The Royal Society of Edinburgh

The Higgs boson: what, why, how?

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Questions, questions, questions…

In 1964, Peter Higgs came up with an idea which turned the world of physics upside down – a theory which helped to explain how the universe came into being and why it does not fall apart. The critical component of Higgs' revolutionary theory was a mysterious sub-atomic particle called the "Higgs boson," but 45 years later, no-one has been able to prove it exists.

At the RSE in April 2009, Professor Higgs was joined by Professor Edward Witten and Professor David Saxon to discuss the missing piece in physics' jigsaw – and the Large Hadron Collider (LHC) at CERN which is seeking to find it. The panel discussion which ensued was chaired by Sir Michael Atiyah, OM, FRS, Past President of the RSE.

Professor Higgs described how the concept was born, Professor Witten (Institute for Advanced Study and European Organisation for Nuclear Research) discussed the modern theory of the boson and what's being tested at CERN, and Professor David Saxon (University of Glasgow) outlined the experimental challenges.

The focus of the panel discussion was "what, why and how?" But as the evening developed, it seemed more a question of "when?"

Introduction

RSE President Lord Wilson of Tillyorn introduced the discussion by saying it was part of a series of special events, jointly organised by the RSE and the International Centre for Mathematical Studies, to celebrate the 80th birthday of his predecessor, Sir Michael Atiyah. Describing himself as a mathematician who had become "a pseudo physicist" later in life, Sir Michael then explained that the focus of the evening was to ask "what's going on" with the Higgs boson, posing the question to a panel who between them covered the whole spectrum of physics. He said that he also looked forward to hearing what is happening at CERN – or what *isn't* happening at CERN – as scientists investigate one of the great 'mysteries' of fundamental physics…

Professor Peter Higgs – *The historical background (what?)*

Invited by Sir Michael to talk about 'where it all started,' Professor Higgs modestly suggested that he had only been invited because his work "has interesting mathematical connections" with the topic. He then said the idea of the Higgs boson arose from thinking about "spontaneous breaking of a symmetry" – which he said was about "the consequences of having a ground state of a quantum system where the underlying dynamics respect some symmetry under a group of transformations."

"If the ground state of the quantum system is asymmetric, then that has an interesting impact on the behaviour of the states of the system," said Higgs. According to quantum theory, he continued, electromagnetic and other fields "come in lumps" or packets of energy which behave like particles – or photons. "Such systems can have an asymmetric ground state or a vacuum," he continued, "and when the ground state is asymmetric, then the asymmetry spreads into the excitations which are the particle states and you have a broken symmetry."

Before 1960, the concept of spontaneous symmetry breaking was originally developed in condensed matter physics – e.g. ferromagnets and different kinds of crystal lattice in which matter condenses in various ways, "breaking the continuous translational symmetry that's in the underlying dynamics."

No-one took these theories very seriously, Higgs said, until the theory of superconductivity was developed by Bardeen, Cooper and Schrieffer in 1957, describing how the charged particles in a superconductor move about like a superfluid, without friction. In 1960, Yoichiro Nambu expressed this in the language of quantum field theory, and Higgs explained that his role was to "fill in a gap" in the theory.

Another key figure was Jeffrey Goldstone, who expressed the theory of symmetry breaking in more "easy-to-understand" terms, including a model often referred to as the "wine bottle" potential which helps to visualise the various phenomena. "What happens is that the ground state of the system, which classically is just the state of lowest possible energy, is where the value of the field sits – somewhere in the bottom of the wine bottle, instead of on the axis which would be the symmetry point," Higgs explained.

The trouble, said Higgs, was that in Goldstone's and Nambu's models, there were particle excitations which had a mass of zero. These were easy to understand in Goldstone's language because they corresponded to excitations of the field around the bottom of the trough where you don't need to put in any energy to get it to go in another direction in that two-dimensional space, and the Goldstone Theorem was formulated "as a necessary consequence of trying to combine a relativistically invariant quantum field theory with spontaneous symmetry breaking."

Higgs then explained that the flaw in Goldstone's axioms was the insistence on manifest Lorentz invariance, and that there was an exception well known to that rule of transformations – the class of gauge theories. "The potentials in the Maxwell theory are ill-defined up to what is called the gauge transformation," he continued, "and that is the feature which drives a hole through the axioms in the Goldstone Theorem."

According to Higgs, Philip Anderson said that if you put together the so called Yang–Mills theory (a generalisation of Maxwell's theory) and a system with spontaneous symmetry breaking, their apparent difficulties would cancel one another out. "But he failed to say why there was anything wrong with that theorem," Higgs then explained.

Higgs and other physicists then studied what actually happens when you combine a Maxwell type of theory with spontaneous symmetry breaking, and all independently showed that you give mass to the quanta of the Maxwell type of field as a result of spontaneous symmetry breaking.

"So finally, where's the Higgs boson?" asked Higgs. "There is at least one system in which the Higgs type of excitation has already been detected, and that's in a superconductor."

And that is why there's something for the LHC to look for…

Edward Witten – The theory (why?)

Edward Witten put things in context by saying that particle physics is a modern name for something much older – the quest to understand the laws of nature. In the 20th Century, Witten continued, physicists discovered that subatomic particles play a key role in this quest, and there are "crucial parts of the puzzle" that we can only learn by using an accelerator such as the Large Hadron Collider.

Witten then described how particles are accelerated and how their orbits are bent into circles by powerful magnets. Then, as they go round the ring – two miles across – they collide. The accelerator has to be large, he explained, and use very powerful magnets, to ensure that the particles reach very high speeds so that when they collide, they produce a lot of energy. When Witten was a graduate student, the highest energy for two colliding protons was about 30 times mc^2, but today the LHC studies protons at 2,000 times mc^2. When you go to higher energies, collisions are rarer, said Witten, so the beams have to be more intense. The events also become more complicated, so you need much better particle detectors, which produce vast amounts of data.

Many fundamental questions have already been answered, said Witten, including what holds the nucleus together, but equally big questions still "tantalise" physicists. "Some of these are old riddles," he continued. For example, why does nature have so many different "flavours" of similar particles, including muons and tau particles? There are also riddles like dark matter, he said, and "particle physics is now on the brink of a very big jump into the unknown," because of the LHC.

The LHC will boost the energy from 2,000 times mc^2 to about 14,000 times mc^2, taking it into the terascale range – the equivalent of 14 trillion ordinary electrons with the same power as a flashlight battery.

Witten then described what scientists hope to learn from the LHC, saying that part of the answer is: "We don't know everything that's going to happen, because there is such a big jump in energy." One question Witten believes we can reasonably hope to answer is why electromagnetism is "so different from the weak interactions." We can detect electromagnetic effects (i.e. light waves) with our eyes, he explained, and modern technology is based on electromagnetism. But the weak interactions are much less familiar, he said, and we need special equipment to see them and even to know they exist. Witten then said it was "funny" that we use the same type of equations to describe electromagnetism and the weak interactions, even though they're very different forces. And this raises an obvious question, he said. If electromagnetism and the weak interactions are fundamentally the same, why do they look so different?

It is all to do with symmetry breaking, said Witten, and there are solid reasons to believe that the answer can be found at the terascale – at the energy range of the LHC. The simplest explanation, he continued, involves the existence of a new particle like the Higgs boson, but it hasn't been found yet so the theory has not yet been proved. "It's a question that's been with us since I was a student," said Witten, "so we've had the chance to dream up a lot of variants and competing theories."

Finally, said Witten, the LHC will give physicists the chance to look at the terascale and find out what's going on there – whether there's a Higgs particle, whether there's a more complicated theory, or whether there's the Higgs particle plus other things. "But whatever is the nature of the electro-weak symmetry breaking," said Witten, "we ought to find out once the LHC is operating."

The search for the nature of symmetry breaking is also linked to many other questions, said Witten. "For example," he continued, "it's believed that the symmetry breaking process is the origin of the masses of familiar particles such as the electron. It's also the origin of a crucial part of the masses of the protons and neutrons."

The symmetry between the weak interactions and electromagnetism is what interests Witten the most, "because the origin of masses is what is perhaps most often explained, and because the symmetry breaking is very important."

Witten then described the other big questions that the LHC might answer, including dark matter – the invisible stuff which has a major effect on the orbits of planets and stars. "We don't know what the dark matter is made of, but there is a very interesting theory that it consists of exotic elementary particles that are part of the cosmic rays," said Witten – particles even more exotic than muons. To really understand dark matter, the particles will need to be produced and detected in the laboratory, he said, and the LHC has a good chance of detecting the exotic particles, “lurking at the terascale.”

An even more speculative project, said Witten, is to probe the unity of the laws of nature at a much deeper level than ever before. “The three main forces in particle physics are the electromagnetic and weak force, the symmetry breaking and something else called the strong force,” he said, and the LHC may help to prove the unity of all elementary particle forces, using supersymmetry. Ultimately, this would update Einstein’s theory in the light of quantum theory, stating that as well as space and time, there is an additional quantum dimension in which an ordinary particle could vibrate – leading to the existence of new particles which could be produced and detected at the LHC or other accelerators now being planned, including the International Linear Collider...

David Saxon – The experiment (how?)

Saxon talked about how to detect the Higgs bosons, starting off with protons – the nuclei of hydrogen atoms – then accelerating them to gain kinetic energy. There are two ways to accelerate the protons, he explained – in a straight line (rather difficult and costly) or by using a ring so the particles go round and round and return through the same accelerating element again and again, eventually leading to head-on collisions, with 7TeV (seven trillion electron volts) hitting 7TeV coming in the opposite direction. “The colliding beam is the efficient way to destroy energy to create mass,” said Saxon – this technique was invented by Bruno Touschek, who did his PhD in Glasgow.

A head-on collision is called an event, and detecting events will help to capture the characteristic Higgs signatures, Saxon explained. Theories today are like jigsaw puzzles that we’ve almost completed, and the Higgs boson is the last piece. We already know a lot about its properties, but there’s one thing we don’t know – how massive it is – and that is critical because as the mass of the Higgs boson candidate alters, its properties vary, so to cover the range of possible masses, the detectors must be sensitive to many different processes. Production of the Higgs boson is rare – one event in 10^{11} – and this means different experiments (such as hunting for muons) have to run simultaneously. “You have to be alert to all possibilities all the time,” Saxon explained, with events arriving at a rate of 40 million a second.

The Large Hadron Collider is the world’s most powerful accelerator, with the most powerful detectors and the most powerful computing infrastructure, said Saxon. It also involves the widest international collaboration and uses the most innovative concepts in technology. The key to the project is the CERN laboratory in Geneva, set up in 1954. Today, it has 20 member states and eight observers, plus a budget of about £600 million pounds per annum – roughly the cost of one cup of coffee per person, per year.

The CERN collider is 100 metres below the ground and 27km in circumference, traversing the Franco-Swiss border. One bunch of the protons go clockwise around the ring, while another bunch run anti-clockwise, and there are collisions at four points around the ring. “There’s a huge amount of energy,” said Saxon – equivalent to 20 one-volt batteries for every star in our galaxy or 10^{14} times room temperature. These staggering statistics have made people worry that the LHC would create black holes, but Saxon explained that although a black hole may be created by one proton colliding with another, fortunately these black holes don’t breed – because of Hawking radiation, they die very quickly, and only produce enough energy (about one micro-joule) to swat a mosquito.

The most challenging components in the LHC are the superconducting magnets, said Saxon, and that is what broke in the 2008 start-up. The accelerator is also one of the coldest places in the universe, cooled to 1.9 Kelvin – compared to 3 degrees Kelvin in outer space. It is also a “superfluid” – the largest quantum state that has ever existed – and the energy stored in the beams is enough to melt half a tonne of copper.

Saxon then described the detectors, explaining that the proton beams collide with each other every 25 nanoseconds, producing an average of about 10 interactions, out of which come particles. The detector first determines if it was a very short-lived particle, then the momentum and the energy, and finally it measures the outgoing muons. It’s constructed in a multi-layered way so that different studies can co-habit, but this means it is very complicated and as big as a cathedral – 45 metres long and 25 metres in diameter.

The detectors produce data 40 million times a second, but all this is useless without collaboration, said Saxon. The final version of the data is published only after independent analysis and there are powerful safeguards. Mistakes and disagreements are inevitable, but everyone must feel a sense of ownership over the data and overcome internal rivalries. It wouldn’t do, for example, if a Scottish group claimed to discover the Higgs boson and another group looked at the same data and said: “No you haven’t!” Saxon suggested that what holds them together is hope.

The readout system has 100 million electronic channels and 300km of cable, and involves some “tricky” engineering, said Saxon, adding that we have a good idea what a Higgs event might look like, but so far we only have an artist’s impressions.

Saxon then described the computing resources required to analyse the data produced by the accelerator. Each LHC experiment produces 10 petabytes (a million gigabytes) and this requires the processing power of about 100,000 computers, and a network of computer centres – what’s called “The Grid.” The world wide web was invented at CERN, but Saxon said The Grid is much more organised than that, because the data in themselves are valueless. “What is valuable,” Saxon explained, “is what we call the metadata – which tells you how it was measured and specifies all the conditions that it was done under, and which version of the program it was processed under.” We can’t afford to repeat calculations that have already been done in America, Saxon continued. We need all the computing resources to hand.

The Grid provides seamless access to computing power and data storage distributed all round the world. “Once the LHC starts producing for real it will be like a bicycle race,” said Saxon. “At the moment it’s like learning to ride a bicycle.” In the UK, he explained, the effort is led from Glasgow by Tony Doyle and Dave Britton – a £60 million project over 11 years, funded in part by the Scottish Funding Council. The idea of The Grid started in particle physics but other disciplines are now showing interest, he said – e.g. for research into DNA coding.

“Present data tell us that the Higgs mass should be between 114 and 200 GeV, based on the minimal theory,” said Saxon. But even if there’s only one piece left in the jigsaw, there could be another page missing. The standard model without the Higgs violates unitarity – e.g. the theory that if you fire 10 arrows at a target, the number that hit won’t be greater than 10 – but the difference between the theory and the model is that if you take a model up to high energy, it always violates unitarity, while if you take a theory up to high energy, it works beautifully. “We need people like Witten and Higgs to explain why that works,” he continued, “but the theory without the Higgs is incomplete – it must lead to a contradiction and to a disagreement with data. Something Higgs or Higgs-like must occur.”

Superconducting magnets were pioneered for particle physics, said Saxon, and now these are routinely used in MRI scans, with the “nuclear” component which makes it safe. “Real life is much more complicated than headline writing,” said Saxon, citing other “side-benefits” of nuclear research such as medical imaging, cancer therapy and security scanners, as well as The Grid – not to mention the benefit of working in an organisation of 2,000 people.

“Seeking answers to fundamental questions about elementary particle physics in the universe – that’s why we do it,” said Saxon. There’s going to be a new era of discoveries, starting at the LHC. We’re advancing the frontiers of technology, training young people and bringing nations together through science.”

Q&A

Q: How do you select which events to analyse?

“In the trade, that’s called triggering,” said Saxon. You capture the data and store an event for a fraction of a second, and in that time you have to do enough computation to identify two candidate electrons – with 20 to 50 triggers at any one time. “The crucial step in the game is knowing what to preserve for future study,” he said.

Q: What about superstring theory?

Witten said that supersymmetry and string theory “grew up together,” and hopes the LHC will confirm supersymmetry. Saxon explained that in the standard model, there is the minimum Higgs, then the Minimal Supersymmetric Model, and so on. In the simplest supersymmetric model, he continued, there is not one Higgs boson but four Higgs bosons of different masses, with the same decay possibilities but different ratios. So, when you see something that looks like a Higgs, you have to check if it’s obeying all the standard model predictions.

Q: How long will it take to hand on some of this exciting physics to the young generation – given that the experiments take many years and involve so many people?

Saxon said he was amazed the project had survived since 1990, and said that “hope” had kept it going through the years. Witten said young people are excited about large projects like the LHC because they have so many crucial sub-components which are challenging projects in their own right.

Q: What leads us to believe the 14 tera-electron volt scale is the right scale to look at?

Witten re-worded the question as: “What gives us confidence that the energy of the LHC is sufficient to explain symmetry breaking between the weak interactions and electromagnetism?” He then said that an earlier collider at CERN had discovered the heavy particles responsible for weak interactions in the 1980s – the W and Z particles. “We know their masses already, and we know that the mechanism that breaks the symmetry can’t involve energies that are too much higher than that, or the model stops making sense,” he continued. “The data tells us that the standard model works if you try to complete it with the Higgs particle that weighs not more than a few tenths of a TeV – and it doesn’t work otherwise.”

Q: Does CERN also hope to reveal some insight into gravity?

Witten said the LHC could “possibly shed light on quantum gravity,” but thought it less likely than the study of “symmetry breaking” and perhaps the discovery of supersymmetry – “which would combine Einstein’s special relativity with quantum mechanics, and give us more confidence in going on to combine his general relativity with quantum mechanics."

Q: You're firing protons at protons. Whatever happened to the promise of controlled nuclear fusion?

Firing protons at protons is one way to do nuclear fusion, said Saxon. There are large machines which get "close to ignition" – i.e. get more energy out than put in – but it is not yet "remotely economic," he added. Witten explained that accelerators like CERN involve a lot of particles and energy, but for fusion, you need more of both – and not enough collisions for a fusion machine, even though the energy in each collision is "vastly bigger than it would be to do fusion."

Q: What if you find nothing? Have you got a Plan B or will you just go on?

Saxon said that the theory without the Higgs is known to give impossible answers, so whatever is found will be different. He also said he wasn't worried because half of the large accelerators built around the world were built for reasons which got out of date, and instead did something "unexpected and different." Witten said the standard model without the Higgs particle doesn't make sense mathematically at LHC energies, "so we'd have a kind of contradiction."

Q: How do you see this filtering down through the education system?

Saxon said you need a lot of vocabulary to teach undergraduates, so it's hard to do a master class in particle physics. He recommended "hands-on practical experiments."

Finally, Alan Walker then drew attention to the exhibition upstairs, *Particle Physics for Scottish Schools*, and said that a primary school in Musselburgh had invited him to take the exhibition to its school fair – a breakthrough which Sir Michael described as a good note on which to end the discussion.

Edited by Peter Barr

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