Praise for *The Particle at the End of the Universe*

“A wide-ranging tour to show how the newly discovered boson fits into current thinking about particle physics and cosmology... Science is the quest for the awesome.”

Clive Cookson, *Financial Times*

“In this superb book, Sean Carroll provides a fascinating and lucid look at the most mysterious and important particle in nature, and the experiment that revealed it.”

Leonard Mlodinow, author of the international bestseller *The Drunkard’s Walk*

“If you want to know why the Higgs boson has excited so much interest, this book is an excellent place to start.”

*Times Higher Education*

“After you read this book – an enticing cocktail of personal anecdote, clever analogy, and a small dose of mind-bending theory – you will truly grasp why the Higgs boson has been sought after for so long by so many.”

Morgan Freeman, actor and executive producer of *Through the Wormhole*

“Excellent... Carroll has an unintimidating style, and as befits a first-rate particle cosmologist, he presents the real information with little blurring... Carroll is an eloquent and able guide.”

*Nature*

“The science is authoritative, yet bold and lively. The narrative is richly documented, yet full of human drama. Carroll’s saga pulls you aboard a modern voyage of discovery.”

Frank Wilczek, Nobel Laureate in Physics

“The *Particle at the End of the Universe* is a scientific detective story, the saga of the search for the Higgs... Carroll gives a lot of context: facts and figures, yes, but also passion, characters, history.”

*Los Angeles Times*
To Mom,
who took me to the library
People underestimate the impact of a new reality.

—JOE INCANDELA, SPOKESPERSON FOR THE CMS COLLABORATION AT THE LARGE HADRON COLLIDER
# CONTENTS

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>PROLOGUE</td>
<td>1</td>
</tr>
<tr>
<td>ONE   THE POINT</td>
<td>7</td>
</tr>
<tr>
<td>TWO   NEXT TO GODLINESS</td>
<td>19</td>
</tr>
<tr>
<td>THREE  ATOMS AND PARTICLES</td>
<td>39</td>
</tr>
<tr>
<td>FOUR   THE ACCELERATOR STORY</td>
<td>55</td>
</tr>
<tr>
<td>FIVE   THE LARGEST MACHINE EVER BUILT</td>
<td>75</td>
</tr>
<tr>
<td>SIX    WISDOM THROUGH SMASHING</td>
<td>93</td>
</tr>
<tr>
<td>SEVEN  PARTICLES IN THE WAVES</td>
<td>115</td>
</tr>
<tr>
<td>EIGHT  THROUGH A BROKEN MIRROR</td>
<td>135</td>
</tr>
<tr>
<td>NINE   BRINGING DOWN THE HOUSE</td>
<td>163</td>
</tr>
<tr>
<td>TEN    SPREADING THE WORD</td>
<td>189</td>
</tr>
<tr>
<td>ELEVEN NOBEL DREAMS</td>
<td>209</td>
</tr>
<tr>
<td>TWELVE BEYOND THIS HORIZON</td>
<td>243</td>
</tr>
<tr>
<td>THIRTEEN MAKING IT WORTH DEFENDING</td>
<td>269</td>
</tr>
</tbody>
</table>

## CONTENTS

**APPENDIX ONE**
MASS AND SPIN  
283

**APPENDIX TWO**
STANDARD MODEL PARTICLES  
293

**APPENDIX THREE**
PARTICLES AND THEIR INTERACTIONS  
300

FURTHER READING  
311

REFERENCES  
313

ACKNOWLEDGMENTS  
321

INDEX  
323
JoAnne Hewett is feeling giddy, smiling broadly as she speaks enthusiastically into a video camera. An excited buzz filters up from partygoers at the Swiss consulate in San Francisco. It’s a unique event, celebrating the first protons circulating in the underground tunnel of the Large Hadron Collider (LHC) outside Geneva—an enormous particle accelerator on the French-Swiss border that has begun its quest to unlock the secrets of the universe. The champagne flows freely, and no wonder. Hewett’s voice rises with emphasis: “I’ve been waiting for this day for Twenty. Five. Years.”

It’s a big moment. At this point in 2008, physicists have finally achieved what they have long insisted was necessary to make the next big step forward: a giant accelerator that would smash protons together at very high energies. Construction had even begun on one such a machine, but things didn’t work out as anticipated. Hewett was just beginning graduate school in 1983, when the U.S. Congress first approved construction of the Superconducting Super Collider (SSC) in Texas. Slated to begin operation before the year 2000, it would have been the largest collider ever built. She, like so many of the brilliant and ambitious physicists of her generation, believed that discoveries there would form the foundation of their research careers.
But the SSC was canceled, pulling the rug out from under physicists who had counted on it to shape the course of their field for decades to come. Politics and bureaucracy and infighting got in the way. Now the LHC, similar in many ways to what the SSC would have been, is at long last about to fire up for the first time, and Hewett and her colleagues are more than ready for it. “What I’ve done over the past twenty-five years is take every new crazy theory that anybody’s ever come up with and calculated its signature [how we identify new particles] at the SSC or LHC,” she says.

There is another, more personal reason for Hewett’s giddiness. In the video, her red hair is very short, almost a crew cut. It’s not a fashion choice. Earlier in the year she was diagnosed with invasive breast cancer, with about a one-in-five chance that it would be terminal. She opted for an extremely aggressive treatment program, involving harsh chemotherapy and a seemingly endless series of surgeries. Her trademark red hair, usually reaching down to her waist, disappeared quickly. At times, she admits with a laugh, she kept her spirits up by thinking about what new particles would be found at the LHC.

JoAnne and I have known each other for years, as friends and colleagues. My own expertise is primarily in cosmology, the study of the universe as a whole, which has recently enjoyed a golden age of new data and surprising discoveries. Particle physics, which has become inseparable from cosmology as an intellectual discipline, has nevertheless been starved for new experimental results that will upend the theoretical applecart and lead us forward to new ideas. The pressure has been building for a long time. Another physicist at the party, Gordon Watts of the University of Washington, was asked whether the long anticipation for the LHC has been stressful. “Oh yeah, completely. I have this shock of gray hair here now. My wife claims it’s because of our kid, but it’s really because of the LHC.”

Particle physics stands on the brink of a new era, in which some theories are going to come crashing down, and perhaps others will turn out to be right on the money. Every physicist at the party has their favor-
ite models—Higgs bosons, supersymmetry, technicolor, extra dimensions, dark matter—a tumble of exotic ideas and fantastic implications.

“My hope for what the LHC will find is ‘none of the above,’” Hewett enthuses. “I honestly think it’s going to be a surprise, because I think nature is smarter than we are, and she’s got some surprises in store for us, and we’re going to have a hell of a fun time trying to figure it all out. And it’s going to be great!”

That was 2008. In 2012, the San Francisco party to celebrate the inauguration of the LHC is over, and the era of discovery has been officially launched. Hewett’s hair has grown back. The treatments were agonizing, but they seem to have worked. And the experiment she’s been anticipating for her entire career is making history. After two and a half decades of theorizing, her ideas are finally being tested against real data—particles and interactions never seen before by human beings, surprises that nature has been keeping hidden from us. Until now.

Jump to July 4, 2012, opening day of the International Conference on High Energy Physics. It’s a biannual gathering, moving from city to city around the world, this year winding up in Melbourne, Australia. Hundreds of particle physicists, Hewett included, have filled the main auditorium to hear a special seminar. All the investment in the LHC, all the anticipation that has built up over the years, is about to pay off.

The presentation itself is beamed to Melbourne from CERN, the laboratory in Geneva that is home to the LHC. There are two talks, which would ordinarily have been presented in Melbourne as part of the conference program. At the last minute, however, the powers that be decided that a moment of this magnitude should be shared with the many people who had helped make the LHC such a success. The sentiment was appreciated—hundreds of physicists at CERN have lined up for hours before the talks were scheduled to begin at nine a.m., Geneva time, camping out overnight with sleeping bags in hopes of getting a good seat.

Rolf Heuer, director general of CERN, introduces the proceedings. There will be talks by American physicist Joe Incandela and Italian
physicist Fabiola Gianotti, the spokespersons for the two major experiments that work to collect and analyze LHC data. Both experiments include more than three thousand collaborators each, most of whom are glued to computer monitors scattered around the globe. The event is being live-streamed, not only to Melbourne, but to anyone who wants to hear the results in real-time. It’s an appropriate medium for this celebration of modern Big Science—a high-tech international effort with big stakes and exhilarating rewards.

Traces of nervous energy are evident in both Gianotti’s and Incandela’s talks, but the presentations speak for themselves. They each give heartfelt thanks to the many engineers and scientists who helped make the experiments possible. Then they carefully explain why we should all believe the results they are about to present, demonstrating that they understand how their machines are working and that the analysis of the data is precise and reliable. Only after the stage has been immaculately set do they show us what they’ve found.

And there it is. A handful of graphs that wouldn’t seem like much to the untutored eye, but with a consistent feature: more events (collections of particles streaming from a single collision) than expected with a certain particular energy. All the physicists in the audience know immediately what it means: a new particle. The LHC has glimpsed a part of nature that had heretofore never been seen. Incandela and Gianotti go through the painstaking statistical analysis meant to separate true discoveries from unfortunate statistical fluctuations, and the results in both cases speak without ambiguity: This is something real.

Applause. In Geneva, Melbourne, and around the world. The data are so precise and clear that even scientists who had worked on the experiments for years are taken aback. Welsh physicist Lyn Evans, who more than anyone else was responsible for guiding the LHC through its rocky path to completion, declared himself “gobsmacked” at the exquisite agreement between the two experiments.

I was at CERN myself that day, masquerading as a journalist in a pressroom next to the main auditorium. Journalists aren’t supposed to
clap at the news events they cover, but the assembled reporters gave in to the overwhelming emotion of the moment. This wasn’t just a success for CERN, or for physics; this was a success for the human race.

We think we know what’s been found: an elementary particle called the “Higgs boson,” after British physicist Peter Higgs. Higgs himself was in the room for the seminars, eighty-three years old and visibly moved: “I never thought I’d see this happen in my lifetime.” Several other senior physicists who had likewise proposed the same idea back in 1964 were also present; the conventions by which theories are named aren’t always fair, but this was a moment when everyone could join in the celebration.

So what is the Higgs boson? It’s a fundamental particle of nature, of which there aren’t many, and a very special kind of particle to boot. Modern particle physics knows of three kinds of particles. There are particles of matter, like electrons and quarks, that constitute the atoms that make up everything we see. There are the force particles that carry gravity and electromagnetism and the nuclear forces, which hold the matter particles together. And then there is the Higgs, in its own unique category.

The Higgs is important not for what it is but for what it does. The Higgs particle arises from a field pervading space, known as the “Higgs field.” Everything in the known universe, as it travels through space, moves through the Higgs field; it’s always there, lurking invisibly in the background. And it matters: Without the Higgs, electrons and quarks would be massless, just like photons, the particles of light. They would move at the speed of light themselves, and it would be impossible to form atoms and molecules, much less life as we know it. The Higgs field isn’t an active player in the dynamics of ordinary matter, but its presence in the background is crucial. Without it, the world would be an utterly different place. And now we’ve found it.

Some words of caution are in order. What we actually have in hand is evidence for a very Higgs-like particle. It has the right mass, it is produced and decays in roughly the expected ways. But it’s too early in the game to say for sure that what we’ve discovered is definitely the
simple Higgs predicted by the original models. It could be something more complicated, or be part of an elaborate web of related particles. But we’ve definitely found some new particle, and it acts like we think a Higgs boson should. For the purposes of this book, I’m going to treat July 4, 2012, as the day the discovery of the Higgs boson was announced. If reality turns out to be more subtle, then all the better for everyone—physicists live for surprises.

Hopes are high that the Higgs discovery represents the beginning of a new age in particle physics. We know that there is more to physics than we currently understand; studying the Higgs offers a new window into worlds yet unseen. Experimenters like Gianotti and Incandela have a new specimen to study; theorists like Hewett have new clues to build better models. Our understanding of the universe has taken a huge, long-anticipated step forward.

This is the story of the people who have devoted their lives to discovering the ultimate nature of reality, of which the Higgs is a crucial component. There are theorists, sitting with pencil and paper, fueled by espresso and heated disputes with colleagues, turning over abstract ideas in their minds. There are engineers, pushing machines and electronics well beyond the limits of existing technology. And most of all there are the experimenters, bringing the machines and the ideas together to discover something new about nature. Modern physics at the cutting edge involves projects that cost billions of dollars and take decades to complete, requiring extraordinary devotion and a willingness to bet high stakes in search of unique rewards. When it all comes together, the world changes.

Life is good. Have another glass of champagne.
ONE
THE POINT

In which we ask why a group of talented and dedicated people would devote their lives to the pursuit of things too small to be seen.

Particle physics is a curious activity. Thousands of people spend billions of dollars building giant machines miles across, whipping around subatomic particles at close to the speed of light and crashing them together, all to discover and study other subatomic particles that have essentially no impact on the daily lives of anyone who is not a particle physicist.

That’s one way of looking at it, anyway. Here’s another way: Particle physics is the purest manifestation of human curiosity about the world in which we live. Human beings have always asked questions, and since the ancient Greeks more than two millennia ago, the impulse to explore has grown into a systematic, worldwide effort to discover the basic rules governing how the universe works. Particle physics arises directly from our restless desire to understand our world; it’s not the particles that motivate us, it’s our human desire to figure out what we don’t understand.

The early years of the twenty-first century are a turning point. The last truly surprising experimental result to emerge from a particle accelerator was in the 1970s, more than thirty-five years ago. (The precise date would depend on your definition of “surprising.”) It’s not because the experimentalists have been asleep at the switch—far from it. The machines have
improved by leaps and bounds, reaching into realms that seemed impos-
sibly far away just a short time ago. The problem is that they haven’t seen
anything we didn’t already expect them to see. For scientists, who are al-
ways hoping to be surprised, that’s extremely annoying.

The problem, in other words, isn’t that the experiments have been
inadequate—it’s that the theory has been too good. In the specialized
world of modern science, the roles of “experimentalists” and “theorists”
have become quite distinct, especially in particle physics. Gone are the
days—as recent as the first half of the twentieth century—when a ge-
nius like Italian physicist Enrico Fermi could propose a new theory of
the weak interactions, then turn around and guide the construction
of the first self-sustained artificial nuclear chain reaction. Today, particle
theorists scribble equations on blackboards, which ultimately become
specific models, which are tested by experimentalists who gather data
from exquisitely precise machines. The best theorists keep close tabs on
experiments and vice versa, but no one person is a master of both.

The 1970s saw the finishing touches put on our best theory of par-
ticle physics, which goes by the fantastically uninspiring name of the
“Standard Model.” It’s the Standard Model that describes quarks, glu-
ons, neutrinos, and all the other elementary particles you may have
heard of. Like Hollywood celebrities or charismatic politicians, scientific
theories are put on a pedestal just so we can tear them down. You don’t
become a famous physicist by showing that someone else’s theory
is right; you become famous by showing where someone else’s theory
goes wrong, or by proposing a better theory.

But the Standard Model is stubborn. For decades now, every ex-
periment that we can do here on earth has duly confirmed its pre-
dictions. An entire generation of particle physicists has risen up the
academic ladder from students to senior professors, all without having
a single new phenomenon that they could discover or explain. The
anticipation has been close to unbearable.

All this is changing. The Large Hadron Collider represents a new
era in physics, smashing together particles with an energy never before
achieved by humankind. And it’s not just higher energy. It’s an energy we’ve been dreaming about for years, in which we expect to find new theoretically predicted particles and hopefully some surprises—the energy where the force known as the “weak interaction” hides its secrets.

The stakes are high. Peering into the unknown for the first time, anything could happen. There are scads of competing theoretical models hoping to anticipate what the LHC will find. You don’t know what you’re going to see until you look. At the center of the speculation lies the Higgs boson, an unassuming particle that represents both the last piece of the Standard Model, and the first glimpse into the world beyond.

A big universe made of little pieces

Near the Pacific coast in Southern California, about an hour-and-a-half drive south of where I live in Los Angeles, there is a magical place where dreams come to life: Legoland. At Dino Island, Fun Town, and other attractions, children marvel at an elaborate world constructed from Legos, tiny plastic blocks that can be fitted together in limitless combinations.

Legoland is a lot like the real world. At any moment, your immediate environment typically contains all sorts of substances: wood, plastic, fabric, glass, metal, air, water, living bodies. Very different kinds of things, with very different properties. But when you look more closely, you discover that these substances aren’t truly distinct from one another. They are simply different arrangements of a small number of fundamental building blocks. These building blocks are the elementary particles. Like the buildings in Legoland, tables and cars and trees and people represent some of the amazing diversity you can achieve by starting with a small number of simple pieces and fitting them together in a variety of ways. An atom is about one-trillionth the size of a Lego block, but the principles are similar.

We take for granted the idea that matter is made of atoms. It’s
something we’re taught in school, where we do chemistry experiments in classrooms with the periodic table of the elements hanging on the wall. It’s easy to lose sight of how amazing that fact is. Some things are hard, some are soft; some things are light, some are heavy; some things are liquid, some are solid, some are gas; some things are transparent, some are opaque; some things are alive, some are not. But beneath the surface, all these things are really the same kind of stuff. There are about one hundred atoms listed in the periodic table, and everything around us is just some combination of those atoms.

The hope that we can understand the world in terms of a few basic ingredients is an old idea. In ancient times, a number of different cultures—Babylonians, Greeks, Hindus, and others—invented a remarkably consistent set of five “elements” out of which everything else was made. The ones we are most familiar with are earth, air, fire, and water, but there was also a heavenly fifth element of aether, or quintessence. (Yes, that’s where the movie with Bruce Willis and Milla Jovovich got its name.) Like many ideas, this one was developed into an elaborate system by Aristotle. He suggested that each element sought a particular natural state; for example, earth tends to fall and air tends to rise. By mixing the elements in different combinations, we could account for the different substances we see around us.

Democritus, a Greek philosopher who predated Aristotle, originally suggested that everything we know is made of certain tiny indivisible pieces, which he called “atoms.” It’s an unfortunate accident of history that this terminology was seized upon by John Dalton, a chemist who worked in the early 1800s, to refer to the pieces that define chemical elements. What we now think of as an atom is not indivisible at all—it consists of a nucleus made of protons and neutrons, around which orbit a collection of electrons. Even the protons and neutrons aren’t indivisible; they are made of smaller pieces called “quarks.”

The quarks and electrons are the real atoms, in Democritus’s sense of indivisible building blocks of matter. Today we call them “elementary particles.” Two kinds of quarks—known playfully as “up” and “down”—go
into making the protons and neutrons of an atomic nucleus. So, all told, we need only three elementary particles to make up every single piece of matter that we immediately perceive in the environment around us—electrons, up quarks, and down quarks. That’s an improvement over the five elements of antiquity, and a big improvement over the periodic table.

Boiling the world down to just three particles is a bit of an exaggeration, however. While electrons and up and down quarks are enough to account for cars and rivers and puppies, they aren’t the only particles we’ve discovered. There are actually twelve different kinds of matter particles: six quarks that interact strongly and get confined inside larger collections like protons and neutrons, and six “leptons” that can travel individually through space. We also have force-carrying particles that hold them together in the different combinations we see. Without force particles, the world would be a boring place indeed—individual particles would just move on straight lines through space, never interacting with one another. It’s a fairly small set of ingredients to explain everything we see around us, but frankly, it could be simpler. Modern particle physicists are driven by a desire to do better.

The Higgs boson

That’s the Standard Model of particle physics: twelve matter particles, plus a group of force-carrying particles to hold them all together. Not the tidiest picture in the world, but it fits all the data. We have assembled all the pieces needed to successfully describe the world around us, at least here on earth. Out in space we find evidence for things like dark matter and dark energy, stubborn reminders that we certainly don’t understand everything yet—these are most certainly not explained by the Standard Model.

For the most part the Standard Model divides nicely into matter particles and force-carrying particles. The Higgs boson is different. Named after Peter Higgs, who was one of several people who proposed
the idea back in the 1960s, the Higgs boson is somewhat of an ugly duckling. Technically speaking it’s a force-carrying particle, but it’s a different kind of force carrier from the ones we’re most familiar with. From the viewpoint of a theoretical physicist the Higgs seems like an arbitrary and whimsical addition to an otherwise beautiful structure. If it weren’t for the Higgs boson, the Standard Model would be the epitome of elegance and virtue; as it is, it’s a bit of a mess. And finding the mess-maker has proven to be quite a challenge.

So why were so many physicists convinced that the Higgs boson must exist? You’ll hear explanations like “to give mass to other particles” and “to break symmetries,” both of which are true but not easy to absorb at first glance. The main point is that without the Higgs boson, the Standard Model would look very different, and not at all like the real world. With the Higgs boson, it’s a perfect match.

Theoretical physicists certainly tried their best to come up with theories that didn’t have a Higgs boson, or one in which the boson was quite different from the standard story. Many of the theories failed when confronted with the data, and others seemed unnecessarily complicated. None looked like a true upgrade.

And now we’ve found it. Or something very much like it. Depending on how careful physicists are being, they will say either, “We’ve discovered the Higgs boson,” or “We’ve discovered a Higgs-like particle,” or even “we’ve discovered a particle that resembles the Higgs.” The July 4 announcement described a particle that behaves very much like the Higgs is supposed to behave—it decays into certain other particles in more or less the ways we expect it to. But it’s still early, and as we collect more data there is plenty of room for surprises. Physicists don’t want it to be the Higgs we all expect; it’s always more interesting and fun to find something unexpected. There are already tiny hints in the data that this new particle might not be exactly the Higgs we expect. Only further experiments will reveal the truth.
Why we care

I was once interviewed by a local radio station about particle physics, gravitation, cosmology, things like that. It was 2005, the centenary of Albert Einstein’s “miraculous year” of 1905, in which he published a handful of papers that turned the world of physics on its head. I did my best to explain some of these abstract concepts, waving my hands up and down, which I can’t help but do even when I know I’m on the radio.

The interviewer seemed happy, but after we finished and he was packing up his recording gear, a lightbulb went off in his head. He asked if I would answer one more question. I said sure, and he once again deployed his microphone and headphones. The question was simple: “Why should anybody care?” None of this research is going to lead to a cure for cancer or a cheaper smartphone, after all.

The answer I came up with still makes sense to me: “When you’re six years old, everyone asks these questions. Why is the sky blue? Why do things fall down? Why are some things hot and others cold? How does it all work?” We don’t have to learn how to become interested in science—children are natural scientists. That innate curiosity is beaten out of us by years of schooling and the pressures of real life. We start caring about how to get a job, meet someone special, raise our own kids. We stop asking how the world works, and start asking how we can make it work for us. Later I found studies showing that kids love science up until the ages of ten to fourteen years old.

These days, after pursuing science seriously for more than four hundred years, we actually have quite a few answers to offer the six-year-old inside each of us. We know so much about the physical world that the unanswered questions are to be found in remote places and extreme environments. That’s physics, anyway; in fields like biology or neuroscience, we have no difficulty at all asking questions to which the answers are still elusive. But physics—at least the subfield of “elementary” physics, which looks for the basic building blocks of reality—has pushed the
boundaries of understanding so far that we need to build giant accelerators and telescopes just to gather new data that won’t fit into our current theories.

Over and over again in the history of science, basic research—pursued just for the sake of curiosity, not for any immediate tangible benefit—has proven, almost despite itself, to lead to enormous tangible benefits. Way back in 1831, Michael Faraday, one of the founders of our modern understanding of electromagnetism, was asked by an inquiring politician about the usefulness of this newfangled “electricity” stuff. His apocryphal reply: “I know not, but I wager that one day your government will tax it.” (Evidence for this exchange is sketchy, but it’s a sufficiently good story that people keep repeating it.) A century later, some of the greatest minds in science were struggling with the new field of quantum mechanics, driven by a few puzzling experimental results that ended up overthrowing the basic foundations of all of physics. It was fairly abstract at the time, but subsequently led to transistors, lasers, superconductivity, light-emitting diodes, and everything we know about nuclear power (and nuclear weapons). Without this basic research, our world today would look like a completely different place.

Even general relativity, Einstein’s brilliant theory of space and time, turns out to have down-to-earth applications. If you’ve ever used a global positioning system (GPS) device to find directions somewhere, you’ve made use of general relativity. A GPS unit, which you might find in your cell phone or car navigation system, takes signals from a series of orbiting satellites and uses the precise timing of those signals to triangulate its way to a location here on the ground. But according to Einstein, clocks in orbit (and therefore in a weaker gravitational field) tick just a bit faster than those at sea level. A small effect, to be sure, but it builds up. If relativity weren’t taken into account, GPS signals would gradually drift away from being useful—over the course of just one day, your location would be off by a few miles.

But technological applications, while important, are ultimately not the point for me or JoAnne Hewett or any of the experimentalists who
spend long hours building equipment and sifting through data. They’re
great when they happen, and we won’t turn up our noses if someone
uses the Higgs boson to find a cure for aging. But it’s not why we are
looking for it. We’re looking because we are curious. The Higgs is the
final piece to a puzzle we’ve been working on solving for an awful long
time. Finding it is its own reward.

The Large Hadron Collider

We wouldn’t have found the Higgs without the Large Hadron Collider—
another dreary name for an inspiring embodiment of the human pas-
sion for discovery. The LHC is the largest, most complex machine ever
built by human beings, and it came in at a cool nine billion dollars. The
scientists who work at CERN hope it will run productively for fifty
years. But they aren’t that patient; it would be nice to get some world-
changing discoveries right away, thank you very much.

The LHC is gargantuan in every way it can be measured. It was
first dreamed up in the 1980s, and approval to start building was given
in 1994. Well before it was turned on, the LHC had made big news,
as lawsuits attempted to halt its construction on the grounds that it
might produce world-consuming black holes. Those were successfully
squashed, and the giant collider went to work in earnest in 2009.

Around the world on December 13, 2011, physicists—and quite a
few interested onlookers—huddled in seminar rooms and around com-
puter terminals to listen to two talks by researchers from the LHC. The
subject was the search for the Higgs boson. This kind of topic is a very
frequent subject for physics seminars, and the message is almost always
“The search is going well! Wish us luck!” This time was different. Ru-
mors had sped around the Internet for several days before, hinting that
we weren’t just going to get the usual message—this time, they would
be saying, “Okay, we might actually be seeing something. Maybe we’ve
finally found evidence that the Higgs boson is really there.”
The answer is yes, there were hints that the LHC was actually seeing the Higgs. Just hints, mind you; not the final word. The LHC smashed protons together at unbelievable energies, and two giant experimental detectors looked at what particles emerged from those collisions; the number of times that two high-energy photons (particles of light) were produced at a certain energy was just a smidgen bigger than we would have expected if there were no Higgs boson. Evidence that something was likely going on, to be sure, but not yet a discovery. But everything smelled right. Rolf Heuer ended the press conference with a flourish: “See you next year with a discovery.”

And so they did. On July 4, 2012, two more seminars brought us an update on the search for the Higgs. This time it wasn’t a matter of tantalizing hints; they had found a new particle, without question. Thousands of physicists around the world clapped with joy but also exhaled with relief; the LHC was a success.

Crossroads

Particle physics stands at a critical threshold. It’s a foundational part of the human race’s long-standing quest to better understand how the universe works. It’s also very expensive. And its future is unclear.

The search for the Higgs boson isn’t just a story of subatomic particles and esoteric ideas. It’s also a tale of money, politics, and jealousy. A project that involves so many people, unprecedented international cooperation, and more than a few technological breakthroughs doesn’t happen without a certain amount of conniving, dealing, and occasional skullduggery.

The LHC isn’t the first giant particle accelerator that aimed to find the Higgs. There was the Tevatron at Fermi National Accelerator Laboratory (Fermilab), just outside Chicago, which turned on in 1983 and finally turned off in September 2011, after a productive lifespan that included the discovery of the top quark—but no Higgs. There was the
Large Electron-Positron collider (LEP), which ran from 1989 to 2000 in the same underground tunnel where the LHC now sits. Rather than colliding relatively massive protons, which tend to create messy splashes of particles when they meet, LEP collided electrons and their antimatter siblings, positrons. That configuration made it possible to do very precise measurements—but none of those measurements revealed the Higgs.

And then there was the Superconducting Super Collider, or SSC, to which Hewett wistfully referred. The SSC was the American version of the LHC—only bigger, better, and scheduled to be ready first. Proposed in the 1980s, the SSC planned to run at energies almost three times as high as the LHC will someday reach (five times as high as it’s achieving right now). But the LHC can boast one enormous advantage over the SSC: It got built.

After only a couple of years of running, the LHC has bequeathed to us a genuine discovery, a particle that looks very much like the Higgs boson. It’s the end of one era but also the beginning of another. The Higgs is not merely one more particle—it’s a special kind of particle, one that can very naturally interact with other kinds of particles we haven’t yet detected. We know the Standard Model is not the final answer; the dark matter mapped out by astronomers is clear evidence of that. The Higgs could be the portal that connects our world with another one lurking just out of our reach. Having found a new particle, we have decades of work ahead of us learning about its properties and where else it might lead.

The long-term future of experimental particle physics remains murky. A century or even fifty years ago, it was possible to make a foundational discovery in particle physics with the kind of equipment that could be set up by an individual scientist and a team of students. Those days might be over. If the LHC gives us the Higgs and nothing else, it will be increasingly difficult to convince skeptical governments to allocate even more money to build a next-generation collider.

A machine like the LHC represents an investment of billions of dollars but also of thousands of person-years of effort from dedicated
scientists who are devoting their lives to dig just a little bit deeper into nature’s mysteries. People like Lyn Evans, who helped build the LHC, or JoAnne Hewett, who studied countless theoretical models, or Fabiola Gianotti and Joe Incandela, who led their experiments to a historic achievement, have placed an enormous wager. They have gambled that this machine will usher in a new age of discovery, and the stakes they’ve placed are many years of their professional lives. Finding the Higgs is a vindication of all the work they’ve done. But as Hewett says, what we really want is to be surprised—to discover something nobody anticipated. That’s what would really get our minds going.

Historically, nature has been very good at surprising us.