

Understanding the

# Higgs Boson

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# Understanding the **Higgs Boson**

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**Summer Science Exhibition  
1st-7th July 2013**

**THE ROYAL SOCIETY**  
6 Carlton House Terrace, London SW1Y 5AG

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*Understanding the Higgs boson* was made possible through help and support  
from the participating institutes (page 115), and from:

CERN: European Laboratory for Particle Physics  
GridPP: UK Computing for Particle Physics  
Higgs Centre for Theoretical Physics  
Science and Technology Facilities Council  
SEPnet: South East Physics Network

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# SCIENCE ON AN EPIC SCALE

by Cristina Lazzeroni

In July 2012, the ATLAS and CMS experiments at the Large Hadron Collider announced the discovery of a new particle, consistent with a Higgs boson. The discovery was front-page news around the world, and became a top trend on Twitter.

The story of the Higgs boson begins in the 1960s. Progress towards finding a theory for the weak force, which plays an essential role in powering the sun, had stalled. The short range of the weak force implied that the associated force carriers must have large mass, but introducing

force carriers with non-zero mass into the theory gave nonsensical results. A way around the difficulties was found in 1964, by six physicists, working in three independent groups: Robert Brout and François Englert in Brussels; Peter Higgs in Edinburgh; Gerald Guralnik, Carl Hagen and Tom Kibble at Imperial College in London.

The solution proposed in 1964 required the existence of a new type of field, now known as the Higgs field, permeating all of space. Interactions with this field give the carriers

of the weak force their mass, in a way allowing construction of a viable theory of the weak force. It was later realised that a similar mechanism could also explain the origin of the masses of quarks and leptons, the building blocks of the Universe. The existence of the Higgs field implied the existence of a new particle: a Higgs boson.

The quest to find a Higgs boson has spanned half a century, stimulating advances in technology in many different areas. It has involved thousands of physicists and engineers, in some of the most ambitious scientific experiments ever seen. It was one of the motivations behind construction of the world's most powerful particle accelerator: the Large Hadron Collider, at the European Laboratory for Particle Physics (CERN), near Geneva.

Experiments prior to the first LHC collisions, in November 2009, found no clear evidence for the existence of a Higgs boson, but placed constraints on its mass. Measurements made by the ATLAS and

CMS experiments at the time of their discovery announcement showed that they had found a particle with mass, production rate and decay probabilities consistent with a Higgs boson. Subsequent measurements have reinforced the earlier results, and the consensus is that the new particle is indeed a Higgs boson. Whether it is the only type of Higgs boson, or the first of several Higgs particles, remains an open question.

The search for a Higgs boson is science on an epic scale. The resulting theoretical and experimental advances are the subject of *Understanding the Higgs boson*. The stories behind some of these advances are told here through eyewitness accounts.



## CRISTINA LAZZERONI

Cristina Lazzeroni is a Reader in Particle Physics at the University of Birmingham, having previously been a Royal Society University Research Fellow. She studies rare decays in experiments at CERN, and is a keen supporter of events that bring the excitement of particle physics to the general public.

# INTRODUCTION TO PARTICLE PHYSICS

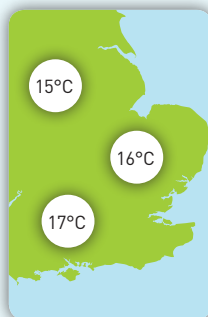
Some of the accounts in this collection include technical terms or notation. It shouldn't be necessary to understand every detail to gain a sense of what's being described, which is the main point here, but the following provides some background information.

## SCALARS, VECTORS AND FIELDS

A physical quantity is something that can be measured, and can be expressed in terms of one or more numbers, with associated units. A quantity that's measured by a single number — for example, temperature — is a scalar. A quantity that's measured by a single number and a direction — for example, the velocity (speed and direction) of the wind — is a vector.

A field, in physics, is a region in time and space where a value for a particular quantity is defined at every point. This may be a scalar field or a vector field, depending on whether the quantity considered is a scalar or a vector. In weather forecasting, a map of temperatures defines a scalar field, and a map of wind velocities defines a vector field.

### SCALAR FIELD



### VECTOR FIELD



## POWERS OF TEN

Physics deals both with very big numbers and with very small numbers. To avoid having to write out lots of zeroes, these numbers are often shown as multiples of 10 to some power, written as a superscript. If the power is positive, it indicates how many times the number must be multiplied by 10. If the power is negative, it indicates how many times the number must be divided by 10. For example:

$$1.2 \times 10^6 = 1.2 \times 10 \times 10 \times 10 \times 10 \times 10 \times 10 = 1\,200\,000;$$

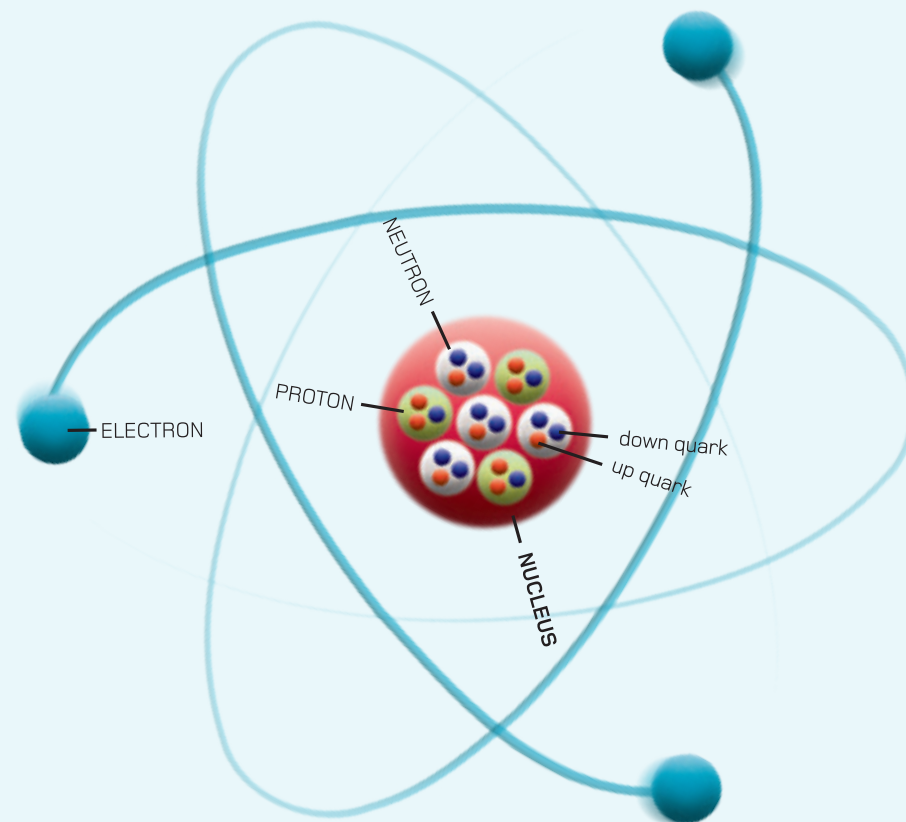
$$1.2 \times 10^{-6} = 1.2 / (10 \times 10 \times 10 \times 10 \times 10 \times 10) = 0.000\,012.$$

Prefixes corresponding to powers of ten are used with units. For example:

$$1 \text{ Gigabyte} = 10^9 \text{ bytes} = 1\,000\,000\,000 \text{ bytes};$$

$$1 \text{ millimetre} = 10^{-3} \text{ metres} = 0.001 \text{ metres}.$$

Power of ten	Number	Symbol
$10^{-12}$	0.000000000001	p (pico)
$10^{-9}$	0.000000001	n (nano)
$10^{-6}$	0.000001	$\mu$ (micro)
$10^{-3}$	0.001	m (milli)
$10^{-2}$	0.01	
$10^{-1}$	0.1	
$10^0$	1	
$10^1$	10	
$10^2$	100	
$10^3$	1,000	k (kilo)
$10^6$	1,000,000	M (mega)
$10^9$	1,000,000,000	G (giga)
$10^{12}$	1,000,000,000,000	T (tera)
$10^{15}$	1,000,000,000,000,000	P (peta)



## BUILDING BLOCKS OF MATTER

The substance that makes up the gasses, liquids and solids encountered in everyday life is referred to as matter. The smallest unit of matter that has well-defined chemical properties is an atom, which consists of a small, dense nucleus, orbited by electrons. An atomic nucleus is built up from protons and neutrons, collectively known as nucleons, and these in turn are made of two types of quark — the u quark and the d quark. The electron and the quarks have no structure at distances that can currently be measured, and are known as fundamental particles. A fourth type of fundamental particle, the electron-neutrino, has a role in radioactive decay. The electron and its neutrino belong to a category of particles called leptons.

The two quarks and two leptons associated with everyday matter constitute the first generation of matter particles. Two other generations of matter particles are known, each essentially a replica of the first generation, but with higher mass. For each matter particle there is a corresponding antiparticle, having the same mass but oppositely signed electric charge. Quarks and antiquarks have never been detected in isolation, but are confined in composite particles known as hadrons. These may consist of three quarks (baryon), three antiquarks (antibaryon) or as a quark-antiquark pair (meson). Protons and neutrons are examples of baryons.



## PARTICLE INTERACTIONS AND DECAYS

The matter particles interact with one another through four types of force, each involving one or more force carriers (also called field quanta). Like quarks and leptons, the field carriers are fundamental particles. The strong force, experienced by quarks but not by leptons, is carried by gluons; the weak force, experienced by all matter particles, is carried by the W and Z particles; the electromagnetic force, experienced by particles with non-zero electric charge, is carried by photons; and the gravitational force, experienced by particles with non-zero mass, is hypothesised as being carried by gravitons.

The field carriers are also involved in decay processes, where a heavier particle transforms into two or more lighter particles. The different ways in which a particle can decay are its decay modes or decay channels.

## ENERGY AND MASS

Energies in particle physics are usually measured in multiples of the electronvolt (eV), the energy gained by an electron when accelerated through an electric potential of 1 volt.

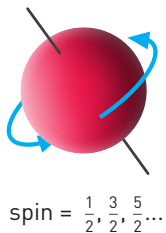
A particle's energy, E, and mass, m, are related as:

$$E=mc^2$$

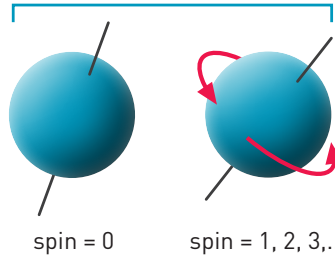
where c is the speed of light. A particle's mass is often specified in terms of its energy equivalent. For example, a proton and neutron each have a mass of a little under 1 GeV.

## FERMIONS AND BOSONS

### FERMIONS



### BOSONS

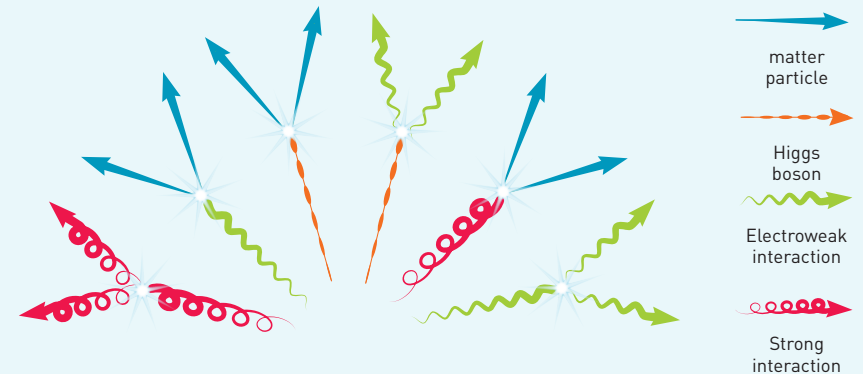


Particles behave as if they're spinning about an axis. The allowed spin values are multiples of a base quantity, conventionally written  $\hbar/2$ . Particles are known as fermions if their spin value is an odd multiple of the base quantity, and are known as bosons if it is an even multiple. Quarks, leptons, baryons and antibaryons are all fermions. Force carriers and mesons are all bosons.

## THE STANDARD MODEL OF PARTICLE PHYSICS

The dynamics of particle interactions are described mathematically by theories known as quantum field theories. The Standard Model provides theories of the strong, weak and electromagnetic forces. It doesn't include a description of the gravitational force, which is negligible in sub-atomic processes at the energy scales that can currently be studied.

Early formulations of quantum field theories were plagued by infinities, which led to them giving nonsensical results. Overcoming these problems involved a technique termed renormalisation, and the introduction of a new scalar field, now known as the Higgs field, which permeates all space. The quantum associated with this field is the Higgs boson, and particle-field interactions are at the origin of particle masses.

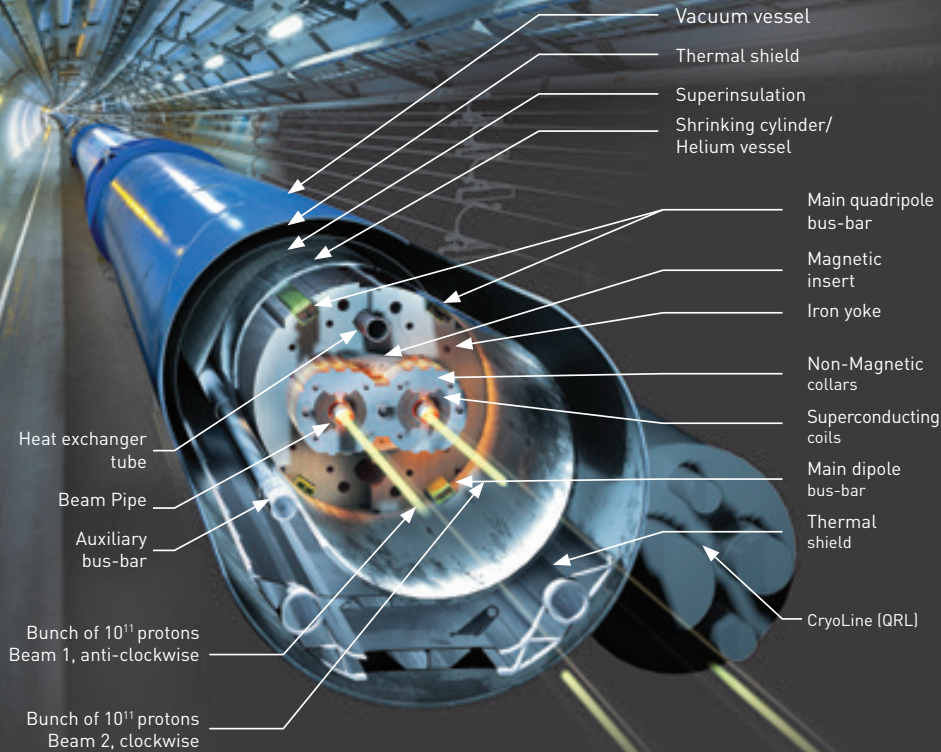


## FEYNMAN DIAGRAMS

Particle interactions and decays are represented pictorially in Feynman diagrams, where different types of lines are used to identify different types of particle.

The interactions are at points where lines meet, which are called vertices. Feynman diagrams are powerful calculational tools, as the lines and vertices are shorthand for lengthy mathematical expressions.

## PARTICLE COLLIDERS



Particle colliders use electric and magnetic fields to produce and steer high-energy beams of charged particles, where the particles are usually clustered in bunches. The most-powerful colliders are synchrotrons, where two beams of particles are accelerated in opposite directions around a ring, which can be many kilometres in circumference. The counter-rotating beams are kept orbiting the ring, crossing over at certain points, where particle collisions may occur.

Examples of particle accelerators include the Tevatron proton-antiproton collider, at the Fermi National Accelerator Laboratory (Fermilab), near Chicago; and the Large Hadron Collider (LHC), at the European Laboratory for Particle Physics (CERN), near Geneva.

The probability that two particles interact is dependent on the effective cross-sectional area that they present to one another. This cross section is conventionally measured in multiples of a unit called the barn (b), where  $1 \text{ b} = 10^{-28} \text{ m}^2$ .

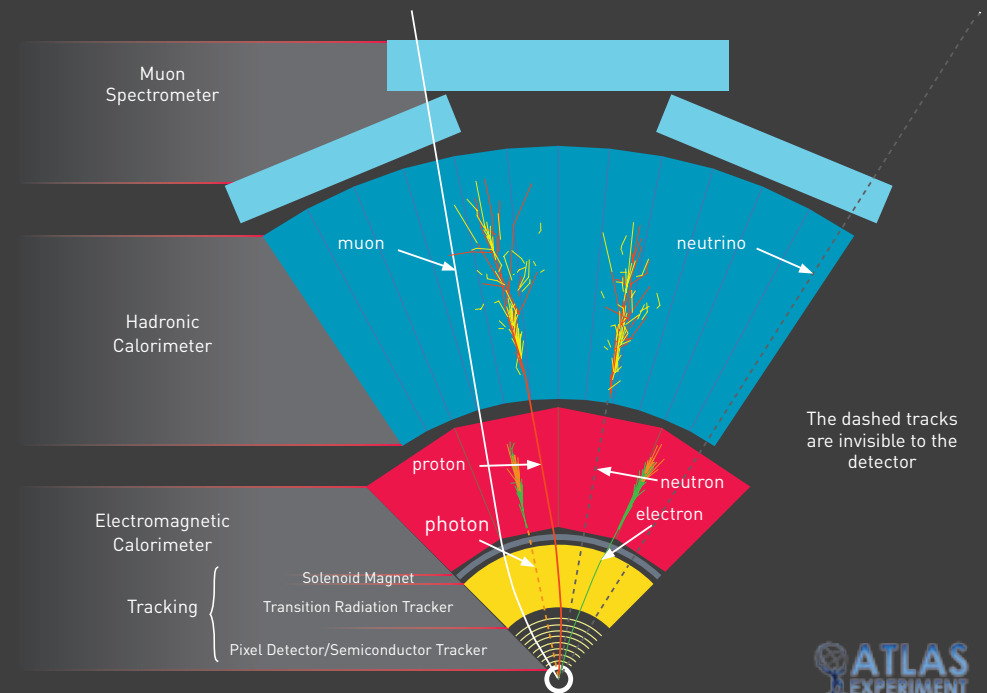
The number of collisions recorded at a collider, over a given time period, is referred to as the (integrated) luminosity. This is measured in units of inverse barn, so that the product of a cross section and a luminosity corresponds to a number of collisions. At the LHC, a luminosity of 1 inverse femtobarn ( $1 \text{ fb}^{-1}$ ) is equivalent to about  $10^{14}$  (100 trillion) proton-proton collisions.

## PARTICLE-PHYSICS EXPERIMENTS

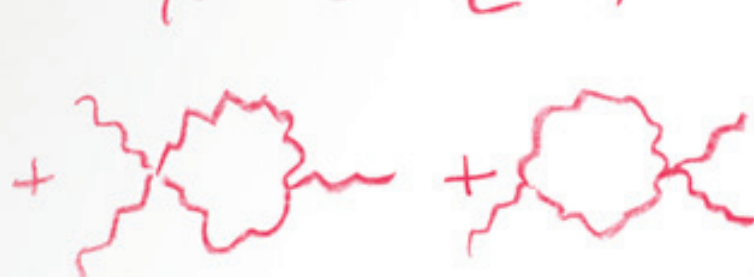
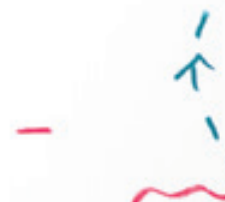
Experiments to study particle interactions and decays use purpose-built detectors. At the highest-energy colliders, these are massive structures, built up in layers. Starting from the inner layers, which are closest to the collision region, each detector typically consists of: tracking devices, to measure the paths of charged particles; calorimeters, to stop photons, electrons and hadrons, and measure their energies; components to record muons, the only charged particles that reach the outermost layers. Sophisticated electronics and dedicated computers are used to determine when a collision (often called an event) has occurred, and to decide whether it should be recorded. The recorded data are analysed in detail, harnessing enormous amounts of computing power.

The teams who carry out particle-physics experiments have become larger as the experiments themselves have become more complex. ATLAS (A Toroidal LHC Apparatus) and CMS (Compact Muon Solenoid), the two general-purpose experiments at the LHC, each involves around 3000 scientists and engineers. These include men and women from around 40 countries, drawn from all continents except Antarctica. The youngest are in their twenties — doctoral (PhD) students and postdoctoral researchers (postdocs). The oldest are over seventy. They have a wide variety of specialisations, including detector construction, electronics design, mathematical modelling and statistical data analysis.

## PARTICLE DETECTION



$$\mathcal{L}^{\text{YM}} = -\frac{1}{4} G_{\mu\nu} G_{\mu\nu} - \bar{\psi} (\gamma D + m) \psi - \frac{1}{2} (\partial_\mu A_\mu)^2$$



+



## TREASURE MAP

Image: Part of the mathematical formulation of the Standard Model, associated Feynman diagrams and (bottom right) the potential of the Higgs field. The drawing is by Gerardus 't Hooft, who made key contributions to the development of the Standard Model, and was awarded the Nobel Prize for Physics in 1999. This is one of a set of twenty-one drawings by winners of a Nobel Prize for work relating to Particle Physics. The drawings were produced for the exhibition *Accelerating Nobels*, staged at CERN in 2008, as part of the celebrations to mark the inauguration of the Large Hadron Collider.

Gerard 't Hooft



# ELECTROWEAK UNIFICATION

## AND THE HIGGS MECHANISM

by Tom Kibble

Over the last fifty years particle physicists have gradually built up what we now call the standard model. It provides an amazingly accurate description of almost all the experimental data. Here I want to give a personal account, from my own perspective at Imperial College, of how one segment of this model developed, the unified theory of weak and electromagnetic interactions.

I was very fortunate to be able to join the Imperial College Theoretical Physics Group in 1959, less than three years after it had been founded by the brilliant and charismatic Pakistani physicist Abdus Salam.

We distinguish four types of fundamental particle interactions, the familiar long-range electromagnetic and gravitational forces, and the short-range strong and weak nuclear interactions. The great post-war success story was quantum electrodynamics (QED), which describes the electromagnetic interactions between charged particles in terms of the exchange of photons, particles of light. (Wave fields

and particles are two sides of the same coin in quantum theory.) Following this triumph, many people were searching for similarly successful theories of the other interactions, or even better a unified theory of all of them, something we still lack. Salam was convinced from an early stage that such a theory should be, like QED, a gauge theory, that is one incorporating a special kind of symmetry (of which one very simple instance is that only voltage differences, not absolute voltages, are relevant). So there was a lot of interest in gauge theories at Imperial College. I did some early work in 1961 on the possibility of constructing a gauge theory of gravity.

### TOM KIBBLE

Tom Kibble is an Emeritus Professor of Theoretical Physics at Imperial College London, and is a Fellow of the Royal Society. His research interests have spanned quantum field theory, particle physics and cosmology, and his achievements have been recognized through awards including the Hughes Medal and Royal Medal, the Sakurai Prize of the American Physical Society, and a CBE.



Blackett Laboratory Photographic Section © Imperial College London

Imperial College's Theoretical Physics Group, 1964, including Tom Kibble and Abdus Salam, third and fourth from left in front row.

***I was very fortunate to be able to join the Imperial College Theoretical Physics Group in 1959, less than three years after it had been founded by the brilliant and charismatic Pakistani physicist Abdus Salam.***

In 1956, Julian Schwinger suggested that the weak interactions, which are responsible for radioactive nuclear beta decay, and play a vital role in the energy generation in the Sun, might be understood in terms of a gauge theory involving a pair of mediating particles or gauge bosons, called  $W^+$  and  $W^-$ , the superscript indicating electric charge. He went on to suggest that there might perhaps be a unified theory

of weak and electromagnetic interactions, involving some kind of symmetry between the three gauge bosons: the  $W^+$ , the  $W^-$  and the photon. In 1961, Sheldon Glashow added a fourth gauge boson,  $Z^0$ , to cure a problem with mirror symmetry.

There was still a big problem. To explain the short range and weakness of the weak interactions, it is essential that the mediating particles,  $W^+$ ,  $W^-$  and the  $Z^0$ , should be very heavy. This is in contrast with the photon, which is massless, in the sense that its rest mass is zero; in vacuum it can never be at rest, but always travels with the speed of light. Indeed, gauge bosons are naturally massless. If there is some kind of symmetry between these four gauge bosons, it must be broken in some way. Simply adding masses by hand spoils the nice properties of gauge theories, rendering them inconsistent. ►

An alternative idea was that the symmetry could be broken spontaneously. When Steven Weinberg spent a sabbatical year at Imperial College in 1961-62, he and Salam spent a lot of time studying that possibility, but the result, published in a joint paper with Jeffrey Goldstone, was disappointing. It seemed that such a mechanism could not work in a fundamental theory compatible with Einstein's special relativity.

When an American postdoc, Gerald Guralnik, arrived in 1964, I was very interested to find that he had been working on this problem, and had already published some ideas about it. Together with another American visitor, Carl Richard Hagen, we developed these ideas, and eventually found the solution, now called the Higgs mechanism.

Communications were slower in those days and, just as we were preparing the final draft, we discovered two earlier papers on the same problem, the first by François Englert and Robert Brout in Brussels, and the second by Peter Higgs in Edinburgh. The three groups all reached essentially the same conclusion, but approached the problem from very different perspectives. We felt we still had something distinctive to say, especially about how the mechanism

manages to avoid the previously envisaged constraints. Physical Review Letters later selected all three papers for its list of the outstanding papers from each of the last fifty years.

This mechanism for spontaneous symmetry breaking eventually formed a key part of electro-weak unification. I did some further work, in early 1967, on the detailed application of the mechanism to more complex gauge theories. (The first three papers dealt with the simplest possible gauge theory.) This work helped, I believe, to revive Salam's interest in the problem. Later that year, Weinberg proposed a unified theory of weak and electromagnetic interactions, essentially Glashow's 1961 model with the Higgs mechanism incorporated. Salam presented essentially the same idea in lectures he gave at Imperial College around the same time, and published it the following year. Over the next few years, experiments at CERN and elsewhere established that this is indeed the correct theory of weak and electromagnetic interactions, leading to the Nobel Prize for Glashow, Salam and Weinberg in 1979. More recently, of course, the Higgs boson itself has been found at the Large Hadron Collider.

Abdus Salam and Tom Kibble in the former's office at Imperial College, 1970s

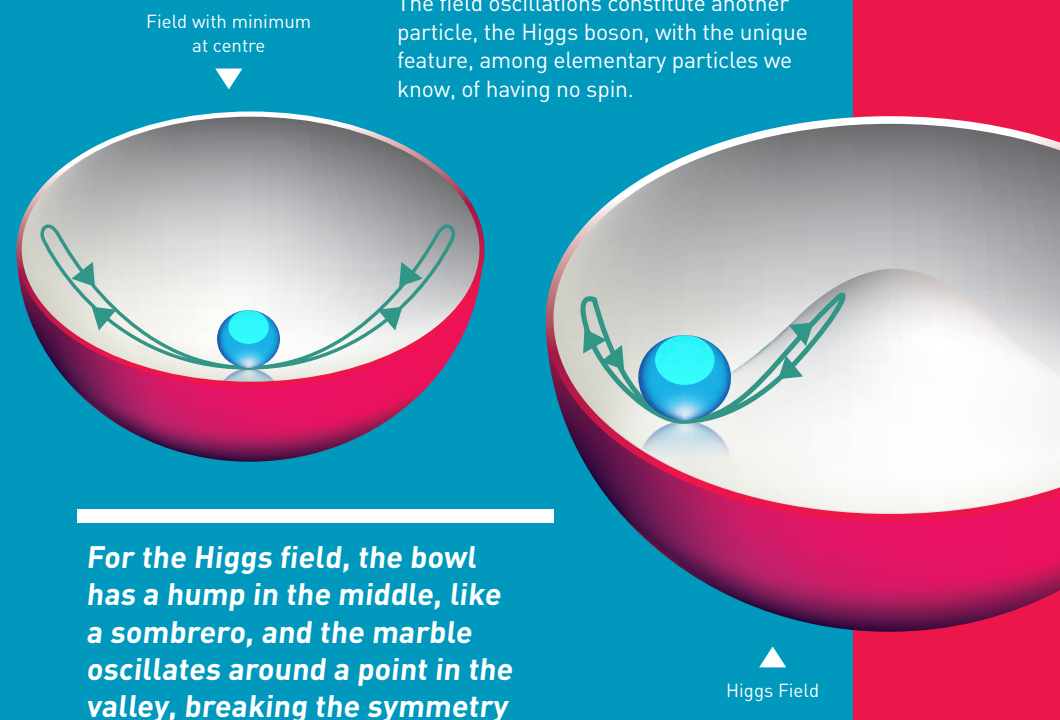


Blackett Laboratory Photographic Section © Imperial College London

# SPONTANEOUS SYMMETRY BREAKING

This means that the symmetry is present in the underlying physical theory, but not in the actual realization. The phenomenon is ubiquitous in condensed matter physics, for example in crystallization. A circular bowl of water looks the same from all directions – it has rotational symmetry. When it freezes, however, the ice crystals line up in particular directions, breaking the symmetry.

It had been believed that such a mechanism could not work in a fundamental theory compatible with Einstein's special relativity. It turns out that that is not true for a gauge theory. In this case, the symmetry breaking is induced by another field, the Higgs field, which has the peculiar property that it wants to be non-zero. Most fields oscillate about a zero average, like a marble rolling in a circular bowl. For the Higgs field, the bowl has a hump in the middle, like a sombrero, and the marble oscillates around a point in the valley, breaking the symmetry. This non-zero mean value also gives masses to the particles with which the field interacts, including the three weak gauge bosons. The field oscillations constitute another particle, the Higgs boson, with the unique feature, among elementary particles we know, of having no spin.





# BONFIRE OF THE INFINITIES

by Frank Close

Half a century after its existence was first suggested, the Higgs boson has been found “beyond reasonable doubt”. The quest for this particle has captured public imagination for over twenty years, since William Waldegrave, as UK Science Minister in the early 1990s, challenged scientists to describe the basic ideas “on a single sheet of A4”. Five years ago, I decided to write a book about the history of the quest. To get to the facts behind the theory, I interviewed all of the major contributors. The result, *The Infinity Puzzle*, shows how memories play tricks and, as historians know, original documents prove invaluable. The following is a summary of the history, as best as I have reconstructed it.

In 1961, Sheldon Glashow discovered the mathematical structure that allowed the electromagnetic and weak forces to be treated as different manifestations of a single phenomenon – the electroweak force. In addition to the familiar photon, associated with the electromagnetic force, Glashow’s model required electrically charged W bosons and an electrically neutral Z boson.

The immediate theoretical difficulty, when Glashow produced his model, was associated with the fact that his W and Z had to be massive. This was necessary to understand why the weak force is so feeble compared with the electromagnetic force. However, it created a mathematical problem. Calculations beyond the simplest approximation gave nonsense: some processes were predicted to occur with a probability of infinite percent. A solution to a similar problem in the theory of the electromagnetic force had been found in 1947, using a technique known as renormalisation, but worked because the photon has no mass.

The fact that the W and Z have large masses seemed to leave an insuperable infinity puzzle. First clues towards solving the puzzle came in 1964, with the work of six theoretical physicists, in three independent collaborations: Robert Brout and François

Englert in Brussels; Peter Higgs in Edinburgh; Gerald Guralnik, Carl Hagen and Tom Kibble at Imperial College in London. They showed that if there is an all-pervading field – now known, rather unfairly, as the Higgs field – particles such as photons can gain mass from their interactions with this field. In 1964, this was a demonstration of principle.

Among the six, Higgs alone drew attention to a consequence of the theory, which can be used to establish the reality of the field and the mass mechanism. The presence of an electromagnetic field can be inferred by our ability to excite quantum bundles of radiation – photons. Analogously, exciting Higgs bosons can prove the existence of the Higgs field.

In 1966, Higgs pointed out that the new massive boson could decay to a pair of vector bosons – a pair of photons, a pair of W bosons or a pair of Z bosons – and this could be used to test the theory. An essential feature here is that the probability of a decay to a given type of vector boson is proportional to the boson mass. This differs radically from normal decay patterns.

Cartoon representation of the winning entry to William Waldegrave’s challenge to produce a one-page answer to the question: “What is the Higgs boson, and why do we want to find it?” The entry was by David Miller, a Professor of Physics at University College London



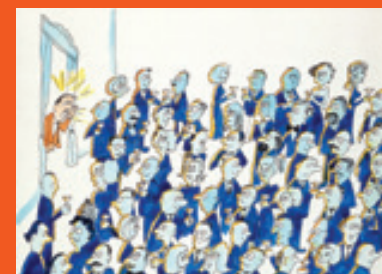
To understand the Higgs mechanism, imagine that a room full of physicists chattering quietly is like space filled with the Higgs field...



...a well-known scientist walks in, creating a disturbance as he moves across the room and attracting a cluster of admirers with each step...



...this increases his resistance to movement, in other words, he acquires mass, just like a particle moving through the Higgs field...



...if a rumour crosses the room...



...it creates the same kind of clustering, but this time among the scientists themselves. In this analogy, these clusters are the Higgs particles.



## FRANK CLOSE

Frank Close is a Professor of Theoretical Physics at the University of Oxford, and a Fellow of Exeter College. In addition to research into the properties of quarks and gluons, he is dedicated to popularising physics, his most recent book being *The Infinity Puzzle*, about the history of the Higgs boson.



In 1967, some major advances occurred. First, Kibble showed that it is possible to combine the basic ideas of the 1964 work with the mathematics of group theory, in such a way that some vector bosons become massive, but others don't. This paved the way to the real world, where the photon is empirically massless. Kibble tutored his colleague, Abdus Salam, on the subject, and Salam developed the ideas in unpublished talks, given in October 1967 at Imperial College. On reading Kibble's paper, Steven Weinberg realised that its results could be incorporated into the theory of the electroweak force, potentially solving the infinity puzzle. Weinberg also suggested that the mass mechanism could give rise to the masses of matter particles (fermions), as well as to the masses of the W and Z.

Although the W and Z bosons were too massive to be produced in the experiments of the 1960s and 1970, their presence could be inferred indirectly. In particular, theory predicted that particles should be able to interact by exchanging a Z boson – resulting in new processes, known as weak neutral-current interactions. For example, neutrinos should be able to bounce off matter without transferring electric charge, and mirror symmetry should be violated in the interactions of electrons. Such phenomena were measured experimentally during the 1970s. This helped establish the theory sufficiently that, in 1979, Glashow, Weinberg and Salam shared the Nobel Prize for Physics.

**Discovery of the Higgs boson both completes half a century of advance in theory and experiment, and provides a window into new phenomena, currently inaccessible by other means.**

Meanwhile, a hugely important theoretical advance had also taken place. Gerard 't Hooft and Martinus Veltman, at Utrecht University, had formally proved that electroweak theory, incorporating the mass mechanism of Higgs and the others, could be renormalised. This was confirmation that the theory was free of nonsensical infinities.

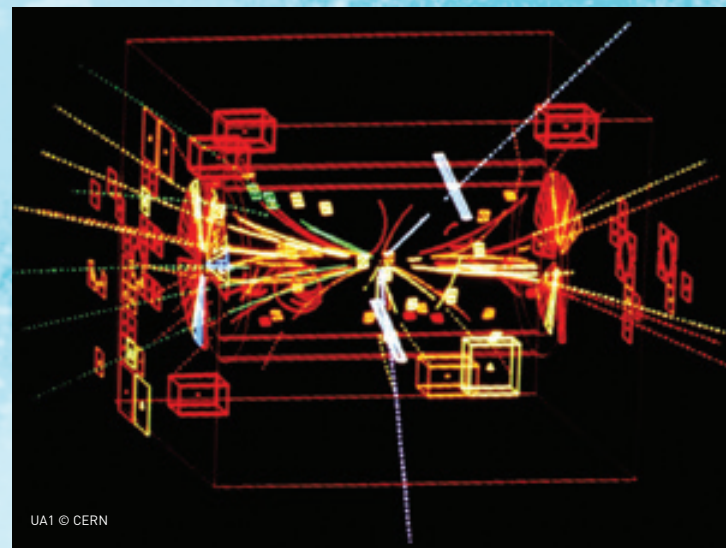
The W and Z were finally produced in 1983, in experiments at CERN, and were found to have masses of about 80 GeV and 90 GeV respectively, as predicted by theory. However, precision measurements of the W and Z masses and decays revealed subtle deviations, at the level of one part in a thousand, from naïve expectations. In electroweak theory, these arise from quantum mechanical effects, where particles too massive to be produced directly can transiently bubble in and out of existence. These virtual particles influence measurable quantities, in ways that the theory can predict.

Electroweak theory showed that the precision data could be explained if the menu of virtual particles included a very massive quark, given the name of top quark, with

a mass of around 175 GeV. The first accelerator capable of producing such a particle directly was Fermilab's Tevatron. The top quark was discovered there in 1995, with the predicted mass.

Detailed measurements of the properties of the top quark, W and Z revealed a further subtle deviation from theory. This could be understood as arising from the presence of a Higgs boson, the mass of which would have to be somewhat above 100 GeV. The discovery, in 2012, of a Higgs boson with a mass around 125 GeV, completes this history.

If there are new varieties of matter, such as supersymmetric particles, the presence of these may affect the properties of the Higgs boson, and be revealed in precision data. Electroweak theory may then give us clues as to what lies beyond the horizon. In this way, discovery of the Higgs boson both completes half a century of advance in theory and experiment, and provides a window into new phenomena, currently inaccessible by other means.



First direct detection of a Z boson – UA1 experiment, 30 April 1983. The pale-blue tracks are an electron-positron pair from the Z decay



# CALCULATING THE PRODUCTION OF HIGGS BOSONS

by James Stirling



## JAMES STIRLING

James Stirling is Jacksonian Professor of Natural Philosophy, and Head of Department, at the Cavendish Laboratory, University of Cambridge. He works on research topics in theoretical particle physics, with a focus on phenomenology, and has been one of the key figures in developing parton distribution functions, essential for calculating the rates of different processes at the Large Hadron Collider. He is a Fellow of the Royal Society, and has been awarded a CBE for services to science.

Modern high-energy particle colliders are invariably designed and constructed with a particular discovery in mind. CERN's proton-antiproton collider, which operated in the 1980s, was designed to discover the W and Z particles. Fermilab's Tevatron proton-antiproton collider, operated between 1985 and 2011, had as a high priority the discovery of the top quark. More recently, CERN's Large Hadron Collider (LHC), and two of the giant detectors installed there, were specifically designed to search for the Higgs boson.

Careful theoretical studies are required during an accelerator's design phase, to assess whether a new particle would be within reach of the proposed machine. Such studies often determine both the collider energy and the detector requirements. If the new particle has mass  $M$ , and the accelerator collides beams of particles at an energy  $E$ , the new particle might be expected to be produced in  $N$  collisions (also called events) in a given time interval. The value of  $N$  will depend on the cross section,  $\sigma(M, E)$ , for production of the new particle, and on the luminosity,  $L$ , of the colliding beams:

$$N = \sigma(M, E) \times L$$

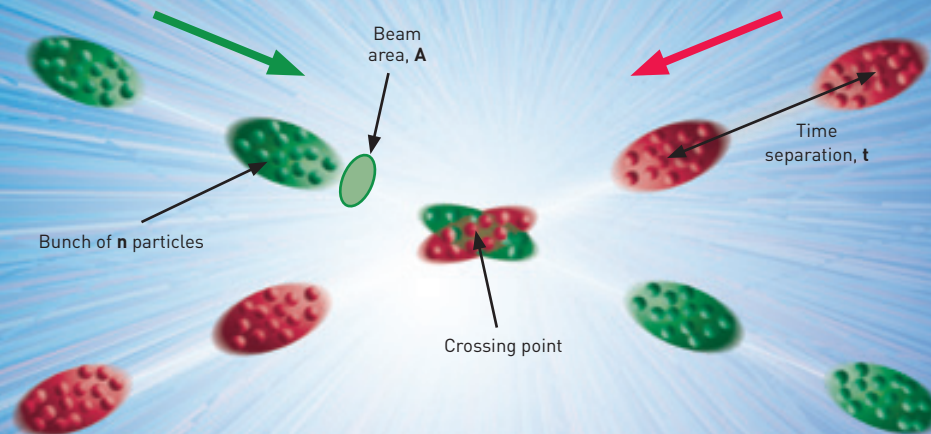
The cross section is a quantity that can generally be calculated theoretically. The term derives from early studies of particle scattering, where the cross-sectional area that one particle presents to another determines the likelihood of a collision. The unit conventionally used to measure cross sections in particle physics is the barn, where 1 barn is equal to  $10^{-28} \text{ m}^2$ , roughly the area presented by a uranium nucleus. The name is attributed to scientists who worked on the atomic bomb during World War II, and who described the uranium nucleus as being "big as a barn".

Luminosity is a measure of the intensity of a beam of particles, and is a key quantity for accelerator physicists. A higher luminosity means a higher number of

events per unit time. At a collider like the LHC, the luminosity depends on quantities such as the number of bunches of protons in the beam, the number of protons in each bunch, the beam area, and the time for the beam particles to complete a circuit of the accelerator ring.

The cross section, and so the number of events, usually increases as the collision energy increases, and decreases as the mass of the new particle increases. For a given particle mass, the collider energy and luminosity can then be chosen at the design stage to guarantee a minimum number of observed events. If, as in the case of the Higgs boson, a new particle is eventually observed, comparison of the observed and expected rates provides a powerful check of the underlying theory.

## PARTICLE BEAMS AT COLLISION



$$\text{Luminosity} \approx \frac{n^2}{A \times t}$$



Precise calculation of the cross sections for particle production, both in processes described by the Standard Model and in possible new physics processes, has become a major industry in the theory community. Achieving accurate results in the case of proton-proton collisions is a challenge. One reason for this is that the protons are made up of quarks and gluons, collectively known as partons, and the way in which partons bind together is only partially understood. When protons collide, the particles created are the result of an interaction between two partons — one from each proton. At the LHC, for example, Higgs bosons are created mainly through the fusion of two gluons.

Understanding exactly how the energy of a fast-moving proton is shared among its constituent partons is key to predicting cross sections accurately. Our knowledge of the strong interaction, described by a theory called Quantum Chromodynamics (QCD), is not yet good enough for us to be able to calculate this parton structure from first principles. Instead, we have to extract the information from other scattering processes involving protons. The relevant extracted quantities are called parton distribution functions, and are obtained by fitting a set of mathematical functions to a large range of experimental data. Such fitting is nowadays a major focus of several groups worldwide. These groups produce off-the-shelf distributions, for use by others in cross-section calculations.

**When protons collide, the particles created are the result of an interaction between two partons — one from each proton**

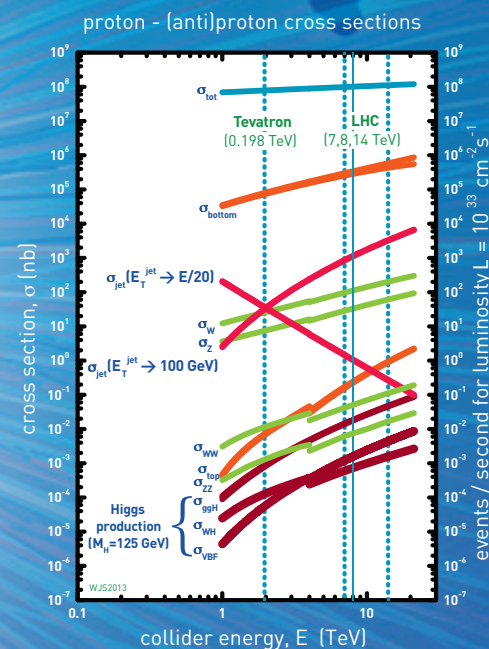
I first became involved in fitting parton distribution functions in 1987, shortly after moving from CERN to take up a lectureship at Durham University. Alan Martin, Richard Roberts (then at Rutherford Appleton Laboratory) and I were interested in measurements of W and Z bosons, being made at that time at the CERN proton-antiproton collider. We needed a set of parton distribution functions, but found that the few sets publically available were out-of-date, and not accurate enough for our calculations.

We embarked on our own fitting programme, which led to the first set of MRS parton distributions. Over the years, we and our collaborators developed new sets. These have been widely adopted, and are regarded as industry standards. The most recent set, Martin-Stirling-Thorne-

Watt (MSTW2008), is used extensively in LHC physics studies. In fact, the original MSTW2008 research publication (European Journal of Physics C63 (2009), pages 189 to 285) is the world's most highly cited post-2008 publication on particle physics.

Cross sections at the LHC are calculated by combining the parton distribution functions of the colliding protons with the cross sections for partons to produce the final-state of interest, for example a Higgs boson. The parton cross sections can be calculated from first principles in Quantum Chromodynamics, but it has taken decades of hard work by theorists to make this possible. New calculational techniques have had to be developed, leading to deeper insight into the structure of quantum field theory.

As a result of the progress made over many years, both on parton distributions and on parton cross sections, predictions for many processes at the LHC, and including the production of Higgs bosons, can be made with an accuracy at the level of a few per cent.



© James Stirling

Particle production in collisions involving protons or antiprotons. The cross section,  $\sigma$ , is shown for a variety of processes, as a function of energy. The key points here are that cross sections increase with increasing energy, and that the cross sections for producing Higgs bosons are small compared with the cross sections for other processes. The solid vertical line at 8 TeV indicates the LHC collision energy for 2012. Values read from the right-hand scale give the numbers of events per second at the LHC, for the nominal 2012 operating conditions



# EXPLORATION

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Image: The Geneva region, with outline of the LEP ring, stradling the France-Switzerland border.



# THE PIONEERING LARGE SCALE HIGGS-HUNTING EXPEDITION: LEP (1989-2000)

by Pedro Teixeira-Dias

From 1983 to 1988, the biggest civil engineering project in Europe was in progress just outside CERN. This was the digging of a near-circular tunnel, 27 km in circumference and at a distance below ground of between 50 metres and 175 metres. The tunnel was to house the Large Electron-Positron collider (LEP for short), which accelerated counter-rotating beams of electrons and their anti-matter counterparts, positrons. The beams crossed over, producing particle collisions, in four large and complex detectors, distributed around the accelerator ring. These were the detectors of the four LEP experiments: ALEPH, DELPHI, L3 and OPAL. Each was operated by a team of several hundred physicists, from Universities from all over the world.

First collisions were recorded in August 1989. From then until the end of 1994, LEP was operated with a collision energy precisely tuned to 91.2 GeV — equal to the mass of the Z boson, and so maximising its production probability. The Z boson is short lived, and almost immediately after being created will transform, or *decay* into particles that are less heavy, and more stable. There are several allowed decay modes for the Z boson, all into a matter and anti-matter particle pair. The particles from the decay can be electrons, muons, taus, neutrinos, or any of the five types of quark (u, d, s, c, b) less heavy than the Z. Between them, the four LEP experiments recorded a total of about 20 million Z decays.

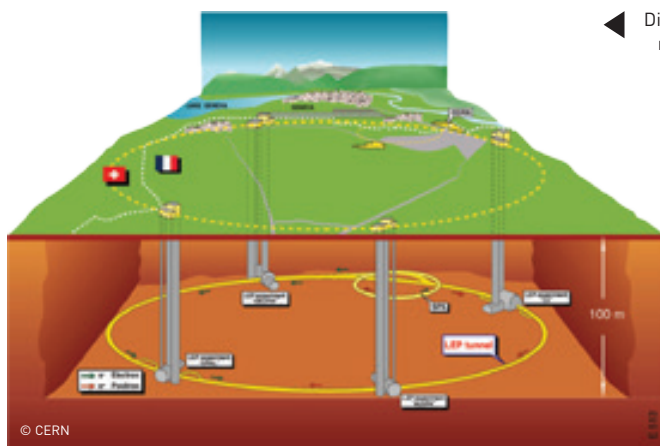


Diagram of the LEP underground ring, showing the access shafts to the underground caverns housing the detectors of the four LEP experiments: ALEPH, DELPHI, L3 and OPAL.

© CERN



## PEDRO TEIXEIRA-DIAS

Pedro Teixeira-Dias is a Reader in Particle Physics at Royal Holloway, University of London. He worked on searches for the Higgs boson on two of the four experiments at the Large Electron-Positron collider — OPAL (1990-1994) and ALEPH (1995-2006) — and was part of the group that combined search results from all four experiments.

In addition to detailed studies of the Z boson, the LEP experiments mounted a concerted effort to search for evidence of Higgs particles in their data. For the initial collision energy at LEP, a Higgs particle would usually be produced in association with a Z boson, through a process called Higgs-strahlung (from the German for *Higgs radiation*).

It might seem impossible to produce a Higgs boson in addition to a Z boson, and still conserve energy, when the collision energy is just enough to produce a Z. It turns out that the Z can be produced as a so-called virtual particle, with a mass significantly lower than that of a real Z. This phenomenon frees some energy, which is then available for creating a Higgs boson.

In particle physics as in real life, there is no such thing as a free lunch: virtual Z particles with masses more different from the mass of a real Z are less likely to be produced. Searches for heavier Higgs particles, during the first phase of LEP, then became harder and harder,

The LEP tunnel. © CERN

and were essentially impossible for a Higgs mass greater than about 65 GeV.

A Higgs boson will decay with highest probability to the heaviest quark or lepton that is energetically allowed. At LEP, this meant that Higgs bosons would decay predominantly to pairs of b quarks.

During the second phase of LEP operation, from 1995 onwards, the collision energy was increased every year, extending the range of Higgs masses that could be searched for. Although Higgs production in association with a virtual Z particle was still theoretically possible for a collision energy greater than the real Z mass, the probability was small. Higgs searches during the second phase of LEP consequently focused on production of a Higgs particle in association with a real Z. In 2000, its final year of operation, LEP produced collisions at energies in the range 202–209 GeV.

The LEP experiments were not the first to search for Higgs particles. Some searches had been carried out already in the 1980s, for example by experiments at lower-energy electron-positron colliders. These were focused mostly on types of Higgs particle other than the big catch, the Higgs particle of the Standard Model.

Prior to LEP, relatively little was known experimentally about Higgs particles. Over

their decade-long operation, the four LEP experiments undertook the first systematic exploration of a large range of masses where the Higgs could have been hiding. No positive evidence of a signal was found in the data however, but strong limits were set, excluding the existence of a Standard-Model Higgs particle with a mass less than 114.4 GeV.

During the second phase of LEP, I was convenor of the ALEPH group that searched for Higgs particles in four-jet events. These were the events where first evidence of Higgs particles were expected, in the case of a discovery.

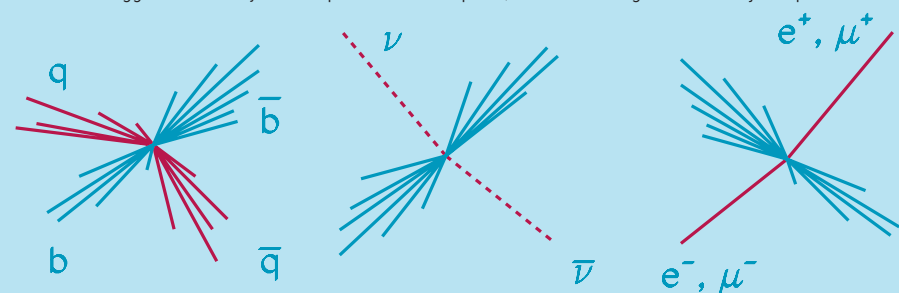
Tantalisingly, in the summer of 2000, with the planned LEP closure looming, the ALEPH collaboration collected a handful of four-jet events that looked consistent with the production of a Higgs particle having a mass of 115–116 GeV, and were in excess of the expected contribution from non-Higgs processes. This generated a huge amount of interest and excitement, as it raised the possibility of a discovery being just around the corner. To allow further investigation, LEP operation was extended by six weeks, during which time the amount of data collected at the top collision energy was almost doubled. When the new data were analysed the statistical evidence for a possible signal was deemed not to be sufficiently strong to warrant

further extensions. The LEP programme was terminated, making way for the Large Hadron Collider, which would reuse the LEP tunnel.

The LEP searches for a Higgs boson were not confined to search for the Higgs boson of the Standard Model. Other types of Higgs bosons for which searches were performed included fermiophobic Higgs bosons, which decay predominantly to two photons or two W bosons; charged Higgs bosons; and Higgs bosons with invisible decay modes.

LEP was the pioneering Higgs-hunting expedition. Its main result was to establish experimentally the non-existence of different types of Higgs particles, over a large range of possible masses. Many of the key experimental techniques and methods necessary for Higgs searches were developed at LEP. This paved the way for the later searches — at the Tevatron collider and at the Large Hadron Collider — and for the discovery by the ATLAS and CMS experiments, in 2012, of a Higgs boson with a mass close to 125 GeV.

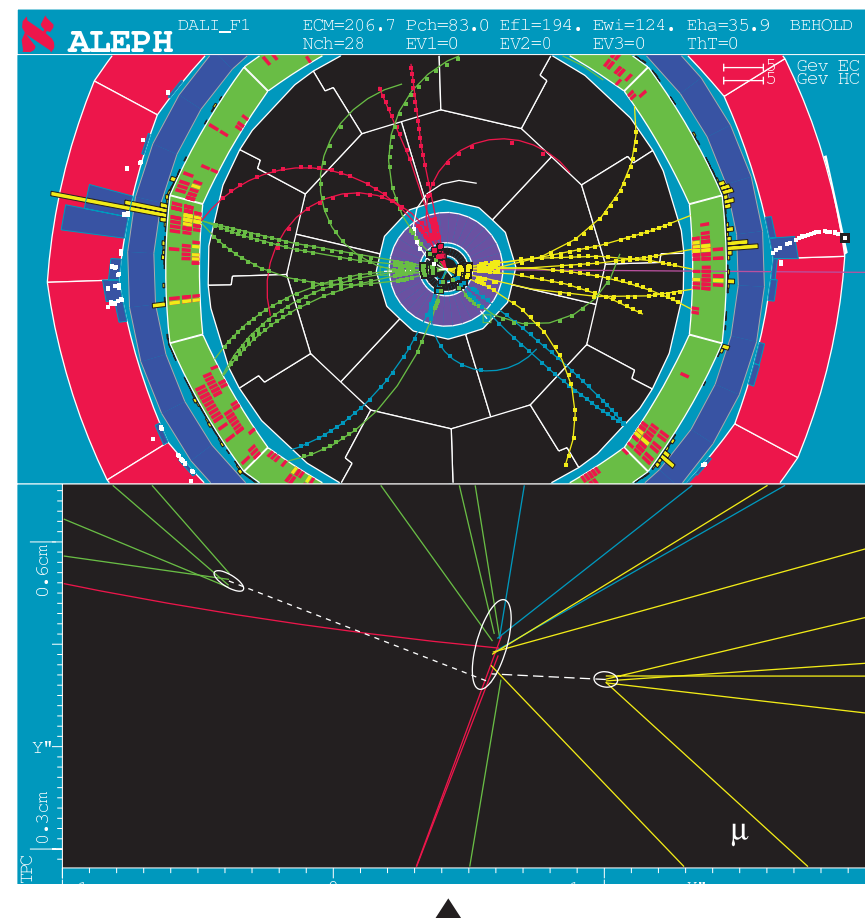
Sketches of how events with a Higgs boson and a Z boson would have appeared in a LEP detector. The Higgs boson decays to a b quark and  $\bar{b}$  antiquark, each of which gives rise to a jet of particles.



The Z boson decays to a quark and associated antiquark, each producing a jet of particles, resulting in a 4-jet event.

The Z boson decays to a neutrino and antineutrino, neither of which is seen by the detector, resulting in a missing-energy event.

The Z boson decays to a pair of electrons or muons, resulting in a leptonic event (electrons and muons being leptons).



Computer display of a four-jet event. This was recorded by the ALEPH experiment on 14th June 2000, and was thought to be consistent with the production of a Higgs boson. Two of the jets, shown in yellow and in green, have been identified as originating from b quarks. The diameter of the full detector, shown in the upper view, is about 15 m. The lower view shows a region with dimensions of about 1 cm x 3 cm, approximately centred on the interaction point. ALEPH © CERN



# HINTS OF A HIGGS SIGNAL

by Stefan Söldner-Rembold

I spent most of the late 1990s at CERN, working on the OPAL experiment – one of the four experiments at the Large Electron-Positron collider (LEP). The last days of LEP were truly dramatic: we'd caught a glimpse of the Higgs boson, and felt that its discovery might be just around the corner. We campaigned to extend LEP operation by a couple of years, to collect more data. Higgs bosons produced in electron-positron collisions would be easier to observe than at the LHC, since they contain none of the debris that come with proton collisions. Unfortunately, the LEP energy was just slightly too low, and the machine was finally shut down in November 2000. Even though the Higgs boson was not discovered by the LEP experiments, the results of these experiments told us that the Higgs boson had to be heavier than 114 GeV, but probably not much heavier.

In 2001, I moved from the Swiss Alps to the prairies of the Midwest, to work at Fermilab, near Chicago, on studies at the Tevatron. This had been the highest-energy particle accelerator for more than a decade – and would remain at the

high-energy frontier until 2010, when its energy record was broken by the LHC. The Tevatron experiments had already made a major discovery, their 1995 detection of the top quark completing the set of quarks of the Standard Model. The top quark remains the heaviest fundamental particle measured – about 40% heavier than a Higgs boson.

The Tevatron and its detectors were upgraded to run at higher energies, and with higher beam intensities. First proton-antiproton collisions at the upgraded Tevatron were observed in 2001, and we were kept busy commissioning the experiments, and collecting as much data as we could. I very much enjoyed life and work at Fermilab, where I had done research for my PhD more than a decade earlier.

Different from CERN, Fermilab is a US National Laboratory. Much has been written about the Race for the Higgs between the US and Europe, between CERN and Fermilab. In reality, half of us working on the Tevatron experiments were from Europe and other parts of the world, making these truly international projects.

Collaboration in Science is often easier between different countries than between two competing experiments. However, it is difficult to identify a Higgs boson in the busy environment of a proton-antiproton collider like the Tevatron. We quickly realised that our only hope of reaching the sensitivity needed was to combine results from both Tevatron experiments – CDF and DØ. By 2009, when I was elected to be one of the two Spokespersons of DØ, we were able to say that the Higgs boson was very likely to be lighter than about 160 GeV. This left only a small range of mass values where it could potentially exist, above the 114 GeV limit from LEP.



▲  
DØ collaboration, at an event marking the end of Tevatron operations

**The last days of LEP were truly dramatic: we'd caught a glimpse of the Higgs boson, and felt that its discovery might be just around the corner**



## STEFAN SÖLDNER-REMBOLD

Stefan Söldner-Rembold is a Professor of Particle Physics at the University of Manchester. He was Spokesperson of the DØ experiment from 2009 until 2011; served as Physics Coordinator for both DØ (2007-2009) and OPAL (2000-2001); and was awarded a Royal Society Wolfson Research Merit Award for his work on the origin of mass.



After years of hard work, we had finally reached the point where the Tevatron had collected enough collisions to search seriously for the Higgs boson. On top of this, the LHC project had been delayed, following an incident involving its superconducting magnets. We had cornered the Higgs boson in the mass range 114-160 GeV, and evidence started to accumulate that a Higgs signal was actually visible in the data.

Debates heated up after we published our tantalising hints of a Higgs signal. Should we extend the Tevatron operation for several more years? Would the detectors continue to operate beyond their anticipated lifetime? Would the Tevatron be able to compete with the LHC, and complement its results?

It was finally decided to end Tevatron operations in 2011. At an emotional farewell ceremony, and following more than a quarter of a century of operation, the last proton-antiproton collisions took place on 30 September 2011. Analysis of the collision data is an ongoing effort, and will continue for many years.

The Tevatron story also has a happy ending. A light Higgs boson, with a mass of around 125 GeV will mainly decay into pairs of bottom quarks. The Tevatron data are much better suited to searches for these decays than the LHC data, a fortunate consequence of the Tevatron's lower-energy proton-antiproton collisions. (The LHC collides protons on protons.)

When the LHC announced the discovery of the Higgs boson, in July 2012, CDF and DØ published first evidence for Higgs decays into bottom-quark pairs. This important signal remains unique to the Tevatron – and provides important confirmation that the Higgs particle behaves as we expect.



© Fermilab

▲  
Press briefing on Higgs results

***At an emotional farewell ceremony, and following more than a quarter of a century of operation, the last proton-antiproton collisions took place on 30 September 2011***

***Would the detectors continue to operate beyond their anticipated lifetime? Would the Tevatron be able to compete with the LHC, and complement its results?***







DØ control room. © Fermilab

*Even though we had still not seen any hint of the Higgs' existence, we knew that we were getting closer.*

# MEASURING ZERO

by Kathryn Grimm

The DØ experiment was one of two multi-purpose experiments that measured proton-antiproton collisions at the Tevatron, an accelerator at Fermilab, near Chicago, Illinois. Although initially approved to run for only two years, starting in 1992, the DØ experiment exceeded all expectations of its capabilities for physics studies, and recorded data over a nineteen-year period.

Along with the other Tevatron experiment, CDF, DØ discovered the top quark. It also measured parton distribution functions – maps of the insides of protons – with the highest precision so far achieved, and studied the matter-antimatter balance in the Universe.

It wasn't until there was talk of upgrading the Tevatron accelerator and the DØ detector that people began to believe that the discovery of the Higgs might also be possible. A 1996 study group, in a report Future ElectroWeak Physics at the Fermilab Tevatron, came to the conclusion: "Although further study is needed, the opportunity to detect a light Higgs boson at the Fermilab Tevatron appears to be real."

Finding the Higgs was a huge challenge, because its production at laboratory energies is extremely rare. The upgrade to the Tevatron gave the accelerator a higher luminosity – more particle collisions every second – so that the chances of seeing the Higgs would be greater.

I joined the DØ collaboration in 2009. By that time, looking for the Higgs in DØ had gone from a distant possibility to a high priority. I travelled to Chicago six times a year, to work with the 50 or so other people in DØ searching for the Higgs. Like many physicists, I stayed in an old farmhouse, on one of the still-running farms at Fermilab. This made for an interesting mix of cutting-edge science and rural life.

The atmosphere at Fermilab was one of excitement. After years of running, the DØ detector was understood in tremendous detail, and the upgraded Tevatron provided huge amounts of data each year. Even though we had still not seen any hint of the Higgs' existence, we knew that we were getting closer – either closer to seeing the Higgs or closer to being able to say definitively that it didn't exist.



© Pamela Tan

## KATHRYN GRIMM

Kathryn Grimm is a Research Associate in the Experimental Particle Physics group at Lancaster University. She carried out Higgs searches at the Tevatron for her PhD, and currently works on the ATLAS experiment.



**The LHC experiments would be able to collect data at high energy and high luminosity very quickly, so we knew that the race to find the Higgs was heating up.**

We reported our results as a measure of how frequently a Higgs would have to be produced for us to see it with the data that we had. This ruled out theories in which the Higgs production was much higher than predicted by the Standard Model, but it also told us how much more data we would need in order to see, or be able to rule out, the Standard-Model Higgs. For example, in 2010 we could say that we needed twice as much data as we had to be able to say whether the Higgs boson existed at a low mass, but we could say with high confidence that no Higgs boson existed over a range of high mass values.

In 2010, the LHC started producing data. The LHC experiments would be able to collect data at high energy and high luminosity very quickly, so we knew that the race to find the Higgs was heating up. Each new result from the Tevatron at that time showed a better understanding of where the Higgs didn't exist – more and more of the high mass region was ruled out. We joked that we were getting really good at measuring zero, but really it was a tremendous advance to be able to rule out larger and larger mass regions.

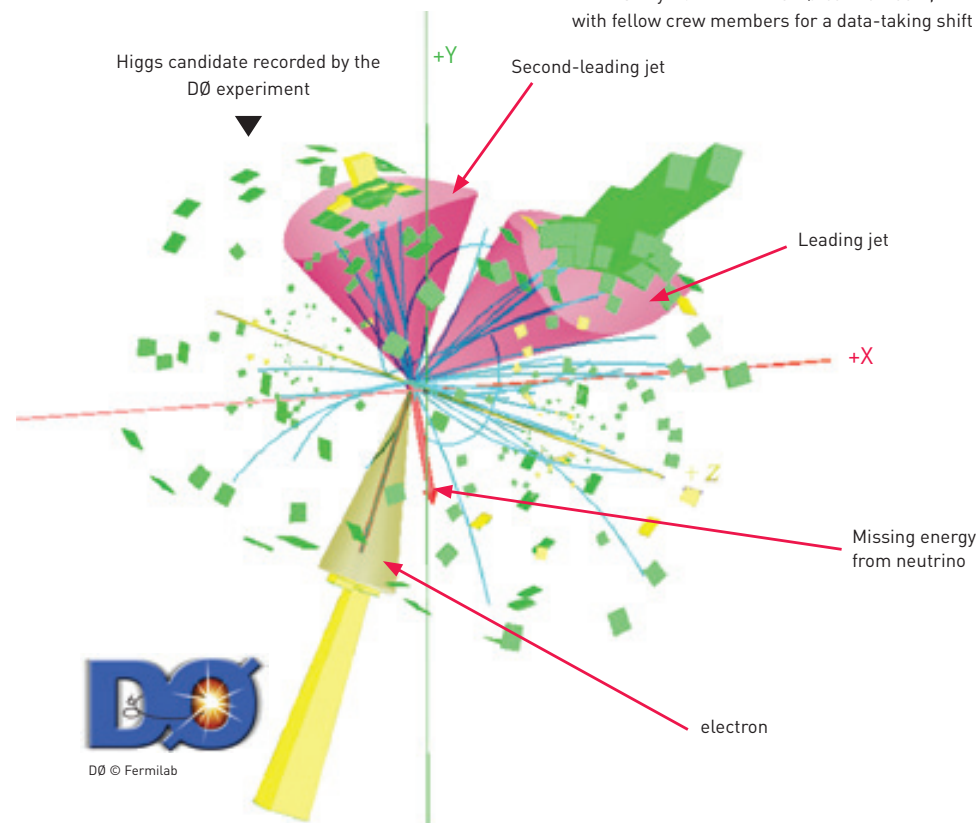
One of the biggest particle-physics events of the year is the Rencontres de Moriond, held in the Italian Alps. At the 2011 conference, I presented my results from looking for Higgs decays to two tau particles. In this channel we still needed 12 times the existing data to rule out the Higgs. The higher-mass searches, focusing on decays to W and Z bosons, and combining data from DØ and CDF, showed that the Higgs boson had been ruled out in the mass range between 158 GeV and 173 GeV.

With mounting competition from the LHC experiments, 2012 brought the biggest push of the DØ Higgs searches. At the 2012 Moriond conference, the DØ and CDF combined results gave a first hint of a Higgs boson in the low-mass region! Having seen only background particles for years, we now saw particles that matched the simulations we had for the Higgs.

On 2nd July 2012, in a press conference at Fermilab, DØ and CDF presented their updated results, saying that they were 99.7% certain that they were seeing the Higgs boson! Two days later, at CERN, the ATLAS and CMS experiments confirmed that they too saw the Higgs, in the same mass region as at the Tevatron, and with more than 99.99% certainty.



Kathryn Grimm in the DØ control room, with fellow crew members for a data-taking shift





# SEARCHING FOR THE HIGGS AT CDF

by Aidan Robson



## AIDAN ROBSON

Aidan Robson is a Lecturer in Physics at the University of Glasgow. Since 2005, he has been Higgs-hunting in the CDF experiment, at Fermilab in the USA

The CDF experiment, at Fermilab's Tevatron, has been searching for the Higgs boson since the 1980s. In the early days, the searches focused on a very light particle – fifty times lighter than the one now observed!

Following the 1995 discovery of the top quark – by CDF and  $D\bar{0}$ , the second Tevatron experiment – the Higgs boson

was expected to have a mass of around 100 GeV. It was only in the mid-2000s that CDF started to accumulate the data needed for such a particle to be within reach. The combination of new data and delays to the LHC gave a window of opportunity for discovery. Although there was competition between the Tevatron and the LHC, most of the people involved were participating in both.

I was part of the Glasgow group, led by Richard St Denis, that joined teams from Santa Barbara, Duke University and Fermilab, to develop the search for a Higgs particle decaying to two W bosons. This became the Tevatron's most-sensitive Higgs search. By the end of 2009, the combined CDF and  $D\bar{0}$  data samples were finally large enough for us to find a heavy Higgs boson, if it was there. It was a very exciting time.

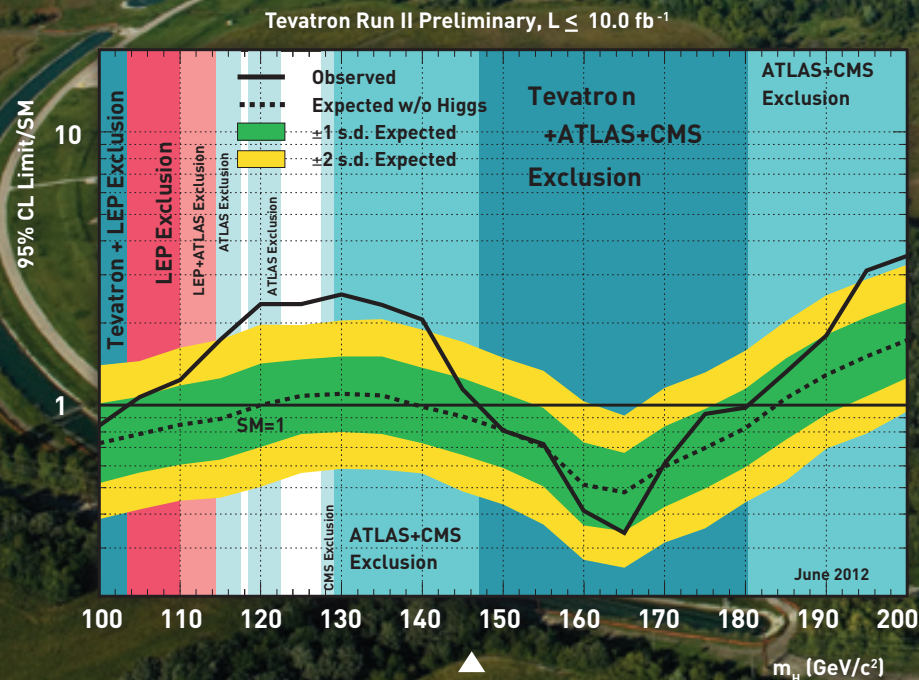
Looking ahead, Tevatron measurements of the W boson mass are likely to remain the world's best for the foreseeable future. This mass value is one of the key inputs for determining whether we have a self-consistent picture of the Standard Model, or whether the Higgs discovery already points us in the direction of new physics.

We developed new search techniques, now used at the LHC, and ruled out larger and larger mass ranges where a new particle could be. At the same time, searches for the Higgs boson in its decays to b-quarks were developed, extending the search to lower masses.

The final results, combining all of the data from CDF and  $D\bar{0}$ , were obtained in June 2012. These excluded a large range of potential masses, and provided evidence for a new particle at a mass of between 115 GeV and 135 GeV, consistent with the LHC discovery.



CDF Higgs-hunters, 2010. Back (left to right): Roman Lysák, Eric James, Sergo Jindariani, Aidan Robson (Glasgow). Front L-R: Jason Nett, Richard St Denis (Glasgow), Massimo Casarsa, Tom Junk



Combined CDF and  $D\bar{0}$  results from June 2012. Possible mass values for the Higgs are indicated on the horizontal axis. Values are excluded by the Tevatron measurements where the solid black curve falls below the horizontal line labelled SM=1. CDF and  $D\bar{0}$  © Fermilab

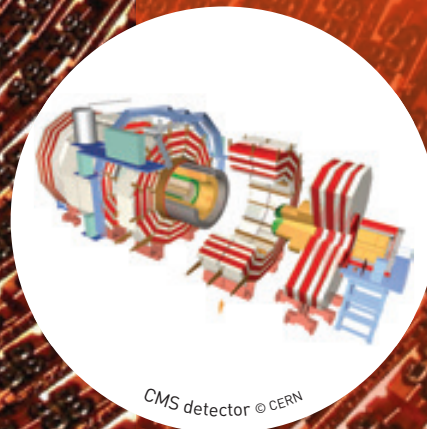
**By the end of 2009, the combined CDF and  $D\bar{0}$  data samples were finally large enough for us to find a heavy Higgs boson, if it was there. It was a very exciting time.**

Background image: Fermilab accelerator complex  
© Fermilab

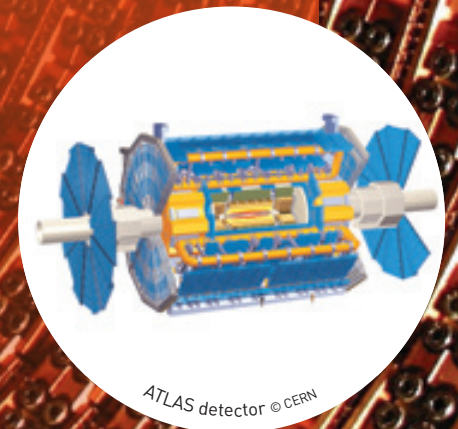


# GIANTS

Image: ATLAS calorimeter



CMS detector © CERN



ATLAS detector © CERN



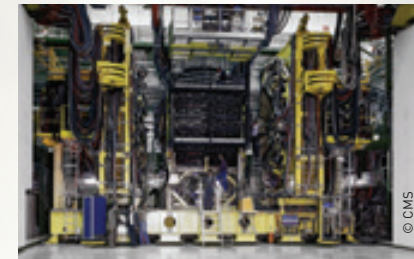
# EARLY DAYS OF ATLAS

by Andy Parker

The idea of a hadron collider was considered at least as far back as 1977, when the Large Electron-Positron (LEP) accelerator was being discussed. LEP was approved in 1981, and the 27 km tunnel for colliding electrons and positrons was duly built. Since positrons are the antimatter equivalent of electrons, they annihilate one another, with the energy converted into new particles. This is the simplest system for physicists to analyse, and many were sceptical that it would be possible to do precision measurements using proton collisions. Protons are each composed of three quarks, making for very complicated interactions when they smash together. Some dismissed the idea as like throwing dustbins at each other!

In 1983, however, when the UA1 and UA2 experiments, using protons and antiprotons, made the Nobel-prize winning discovery of the W and Z bosons, responsible for the weak nuclear force, it became clear that hadron colliders were capable of great things. Discussions of the Large Hadron Collider (LHC) gathered pace, with workshops starting in 1984. By 1989, it was clear that CERN was going ahead, and Peter Jenni, leader of the UA2 group, called a first meeting of people interested in forming a new experimental collaboration.

Detector of the UA2 experiment – the start of the art before developments for the LHC



I remember the day very well. I stopped my work, looking for the top quark with the UA2 detector, and walked up the hill at CERN to a large seminar room. The meeting was a distraction from the day job, and I arrived with no great expectations, to find 50 or 60 people present. We began to discuss what would be needed to do experiments at such a machine. It rapidly became clear that the challenge was enormous – the increase in beam energy, together with the huge interaction rates, meant that the technology that we had lovingly developed for the state-of-the-art UA detectors would be incapable of functioning. The

## ANDY PARKER

Andy Parker is leader of the High Energy Physics Group at the Cavendish Laboratory, University of Cambridge. As a CERN staff member, he was present at the first meeting (1989) of the collaboration that became ATLAS, and for six years led the project to build the Inner Detector.



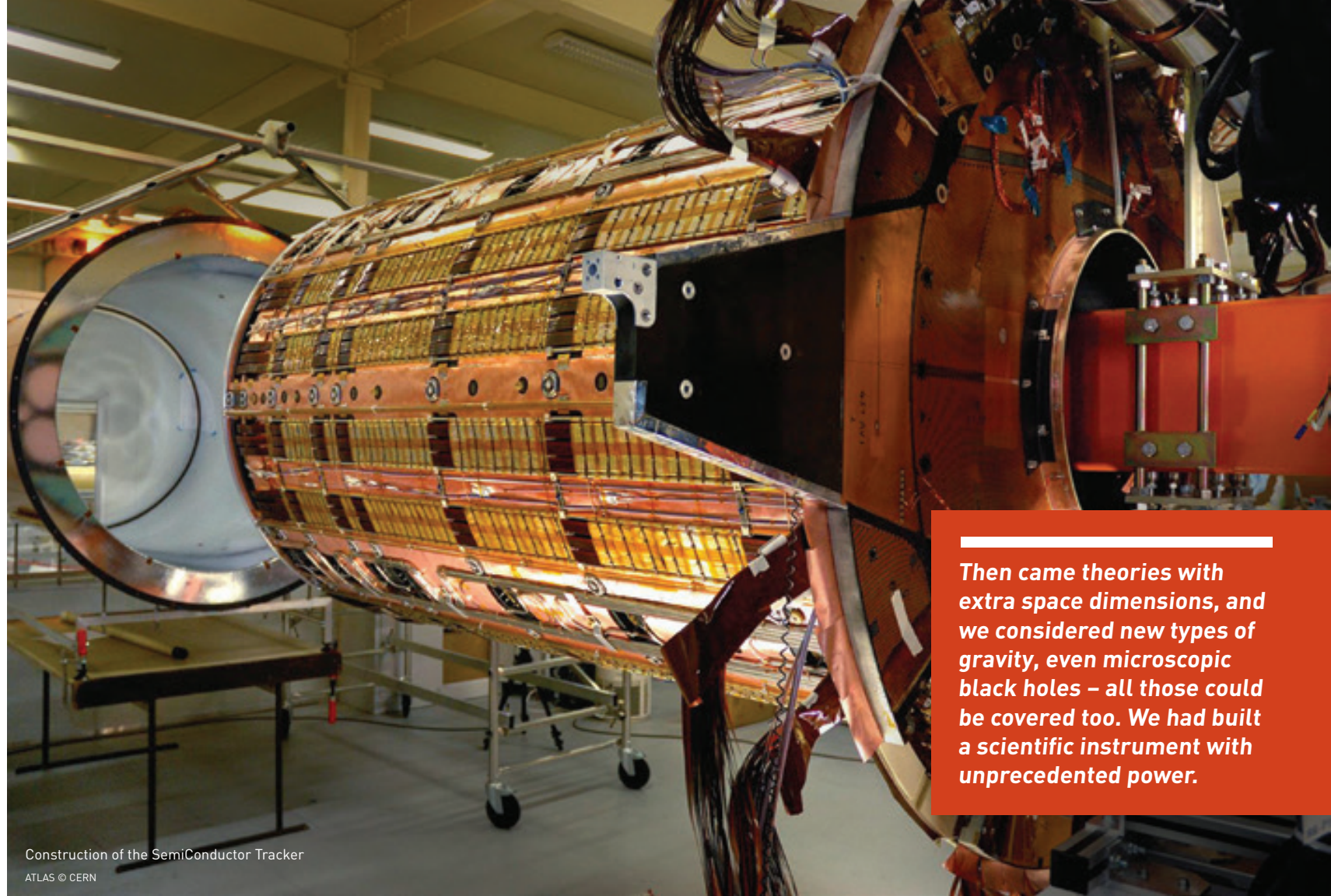
Constructing the ATLAS experimental cavern, 2008



scale of the detector that emerged on the blackboard also stunned me. I had thought that UA2 was a big experiment, standing over 6m tall, but the new detector would need to be at least four times that size in every direction! And its goal would not just be to explore the Standard Model, established as a solid theory by the W and Z discoveries. It was to reveal what lay beyond, in unexplored territory, where theory was an unreliable guide.

I walked back to my office into a whole new world. Work began on designing detector systems capable of surviving the pounding that they would receive from the particles in the new machine. I worked on the silicon detectors, at first painfully measuring irradiated slivers of silicon, then designing huge arrays of sensors, a hundred times larger than anything attempted before. Eventually I found myself “leading” a collaboration of fifty institutes, attempting to design the most complex tracking detector ever attempted – leading in the CERN sense, where you are elected to manage the project, but without formal control of any people or money. Force of argument has to suffice or, failing that, boring the opposition into agreement in endless meetings can work.

Teams of physicists formed rival collaborations, which later merged. By November 1992, we were ready to present a *Letter of Intent* on behalf of the newly christened ATLAS Collaboration. This was favourably received, and the work grew in scope as more physicists worldwide flocked to the banner. By 1994, we had a slim volume grandly named the *Technical Proposal* and, in my naivety, I thought we had the problem under control. My bookshelf in Cambridge now contains several feet of *Technical Design Reports*, which show how far we still had to go. It was not until 1997 that the design of the Inner Detector was complete, and with a sigh of relief I was able to pass the baton to the people who would actually construct and operate it.



Construction of the SemiConductor Tracker  
ATLAS © CERN

In Cambridge, we studied what our new baby might be capable of doing, when it finally got to work. The search for the Higgs boson of course, but also it could look for supersymmetry, new layers of matter, dark matter: we had all those under control. Then came theories with extra space dimensions, and we considered new types of gravity, even

microscopic black holes – all those could be covered too. We had built a scientific instrument with unprecedented power.

And finally the data started to arrive. Bleary-eyed students emerged from the ATLAS pit after night shifts, and even-more-tired-looking postdocs slaved for hours over their keyboards – processing, calibrating, and analysing the flood of

**Then came theories with extra space dimensions, and we considered new types of gravity, even microscopic black holes – all those could be covered too. We had built a scientific instrument with unprecedented power.**

data. The first reward was earlier than I had anticipated, with the hints, and then confirmation, of the Higgs discovery. But that is only the beginning. The dream of new physics, beyond the Standard Model, still remains. When the LHC doubles its energy, in 2014, a twenty-five year trek to terra incognita will finally reach its destination.



# VOYAGE OF DISCOVERY AT CMS

by Tejinder Virdee

The following is an account of a few of the enormous challenges faced, and overcome, by people working on the Compact Muon Solenoid (CMS) experiment. This is one of the two general-purpose experiments at the Large Hadron Collider (LHC) at CERN, Geneva. It was created to search for the elusive Higgs boson, and to probe Nature under the conditions that existed a small fraction of a second after the Universe came into existence.

## HISTORICAL INTRODUCTION

In 1987, a CERN committee, set up to look at the laboratory's long-term future, and under the chairmanship of the Nobel Laureate Carlo Rubbia, recommended that a proton-proton machine, the Large Hadron Collider (LHC), be constructed in the tunnel then being excavated for the Large Electron-Positron (LEP) Collider. I recall seeing this as an exciting opportunity for a young researcher, as I was at the time, to think about the challenges of doing physics at an energy some ten times larger than anyone had reached before. For me, there was every expectation that what we physicists would find at the LHC would alter the way we look at Nature at the most fundamental level. So it was without too much deliberation that I decided to skip participation in the LEP experiments, which were in their construction phase, and chose to spend, as it's turned out, the remainder of my professional life working on the LHC.

The first key scientific goal of the LHC, but by no means the only one, was going to be the hunt for the Higgs boson of the Standard Model. This aim heavily influenced the conceptual design of the general-purpose detectors. The design had to enable a search across the entire allowed

range of masses: from around 50 GeV — the lower limit at the time, and some 50 times larger than the mass of a proton — up to the largest possible value, of around 1000 GeV.

In the Standard Model, the mass of the Higgs boson determines all of the particle's other properties. The only question was whether the Higgs boson existed or not. It was also common knowledge that finding the Higgs boson would immediately raise a more puzzling question: why should it have such a low mass? It was widely believed that the answer to this question would lie in new physics, meaning physics beyond the scope of the Standard Model. One appealing hypothesis — much discussed at the time, and still being investigated — predicts a new symmetry, labelled supersymmetry. This limits the mass of the Higgs boson to be below about 150 GeV, at the same time doubling the number of fundamental particles. The lightest of this new species of particle would be a candidate for dark matter, which is around five times more abundant in the Universe than everyday matter.

In October 1990, I participated in the Large Hadron Collider Workshop, organised

## TEJINDER VIRDEE

Tejinder Virdee is a Professor of Physics at Imperial College London, and a Fellow of the Royal Society. He is one of the founding fathers of the Compact Muon Solenoid (CMS) experiment, contributed much to the conceptual design, pioneered techniques used in the calorimeters, and led the teams that designed, constructed and commissioned the CMS detector, over the course of twenty-two years. His achievements have been recognized through awards including the High Energy Particle Physics Prize (2007) and the Chadwick Medal and Prize (2009) of the Institute of Physics, the Special Fundamental Physics Prize (2012), and High Energy and Particle Physics Prize (2013) of the European Physical Society.

CMS © CERN



by the European Committee for Future Accelerators, in Aachen, Germany. Lively discussions took place to understand the physics potential, and challenges, of a high-energy hadron collider with high interaction rate; and to understand the requirements on detector technologies. Various study groups were set up, and I became one of the conveners of the study group focusing on calorimetry.

At the time, much emphasis was put on allowing searches for the different ways in which the Higgs boson decays, depending on its mass. Momenta of charged particles, and the energies of photons and electrons, would have to be measured more precisely than ever before. At the Aachen meeting, I presented with Chris Seez, a colleague at Imperial College, the first detailed study of searching for the Higgs boson in the low mass region, via the particle's decay to two photons — considered the most promising decay for making a discovery. These

## EARLY YEARS OF THE COMPACT MUON SOLENOID

In October 1992, three competing experiment designs, including CMS, were submitted to CERN's newly formed LHC Committee (LHCC), which comprised world-renowned scientists. The CMS proposal was for a giant detector, that can be likened to a 100-Megapixel digital camera able to record three-dimensional images at a rate of 40 million per second. The CMS design centred on a single large solenoid, having a high magnetic field; a tracking detector, based on silicon microstrips; and a high-performance electromagnetic calorimeter, based on scintillating crystals.

In June 1993, after several intense meetings between the experiment teams and the LHCC, the Committee recommended that two of the proposed experiments should go forward: CMS and ATLAS. For me, it was a moment of

studies led to stringent requirements on the electromagnetic calorimeters to be used at the LHC.

After the Aachen workshop, many felt, for the first time, that the formidable experimental challenges could be manageable, if appropriate development of detector technologies could be carried out. It wasn't long before several groups of physicists and engineers started putting together full experiment designs. I led a team working on a design based around a large superconducting solenoid (high-magnetic field), and a high-performance electromagnetic calorimeter. After a short time, we joined a team that had similar ideas to ours, the team of the Compact Muon Solenoid (CMS).

tremendous relief and exhilaration, but a moment that brought with it a realisation of the weight of responsibility that fell on our shoulders. Foreseeing the technical, industrial, financial and human challenges that lay ahead was almost impossible.

One of our first tasks was to find new collaborators, and this was to require a major effort during the early years. It meant travelling widely, to countries in Europe and to countries further away, to motivate, and invite, the participation of their physicists. Value was placed not only on material contributions, but also on intellectual ones. Formal approval for construction of the CMS detector was finally given in July 1997, by the CERN Director-General (1994-1998), Chris Llewellyn Smith. The material cost ceiling was set at 475 million Swiss Francs (at the time, about £190 million).

## DESIGN AND CONSTRUCTION OF THE ELECTROMAGNETIC CALORIMETER

Behind almost every aspect of the CMS detector there is a story — from the colour of the cables for the different parts to the technology choice for each detector layer. The following is a brief account of some of the hurdles that we faced during the design and construction of the electromagnetic calorimeter.

In the summer of 1993, I attended an instrumentation conference on the Island of Elba, Italy, where I saw results for a novel device for photon detection, a silicon avalanche photodiode. This could operate in a high magnetic field, and could provide modest signal amplification.

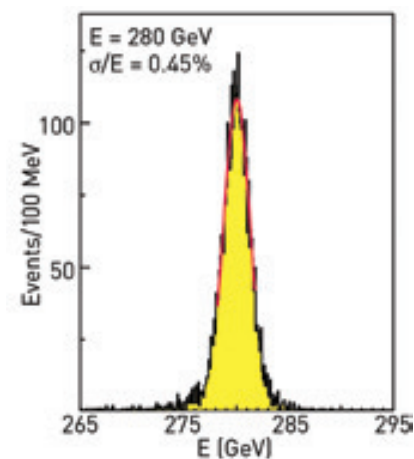
A few months later, on a collaboration-building visit to the Kharkov Institute of Physics and Technology, Ukraine, I was shown some remarkable measurements for a new, dense scintillating crystal — lead tungstate. These crystals were being grown in a poorly lit laboratory in the basement of the building where our meeting was being held. The crystals

offered several advantages from the point of view of CMS, but they weren't immediately suitable for deployment. Compared with other crystals in use at the time, there was a low yield of scintillation light (light generated from energy deposited by photons or charged particles). Also, the photomultipliers that had been used to measure the light from the crystals couldn't function in the high magnetic field of CMS.

I proposed using the lead-tungstate crystals in combination with the silicon avalanche photodiodes. Back at CERN, we tested this idea, using an electron beam, and the results were extremely promising. We undertook intensive research and development, working closely with industry, and paying particular attention to quality and performance. This enabled us to produce crystals and avalanche photodiodes that satisfied our stringent requirements. The technology that we developed has applications today in medical imaging, especially in cameras for positron-emission tomography.

The electromagnetic calorimeter that we designed required a total of 75,000 lead-tungstate crystals. To grow these, we set up a round-the-clock production line in the small Russian town of Bogoroditsk, near Tula, some 200 kilometres from Moscow. The factory that we used had previously been deployed in the Russian military-industrial sector, and the local people's livelihood depended on this factory's continued output. We obtained funds for its conversion to non-military use from the International Science and Technology Centre, set up in 1992 by the USA, Europe, Japan and Canada.

In the mid-1990s, when the contracts for crystal production were first negotiated, a reasonable price per unit volume had been agreed, in US dollars. As Russia's economy



Measurements, using lead tungstate crystals and silicon avalanche photodiodes, of the energy deposited by electrons of 280 GeV. The width of the distribution represents the figure of merit for the design. CMS © CERN





*I had to learn quickly about negotiating deals for borrowing precious metals, shipping them to China, and getting them back to Switzerland*

Cut and polished lead-tungstate crystals, including one with silicon avalanche photodiode mounted  
CMS © CERN

began to pick up, prices for raw materials and energy started to increase. In 2004, the people running the factory in Bogoroditsk told us that the unit price would have to triple, or they would be unable to continue production. A period of intense dialogue ensued, also involving the Russian Minister of Science and Technology, Andrei Fursenko, and the CERN Director-General (2004-2008), Robert Aymar. A few months later, and to our relief, a new mutually acceptable price was agreed. It was also stipulated that all later contracts (covering about half the crystals) would be in Russian roubles, now considered to be a stronger currency than the US dollar.

For much of the time that the crystal production was in progress, I had an

open visa for travel to Russia, and visited frequently. Back in the early 1990s, I used to take several bottles of water, boxes of chocolates, packets of dried fruits and other preserves, as there were no restaurants in town. Much has changed since then, and for the better, although prices now can be high.

Following the difficult 2004 negotiations, we also made contact with another supplier, in China, who eventually provided about 10% of the crystals that we needed. This supplier wanted CMS to provide the platinum needed to line the insides of the ceramic crucibles in which the lead-tungstate ingots are grown, in ovens operating at 1200 °C. This platinum can be recovered and reused when the

crucibles are broken up, after some number of growth cycles. The Swiss bank UBS holds considerable reserves of precious metals in its vaults in Zurich, and we were able to arrange a loan of platinum worth \$10 million (at the time, about £7 million). I had to learn quickly about negotiating deals for borrowing precious metals, shipping them to China, and getting them back to Switzerland.

After all of the research, development and production, we finally received the last consignment of crystals in March 2008. It had taken a total of fifteen years from novel idea to realisation. This was, and still is, a great achievement for CMS.

## COMPLETION AND INSTALLATION OF CMS

Construction of the CMS detector started in 1998, and was completed in ten years. The detector was mostly assembled in a large surface hall, in 15 slices. Using a huge custom-built gantry, it was then meticulously lowered, element by element, through a shaft of 23 m diameter, into a gigantic underground cavern, some 100 m underground. It was the first detector of its kind to be built in this way. One of the most spectacular operations took place on 28th February 2007. This was the lowering of the central, and heaviest, slice, weighing about 2000 tons. The installation and commissioning of the experiment was completed on 1st August 2008. This was a day when champagne flowed, as many CMS physicists and engineers celebrated the end of the long, painstaking construction phase, and looked forward to the momentous day of the startup of the LHC.



CMS © CERN

Nested layers of electronics for around 1700 crystals of the barrel section of the electromagnetic calorimeter.





## FIRST PARTICLE BEAMS IN THE LHC

With our CMS detector now ready to record data, the eyes of the world were on the LHC. The date for circulating first particle beams at the Large Hadron Collider was chosen by CERN to be 10th September 2008, coined "Big Bang Day". Television reporters and newspaper journalists flooded into CERN, joining scientists from around the world to witness this unique occasion. In the early hours of the morning, hundreds of physicists, from all the experiments, sat in front of their computer screens, waiting nervously for the first beams of protons to circulate inside the LHC. At precisely 10:28 a.m., the first beams whizzed through the 27 km tunnel, at almost the speed of light.

Nine days later, during a test of the last octant of the accelerator ring, a flurry of alarms reached the consoles of the LHC control room, and safety systems were activated. The root cause turned out to be the failure of one of the 50,000 soldered joints. This had led to an electrical arc, which had pierced the vacuum enclosure of a superconducting bending magnet. The pressure wave from the resulting massive escape of helium caused considerable collateral damage. The accelerator had to be taken offline for nine months of repair work.

**Television reporters and newspaper journalists flooded into CERN, joining scientists from around the world to witness this unique occasion**

## FIRST PROTON-PROTON COLLISIONS AT THE LHC

After the LHC had gone offline, the CMS experiment continued to run round-the-clock for a few months, recording billions of traversals of cosmic rays. The data collected demonstrated that the detector was in a good shape, and were used to guide further improvements. The experiment was then perfectly prepared for the LHC's first particle collisions, which came on 22nd November 2009. It was astonishing how quickly the first collision data were distributed and analysed, to produce physics results.

In the following year, 2010, sufficient data were recorded to demonstrate not only that the CMS experiment was working according to the ambitious design specifications, but also that it was producing results for known processes that were consistent with the predictions of the Standard Model. More importantly, CMS was now ready to delve into the unknown, and look for new phenomena. My group at Imperial College and I decided to focus analysis efforts back onto the hunt for the Higgs boson, via its decay to two photons, the very same channel that we had studied in the early 1990s, and presented at Aachen.

Background image:  
Barrel section of the CMS electromagnetic calorimeter  
CMS © CERN

## DISCOVERY OF A NEW HEAVY BOSON

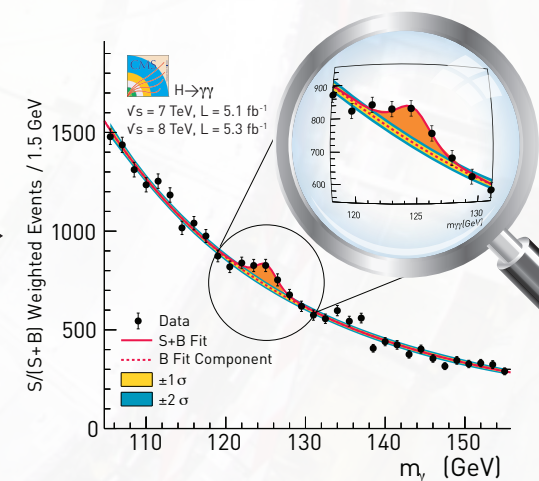
In December 2011, after two years of data taking, the first "tantalizing hints" of something new, from the CMS and ATLAS experiments, were announced at CERN. The general conclusion was that both experiments were seeing an excess of unusual events, at roughly the same mass, in two different decay channels. This set the stage for the next year's data collection. By June 2012, the number of high-energy collisions examined had been doubled, and CMS and ATLAS had greatly improved their analyses. To avoid inadvertently introducing any bias, it was decided that the mass region that had shown the excess of events should be looked at only after all of the selection procedures had been agreed.

In CMS, the day for unveiling new results from the search for the Higgs boson was 15th June. Just before lunch, after finishing a tutorial at Imperial College, I telephoned two of my colleagues at CERN, who sent me, by e-mail, advance copies of two spectacular mass plots. Both showed a peak at the same place, around 125 times the mass of the proton. Looking at these beautiful peaks, it was clear to me that we were on the verge of an incredible discovery. It was a truly memorable moment.

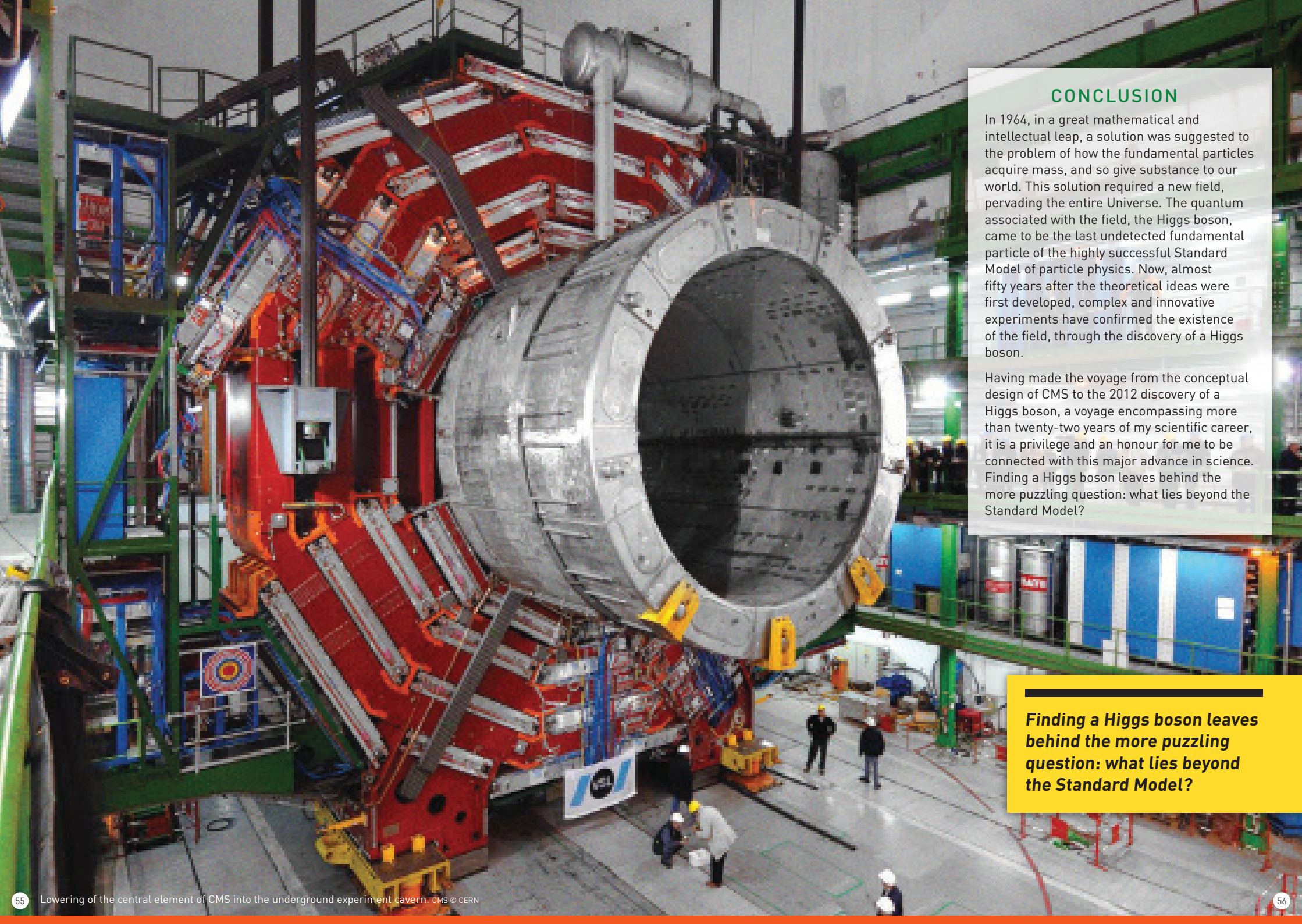
For the next fortnight, the analysis results were a closely guarded secret within the CMS collaboration. More data were examined, only reinforcing the view that CMS was on the verge of a major discovery.

A seminar was scheduled at CERN for 4th July, when CMS and ATLAS would both show their latest results. The theoreticians who had postulated the mechanism that generates mass were invited to attend. These included British physicists Peter Higgs and Tom Kibble; only Peter Higgs managed to be there.

The two-photon mass distribution, from the results published by CMS in August 2012. The peak at around 125 GeV is the signal for the Higgs decay.  
CMS © CERN







## CONCLUSION

In 1964, in a great mathematical and intellectual leap, a solution was suggested to the problem of how the fundamental particles acquire mass, and so give substance to our world. This solution required a new field, pervading the entire Universe. The quantum associated with the field, the Higgs boson, came to be the last undetected fundamental particle of the highly successful Standard Model of particle physics. Now, almost fifty years after the theoretical ideas were first developed, complex and innovative experiments have confirmed the existence of the field, through the discovery of a Higgs boson.

Having made the voyage from the conceptual design of CMS to the 2012 discovery of a Higgs boson, a voyage encompassing more than twenty-two years of my scientific career, it is a privilege and an honour for me to be connected with this major advance in science. Finding a Higgs boson leaves behind the more puzzling question: what lies beyond the Standard Model?

***Finding a Higgs boson leaves behind the more puzzling question: what lies beyond the Standard Model?***



# SUPER-FAST DIGITAL CAMERA

by Steve McMahon

Fifty physicists crowded into the ATLAS control room, to wait for a beam of protons to slam into a block of metal called a collimator. What has this got to do with the Higgs boson? Read on!

The ATLAS SemiConductor Tracker (SCT) is part of the Inner Detector, at the heart of the ATLAS experiment, in a region of high magnetic field. It tracks charged particles as they stream out of proton-proton collisions at the centre of ATLAS. When a charged particle crosses the detector, it produces a series of electronic signals in small silicon strips, 120 mm long and 0.080 mm wide. By identifying the strips that record a signal, and joining them up, we reconstruct the particle paths. These are curved because of the magnetic field. By measuring the path curvature, we can then determine a particle's momentum (the product of mass and velocity).

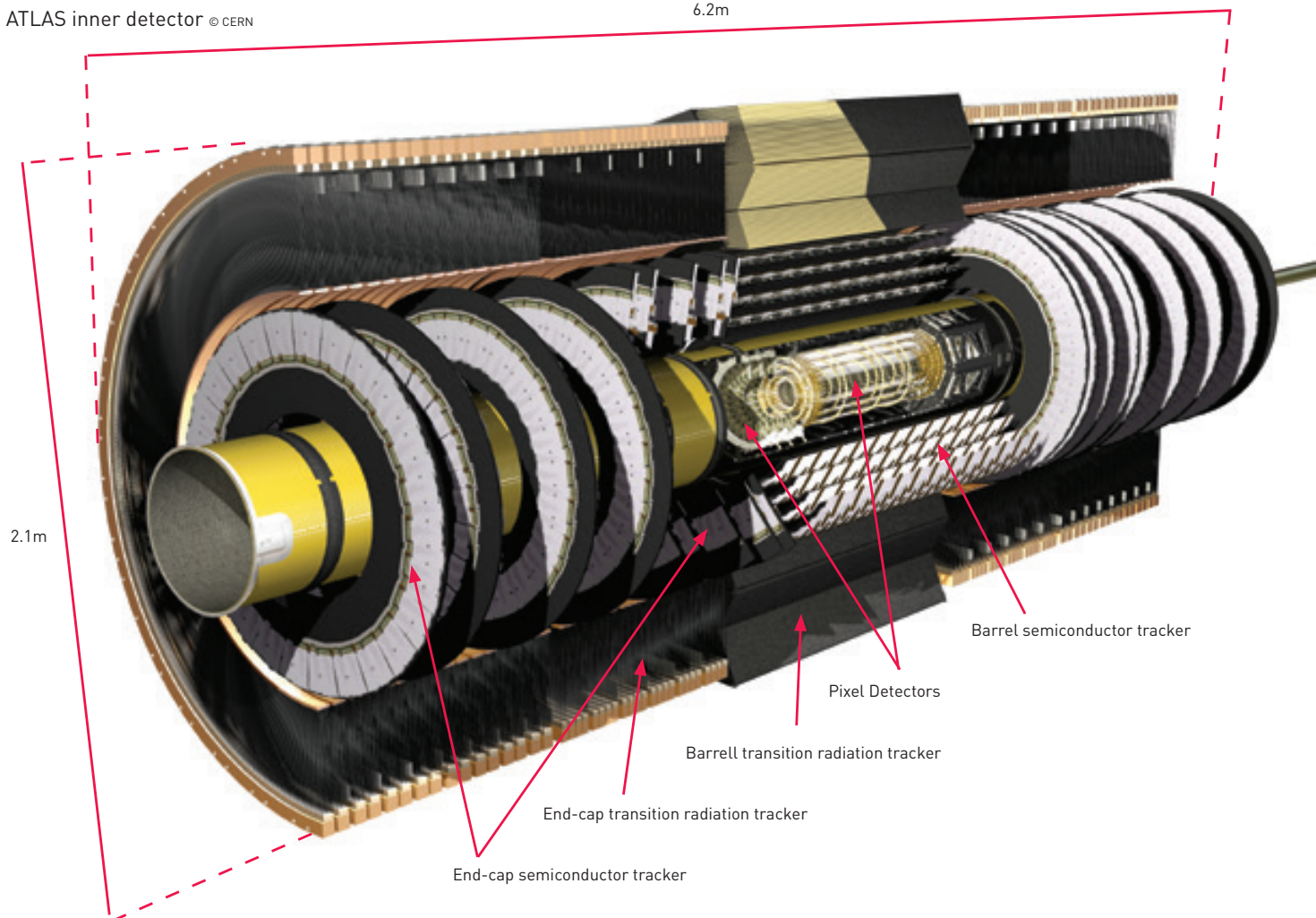
Recording particle paths with the SCT is like taking pictures of the interactions with a digital camera, but this camera can take pictures 40 million times per second, and can record the interesting ones at a rate of 100,000 per second. Try doing that on a point-and-click camera!

The SCT is essential for identifying all types of charged particles, vital to our searches for the Higgs boson. The SCT also complements measurements by other ATLAS components. In our search for Higgs decays to two photons, for example, the electrically neutral photons are identified from there being no signal in the SCT, followed by an energy deposition in the experiment's Calorimeter (outside the SCT).

ATLAS inner detector © CERN

6.2m

2.1m



Construction of the barrel section of the ATLAS SCT



## STEVE MCMAHON

Steve McMahon is a researcher in the Particle Physics Department at the STFC Rutherford Appleton Laboratory. He has worked on the ATLAS experiment for more than twelve years, enjoying every minute, and was Project Leader for construction of the SemiConductor Tracker.





Steve McMahon (pale blue shirt) and other physicists in the ATLAS control room celebrate the first beam-splash event after the LHC restart, November 2009

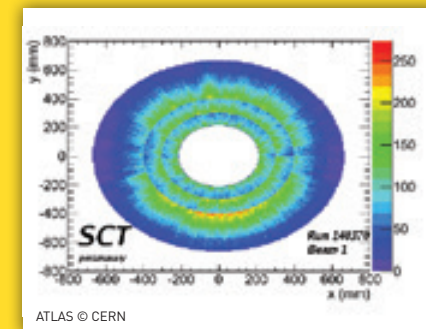
Construction of the SCT was an international effort, undertaken by teams from Australia, CERN, Germany, Japan, Netherlands, Norway, Poland, Slovenia, Spain, Sweden, Switzerland, UK, USA. The UK was the largest contributor, with participating teams from the universities of Birmingham, Cambridge, Glasgow, Lancaster, Liverpool, Manchester, Oxford, Queen Mary, Sheffield, University College London, and from the STFC Rutherford

Appleton Laboratory. Physicists from the UK groups filled many of the key leadership roles.

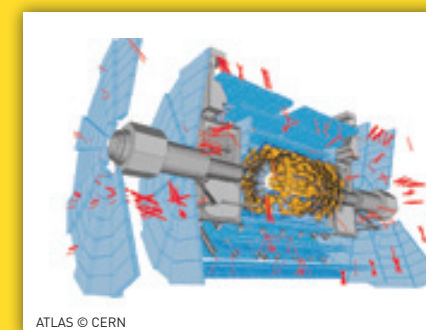
Once we'd installed the SCT in the ATLAS experimental area, one of the best ways to test that everything was working was to slam a beam of LHC protons into a block of metal, just downstream of ATLAS. We could then watch the SCT light up, like a Christmas tree, as the particle debris flowed through the detector. By analysing

the result, known as a beam-splash event, we were able to check the performance of each silicon strip.

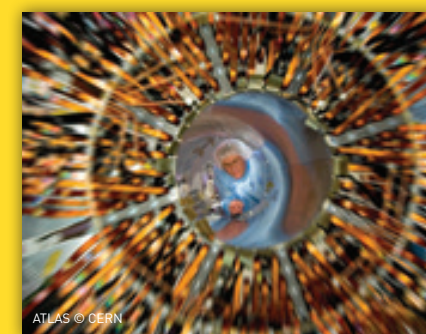
For me and the other physicists and technicians who'd worked on the SCT – many for fifteen or more years – the beam-splash events gave us the first chance to enjoy the fruits of our labours. There was an incredible reaction as we saw that the detector responded exactly as we'd dreamed. What a relief!



Map of signals recorded by the SCT, viewed end on, in response to a beam-splash event



First beam-splash event after the LHC restart, November 2009



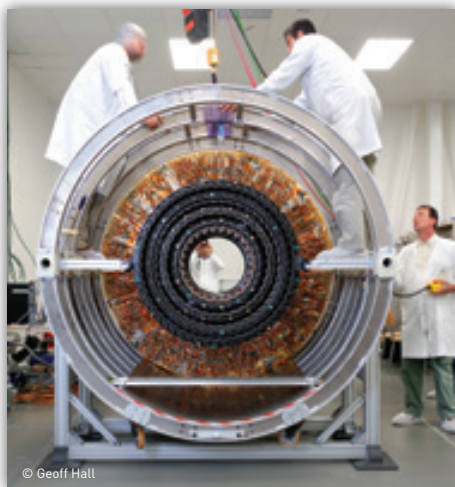
Work on the ATLAS semiconductor tracker barrel



# CMS TRACKING DETECTOR

by Geoff Hall

When planning for the LHC experiments began in earnest, in the early 1990s, there were more than a few challenges to be overcome. Some of the most-ambitious targets were set for the tracking detectors that would surround the beam pipe, and measure the trajectories of charged particles emerging from collisions. Proton beams would cross at a rate of forty millions times per second, with up to about twenty proton collisions in each crossing. The very high fluxes of charged and neutral particles produced would expose nearby detector components to unprecedented levels of radiation – similar to those encountered inside a nuclear reactor.



© Geoff Hall

Checking of the inner barrel of the CMS Tracking Detector, soon after its arrival at the CERN integration centre

It was not known whether sensor materials could survive these conditions for long enough to carry out experiments. No electronics capable of sustaining the radiation, or operating with sufficient speed, had been used in the past. The only precedents were technologies used for military purposes, and it was unclear if they were affordable, even if applicable. Intensive research and development, carried out by detector physicists, was the only possible response, with no guarantee of success. It was my job to steer the electronic developments, and see them through to a fully working tracking detector in the CMS experiment.

## GEOFF HALL

Geoff Hall (pictured holding a module from the CMS Tracking Detector) is a Professor of Physics at Imperial College London, and leads the UK CMS collaboration. He has been a member of the CMS experiment since it was proposed in 1992, working particularly on tracking detectors and readout electronics.



Over twenty years on, the results are plain to see. CMS has the largest tracking detector of its kind ever built, containing over 200 m<sup>2</sup> of silicon sensors and 70 million channels of custom electronics designed using state-of-the-art commercial technologies.

Signals are sent optically from the detector over 4000 km of fibres, transmitted and received using semiconductor lasers and sensors. Outside the detector, fast programmable digital circuits, in arrays of boards and crates, process and compress the incoming data, and transmit it to the

thousands of computers that reconstruct the particle tracks.

The detector was commissioned underground, using cosmic-ray interactions, during 2008, after a lengthy period of testing, in a CERN laboratory. It was able to measure the first collision events in late 2009, and was key to the first physics papers. The discovery of the Higgs boson relied as crucially on the capability of reconstructing all the tracks in each of the events recorded, as on signals from calorimeters and muon detectors.



**It was my job to steer the electronic developments, and see them through to a fully working tracking detector in the CMS experiment**

An Imperial College physicist, Rob Bainbridge, inspecting the interior of part of the assembled CMS Tracking Detector, during the final stages of construction at CERN Stuart Boreham © STFC



# PHOTODETECTOR DEVELOPMENT FOR THE ENDCAP ELECTROMAGNETIC CALORIMETER OF CMS

by Peter Hobson

## PETER HOBSON

Peter Hobson (pictured with superconducting magnet) is a Professor of Physics at Brunel University, Head of the Particle Physics Group, and Deputy Head of the School of Engineering and Design. He has worked on the CMS experiment since 1995, and contributed to scintillator and photodetector development for the UK-designed endcap of the electromagnetic calorimeter.

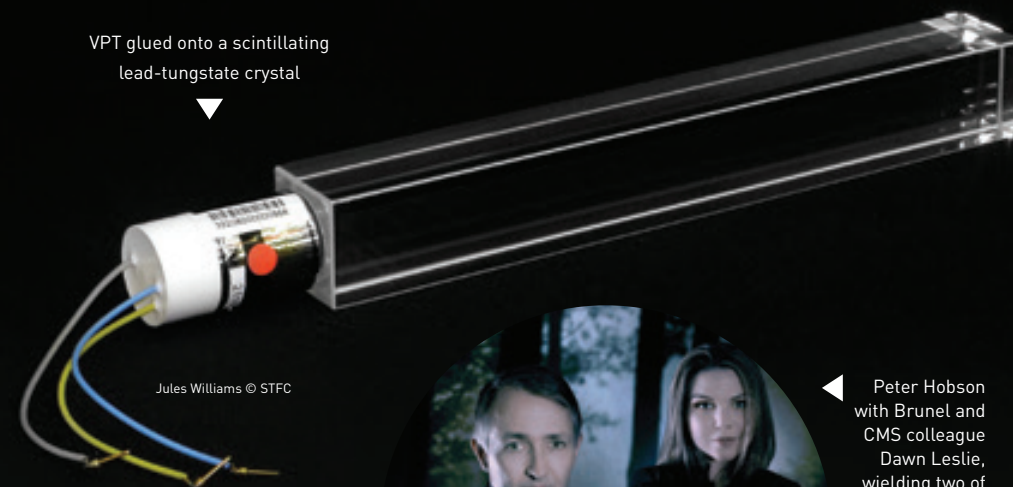


The CMS electromagnetic calorimeter sits within the superconducting coil of the central magnet, and is the sub-detector that allows us to measure precisely the energies of electrons and photons produced in the primary proton collisions. Key signatures for the decay of a Higgs boson involve the detection of photons or electrons of high energy.

In the central *barrel* region, silicon photodiodes are used to detect the scintillation light from particle showers in the calorimeter's dense, lead-tungstate crystals. In the *endcaps*, where there is a challenging radiation environment, we needed a different technology. Vacuum photodetectors appeared to be suitable. Groups from The University of Bristol, Brunel University, and Rutherford Appleton Laboratory, with industry support, were able to develop devices that could operate in a high magnetic field, and were radiation tolerant. At Brunel, we had experimental facilities for measuring the response of a vacuum phototriode (VPT) inside the

high magnetic field present in CMS. This was a critical parameter, as we could only tolerate a small reduction in signal amplification compared with zero field. Our superconducting magnet is vastly smaller than the CMS magnet, but large enough to contain a VPT.

Over a period lasting more than a decade, we evaluated prototype devices, and measured 15% of the 16000 VPTs produced for the experiment. The component susceptible to radiation damage is the thin glass window through which light travels into the VPT. Using our large gamma-irradiation facility, and armed with my previous experience of irradiating a wide variety of glasses, I identified an appropriate glass that could be bonded reliably with the body of the VPT. This glass was made in a number of different batches in Russia. For each batch, a number of faceplates were made, sent to Brunel, and irradiated. My analysis of the induced optical absorbance determined whether the batch could then be used to make production devices.



VPT glued onto a scintillating lead-tungstate crystal

Jules Williams © STFC

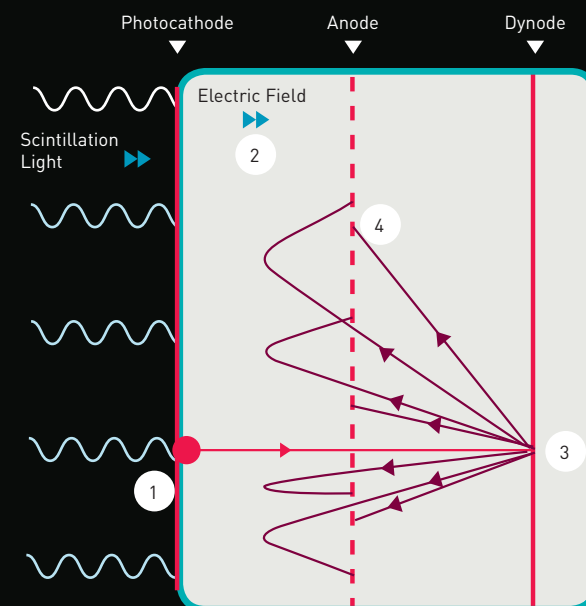


Peter Hobson with Brunel and CMS colleague Dawn Leslie, wielding two of the lead-tungstate crystals used in the endcap of the CMS electromagnetic calorimeter

## WHAT IS A VPT?

- 1 About 20% of the photons that strike the photocathode liberate a photoelectron into the vacuum.
- 2 An electric field accelerates photoelectrons towards a second electrode, the dynode, the dynode.
- 3 Each photoelectron that strikes the dynode releases around 20 low-energy secondary electrons, this electron multiplication resulting in signal gain.
- 4 Secondary electrons are accelerated back towards a third electrode, the anode, and produce a fast electrical pulse.

- photon
- photoelectron
- secondary electron





# DELUGE

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# QUICK DECISIONS

by Valeria Bartsch

## VALERIA BARTSCH

Valeria Bartsch is a Postdoctoral Research Fellow in the Experimental Particle Physics Group at the University of Sussex. She works on real-time event selection in the ATLAS experiment.



As a research student, working on the CMS experiment in the early 2000s, I was fascinated by the prospect of discovering the Higgs boson at the Large Hadron Collider! My studies addressed the question: would my experiment be able to discover the Higgs particle? I went on to work in other areas of particle physics – developing distributed computing systems, and designing new detectors – but always kept my enthusiasm for the Higgs boson. I followed the experimental results, trying to figure out which of the Higgs hunters could actually make a discovery.

In 2009, I joined the ATLAS experiment, and again became a part of the chase for the Higgs. I work on the real-time event selection – deciding which events are interesting, within seconds of the proton collisions that produced them. Roughly 1 event every billion contains a Higgs boson. Without an effective real-time selection, searches for this particle would be hopeless.

The ATLAS real-time selection is carried out in three stages. In the first stage, events are processed in series using fast electronics, located on the detector. Events that survive this initial filtering are transferred to a computing farm. The subsequent selection stages are performed here, with many events examined in parallel. Under 2012 operating conditions, there were typically 20 million proton-proton collisions per second. About 1 event every 20,000 passed the selection criteria, and was recorded to disk for further analysis.

The Higgs boson decays rapidly into lighter particles. We aim to reconstruct the properties of the Higgs boson by measuring the decay particles in the detector. The way in which the Higgs boson decays depends on its mass. At the lower end of the mass interval considered in ATLAS, the Higgs boson decays mainly into pairs of b quarks. These also decay, and are seen in the detector as jets of particles, travelling in the same direction. Unfortunately, the number of events with two b-quark jets is many times higher for uninteresting processes (background) than for Higgs events (signal). Distinguishing signal from background is extremely difficult!

Another strategy, and one that has ultimately been successful, is to look for decays that are less common than the decays to b quarks,

but have lower backgrounds. This means decays to pairs of photons, pairs of Z bosons and pairs of W bosons. The Z and W both decay themselves, the decay particles being electrons or muons in a certain fraction of cases. We set up the real-time selection to choose events containing photons, electrons and muons of high energy, then just had to wait to capture enough events with the characteristics expected from the decay of a Higgs boson.

The team responsible for the Large Hadron Collider achieved an amazing number of collisions in 2011, and then doubled the rate in 2012. This gave ATLAS enough data to be able to confirm, or rule out, the existence of the Higgs boson. I was involved on the operations side, monitoring the event selection, making sure that the computing farm ran smoothly, and checking the quality of the data that we collected. It was an exhausting time. We were continuously improving the system, and the people working on the Higgs analysis couldn't wait to get their hands on new data.

Finally, a meeting was scheduled for an update on the status of the Higgs search. It wasn't clear to most of us if we'd found something. I fondly remember the meeting webcast on 4 July 2012, when it was announced that we'd discovered a particle consistent with the Higgs Boson. It filled me with pride to know that my work had contributed to the discovery.



Optical Links going to the Readout Module of the ATLAS Readout System

**The team responsible for the Large Hadron Collider achieved an amazing number of collisions in 2011, and then doubled the rate in 2012. This gave ATLAS enough data to be able to confirm, or rule out, the existence of the Higgs boson.**

**Real-time selection for 2012 operation, starting from 20,000,000 proton-proton collisions per second**

Selection stage	Decision time per event (seconds)	Events per second after selection
1	0.000001	70,000
2	0.075	6,500
3	1	1,000



# LOOKING FOR A SPECIAL PIECE OF HAY IN A HAYSTACK

by David Britton

## WHY IS SO MUCH COMPUTING REQUIRED?

Looking for a Higgs boson is like looking for a special piece of hay in a haystack. This is a much harder problem than searching for a needle in a haystack – with a needle, you at least know when you’ve found it. At the LHC, a Higgs boson is produced in about one interaction in a billion, and an individual Higgs event is indistinguishable from the rest. To find the Higgs events, all of an experiment’s interactions need to be analysed by computer, to try to find a tiny excess in the number of particle decays at a specific, but unknown, mass. It’s like having a hundred or so pieces of hay, cut to the same length, and hidden at random places in an enormous haystack. The only way of identifying them would be to sort through all of the pieces of hay in the stack, divide them into piles by length, and identify the pile with a slight excess.

## DAVID BRITTON

David Britton is a Professor of Physics at the University of Glasgow, and is leader of the GridPP project, having been a founder member in 2001. He has worked on both ATLAS, his current experiment, and CMS.



Throughout the 1990s, the focus of the LHC collaborations was on the design and prototyping of the LHC detectors. I was a member of the CMS collaboration at the time, and spent several years working on the crystals for the endcap electromagnetic calorimeter. However, by the end of that decade, the detectors were well into the construction phase, which freed up some of us to tackle new challenges. One of these was the LHC computing, which was rapidly becoming the elephant in the room.

History shows that computing for the LHC was largely ignored and, at best, woefully underestimated in the original proposals. By 1997, there was a growing realisation that the LHC would produce a data deluge, and work started on understanding how this could be managed. The structure of the LHC computing, based on a set of hierarchical Tier centres was established using simulations from a project called MONARC (Models of Networked Analysis at Regional Centres) for LHC experiments. Among other things, this project looked at the expected growth of global network capabilities. Again, time shows that the assumptions used were wildly incorrect, and network bandwidths grew much quicker than was ever predicted. This, of course, was good news, except that the strictly hierarchical structure chosen was perhaps not necessary, and we might have designed things differently if we’d known.

By 1999, the concept of Grid-Computing had just been introduced by Ian Foster and Carl Kesselman in their seminal work *The Grid: Blueprint for a New Computing Infrastructure*, and this immediately struck a cord with the High Energy Physics community. The CERN LHC Computing Grid (LCG) project was born, and was kick-started by substantial funding from the UK via the GridPP project, the UK arm of what was to become the Worldwide LHC Computing Grid (wLCG).

I got involved in 2000 when Paul Jeffries, a CMS colleague from the Rutherford Appleton Laboratory, asked me to help him put together the UK proposal. He and Steve Lloyd, from Queen Mary, had already drafted a more-limited proposal but significant Government funding for e-Science seemed likely. So the original bid was withdrawn, and we started to put together something much more ambitious.

It was a chaotic, hectic, but exhilarating time, as we tried to forge consensus across about seventeen institutes in the UK, together with CERN. I largely worked on the finance side, and remember making changes of several million pounds to the balance of the proposal, even in the few days before submission. Some people felt that we needed to ask for more staff; others, more hardware; and everyone felt that their own institute should be a slightly larger player! However, it is one of the great strengths of the Particle Physics community that we are able to have these frank discussions internally and then reach a consensus based on common sense and a common goal. The original GridPP proposal was funded with £17m for three years, and work started in 2001.

The early days were all about trying to figure out what we wanted to do, and how we could, realistically, achieve it. As Project Manager of GridPP, my job was a bit of a nightmare, because there was no linear path from A to B. We worked on multiple possible solutions to the same problem; we made leaps of faith that other things would appear from international collaborators; we changed tack with breathtaking agility! This was really greenfield research: we knew, roughly, what we were trying to build, but were starting from almost nothing.



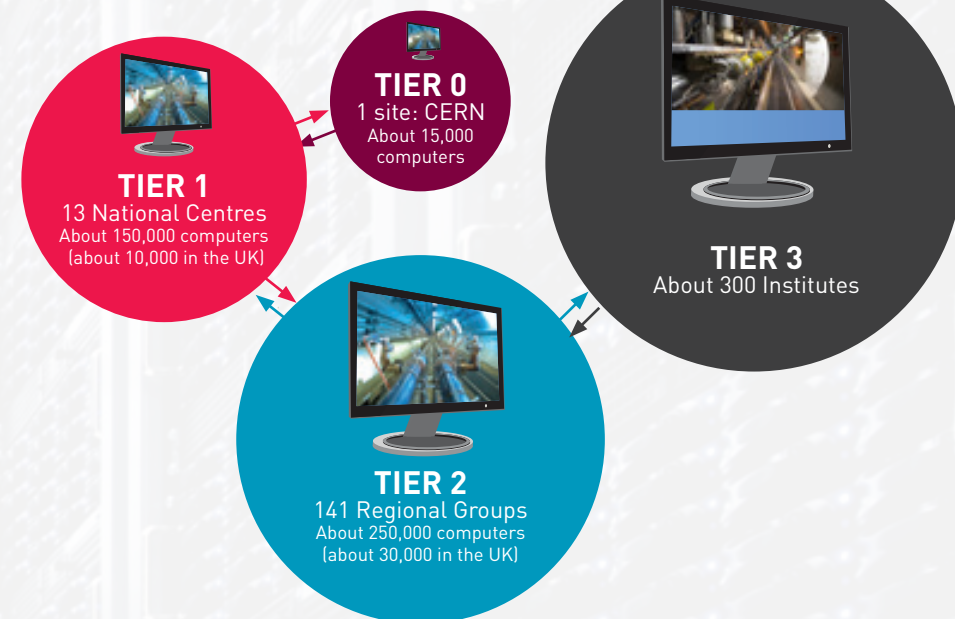
The traditional Gantt-chart approach to project management was clearly impossible. To satisfy our oversight committee, I invented a completely different methodology, which I called the Project Map. It was like taking a Gantt-chart and looking at it end-on, so that all one saw was boxes – the end of the bars if you like, but the dependencies and time-sequencing were less visible. I also built in a change-process, which acknowledged the fact that we would constantly be modifying things as we went along. Once the Project Map was established, our relationship with our oversight committee improved, and we were able to express our direction and progress much more clearly.

The original GridPP project was followed by three more phases. Over the years we first built a prototype, then deployed a production system and finally operated the infrastructure in anger as the LHC data arrived. Over the years, the system has grown to some 40,000 logical CPUs; 23 PB of disk; and 12 PB of tape storage. But it has been far from an easy, or indeed linear, process. We were working in a complex international collaborative environment. We contributed significantly to the European DataGrid project, and later to the EGEE projects (Enabling Grids for e-Science), which developed some of the Grid tools. At the same time, we had to ensure that we maintained close links with the LHC experiments so that we were user-driven. The earliest instantiations of the Grid were rudimentary and flaky, and early-adopters, such as the BaBar experiment, were less than satisfied.

As the date for the LHC turn-on got closer, we participated in international challenges, designed to test the infrastructure at progressively higher and higher capacities. At first, these were heroic efforts and, by the end of a month-long challenge we were all exhausted.

The delay in the LHC schedule gave us some breathing space, and by the time real data arrived we were more than ready. Since then, I think it is fair to say that the Grid has delivered on-time, above specification, and under budget. Data rates from CERN are regularly sustained above the design specification, and the speed at which data have been processed on the Grid has surpassed all expectations. The ATLAS dataset for the Higgs discovery contained data that had been recorded less than a week earlier, and had been through all the procedures for reconstruction, validation, selection, and analysis.

## LHC COMPUTING MODEL



*It was a chaotic, hectic, but exhilarating time, as we tried to forge consensus across about seventeen institutes in the UK, together with CERN*



# BUILDING & TESTING THE GRID FOR ATLAS

by Steve Lloyd

In February 2000, together with Paul Jeffries from the Rutherford Appleton Laboratory (RAL), I wrote a £6.2m proposal to fund a prototype Tier-1 Centre at RAL for the European Commission funded DataGrid project, a testbed for today's Worldwide LHC Computing grid (WLCG). This was submitted to the Joint Infrastructure Fund, set up in 1998 to fund enhancements and modernisation of the research infrastructure in the UK university sector. RAL was chosen as the location of the Tier-1 Centre because it already hosted the UK Computing Centre for the BaBar experiment, and it had a long history of delivering large-scale computing and data storage to UK particle physics. This bid was eventually withdrawn, when the government announced funding to enable UK physicists to play a lead role in developing the key technologies underpinning the government's e-Science initiative, and the next-generation internet.

The e-Science money awarded to the Particle Physics and Astronomy Research Council (forerunner of today's Science and Technology Facilities Council) was used to fund the prototype Tier-1 Centre at RAL, to provide staff to contribute to the middleware (software that runs the Grid) being written by the DataGrid project, and to provide staff for CERN to help kickstart what is now the WLCG.



General view of the CERN Computer Centre  
© CERN

The GridPP Collaboration was created in 2001 to coordinate the UK Grid effort. The first GridPP Collaboration Meeting was held at Cosener's House, in Oxfordshire, on 24th and 25 May 2001.

By 2004, the UK Grid consisted of the Tier-1 Centre plus four regional Tier-2s: London, NorthGrid, ScotGrid and SouthGrid. The prototype Grid was being used by the LHC experiments to test their own software, and to generate simulated 'Monte Carlo' data to test their algorithms. Since the middleware was still being developed, many jobs failed for one reason or another.

In 2007, it became clear to me that a more systematic approach to testing was required. I developed a set of three ATLAS jobs that used the ATLAS software framework:

- to echo 'Hello World';
- to compile and run a new ATLAS analysis algorithm
- to run a real analysis job to read simulated events where a Z decays to an electron-positron pair, and reconstruct the Z mass.

These jobs were submitted to all of the UK Grid sites once an hour, and results were made available on a publicly accessible website. By clicking on the failed jobs, system administrators could drill down through the output and logfiles, to find out what went wrong. Sometimes this threw up interesting results.

At one site things were working almost perfectly but occasional jobs failed. My tests showed that these failures were confined to one particular machine and it eventually transpired that this machine had no compiler installed!

The tests became known as Steve's tests, and eventually expanded to probe many features

## STEVE LLOYD

Steve Lloyd is Head of the School of Physics and Astronomy at Queen Mary, University of London, and was formerly leader of the Experimental Particle Physics Group. He is part of the collaboration that has developed and operates the UK Grid for Particle Physics (GridPP), having been a founder member in 2001, and works in ATLAS on monitoring Grid performance.



of the Grid middleware. Inside ATLAS, my tests have mainly been superseded by more sophisticated central monitoring of ATLAS production jobs, but they are still useful for other small experiments and projects.

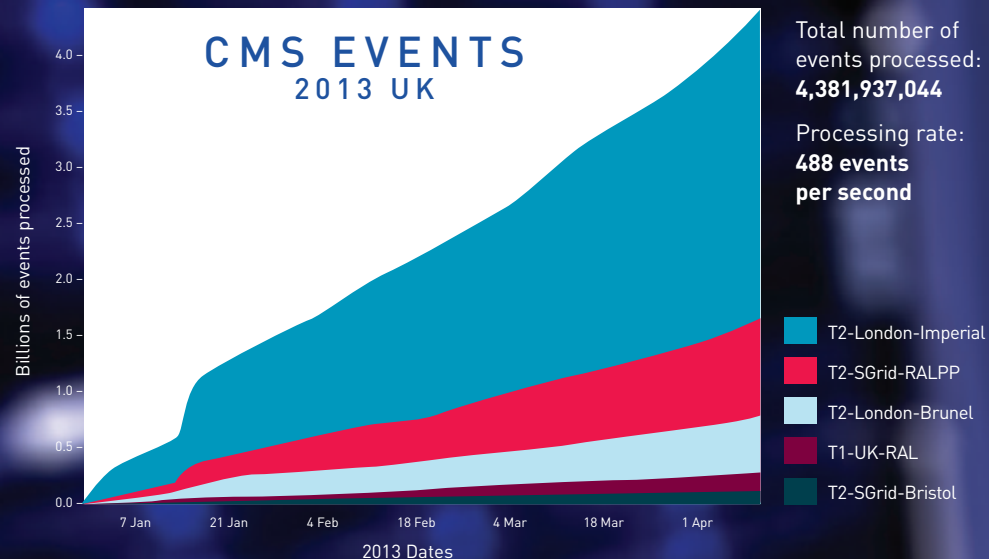
In 2005 the UK Grid consisted of approximately 6,000 CPU cores, 1 PB of disk and 330 TB of tape. Today, this has grown to 30,000 CPU cores, 23 PB of disk and 11 PB of tape, out of the WLCG total of about 400,000 CPU cores, 260 PB of disk and 217 PB of tape. This infrastructure allows ATLAS to run approximately 350,000 jobs a day. This was vital in allowing the analysis and simulation leading to the Higgs discovery to be carried out in such a short time.



# ABRA-CRAB-DABRA:

## Using Grid Computing to reveal the Higgs

by Philip Symonds



I returned to my home institute, Brunel University, at the beginning of 2013, having spent an exciting eighteen months out at CERN as a PhD student working on the CMS experiment. When I first arrived at CERN, there was little sign of the Higgs boson. After the full 2011 dataset had been processed, hints of a new particle were first identified. Following the addition of more data, this new particle was confirmed in summer 2012.

The glamour of the biggest scientific discovery in recent years owes much to the workhorse of the particle-physics community. With the vast quantities of data produced, and the processing power required, it is impractical to house all the computing resources under one roof. The Worldwide LHC Computing Grid is the international network of computing

facilities used for storage and processing of data from the LHC experiments. This makes it possible, for example, for a young PhD student based at Brunel to run an analysis on computers based in Taiwan, using data stored in Lisbon. The processed results would then be returned to the very grateful Brunel student.

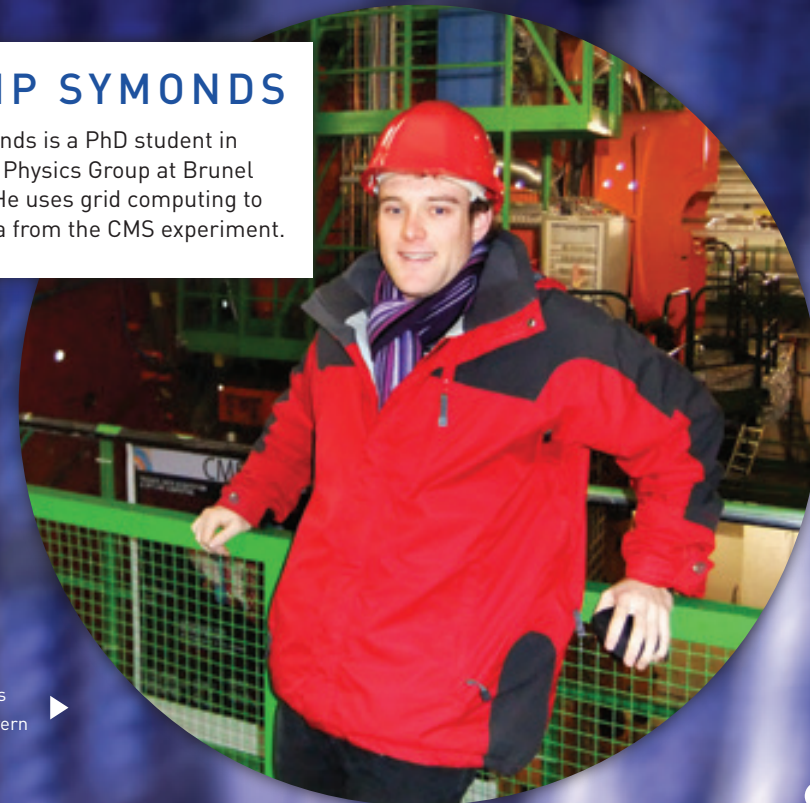
The Grid is not only used to store data originating from the CMS experiment, but is also used to produce data for interaction simulations, based on various theories. Prior to the 2012 discovery, this helped rule out the existence of a higher-mass Higgs boson. During the first three years that CMS recorded data, the Grid was used to reconstruct 12 billion events from the experiment and 20 billion simulated interactions.

The CMS computing resources are arranged into a three-tier structure. Tier-0 consists of one site, CERN, which processes the raw data coming from the detector, and transfers it to the seven Tier-1 sites. The Tier-1 sites are where the most interesting information is extracted, and are also used for the storage and redistribution of data for simulated interactions. Finally, there are around 150 Tier-2 sites – smaller computer centres, based at universities around the world. These sites are accessible by anybody working on the CMS experiment. They're used to produce data for simulated interactions, and are where researchers and students run their Higgs analyses. The Tier-2 centres store about 70 petabytes of data – roughly equivalent to the amount of data streamed through the BBC iPlayer in a year.

As long as an internet connection is available, it is possible to run an analysis on any CMS data from anywhere on the planet. Grid computing tasks are defined using a piece of software called CRAB (CMS Remote Analysis Builder). This splits a computing task into many sub-tasks, which can be carried out in parallel, greatly reducing the start-to-finish time for completing an analysis. This was invaluable for meeting the tight deadlines for the Higgs analysis. CRAB also has an online interface which allows the progress of an analysis to be monitored using a web browser, and is even kind enough to restart processing automatically in case of failures. It also allows some analyses to be assigned higher priority than others, something that was particularly useful for people working in the Higgs group, whose analyses were given top priority in the days leading up to the discovery announcement.

## PHILIP SYMONDS

Philip Symonds is a PhD student in the Particle Physics Group at Brunel University. He uses grid computing to analyse data from the CMS experiment.



Philip Symonds  
at the CMS cavern





# DISCOVERY

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Image: "In search of the Higgs boson: Higgs to bottom bottom"  
by Xavier Cortada (with physicist Pete Markowitz).



# LONG ODDS

## STATISTICS AND THE SEARCH FOR THE HIGGS

by Glen Cowan

Randomness plays a subtle, but important, role in the fundamental laws of physics. This directly influences the methods needed to discover a new elementary particle.

Here, I outline how probability and statistics have been crucial ingredients in the search for the Higgs boson.

Very quickly after being produced in the collision of two protons, a Higgs boson will disintegrate, or decay, into other particles. The decay will be in one of several channels — for example, to a pair of photons or Z bosons, to a quark-antiquark pair, or to a pair of oppositely charged W bosons. Searching for the Higgs boson amounts to looking for collisions (events) where specific particles, with characteristic energies and directions of flight, emerge from the collision point.

If we find events with the characteristics of a Higgs decay, it might seem reasonable to think that we could immediately claim to have seen the Higgs. Unfortunately, there are other ways that a proton-proton collision can result in almost the same set of particles being produced, and so mimic a Higgs event. We can think of the sought-after event type as signal, and the rest as background. If the signal process exists at all in Nature, the LHC will produce a random mixture of signal and background. Otherwise, we will get only the latter. So the task now seems impossible: even if we see what appear to be Higgs events, we can't be absolutely certain that they aren't background. This is where probability and statistics play a crucial role.

One quantity that we can calculate is the average number of background events that we expect to see in a given sample of data. For example, for a given decay channel and a given amount of data, we might expect an average of 3.2 background events. (In the same way that the average family may have 3.2 children, the average background need not be an integer.) To define an average here, we need to imagine repeating the

entire experiment many times, under identical conditions. The repetitions are purely hypothetical — in reality, the experiment may be carried out only once.

The number of events that we observe in an experiment is subject to random fluctuations. Just as the number of chocolate chips may vary from one cookie to the next, so would the number of events fluctuate if we were to repeat the entire experiment under identical conditions. By exploiting a formula published in 1872 by the French mathematician Simeón Denis Poisson, we can calculate the probability for producing a certain number of events once the average number is specified.

### GLEN COWAN

Glen Cowan is a Professor of Physics at Royal Holloway, University of London. As part of a team called the ATLAS Statistics Forum, he develops mathematical techniques and software for statistical data analysis, for Higgs searches and other physics studies.



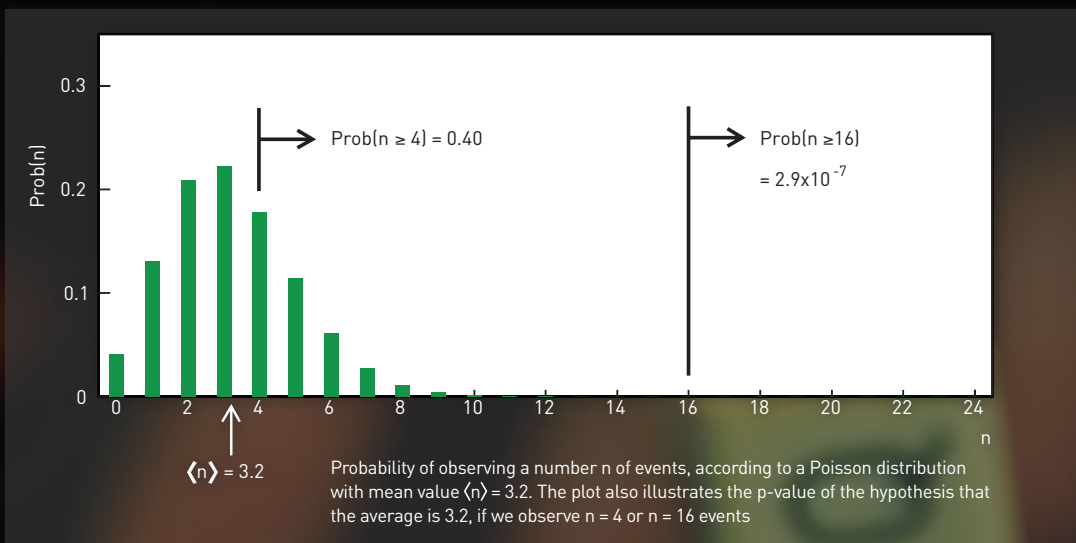


If we now look at the experimental data and, for example, find 4 events, when an average of 3.2 events were expected from background alone, then there is no compelling evidence that any of our 4 events are signal. But what if we see 16 events? The question that we need to answer is: for a given number of events observed, can we reject the hypothesis that they are all due to background processes?

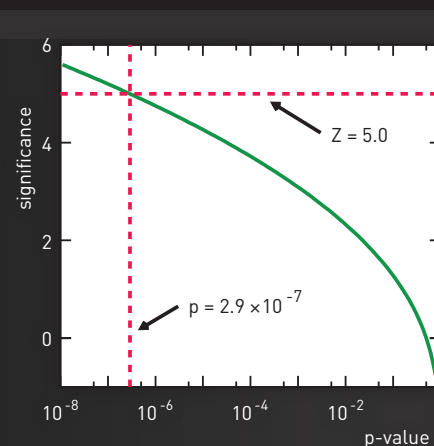
By using probabilities, we can quantify how certain we are that what we've observed is not simply a statistical fluctuation in the number of background events. More precisely, we calculate what is called the

p-value of the background-only hypothesis. This p-value is the probability to have at least as many events as we find, under the assumption that there is no signal.

We return to our example, with an average of 3.2 events expected from background. The probability of actually observing at least 4 events comes out close to 40%. This is not particularly small, and so seeing 4 events would not be at all surprising. In contrast, the p-value for 16 events is only  $2.9 \times 10^{-7}$ . That is, if the average number of events were really 3.2, the chance of seeing 16 events or more would be less than one in a million.

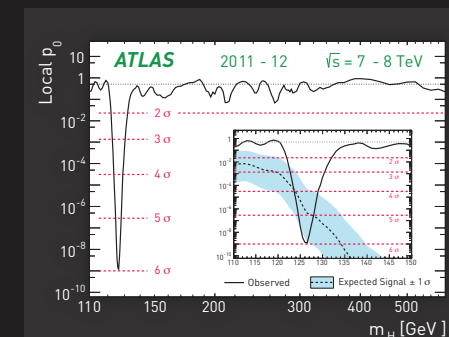


The p-value can be translated into an equivalent quantity, called the significance, which is larger if the p-value is smaller. The p-value of  $2.9 \times 10^{-7}$  corresponds to a significance close to 5.0. This is often referred to as a 5-sigma effect, and is generally used in particle physics as the threshold for claiming a discovery. If the significance is 5.0 or more, the probability of obtaining data so incompatible with the background-only hypothesis is extremely small, and we conclude that some non-background process must occur.



The significance  $Z$  is related to the p-value through the curve shown above, which comes from a particular mathematical equation. The significance turns out to be approximately equal to the estimated number of signal events divided by the estimate's uncertainty or standard deviation, the latter often being denoted by the Greek letter sigma. A p-value of  $2.9 \times 10^{-7}$  corresponds to a significance close to 5.0, so that the estimated amount of signal is five times the measurement uncertainty – a 5-sigma effect. In such a case, we are confident that a value of zero signal is ruled out claiming a discovery.

The search for the Higgs was complicated because we didn't know in advance the exact mass of the Higgs boson. This meant that we had to carry out an analysis, of the type described above, for all hypothetical masses within a broad range. Also, various decay channels of the Higgs boson were analysed independently. No individual channel gave conclusive results, and information from different channels had to be combined. On 4th July 2012, when both the ATLAS and CMS experiments announced their results, the combined significance from several decay channels, for a Higgs mass of around 126 GeV, had just reached the 5 sigma threshold from each experiment. Following analysis of additional data, the significance was higher still by the time that the discovery papers were published.



The p-value of the background-only (no-Higgs) hypothesis, as a function of the mass of the Higgs boson. The sudden drop at a mass of 126 GeV corresponds to a significance of 6.0 (6-sigma effect), and points to the discovery of a new particle

**Just as the number of chocolate chips may vary from one cookie to the next, so would the number of events fluctuate if we were to repeat the entire experiment**





# ATLAS HIGGS STUDIES

## A PERSONAL OVERVIEW

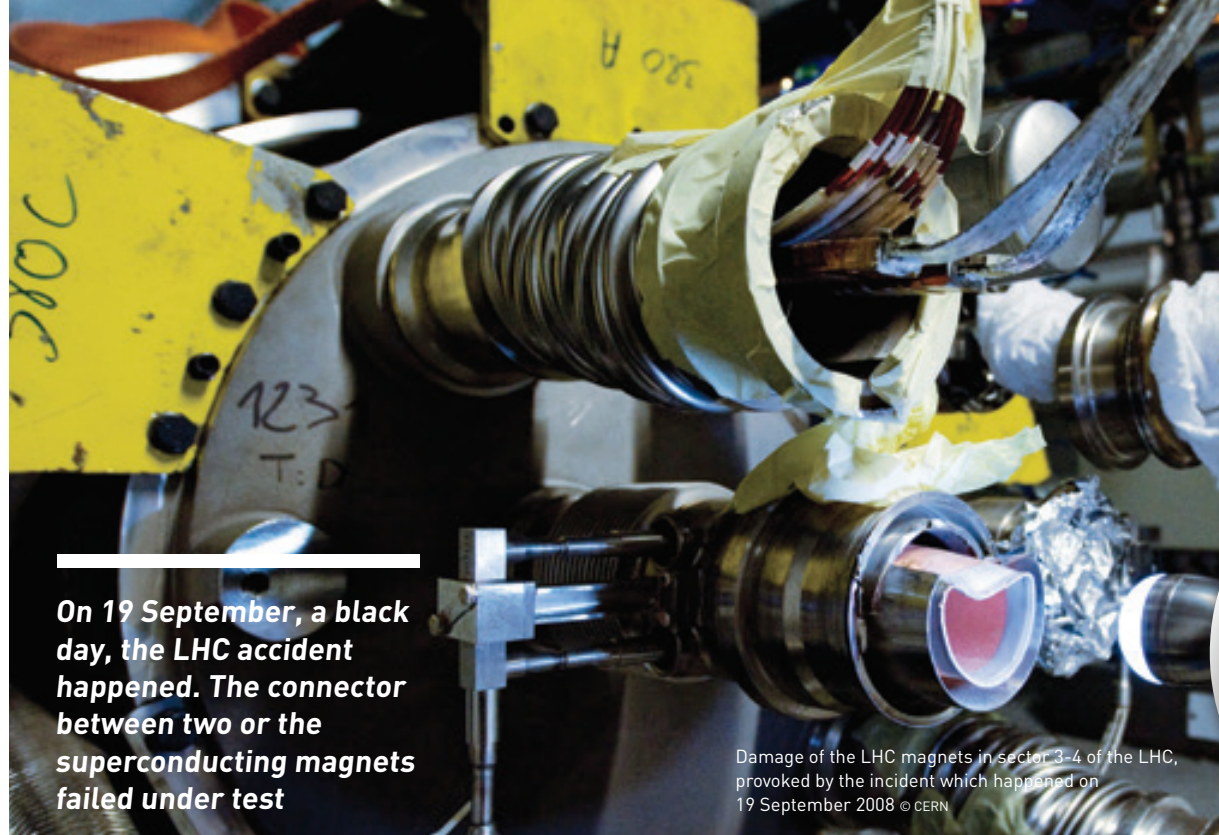
by Bill Murray

On 18 September 2008, I moved with my family to CERN, to be close to the centre of activity of ATLAS for the first year of data-taking at the Large Hadron Collider (LHC). It was an exciting and long-anticipated event, but it didn't work out as planned. The very next day, things took a horrible and unexpected turn.

The wait for LHC data had been a long one. I had worked on the Higgs search at the Large Electron-Positron collider (LEP) at the end of the twentieth century – putting together results from the four big experiments, and being tantalised by what seemed to be a glimpse of the Higgs boson, the hypothetical particle that was supposed to explain mass.

LEP was closed at the end of the year 2000, the final data giving hints of a Higgs boson with a mass of 115 GeV. I turned my attention to building the ATLAS tracking detector. At the same time, I nervously watched progress at the Tevatron in Chicago, hoping that LEP would be proved right, but not really wanting this to be done by someone else.

Startup of the LHC had been delayed until 2008, and the Tevatron experiments were starting to make inroads into the Higgs territory. I was at a summer school in Oxfordshire when proton beams were circulated in the LHC for the first time, on 10 September 2008. The students celebrated with LHC cake. The excitement was intense – and again the worry that I was missing out. A few days later, I drove with my family to our new home.



**On 19 September, a black day, the LHC accident happened. The connector between two of the superconducting magnets failed under test**

Damage of the LHC magnets in sector 3-4 of the LHC, provoked by the incident which happened on 19 September 2008 © CERN

On 19 September, a black day, the LHC accident happened. The connector between two of the superconducting magnets failed under test. A current of 8000 amps was released, melting the beam pipes, and boiling the liquid helium used as coolant. The damage caused by 6 tons of high-pressure gas resulted in a year-long shutdown, for remedial work. It also led to the decision that, as a safety measure, the first years of operation should be at only half the design energy.

I was now at CERN, with my children in French schools, and no LHC! In ATLAS, fortunately, we still had our detector. We put the year's delay to good use, carrying out studies using the particles that nature's cosmic-ray collider provides for free. We were able to understand the detector response and reconstruction software in detail. I worked on timing adjustments,

alignments and efficiency measurements, to ensure that the tracking detector that I had helped build performed beautifully, at the heart of the whole ATLAS system.

Of course, it wasn't all plain sailing. Nearly ten months passed before we noticed one problem. Some of the detector modules had been mounted backwards. This was well-known, and could easily be fixed in software, by reversing the relevant data. In fact the fix was too easily applied, and the data were being reversed twice during processing, getting the modules back to where they started. Once teething troubles like this had been sorted out, we saw wonderful efficiency, well over 99%. The detector was ready.

The LHC was cautiously restarted on 20 November 2009, and ten days later took the Tevatron's place as the world's highest-

energy particle accelerator. The real journey was beginning at last. Final preparations were made over the winter break, and 30 March 2010 saw the start of the LHC physics programme, with 7 TeV collisions.

Meanwhile, I had been preparing for the Higgs search. I was put in charge of a subgroup that studied Higgs-boson production in association with top quarks, and we contributed to Expected performance of the ATLAS experiment, a book of almost 2000 pages, published in December 2008.

In July 2009, I accepted the role of Higgs co-convenor, meaning that I would be one of the two people responsible for overseeing all Higgs studies in ATLAS. I was thrilled – I got to work alongside Ketevi Assamagan, whose knowledge of Higgs physics was awesome. I felt totally inadequate.

## BILL MURRAY

Bill Murray has been a Research Physicist at Rutherford Appleton Laboratory since 1993, working for most of this time on searches for the Higgs boson. Between July 2009 and December 2011, in the run up to the new-particle discovery, he was co-convenor of the ATLAS Higgs group.





Fortunately, it was a slow start. At first there were no data, and not even many people. We knew that the Higgs boson would not be easy to find. The book that we had prepared told us that we needed a lot of data – how much depended on the particle's mass. Somewhat paradoxically, a Higgs boson of lower mass would be harder to find. To see something at 115 GeV, the mass hinted at by LEP, we would need perhaps  $30 \text{ fb}^{-1}$  of data, or about what we could collect during two or three years of data collection at design energy. Some of the other delights that the LHC might have in store – such as black holes, or dark matter – could potentially be found with far less data. Most people chased after these, or worked on the basic physics of more common processes.

## ORGANISATION OF HIGGS STUDIES IN ATLAS

Higgs studies in ATLAS are overseen by two co-conveners, one of whom is replaced each year. The Higgs group is divided into several subgroups, each focusing on a different decay channel, and each with its own sub-convenor. As of 2013, around 900 members of ATLAS subscribe to the main Higgs news group, and around 300 are subscribed to the subgroup dedicated to studying decays to W pairs.

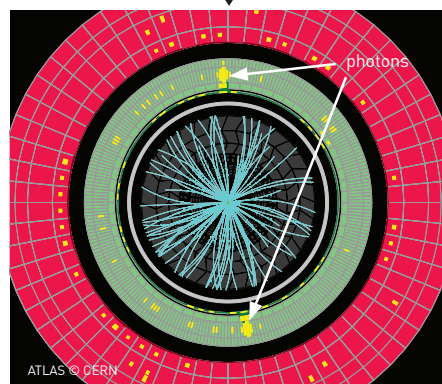
Before being made public, Higgs analysis results must be presented at a group meeting, must be signed off by the co-conveners, and must be approved by the ATLAS collaboration as a whole. An internal note is then prepared, typically signed by around 100 co-authors, and may be the basis of a journal publication, signed by all members of the collaboration. Throughout the process, there are many checks and studies, to guarantee that the final results are reliable.

We pushed people to work on Higgs studies, and we went to the 2010 summer conferences to publicise our first result. This was a measurement of singly produced W bosons, a background for Higgs decays to W-boson pairs, and was based on  $0.0003 \text{ fb}^{-1}$  of data. It wasn't much, but it felt so good. We had really started on the data analysis for the one guaranteed discovery at the LHC. And our competition, the CMS experiment, had showed nothing.

In February 2011, I found myself at a meeting with the LHC machine experts, to discuss the hopes and wishes of the experiments. I asked for  $1 \text{ fb}^{-1}$  of data in time for the summer conferences, and for  $5 \text{ fb}^{-1}$  by the end of the year. These requests, meaning 100 times the data of the previous year, seemed outlandish to many people – but the LHC would deliver.

Reaching  $1 \text{ fb}^{-1}$  of data would be game changing. If we didn't see the Higgs boson, we would be able to rule out most mass values. The only region that we wouldn't be able to explore was the low-mass region, between 115 GeV and 130 GeV. Three Higgs decay channels looked especially promising – the decays to photon pairs, to Z pairs, and to W pairs – and we would need all of them to make a discovery.

Candidate Higgs decay to a pair of photons



Bill Murray (seated) enjoys a champagne moment with ATLAS and CMS Higgs hunters, Grenoble conference, July 2011



**Things magically fell into place just in time. We showed our results, and watched with trepidation to see what CMS had to say**

The data started to flow in. In the two-photon search, we saw a bump in the mass spectrum near 115 GeV, but with more data this was smoothed over. Then there was another bump at 128 GeV, but we didn't have enough data to reach a firm conclusion. In the analysis of W pairs, we saw an event excess suggesting a Higgs boson somewhere between 120 GeV and 150 GeV. This one was serious: could it be what we were searching for?

We had 8 a.m. meetings, seven days a week, in the two months leading up to the 2011 Europhysics Conference on High Energy Physics, being held in July at Grenoble. We combined results from the three main search channels. The events with W pairs had a high rate, but couldn't accurately measure the Higgs mass. The events with Z pairs were beautifully clean, and could tell us the mass, but they were very rare. There was one Z pair, just one, with a mass of 143 GeV. Was this it? The W pairs told us that something was there, and the Z pairs told

us where. There was still the bump at 128 GeV from photon pairs, but nobody gave this much attention.

The Grenoble conference was a nightmare. At lunchtime on the Higgs day, none of the analyses that I wanted us to present that afternoon had been signed off by the collaboration, and only one of my speakers had turned up. Things magically fell into place just in time. We showed our results, and watched with trepidation to see what CMS had to say. Amazingly, the CMS results matched: a broad excess from W pairs, and a bump at 141 GeV – from photon pairs rather than from Z pairs. Could this just be a fluke? There wasn't enough evidence to be sure. We all felt that it pointed to a Higgs boson with a mass of around 142 GeV, but we needed more data.

We didn't have to wait long. By the time of the next conferences, at the end of August, the LHC had doubled our data sample. But what had happened? The new data showed



no excess in any of the decay channels. Everything was consistent with the expected background processes. A Higgs boson at 142 GeV was ruled out, and the only mass values still allowed were between 115 GeV and 141 GeV. Was the model right? My confidence in it started to wane.

In October, I gave a talk at the University of Edinburgh, to an audience including my parents and Peter Higgs. Morale was at a low ebb. We had a lot more data waiting to be analysed, but didn't know then what it would show.

On 13 December 2011, the first ATLAS and CMS results with  $5 \text{ fb}^{-1}$  of data were to be shown at a seminar at CERN. On the ATLAS side, we now had a mass peak at about 126 GeV both for photon pairs and for Z pairs, and the sizes of the peaks for the two channels were about as expected from the Standard Model. The chances of this happening with only background were one in a thousand. Better still, we were able to exclude a Higgs boson with a mass of around 115, so had upper and lower limits on the allowed range. It was starting to look promising.

At the seminar, the CMS results again matched the ATLAS results. Both experiments had achieved about ten times the significance they'd had in July, and almost all higher and lower mass values had been ruled out. It looked like a Higgs at 125-126 GeV or nothing. Mindful of the coincidence at the Grenoble conference, at a mass that was now excluded, we still couldn't be sure. So we told the world the truth: our results were interesting, but we needed more data.

In a private ATLAS meeting, I declared that we had "evidence for a Higgs boson", and stepped down from leading the search. I had enjoyed an incredible twenty-eight months, made possible by the thousands of people working either on the LHC machine or on ATLAS, keeping the whole system running. It had been a privilege.

On 5 April 2012, following the winter shutdown, the LHC was restarted with the collision energy raised to 8 TeV, increasing the Higgs rate by about 30%. An additional  $5 \text{ fb}^{-1}$  of data were quickly collected, doubling our sample size. Would the December peaks prove to have been chance fluctuations? We performed a blind analysis, hiding the results until the very end, to avoid introducing biases. When we finally looked at what we had, we found that our evidence for a Higgs signal had gotten stronger.

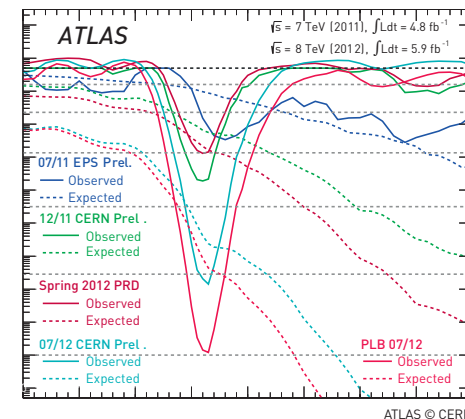
Updated results were to be presented at a seminar on 4 July 2012. The tension was unbelievable. The seats in the auditorium were all taken – many people had queued all night. I was lucky, and had a place reserved, but I was still told that I needed to arrive at least an hour before the start, or I wouldn't get in. I pushed my way through the crowd, to the security guard.

"Bill Murray," I said, "I have a seat."

"I'm sorry," he replied, "but you're not on the list."

Fortunately, people in the queue recognised me, and persuaded the guard that I should be allowed in.

Here it was – the LHC's only guaranteed discovery. Was the Higgs mechanism right or wrong? The ATLAS data seemed solid – there was less than one chance in a million that our results were a fluke. But we had been wrong before. So when the CMS results were revealed, showing a particle at the same mass as we saw, and with similar significance, we knew we had the truth. The press went wild. A forty-eight year quest had come to an end, and the Universe really could be described and predicted by mathematics.



Growth of the Higgs signal. The solid lines show, as a function of mass, the probability of obtaining the observed result if no Higgs boson exists. The probability at a mass of around 126 GeV has become smaller with time, as more data are collected. For this mass value, the red curve for July 2012 shows a probability of just above  $10^{-9}$  (one in a billion) that no Higgs boson





# A GOOD DAY FOR PARTICLE PHYSICS

by Konstantinos Nikolopoulos

The process where the Higgs boson decays to two Z bosons, and each of these decays to either two electrons or two muons, has long been considered the golden channel for discovering the Higgs boson at the LHC. Although the expected rate for this process is low, the presence of the four charged leptons provides a distinct experimental signature. Other processes can also result in combinations of two electrons and two muons. However, the mass reconstructed from the four

leptons in the case of a Higgs decay will, within the limits of the experimental resolution, be equal to the mass of the Higgs boson. For other processes, the mass value will be randomly distributed. In a mass plot for four-lepton events, Higgs decays then show up as a narrow signal peak, on top of a smooth background.

In ATLAS, I've had the honour, and responsibility, of leading a group of around 80 physicists, searching for Higgs decays in four-lepton events. We reached an important milestone for the CERN Higgs seminar of 13th December 2011, with our results showing the first glimpse of a new particle, in the mass range between 120 GeV and 130 GeV. We knew that the next year's data collection would be critical.

In the first part of 2012, we focused on improving our ability to disentangle signal and background, through changes to our strategy for identifying leptons, and through a reoptimisation of our analysis procedure. This effort concluded with a reanalysis of the 2011 dataset, the results of which we presented to the ATLAS Higgs group at the beginning of June 2012.

◀ Candidate Higgs decay to two muon pairs.

We went on to analyse the new data, which had been arriving since early April 2012. We presented an update, relative to  $3.2 \text{ fb}^{-1}$  of data, at a meeting of the Higgs group on 15th June. In the mass region of interest, the number of events that we saw was consistent with the expected background. To increase the tension, the ATLAS sub-group searching for Higgs decays to two photons was seeing hints of a signal. We would have to wait for more data to clarify the situation.

We were working long hours. We needed to cross-check all aspects of the analysis, write up our results, answer questions from ATLAS colleagues, and analyse new data — made available through the hard work of the groups responsible for data preparation and distributed computing.

In the early hours of Monday 25th June, we arrived at the list of candidate Higgs decays for our full dataset, corresponding to  $5.8 \text{ fb}^{-1}$ . Several candidates had been found in the more-recent data, producing a peak in the mass plot. The new particle had appeared in front of our eyes for the first time!

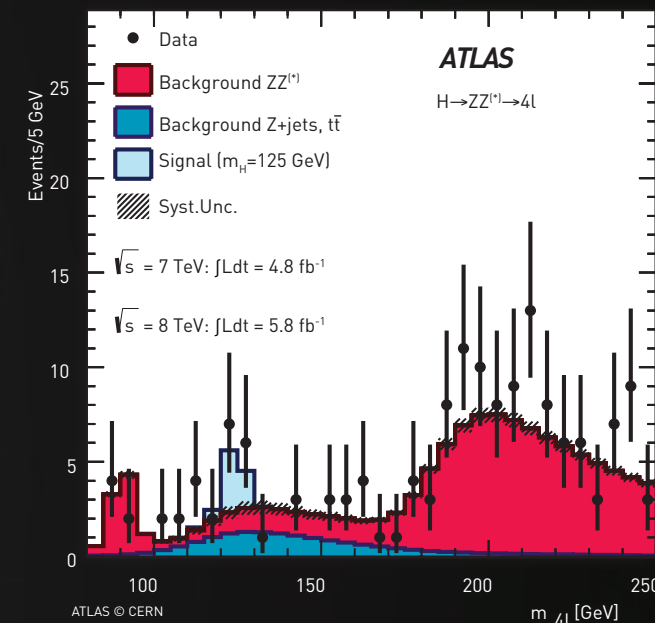
## KONSTANTINOS NIKOLOPOULOS

Konstantinos Nikolopoulos is a Birmingham Fellow in the Particle-Physics Group at the University of Birmingham. He works on the ATLAS experiment, and between October 2010 and October 2012 led the search for Higgs decays in four-lepton events.



Four-lepton mass spectrum. The small peak at around 125 GeV is the signal for Higgs decays

**The new particle had appeared in front of our eyes for the first time!**





Over the next few days, we presented our analysis twice to the whole collaboration, aiming to have our results approved for public release. The next CERN Higgs seminar, scheduled for 4th July, was approaching rapidly. These were really hectic days. All plots and numbers needed to be cross-checked for yet another time!

The 2012 International Conference for High-Energy Physics was in Melbourne. I was to present results on the search for Higgs decays in four-lepton events, and my flight was on 2nd July. I recall sending plots to colleagues just before boarding. I followed the seminar from the conference venue. As there had been no possibility of communication during the flight, I didn't know whether a discovery would be claimed, or if a more-conservative statement would be made. The feelings were overwhelming when the CERN Director-General concluded that we had observed a new particle!

I sent an e-mail message to the four-leptons group:

**"I'd like to thank everybody for their contribution to making this analysis better: it was the synthesis of all contributions that made the analysis robust.**

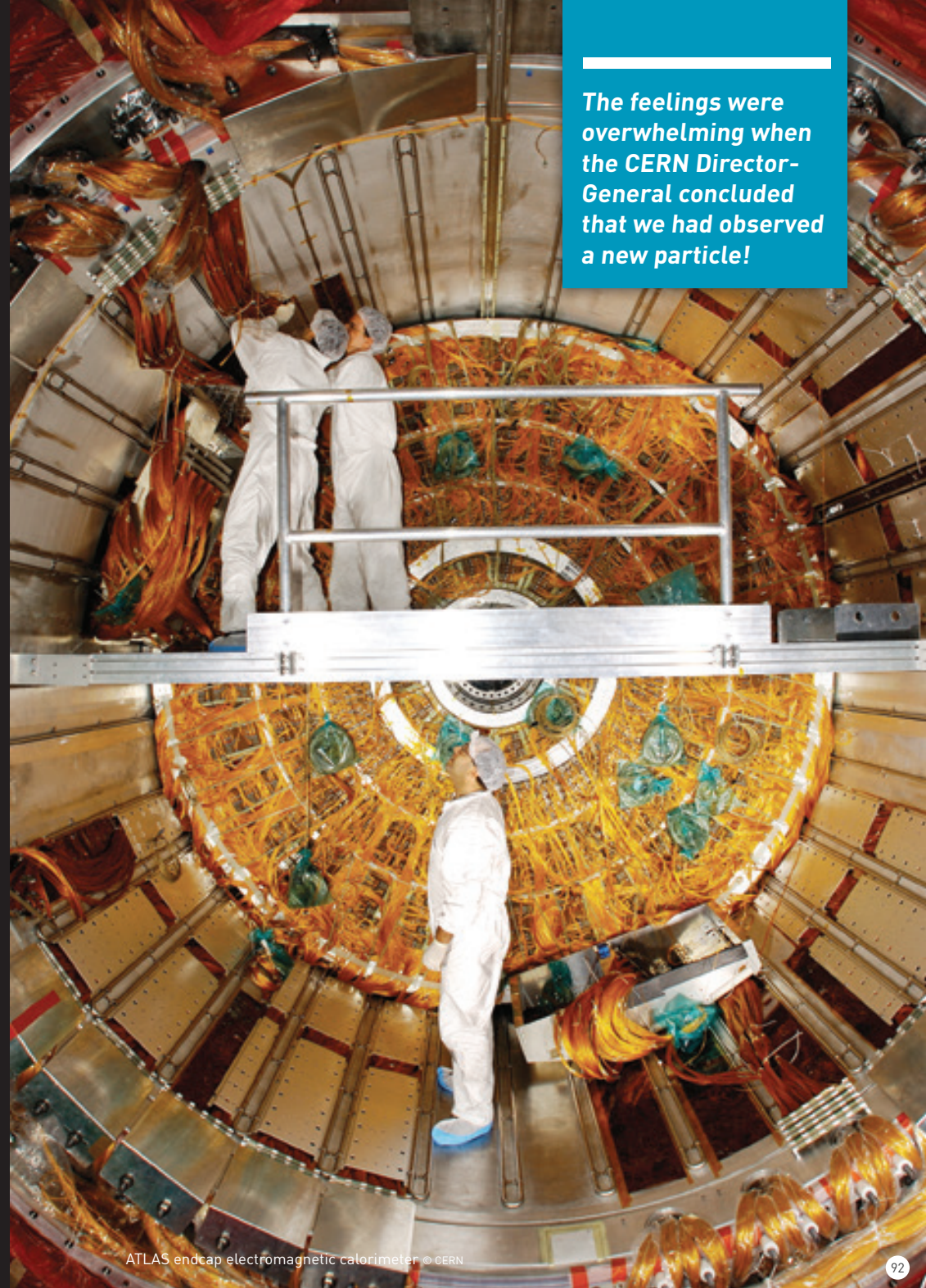
**For the younger of us, this is the first time that we make a discovery. For the more experienced people in the group, this probably feels like a return to a known place. No matter what, it will take some time to make complete sense of what just happened.**

**Congratulations to everybody. This was a good day for particle physics. Now we look forward to the measurement era."**

**The feelings were overwhelming when the CERN Director-General concluded that we had observed a new particle!**



© CERN



ATLAS endcap electromagnetic calorimeter © CERN



# COUNTDOWN TO DISCOVERY

by Stathes Paganis

## 2004 DETECTOR TESTS

In 2004, we tested a slice of the full ATLAS detector for the first time, using beams of high energy particles. These tests were invaluable for understanding the performance of the electromagnetic calorimeter, the detector designed to measure the energy of electrons and photons.

The initial measurements gave some unexpected results. This led me to walk along the beamline, to check the engineering plans, and I discovered a significant amount of material that we hadn't been taking into account. Once we'd corrected for this, we were able to obtain excellent agreement between the experimental data and our computer simulation of the detector.



ATLAS © CERN

Setup for first tests of a slice of the ATLAS detector. The electromagnetic calorimeter, in its cryostat, is towards the centre of the photograph

## STATHES PAGANIS

Stathes Paganis is a Reader in Particle Physics at the University of Sheffield. He works on the ATLAS experiment, where he currently coordinates searches for Higgs decays to a Z and a photon, and previously acted as convenor for the sub-group that focuses on Higgs decays with four leptons in the final state.



## 2004-2009 DETECTOR CALIBRATION

Our test studies gave us a good understanding of the way that the electromagnetic calorimeter behaved for different particle types. This allowed us to calibrate the detector with great accuracy, improving the potential of Higgs searches involving electrons and photons.

While working on the analysis of the test data, I realised that calorimetric measurements of energy along a particle's track could provide information on residual material. This approach was to be developed in 2012, to help reduce uncertainties on the Higgs mass.

## 2006-2012 SEARCH FOR HIGGS DECAYS TO FOUR LEPTONS

In 2008, while testing the ATLAS computing infrastructure, we ran a first realistic analysis of the search for Higgs decays to four leptons, using data from simulated interactions. This work laid the foundations for the Higgs discovery.

In 2010, after much effort to improve the electron identification, we introduced a number of novel ideas for using experimental data to estimate the Higgs background from Z boson production. This was pioneering work, vital to the Higgs searches.

Analysis of reconstructed Higgs decays to four leptons in simulated interactions showed that the value found for the Higgs mass could be significantly lower than the

true mass. I realised that this was because some of the missing mass was due to the leptons emitting low-energy photons, which we weren't taking into account in the analysis. Most of these photons travel almost parallel to the leptons, and are very hard to find.

At Sheffield, we changed the algorithm for calculating energies in the calorimeter, and used information on how energy is distributed along particle tracks. This allowed us to successfully identify the low-energy photons. Including these photons had a significant effect on the shape of the mass peak for decays to leptons. Our revised algorithm was subsequently adopted for Higgs searches.

## 2012 DISCOVERY

I spent the summer of 2012 at CERN. By early June, the searches for Higgs decays to four leptons and to two photons both gave clear peaks in the mass spectrum, at about 125-126 GeV.

On 4th July, at 6 a.m., I drove to CERN, and joined the long queue of people hoping to get into the Auditorium, for the presentation of the Higgs results. Unfortunately I didn't make it. Together with another 500 people or more, I headed to the overflow room, to watch the live video transmission. I really felt sorry for all of these people who'd dedicated years of their lives to building the experiments. After the event had ended, we drank champagne at a celebratory gathering organised by the ATLAS Higgs group.

In August 2012, I moved my attention to the search for Higgs decays to a Z and a photon, a search which I am now leading. Observation of this decay could tell us if new heavy particles are waiting to be found, and can test for physics beyond the Standard Model.



Background image: Inside the ATLAS solenoid cryostat © CERN



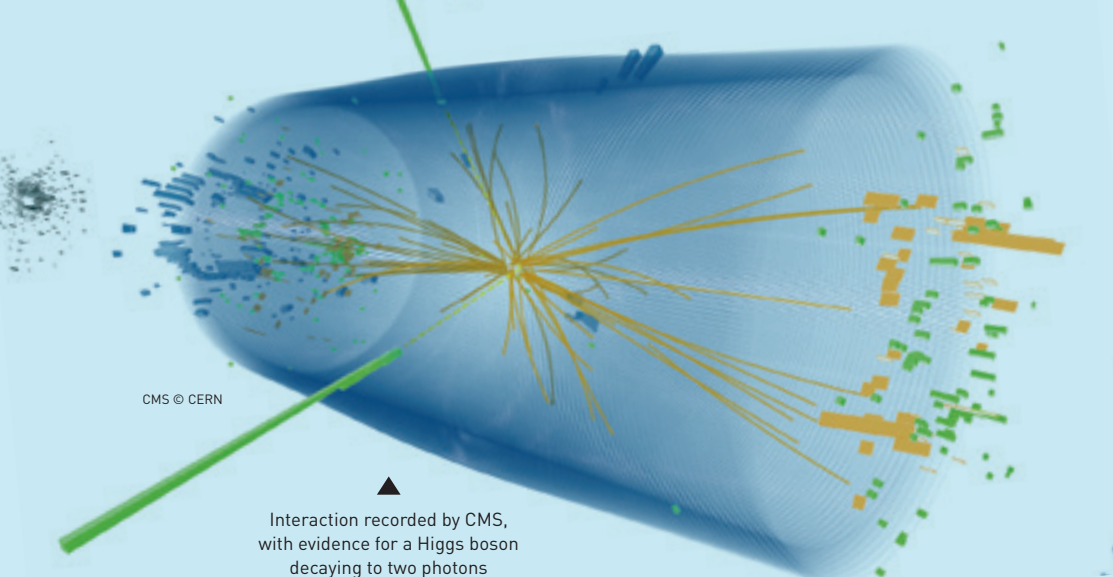
# FINDING THE HIGGS BOSON IN THE EXPERIMENT I READ ABOUT AT SCHOOL

by Nicholas Wardle

**A**fter the momentous events of the past year, it's hard to imagine a time when I had never heard of the Higgs boson. Back before I really understood anything about particle physics, I can remember reading about scientists at CERN building experiments at the LHC. I was instantly captivated, and wanted to know more.

Fast forward through school and university, and I was lucky enough to get the chance to work on the experiment that I had read about all those years ago, when it was just being constructed. I was going to work with the CMS group, searching for the Higgs boson decaying to two photons.

As the two-photon decay is one of the most sensitive channels in the search for the Higgs boson, it was an incredibly exciting team to join. As one of the people who worked on analysing the latest data, I was among the first to see that the Higgs boson had finally revealed itself. With all eyes on us, and many probing questions from inquisitive family and friends, keeping such a huge discovery a secret wasn't easy!



When the Higgs decays to two photons, we detect it as two bright spots in the CMS electromagnetic calorimeter (ECAL). This consists of nearly 80,000 lead-tungstate crystals, which absorb photon energies. By making accurate measurements of the energies of the two photons produced when a Higgs boson decays, the mass of the decaying particle can be determined with high precision. As more and more data are analysed, a signal for the Higgs boson builds up as a narrow mass bump in the distribution of the measured masses. The

fact that this bump appears makes the two-photon decay one of the most sensitive channels when searching for the Higgs boson.



## NICHOLAS WARDLE

Nicholas Wardle is a Research Assistant in the High Energy Physics group at Imperial College London. He works on the CMS experiment, analysing Higgs decays to two photons.

I flew back to CERN the day before the seminar on July 4th, to find out if people working on ATLAS had also seen the Higgs signal, and to join the rest of the CMS physicists eagerly waiting to hear our discovery officially announced. With the whole world focused on us, the atmosphere at CERN was palpable, with the feeling of a job well done. It was like nothing I had ever experienced there before. Being physicists, of course, once the conference was over, it was back to work as usual. I spent the afternoon in a meeting room, with the rest of the analysis group, discussing what to do next. That's not to say that I didn't get in a few celebratory drinks before the end of the day!



# FROM BEAN COUNTER TO B COUNTER

by Wahid Bhimji

I watched the LHC finally being turned on, in September 2008, not from CERN but from an office in Whitehall. I was a civil servant, thinking my days as a physicist were behind me. A few days after the accelerator startup, an electrical fault in the magnets led to a large explosion, which brought things to an immediate halt. The LHC explosion was a disaster for many of my former colleagues, but an opportunity for me: to return, and witness from inside, the most exciting period in particle physics in my lifetime.

***The LHC explosion was a disaster for many of my former colleagues, but an opportunity for me.***

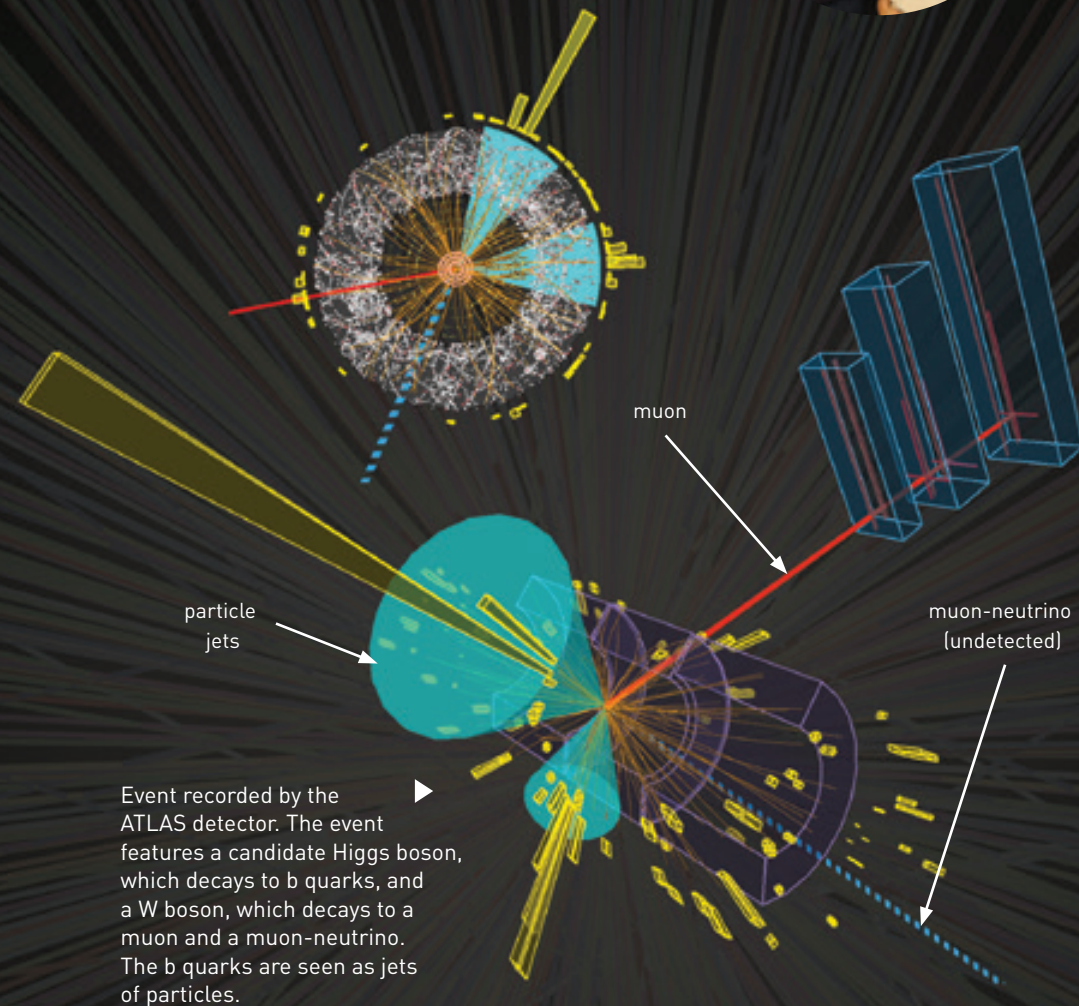
By the time the LHC restarted, a year later, I was back in the world of particle physics: at Edinburgh University, the home of Peter Higgs. With colleagues, I helped start an effort here focused on finding the Higgs boson by looking at how it might decay into two other particles, called b-quarks. But honestly, by mid-2011, I thought we weren't going to find it at all. Even at Christmas that year, when we were sharing our hints of a new particle with Peter Higgs, in an Edinburgh lecture theatre, I remained sceptical.

## WAHID BHIMJI

Wahid Bhimji is a Research Associate in the Particle Physics Experiment Group at the University of Edinburgh. He spends his time investigating Higgs-boson decays, and dealing with the computing challenges of the Large Hadron Collider.

I was wrong. For our "Higgs to b-quarks" group, the discovery of a new "Higgs-like" particle was just the beginning. Looking at the data, it should be possible to observe the new particle's decay to b-quarks. Possible, but hard: there are many ways that these quarks could be produced at the LHC, so disentangling the ones that come from a Higgs presents a challenge. We need to meet the challenge, as measuring the different decays is a way of being sure that the new particle is indeed a Higgs boson. We're getting there, we've started to find possible Higgs to b-quark decays in ATLAS, and there are hopefully many more to follow.

A Higgs-Bhimji interaction, observed at the University of Edinburgh in July 2012



Event recorded by the ATLAS detector. The event features a candidate Higgs boson, which decays to b quarks, and a W boson, which decays to a muon and a muon-neutrino. The b quarks are seen as jets of particles.



# SEARCH FOR THE HIGGS DECAYING TO TAU LEPTONS

by Sinéad Farrington

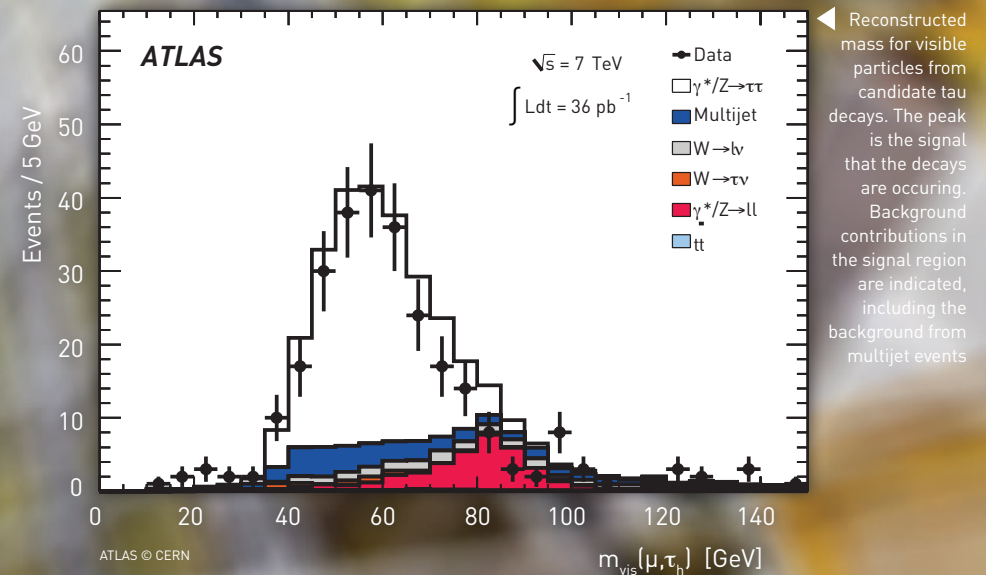
The Higgs boson of the Standard Model can decay in many ways, and we experimentalists choose our favourite decay as a search channel. Jumping straight to the punch line, the particle recently discovered, with a mass of 125 GeV, hasn't yet (June 2013) revealed whether it can decay to tau leptons. This is despite many of us having dedicated ourselves to the search for several years!

The stubbornness of the decay to tau leptons to reveal itself could be for fundamental reasons, which would shake the Standard Model to its core. The new particle could perform the job of the Higgs boson but be a surrogate from a completely different theory, so that the decay to tau leptons might not occur at the expected rate, or might not happen at all. This is an open puzzle. To solve it, we must be smarter with the data that we've already recorded, or will have to wait until ATLAS records more data — in 2015, when the LHC is switched back on, following extensive upgrades.

I outline in this account how we, at Warwick, have been a part of the so-far-puzzling search for the Higgs decaying to tau leptons. First, I show that we know exactly what a Higgs decay to tau leptons would look like. I do this by recounting our measurement of a different boson, the Z, decaying in the same way. Second, I describe the latest results from searches for Higgs decays to tau leptons. These were discussed at two conferences in Japan, in November 2012 – at the Hadron Collider Physics Symposium, in Kyoto; then at the Higgs Coupling Workshop, in Tokyo, where I presented the tau results.

## SINÉAD FARRINGTON

Sinéad Farrington is a Lecturer in Physics at the University of Warwick, having previously been an STFC Advanced Research Fellow at the University of Oxford. She works on the ATLAS experiment, searching for Higgs bosons decaying to tau leptons.



## A STANDARD CANDLE

ATLAS is designed to reconstruct particle decays by piecing together electronic information, building up a picture of what happens when protons collide. Tau leptons are especially difficult to identify, since their presence can only be inferred from observation of particles from their decays: electrons; muons; and hadrons, made up of quarks. In addition to these objects, the decays always include at least one neutrino – a type of particle that is impossible to detect in ATLAS, except by invoking the principle of conservation of momentum

. As tau leptons decay in several ways, and not all of the decay particles are detected, the decays (signal) can be hard to distinguish from other processes (background) that look very similar.

During 2009 and 2010, while at Oxford, I worked with Aimee Lerner, a PhD student, and Elias Coniavitis, a postdoc, on a benchmarking measurement of Z-boson decays to tau leptons. The Z was discovered at CERN, in 1983, and its properties were measured with incredible

accuracy at the LEP collider, the precursor to the LHC. These precision measurements, complemented by detailed theoretical understanding, make the Z invaluable as a standard candle, useful for calibrating detector performance, and for evaluating analysis methods.

Among other projects, Aimee, Elias and I established a procedure to measure the background from proton-proton collisions that give rise to multiple jets of hadrons, which can look exactly like a Z or a Higgs decaying to tau leptons. Starting from the mass spectrum for our decay candidates, we defined control regions, where we didn't expect any signal. We were then able to calculate the background fraction in the signal regions by extrapolating. After allowing for the background contribution that we found, it was very satisfying that the measured rate for Z-boson production agreed with the theorists' predictions – although a startling disagreement would have been even more exciting! This convinced us that all the complexities of measuring decays to taus were under control, and we were ready to go on a hunt for Higgs bosons decaying in the same way.



# HIGGS HUNTING

My new team, at Warwick, has been able to apply the various techniques that I helped develop. Through work mainly done by Elisabetta Pianori, one of our Research Assistants, we've focused on understanding the uncertainties on the theoretical calculations of Higgs-boson production. This is a complicated, and rapidly developing, field. Theorists are continuously refining their calculations, and producing new software packages, to help experimentalists take theoretical uncertainties into account in their data analysis. This is extremely important. When we claim to rule out, or observe, the Higgs at a given mass, we are always doing this with reference to theoretical predictions. Misapplication of these predictions could mean that we obtain a false result.

In November 2012, with the autumn colours in full splendour, hundreds of us flocked to Kyoto to see the latest Higgs results unveiled. Although we've seen events that look very much like Higgs decays to tau pairs, neither ATLAS nor CMS has conclusive evidence that this decay occurs. To be able to say anything more, we need more data or smarter techniques.



*For me, the most thrilling outcome of the conference was the certainty that we'd discovered a new particle*

Participants at the workshop on Higgs Coupling, Tokyo, November 2012



Following a rapid bullet-train ride to Tokyo, I gave a talk at the first in a planned series of conferences on Higgs Couplings. These conferences are designed to bring experimentalists and theorists together, to plan the next steps in pinning down the properties of the Higgs boson.

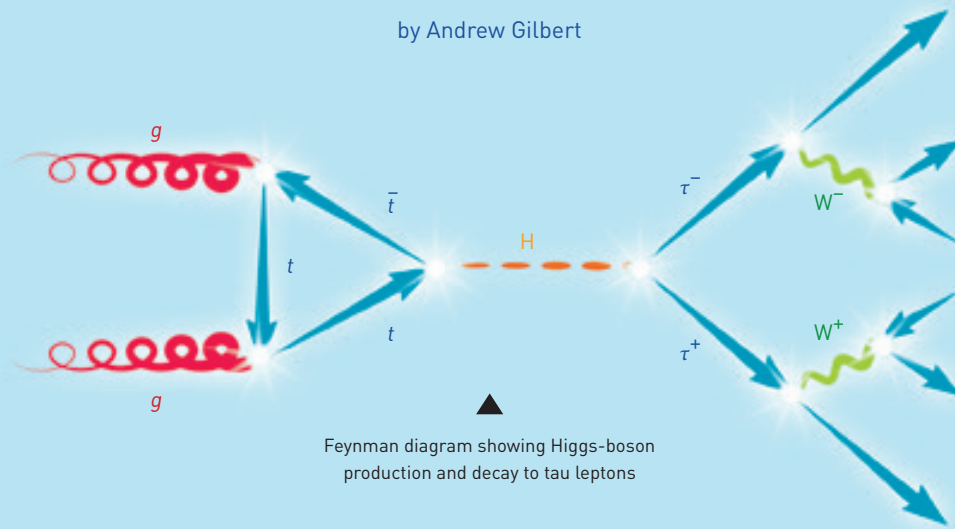
In Tokyo, we tried to figure out how to agree on theoretical uncertainties, so that CMS and ATLAS present comparable results. This is especially important now that we're using more complex techniques. We excitedly discussed the projections of how accurately we will measure the Higgs properties with the LHC data, and looked ahead to the possibility of an entirely new collider, which could be built in Japan, for precision measurements.

For me, the most thrilling outcome of the conference was the certainty that we'd discovered a new particle, and the growing acceptance that this is very likely to be the Higgs boson of the Standard Model, a particle predicted almost fifty years ago. As the summary speaker put it: "It smells like fish, looks like sushi, tastes like sushi." So it might very well be sushi! Until we know for sure whether the new particle can decay to tau leptons, I'll retain just a little doubt.



# IDENTIFYING HIGGS DECAYS TO TAU PAIRS

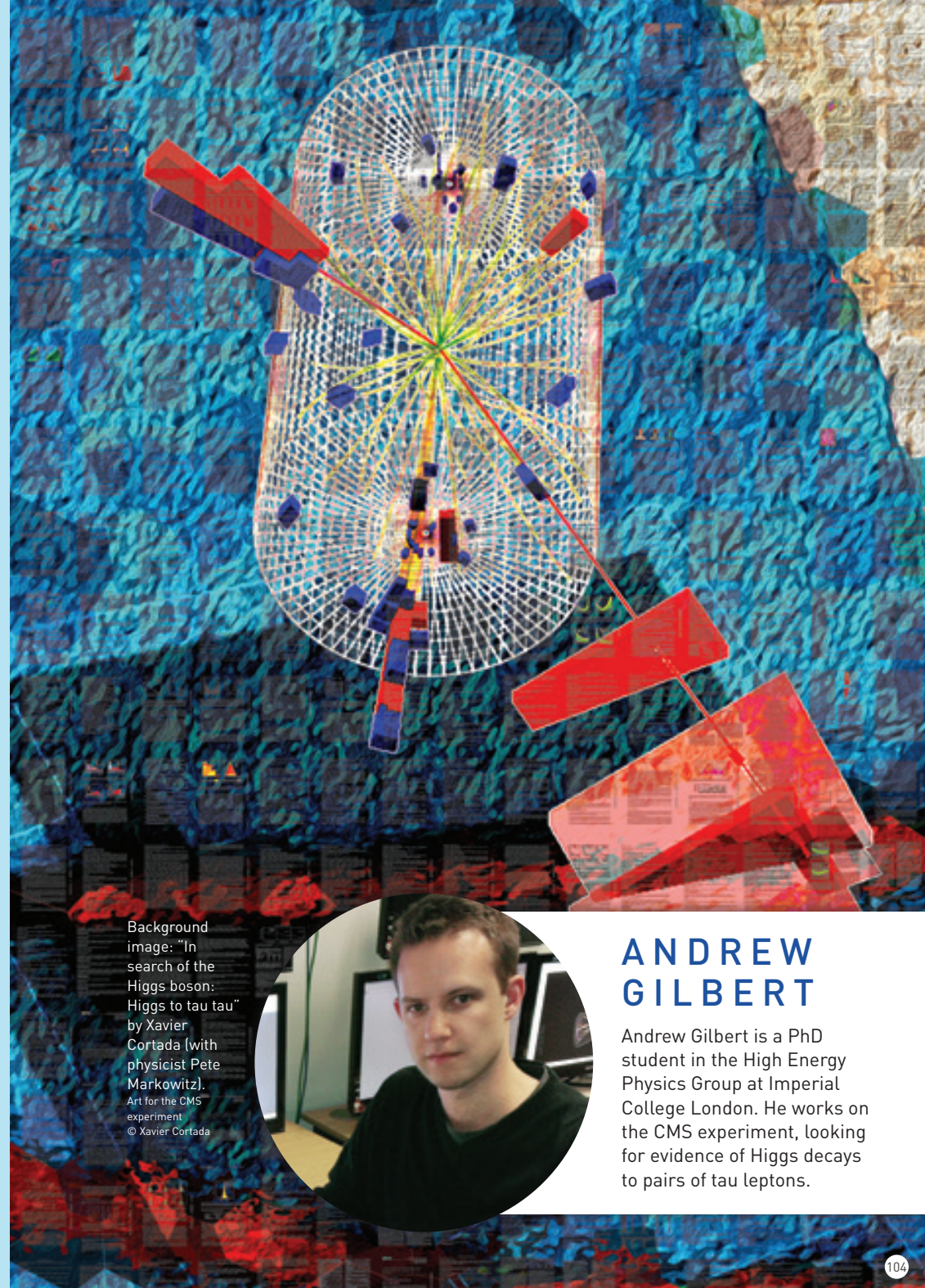
by Andrew Gilbert



At the LHC we search for the Higgs boson by looking for the different particles into which it decays. Since March 2012, I've been working in a group that has been searching for Higgs decays to two tau particles. A tau is similar to an electron – and is part of the same family of particles, called leptons – but its mass is almost 3,500 times larger. Unlike the electron, the tau is unstable, and decays almost instantly into a host of lighter particles.

It's by identifying the particles from tau decays that we can infer the presence of a pair of tau leptons, which may come from a Higgs. However, the signal for this Higgs decay is dwarfed by similar-looking background processes. A large part of our work over the last year has been to devise better ways of isolating the signal. We do this by identifying characteristic features of the Higgs decays, and then only selecting collision events that contain one or more of these features. For example, we select events where, in addition to two tau leptons being emitted, a jet of high-energy particles is produced. This jet production is more likely in Higgs events.

After careful analysis of all of the data recorded by CMS between 2011 and 2013, we have seen the indications that the Higgs does indeed decay to tau particles. In March 2013, we released results that show an excess of events, in line with the predictions of the Standard Model. This is far from being the end of the story. When the LHC is restarted, in 2015, we will collect much more data, allowing us to understand the properties of the new particle in greater detail. The decay to tau particles will be important for pinning down exactly what kind of Higgs boson we've found.



Background image: "In search of the Higgs boson: Higgs to tau tau" by Xavier Cortada (with physicist Pete Markowitz). Art for the CMS experiment  
© Xavier Cortada

## ANDREW GILBERT

Andrew Gilbert is a PhD student in the High Energy Physics Group at Imperial College London. He works on the CMS experiment, looking for evidence of Higgs decays to pairs of tau leptons.



# STUDENTS CAPTURE BUZZ OF HIGGS-BOSON ANNOUNCEMENT IN GENEVA

by Harald Fox

## HARALD FOX

Harald Fox is a Lecturer in Physics at Lancaster University. He studies Higgs decays to tau leptons in the ATLAS experiment, and previously worked on Higgs searches in DØ.

Along with several undergraduate students, postgraduate students and other researchers from Lancaster University, I was in Geneva on 4 July 2012 to witness first hand one of the biggest scientific announcements for a generation.

The excitement built up slowly in the few days after the seminar was announced. Everyone could feel that something big was going to happen. On the day of the seminar, Lancaster postgraduate student Harvey Maddocks started queuing at 4:45 in the morning for one of the coveted seats in CERN's Main Auditorium. He was lucky, and managed to get one of the last seats in the back row – in time to see Peter Higgs enter the Auditorium, shortly after 9, to great applause.

Most of those at CERN watched the live transmissions in two large, crowded halls. Physicists from further afield, including participants at a major conference in Melbourne, Australia, joined the seminar via video link.

The spokespersons from CMS and ATLAS went through each analysis step-by-step, in exacting detail, and the evidence for the Higgs boson kept mounting: 4.1 sigma significance in one analysis, 3.2 sigma in another, and 5.0 sigma in yet another. It's not often that one can sense some nervousness and excitement when such seasoned scientists give a physics talk – but this occasion was special. In the end, it was summarised by Rolf Heuer, the Director General of CERN, as he exclaimed: "I think we have it!"

Shortly after 10, everything had been said and done, and the scientists left the meeting halls – some to celebrate, some to talk to visitors and the press, and some to go back to work, to see what else was waiting to be discovered.

Fabiola Giannotti (ATLAS spokesperson) presents the ATLAS results at VERN Higgs seminar.

© CERN

Nicholas Barton, Matt Buckland, Matt Roscoe, and Oscar Scott – four undergraduates from Lancaster University's Physics and Astronomy Society – captured on film the anticipation in the run-up to the announcement, and recorded an interview with Philippe Bloch, Head of CERN's Physics Department. The experience was summed up by Oscar Scott:

***"A trip to CERN is an inspiring visit and I would highly recommend it to any physics student. It was amazing to see the Higgs seminar while I was there. I could really feel the anticipation of all the researchers around me who had worked so hard to get the results."***

Stills from short film produced by undergraduates belonging to Lancaster University's Physics and Astronomy Society

Behind Closed Doors  
Discovery of the Higgs?





# UNKNOWN LANDS

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Image: Cristina Lazzeroni (pages 3-4) demonstrates some of the physics behind particle detectors to potential future scientists – *Particles from outer space* at Bang Goes the Theory Live, Poole, June 2012.





# THE NEXT STEP

by Jordan Nash

Building the CMS detector took nearly twenty years, from the first concepts to the start of data taking. Even before we had recorded any collisions at the LHC, we began thinking about what we would need to do to extend the detector's life. We hope to continue taking data for another two decades, but this won't be straightforward, and will require many years of preparation.

To perform detailed studies of the Higgs bosons, and anything else that we discover at the LHC, we will need to produce as many of the new particles as we can. One way of making many more particles is to increase the intensity of the proton beams that circulate at the LHC, and so increase the collision rate. This will give us more of the interesting particles that we want, but the extra collisions will put very great demands on our detectors. We need to make changes to them, to cope with high intensities.

About ten years ago, we began to study how the different parts of the detector would perform if we increase the

LHC intensity to ten times its design specification, an increase now planned for around 2023. Some outer parts of the detector cope fairly well with this increase. Other parts of the detector, close to the beam collisions, struggle with measuring much-larger numbers of particles than were originally foreseen, and could be damaged by being bombarded by so many particles.

In 2011, we published our first plans for upgrading the CMS detector. The upgrade will involve changes to the central pixel detector, which sits just outside the beampipe, and other changes to optimise performance during the present decade.

We are studying how to improve our detectors, to be able to operate after the ten-fold increase in the LHC intensity. One of the big challenges is to spot interesting events, when there are many more particles around. A possible solution being considered is to build custom electronics, able to measure the momentum of the particles in our tracking detectors, for 40-million events a second. The first prototypes of this new generation of technology are being assembled and tested.

Photograph of a prototype CMS module, currently being tested at Imperial College London, for real-time measurement of particle momentum.

The module consists of two layers of silicon-strip detectors, connected to custom-designed electronics

© Imperial College London

About ten years ago, we began to study how the different parts of the detector would perform if we increase the LHC intensity to ten times its design specification, an increase now planned for around 2023.



## JORDAN NASH

Jordan Nash is a Professor of Particle Physics at Imperial College London. He was the initial project leader for the upgrade of the CMS detector.



# START OF A NEW ERA

by Dave Charlton

The discovery of a Higgs boson – a new type of particle, different from the matter and force-carrying particles previously known – is a defining moment in the exploration of the basic structure of nature. It leads on to a host of further questions: is the new boson unique, or is it one of several new Higgs particles? Does it behave as expected of the Higgs boson of the Standard Model, or is it a different object? If it is different, is it connected to the dark matter that we see in the Universe? The LHC's voyage of discovery has barely begun: after the 2013-14 shutdown, the energy of the collisions will be almost doubled, and the opportunity to find other new particles will be greatly increased. In addition, measurements of some special processes, such as the scattering off one another of two W or Z particles, will provide further crucial tests of the Standard Model.

To test if the Higgs boson looks like the particle predicted in the Standard Model, we should measure as many of the production mechanisms, and decay modes, as possible. Since it interacts with particles according to their mass – the essence of the Higgs mechanism – we expect to see the Higgs particle produced from, or decaying into, high-mass particles, such as the W and Z bosons. It cannot decay to the even-more-massive top quark, because this is heavier than the Higgs particle!

Measurements made already tell us that the Higgs interacts with W and Z particles roughly as expected, and that it seems to interact with photons only via rare loop

processes. Indirect evidence tells us that the Higgs interacts strongly with the top quark, and, with the current data, we also start to see evidence of interactions with the heavy tau leptons.

To establish the nature of the new particle, we should measure the strengths of the interactions to lighter matter particles, such as the muon – a second-generation particle – and even the strength with which the Higgs particle interacts with other particles like itself. This latter is known as the Higgs self-coupling.



Dave Charlton (far right) leads a group including the Russian deputy prime minister, Olga Golodets (second from left), on a visit to the ATLAS cavern © CERN

## DAVE CHARLTON

Dave Charlton is a Professor of Particle Physics at the University of Birmingham. He is the ATLAS Spokesperson, meaning that he is the scientific leader of the experiment, and represents the collaboration in many external contexts.

**The LHC's voyage of discovery has barely begun: after the 2013-14 shutdown, the energy of the collisions will be almost doubled, and the opportunity to find other new particles will be greatly increased**





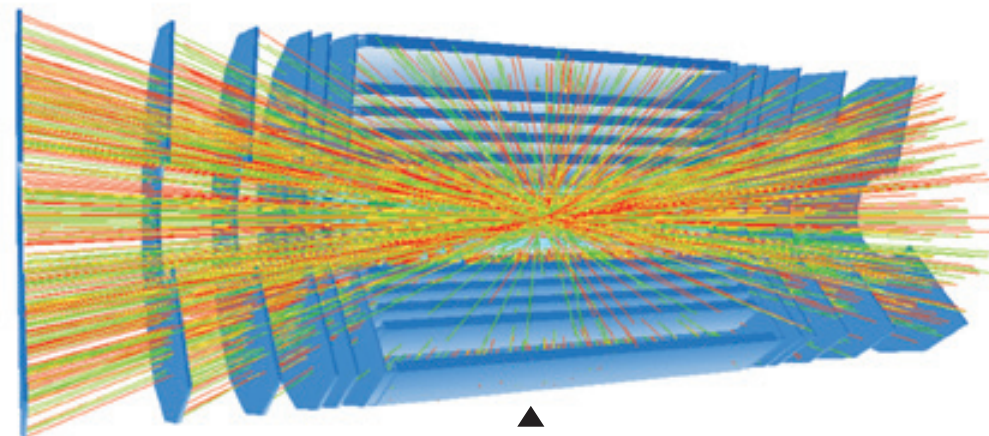
**Beyond 2022, the intensity of the proton-proton collisions will be increased again, to give another ten-fold increase in the number of Higgs particles produced**

The detailed studies of the Higgs particle require a lot more data than we have so far. The plan is to collect about ten-times more data from 2015 to 2022, at proton-proton collision energies up to the LHC design energy of 14 TeV. This data sample will allow us to improve the measurements of many decays by about a factor three – the decays to the third-generation of matter particles (tau and b quarks, in particular) will be measured to an accuracy of about 20%.

Beyond 2022, the intensity of the proton-proton collisions will be increased again, to give another ten-fold increase in the number of Higgs particles produced.

With these data, the LHC becomes a Higgs factory. In order to cope with the large rates, parts of the ATLAS detector will be replaced with higher-capacity components. The biggest change will be the replacement of the inner tracking detector. The new design uses silicon sensors throughout, and the construction will be a multi-year project which should start around the middle of the decade.

The upgrades to the ATLAS detector will allow the experiment to continue studies at the energy frontier until the early 2030s – delivering a programme of breathtaking physics, quite likely including new discoveries, over more than twenty years.

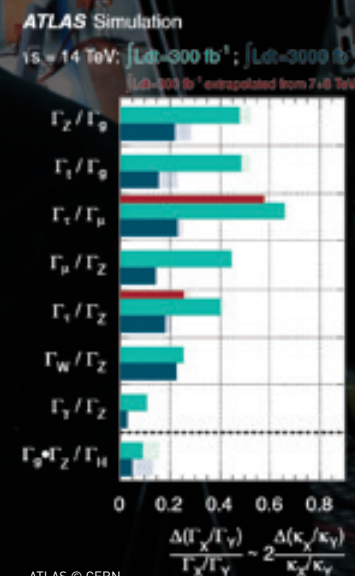


Simulation of a typical event in the upgraded ATLAS tracking detector, with the LHC operating at the high luminosity planned for the 2020s.

ATLAS © CERN

## MEASUREMENT ACCURACIES AFTER THE ATLAS UPGRADE

The graphic illustrates the accuracy with which the strengths of the Higgs boson interactions with different particle types can be measured. The horizontal axis shows the fractional accuracy with which the different decays of the Higgs can be measured – shorter bars indicating more precise measurements. The green bars show measurement accuracies with the 300 fb<sup>-1</sup> of data expected by 2022. The blue bars show the improved accuracies, between a few percent and around 20%, with the 3000 fb<sup>-1</sup> of data expected from high-luminosity running in the 2020s, after the ATLAS upgrade.





# EXHIBIT TEAM

*Understanding the Higgs boson* was organised, with help from a few friends, by researchers from the UK Particle-Physics groups that collaborate on the ATLAS and CMS experiments, at the Large Hadron Collider, near Geneva.

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