HIGGS BOSON - Curated Transcript of BBC In Our Time podcast

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In Our Time is hosted by Melvyn Bragg. Melvyn's guests on this podcast are:

Jim Al-Khalili, Senior Lecturer in Physics at the University of Surrey;

David Wark, Professor of Experimental Physics at Imperial College London and the Rutherford Appleton Laboratory;

Professor Roger Cashmore, former Research Director at CERN and now Principal of Brasenose College, Oxford.

Transcript:

[Melvyn Bragg] Hello. One weekend in 1964, the scottish scientist Peter Higgs was walking in the Cairngorn Mountains. On his return to his laboratory in Edinburgh the following Monday, he declared to his colleagues that he'd just experienced his "one big idea" and now had an answer to the mystery of how matter in universe got its mass. That big idea took many years of refining, but it's now generated so much international interest and has such an important place in physics that well over one billion pounds is being spent on a collider in CERN in the hope that he was right. It's the biggest science project on earth. The quest... to find the Higgs boson, a fundamental constituent of nature that, if it does exist, has such a central role in defining the universe that it's also known as "God's Particle". What is the Higgs boson? Why is it so important to scientists, and how are they planning to find it? With me to voyage into the quantum realm of the Higgs boson is Professor Roger Cashmore, the former director of research at CERN and now principal of Brasenose College, Oxford, David Walk, Professor of experimental physics at Imperial College London and the Rutherford Appleton Laboratory, and Jim Al Khalili, senior lecturer in physics at the University of Surrey.

[Melvyn Bragg] Jim Al Khalili, before we start, why is this quest so important? Just as it were, a "headline"...

[Jim Al-Khalili] Well, I think ever since the ancient Greeks, we've been trying to understand the fundamental building blocks of everything in the universe. And we've come a long journey, and we've reached a stage now where we believe we know pretty much what everything is made of, the very constituents of all matter in the universe. But we are missing one or two pieces in the jigsaw, and we've got to this point where we're just waiting to be able to complete our picture of fundamental particles.

[Melvyn Bragg] What is a fundamental particle?

[Jim Al-Khalili] Well, basically, it's an entity which isn't itself composed of anything more basic. It's the most basic constituents of matter.

[Melvyn Bragg] So it's a basic building block of everything around us, this table, us, everything around us?

[Jim Al-Khalili] That's right. And I think the very first fundamental particle to be discovered was, of course, the electron, back in the end of the 19th century. And since then, we've been discovering more and more particles. Some of them we've then discovered that are themselves made of more constituent pieces. We think we know what most of those constituent pieces are now, but there are still one or two gaps in our understanding.

[Melvyn Bragg] So there's a "Standard Model" of particles, isn't there? But there is this key missing gap which is going to be filled, we hope.

[Jim Al-Khalili] That's right. The Standard Model is our best understanding of the particles that make up all of matter in the universe and the forces between them. And it categorizes particles into groups and families, these fundamental particles.

[Melvyn Bragg] It's still rather strange to get your mind around these particles, things we can't see, and ... make up everything that can be kicked, as it were, and looked at. Now, how do you find dealing with that, actually? Is it an active imagination all the time?

[Jim Al-Khalili] I think many non scientists would think that they would see physicists as suggesting that a particle would exist, and then they go away, and lo and behold, they'd find it in an experiment. But science doesn't work that way. There are so many checks and verifications necessary to prove that a particle exists.

[Melvyn Bragg] Can you tell us the families of particles, briefly,... what are these fundamental particles?

[Jim Al-Khalili] Well, there are two categories. There are the particles of matter known as the fermions, and then there are particles that somehow mediate the force between these matter particles, the fermions. And those are called bosons. And there are a number of particles in each category, so they're subdivided into other groupings and families.

[Melvyn Bragg] So we have quarks and leptons and bosons?

[Jim Al-Khalili] Quarks and leptons are both the matter particles that make up everything, make up atoms, make up all of us and the universe. The bosons are the particles of force that are exchanged between the matter particles.

[Melvyn Bragg] David Wark, let's talk about leptons first of all. Can you give the listeners some idea of how small they are and then, more importantly, what function they play?

[David Wark] Okay. Well, as for how small... this is in one of those concepts which doesn't actually work very well when you start talking about fundamental particles. We don't usually think of a fundamental particle being like a marble that has a hard surface and therefore a very well-defined size. Particles have properties of particles - they carry discrete amounts of energy, for instance. But they also have the properties of waves. And if you look at a particle in great detail, what you find are the wave-like properties. And, of course, a wave doesn't have as well defined a size.

[Melvyn Bragg] How do you look at a particle?

[David Wark] Well, mostly by bouncing off other particles off of it. Now, this might sound circular, but you can actually do this by producing beams of particles, either in accelerators or nature produces particles for us in many cases. And you can then detect these particles using detectors, which mostly rely on the fact that some of the particles carry electric charge. So as they travel through these detectors, they will leave a detectable signal, either light or heat or ionization. And so by taking a well-defined set of particles, which we produce, and then bouncing them off another set of particles, we can understand the properties of both.

[Melvyn Bragg] So by smashing things up, you find the smallest thing?

[David Wark] Yes. Wolfgang Panofsky once said it was like taking two watches and smashing them together at hundreds of miles an hour and trying to figure out how a watch works by looking at the bits that fly off. It might sound a bit silly, but it's the best way we found so far.

[Melvyn Bragg] So what does a lepton do in all this, given that it's so important to us as we're talking, that we're full of leptons? And what is a lepton doing?

[David Wark] Okay, well, leptons.. the word just comes from the greek word for light. And they're named that because the first lepton found, the electron, is much lighter than the other particles which were known at the time, which were protons and neutrons, which we now don't believe to be fundamental particles. The leptons, there's only six of them. There are the three charged leptons, the electron, the muon, and the tau, and then there are three neutrinos that go along with them. The very puzzling thing we don't understand is why there are three. Okay? The muon and the tau are much heavier than the electron, but otherwise seem to have the same properties. So we have these three so called families, these three copies of the particles, and we don't know why there are three.

[Melvyn Bragg] Have you any idea why I think they're three?

[David Wark] Well, I'm a poor, dumb experimentalist, you know. It's a theorist job to do that. But one speculation, one reason you might think there are three is we know that in order to get the universe that we see, the laws of physics have to be different for particles and antiparticles. And also the laws of physics have to be different for time going forward and time going back. Now, we know ways to generate such differences, but you have to have three generations of particles before you can do that. So there is an "anthropic" principle argument that states that three is the smallest number of particles you can have and make a universe like what we see...

[Melvyn Bragg] It's also the smallest number of family [members] you can have, isn't it? [laughter]

[David Wark] ... I think that why there are three and not two or four is one of those mysteries that we hope to solve by understanding physics beyond the Standard Model.

[9:36]

[Melvyn Bragg] Still on the fundamental particles, Roger Cashmore, people have heard of quarks, partly because it's such a lovely word. Can you tell us what they are and how they relate to leptons?

[Roger Cashmore] Well as you heard a few moments ago, Dave mentioned protons and neutrons. And once upon a time, they were thought to be fundamental particles as well. But in the fifties and sixties, we started to find a plethora of particles, and clearly that wasn't the answer. And what grew up then was the idea that these protons and neutrons, which had many properties in common, but some different, could be made up of some other particles and these were the quarks that Gell-Mann and George Zweig invented. And you can construct...

[Melvyn Bragg] Excuse me, you said "invented" rather than "discovered". I know they have the same meaning, but it's interesting you chose, invented. They thought of it rather than found it...

[Roger Cashmore] Well, they had patterns of particles to do it. So it's a bit like having a lego that you're going to put together to make up different shapes. And they.... When I started my life in particle physics, [we had of] the order of 50 to 100 fundamental particles. So we thought they were there was, obviously... but they came in patterns and Gell-Mann was one of the first people to recognize this pattern and said, once you get a pattern in science, there's probably something else underneath the pattern that produced it for you. And that was where the idea of quarks came from; he and George Zweig produced that idea. And then you could start with just three quarks make up protons, neutrons, and many of the other particles that we see today. And that was a great step forward, but I remember when it was first invented, people thought this was just a simple way of trying to do complicated mathematics. And it ... appealed to me because I was able then to understand what was going on. But it took a long while before people really believed that these quarks were there. And one of the ways that that happened was in the late sixties, there were experiments that were being done in California at Stanford, where you scattered the electrons, the things that Dave had been talking about, off a proton, and it looked as though from those experiments, the actual electron was scattering off little granular objects inside the proton. So the idea that there were really quarks locked up inside a proton, and they were, then they produced the patterns of all the other particles, was then started to be really accepted.

[Melvyn Bragg] So you've got the leptons and we've got the quarks.... We're convinced these are fundamental, are we? There's not going to be more fundamental inside these fundamental particles?

[Roger Cashmore] You see, you're never sure. You're never sure. We're experimental scientists. I mean, you go and look at the world around you and you see things that are there. We have this one thing where we have the patterns, we have these three families. We have three families of leptons that Dave was talking about. We also have three families of quarks. And then that's one made of an up and a down quark, another one made of a charm and a strange quark, another one of a top and a bottom quark. Now, when you see things being replicated this way, any physicist says, is there something else going on deep down underneath or not? At the moment, we can't see that they're made of anything themselves, following the same sort of idea, but who can tell?

[Melvyn Bragg] So we're still talking about the building blocks... and everything in existence coming from these things that we can't see, and we can see traces of them ... after massive experiments. So we've got what? We've got the leptons.

[Roger Cashmore] Yeah.

[Melvyn Bragg] We've got the quarks, and then we come to the bosons? Right, can you just tell us what they are first?

[Roger Cashmore] Well, you have the question of, as Jim said earlier, of how these particles, let's take the quarks, hold together inside a proton. If I said there were two up quarks inside a proton and a down quark, the up quarks carry charge, and the natural inclination of them is to repel one another. So what we have to do is come up with another force that will hold these things together, [that] will beat that repulsion. Now, all of these forces we think of as being "mediated" by bosons, the carriers of these forces, and that's where the bosons come in. They give these quite.

[Melvyn Bragg] They give the quarks and the leptons mass? They carry a force?

[Roger Cashmore] They carry a force, but they carry the forces that are the interactions between [them]. We haven't got to the mass of the, of the leptons. That was the big problem.

[Melvyn Bragg] So we didn't know how they got their mass, these fundamental particles. There they were. They were fundamental particles, and the easiest way to [deal with their mass] was by calling [it to be] zero. But you knew they also had mass. But where did the mass come from?

[Roger Cashmore] Exactly. And, I mean, that was a great conundrum that people faced when Higgs came up with his idea, because many people, Salam, Weinberg [Glashow?] got the Nobel Prize for unifying some of these forces that we observed, but it remainded that all the particles [would need] to be massless [in their theories]. And that was Higgs's great triumph, .. to go away and come back with an idea of how to give them some mass.

[Melvyn Bragg] It is wonderfully romantic that a man goes for a walk on the Scottish mountains and comes back on Monday and actually realizes that he's had his one good idea, and then 40 years later, you're spending billions and billions of dollars trying to prove what he discovered on top of the Cairngorms one misty morning. So what did he say that is so very, very important? Can we come to the bosons now, Jim?

[Jim Al-Khalili] Yeah. Well, Peter Higgs' idea actually comes from another field of physics. We know that when electrons move through a crystal lattice, ... it looks like they have more mass.

[Melvyn Bragg] Why should they move through a crystal? What are they moving through this crystal lattice for?

[Jim Al-Khalili] Well, ... any object that conducts electricity, say, will allow electrons to move through it. These electrons, because they're moving through atoms with positive charge, if they're positive ions, they will try and slow down the electrons. They try and impede their progress through the lattice. And so it looks, viewing this from the outside, as though the electrons are heavier than they really are. This was the idea that Peter Higgs then borrowed and applied to particle physics. Now, the idea, the whole idea in particle physics is we're trying to understand, unify all the forces of nature, understand, hopefully, one grand theory that describes...

[Melvyn Bragg] All right across the universe from one and the other, the thing called the electron is the same at one end as it is at the other end and in the middle as well. That's the one thing?

[Jim Al-Khalili] Exactly, and the thing that Weinberg and Salam and others, that Roger mentioned, described was how two of these forces of nature fit together and are really part of one overriding force. Now, the four forces of nature, there's the force of gravity. Then there's the electromagnetic force, which basically holds us together. It's the force that keeps electrons in orbit around the atomic nucleus. And then there are two other forces which act inside the nucleus of atoms. And with quantum mechanics throughout the 20th century, we've been able to understand how three of these four forces act. The one that's the odd one out is the force of gravity, and that's what many physicists are working on now. But to describe how these three forces fit within what we call the Standard Model requires seeing what they have in connection with each other. And two of these forces fit together. Now, the problem is that the electromagnetic force comes about through particles exchanging one type of boson, namely the photon. Another type of force, the Weak nuclear force, comes about through exchange of two other types of bosons, called the W and Z particles. Now, in the simplest version of the Standard Model, you would like to think that all these particles have no mass whatsoever. That's a nice, neat, symmetrical picture of nature. But unfortunately, the W and Z particles are heavy. The photon doesn't have any mass at all. So the problem that Peter Higgs was addressing was, how come the W and Z particles are heavy, despite the fact that they should, in this nice theory, look just like photons.

[Melvyn Bragg] And so he invented this field, David. He imagined this field. Now, can you tell us about this field and what its function is with regard to the other particles?

[18:05]

[David Wark] Well, the Higgs field has,

[Melvyn Bragg] ...Which goes right across the universe. That's the field.... It's a big field. He [Higgs] was on a big mountain, but it's a big field. [laughter]

[David Wark] It's a big field. The Higgs field has a very interesting property, and that is why it has this effect that it can give things mass. The Higgs field has the property that in the ground state, the lowest energy state (we believe that in nature, things tend to gravitate to the lowest energy state)... the Higgs field doesn't have a zero value. The lowest energy state with respect to, say, photons, is to have no photons at all, or the lowest energy state with respect to electrons is just not to have any.

[Melvyn Bragg] You're kind-of losing me, but still, you better go on because we haven't got all that much time, right...

[David Wark] Okay.... Well, the lowest energy state of the Higgs field, you actually have Higgses [Higgs particles] present. The vacuum...the state if you go out far away from any object, has a field of Higgses. Now, as other particles try to propagate through the vacuum, so an electron is just moving along, it sees these Higgs particles, it sees this Higgs field, and it makes it harder to move the electron. The electron has to drag some of this Higgs field along with it, and that gives the electrons mass.

[Melvyn Bragg] So mass is kind of.... Can we imagine it as if the Higgs boat is "magnetising the particle"? Can we use that word with any sense at all?

[Roger Cashmore] No, I wouldn't have said "magnetising". I would have said sort of an analogy [that] people I think might be familiar with [would be] bottles of syrup and water. And if you drop a ball bearing into such, one of those...bottles, you'll see it'll fall in a different way. When you go down through the bottle, you go down through the water very much more ... slowly than if the bottle was empty. And if it went into the glycerin or the syrup, it would go even more slowly. So it's that sort of interaction with the medium around it, which gives it, apparently different properties, different dynamical properties, different properties of mass.

[Melvyn Bragg] So let's get this... Let's just pause here for a moment. This Higgs field is full of this stuff, and it's this stuff, whatever it is, these particles, and the boson is the activating force, which works on other particles, leptons and quarks coming through and gives some of them mass. And out of that mass eventually comes everything around us at the moment. That's the deal, is it?

[Roger Cashmore] That's the deal. That's the idea.

[Melvyn Bragg] Good.

[Roger Cashmore] You've got it. [laughter]

[Jim Al-Khalili] I think something that non-physicists have difficulty with is that the idea of a field itself, and the simplest example is a magnetic field. It's not something you can see or touch, but you place certain objects in that field, and they know it exists. They feel its influence. So this Higgs field is something invisible. It pervades the whole of the universe, if it exists, but it influences all particles traveling through it, and every force is associated with a field. The electromagnetic field manifests itself as a particle, as the photon. All fields have particles.

[Melvyn Bragg] Why does an electromagnetic field [have to] manifest itself as a photon? ...

[Roger Cashmore] This goes back to what I think Dave was saying earlier, that we've now got a place in physics where we know that you have this duality between waves and between particles, so that we don't talk about things as just one or the other. Electrons ... we can see them behaving as wave-like particles and being bent around, diffracted aound objects, so that we always expect everything to come up in these two guizes as manifestations, as a field or as a particle. And so if we want to look for a Higgs field, then we'll also look for a Higgs particle. That's the idea that we have behind it.

[Melvyn Bragg] So we just have to take for granted now that there are waves and particles, this wave system is a zapping between them. Packages of particles.

[Roger Cashmore] Absolutely.

[Melvyn Bragg] Does the wave change into a particle, or ...do they coexist as waves and particles?

[Roger Cashmore] Well, this is the way I think about it, is that they coexist depending on exactly which situation you're talking about. You use the most convenient description that you've got available to you. For instance, in the case of electromagnetism, if you have electromagnetic waves, which, of course, our listeners today are benefiting from electromagnetic waves, they wouldn't get this broadcast if there weren't electromagnetic waves. But we also know, and when we can get what are called packets of energy, the photons, which set off photomultipliers, which is the sort of experiments that Dave does, he's ... looking for these photons all the time in photomultipliers from experiments he does. But they're very important in a lot of other areas of science for medical diagnostics and things like this.

[Melvyn Bragg] Dave, do you want to talk about looking for these particles? ... Because people, they're so very difficult to sort of get any grip or hold on them. And yet they're essential to any understanding or to the basic understanding of how we've arrived at what we are.

[23:29]

[David Wark] I think one can go too far in trying to make these things mysterious. It's only hard to see an electron because it's very small and your eye is very big. But essentially, the way that you see an electron is no different than the way you see anything else. You make radiation, interact with it [and the radiation] comes off. For instance, we now have the capability to trap and hold a single electron in a trap, scatter radio photons off of it, and detect them. So you can see a single electron by scattering something off it. Now, you can't do that with your eye, because your eye isn't sensitive enough to see a single radio photon. But there's no fundamental difference between the two. ...When you look out in this room and see the walls, you're just seeing light scattering off of the electrons that make up the material in the wall. So what we do in the case of our experiments is usually we try to make it easier to see a single particle, and we do that mostly by just making the energy very high. If you make the energy very high, then you can get a much greater disturbance off of a single particle, and then you can see it much more easily. Now, in the case of the Higgs, we have a second reason to try to make the energy very high, which is that you can't make any particle until you put enough energy into the system to produce its rest mass. Okay. Einstein's famous e equals Mc squared. In order to make a particle, you first have to put in an amount of energy equal to Mc squared, and then you have to put in some more, usually in order to get the particle to have enough energy that you can pick it up in your detectors. Now, in the case of the Higgs, it gives everything else mass. But in the theory itself, the mass of the Higgs isn't specified. We know it has a mass, but we don't know what it is. And so we've had to search for a very long time for ...the Higgs particle by banging things together. And what we know is that we haven't done enough yet. We haven't banged things together hard enough yet to actually produce a Higgs boson.

[Melvyn Bragg] How did the Higgs field get there? This has been researching for this program, which has been hard, but a great pleasure. I've come across wonderful phrases, but there is no better phrase than "spontaneous symmetry breaking", which is just a wonderful phrase. Should be the title of a series of novels, really. Now, in spontaneous symmetry breaking was very important in creating the Higgs field, as I understand it. Would you like a crack at that, Jim?

[25:57]

[Jim Al-Khalili] Yeah. The idea of it goes back to the idea of symmetry in physics. Now, we know in common-use language, when we talk about something symmetrical, we mean it looks the same under certain rotations, a mirror image or something spherical. It's symmetrical, doesn't change. However you look at it in physics or even in pure mathematics, symmetry has a more basic meaning. It means certain properties stay the same when you change other properties. One of these properties in this context is the mass of these fundamental particles. The standard model suggests that.... the simplest version of it suggests that ... particles should all have zero mass and all the forces are somehow the same. But we know that's not the case. We now believe that just after the Big Bang, for instance, the forces were unified; they were all part of one superforce. But as the universe expanded and cooled, the forces took on different properties, and the particles took on different properties.

[Melvyn Bragg] But how did this feel? And I wasn't. I mean, obviously, I like the fresh, spontaneous symmetry breaking, but that actually was essential in the creation of the Higgs field, wasn't it? Because out of the symmetry, it broke the symmetry. It broke spontaneously. Now, how did it break spontaneously? And have we any idea why it broke spontaneously? Could you, and maybe Roger, take this up as well?

[Jim Al-Khalili] Well, just.. there's a nice example of what breaking symmetry means. If you have a blank piece of paper, it's symmetrical in the sense that you don't know if it's upside down or one side or the other. But as soon as you start writing on it, you break the symmetry, because now you have an up and a down. You have a front and a back. So something has to change so that you lose this symmetry.

[Melvyn Bragg] So how did... what happened to create the Higgs field? Roger? That's not a small question.

[Roger Cashmore] It's not a small question at all. In fact, it's a question that a lot of people will juggle with for a very long while. I mean, I don't know [if] I can answer that question, actually. ...

[Melvyn Bragg] All right, well, describe what it meant, then. What it means is that if symmetry breaks down, what do we get instead of symmetry that makes it a Higgs field?

[Roger Cashmore] Well, let me say it goes back a little bit to what Dave was talking about a little earlier. We expect, as Jim was also saying, that you have a symmetry in any of our interactions. Let me give you another example, just for one way, so people get an idea. I mean, the standard example of spontaneous symmetry breaking is that you all sit down at a circular dinner table, and there is a plate laid out, and on the left hand side of the plate, there's a fork. On the right hand side, there's a knife, and then there's a napkin. Then you go on. Then there's a fork, then there's a plate, then there's a knife, there's a napkin. You go all around the table, you all sit down for dinner. Now, it's completely symmetrical. Whether you go left or right, the pattern is there. As soon as the first person picks up a napkin, everybody else has to pick up the napkin in the same way, because otherwise you'll never, all of you, get napkins, or somebody will be left with two. So that's an example where something looked completely symmetrical to begin with. Actually, when you make a move, everything comes out that way. Now, that's the idea. Some of the idea in spontaneous symmetry with the Higgs field is that... once one choice is made, then you get this resulting pattern of particles, and that's the spontaneous symmetry breaking.

[Melvyn Bragg] Right... so...this is sometime after the Big Bang, the Higgs field, they...go on... you tell me.

[David Wark] Let me risk a slightly technical example. This is the standard one in textbooks. It's the example of a ferromagnet. Now, if you have a magnet, it's made up of a bunch of atoms, and each atom is a little magnet itself and generates a little magnetic field. Now, that's true of pretty much all atoms, even the atoms in the wood in this table. But all of the atoms in the wood in this table are pointing in different directions, so there's no net magnetic field. What happens in a ferromagnet is all the atoms line up, and in the process of lining up, they produce an exterior magnetic field, a B field, a magnetic field we can see outside. And in the process, they break the symmetry, because if you initially start out with a very hot magnet, so the temperature is enough to randomize the direction of all the magnets, there's no net magnetic field, there's no preferred orientation in space. It's totally symmetric. All directions look the same. As you cool it down, you reach a critical temperature, all the magnets line up, and now there's a specified direction in space, and that spontaneous symmetry breaking generates the magnetic field. Now, the Higgs does something analogous to that. At very high energies... there's no preferred orientation to an internal symmetry of the Higgs field (we don't want to get into that detail)... there's no preferred orientation. As you cool it down, it has to pick one direction for this particular parameter. And when it does so, it actually generates a Higgs field. It generates this non-zero Higgs field that goes all throughout the universe.

[Melvyn Bragg] This is called a phase shift, isn't it, Jim? And they all point the same... and it becomes like a magnet there.

[Jim Al-Khalili] Yes. I think Dave's analogy is very good, that the magnetic field that is produced when these atoms line up their magnetic fields produces the magnetic field around it. In the same way, as the universe cools and the symmetry is broken, it produces the Higgs field. And it's that field, then, that says that certain particles will behave differently to other particles in the sense that some ... are heavy, some have large mass, others have very small mass or no mass at all.

[Melvyn Bragg] But this is spontaneous in the sense that it happened, as Roger was describing... you have to pick up now...

[31:47]

[Jim Al-Khalili] It's a sudden process. Yes. In that sense, it's a phase transition. It's not a gradual thing....

[Melvyn Bragg] Yeah. And then once it's in that direction, it could change again, of course. Could change back again? Well, let's leave that out. [laughter]

[Roger Cashmore] Everything settles down. But what you'd have to do is inject a lot of energy back into the system to get it up again when it came out of that rest-energy position, and then it could fall down into another state as well. Now, we don't think there's enough energy around to be able to make that to happen.

[Melvyn Bragg] So that happened then thousands of millions of years ago, and particles went through and mass accumulated. But we're still looking for this wonderful theory, the Higgs boson. Nobody's seen it. And you were running CERN, Roger Cashmore. And now can you just tell us the size of this job to find this particle? How big is the collider? We know masses of money has gone into it. And can you just give us some practical idea of it?

[Roger Cashmore] Well, okay. The accelerators being built at CERN, the Large Hadron Collider, LHC, is being built in a tunnel that housed a previous accelerator at CERN, which had a lot to do with the detailed discussion of the Higgs, maybe I will come back to that later. But it's 27 km in circumference. It's about 100 metres underground. And running through this tunnel, there will be a large number of superconducting magnets which run with very high magnetic fields in them. Now, the idea of that is ... particles when they move in, a magnetic field, get deflected, so what you're doing is you're deflecting them, so they're going around a circle in this magnetic field. And as they go around this circle, you give them a kick at regular intervals to increase their energy with an electric field. And as they get more energetic, you need a higher [magnetic field] to keep them in the same orbit. And so we keep them going round until we get to very high energies. Then we have ... protons going one way, protons going the other way, and we bring them into collision with the very high energies that we'll be able to achieve with ... that accelerator.

[Melvyn Bragg] And then you have the detectors to see what happens when this collision [takes place]?

[Roger Cashmore] So at ... four points round... big detectors [are being built] that between them will cost almost as much as the accelerator itself. They're very sophisticated detectors, and what they're looking for is when the protons collide, or rather the quarks that are inside the protons collide with one another, they will potentially have enough energy to put this energy, E, into a very small area to produce a large mass if there's any particles around. Using, again, good old Einstein and E equals m c-squared. So the idea is that we build an accelerator which we know must be able to ... get up to sufficient masses that we've got to find the Higgs, if the Higgs exists.

[Melvyn Bragg] David, you want to add to that?

[34:54]

[David Wark] Well, the detectors themselves are an incredible piece of technology. If you look at the largest of these, the ATLAS detector, it's the size of Broadcasting House, essentially set on its side. And the reason for that is just that we're producing particles of very high energies. And if you want to measure them very accurately, you have to stop them. It requires a huge amount of material to stop them. But this material is the most complex detector, certainly ever built in particle physics. And in addition to that, it sits in this incredibly high radiation environment near the collision points between the two protons. And so it has to be able to withstand levels of radiation that are even higher than the core of a nuclear reactor. And it still has to work after ten years of this. So this has been an enormous effort to do this, and it's required thousands of physicists from around the world to build these [accelerators]. They really are an amazing example of physicists from all over the world working together to produce these common goals.

[Roger Cashmore] Yeah. If I was to say, I mean, way back in 1982, when we first thought of the Large Hadron Collider, we didn't know how to build the accelerator. It took ten years to develop the magnets and the technology to be able to build the accelerator. That took us up to about 1992. Then we knew we could build the accelerator. Then came the issue [of] can we build the detectors that will be able to detect the Higgs if it's produced in these collisions? That took about another ten years, really, to develop the technology to do it, which has really pushed all elements of electronics, sensors and things like this to an unprecedented level. Now we're building it and we know we can do it. So it's a good example of people, scientists, setting off an objective to do something and then achieving it, but it takes a while.

[Jim Al-Khalili] And, of course, the reason why there's so much technical difficulty in building these detectors ... two reasons, really. One is that, of course, even if we do have enough energy to create the Higgs, that's not the only particle that is going to be created. We're smashing protons together at such high energy that anything that can be produced with that energy, through E eqals m c-squared. will be produced. And so the big problem is looking through these billions of events that are going on and pulling out the one event that is important that suggests the Higgs exists. The other problem, of course, is that when the Higgs is created, it doesn't hang around for long, as [it has] a very, very short lifetime.

[Melvyn Bragg] What's "short" in your terms?

[Jim Al-Khalili] I don't know exactly what the lifetime is, but these are tiny, tiny fraction... billionths of a second. And the problem is then you don't look for the Higgs particle itself. You look for the decay products of the Higgs, the particles that the Higgs will decay into. And it has certain signatures, and that in itself is very, very difficult, because, see, what it turns into depends on what mass it has. And since we don't know what its mass is, we're not quite sure what we're looking for. So it's a tremendously difficult problem. But on the whole, I think the majority of physicists are nevertheless encouraged that they will find the Higgs sooner or later.

[Melvyn Bragg] Do you see this as a high risk experiment? So many people seem involved in so much money in cautious countries like Switzerland, [laughter] with...British physicists at the fore, like a gentleman on my right here. So it seems very steady and sensible. But looked at from where I'm sitting, to spend billions of pounds chasing something you don't know exists and you might not see...

[David Wark] Oh, no, no, that's the guaranteed payoff part. If we don't see the Higgs, that would in many ways be much more interesting than to see the Higgs. OK? The Standard Model is magnificently successful at predicting what it predicts and magnificently useless at predicting anything else. For instance, when I say that the Higgs gives the mass to all the fermions, you might think that I've now explained the mass of all the leptons and the quarks. But I haven't really. I said where it comes from, but I haven't said how big it would be. We now know that if you take the lightest of the neutrinos to the heaviest top quark, there's sort-of 14 orders of magnitude range and mass there. And the Standard Model doesn't explain where this 14 orders of magnitude range comes from. In fact, in the Standard Model, that 14 orders of magnitude creates real problems. It's very difficult to have a theory where you can have such a huge range of masses and it's [(the particles are)] stable. And so we think there must be some physics beyond the Standard Model. There must be something that's explaining these 14 orders of magnitude. And by not finding the Higgs, we might actually get a better hint as to what that is.

[Roger Cashmore] Yeah, I mean, let me pick up on that. I mean, it's not such a random activity that we're engaged in. I mean, if we look around at all the particles that we've got at the moment, and the previous accelerators (CERN LEP was magnificent in doing this), we've measured them. We've understood how they interact with one another. We've got very accurate measurements of lots of the parameters of, as we call it, the Standard Model. However, it doesn't work. There's some missing ingredient. That's Mister Higgs's particle. And it's wonderful if we do, in fact, come up with the Higgs's particle, but we know there's a missing ingredient, and we know that the experiments at the LHC that we will … break… the theories break down unless something new comes in the Higgs particle, possibly. Because it could be something else. I mean, it's experimental science. You actually don't know that Mister Higgs is right until you've seen his experiment.

[Melvyn Bragg] When you say your theories will break down, does that mean that the world changes or you just. You change? I mean, this table's still the table. I mean.

[Roger Cashmore] Exactly. Exactly. We're experimental scientists, so the table still stays there. We've still got our observations, but we try to understand how they all relate to one another. And at the moment, they don't relate to one another unless you have a Higgs particle.

[Melvyn Bragg] Is this why it was called the God's particle by one… by a physicist colleague of yours?

[Jim Al-Khalili] Yes. I think [it was] Leon Lederman, American Nobel Prize winner, because it's the… as Roger says, it's the missing piece in the jigsaw. We think we know all the fundamental particles that make up the universe, apart from the Higgs boson. Now, it may well be that even the Higgs itself isn't a fundamental particle. I mean, there are many theories that suggest there's … something else that we should be looking for. In fact, one theory called "Super Symmetry" suggests that every particle that we know of has another as yet undiscovered partner. It may well be that that's the way our universe works. We simply don't know. The Higgs could be the missing piece in the jigsaw. But then, as David says, even if we don't find it, there's a wonderful,… different picture that we need to discover.

[David Wark] Yeah, when I say we won't, we *may* not find the Higgs. As Roger says, there's a very, very, very strong indications we have to find something. It just might not have exactly the properties of the Higgs boson in the Standard Model. For instance, it was mentioned earlier that the Higgs model is related to condensed matter theories. And in condensed matter, there's an analogous thing to the Higgs called the Cooper Pair, and you would never actually find a Cooper Pair in nature. It may be that Higgs is a similar thing, that it is a property of the theory that doesn't correspond to… an actual particle. And so we may discover when we look at it, that we find some deeper understanding of the theory that doesn't correspond to an actual particle.

[Melvyn Bragg] Briefly, it's an awfully awful question to ask you to answer briefly, Roger. But when we're talking about Faraday and other scientists, ... they're doing experiments. They're discovering things for the sake of discovering. Then modern worlds are created out of their discoveries. Do you see any... have you any idea of any practical consequences of finding, if you do find this Higgs boson and this God's particle?

[Roger Cashmore] Other than the fact that we will have understood physics somewhat better and understand how physics works and the world around us perhaps works and can use those ideas, and perhaps, as we've been hearing, move those ideas over into some other area, which will have great benefit, I don't think I can, honestly. I mean, here we're really seeking after what made the world around us the way it is. Where did it come from? And I think those are great things to go for as well, but I think ...I can't see any practical application. But you should always be worried. I mean, even Faraday thought that he didn't know quite how his discoveries would be used. Except he said [to] one Chancellor, "You'll tax it".

[Melvyn Bragg] Thank you all very much indeed. That was terrific.
