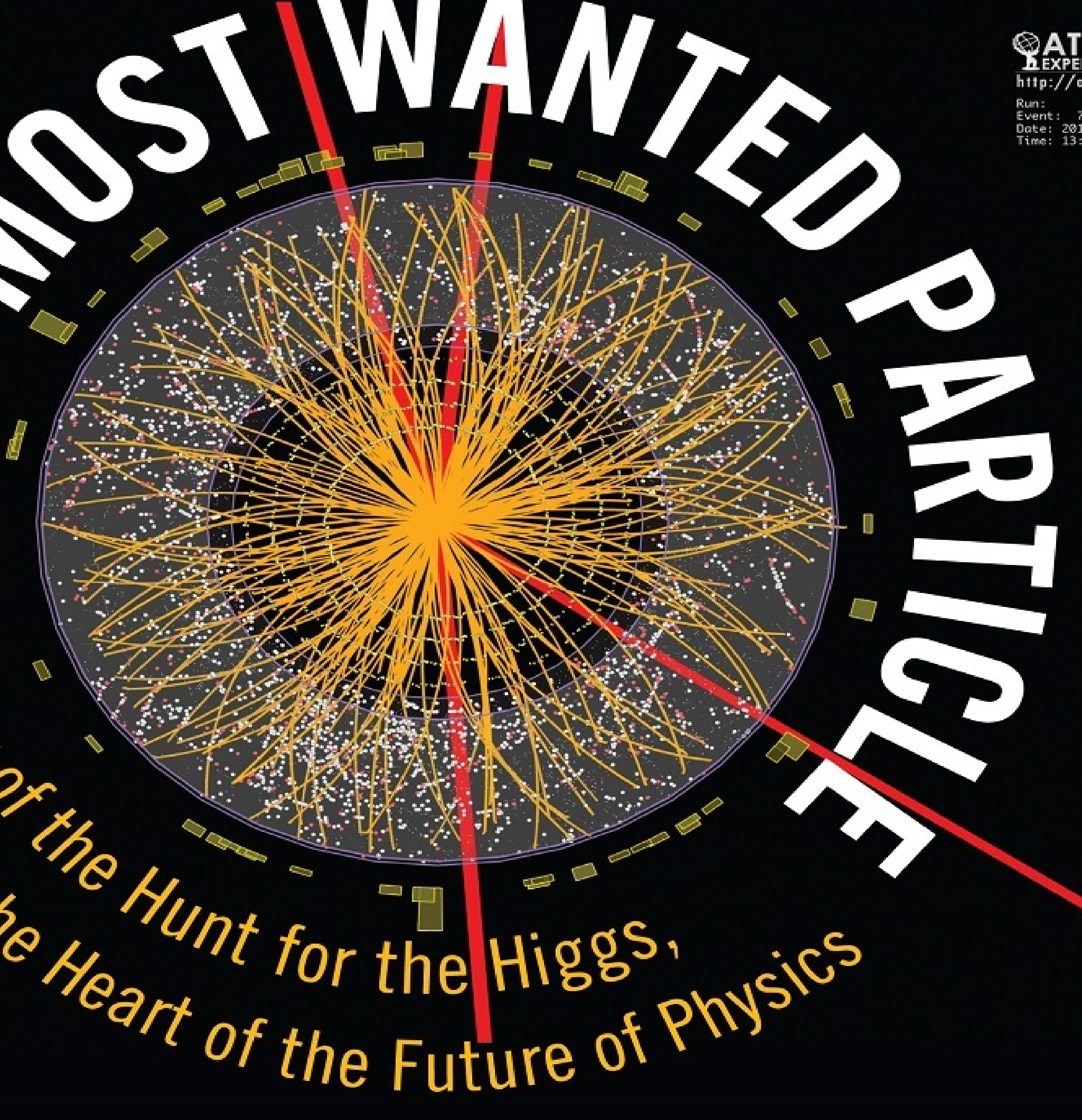
"Jon Butterworth is an experimentalist and is the first to give **a vivid account of what the process of discovery was really like** for an insider."
—**PETER HIGGS,** Winner of the Nobel Prize in Physics

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

PRAISE FOR

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 experimentalis 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 characte 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 hi to tell: a breezy recounting of the discovery of the Higgs boson that turns out to be both **an accessibl 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 Discove 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 discover . . . 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 moment of peril and uncertainty to reach the triumphant discovery of the Higgs Boson. It is **a great chronicl** 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 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

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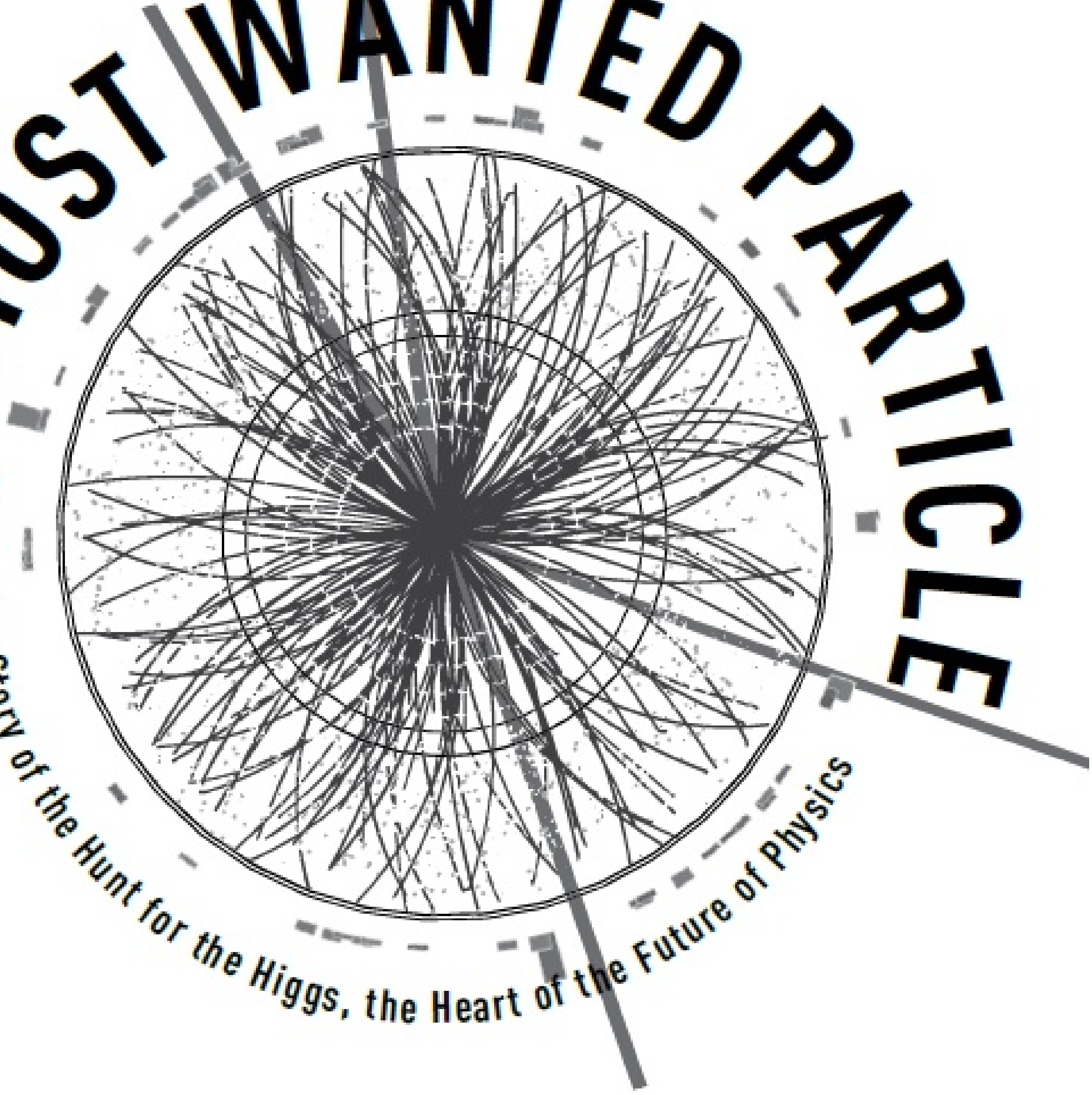

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To Susanna, Leon, Felix and Edie

Contents

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

Max Gluckma

Foreword

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

On that day in 2012, the world that we particle physicists know and study changed forever. prediction that Peter Higgs had made about fifty years earlier was confirmed, as was the theory of th mechanism that Higgs, the team of Robert Brout and François Englert, and several others ha developed. This discovery helped physicists not only more fully understand the Standard Model particle physics—the theory of matter's most basic elements and interactions—but it provide theoretical physicists like me with essential information about how to grapple with the physics th 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 mo immediate fashion. The many physicists working on the two major general-purpose LHC experiment ATLAS and CMS, had successfully completed their first major LHC goal: to find this particle, show did not exist, or demonstrate that a more complicated or subtle model was at work. The discove accomplished the first of these possibilities, but also meant that the experimenters who had been s successful in this first mission now had even more work cut out for them. They could now perform th detailed measurements that would determine the new particle's properties sufficiently well to eith 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 mar questions I was being asked. As a response to this wonderful excitement and curiosity, I wrote a sho book about the Higgs as a coda to *Knocking on Heaven's Door*, which I'd written while anticipatir results from the LHC. *Higgs Discovery: The Power of Empty Space* was an opportunity for me explain both the discovery and what it meant for theoretical physicists like myself, who predict ar 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 w actively working at CERN (the facility where the LHC is located) on the ATLAS experiment and wh was privy to many of the internal discussions and activities that led to that thrilling moment in Ju when the results were announced. Jon is the ideal experimenter to tell the story of the anticipation ar preparation, the team's experiences at the time of discovery, and the implications of the discovery fo his colleagues and him. He is the rare scientist who can actively engage in research while also clear explaining to the public what he is doing and why it is important. He participates in groundbreakin physics research, but he is also getting the word out through his blog and his writings for the *Guardi* newspaper in Britain and elsewhere.

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

But one day in a conversation about analysis methods, I heard about some interesting analys tools and learned that Jon was working on these, too, meaning he is not solely an excelle communicator but a true experimenter in the best sense of the word. Jon is someone who can talk theorists and who also knows ATLAS inside and out. Most importantly for this book, he is someon who can successfully translate the process and the physics for the public while providing a sense 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 lea some of the better ones—often have, captures the wonder and elation that I and others experienc when first witnessing the machine and the experiments. Jon tells us what the LHC is, what it designed to study, and why people work there. And his first-person account reveals what life wa really like as a physicist at the LHC before, during, and after the discovery, from the initial circulatin protons in 2008, the disaster that ensued nine days later that delayed the actual physics run for a yea the following year's hard work of fixing the machine and properly readying the experiments, a 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 li to be there as an experimenter participating in this enormous collaboration, but teaches a lot physics along the way. Jon conveys the excitement, the anxiety, the sleep-deprivation, and the sense satisfaction that went into the results. He describes how the LHC, twenty-five years into its histor was responsible for the discovery of an actual new particle in the universe—one that was predicted 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. M colleagues and I still discuss over lunch the bizarreness of its actual existence. When fir contemplated, it was a theory. The model could have taken many forms. The Higgs boson was part the simplest versions of that theory—one that doesn't even seem to fully make sense when taken the full context. Yet it was a precise model with specific predictions that could be searched for. fact, by the time the LHC turned on—despite the theoretical misgivings—experimental results seem to indicate that indeed the particle did exist and should be just barely accessible to the first major LH implementation—even before the upgrade to higher energy that is now underway. And with th extended LHC run that finished in 2012, the anticipation culminated in the now-famous uncovering 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 als describes the challenges that science faces in the precarious political and economic climate of toda Jon's tales from the front lines of the debates over the role of science in Britain impart lessons th apply to all of us around the world. I hope Jon's book encourages people to value the amazing insigh into nature that discoveries like the Higgs boson reveal, as well as inspires future generations to lea more about how our world really works.

Lisa Randall, Harvard University theoretical physicist and author of *Warped Passages*, *Hig 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 ear 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 viewe 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 intere demonstrated by the fact that Tom, along with many other journalists, came out for a day and spoke 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 w a significant milestone in people's increasing engagement with the science that lies behind o civilisation. I really mean the science, not just the technology but the processes of science – to wh extent it is self-correcting, and what constitutes scientific certainty (very little!) and scientif knowledge (a lot!).

Meyrin is significant here because CERN, the European laboratory for particle physics, is ju five minutes up the road. Meyrin village is quite picturesque, but the part Tom and I were in, Ci Meyrin, is a series of blocks of flats that would be a urine-smelling, graffiti-ridden concrete jung pretty much anywhere else in the world. However, because this is Switzerland (just – by about 100n 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 a over the world, I do most of my research at CERN. The UCL commuter flat is in Meyrin, and m colleagues and I spend a lot of time there. In particular, I ran a working group on the ATLA experiment at CERN from October 2010 to October 2012, the period during which we got our fi 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 Hig boson; it is not a diary; and it is not a manifesto for greater engagement between scientists and t general public. It does contain elements of all these things, however. You will learn a lot abou particle physics and what it is like to be a particle physicist, about how science works (a occasionally doesn't), about how research sometimes struggles to thrive and survive, and about t people who do it, including a bunch of personal opinions from me. I hope it will also explain why To 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 unfamili pieces of information. Some of them won't seem very relevant the first time they appear, like isolat 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 a you follow the story collecting the pieces – and gain a sense of excitement. Because fun ar excitement are the two impressions that dominate my memory of the first high-energy run of th biggest scientific apparatus ever constructed: the Large Hadron Collider.

ONE

Before the Data

1.1 Why So Big?

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

Imagine setting off from Meyrin, on the Swiss–French border near the airport, and drivi towards the French countryside. The Jura Mountains are in front of you, Geneva Airport is behind. A you pass the border, you also pass the main site of the CERN laboratory on your left, and if you loo to the right you will see a big wooden globe that looks like a sort of eco-nuclear reactor (it’s not, it an exhibition space, though it is eco-friendly, apparently), and you might catch a glimpse of th building housing the control room of the ATLAS experiment. You will know it if you see it, because 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 hidde underground, positioned at one of the interaction points of the LHC. These are the points where th two highest-energy particle beams in the world are brought into head-on collision. ATLAS is one o 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 th side if this helps.

Pass through the village of St-Genis and continue into the Pays de Gex, in the foothills of the Ju Mountains. You are now surrounded by the LHC. If you are imagining yourself in winter, you migh see the lifts of Crozet, the little Monts Jura ski resort, chugging away ahead of you. (Mont Blanc behind you on the horizon, but keep your eyes on the road.) Keep driving, bear right towards Ge maybe pass through the villages of Pregnin, Véraz and Brétigny. After about 25 minutes’ drivin through the French countryside – longer if you get stuck behind a tractor – you will get to the villa of Cessy, near Gex. Here you will find the top of the shaft that leads down to CMS, the other b general-purpose detector on the LHC ring. ATLAS and CMS are independent rivals, designe differently by different collaborations of physicists, but with the same goal: to measure as well possible the particles produced when protons collide in the LHC. They were designed to cross-chec 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 o
the world’s biggest physics experiment. You entered it at the border when you passed ATLAS, an
have now crossed its diameter.

The LHC is designed to collide subatomic particles at the highest energies ever achieved in
particle accelerator. We do this to study the fabric of the universe at the smallest distances possibl
which for reasons to be described later also implies the highest energies possible. Given that th
experiment is designed to look at very small things, it might be a surprise that it is so big. Building
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 acce
the fact that to study small stuff you need high energies (please do, for now at least), you ca
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
Newton’s laws of motion. In everyday life it isn’t completely obvious (Newton was quite clever
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 practical
everything that moves has forces due to friction and air resistance acting on it, and everythin
experiences gravity. This is why if you set a ball rolling, it will eventually stop. Friction and a
resistance act on it to slow it down. And if you throw a ball in the air, gravity will slow it down an
eventually drag it back.

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

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

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

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

times velocity – and this is probably the right answer if you are taking a school course in physic

However, the exact expression is a little different, and the difference gets more and more important a speeds approach the speed of light. Then you need Einstein and relativity (of which more later), rath 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 b Hence the brakes on a lorry need to be able to exert more force than the brakes on a van, because eve if the velocity is the same, the mass of the lorry is bigger so the change in momentum involved making it stop is bigger.

This is the situation of the protons in the LHC tunnel. These are the highest-energy, and highes momentum, subatomic particles ever accelerated in a laboratory. Even though the mass of a proton tiny, their speed is tremendously high. They are really, really determined to travel in a straight lin So, to make the two beams of protons bend around the LHC and come into collision requires a hug 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 th accelerator is and how high the proton momentum can be. Back to the van: this is exactly equivale to the fact that there is a maximum speed at which you can take a given corner without skidding. If th corner is sharp, the speed has to be low, but for a gentle curve you can go faster. This, then, is why th 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 an 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 b large if they are to get to high energies. For the other commonly collided particle, the electron, there 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 o the electron, carrying positive charge, in contrast to the electron's negative. LEP collided electron 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 200 because it had explored most of the physics within its reach and could not increase its energy furthe The reason it could not go higher was, as with all the protons, also connected to the size of the tunne but in a different way.

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

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

The effect is actually much more pronounced for particles with low mass. The amount synchrotron radiation given off when a particle accelerates depends very strongly on the mass: if th particle mass drops, the energy loss increases by the mass-drop to the fourth power. So, as the proto mass is 1800 times bigger, the energy lost on the bends for electrons is (1800 x 1800 x 1800 x 180 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 th way, and with every revolution of the beam around the ring, more energy had to be pumped in compensate. This is done by radio-frequency electromagnetic waves confined in big metal structur at intervals around the ring. Electric and magnetic fields oscillate in these structures precisely in tin with the passing of the bunches of electrons, so that every time a bunch arrives it gets a kick from th field. This is true in all such machines. But at some point you reach a beam energy where so much lost in synchrotron radiation that the electromagnetic waves in those structures cannot replace 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 gent curve. If it were smaller, the bends would be sharper, the acceleration would need to be bigger, so th energy lost through synchrotron radiation would be greater, and the maximum collision energy woul be lower.

As an aside, this synchrotron radiation is very useful in other contexts. The Diamond Lig Source at Harwell in Oxfordshire, in South East England, for example, was built to produce intentionally. The radiated beams of photons are used to study atoms, crystals, molecules, materia and surfaces. Many machines and laboratories originally built to study particle physics have bee converted to become light sources once they have been superseded in the quest for higher energies. have reason to be grateful for this personally, in fact. I did my doctoral work in Hamburg, at the DES (Deutsches Elektronen-Synchrotron) laboratory. The particle physics of interest there at the time wa the HERA electron–proton collider, where I worked in the ZEUS collaboration, the team of physicis responsible for one of the main particle detectors at the laboratory. But my then girlfriend was crystallographer, using synchrotron light to work out the structure of proteins and other stuff. Becau of the symbiotic relationship between particle-physics accelerators and synchrotron light source there is a branch of the European Molecular Biology Lab at DESY, and after a high-level discussion i the crowd at a St Pauli football match, Susanna managed to get her PhD supervisor to send her Hamburg for most of her research. We've been married 20 years now, and it's all very fine an 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 ca get to higher energies because it collides protons with 11 trillion times less of a synchrotron radiatic problem, but it requires the most powerful bending magnets you can make if you want to get to th highest possible momentum.

The formal approval for construction of ATLAS and CMS was given on 1 July 1997 by the the 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 v got our first high-energy collisions. Believe it or not, this makes me a bit of a Johnny-come-lately the experiment. Options for a large hadron collider had already been considered in the design of th

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

Back in 1997, I had just moved to London from Hamburg and was still completely absorbed work at HERA. It is a feature of big collaborations that you accumulate responsibilities along with bank of experience and expert knowledge that can make it hard to disengage. It is difficult to climb new learning curve on another experiment, with its confusing software and hardware and unfamili 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 priori that I managed to say no to a whole bunch of managerial and technical roles within the ZEU collaboration. I wanted no responsibilities that would conflict with the terrifying challenges of lookin 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 bonus, I had lots of free time to think creatively about physics. One of the things I'd long bee wanting to do was read enough and think enough to get my head around physics at the LHC, whic was by then under construction at CERN. This holiday from HERA heat was the opportunity. With couple of friends, Jeff and Brian, also HERA physicists,[2] I'd been thinking about what we might do what the most exciting things to study would be. We were all very sceptical about new 'Beyond th Standard Model' physics and were keen to work on measurements of real things that would actual happen, rather than seeking evidence for speculative ideas to which we accorded little credibility. think this may have been because we all came from a HERA background, where precisio measurement was the main goal. Although to be honest, the main legacy of LEP was also precisio 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 dimension or Technicolor, all of them speculative extensions of the Standard Model designed to solve some o the problems with it. We didn't even believe in the Higgs boson – an integral part of the Standar Model, but one lacking experimental verification. So we asked ourselves, 'What is the most importa and interesting thing to measure if there are no new particles?' A pessimist's approach, perhaps, bu still fun.

The answer we came up with[3] was vector-boson scattering. This is a peculiar and rare scatterin process that is expected to happen occasionally in very high-energy collisions, and it lay behind wh was called the 'no lose' theorem at the LHC. It is very deeply connected to the reasons why the Higg 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

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 th electromagnetic force, is a vector boson. Of more interest here, though, are the W, and to some exten the Z, bosons. These carry the weak force, and one of the oddest things about them is that, unlike th photon, they have mass.

In a proton–proton collision at the LHC, you have to picture two quarks, one from a proton each beam, zooming towards each other. There is a small but non-zero chance that, as they do thi each will radiate a W boson. There's an even smaller, but still non-zero, chance that these W boson will hit each other. That is vector-boson scattering – WW scattering in this case. It could happen wi Zs or photons too. There are a bunch of different ways the bosons can bounce off each other, or fu together and break up again. As is always the case in quantum mechanics, all the possibilities have be taken into account and combined[4] – sometimes they add up, sometimes they subtract from eac 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 incluc a Higgs boson, and at the time there was no direct evidence for such a beast. However, if you do th sum and do not include a Higgs boson, then as you go to higher and higher energies, the probability WW scattering grows and grows.[5] At some point you get nonsense answers involving probabilitie bigger than one, or infinities. That is just a sign that your theory is broken – there won't be infiniti in nature – but what it meant was that either a Higgs boson would be discovered at the LHC, or son 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 WV scattering might well be the only, or best, clue as to what was going on. It certainly had to involv either a Higgs boson or something else new – hence the 'no lose' theorem. By studying the scatterings we were certain we would discover some interesting physics.

Measuring WW scattering properly would be difficult, and we found lots of fun challenges. Th Universtiy 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 lo of simulation jobs to test our ideas, then popping over the road to the pub for beer and dinner to argu about newer ideas. This was still before my son was born, but I had already divested myself of lots other responsibilities. We submitted the paper in January 2002 and it was more or less ignored for si years, though it later became more fashionable and I'm very proud of it. One of the ideas we us 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, became increasingly obvious that quite a lot of people were going to be interested in the project, f all kinds of reasons. For the engineering and science, of course. But also because of the sheer scal including the cost of the thing. The international collaboration and the sociology of several thousa physicists working together were intriguing to quite a few people, including academics in soci sciences. Plus, of course, there were the two or three delusional publicity-seekers who thought, 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 med coverage, 'because of balance'.[6] The only way to deal with that is to get real information out ther Also, since the European taxpayer had been investing something like the equivalent of a billion eur 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 a sure, James Gillies, the head of communications at CERN, and many good science journalists. This presumably why, in 2008, the doors of CERN were flung open to the world's media for 'Big Ba Day', when we switched on the machine.

Such thinking was certainly one reason why I agreed to be part of a series of short documenta films called *Colliding Particles*. These were a sort of 'fly on the wall' affair that started in t summer of 2008. Mike Paterson was the cameraman, producer, interviewer and director – everythin in fact, except animator and occasionally soundman. He won some support from the Science a Technology Facilities Council (STFC), the research council that funds particle physics in the UK, make the films. They were aimed at schools, specifically at a then new part of the curriculum based learning how science works. Apparently pupils would learn this by watching some physicists fro behind Mike's camera.