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Unraveling the mysteries of matter at the CERN Large Hadron Collider (LHC)

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Unravelling the Mysteries of Matter with the CERN Large Hadron Collider

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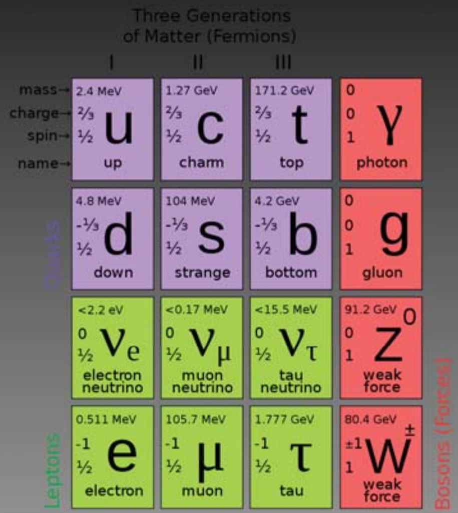
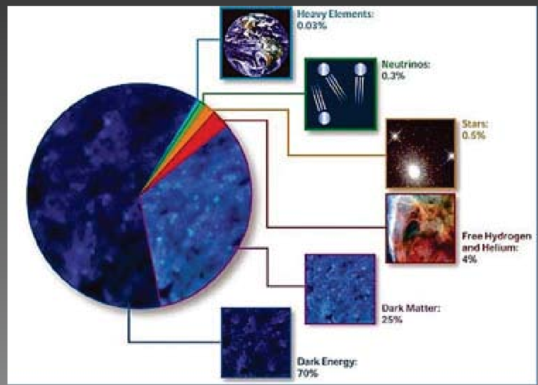
The International Center for Theoretical Physics

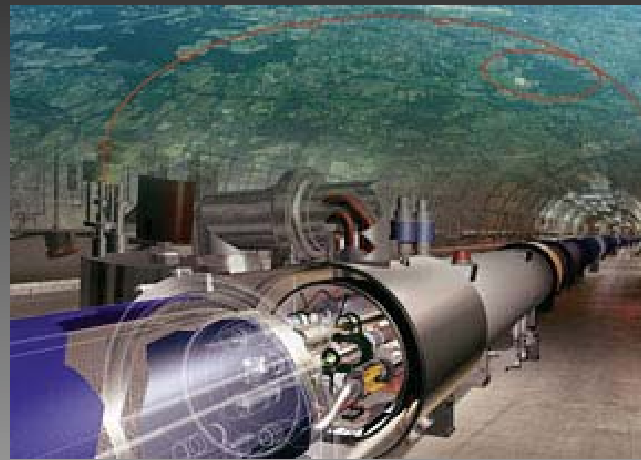
Particles, the Universe and the LHC



All known elementary particles



Energy of the Universe



Large Hadron Collider

This talk is about why and what the LHC is for.

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, ATOMIC, classification

This strongly suggests an underlying, simpler structure

Particles, Matter and the Universe

All the matter ever studied on Earth falls into the period table

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

The planets seem to be made of atoms

So, too, do the stars

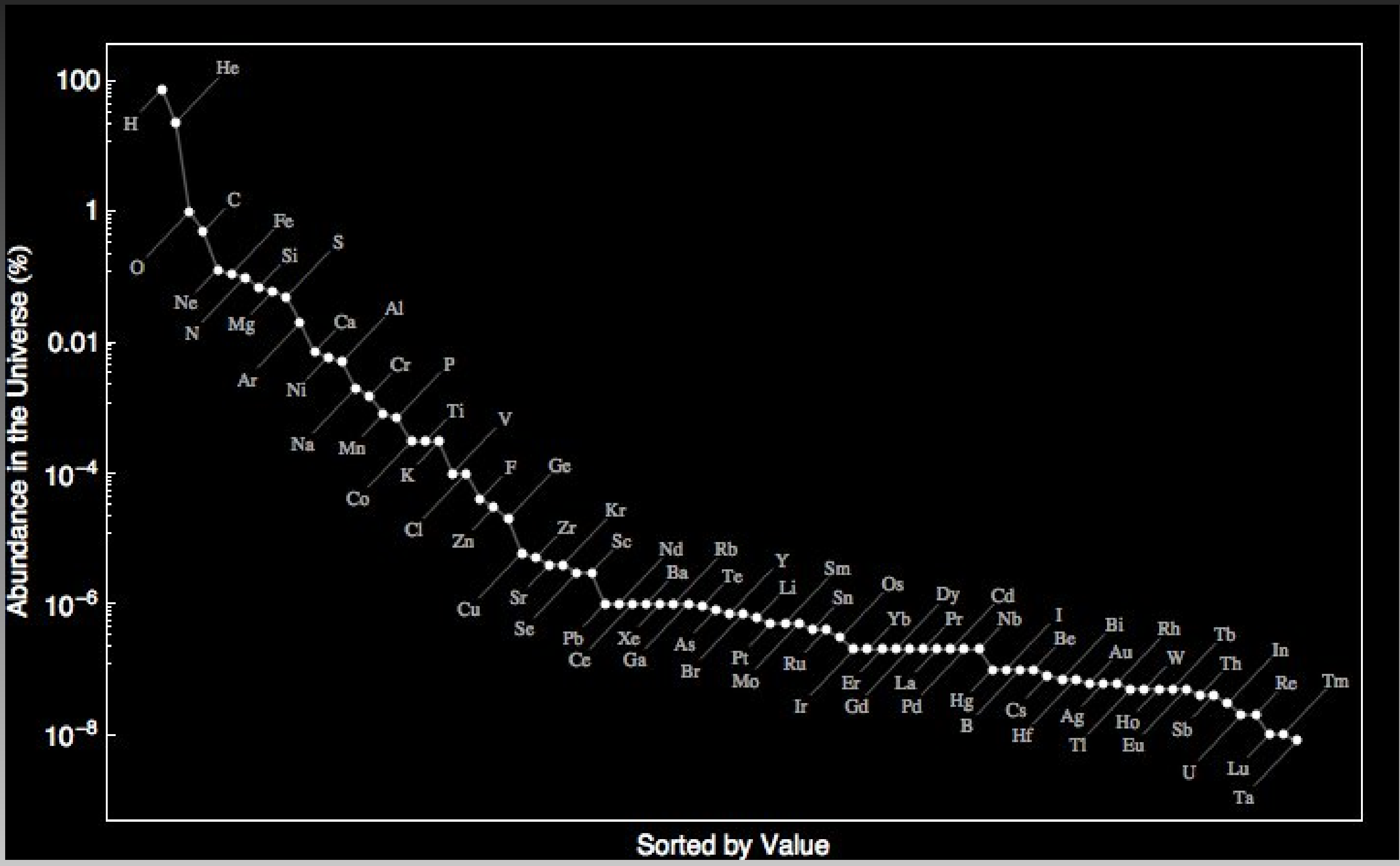
The galaxy contains hundreds of billions (i.e. $\sim 10^{11}$) of stars which are basically alike: so much of the galaxy is also be made of atoms.

Moreover, all of the galaxies (and there are $\sim 10^{11}$ of them) 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 emits negatively charged particles. This showed that atoms contained "electrons".

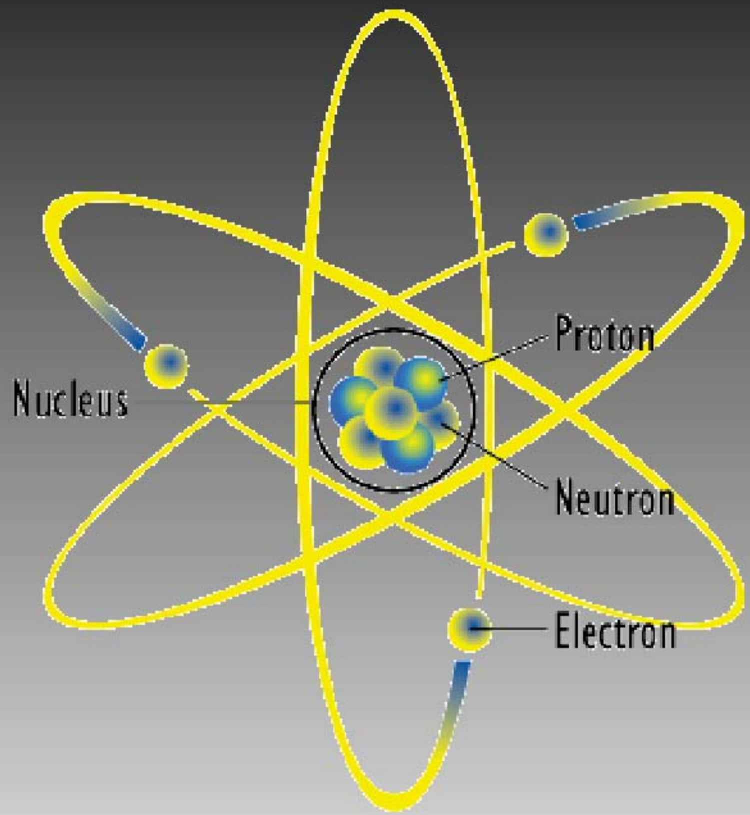
α-particles (now known to be Helium nuclei) were discovered as radiation emitted by various radioactive elements and compounds

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.

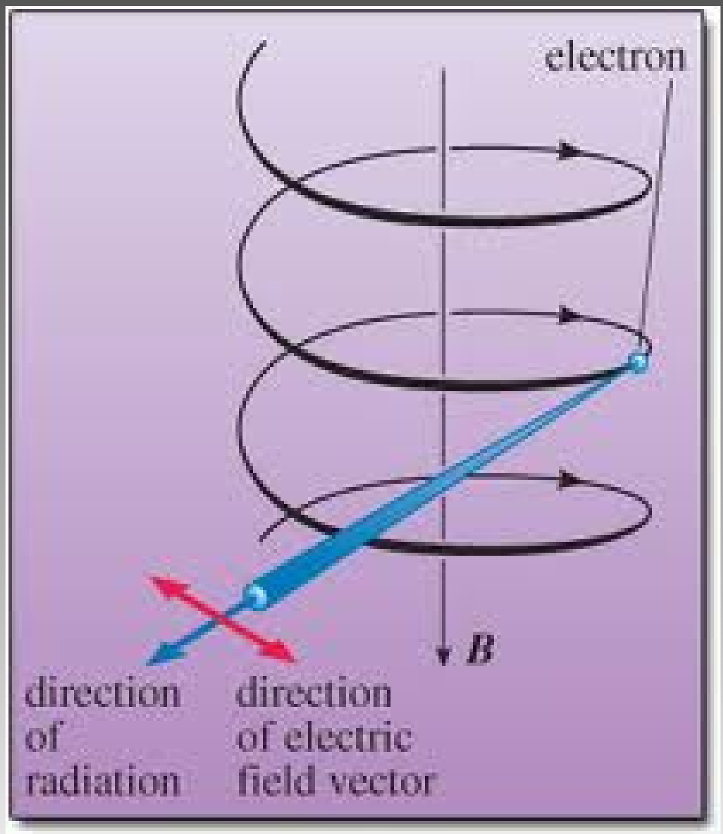
Shortly after this, the Bohr model of the atom (protons and neutrons in a dense nucleus, surrounded by a cloud of electrons) was "established".

The Atom



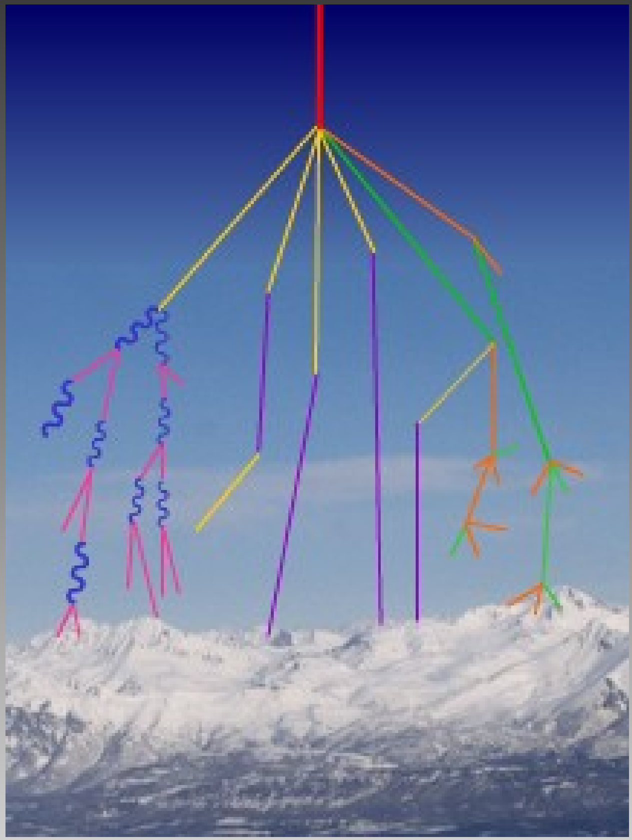
- The atom consists of a very dense nucleus surrounded by a "cloud of electrons"
- Atoms have sizes of order 10^{-11} to 10^{-10} m.
- Protons are positively charged. Neutrons are neutral.
- Electrons have equal and opposite charge to protons and are much lighter than them ($m_e \sim m_p/2000$)
- **But are atoms fundamental? Are these the only particles?**

Charged particles in Magnetic Fields



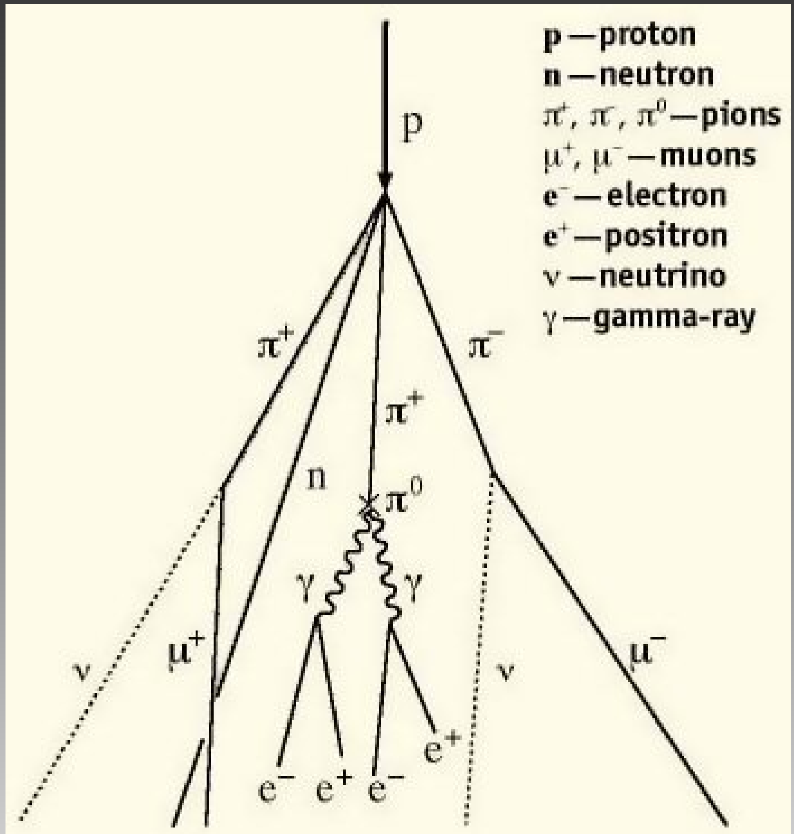
- Electric current is just moving charge
- You can create a magnetic field by coiling a current carrying wire
- By the same token, a magnetic field exerts a force on charged particles
- So, strong magnetic fields can be used to accelerate charged particles to high energies!
- This is how particle accelerators work: the most powerful (superconducting) magnets in the world are

The galaxy is a particle accelerator!



- The galaxy has a strong magnetic field and charged particles!
- A particle is accelerated to high energy 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 accelerator!

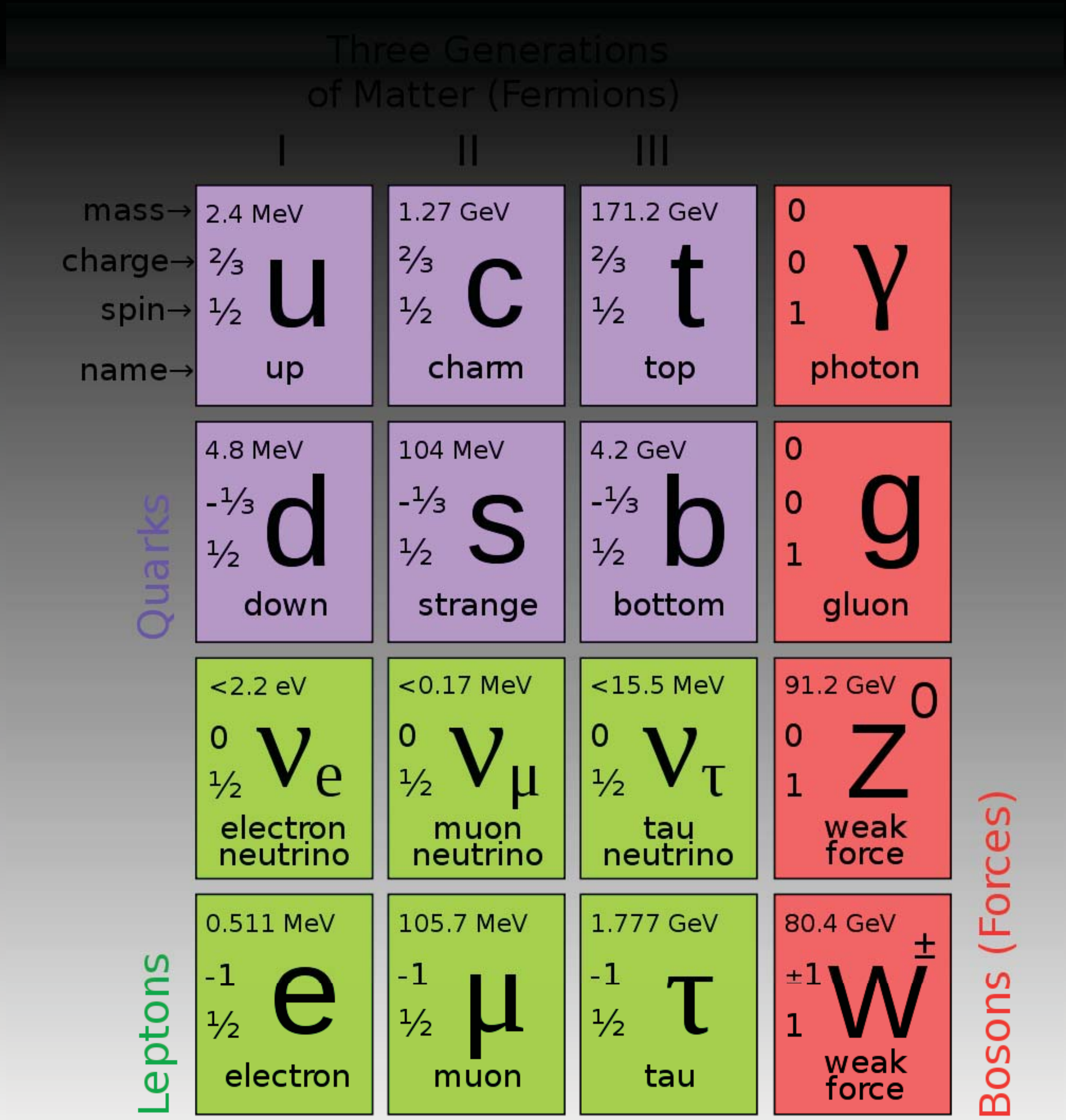


- This is a particular example when the original particle is a proton
- This example produces pions, photons, muons, electrons and neutrinos!
- A muon from a cosmic ray like this just passed through your body!
- In fact, muons and pions were discovered in cosmic rays

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
- We also know that protons and neutrons have many 'cousins' which are also made of quarks. 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 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?

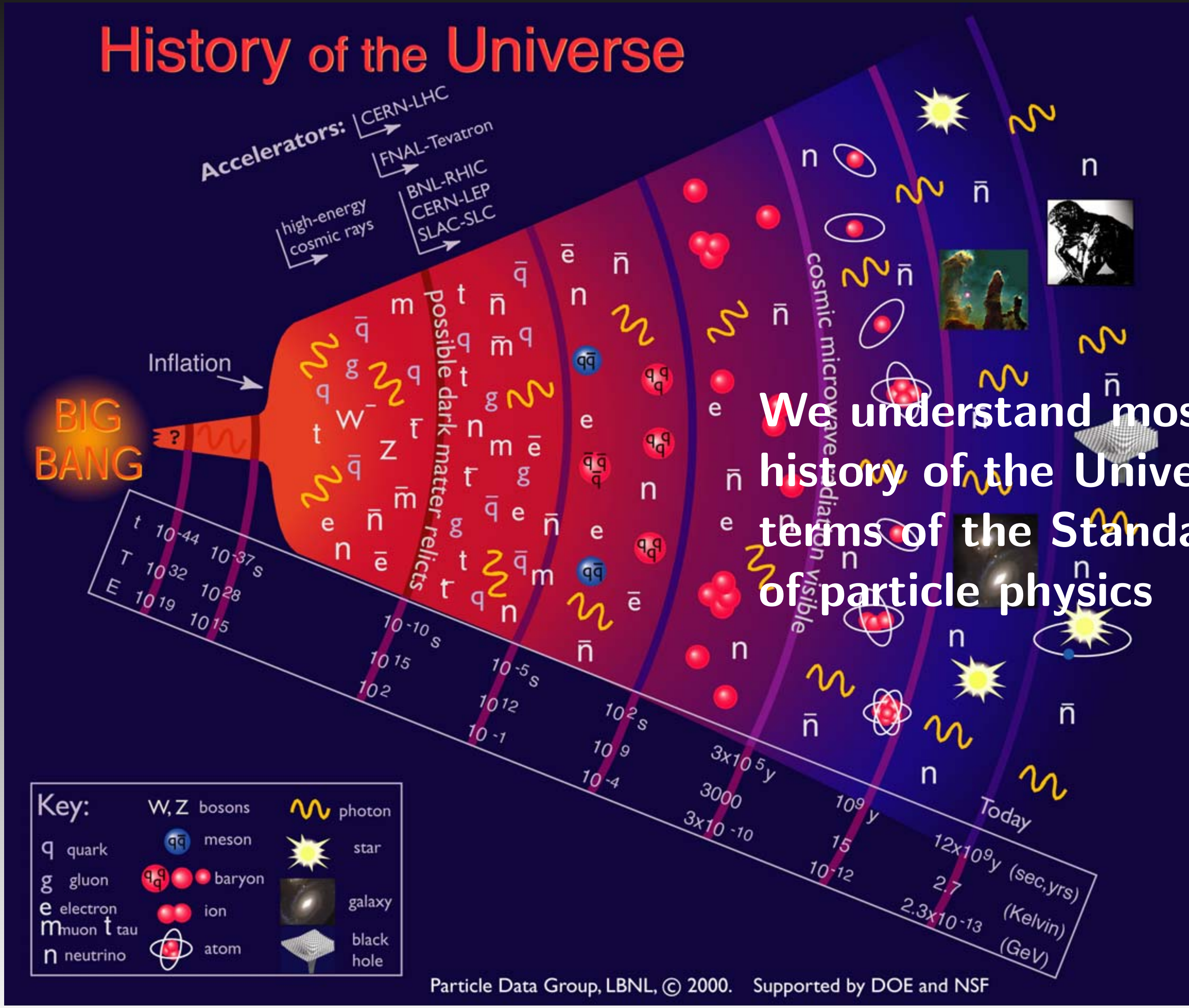
Mass and The Higgs Boson

- There is one particle predicted by the Standard Model which has not yet been discovered
- This is the so-called Higgs boson, after Peter Higgs who made significant contributions to this part of the Standard Model
- 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 is 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

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"!
- There are some plausible arguments that particles made of dark matter could be produced directly at the LHC (more on this later)

Cosmic History

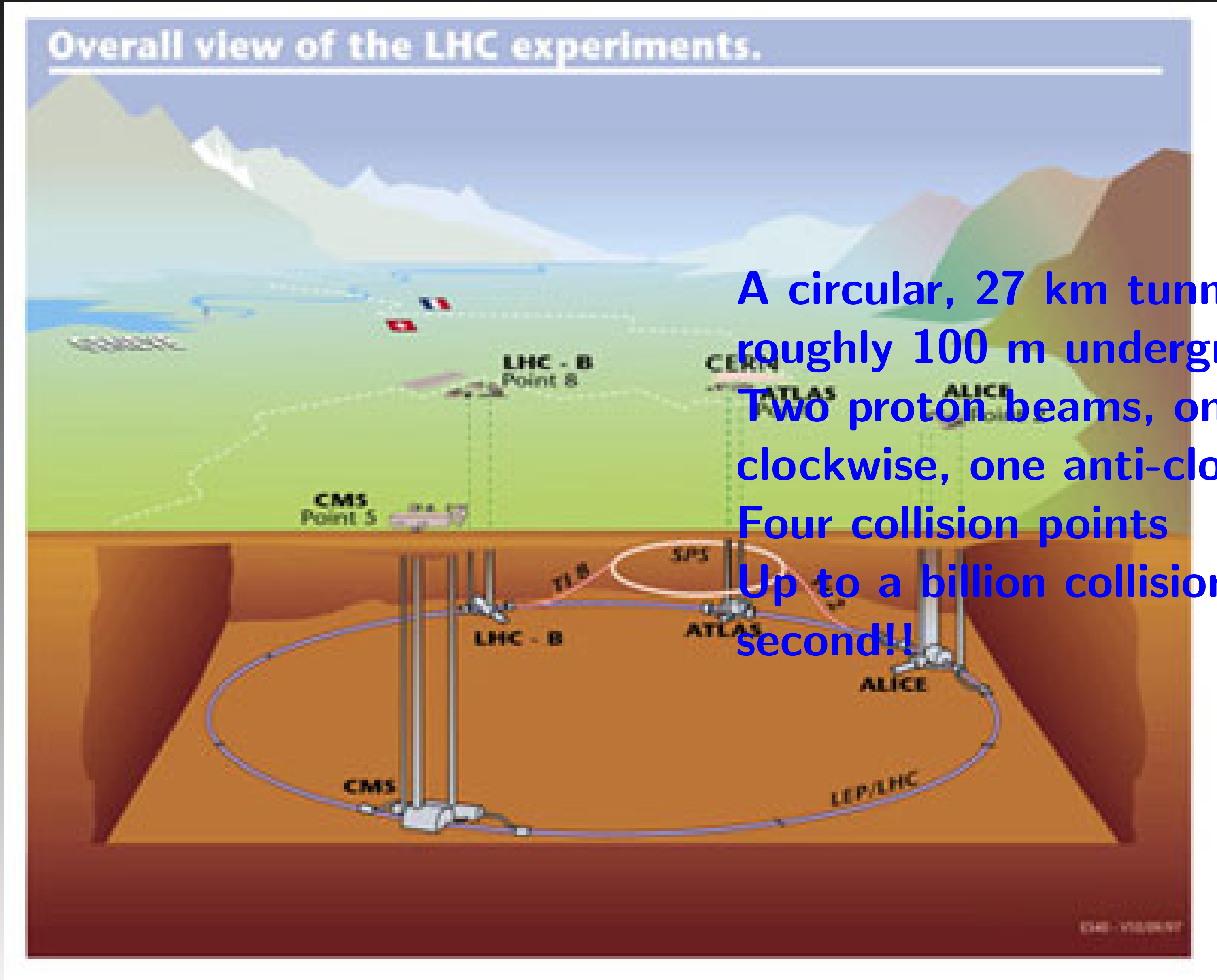


We understand most of the history of the Universe in terms of the Standard Model of particle physics

The Large Hadron Collider

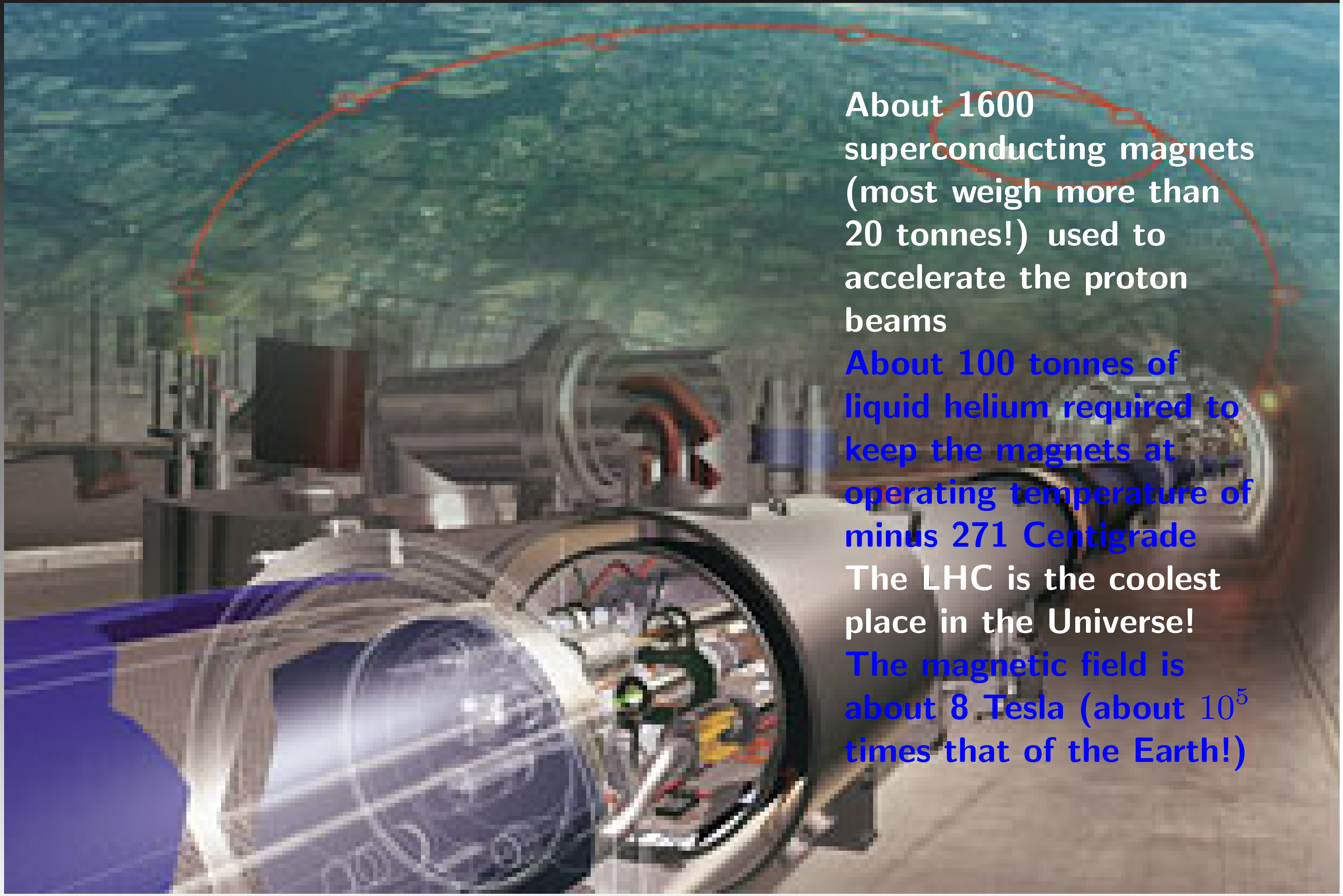
- The basic idea is to :
  - accelerate beams of protons to as high energy as possible
  - smash them into each other as often as possible
  - Create new particles like the Higgs boson or dark matter
  - Detect these particles in "particle detectors" which surround the "collisions"
- The LHC has started running and is working extremely well
- The production of "new particles" is rare, so the more collisions we have the better
- This year will be a very exciting one with a huge amount of data generated and analysed!

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.
- 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

The ATLAS Detector

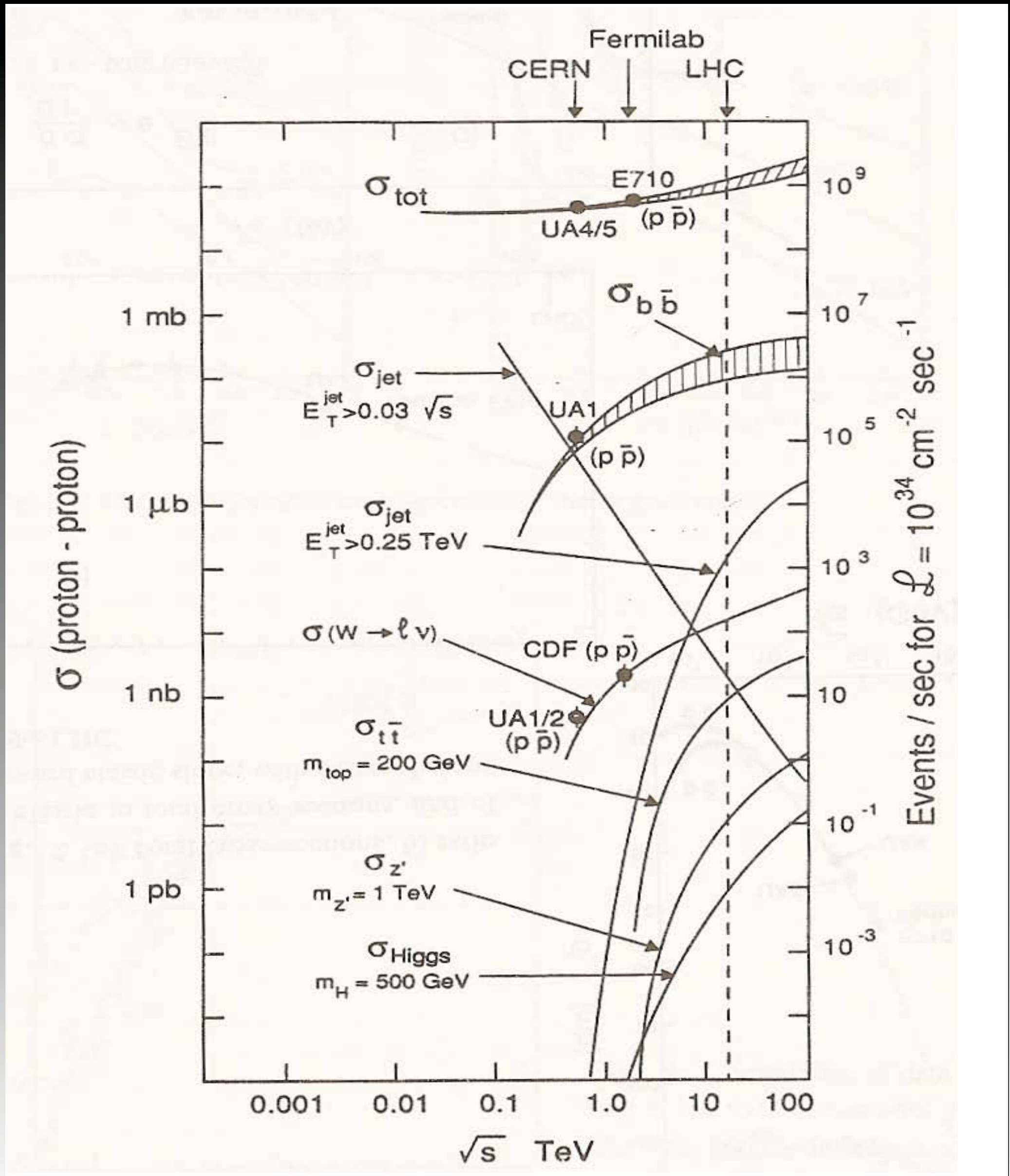
A Particle Detector

ATLAS animation

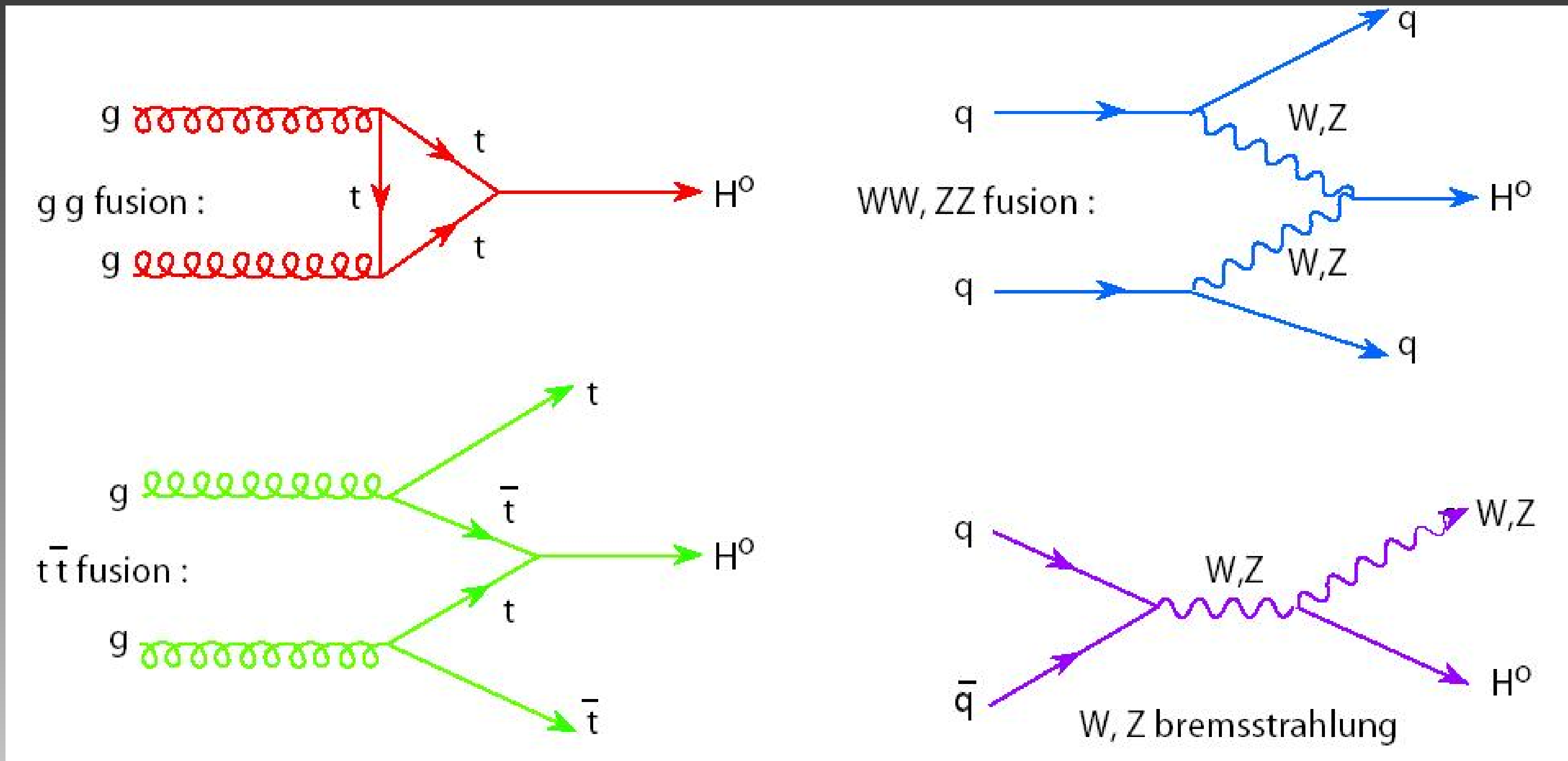
Particle Detection in ATLAS

Particle Detection in ATLAS

Processes and Production Rates at the LHC



Producing Higgs Bosons with 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!
- This year, if these ideas are not discovered at the LHC, very strong constraints on them will be obtained!

Conclusions

- Atomic Matter can be very simply classified and "explained" by a few "elementary" particles and the Standard Model of particle physics
- Particle Accelerators and colliders can be used to further unravel the mysteries of matter
- Two of these mysteries are the existence of the Higgs boson and the nature of dark matter
- The Large Hadron Collider will help us to solve these mysteries, perhaps by directly producing the Higgs and/or dark matter!
- We will already have strong results on these these and other mysteries this year!

THANK YOU!