the quarks and leptons their mass
- The heavier the particle, the stronger its interactions with the Higgs particle, so the top quark has the strongest interaction with the Higgs, the electron the weakest one.
- One of the main reasons for the LHC physics programme was to find the Higgs boson, or prove that it doesn't exist!
- It's discovery would shed enormous light on the nature and origin of mass and "complete" the story of the Standard Model

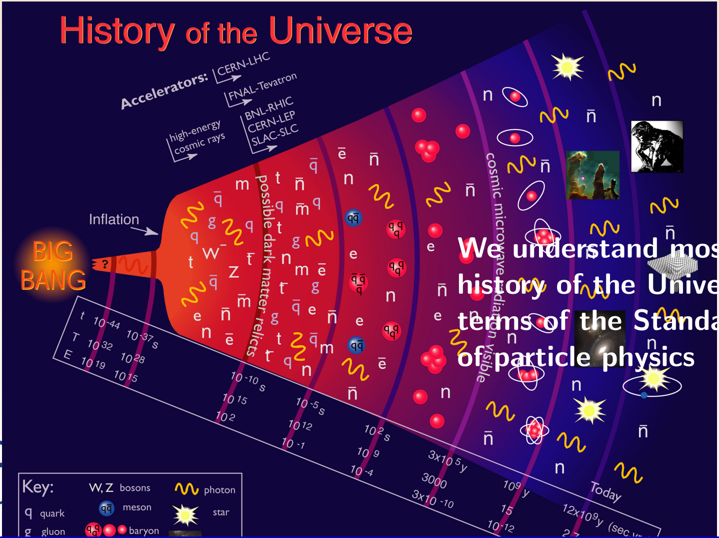
The LHC and The Higgs Boson

- Much data from the LHC collected in 2011 and 2012, 2015 and 2016.
- The Higgs boson was discovered by the LHC experiments!! 48 years after it was predicted!
- More data is being collected and analysed to determine if the Standard Model is correct
- These are very exciting times. More about the LHC and the Higgs boson later in the course.

Dark Matter

- Einstein's theory of gravity has been tested with remarkable accuracy in various systems within the galaxy
- But, if you estimate the mass of galaxies by the number of atoms that they contain, there's a huge problem
- Galaxies of that mass would not move in the way that the galaxies have been observed to be moving
- There is now very strong evidence that there is additional, "dark" matter in the Universe, beyond protons, neutrons, electrons, photons and neutrinos
- In fact there seems to be about five times more dark matter than "atomic matter"!
- You will learn more about dark matter in the astro/cosmo lectures.
- There are some plausible arguments that particles made of dark matter could be produced directly at the LHC (more on this later)

Cosmic History

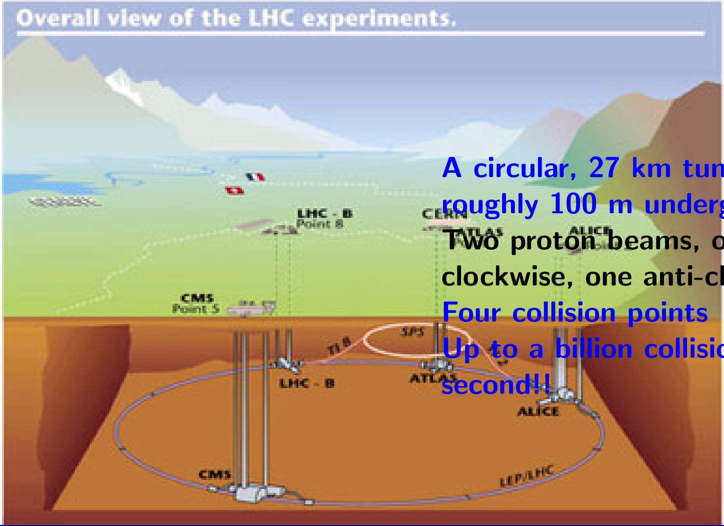


We understand most of the history of the Universe in terms of the Standard Model of particle physics

The Large Hadron Collider

- The basic idea is to :
  - accelerate beams of protons to as high energy as possible
  - smash them into each other as often as possible
  - Create new particles like the Higgs boson or dark matter
  - Detect these particles in "particle detectors" which surround the "collisions"
- The production of "new particles" is rare, so the more collisions we have the better
- The LHC ran successfully in 2011 and 2012. In 2015 and 2016 it restarted at even higher energies and lots of new results will be explained this week at the ICHEP conference.

The LHC Accelerator complex



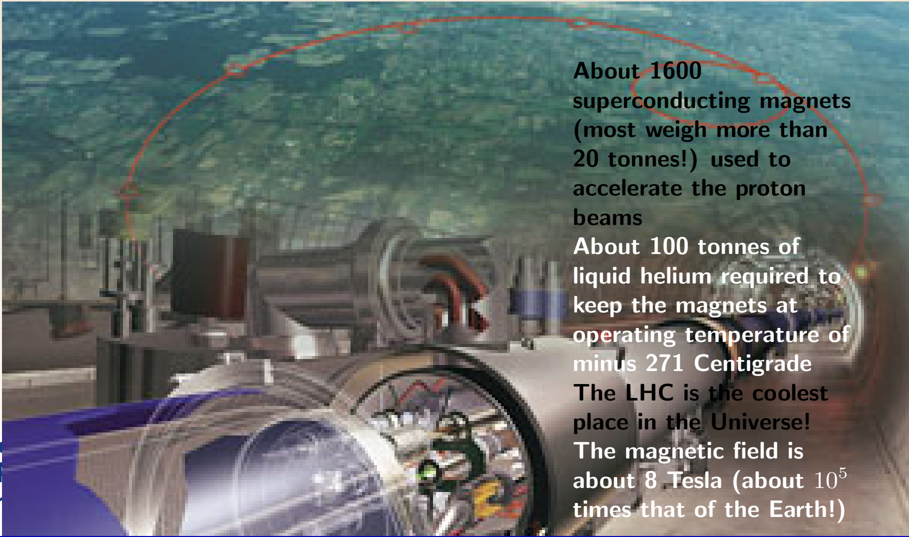
A circular, 27 km tunnel, roughly 100 m underground

Two proton beams, one clockwise, one anti-clockwise

Four collision points

Up to a billion collisions per second!!

The LHC Accelerator complex



About 1600 superconducting magnets (most weigh more than 20 tonnes!) used to accelerate the proton beams

About 100 tonnes of liquid helium required to keep the magnets at operating temperature of minus 271 Centigrade

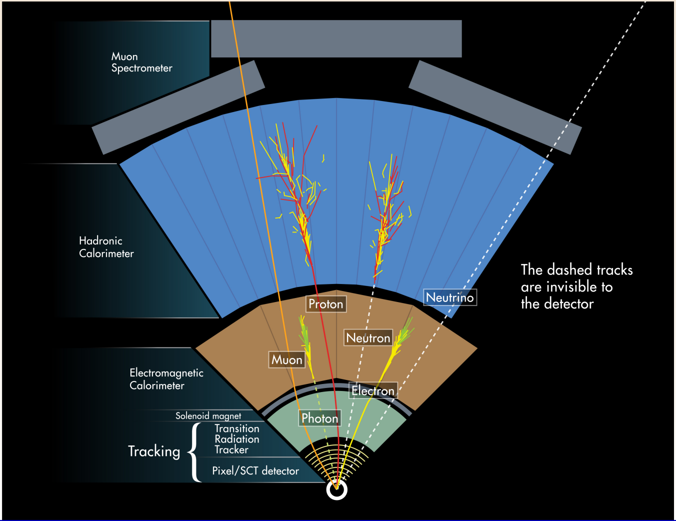
The LHC is the coolest place in the Universe!

The magnetic field is about 8 Tesla (about 10^5 times that of the Earth!)

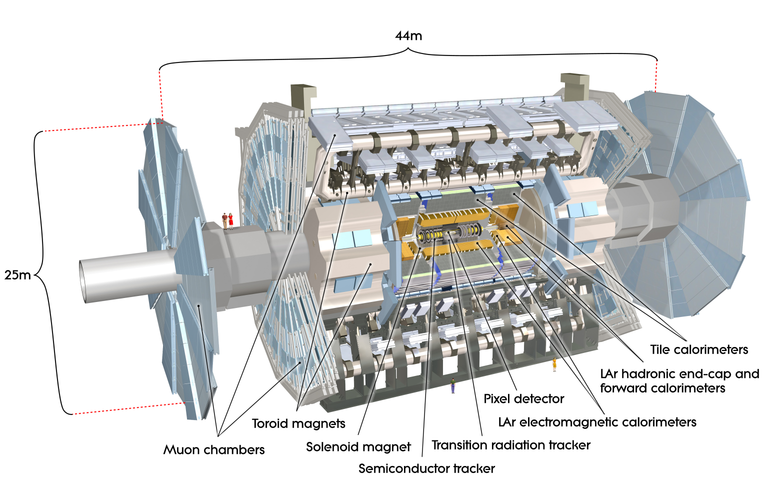
The LHC beam and Energy

- Each proton beam is made of bunches of protons. Up to 2808 bunches with 10^{11} protons each. Energy of each proton 7000 GeV.
- Note: One GeV = about 1.6×10^{-10} Joules and 1 J = 1 Watt second.
- Energy per beam $= 2808 \times 10^{11} \times 7000$ GeV $= 2808 \times 10^{11} \times 7000 \times 1.6 \times 10^{-10}$J = 362 MJ
- Equivalent to 87 Kilograms of TNT, which has about 10^{16} times as many protons as the LHC beam!
- Equivalent to the Kinetic Energy of a small aircraft carrier moving at 40 km per hour!
- The energy in the magnets is about 10^{10} Joules. (A typical house in Europe consumes about 2000 Joules per second on average).

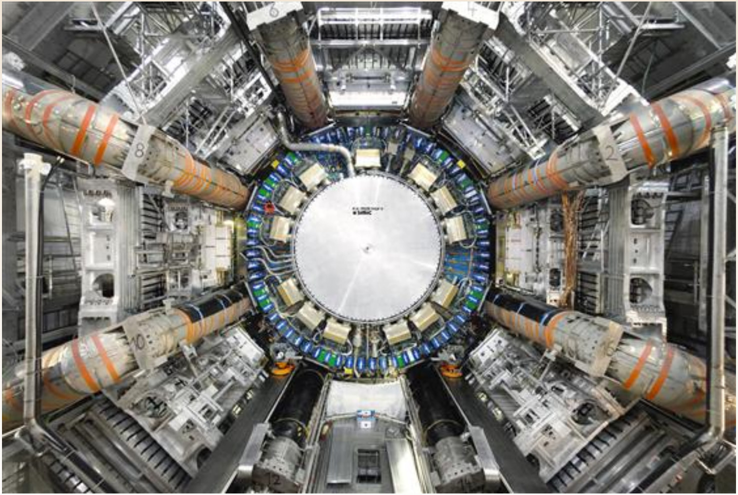
A Particle Detector



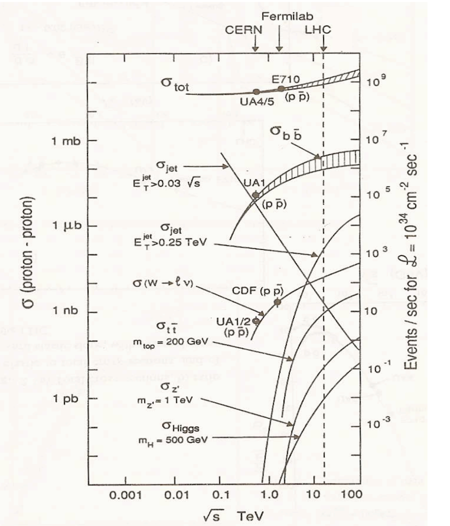
A Particle Detector



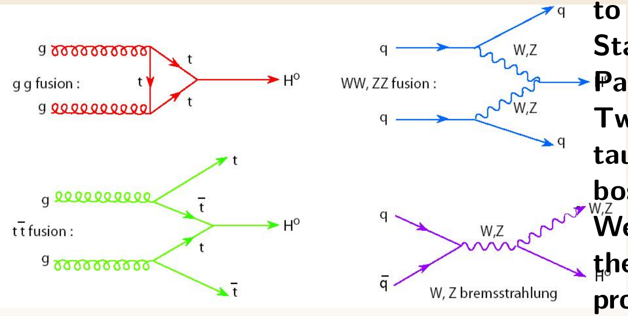
Particle Detection in ATLAS



Processes and Production Rates at the LHC



Producing Higgs Bosons with the LHC



Once produced, the Higgs decays to lighter Standard Model Particles

Two photons, two tau leptons, two Z bosons,...

We then measure these decay products and "reconstruct" the Higgs!

Many ideas to be explored.....

- Theoretical physicists have come up with many ideas for physics beyond the Standard Model
- These predict new particles and phenomena for the LHC:
- Supersymmetry predicts a new particle for every Standard Model particle eg a super-electron (or selectron).
- The LHC may discover extra dimensions. These are predicted by string theory and could lead to the discovery of tiny black holes!
- So far, these ideas have not been discovered at the LHC, so limits on such models have been obtained!