

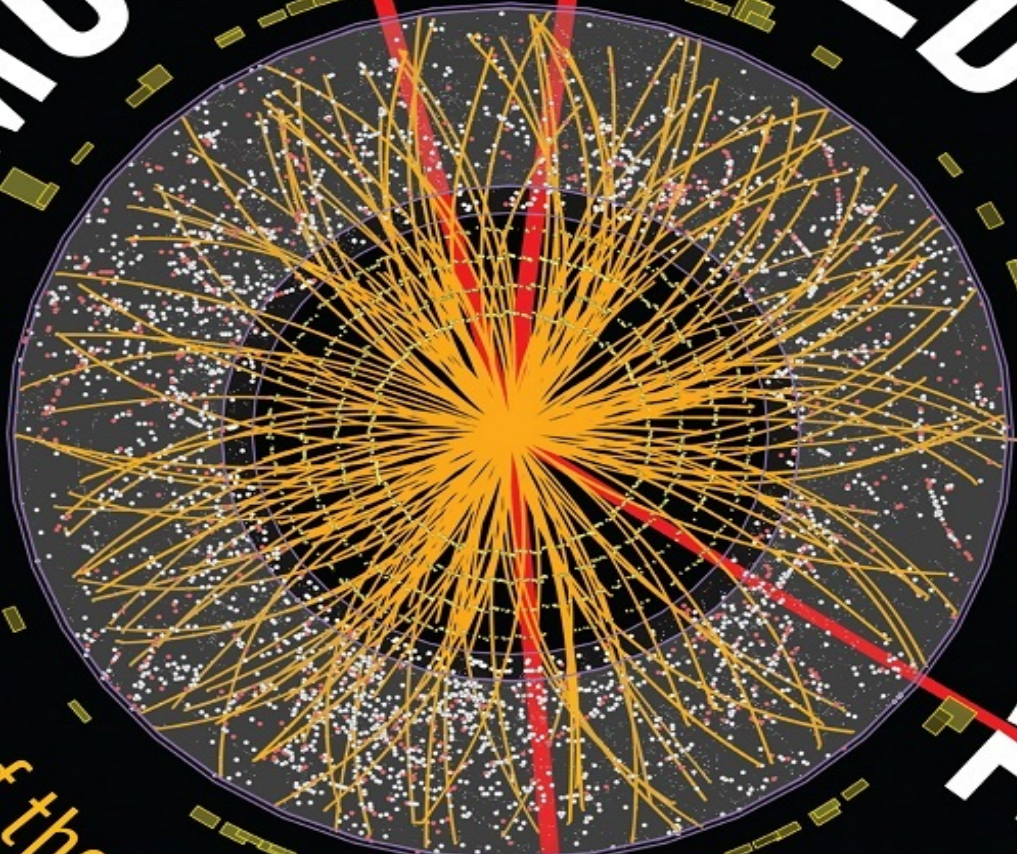
“Jon Butterworth is an experimentalist and is the first to give a **vivid account of what the process of discovery was really like** for an insider.”

—**PETER HIGGS**, Winner of the Nobel Prize in Physics

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MOST WANTED PARTICLE

The Inside Story of the Hunt for the Higgs,
the Heart of the Future of Physics



JON BUTTERWORTH

leading member of ATLAS at the Large Hadron Collider

FOREWORD BY LISA RANDALL, *New York Times* best-selling author and Harvard University theoretical physicist

MOST WANTED PARTICLE

An *Observer* Top Ten Science and Technology book

“Most of the existing popular accounts of the events leading up to the July 2012 discovery claim at CERN are written from a theoretical perspective by outsiders. Jon Butterworth is an experimentalist and is **the first to give a vivid account of what the process of discovery was really like for an insider.**”

—**Peter Higgs**, Winner of the Nobel Prize in Physics

“The story of the search for the Higgs boson is so **edge-of-your-seat exciting** that it practically tells itself—but still, why not get **the story from someone who was there for every step along the way**? Jon Butterworth is a talented writer and a world expert in the physics, and his book is hard to put down.”

—**Sean Carroll**, physicist at Caltech and author of *The Particle at the End of the Universe*

“This is **a unique book**, which captures the highs and lows of the last 20 years of particle physics, culminating with the discovery of the Higgs Boson. I’ve known Jon for most of my career—he’s an insightful, creative, diplomatic and occasionally outspoken physicist, and every facet of his character is on display in this beautifully written book. **If you want to know what being a professional scientist is really like, read it!**”

—**Brian Cox**, author of *Why Does $E=mc^2$?* and *The Quantum Universe*

“If you met Jon Butterworth in a pub—which, judging from the many anecdotes in *Most Wanted Particle*, is a non-trivial probability—his is the voice you’d like to hear, this is the tale you’d want him to tell: a breezy recounting of the discovery of the Higgs boson that turns out to be both **an accessible primer on particle physics and a lively look at behind-the-scenes Big Science.**”

—**Richard Panek**, author of *The 4% Universe: Dark Matter, Dark Energy, and the Race to Discover the Rest of Reality*

“[A] **charming, enlightening** bulletin from one of the most exciting fields of human endeavor.”

—*Guardian*

“The book contains a **fascinating inside perspective of the discovery of the Higgs boson**. It offers a insight into the intense, bewildering and intimidating media scrutiny that physicists aren’t used to, combined with intimate details about the life of a high-powered physicist and some lovely explanations of the physics behind the discovery.”

—*New Scientist*

“This is more than just another telling of the story of the hunt for the Higgs at the LHC—**the reader here is utterly immersed in the politics, excitement and sheer intellectual adventure of discovery . . . from someone who was actually there!** The process of scientific research is laid bare in all its glory, warts and all, and emerges as a delightful example of what is best about human intellectual endeavor.”

—**Jim Al-Khalili**, author of *Quantum: A Guide for the Perplexed*

“Like *The Lord of the Rings*, *Most Wanted Particle* takes readers on a long path with many moments of peril and uncertainty to reach the triumphant discovery of the Higgs Boson. It is **a great chronicle** of a part of the endless chain of progress in science at the LHC.”

—**Jim Gates**, University System of Maryland Regents Professor of Physics

“A smashing journey.”

—*Physics World*

“**An excellent, accessible guide to one of science’s greatest discoveries** . . . vivid insights into the doing of science, including the customs of various scientific tribes at CERN.”

—*Sunday Times*

“The mix of technical description, anecdote and humour works brilliantly and feels completely fresh in my experience of science writing—it really **unlocks the holy grail of combining entertainment and understanding.**”

—*PFILM*

“**Riveting!** Gonzo journalism but in the entrails of experimental particle physics.”

—**Pedro G. Ferreira**, author of *The Perfect Theory*

“A great read if you’re curious about the Higgs boson, the work done at the LHC, what it’s like to be a physicist or how life as a research scientist has to dovetail with the ‘real’ world in terms of politics,

economics and justifying to the public why science is important and should be funded. **If you're remotely curious about the universe, read this.**"

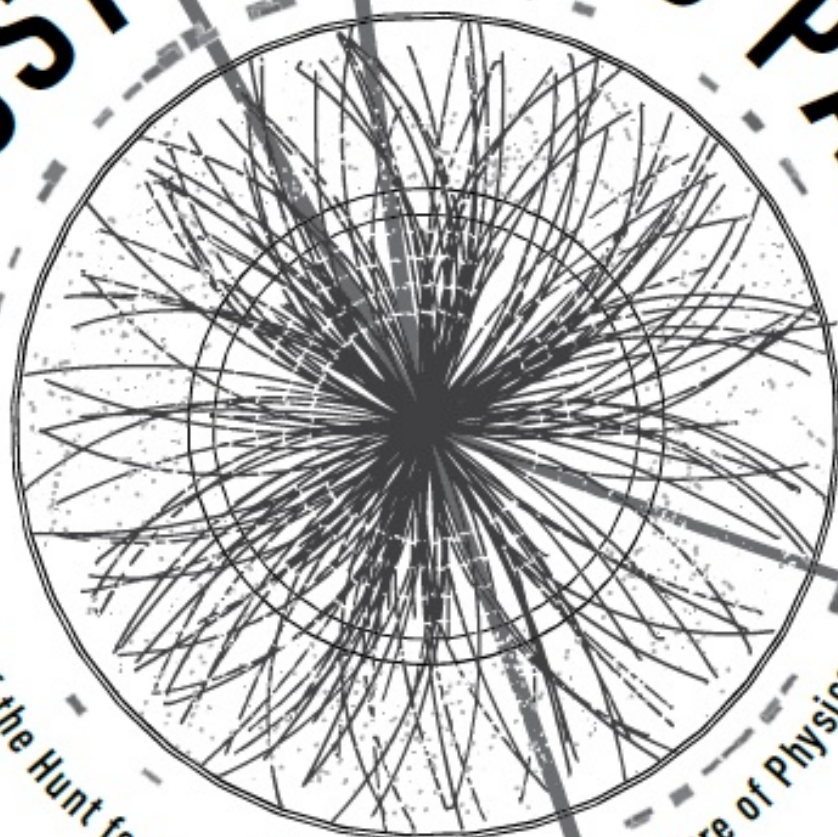
—**Steven Thompson** of Physics Steve, a theoretical physics blog



BECAUSE EVERY BOOK IS A TEST OF NEW IDEAS

MOST WANTED PARTICLE

The Inside Story of the Hunt for the Higgs, the Heart of the Future of Physics



JON BUTTERWORTH

FOREWORD BY LISA RANDALL



NEW YORK

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To Susanna, Leon, Felix and Edie

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A science is any discipline in which the fool of this generation can go beyond the point reached by the

genius of the last generation.

Max Gluckman

Foreword

On July 4, 2012, two large groups of physicists working at the Large Hadron Collider, the enormous machine near Geneva that smashes together two very energetic beams of protons in the hopes of creating matter never before observed on Earth, announced a momentous discovery. They had found the particle known as the Higgs boson.

On that day in 2012, the world that we particle physicists know and study changed forever. A prediction that Peter Higgs had made about fifty years earlier was confirmed, as was the theory of the mechanism that Higgs, the team of Robert Brout and François Englert, and several others had developed. This discovery helped physicists not only more fully understand the Standard Model of particle physics—the theory of matter’s most basic elements and interactions—but it provided theoretical physicists like me with essential information about how to grapple with the physics that underlies the Standard Model in the hopes of advancing beyond the status quo.

But for experimenters like Jon Butterworth, the Higgs discovery changed the world in a more immediate fashion. The many physicists working on the two major general-purpose LHC experiments, ATLAS and CMS, had successfully completed their first major LHC goal: to find this particle, show it did not exist, or demonstrate that a more complicated or subtle model was at work. The discovery accomplished the first of these possibilities, but also meant that the experimenters who had been so successful in this first mission now had even more work cut out for them. They could now perform the detailed measurements that would determine the new particle’s properties sufficiently well to either confirm theoretical predictions or determine that they did not precisely conform to expectation, paving the way for something new.

At the time of discovery, I was overwhelmed by what it meant for science—and also by the many questions I was being asked. As a response to this wonderful excitement and curiosity, I wrote a short book about the Higgs as a coda to *Knocking on Heaven’s Door*, which I’d written while anticipating results from the LHC. *Higgs Discovery: The Power of Empty Space* was an opportunity for me to explain both the discovery and what it meant for theoretical physicists like myself, who predict and respond to experimental results in an attempt to piece together their implications.

But Jon Butterworth has a different story to tell. He is not a theorist but an experimenter who was actively working at CERN (the facility where the LHC is located) on the ATLAS experiment and who was privy to many of the internal discussions and activities that led to that thrilling moment in July when the results were announced. Jon is the ideal experimenter to tell the story of the anticipation and preparation, the team’s experiences at the time of discovery, and the implications of the discovery for his colleagues and him. He is the rare scientist who can actively engage in research while also clearly

explaining to the public what he is doing and why it is important. He participates in groundbreaking physics research, but he is also getting the word out through his blog and his writings for the *Guardian* newspaper in Britain and elsewhere.

In fact, I think I first heard Jon Butterworth's name from his public writing. Experimental collaborations at the LHC have a few thousand people, so theorists don't immediately know them all. He also shares my fondness for Twitter as a means of communicating scientific results, so we can learn some science from each other that way, too. We are not alone in this. I was amused when, while we were out for drinks, Jon introduced me to Mark, one of his colleagues, who then promptly informed me that I knew him already from his informative ATLAS tweets. He was right. Indeed, without thinking I spouted off Mark Tibbetts' full name.

But one day in a conversation about analysis methods, I heard about some interesting analysis tools and learned that Jon was working on these, too, meaning he is not solely an excellent communicator but a true experimenter in the best sense of the word. Jon is someone who can talk to theorists and who also knows ATLAS inside and out. Most importantly for this book, he is someone who can successfully translate the process and the physics for the public while providing a sense of the experience of a physicist who is heavily involved in the cutting edge of the field.

In this book, Jon, with his delightfully nerdy self-referential humor that physicists—well, at least some of the better ones—often have, captures the wonder and elation that I and others experienced when first witnessing the machine and the experiments. Jon tells us what the LHC is, what it was designed to study, and why people work there. And his first-person account reveals what life was really like as a physicist at the LHC before, during, and after the discovery, from the initial circulating of protons in 2008, the disaster that ensued nine days later that delayed the actual physics run for a year, the following year's hard work of fixing the machine and properly readying the experiments, and finally the completion of the actual physics run.

It is a great story, and Jon's telling of it not only gives readers a visceral feel for what it was like to be there as an experimenter participating in this enormous collaboration, but teaches a lot of physics along the way. Jon conveys the excitement, the anxiety, the sleep-deprivation, and the sense of satisfaction that went into the results. He describes how the LHC, twenty-five years into its history, was responsible for the discovery of an actual new particle in the universe—one that was predicted on purely theoretical grounds and found through the hard work of scientists and engineers.

Finding the Higgs boson was one of the most amazing experimental results of my lifetime. My colleagues and I still discuss over lunch the bizarreness of its actual existence. When first contemplated, it was a theory. The model could have taken many forms. The Higgs boson was part of the simplest versions of that theory—one that doesn't even seem to fully make sense when taken in the full context. Yet it was a precise model with specific predictions that could be searched for. In fact, by the time the LHC turned on—despite the theoretical misgivings—experimental results seemed

to indicate that indeed the particle did exist and should be just barely accessible to the first major LHC implementation—even before the upgrade to higher energy that is now underway. And with the extended LHC run that finished in 2012, the anticipation culminated in the now-famous uncovering of the actual particle—buried in the mountains of data the experimenters had collected.

This book shares the joy of that discovery as well as the joy of science more generally. It also describes the challenges that science faces in the precarious political and economic climate of today. Jon's tales from the front lines of the debates over the role of science in Britain impart lessons that apply to all of us around the world. I hope Jon's book encourages people to value the amazing insights into nature that discoveries like the Higgs boson reveal, as well as inspires future generations to learn more about how our world really works.

Lisa Randall, Harvard University theoretical physicist and author of *Warped Passages*, *Higgs Discovery*, and *Knocking on Heaven's Door*

Introduction

There is a kebab restaurant in the Meyrin suburb of Geneva that has half a dozen pool tables. In early July 2012, I found myself playing pool with Tom Clarke, the science correspondent of Channel News, one of the UK's major TV news bulletins, by way of trying to explain to him and his viewers the significance of the discovery we had just made at the Large Hadron Collider.

I still find that last sentence amazing – both the discovery and the huge public interest demonstrated by the fact that Tom, along with many other journalists, came out for a day and spoke to dozens of physicists. His report was the lead item on the 4 July bulletin.

The discovery we announced that day was a huge step forward in physics. The public interest was a significant milestone in people's increasing engagement with the science that lies behind our civilisation. I really mean the science, not just the technology but the processes of science – to what extent it is self-correcting, and what constitutes scientific certainty (very little!) and scientific knowledge (a lot!).

Meyrin is significant here because CERN, the European laboratory for particle physics, is just five minutes up the road. Meyrin village is quite picturesque, but the part Tom and I were in, Cité Meyrin, is a series of blocks of flats that would be a urine-smelling, graffiti-ridden concrete jungle pretty much anywhere else in the world. However, because this is Switzerland (just – by about 100m) it is a clean, orderly concrete jungle. It is also where many of the scientists working at CERN stay.

I work for University College London (UCL), but, along with many particle physicists from all over the world, I do most of my research at CERN. The UCL commuter flat is in Meyrin, and many colleagues and I spend a lot of time there. In particular, I ran a working group on the ATLAS experiment at CERN from October 2010 to October 2012, the period during which we got our first flood of high-energy data. During that time, I was there more or less every week.

This book is not a physics textbook; it is not a historical account of the discovery of the Higgs boson; it is not a diary; and it is not a manifesto for greater engagement between scientists and the general public. It does contain elements of all these things, however. You will learn a lot about particle physics and what it is like to be a particle physicist, about how science works (and occasionally doesn't), about how research sometimes struggles to thrive and survive, and about the people who do it, including a bunch of personal opinions from me. I hope it will also explain why Tom Clarke and much of the world's media descended on Meyrin that July.

To get that far, though, I need to introduce a number of interconnected and probably unfamiliar pieces of information. Some of them won't seem very relevant the first time they appear, like isolated pieces of a jigsaw puzzle, but as you collect them through the book, hopefully they will start

reinforce each other and in the end the full picture will emerge. And if I succeed, you'll have fun as you follow the story collecting the pieces – and gain a sense of excitement. Because fun and excitement are the two impressions that dominate my memory of the first high-energy run of the biggest scientific apparatus ever constructed: the Large Hadron Collider.

Before the Data

1.1 Why So Big?

The Large Hadron Collider (LHC) sits in a tunnel 27km (nearly 17 miles) long and about 100m (almost 330 feet) underground. If you know London, it might help you to know that 27km is about as long as the Circle Line on the Underground, and the tunnel itself is similar in size to the Northern Line. If that doesn't help, then try this.

Imagine setting off from Meyrin, on the Swiss–French border near the airport, and driving towards the French countryside. The Jura Mountains are in front of you, Geneva Airport is behind. As you pass the border, you also pass the main site of the CERN laboratory on your left, and if you look to the right you will see a big wooden globe that looks like a sort of eco-nuclear reactor (it's not, it's an exhibition space, though it is eco-friendly, apparently), and you might catch a glimpse of the building housing the control room of the ATLAS experiment. You will know it if you see it, because it has a huge mural of the ATLAS detector itself on the wall.

Big though it is, the mural is painted to only one-third scale. ATLAS is very large, and is hidden underground, positioned at one of the interaction points of the LHC. These are the points where the two highest-energy particle beams in the world are brought into head-on collision. ATLAS is one of the two big general-purpose particle detectors designed to measure the results of these collisions.

Continue driving. You may imagine yourself in a nerdy little white van with a CERN logo on the side if this helps.

Pass through the village of St-Genis and continue into the Pays de Gex, in the foothills of the Jura Mountains. You are now surrounded by the LHC. If you are imagining yourself in winter, you might see the lifts of Crozet, the little Monts Jura ski resort, chugging away ahead of you. (Mont Blanc is behind you on the horizon, but keep your eyes on the road.) Keep driving, bear right towards Gex, maybe pass through the villages of Pregnin, Vézaz and Brétigny. After about 25 minutes' driving through the French countryside – longer if you get stuck behind a tractor – you will get to the village of Cessy, near Gex. Here you will find the top of the shaft that leads down to CMS, the other big general-purpose detector on the LHC ring. ATLAS and CMS are independent rivals, designed differently by different collaborations of physicists, but with the same goal: to measure as well as possible the particles produced when protons collide in the LHC. They were designed to cross-check

each other's observations, and to compete head-to-head for the quickest and best results.

All this time, on your journey from ATLAS to CMS, you have been inside the circumference of the world's biggest physics experiment. You entered it at the border when you passed ATLAS, and have now crossed its diameter.

The LHC is designed to collide subatomic particles at the highest energies ever achieved in a particle accelerator. We do this to study the fabric of the universe at the smallest distances possible, which for reasons to be described later also implies the highest energies possible. Given that the experiment is designed to look at very small things, it might be a surprise that it is so big. Building a long tunnel is very expensive, so why not make a smaller one?

In fact, it is the length of the tunnel that limits the energy of the colliding beams. If you accept the fact that to study small stuff you need high energies (please do, for now at least), you can understand why the LHC needs to be so big just from an understanding of fairly everyday physics.

Particles travel in a straight line at a constant speed, unless a force acts on them. This is one of Newton's laws of motion. In everyday life it isn't completely obvious (Newton was quite clever to work it out), but once you are aware of it, it is easy to see it in action.

The reason it is not completely obvious in everyday experience is that on Earth practically everything that moves has forces due to friction and air resistance acting on it, and everything also experiences gravity. This is why if you set a ball rolling, it will eventually stop. Friction and air resistance act on it to slow it down. And if you throw a ball in the air, gravity will slow it down and eventually drag it back.

But in situations where friction or gravity can be ignored, things are clearer. Driving a fast car, or even a nerdy CERN van, you clearly have to apply a force, via the brakes, to slow it down. And more relevantly in the context of the LHC, if you want to change direction, to turn a corner at speed, this can only be done if there is sufficient friction between the tyres of the van and the road. Otherwise, you will skid.

The driver and passengers experience a rapid turn of a corner as a sort of 'pseudo-force'. The van is turning, but your body wants to carry on in a straight line, so you feel as though you are being pressed against the sides of the van. It would be more true to our understanding of physics to think of the sides of the van as pushing against you, to force you to change direction, pushing you round the corner along with the vehicle.

The combination of speed and direction is called velocity. And if you combine the velocity with the mass of the object (the van, for example, or the passenger), you get the momentum. The bigger the mass, or the velocity, the bigger the momentum, and if you want to change the momentum of something, you need to apply a force to it.

I am being deliberately vague about how the velocity and mass combine to give momentum. At speeds much lower than the speed of light, it is good enough to just multiply – momentum is mass

times velocity – and this is probably the right answer if you are taking a school course in physics. However, the exact expression is a little different, and the difference gets more and more important as speeds approach the speed of light. Then you need Einstein and relativity (of which more later), rather than Newtonian mechanics. But don't try this in a van.

Regardless of that, the larger the desired change in momentum, the bigger the force has to be. Hence the brakes on a lorry need to be able to exert more force than the brakes on a van, because even if the velocity is the same, the mass of the lorry is bigger so the change in momentum involved in making it stop is bigger.

This is the situation of the protons in the LHC tunnel. These are the highest-energy, and highest-momentum, subatomic particles ever accelerated in a laboratory. Even though the mass of a proton is tiny, their speed is tremendously high. They are really, really determined to travel in a straight line. So, to make the two beams of protons bend around the LHC and come into collision requires a huge force. The force is provided by the most powerful bending magnets we could build.

Given this maximum force, there is then a trade-off between how sharp the bend in the accelerator is and how high the proton momentum can be. Back to the van: this is exactly equivalent to the fact that there is a maximum speed at which you can take a given corner without skidding. If the corner is sharp, the speed has to be low, but for a gentle curve you can go faster. This, then, is why the LHC is so big. A big ring has more gentle curvature than a small one, and so the protons can get to higher momentum without 'skidding'. Or, in their case, 'catastrophically escaping the LHC and vaporising expensive pieces of magnet or detector'. Something to be avoided.

The maximum bending power of magnets is thus the reason that proton accelerators need to be large if they are to get to high energies. For the other commonly collided particle, the electron, there is another reason that is worth looking at.

Before the LHC was installed, another machine occupied the 27km tunnel under the Swiss-French border. This was LEP – the Large Electron-Positron Collider. (Positrons are the antiparticle of the electron, carrying positive charge, in contrast to the electron's negative. LEP collided electrons and positrons together. Incidentally, people occasionally accuse particle physicists of hyping-up the equipment, but these are very descriptive, even dull, names.) LEP was turned off in the year 2000 because it had explored most of the physics within its reach and could not increase its energy further. The reason it could not go higher was, as with all the protons, also connected to the size of the tunnel, but in a different way.

This is to do with the fact that electrons have a mass about 1800 times smaller than the proton. Now, at the highest energies that doesn't make any significant difference to the force required to bend them round a corner. This is because, whether they are electrons or protons, they are moving very close to the speed of light, so you need the full special relativity expression for momentum, and the net result is that the mass they have when they are at rest is irrelevant for calculating the required

force. So that wasn't the problem.

The problem was synchrotron radiation. This is the energy radiated by charged particles when they are accelerated. It is a universal phenomenon, roughly analogous to the wave a speedboat makes when it turns in the water. As a charged particle accelerates round a corner, photons fly off and carry away energy.

The effect is actually much more pronounced for particles with low mass. The amount of synchrotron radiation given off when a particle accelerates depends very strongly on the mass: if the particle mass drops, the energy loss increases by the mass-drop to the fourth power. So, as the proton mass is 1800 times bigger, the energy lost on the bends for electrons is $(1800 \times 1800 \times 1800 \times 1800)$ or about 11 trillion times larger than it is for protons.

As the electrons and positrons squealed round the corners of LEP, photons were radiated that way, and with every revolution of the beam around the ring, more energy had to be pumped in to compensate. This is done by radio-frequency electromagnetic waves confined in big metal structures at intervals around the ring. Electric and magnetic fields oscillate in these structures precisely in time with the passing of the bunches of electrons, so that every time a bunch arrives it gets a kick from the field. This is true in all such machines. But at some point you reach a beam energy where so much is lost in synchrotron radiation that the electromagnetic waves in those structures cannot replace it. That's your maximum collision energy. LEP hit that wall.

This is where the size of the tunnel comes in again, of course. A 27km tunnel has a rather gentle curve. If it were smaller, the bends would be sharper, the acceleration would need to be bigger, so the energy lost through synchrotron radiation would be greater, and the maximum collision energy would be lower.

As an aside, this synchrotron radiation is very useful in other contexts. The Diamond Light Source at Harwell in Oxfordshire, in South East England, for example, was built to produce synchrotron radiation intentionally. The radiated beams of photons are used to study atoms, crystals, molecules, materials and surfaces. Many machines and laboratories originally built to study particle physics have been converted to become light sources once they have been superseded in the quest for higher energies. I have reason to be grateful for this personally, in fact. I did my doctoral work in Hamburg, at the DESY (Deutsches Elektronen-Synchrotron) laboratory. The particle physics of interest there at the time was the HERA electron-proton collider, where I worked in the ZEUS collaboration, the team of physicists responsible for one of the main particle detectors at the laboratory. But my then girlfriend was a crystallographer, using synchrotron light to work out the structure of proteins and other stuff. Because of the symbiotic relationship between particle-physics accelerators and synchrotron light sources, there is a branch of the European Molecular Biology Lab at DESY, and after a high-level discussion in the crowd at a St Pauli football match, Susanna managed to get her PhD supervisor to send her to Hamburg for most of her research. We've been married 20 years now, and it's all very fine and

romantic. But synchrotron radiation is still a pain in the arse if you want a high-energy electron beam

So, LEP was shut down in 2000 and dismantled, and installation of the LHC began. The LHC can get to higher energies because it collides protons with 11 trillion times less of a synchrotron radiation problem, but it requires the most powerful bending magnets you can make if you want to get to the highest possible momentum.

The formal approval for construction of ATLAS and CMS was given on 1 July 1997 by the then Director General of CERN, Chris Llewellyn Smith.¹

LEP had been good, but the protons promised more.

1. Incidentally, a man who previously, as head of physics at Oxford and afterwards as provost of UCL, seems to have had a period of following me around and being my boss.

Glossary: The Standard Model Particles and Forces

If you just want to crack on with the story and don't mind the odd unfamiliar word, you can skip these 'Glossary' bits. But without knowing something about the Standard Model, some of it might not make much sense.

The Standard Model of particle physics is our current best answer to the question 'What is stuff made of, if you break it down into its smallest components?'

Start with anything – a rock, the air, this book, your head – and pull it into its component parts (I recommend this remains a thought experiment). You will find fascinating layers of structure, micro- and nano-scale bits and pieces: fibres, cells, mitochondria.

You will eventually find molecules. With enough energy you can break them apart into component atoms. Atoms consist of a dense nucleus surrounded by electrons.

With a bit more energy, you can separate the electrons from the nucleus. With more energy still, the nucleus can be broken into protons and neutrons. With still more energy (and now you do need a big collider!), you can see quarks inside those protons and neutrons.

We have never managed to see anything inside a quark, or break one into pieces.

If, at the 'atom-smashing' stage, we had ignored the nucleus and tried breaking up the electron, we'd have reached that point earlier. We have never managed to see anything inside an electron, or break one into pieces. This – the fact that we haven't managed to break one yet – is our working definition of what it means for a particle to be 'fundamental'.

And a key point is that wherever we had started, with whatever material, we would have ended up with electrons and quarks. In the Standard Model, they are the stuff that everything is made of, and they themselves are not made of other stuff.

You will come across a lot of particles in this book, but remember, there aren't many different kinds of fundamental ones when you get right down to it.

Electrons are an example of a class of particles called leptons. There are also muons and taus, which are just like electrons only heavier. The only other leptons are the three kinds of neutrino. Neutrinos do not interact much with other matter, but there are lots of them around. More than a trillion neutrinos pass through you from the Sun every second.

The other class of fundamental-matter particles consists of the quarks. There are six of them, too, just as there are six lepton types. They are called up, down, strange, charm, bottom and top, becoming more massive as you go (but peaking on whimsy in the middle).

Protons and neutrons are made of up and down quarks. Quarks are never found out on their own, they are always stuck together in bigger particles. These particles, the ones made of quarks, are generically called hadrons (hence the Large Hadron Collider, which mostly collides protons but occasionally collides atomic nuclei, which also have neutrons inside).

Those are all the matter particles we know of. They all have anti-particle partners, and they all interact with each other – attracting, repelling, scattering – via forces, which are carried by another kind of particle – vector bosons.

The electromagnetic force is carried by photons (quanta of light) and is experienced by all charged particles. That is, everything except the neutrinos.

The strong force, which holds protons, neutrons, and atomic nuclei together, is carried by gluons, and is only experienced by the quarks.

The weak force is carried by W and Z bosons, and all particles experience this. The weak force is responsible for radioactive beta decay, amongst other things, but because it is weak, it does not feature much in everyday life. Even so, it is crucial to how the Sun works.

To make the Standard Model work, and in particular to allow the fundamental particles to have mass, another unique and completely new object is also required – a Higgs boson. The hunt for this is, of course, the main topic of this story and I'll say much more about it later.

Gravity doesn't fit into the Standard Model. It is described by Einstein's theory of general relativity, but we do not know how to make a working quantum theory of that.

Those are the actors on the stage of the universe. There are lots of open questions in physics, but an astonishingly wide array of data – most of physics, chemistry and biology – from very large to very small distance scales, can be described astonishingly accurately by just these elements: quarks, leptons and the four forces between them, and the Higgs boson.

1.2 The 'No Lose' Theorem

I didn't begin working seriously on the LHC until around 2001. That was about nine years before we got our first high-energy collisions. Believe it or not, this makes me a bit of a Johnny-come-lately to the experiment. Options for a large hadron collider had already been considered in the design of the

27km tunnel for LEP, and were mentioned in the LEP design report in 1984, when I was just finishing secondary school and moving to sixth-form college. There would be many years of scientific, technical, financial and political discussions, followed by R & D, simulation and more politics, before the LHC gained approval in 1997.

Back in 1997, I had just moved to London from Hamburg and was still completely absorbed with my work at HERA. It is a feature of big collaborations that you accumulate responsibilities along with a large bank of experience and expert knowledge that can make it hard to disengage. It is difficult to climb a new learning curve on another experiment, with its confusing software and hardware and unfamiliar physics. Sometimes you need a bit of a shove to really start doing something else.

For me, bizarrely, the shove was the birth of my first child. This was such an overriding priority that I managed to say no to a whole bunch of managerial and technical roles within the ZEUS collaboration. I wanted no responsibilities that would conflict with the terrifying challenges of looking after Susanna during her pregnancy and of being a dad after it.

As it turned out, the whole thing went very smoothly and was generally wonderful. So, as a bonus, I had lots of free time to think creatively about physics. One of the things I'd long been wanting to do was read enough and think enough to get my head around physics at the LHC, which was by then under construction at CERN. This holiday from HERA heat was the opportunity. With a couple of friends, Jeff and Brian, also HERA physicists,² I'd been thinking about what we might do and what the most exciting things to study would be. We were all very sceptical about new 'Beyond the Standard Model' physics and were keen to work on measurements of real things that would actually happen, rather than seeking evidence for speculative ideas to which we accorded little credibility. I think this may have been because we all came from a HERA background, where precision measurement was the main goal. Although to be honest, the main legacy of LEP was also precision measurement, so maybe it made no difference.

2. Jeff Forshaw and Brian Cox, who amongst other things have also written physics books, though not about this yet.

Anyhow. Not only did we not believe in such things as supersymmetry, or large extra dimensions or Technicolor, all of them speculative extensions of the Standard Model designed to solve some of the problems with it. We didn't even believe in the Higgs boson – an integral part of the Standard Model, but one lacking experimental verification. So we asked ourselves, 'What is the most important and interesting thing to measure if there are no new particles?' A pessimist's approach, perhaps, but still fun.

The answer we came up with³ was vector-boson scattering. This is a peculiar and rare scattering process that is expected to happen occasionally in very high-energy collisions, and it lay behind what was called the 'no lose' theorem at the LHC. It is very deeply connected to the reasons why the Higgs

boson is so important. So it wasn't a bad choice for a first bit of LHC physics for us to look at, and it's worth spending a bit of time on now.

3. After some reading around – I'm not claiming we were the first to think of this!

Vector bosons are force carriers. The photon, which is the quantum of light and carries the electromagnetic force, is a vector boson. Of more interest here, though, are the W, and to some extent the Z, bosons. These carry the weak force, and one of the oddest things about them is that, unlike the photon, they have mass.

In a proton–proton collision at the LHC, you have to picture two quarks, one from a proton in each beam, zooming towards each other. There is a small but non-zero chance that, as they do this, each will radiate a W boson. There's an even smaller, but still non-zero, chance that these W bosons will hit each other. That is vector-boson scattering – WW scattering in this case. It could happen with Zs or photons too. There are a bunch of different ways the bosons can bounce off each other, or fuse together and break up again. As is always the case in quantum mechanics, all the possibilities have to be taken into account and combined⁴ – sometimes they add up, sometimes they subtract from each other. Put the whole thing together and you get the probability of the WW scattering occurring.

4. This includes taking into account time orderings other than the quarks-emit-Ws-that-then-collide one I gave here.

The 'no lose' theorem came from this calculation. Some of those scattering possibilities include a Higgs boson, and at the time there was no direct evidence for such a beast. However, if you do the sum and do not include a Higgs boson, then as you go to higher and higher energies, the probability of WW scattering grows and grows.⁵ At some point you get nonsense answers involving probabilities bigger than one, or infinities. That is just a sign that your theory is broken – there won't be infinities in nature – but what it meant was that either a Higgs boson would be discovered at the LHC, or some other new physics would come into play and keep the calculation sane.

5. The possibilities involving the Higgs would contribute with a negative sign, and so they would stop this happening.

So in the pessimist's scenario of no Higgs boson, no black holes, whatever, measuring WW scattering might well be the only, or best, clue as to what was going on. It certainly had to involve either a Higgs boson or something else new – hence the 'no lose' theorem. By studying these scatterings we were certain we would discover some interesting physics.

Measuring WW scattering properly would be difficult, and we found lots of fun challenges. The University of Manchester had done a deal with Apple and had a big new farm of Macs that had ju

started running Unix (OSX), making them useful to us (if still more expensive than the Linux box everyone else had). I have fond memories of sitting in a flat in Saddleworth, feeding the farm with lots of simulation jobs to test our ideas, then popping over the road to the pub for beer and dinner to argue about newer ideas. This was still before my son was born, but I had already divested myself of lots of other responsibilities. We submitted the paper in January 2002 and it was more or less ignored for several years, though it later became more fashionable and I'm very proud of it. One of the ideas we used turned out to be quite widely useful and would feature in the Higgs search itself.

1.3 People Are Going to Be Interested in This . . .

While work was going on at CERN and around the world to construct the LHC and its detectors, it became increasingly obvious that quite a lot of people were going to be interested in the project, for all kinds of reasons. For the engineering and science, of course. But also because of the sheer scale, including the cost of the thing. The international collaboration and the sociology of several thousand physicists working together were intriguing to quite a few people, including academics in social sciences. Plus, of course, there were the two or three delusional publicity-seekers who thought, or claimed to think, that we were about to destroy Switzerland. Or the world. Or the entire universe.

The last bunch – the delusionists and conspiracy theorists – were bound to get lots of media coverage, ‘because of balance’.⁶ The only way to deal with that is to get real information out there. Also, since the European taxpayer had been investing something like the equivalent of a billion euros in CERN every year, we really owed it to people to explain what we'd done with the cash, and why.

6. To quote David Shiffman: ‘World's leading experts say there's a problem with false balance in environmental journalism, but Steve disagrees.’

Thoughts like these were passing through the minds of many people involved, including, I am sure, James Gillies, the head of communications at CERN, and many good science journalists. This was presumably why, in 2008, the doors of CERN were flung open to the world's media for ‘Big Bang Day’, when we switched on the machine.

Such thinking was certainly one reason why I agreed to be part of a series of short documentary films called *Colliding Particles*. These were a sort of ‘fly on the wall’ affair that started in the summer of 2008. Mike Paterson was the cameraman, producer, interviewer and director – everything in fact, except animator and occasionally soundman. He won some support from the Science and Technology Facilities Council (STFC), the research council that funds particle physics in the UK, to make the films. They were aimed at schools, specifically at a then new part of the curriculum based on learning how science works. Apparently pupils would learn this by watching some physicists from behind Mike's camera.

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