

A Zeptospace Odyssey

A Journey into the Physics of the LHC



Gian Francesco Giudice

*CERN, Department of Theoretical Physics
Geneva, Switzerland*

OXFORD
UNIVERSITY PRESS

Contents

1. Prologue	1
PART ONE: A MATTER OF PARTICLES	7
2. Dissecting Matter	9
3. Forces of Nature	29
4. Sublime Marvel	51
PART TWO: THE STARSHIP OF ZEPTOSPACE	77
5. Stairway to Heaven	79
6. The Lord of the Rings	95
7. Telescopes Aimed at Zeptospace	119
PART THREE: MISSIONS IN ZEPTOSPACE	143
8. Breaking Symmetries	145
9. Dealing with Naturalness	177
10. Supersymmetry	187
11. From Extra Dimensions to New Forces	203
12. Exploring the Universe with a Microscope	217
13. Epilogue	241
<i>Glossary</i>	247
<i>Acknowledgements</i>	255
<i>Index</i>	257

1

Prologue

We shall not cease from exploration
And the end of all our exploring
Will be to arrive where we started
And know the place for the first time.

Thomas Stearns Eliot¹

The control room of the Large Hadron Collider (LHC) is packed full of people. Everyone's eyes are fixed on the monitor screen hanging on the wall, which now is showing only a grey background. The last absorber block has already been removed, and so the protons will not find any obstacle to their circular trajectory around the 27-kilometre long underground tunnel. It is 10.28 a.m. on 10 September 2008. We are at CERN, the European research laboratory for particle physics, stretched across the border between France and Switzerland, near Geneva.

Lyn Evans, the director of the LHC project, like a magician ready to perform his most astonishing trick, recites the magic formula in French, but without hiding his lilting Welsh intonation: "Trois, deux, un faisceau!" At that very moment, two white spots appear for an instant on the screen. Everyone bursts into applause. The images from the control room are broadcast live into the main auditorium, where most of the CERN physicists and staff have gathered. There too, everyone joins in spontaneous applause, full of satisfaction and emotion. The adventure, so long worked for and waited for, has really started.

The first official studies for the LHC, the most powerful particle accelerator in the world, date from the early 1980s, but the project was finally approved only in 1994. Fourteen years later, those two small white spots on the screen marked the end of the construction phase and the beginning of the experimental programme in particle physics. Those spots were in fact the two images left on a thin fluorescent film by the proton beam. One spot showed the beam at the instant it was injected

¹ T.S. Eliot, *The Four Quartets*, Harcourt, New York 1943.



Figure 1.1 The LHC control room on 10 September 2008.

Source: CERN.

into the LHC; the second spot was left by the beam at the instant it returned there, after circulating once around the ring, covering 27 kilometres in only 90 millionths of a second. It is true that the proton beam energy was only a small fraction of what it will be when the LHC runs at full power. Also, the density of circulating protons was extremely low. However, the sincere applause of the physicists gathered for the event is well justified, because this was the decisive test that the technology on which the LHC is based really does work.

In the control room, the last five CERN director generals are present. They are the men who led the laboratory during the various phases of LHC planning and construction: Herwig Schopper, Carlo Rubbia, Christopher Llewellyn Smith, Luciano Maiani, and finally Robert Aymar, whose mandate expired at the end of 2008 and who was succeeded by Rolf Heuer. “Only five are present because the others are already dead!” comments Lyn Evans with jovial laughter. Some of the older directors do not share the hilarity. However, visibly delighted, in their suits and ties, they approach Evans, dressed in more traditional CERN attire – jeans and sneakers – to express their joy. Congratulation messages reach CERN from all the main laboratories for particle physics around the world. The most original one is from Nigel Lockyer, director of the Canadian laboratory TRIUMF who writes, rephrasing Neil Armstrong’s words on first setting foot on the moon: “One short trip for a proton, but one giant leap for mankind!”

The LHC represents indeed an extraordinary adventure for mankind. It is a demanding civil engineering adventure with, for instance, excavation of an artificial cavern of almost 80 000 cubic metres at 100 metres below ground – large enough to fill the nave of Canterbury cathedral. It is an adventure at the absolute forefront of technology, with the development of new materials and innovative instruments. It is an unprecedented adventure in information technology, with a flux of data of about a million gigabytes per second – the same as about ten phone calls placed simultaneously through the same operator by every single inhabitant of the earth. But, above all, it is a fantastic intellectual adventure, because the LHC will explore spaces where no previous experiment has ever been able to penetrate. The LHC is a journey inside the deepest structure of matter, aiming at the discovery of the fundamental laws that determine the behaviour of nature. At stake is the understanding of the first principles that govern the universe, of how and – especially – of why nature works in the way we see it operating.

The most fascinating aspect of the LHC is its journey towards the unknown. The LHC acts as a gigantic microscope able to peer at distances less than about 100 zeptometres. The zeptometre is a rarely used unit equal to a billionth of a billionth of a millimetre. The term was invented in 1991 by the Bureau International des Poids et Mesures with the motivation: “the prefix ‘zepto’ is derived from ‘septo’ suggesting the number seven (the seventh power of 1000) and the letter ‘z’ is substituted for the letter ‘s’ to avoid the duplicate use of the letter ‘s’ as a symbol.”² This is quite an odd definition for an odd unit of measurement. Everything about the word “zepto” is so odd that I find it very appropriate to describe the unknown and strange space of extremely small distances. This infinitesimal space, no larger than a few hundred zeptometres, has been accessed so far only by elementary particles and by the wild imagination of theoretical physicists. In this book this space will be referred to as *zeptospace*. The LHC will be the first machine to explore *zeptospace*.

While the manned mission to the moon had a concrete goal – visible to everyone on any cloudless night – the journey that the LHC has begun is an odyssey towards stranger spaces in which no one can predict exactly what we will meet or where we will arrive. It is a search for unknown worlds which is carried out with complex cutting-edge technologies and guided by theoretical speculations whose understanding requires knowledge of advanced physics and mathematics. These are the very aspects that have shrouded the work of physicists in a cloud of esoteric mystery, discouraging the interest of the uninitiated. But this book is intended to show that the issues raised by the results of the LHC

² Resolution 4 of the 19th meeting of the Conférence générale des poids et mesures (1991).

are fascinating and of interest to anyone who believes it worthwhile to ask fundamental questions about nature.

Evidently the governments of the 20 European states members of CERN believe that it is worthwhile to ask these questions, for they have invested significant resources in the enterprise. The construction of the LHC accelerator amounted to about €3 billion, including the tests, the building of the machine, and the CERN contribution to the LHC computing and to the detectors, but without including the cost of CERN manpower. This enormous financial effort would not have been possible without substantial contributions from many countries that are not members of CERN: Canada, India, Japan, Russia, and the USA, among others. The design, construction, and testing of the instrumentation was done with the participation of physicists from 53 countries and five continents (regrettably no physicist or penguin from Antarctica decided to join the effort). The LHC is a stunning example of international collaboration in the name of science. As the LHC was built with the funding, labour, and intellectual contribution from so many different countries, its results are valuable property of all mankind. These results are not obtained just for the benefit of a few physicists, and their technical and specialist nature should not hide the importance of their universal intellectual content.

The LHC is the most complex and ambitious scientific project ever attempted by humanity. Every challenge met in its design and construction required advances in the frontiers of technology. The research that led to the LHC will certainly have spin-offs and practical applications beyond their purely scientific usage. After all, the World Wide Web was invented at CERN in 1989 to allow physicists to exchange data and information between laboratories in different parts of the globe. Four years later, CERN decided to release it into the public domain and, by doing so, gave to the world an instrument that has now become irreplaceable in our everyday life. Fundamental research often bears unexpected applications. In the middle of the 19th century William Gladstone, Chancellor of the Exchequer, asked the physicist Michael Faraday, engaged in research on electromagnetism, what could be the use of his discoveries. “I don’t know, sir,” replied Faraday, “but one day you will be able to tax it.”

But for physicists, the ultimate goal of the LHC is only pure knowledge. Science enriches society well beyond any of its technological applications. In 1969 Robert Wilson, the director of a leading American laboratory for particle physics, was summoned to testify before Congress. The debate was about the possible justifications of spending \$200 million on a particle physics project. Senator John Pastore, of the Congressional Joint Committee on Atomic Energy, questioned Wilson. In his reply, Wilson poignantly expressed the meaning of fundamental research.

- PASTORE: Is there anything connected in the hopes of this accelerator that in any way involves the security of this country?
- WILSON: No, sir. I do not believe so.
- PASTORE: Nothing at all?
- WILSON: Nothing at all.
- PASTORE: It has no value in that respect?
- WILSON: It only has to do with the respect with which we regard one another, the dignity of men, our love of culture. . . . It has nothing to do directly with defending our country, except to make it worth defending.”³

This book deals with the journey made by the LHC: why it was undertaken and what we want to learn from it. This subject is inherently vast, complicated, and of a highly technical nature, while the scope of this book is comparatively modest. I will not cover all the topics systematically and I have no pretensions about giving a full account of the LHC story. My aim is to give just a glimpse of the issues at stake from a physicist’s point of view, while underlining the intellectual broadness and depth of the questions addressed by the LHC. I want to help the reader to understand the meaning of this journey and why the whole scientific community of particle physicists is so excited and is so eagerly awaiting its results.

The first part of this book deals with the particle world and the way physicists came to understand it. The results from the LHC cannot be appreciated without some notion of what the particle world looks like. As the theoretical physicist Richard Feynman once said: “I do not understand why journalists and others want to know about the latest discoveries in physics even when they know nothing about the earlier discoveries that give meaning to the latest discoveries.”⁴

The LHC is a machine of superlatives, where technological complexity is pushed to the extreme. The second part of this book describes what the LHC is and how it operates. The technological innovations required to build the LHC were but one of the many astonishing aspects of this scientific adventure. We will also encounter the detectors used to study the particles created in the collisions between protons at the LHC. These instruments are modern wonders that combine cutting-edge microtechnology with gigantic proportions.

The LHC is a project designed primarily for the exploration of the unknown. So this book culminates with an outline of the scientific aims and expectations at the LHC. The third part addresses some of the most

³ Transcript of the Congressional Joint Committee on Atomic Energy (1969), reprinted in *Proceedings of the American Philosophical Society*, vol. 146, no. 2, 229 (2002).

⁴ R.P. Feynman, as quoted in S. Weinberg, *The Discovery of Subatomic Particles*, Cambridge University Press, Cambridge 2003.

important questions about the goals of the LHC. How do physicists imagine zeptospace? Why should the mysterious Higgs boson exist? Does space hide supersymmetry or extend into extra dimensions? How can colliding protons at the LHC unlock the secrets of the origin of our universe? Is it possible to produce dark matter at the LHC?