What's Next for Particle Physics?

Martin White reviews our current knowledge of particle physics and surveys the hot topics at the research frontier.

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For my parents, Catherine, and the two forces of nature: Henry and Alfred.

Contents

Abstract

Following the discovery of the Higgs boson in 2012, particle physics has entered its most exciting and crucial period for over 50 years. In this book, I first summarise our current understanding of particle physics, and why this knowledge is almost certainly incomplete. We will then see that the Large Hadron Collider provides the means to search for the next theory of particle physics by performing precise measurements of the Higgs boson, and by looking directly for particles that can solve current cosmic mysteries such as the nature of dark matter. Finally, I will anticipate the next decade of particle physics by placing the Large Hadron Collider within the wider context of other experiments. The results expected over the next ten years promise to transform our understanding of what the Universe is made of and how it came to be.

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Dr Martin White is a particle astrophysicist and ARC Future Fellow at the University of Adelaide. He co-leads the GAMBIT collaboration, an international team of physicists and statisticians with members in Australia, Europe and the US, whose novel data mining software can test, for the first time, generic dark matter theories against 20 years of accumulated particle astrophysics data. He also performs searches for new particles and measurements of the Higgs boson with the ATLAS experiment at the Large Hadron Collider, and has co-authored over 600 articles on high energy physics experiment and theory. He is a committed science communicator, with past work including lectures to UK secondary school students at CERN, lectures at the UK music festivals Latitude and the Secret Garden Party, and a BBC-sponsored touring show on the science of Dr Who, produced by The Royal Institution of Australia.

What's Next for Particle Physics?

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1 Introduction

At the end of the 19th century, Lord Kelvin is widely reported to have remarked that 'there is nothing new to be discovered in physics now. All that remains is more and more precise measurement'. The problem, as usual, is that he never actually said it. The sentiment is almost certainly taken from an 1894 speech by Albert Michelson, whose pessimism was presumably removed when, within only a few years, physics was completely revolutionised by the discovery of quantum mechanics and relativity. Since that time, our understanding of all aspects of our universe has increased at a frightening rate, along with our technological capacity.

Were a time machine to bring Michelson from 1894 to the present day, he would no doubt find the pessimistic mood among some particle physicists as comforting and familiar as the current young men's fashion for outrageous facial hair. The prevailing logic in some quarters is that the discovery of the Higgs boson in 2012 provides the last significant piece of the puzzle of particle physics, and the failure to find direct evidence of any new particles at the Large Hadron Collider is a profound milestone in the slow decline of the field. Much like Kelvin's mythical speech, however, reports of the recent death of particle physics are closer to fiction than fact. Indeed, the current era is substantially more exciting than the field I joined in 2003 for the simple reason that the discovery of the Higgs boson has given us an entirely new way to probe our understanding of the Universe and its constituents. Furthermore, the Large Hadron Collider has collected only a small fraction of the data that it will record during its lifetime, meaning that much of the practical work underlying future discoveries remains to be done.

The purpose of this book is to briefly introduce a physics undergraduate to our current knowledge of particle physics, as a prelude to a detailed summary of the problems in particle physics and the prospects for solving them within the next decade. We will see that our best theory has been staggeringly successful at describing a wide range of phenomena, but cannot possibly be the final answer

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due to a number of theoretical and experimental challenges. It is a brave and foolish person indeed who would swear that this theory is the final answer, and you can think of this book as a menu of delicious selections that you might choose to savour in your future career. The best hope of a solution to many of these challenges in the near future remains the Large Hadron Collider, but we will also explore the relationship between physics measurements at the Large Hadron Collider and those at other experiments in particle physics and astrophysics that can potentially answer the same questions.

2 Background

The Standard Model of particle physics

What is the Universe made of? Experiments in the 20th century have led us to the remarkable conclusion that the Universe is essentially a giant set of modelling bricks, with all visible matter comprised of different combinations of fundamental blocks, interacting via four known forces: *gravity*, the *strong force*, the *weak force* and the *electromagnetic force*. In high school, you will have learnt that everything is made of atoms, but atoms are not themselves the real building blocks of matter. Atoms contain a central nucleus (composed of protons and neutrons), and a cloud of electrons which provides the fundamental basis for chemistry. The electron is, as far as we know, a true building block of nature, having no smaller constituents. Protons and neutrons, on the other hand, are built from smaller particles called *quarks* that appear to have no fundamental constituents. Of the forces, gravity is arguably the one that you have known about for longest, followed closely by electromagnetism. The strong force is responsible for binding your protons and nuclei together, and its name arises from the fact that it is indeed the strongest force that we know about in nature. The weak force turns out to provide the explanation for radioactive beta decay.

The complete list of building blocks found in nature is given in figure 1, along with the mass, spin and electromagnetic charge of each particle. The first three columns describe the *matter* in the Universe, which is divided into particles that can interact via the strong, weak and electromagnetic interactions (called *quarks*) and particles that can only interact via the weak and electromagnetic interactions (called *leptons*). It is also worth noting that all matter particles in the Universe have a spin of 1/2, making them *fermions*. In a simple picture, most of the proton and neutron is composed of *u* and *d* quarks (referred to as 'up' and 'down'), and the rest of each atom is populated by electrons. For a reason nobody knows, there are heavier versions of each of these particles, giving three generations of matter. These are easy to produce in our various collider experiments (and indeed anywhere else that has sufficient energy), and there are technically trace elements of the heavier particles in the bizarre quantum-mechanical stew that we commonly think of as a 'proton'. Now, it should not be forgotten that the *names* in this paragraph of jargon are totally arbitrary. We could have called them anything we like, and perhaps a race of aliens refers to them with a completely different pattern of abstract squiggles. The pattern

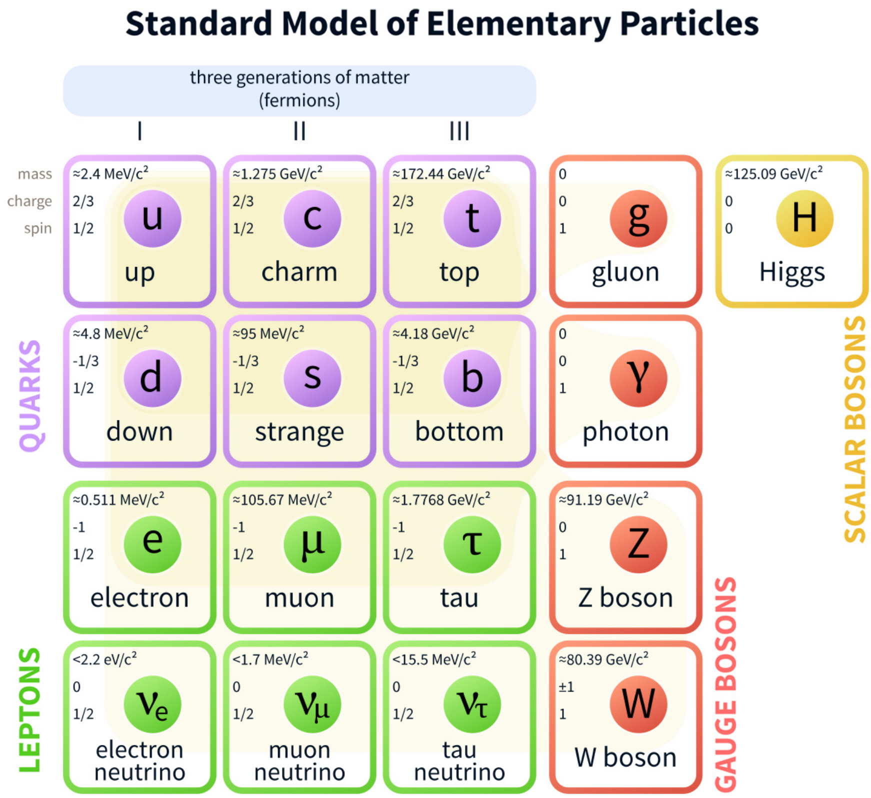

Figure 1. The particles of the Standard Model of particles physics. (Image Credit: MissMJ.)

of charges, spins and generations, however, is not arbitrary, and the elegant structure of the generations of matter is probably hiding some sort of motivating principle, and that we have not yet managed to figure out.

The fourth column of figure 1 lists particles associated with the forces in nature. It is a fundamental property of the theory that each force gets one or more particles associated with it: the photon γ is the force carrier for electromagnetism, eight gluons g mediate the strong force, and the W^+, W^- and Z bosons mediate the weak force. All force particles in nature have integer spin, and the particles are therefore *bosons*. Moreover, some of these particles are massless (the gluons and the photon), but others carry substantial masses (the bosons of the weak force). Introducing a mass for particles in the theory requires something called the *Higgs boson* which is the subject of the next section.

Our collective wisdom on the building blocks of nature is referred to as the 'Standard Model of particle physics' (Standard Model). Loosely speaking, this consists of the information provided by figure 1 plus the mathematical description of how these building blocks interact via the force particles. This can be stated in the following snappy form:

$$
\begin{aligned}
\mathcal{L} = &-\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}tr(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu}) \\
&+ (\overline{\nu}_L, \overline{e}_L)\tilde{\sigma}^{\mu}iD_{\mu}\begin{pmatrix}\nu_L \\ e_L\end{pmatrix} + \overline{e}_R\sigma^{\mu}iD_{\mu}e_R + \overline{\nu}_R\sigma^{\mu}iD_{\mu}\nu_R + (\text{h.c.}) \\
&- \frac{\sqrt{2}}{v}\left[(\overline{\nu}_L, \overline{e}_L)\phi M^{e}e_R + \overline{e}_R\overline{M}^{e}\overline{\phi}\begin{pmatrix}\nu_L \\ e_L\end{pmatrix}\right] \\
&- \frac{\sqrt{2}}{v}\left[(-\overline{e}_L, \overline{\nu}_L)\phi^{*}M^{\nu}\nu_R + \overline{\nu}_R\overline{M}^{\nu}\phi^{T}\begin{pmatrix}-e_L \\ \nu_L\end{pmatrix}\right] \\
&+ (\overline{u}_L, \overline{d}_L)\tilde{\sigma}^{\mu}iD_{\mu}\begin{pmatrix}u_L \\ d_L\end{pmatrix} + \overline{u}_R\sigma^{\mu}iD_{\mu}u_R + \overline{d}_R\sigma^{\mu}iD_{\mu}d_R + (\text{h.c.}) \\
&- \frac{\sqrt{2}}{v}\left[(\overline{u}_L, \overline{d}_L)\phi M^{d}d_R + \overline{d}_R\overline{M}^{d}\overline{\phi}\begin{pmatrix}u_L \\ d_L\end{pmatrix}\right] \\
&- \frac{\sqrt{2}}{v}\left[(-\overline{d}_L, \overline{u}_L)\phi^{*}M^{u}u_R + \overline{u}_R\overline{M}^{u}\phi^{T}\begin{pmatrix}-d_L \\ u_L\end{pmatrix}\right] \\
&+ \overline{(D_{\mu}\phi)}D^{\mu}\phi - m_h^2[\overline{\phi}\phi - v^2/2]^2/2v^2
\end{aligned}
$$

What on Earth does this mean? Even without understanding all the details of this equation, one can learn something about it. Firstly, it is clearly a mix of mathematics that you recognise (negative numbers, fractions, vectors, matrices), and mathematics that will certainly still be obscure. Secondly, it is quite repetitious in its content: certain terms appear more than once with minimal differences, indicating an underlying structure to the theory. The equation is in fact written in the language of *gauge field theory*, in which the matter and forces in the Universe are represented via fields that fill all of space–time. Particles are represented as excitations of these fields so that, for example, there is only one electron field filling all of space–time, and each electron is an excited state of this field. If we had a purely classical theory with no quantum effects, the *vacuum* would correspond to no field excitations and thus no particles. In the quantum theory, however, the fields are allowed to fluctuate even in the absence of any real particles, giving rise to virtual particles. *Nothing* really is *something* after all!

The equation is also an example of a *Lagrangian density*, which can provide the equations of motion for these fields via a recipe that is very closely related to the Lagrangian formulation of classical mechanics. You must take it for granted for now, but the top line describes the force fields of the strong, weak and electromagnetic forces, the second line is there to allow lepton fields to propagate through space and to interact with the force fields, the fifth line does the same for the quark fields, and the remaining lines describe the physics of the Higgs field and the interactions that ultimately give mass to the matter of the Universe (and the force particles of the weak force).

The success of this short equation cannot be overstated. We have used it to predict with amazing accuracy every process measured in our colliders so far, covering a

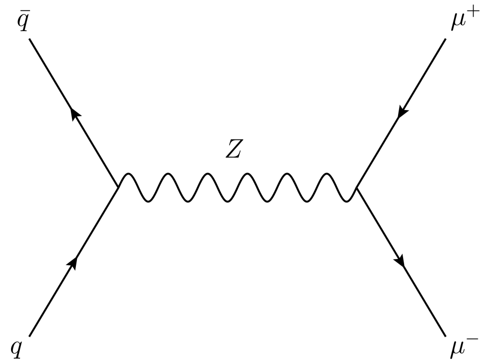

Figure 2. A Feynman diagram for production of a Z boson from two quarks, which subsequently decays to two muons.

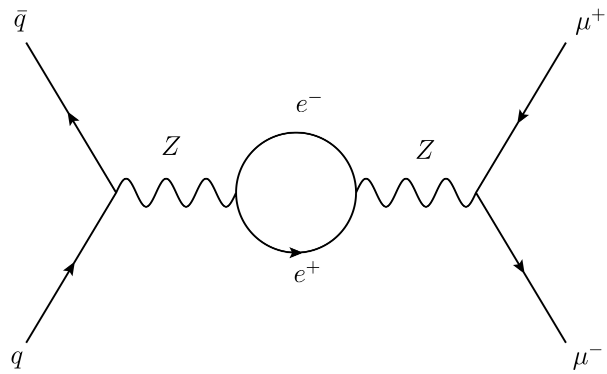

Figure 3. A higher-order Feynman diagram for the production of a Z boson from two quarks, with subsequent decay to two muons. The Z boson can in fact split into an electron-positron pair which come back to be a Z boson, before the decay to muons takes place.

very wide range of energy. A final piece of knowledge that we will need moving forward is the notion of *loop effects*. In quantum field theory, calculations using the Standard Model equation can be represented by diagrams called 'Feynman diagrams'. For example, figure 2 shows a pair of quarks interacting to produce a Z boson, which then decays to give a pair of muons.

This diagram may look like a cartoon, but in fact there is a simple set of rules for taking any particular diagram and working out the rate of the process shown. The diagram in figure 2 is only the first example of how this process can occur, however, and there are *higher order* diagrams that involve extra interactions that occur between the incoming quarks and the outgoing leptons. Figure 3 shows an example of such a loop diagram, and it is stated here without proof that such higher order diagrams give a smaller contribution to the total result than the lower order diagrams. This means that one can truncate the list of possible higher order diagrams for any given calculation to match a desired accuracy (much as one can truncate a series expansion when approximating a function to given accuracy). We will see later that loop effects provide an extremely important window into new physics effects at the LHC.

The Higgs field and the Higgs boson

We have been somewhat mysterious about the Higgs boson so far, stating only that it is needed to give mass to the other particles in the theory. Rather than give a simple (and ultimately false) analogy for this process, we will attempt to describe the details using an appeal to concepts that you will be familiar with from the first couple of years of a physics degree.

A crucial concept in physics is that of *symmetry*. In general cases, a law or equation is said to be symmetric with respect to a particular transformation (e.g. of the variables) if we get the same physics after the transformation as we got before. A classic example is that of Maxwell's equations of electromagnetism, which neatly summarised all known experimental results in electricity and magnetism with four simple equations:

$$\nabla \cdot \mathbf{E} = \rho_{EM}$$
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$
$$\nabla \cdot \mathbf{B} = 0$$
$$\nabla \times \mathbf{B} = \mathbf{j}_{EM} + \frac{\partial \mathbf{E}}{\partial t}$$

where $\boldsymbol{E}$ is the electric field, $\boldsymbol{B}$ is the magnetic field, ρ_{EM} is the density of some charged matter, and $\boldsymbol{j}_{EM}$ is called the current density. Now, you have probably seen that we can define a scalar potential V and a vector potential $\boldsymbol{A}$ in place of the fields $\boldsymbol{E}$ and $\boldsymbol{B}$ via:

$$\mathbf{B} = \nabla \times \mathbf{A}$$
$$\mathbf{E} = -\nabla V - \frac{\partial \mathbf{A}}{\partial t}$$

which is the first step by which we can write Maxwell's equations in a much simpler form. Using V and $\boldsymbol{A}$ gives us exactly the same description of nature as using the original $\boldsymbol{B}$ and $\boldsymbol{E}$, but notice that the forms of V and $\boldsymbol{A}$ are not uniquely determined. We can change them via the following transformation without changing $\boldsymbol{B}$ and $\boldsymbol{E}$

$$\mathbf{A} \rightarrow \mathbf{A}' = \mathbf{A} + \nabla\alpha$$
$$V \rightarrow V' = V - \frac{\partial \alpha}{\partial t}$$

where α is an arbitrary scalar function that can in principle vary with position. For obscure historical reasons, this is known as a *gauge transformation*, and the fact that Maxwell's equations do not change under this redefinition of V and $\boldsymbol{A}$ is called gauge invariance. One can write a quantum field theory of electrodynamics for which the property of gauge invariance is a crucial component, and indeed this is one of the ingredients of the Standard Model equation given above.

While this may seem like an obscure and random aside, gauge invariance is the sacred principle on which all gauge field theories, and therefore the Standard Model, are built. For example, starting from the equations for a theory of particle physics, one can insist that they remain invariant under the gauge transformation of electromagnetism, with the result that, in general, we need to add some terms to the equations to cancel the effects of the gauge transformation. It transpires that these extra terms predict the existence of the photon! Not only that, but by repeating this trick for the strong and weak forces, we find that invariance under transformations of a slightly different form yields exactly the right equations to describe the observed strong and weak interactions.

In the modern view, all forces arise from invariance under a particular gauge transformation, and we therefore have a very general recipe for describing the interactions between the building blocks of nature. Unfortunately, there is a snag when we come to add masses to the theory. If we naively try to add terms to our equation that act as masses for the force fields, they turn out not to be gauge invariant. The sacred principle on which we based our theory of particle physics appears to be broken! Rather than give up gauge field theory for good, however, we use a clever trick: we continue to write a *Lagrangian* using only gauge invariant terms, but we arrange for the *vacuum state* of the theory to break the gauge symmetry. This is accomplished by adding an additional scalar field called the *Higgs field*, excitations of which are called *Higgs bosons*, in such a way that mass terms arise from interactions between the Higgs field and the other particles in the theory. The equation given above represents the simplest way of achieving this mechanism, and it allows the Higgs field to give mass to the W and Z bosons, and to the leptons and quarks.

The Higgs discovery and current measurements

Although first proposed in 1964, it was not until 2012 that definitive evidence for a Higgs boson was uncovered at CERN's Large Hadron Collider (LHC). The LHC accelerates protons to near light speeds in a 27 km underground ring straddling the French-Swiss border near Geneva, before smashing them together at a centre of mass energy of 7 TeV (before 2012), 8 TeV (2012) or 13 TeV (present day). However, this centre of mass energy is only that of the incoming *protons*. Since the proton is a composite object, each collision actually involves a random collision between constituents of the proton at some unknown centre of mass energy, which in a simple picture may be a collision of a quark with a quark, a quark with a gluon or a gluon with a gluon. In each case, the correct way to think of the collision is not as a deterministic process analogous to the collision of billiard balls. Instead, the energy of the incoming proton constituents can be turned into any of the particles of the Standard Model, provided we do not end up with more relativistic energy and momentum than we put in. Following the probabilistic nature of quantum mechanics, each collision is randomly selected from the set of possible options given by the equation of the Standard Model, and the only thing that we can predict is how many of each type of process will be seen in a large sample of events.

The results of LHC proton–proton collisions are recorded by a series of particle detectors around the ring, two of which—ATLAS and CMS—are designed to be general purpose machines capable of detecting any new particles that might be produced at LHC energies. In practice, they were designed to be able to measure the properties of the Higgs boson precisely, and the same design gives them excellent prospects for detecting and measuring the properties of any other particles that we might be lucky enough to discover.

Figure 4 shows four possible ways of making a Higgs boson from proton constituents at the LHC. Although there is no direct interaction between gluons and the Higgs boson, one can make a Higgs boson from gluons if they first interact via top quarks (in which case the Higgs is really interacting with the top quarks, as are the gluons). The same interaction between gluons and top quarks, and the Higgs boson and top quarks, can be used to make a Higgs boson in the presence of two top quarks. Meanwhile, the dominant ways for light quarks to make a Higgs boson are through their interaction with W and Z bosons, which then produce a Higgs boson via its own interaction with the W and Z bosons. A direct light quark–Higgs interaction is in fact allowed, but it is very small due to the small mass of the light quarks.

Once made, the Higgs boson is highly unstable and decays almost instantaneously. An LHC detector works by reconstructing the relativistic energy and momentum of particles passing through it, in addition to providing some idea of what *type* of particle has been seen. The detectors can distinguish between electrons, muons, photons and particles that interact via the strong force (quarks and/or gluons). The first observations of the Higgs boson came via its decays to pairs of

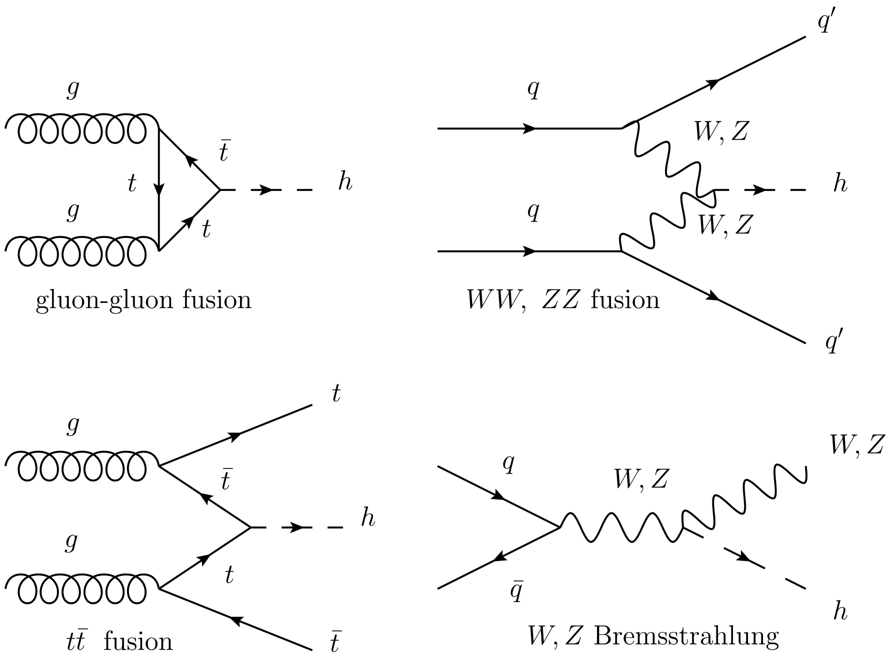

Figure 4. Four ways of producing a Higgs boson.

photons, W bosons and Z bosons. The kinematics of the Higgs decay process obey the familiar rules of special relativity, and a quick relativistic analysis will prove particularly instructive.

Recall that in special relativity, the energy and momentum of a particle can be written as a four-component object (called a four-vector), which, in units where the speed of light $c = 1$, can be written as $P = (E,\boldsymbol{p})$, where E is the relativistic energy, and $\boldsymbol{p}$ is the momentum vector of the particle written in some frame. We can write P^μ to indicate the components of this object, and conservation of momentum in normal mechanics gives way to conservation of four-momentum in special relativity.

Imagine that we have some particle A (at rest in some frame) decaying to two particles. Conservation of four-momentum then tells us that:

$$P^\mu_{(A)} = P^\mu_{(1)} + P^\mu_{(2)}$$

If we square both sides, we simply get the rest mass of the particle A on the left-hand side (using a standard identity for the square of the four momentum of a particle of mass m), and we get the invariant mass of the two daughter four-vectors on the right-hand side. Since this is a Lorentz scalar, this is true in any frame, including that of the LHC detectors.

Conveniently, this gives us a recipe for finding a Higgs boson at the LHC. Knowing that the Higgs boson can decay to two photons, we can simply take all of the proton collision-events that produced pairs of photons, add the two photon four-momenta together and square the result to get the invariant mass. Events in which the two photons were produced by a Higgs boson will have an invariant mass close to the Higgs boson mass—it is not precisely equal to this value due to quantum effects, as well as the fact that the detector is not able to measure the photon four-momenta with perfect precision, which smears out features in the invariant mass distribution. The Standard Model also allows for pairs of photons to form by other processes, and these give a smooth continuum of invariant masses, with no peak at any specific mass. The effect of looking at the invariant mass distribution for all photon-pair events in the CMS detector is shown in figure 5, which is taken from the original Higgs discovery paper.

A peak above the smooth Standard Model prediction is clearly visible in the data at a mass of 125 GeV. Note that this gives us two vital pieces of information: the *position* of the bump along the $m_{\gamma\gamma}$ axis gives us the mass of the Higgs boson, and the *height* of the bump is proportional to the product of the production and decay rates of the Higgs boson.

In the case of a Higgs boson decaying to W and Z bosons, the situation is further complicated by the fact that these particles themselves decay almost immediately after being produced via the decay of the Higgs boson. In this case, we can hunt for the W and Z decay products, and we can also use the known mass of the W and Z from precise measurements at CERN's Large Electron Positron collider in the pre-LHC days.

The rate of occurrence of each possible Higgs production process is given by a number referred to as the 'production cross-section' for that process. The decays,

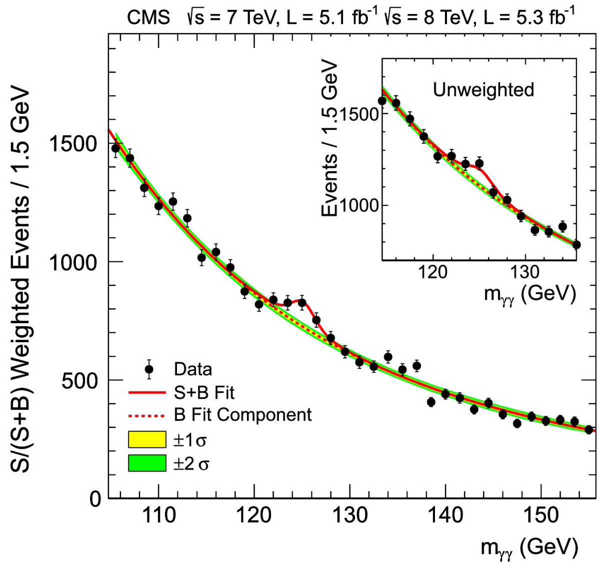

Figure 5. The invariant mass of photon pairs for two-photon events in the CMS experiment data, taken from the original Higgs observation paper. The Higgs is clearly visible as a peak at a mass of 125 GeV, on top of a continuum of photon events produced via other processes. This image is taken from the CMS collaboration paper 'Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC', and is available at http://cds.cern.ch/record/1471016/files/sbweightedmassunweightedinset1_5GeV.png under a Creative Commons Attribution 3.0 (full terms available at https://creativecommons.org/licenses/by/3.0/). (Image credit: CMS Collaboration.)

meanwhile, can be described by branching fractions, which express the probability of decaying into a particular set of particles. When you roll an unbiased six-sided die, the probability of obtaining a 1 is 1/6, as is the probability of obtaining a 2, and so on. For a Higgs decay, the probability of producing a pair of W bosons is a certain number (the branching fraction for the WW decay mode), and one can calculate similar numbers for each possible decay mode, with the sum of the branching ratios equal to 1. The most recent summary of our knowledge of the Higgs boson is given in figure 6, which shows the production cross-section times the branching fraction for all the different production and decay modes that can be measured at the LHC. These are normalised to the Standard Model predictions (such that a value of 1 means that the measurement matches the value predicted by the Standard Model). It can be seen that all measurements are currently consistent with the Standard Model, with the uncertainty of the measurements increasing for rare production and decay modes that cannot currently be observed or measured precisely. These are the points at the bottom of the chart, and it is too early to definitively say if they deviate from the expected behaviour, because the uncertainties are so large. We also know that the Higgs boson is indeed a scalar (spin 0) particle, as predicted by the Standard Model, and we know that its mass is 125.09 ± 0.21 ± 0.11 GeV, where the first uncertainty is statistical, and the second is systematic.

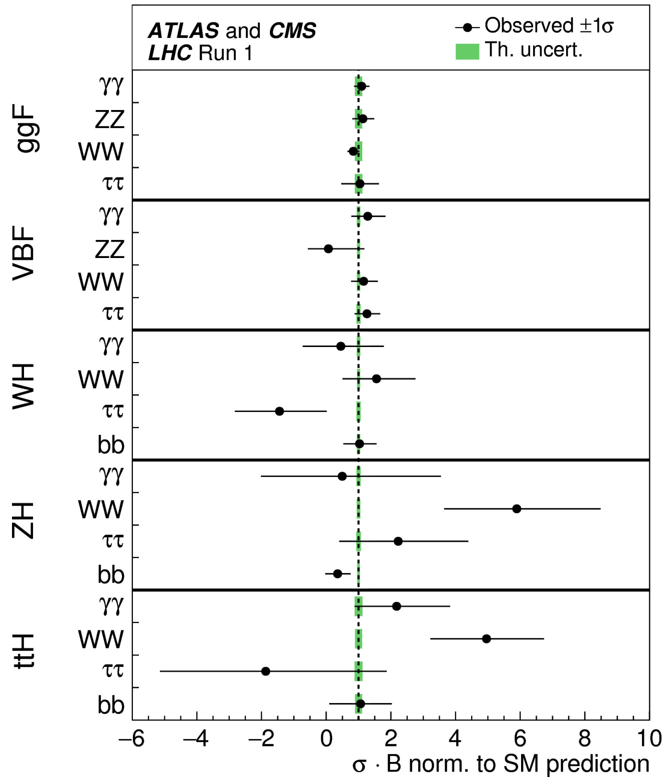

Figure 6. The latest Higgs measurements from the ATLAS and CMS experiments of the LHC. Working in order down the vertical axis, we have the ggF (gluon-gluon fusion), VBF (vector boson fusion), WH (W boson plus Higgs), ZH (Z boson plus Higgs) and ttH (top quarks plus Higgs) production modes, whose Feynman diagrams are shown in figure 4. This figure is taken from the ATLAS and CMS paper 'Measurements of the Higgs boson production and decay rates and constraints on its couplings from a combined ATLAS and CMS analysis of the LHC pp collision data at $\sqrt{s}= 7$ and 8 TeV', and is available at https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2015-07/fig_07.png under a Creative Commons Attribution 4.0 (full terms available at https://creativecommons.org/licenses/by/4.0/). (Image credit: ATLAS & CMS Collaborations.)

3 Current directions

Problems with the Standard Model

Whilst the Standard Model has done an amazing job of explaining all particle physics up to (and including) LHC energies, it is far from perfect. Most physicists assume that the Standard Model is a low-energy limit of a more fundamental theory, and is therefore only valid up to some energy scale Λ.

The theoretical problems start with the fact that the Standard Model famously does not include gravity, a force for which we lack a quantum description. The solution to that problem will guarantee Einstein-like levels of fame for the person who finally obtains it. The Standard Model also does not explain why there are three generations of matter, nor why there is such a strange pattern of particle masses.

More serious is the fact that the Higgs boson mass is much lighter than it should be. Quantum weirdness means that all particles that are propagating through space are constantly able to interact with 'virtual particles', which has a calculable impact on the particle mass. For a scalar particle, this pushes the mass up to approximately Λ^2. Thus, if we believe that the Standard Model is indeed valid up to the scales at which quantum gravity enters, the Higgs mass should be many, many orders of magnitude above the paltry 125 GeV that we have measured at the LHC. This is one of the most important challenges in particle physics, and it is known as the 'hierarchy problem.'

In addition to these theoretical challenges, there is a growing number of experimental results that the Standard Model cannot explain. For example, we know that the Universe is made almost entirely of matter (rather than antimatter), and although we have a mechanism by which this can occur in the Standard Model, the numbers do not work out well enough to explain the matter abundance that we actually observe. In addition, observations of the cosmic microwave background, galaxy rotation curves and gravitational lensing studies have provided us with abundant evidence that most of the matter in the Universe is in the form of 'dark matter', which cannot be comprised of any of the particles in figure 1. The most popular explanation is that there is at least one new massive particle in nature, that interacts with ordinary matter with a strength that is typical of the weak force.

Each of these problems has many hypothesised solutions in the particle physics literature, some of which overlap. An incomplete list of ideas relevant to the next decade of collider physics is the following:

- *Grand unified theories*: The strengths of the forces in the Standard Model are observed to change with energy, and for very high energy interactions the strengths turn out to be very similar. This suggests that perhaps there is only one unified force at high energies, which manifests as different forces at lower energies due to symmetry breaking. The gauge transformations of the Standard Model forces can, in fact, be described using the mathematical formalism of 'group theory', and the suggestion of a unified force amounts to finding a group structure that contains the Standard Model gauge group. Such a grand unified theory would introduce extra forces (and potentially extra matter), leading to observable consequences at the LHC. Unfortunately, the simplest scenarios predict a short lifetime for the proton to decay, and they are therefore heavily constrained by the fact that we have never observed the decay of even a single proton. Our current lower limits on the half-life of proton decay in its various decay modes exceed 1×10^{34} years.
- *Composite scenarios*: It transpires that the Higgs boson could actually be as light as observed, if it is not in fact a fundamental particle, but is comprised of smaller constituents. The same logic can in principle be extended to other Standard Model particles. Just as we observe bound states of quarks in nature (of which the proton is only one example), such a theory would give us many new bound states comprised of these new fundamental particles.
- *Supersymmetry*: You might recall that all matter in the Universe is comprised of fermions, and that force particles are all bosons. Supersymmetry is a hypothesised symmetry of nature that adds fermion partners for each boson,

and vice versa, leading to a doubling of the particle content of the Standard Model. Miraculously, this simple symmetry can cancel the quantum corrections to the Higgs mass, improve the unification of the forces and resolve the hierarchy problem, whilst also giving ideal candidates for the dark matter in the Universe. Supersymmetry gives us lots of particles to hunt for at the LHC, including four extra Higgs bosons and the partners for the quarks, leptons and force particles. None of these have been observed to date, but the search remains a critical part of the LHC programme.
- *Extra space dimensions*: A variety of scenarios exist in which there are more than four spatial dimensions, including string theories. If gravity sees all of these dimensions, but the fields of the Standard Model are confined to a 4D structure; then the weakness of gravity relative to the other forces can be explained naturally. These theories can be used to predict signatures at the LHC that are not dissimilar to those of supersymmetry, albeit from a completely different fundamental framework.

What is next for Higgs physics?

Faced with the problems of the Standard Model, there is a broad consensus within the particle-physics community that the big unknown is not *whether* there are new particles beyond those of the Standard Model, but *what energy scale* they are associated with. If this is too high, we have no prospect of directly producing new particles in our colliders within the near future. Any connection between the lightness of the Higgs mass and new particles, however, suggests that the new particles should have masses near the TeV range that will be probed extensively at the LHC over the next decade.

This means that the next decade of particle-physics research is poised to be the most exciting and crucial since the 1960s. Either we will get a dramatic discovery of one or more of the mechanisms that underpin the structure of the Standard Model, or we must painstakingly test the Standard Model to destruction, using increasingly clever analyses of the LHC data. Moreover, the LHC is operating in a world in which many other experiments will have sensitivity to new particle physics, and there is much to be learned from combining positive and negative results from the LHC with other experimental data. Below, I will review these developments in turn, focussing on topics not covered in the forthcoming Physics World Discovery book on *Hidden Physics at the LHC* by Gavin Hesketh.

We have seen that the Standard Model introduces masses for the force and matter particles through the introduction of a single Higgs field, with its associated Higgs boson. However, this is merely the simplest way of achieving the desired outcome, and no known principle forbids more complicated theoretical structures. To give one example, supersymmetry actually requires extra Higgs bosons in order to work, and one should expect at least 5 type of Higgs boson in that case (one of which could closely resemble the Higgs boson of the Standard Model). After the dramatic discovery of the Standard Model-like boson in 2012, the LHC is now an incredibly powerful and useful machine for studying Higgs physics with impressive precision.

There are a number of open questions in Higgs physics, and all of them will be greatly illuminated by the next decade of LHC measurements. These include:

- *Is the Higgs boson the same as that predicted by the Standard Model?* Figure 6 tells us that, so far, the measured Higgs boson production and decay rates match the Standard Model predictions. Notice, however, that the uncertainty on these measurements increases dramatically for some modes, and deviations from Standard Model behaviour may be observed as the uncertainties shrink with the addition of more LHC data. Recall that, in the Standard Model, loop effects must be included when calculating the rate of a given process to a given accuracy. We know exactly which particles can act in the loops of our Feynman diagrams, and thus we generally get unambiguous calculations of rates that can be compared to experimental data. If there are new particles in nature, they would be expected to appear in loops, and thus would change the rates of processes involving particle production and decay. Since any new physics is likely to affect the Higgs sector of the Standard Model, we can thus use precision measurements of Higgs quantities at the LHC to provide a powerful indirect window on the presence of new particles.
- *Is the Higgs field the same as the Standard Model?* The final term in the Standard Model equation given above is the 'Higgs potential', describing the potential energy function satisfied by the Higgs field. We still have no idea if the Higgs field obeys this equation or not, since the observed Higgs properties could be consistent with a more complex form of the equation. To answer this question, it turns out that we will need to observe the Higgs boson interacting with itself, and then measure the strength of that self-interaction. This is, unfortunately, an exceptionally rare process at the LHC, making the measurement very challenging. Nevertheless, there is a growing literature that suggests that this is not impossible by the end of the LHC's run in 2035. Moreover, such a measurement is a very strong motivation for a future, higher-energy collider.
- *Are there extra Higgs bosons?* The LHC can uncover evidence for extra Higgs bosons in the same way that it discovered the Standard Model-like Higgs boson, by searching for peaks in the invariant mass distributions of the anticipated decay products (photon or fermion pairs, or decay products of W and Z bosons). The simplest example of a more complicated Higgs sector involves two extra neutral Higgs bosons (conventionally referred to as H and A), and two electrically charged Higgs bosons H^+ and H^-. Although current searches have not uncovered evidence for these particles, much of the predicted mass range remains unexplored at the LHC, and will be covered in more detail over the next decade or so.
- *Is the Higgs boson related to dark matter?* The simplest way of explaining dark matter is to add one extra stable particle to the Standard Model, that interacts only with the Higgs boson. This particle then has all the properties of an ideal dark matter candidate and, for light masses, the Higgs boson could decay to pairs of dark matter particles. Since dark matter is invisible at the LHC detector, this scenario can be tested by using clever techniques to try and uncover evidence of invisibly decaying Higgs bosons in the LHC events.

Beyond these immediate Higgs measurements, the LHC still has much more to tell us about a massive range of Standard Model processes that remain poorly explored by previous experiments, including measurements of matter and force particle production at unprecedented energies. Any deviation from Standard Model behaviour in any of these measurements would indicate the existence of new particles. This includes measurements at the LHCb experiment, which probe rare Standard Model decay processes. At the same time, the direct search for new particles continues to exercise a large number of LHC physicists, and the results of searches for supersymmetric partners, new composite states or other exotic signatures promises to transform our knowledge of the Standard Model regardless of whether the results are positive or negative.

Experiments beyond the LHC

Even if the LHC makes a dramatic discovery of one or more new particles in the next decade, it is important to realise that this will not point unambiguously to a specific theory of new physics. A new 'bump' or an excess of observed particles in an invariant mass-distribution could indicate a new Higgs boson, but it could just as easily arise from something else. Evidence for supersymmetry could also be interpreted as evidence for extra spatial dimensions, since the actual signatures in the detector are very similar. Even the production of a dark-matter candidate would be ambiguous, since technically we could only tell that we have made an invisible particle that leaves the detector, and thus has a lifetime greater than a few seconds. Establishing that it is consistent with the matter that has been hanging out in space since shortly after the birth of the Universe requires a joint analysis of LHC and astrophysics data.

It is therefore the case that the LHC will only ever give us clues as to the origin of physics beyond the Standard Model, but happily we have other sources of information. Any theory that could explain these clues will involve adding new particles (and thus new fields), and could, in principle, show up in a long list of other experiments. To start with, this includes all previous collider physics experiments such as CERN's Large Electron Positron (LEP) collider, and the Tevatron collider at Fermilab. In particular, the LEP collider was able to measure properties of the W and Z bosons very precisely (since an electron-positron collider is much cleaner than a hadron collider such as the Tevatron or the LHC), and many attempts to fix the problems of the Standard Model would mess with the masses of these particles through the same notion of loop effects that we discussed earlier. We can therefore use the LEP measurements to give stringent constraints on new theories. One can also gain useful insights from 'beam-dump' experiments done at CERN and other labs, whereby beams are fired at stationary targets rather than being collided with other beams. Finally, there are colliders that operate at much lower energies, but much higher beam *intensities*, which can discover new physics by making super-precise measurements of the rare Standard Model processes that are most sensitive to loop effects induced by new particles. The Belle II experiment at the KEK lab in Japan will start taking data in 2018, and will provide a complementary window to new physics to the LHC.

Beyond colliders, there are very many past and present experiments that either constrain new physics theories through null observation, or offer intriguing hints of possible discoveries. In the latter camp is the measurement of the magnetic moment of the muon. You may recall that we can associate a magnetic moment with the spin of a particle in quantum mechanics, which is a property of the *intrinsic* angular momentum of the particle (i.e. independent of any orbital motion). In quantum mechanics, we can write this in terms of the spin **S** for the charged leptons of the Standard Model as:

$$\mu_S = g\frac{-e}{2m}\mathbf{S}$$

where e is the charge on the electron, muon and tau and g is called the 'gyromagnetic ratio'. A calculation from quantum mechanics based on the Dirac equation gives $g =$ 2 precisely for all charged leptons. Measurements of this quantity for the electron, however, give a difference from two, given by:

$$\frac{1}{2}(g_e - 2) \ = \ 0.00115965218073(28)$$

The difference from the naive calculation arises from loop effects, which require the full machinery of quantum field theory (QFT). The QFT calculation of the magnetic moment of the electron in the Standard Model matches the observation with absurdly high precision, and indeed is one of the key results that established QFT as a valid description of nature.

What happens when we repeat the calculation for the muon? The theoretical result is about 3 standard deviations away from the experimental measurement. The presence of loop effects in the calculation immediately raises the prospect that we are seeing our first tentative discovery of new particles, but unfortunately the calculation is complicated by certain technical aspects that inflate the uncertainties involved. Nevertheless, the precise measurement of the anomalous magnetic moment of the muon can probe new physics in precisely the same mass range as the LHC.

The importance of the dark-matter mystery to modern particle physics is reflected in a wide variety of searches for dark-matter particles. Firstly, one can test new theories of particle physics by trying to predict the pattern of fluctuations in the cosmic microwave background. This gives us our most precise estimate of the *amount* of dark matter in the Universe. Secondly, there are a variety of experiments that search for fluxes of high-energy particles from space, including gamma rays, neutrinos, electrons and positrons. Given a particle theory of dark matter, plus other measurements of the expected abundance of dark matter in distant objects such as dwarf galaxies, we can estimate the flux of particles expected to reach the Earth from distant interactions of dark-matter particles, and compare this with the result of Earth- or space-based telescope observations. This field of physics is undergoing constant revolution, with major facilities operating on the same timescale as the LHC. Finally, one can perform direct searches for dark matter by putting sensitive detectors on the Earth and trying to observe the recoils of nuclei within the detector due to dark-matter particles from our local environment striking the detector volume. A large number of these experiments—such as Xenon, CDMS, LUX and Panda—have been operating for the past couple of decades, with the sensitivity due to increase over the next ten years due to large increases in detector volume, and innovative new detector designs. A striking discovery in one of these experiments would have major implications for possible discoveries at the LHC, since it would prove that a dark matter particle exists that can couple to quarks, and thus potentially be produced in proton–proton collisions.

Elsewhere, it is quite possible that neutrino experiments will ultimately give us the first hints of the theory beyond the Standard Model, or indeed some anomaly observed in nuclear cosmic ray ratios or radio astronomy data. With regards to particle physics, the list of useful information is practically endless.

New methods of processing data

With so much data coming from every direction, it is clear that verifying the next theory of particle physics from positive observations will involve a very careful combination of data from the huge range of particle physics and astrophysics datasets that might be relevant. Let's say, for example, that the LHC discovers one new particle that decays to two photons, and also uncovers evidence for an invisible dark-matter particle. Any theory that explains these two phenomena must be consistent with positive or null observations in any other experiment in which the theory would be visible. There is also the question of internal consistency at the LHC to worry about. A theory of a new particle decaying to photons may easily predict decays to other particles, and if these are not seen at the LHC, one must ensure that the theory remains capable of explaining why not. Reaching the correct theory of new physics from such a giant list of possible results amounts to a *data mining* problem similar to those currently being explored in the global data science industry. In the case of no positive discoveries within the next decade, there is a related problem that is just as interesting: how do we determine as precisely as possible which theories of new physics can be thrown in the bin?

There is in fact a well-known solution for combining data from multiple sources, and that is to perform a 'global statistical fit'. Given a physics model with some set of parameters, one can define a likelihood for each experimental dataset that is a function of the model parameters. The likelihoods for the individual experiments (and/or the list of data values within one experiment) can then be combined to form a composite likelihood that describes how well a particular set of model parameters fits the total set of data. This combination might be as simple as just multiplying the likelihoods together, but might have a more complex form owing to correlated systematic uncertainties. For a given definition of the composite likelihood function, however, one can follow a textbook statistical procedure to find the regions of maximum likelihood (if one follows a Frequentist procedure) or the probability-density for the parameters (if one follows a Bayesian procedure). From there, one can find the most likely/probable regions of the parameter space, define exclusion limits on the parameters, or compare two different models based on the fit results to see which gives the best description of the data.

Although well-defined, the problem with this procedure is that it is computationally expensive. Particle-physics models typically come with a large number of parameters, and we need a clever way of scanning over this large volume of possible options, to obtain results in a reasonable time. It also requires great expertise to model and define a likelihood for a particular dataset based on a given input model, and these likelihood functions themselves may be slow to calculate.

Recently, a collaboration of approximately 30 international particle astrophysicists has developed the Global and Modular Beyond-the-Standard-Model Inference Tool (GAMBIT), a powerful software utility that combines statistics routines with clever sampling algorithms and custom likelihood calculations of a wide range of particle astrophysics data. The modular nature of the package makes it easy to add new models, new datasets and new likelihoods, with much of the code reusable once the user is able to provide certain key requirements. Crucially, the software includes a fast way to implement the results of LHC searches, making it a very powerful suite for comparing LHC results with external data. It is likely that data mining techniques such as these will prove crucial in the next decade in our quest to understand what lies beyond the Standard Model.

4 Outlook

As we reach the end of our brief survey of the research frontier of particle physics, we have seen that the field remains exciting and challenging, with much to study within the next ten years. Crucially, these are the years in which a current physics undergraduate or starting PhD student has the opportunity to be heavily involved in establishing the next wave of discoveries.

The LHC currently has a schedule planned for every year up to 2035, and the key parameters of the machine for understanding the discovery reach for new particles are the centre of mass energy and the luminosity. The former is the centre of mass energy of the proton–proton collisions, with higher energies able to access more massive new particles. The luminosity is a measure of the beam intensity, and higher values correspond to more frequent proton–proton collisions, which will allow us to see rare processes sooner than if the LHC were run with a lower luminosity. In both cases the unit of measurement is rather obscure: the centre of mass energy is conventionally quoted in TeV, whilst the luminosity is given in $cm^{-2}\ s^{-1}$.

The LHC is currently in its second run period, operating at a centre of mass energy of 13 TeV and a luminosity of $1.7 \times 10^{34}\ cm^{-2}\ s^{-1}$. This will continue until May 2018, after which a long shutdown period will enable us to upgrade the collider and detectors. A third run from 2020 to 2022 will operate at a marginally higher luminosity of $2.0 \times 10^{34}\ cm^{-2}\ s^{-1}$, with a centre of mass energy that finally reaches the original design value of 14 TeV. Following this, a much more major upgrade will occur that will keep the LHC energy fixed but dramatically increase the luminosity, which will reach $5.0 \times 10^{34}\ cm^{-2}\ s^{-1}$ in a run period starting in 2025. These machine conditions will persist for the remaining LHC run periods scheduled up to 2035, with the final aim of collecting approximately 50 times more data than we currently have. The current pessimism of some physicists regarding the lack of new particles at the

LHC stems from the fact that it may take a decade to see signals peep over the background with this rate of data collection, if at all. Against this, I have two strongly-held opinions. The first is that this future data very much still has the potential to transform our understanding of the fundamental universe, and the second is that I believe that the *current* data may yet be hiding discoveries that our analysis techniques have thus far failed to uncover. New techniques and/or new data could produce a discovery at any time.

Outside of the LHC, major direct searches for dark matter are reaching the tonne scale, with an excellent reach for weakly-interacting particle dark matter. Meanwhile, a new giant ground-based gamma ray telescope called the Cherenkov Telescope Array will have the power to revolutionise searches for distant dark matter annihilations, by detecting high energy gamma rays over a wide energy range, and with better spatial and energy resolution than ever before. Coupled with the precision Standard Model physics tests of the Belle II facility and the LHCb experiment of the Large Hadron Collider, there is room for considerable excitement as we push our exploration of the fundamental world to new energy and intensity frontiers.

Finally, work has already started on planning the next generation of particle colliders, with proposed facilities including a 250 GeV linear collider in Japan, a 250 GeV circular electron–positron collider in China (which will be superseded by a 70–100 TeV hadron collider) and a new circular collider at CERN requiring a substantially larger tunnel than that for the existing LHC. Timescales are currently up in the air, but it can be expected that one of these facilities will be taking data by 2030, and each of these will give much greater precision on Higgs boson measurements than the LHC.

Additional resources

- An excellent, up-to-date summary of both the experimental and theoretical aspects of the Standard Model is given in *Modern Particle Physics* by Mark Thomson (Cambridge University Press, 2013). For broader coverage of theoretical particle physics, *Quantum Field Theory and the Standard Model* by Matthew Schwartz (Cambridge University Press, 2013) provides outstanding explanations of very complex subjects. My own favourite undergraduate textbook is *Introduction to Elementary Particles* by David Griffiths (2nd edition, Wiley VCH, 2008) which, although it predates the Higgs discovery, is extremely easy to read.
- The definitive book on the LHC is *The Large Hadron Collider* by Lyndon Evans (EPFL Press, 2009), former LHC project leader. This contains much detail on the design of the accelerator itself, the civil engineering challenges and the CMS, ATLAS, LHCb and ALICE experiments.
- A nice experimentalist's view of the Higgs discovery written for the general physicist is the *Science* journal article written by the ATLAS collaboration, available at http://cds.cern.ch/record/1511050.
- The prediction and measurement of the anomalous magnetic moment of the muon are both fascinating topics that together encompass almost the full

breadth of knowledge in particle physics. For a review, see https://arxiv.org/pdf/hep-ph/0703049.

- Particle dark matter is a topic with a considerable literature, and it is no exaggeration to say that tens of thousands of particle astrophysicists are involved in some aspect of dark matter research. A good first summary is *Particle Dark Matter: Observations, Models and Searches* edited by Gianfranco Bertone (Cambridge University Press, 2010). A more recent review covering developments in indirect dark matter searches is available in https://arxiv.org/pdf/1604.00014. There are many direct search experiments, and a nice summary (with a look ahead to the next decade) can be found in https://arxiv.org/pdf/1509.08767.
- The GAMBIT collaboration released their first 9 papers in 2017. The collaboration has a website at gambit.hepforge.org, on which you can find both the code, papers and further information and documentation.