Tony Doyle's talk at CERN

"You've just missed the July revolution, which was the discovery of the Higgs or something like it.

In the next hour I'm going to try to outline some of the things on the theoretical side, talk about the machines, the LHC, the experiments and Glasgow University's role.

We have this 27 kilometre ring, 100 metres underground. We're entering a new era in fundamental science since the LHC started up, a major turning point for all the things we've been doing in particle physics. We've been building up to this for the last 20 years.

Around the ring are distributed four major experiments and I'm going to talk mainly about ATLAS, the general purpose detector we work on at Glasgow and Edinburgh. Then there's CMS, our partner experiment on the other side of the ring. Then there are a couple of other experiments - LHCb, which we work on and ALICE which looks at heavy ion physics. As well as colliding protons the LHC can also collide heavy ions. There are interesting things you can do there to look at quark-gluon plasma.

The starting point is this ruler marked in centimetres with a logarithmic scale. So we can look at the universe on the scale of 10^{28} centimetres right down to the very smallest scales we can conceive of which take us back to the Big Bang. The scales we're looking at here at the LHC around 10^{-16} centimetres.

Einstein and relativity is looking at what happens on the large scale, when gravity dominates all the forces. It's about what happens when the earth goes round the sun; it's about the radius of the galaxies and how galactic clusters spin and form around each other within the universe.

That's one end of the spectrum and lots of experiments are looking at the universe in more and more detail - things like ALMA, AMS, VLT - the very large telescope.

At the other end of the spectrum you're looking more deeply at the constituent elements of matter - the molecules and atoms. Within the atom there's the nucleus surrounding by the electrons. Within the nucleus are protons and neutrons. Within them are these things called quarks - and those are what we eventually collide together at the LHC.

So the LHC you can conceive of as being a super microscope. It's a microscope that can look down to distances of 10^{-16} centimetres - incredibly small. We're trying to study physics at the first moments after the Big Bang - about a billionth of second after. We're trying to understand what we see in terms of the Standard Model of particle physics.

So we have quarks and leptons and the strange thing is that both of these replicate themselves three times. Nobody knows why, but you get slightly heavier versions of the electron called the muon and the tau and you get slightly heavier versions of the up and down quarks, called charm and strangeness, top and bottom.

Those are the matter particles and they're held together by the forces. We have the photon, which carries the electromagnetic force, the gluon which holds the nucleus together and the Z and W particles which are massive versions of the photon. The reason they are massive is intimately tied in with the Higgs boson. The mechanism associated with the Higgs endows the Z and W with mass and the photon has no mass. That's why the electromagnetic force is something you're less aware of than the weak force because it takes a bit of energy to create the matter associated with the mass of the Z and the W.

So here are those four forces - the electromagnetic force, the strong force, the weak force and gravitation. The problem with gravitation though is that it is so very weak that we don't know how to set up a particle theory of gravitation. That has held up progress in theory for many years. It's the kind of thing Einstein was working on but never really reached a solution.

So there are these four fundamental forces described by something called quantum field theories - except for gravitation where we don't really know exactly what's going on. And the Higgs field, this ghost in the machine, addresses the problem of mass - specifically it addresses the problem that these Z and W particles are heavier than the photon. It may also address the reasons these matter particles have different masses and what their relative couplings are.

The LHC machine is a time-machine. $E=mc^2$ tells us there's a relationship between mass and energy, so the reason we want to go to very large energies is that we want to create new massive particles. But in going to higher energies you're also going back in time, to just after the Big Bang. So the energies of 100 GeV which correspond to the W and Z particles - which we create all the time at the LHC - correspond to about one ten billionth of a second after the Big Bang.

There's still a long way to go back, but given the universe has been expanding for 13.7 billion years and we humans have somehow got right back to a billionth of a second after that initial event that's quite an inspiring thing that we've done.

Plays vid of LHC being built - **can we get this from Tony?**

So the point of this part is that the LHC machine is incredibly precise. The whole 27 kilometre ring is aligned to better than a tenth of a millimetre. In order to get up to the very high energies we need to use superfluid helium, which goes down to very low temperatures - the lowest temperatures in the universe in fact.

This is back in Glasgow showing that you have to analyse all the output from the experiment and we do this on something called the Computing Grid - which is distributed all over the world. So this picture shows how all these sites around Europe are all connected together. That's one part of what we work on. The other part is the central tracking detector. This allows you to look with precisions of a few microns at the very heart of these events in the LHC.

Basically the experiments are like cameras taking event pictures. But the camera has a shutter speed of one twenty millionth of a second. So you can see the precision of the things that are done. The ATLAS detector is 14 metres long and 20 metres high but it has to be incredibly precise. You can see the scale of the enterprise. For example on the ATLAS there are 3000 experimentalists working on it.

So that's a bit of background. We're trying to look into these particles and here I've represented them in a diagram with mass proportional to area. **Can we get this image?** So in this Standard Model we have all these particles. We've got the neutrinos and electrons and all the leptons up here. Then we have the quarks. As you can see there's one big one appropriately called the top quark. Then there's the photons and gluons which are the force-carriers, and also the W and Z.

The big thing missing was this Higgs particle which we believe we've discovered, or something like it, last month. So this is Peter Higgs at Edinburgh University. He came to visit the experiments in 2008.

So that's a bit about the theory. Now I want to give you some background to CERN. It's a large enterprise with 20 member states. The big four are Germany, UK, France and Italy, which make about 60% of the contributions that fund CERN. There about 2500 staff, only about 80 of whom are permanent research physicists. But there are a huge number of users - around 10,000, from over 500 universities and institutes.

There are more than 50 experiments, most quite small scale, but four big experiments. The way it works is that CERN provides the accelerator and infrastructure, which operates 24/7 with a three-month accelerator winter shutdown to do work on it.

The users help in the design, construction, operation and analysis of the data from the experiments. That's what we do. The four big experimental collaborations range in size from 600 on LHCb to 3000 physicists on ATLAS. We have an organisational structure with a spokesperson, a technical coordinator, project leaders for the components. It's like a big enterprise in industry although we're all academics and researchers.

We contribute to the detector and members of the collaboration can analyse any of the data that are produced and papers are approved by and carry the names of the whole collaboration.

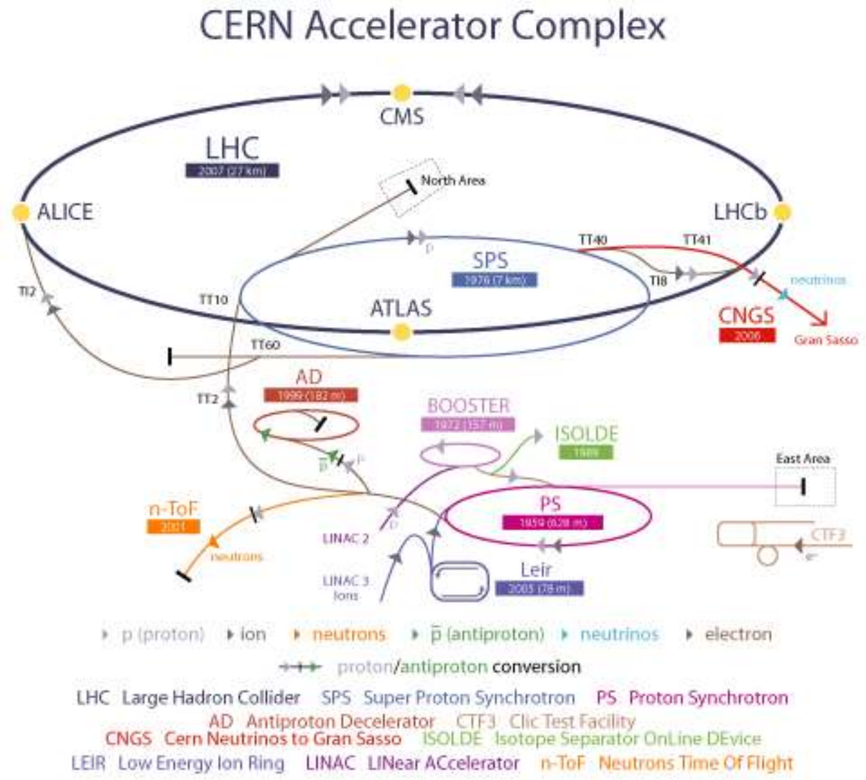
In terms of the machine the LHC is a synchrotron, a colliding machine. What happens there is that you accelerate the particles using an oscillating electric field. So you surf this radio frequency electric field with a high strength. The charged particles are bent round by a magnetic field, so they come back round in a circle and you collide at various points.

The heritage here is that the first electron synchrotron in Europe was constructed in Glasgow in the 1950s. Here you can see the scale, which is smaller than the things we're using now. The principle is basically the same, except the energy is a bit different.

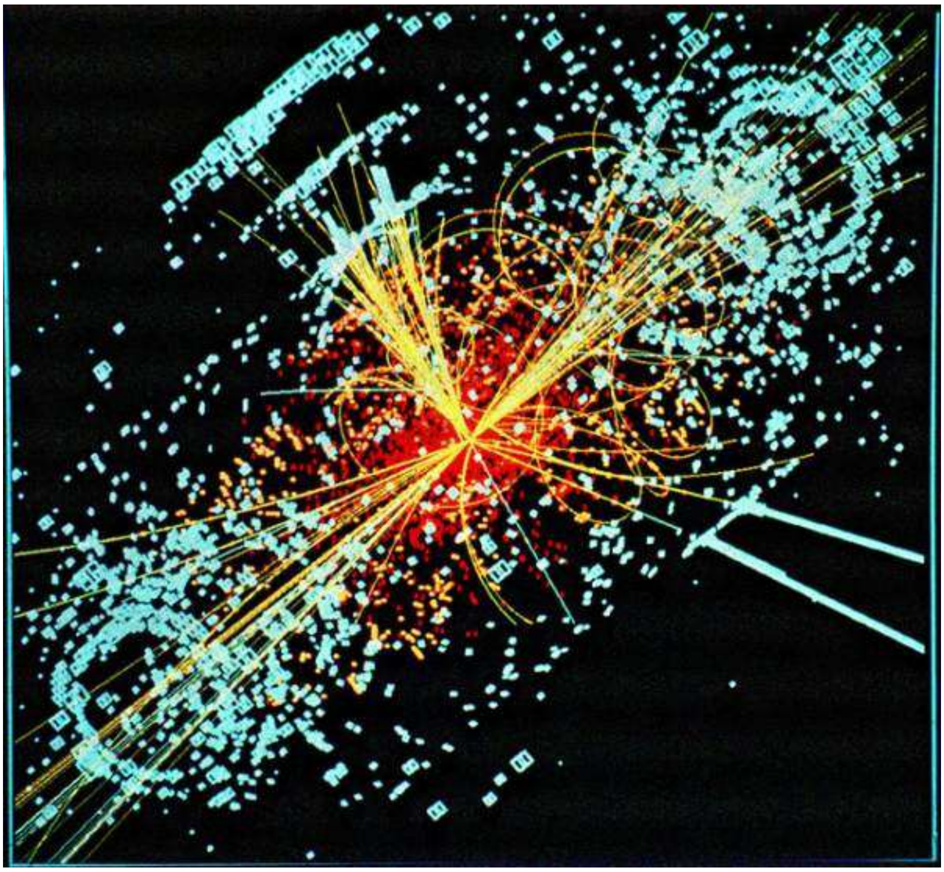
The context for Glasgow is that we want to contribute to two fundamental things, one is this discovery of the Higgs boson and measurements associated with it and then look into the nature of the matter-antimatter asymmetry in the universe, which is what the LHCb experiment does. We've been working on this for 20 years, with developments in analysis, detectors and the computing grid. So I said that the LHC is a synchrotron and what you have to do is keep these beams going round and round in orbit.

As well as the electric field and the magnetic field to send the beams round in a circle you also have to make sure these fields are contained, which you do with quadrupole magnets which focus and defocus the spread of the particles as they go round.

You're continuously accelerating the particles from a standing start. I'm going to illustrate that with this picture of the particle accelerator chain at CERN. We start off in something called the LINAC, then there's a booster, then the proton-synchrotron - and this is increasing in energy as you go up. Then into this super proton synchrotron and then finally into the Large Hadron Collider.



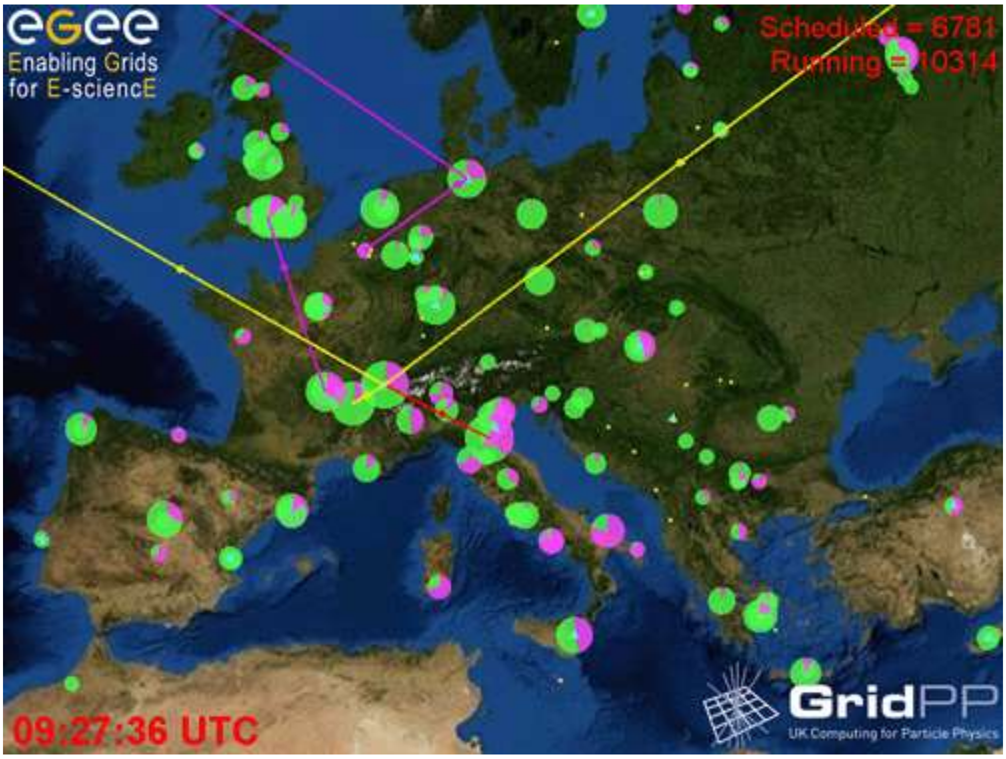
Then at these collision points where you squeeze the beams down to microns in size, you get this sort of effect, with collisions happening once every 20 millionths of a second. And you can take a picture of the ones that are interesting.



So this is the ATLAS detector taking a picture of what's going on in the LHC.

It has taken us ten years from a completely empty hall to the ATLAS experiment, a complex arrangement of various detectors working outwards and looking at the different particles which are given off.

To analyse the data we use this think called the Grid. This has hundreds of thousands of CPUs connected through the internet and distributing petabytes of data.



The grid is used not only for particle physics nowadays, but also in lots of other areas, such as ..... and ....

Here is a snapshot of what's going on in the Grid, with the various sites shown by circles and the movement of data represented by the lines. This is how you analyse huge amounts of data in a reasonably short timescale. We can turn round our analysis typically within a week, which is impressive compared to what we used to be able to do.

So a major LHC motivation was to look for the Higgs particle. We're colliding protons with protons. Within those protons there are quarks. A small fraction of the time what may happen in proton-proton collisions is that quarks radiate W particles, and those create a Higgs particle which can decay to two Zs for example. So this is one event - I won't say it's typical; it's a one in a billion event - where the Higgs was created and decayed into two Z particles which themselves almost instantaneously decayed into two muons on this side - so here's two muons going into the muon chambers - and two muons on this side. So that's an example of what you see.

We sort of knew where we had to look. It's like looking for a needle in a haystack but we knew there were various places where the Higgs might turn up. So it could be at high mass, around 400-500 GeV. It could be at middling mass, about 160 GeV. Or it could be at low mass. And you can see that at low mass there are lots of different decay modes which become relevant.

In fact it's the low mass region where we found this thing. So I don't want to go into any details of what happens but here are histograms of the analysis. This is the kind of thing that you do. You set up histograms of mass distributions and you look for peaks in this mass distribution. So the question is can anybody spot a peak in any of these mass distributions?

Silence.

It's really pressing it to say "I've seen a peak in that distribution and it's there." This was the status back in December. Statistically we didn't have sufficient evidence to say whether or not we had observed the Higgs, but we were looking in lots of different channels.

So what happened in July was we produced these results. So now it becomes a bit more convincing. Here in this channel you can see that here's the background and here's a signal. So that's how the signal was discovered. So July was a great month. If you combined all the data, the ATLAS experiment alone produced six sigma evidence that this was not a background fluctuation that was observed at this mass of 126 GeV.

So there's a publication about to appear about this. But it's not just about the Higgs. There are potentially other things which might occur. One of the big questions in particle physics is why does the Higgs have a mass of 126GeV? In quantum field theory the mass could go off to the Planck scale which is way off what we could measure. So you need some convention to fix the Higgs mass. One of the most used is to introduce something called supersymmetry, in which each of the matter and force particles has a partner. By doing that you can get some cancellations which regulate the Higgs mass.

It produces lots and lots of particles so you can search for these things. For example all these SUSY particles get produced and in principle by measuring all the other particles you can look for something called "missing transverse energy". This would correspond to the lightest one of the supersymmetric particles escaping detection which could be a candidate for the dark matter in the Universe.

Another way in which nature might reveal itself is through extra dimensions. So ordinarily we just have 3-D space but there are other pictures where you can extend into minutely wrapped up dimensions where all these forces are sort of working in this bubbling little mini-universe and if we probe a bit harder in energy we might be able to see the effects of these extra dimensions. One of the ways that could happen, which has generated some interest is we might be able to produce black holes with the LHC.

Gravity which we see as weak might be strong within these tied-up dimensions and that would produce characteristic signatures in the detector. So you'd get things like this, massive decays of many objects going into every area of the experiment.

So most of the people generating all this physics are PhD students and young researchers and we think there'll be many exciting years ahead. We've already discovered the Higgs at some level. We don't know what its properties are. That's one thing we're going to be working on. We'll also be looking at things like supersymmetry, extra dimensions, the matter-antimatter asymmetry in the universe. That's going to be a major area of study for the next 10-15 years.

Any questions?"

Yes, loads.