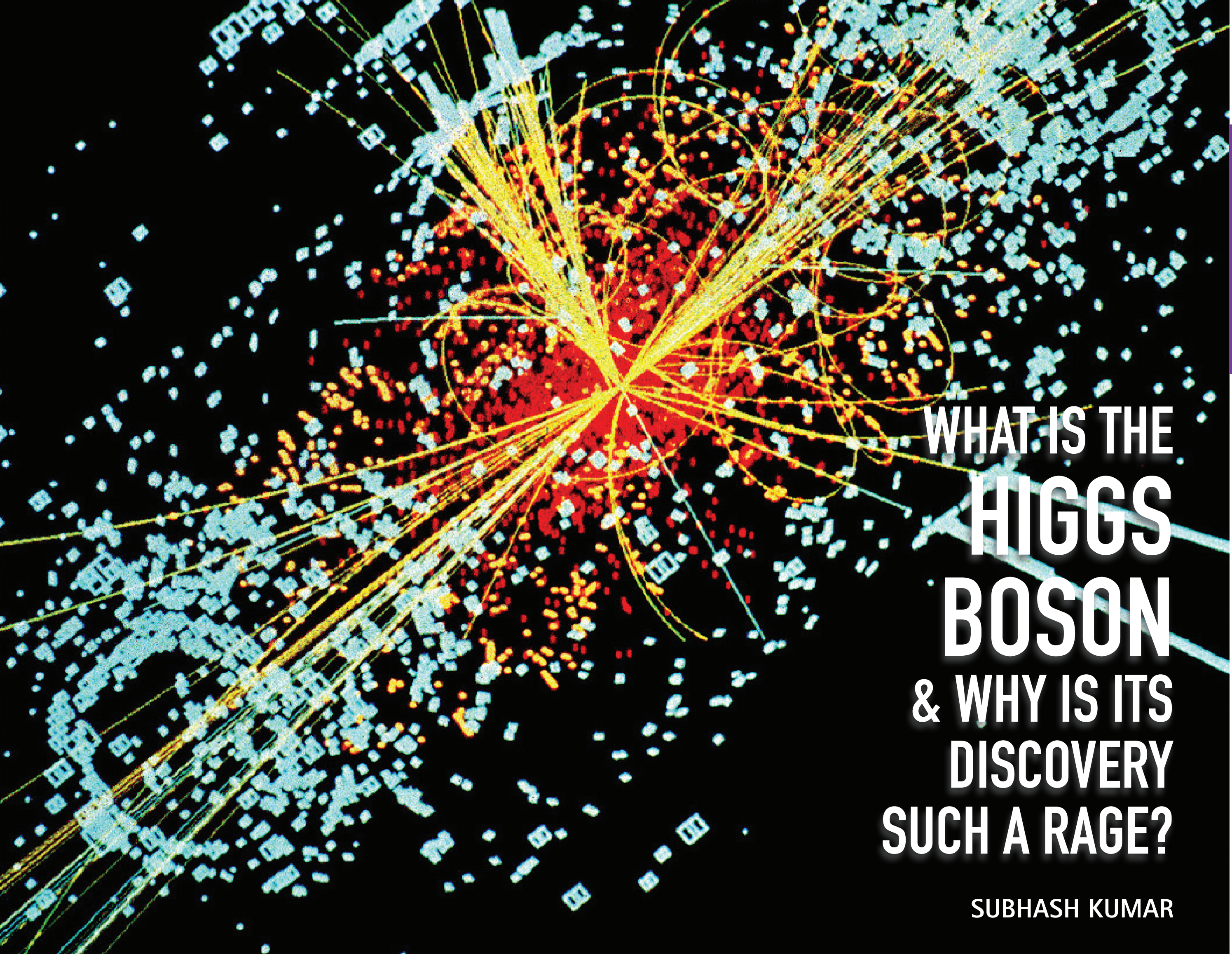


WHAT IS THE HIGGS BOSON & WHY IS ITS DISCOVERY SUCH A RAGE?

SUBHASH KUMAR

What is the Higgs boson? Why is the world of science so excited by its discovery? What are its properties? What impact has this discovery had on theoretical physics?

On 4th July, 2012, scientists at the European Organization for Nuclear Research (CERN) had an important announcement to make — they'd discovered a particle with properties similar to those predicted for the elusive Higgs boson. On 8th October, 2013, Peter Higgs and Francois Englert were awarded the Nobel Prize in Physics for their work on this particle (see **Fig. 1**). These two events commemorated the culmination of a long quest involving generations of experiments and the construction of the world's largest and most powerful particle accelerator — the Large Hadron Collider (LHC).

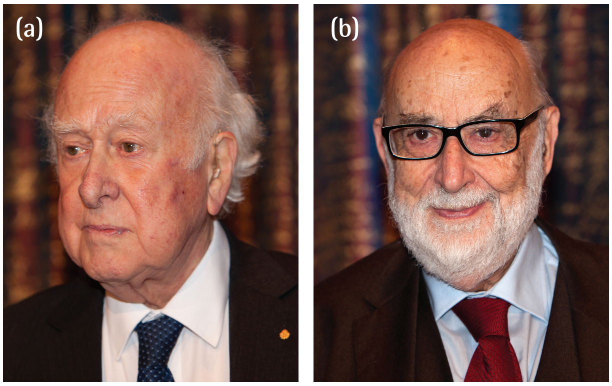


Fig. 1. The Nobel Prize in Physics (2013) was awarded to two scientists for their work on the Higgs boson: **(a)** Peter Higgs. **(b)** Francois Englert.

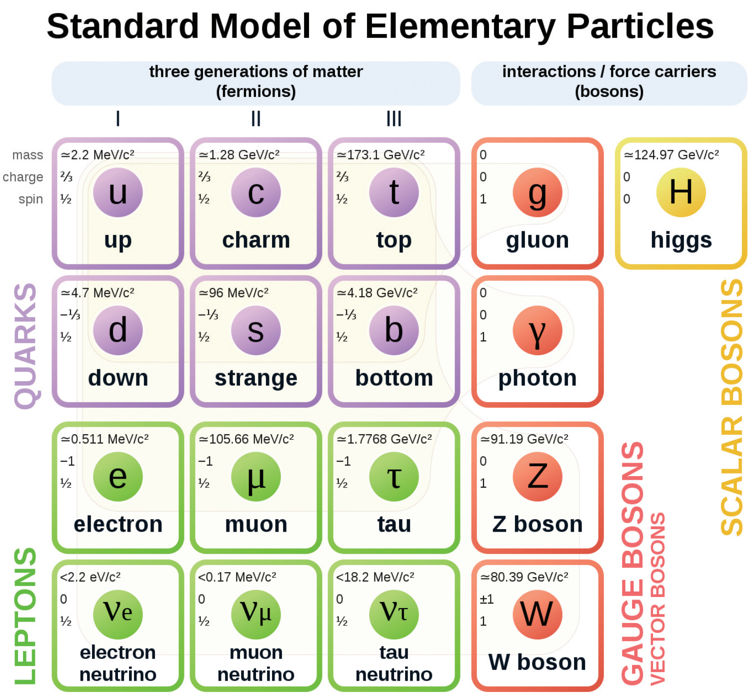
Credits: Bengt Nyman, Wikimedia Commons. URL for (a): https://commons.wikimedia.org/wiki/File:Nobel_Prize_24_2013.jpg, and (b): https://commons.wikimedia.org/wiki/File:Nobel_Prize_31_2013.jpg. License: CC-BY.

Imagining the Higgs boson

The search for the Higgs boson was part of a quest to find answers to a foundational question in physics – what is matter? Science textbooks define it, quite simply, as being any substance with mass and volume. For e.g., you know an object has mass by the resistance you feel when you try to apply force on it. But what is matter made up of, and where does it come from? These are some questions that scientists have been grappling with for centuries.

By the 1970's, physicists had begun to assemble mathematical equations in an elegant theoretical model, the so-called **Standard Model** (see **Fig. 2**), to describe the fundamental units of matter (see **Box 1**) and three of the four fundamental forces (see **Box 2**) that influence their interactions.[1] Gravity is not yet a part of the Standard Model. In fact, the unification of gravitation with the other three fundamental forces remains an outstanding and open problem in Physics (see **Box 3**).

Today, the Standard Model has been found to be largely self-consistent, and many of its experimental predictions have been verified. However, during the early stages of its development, physicists discovered a problem – when applied to nuclear interactions, the equations of the model were found to be inconsistent if its fundamental particles had intrinsic mass (see **Box 4**). This 'contradiction' could be resolved in one of two ways. If it were true that all elementary particles (including photons) possessed intrinsic mass, the Standard model would no longer be valid (in mathematical terms, some of its central predictions would show infinite divergence). On the other hand, if the Standard Model were valid, it would mean that all elementary particles, including the bosons that mediate weak interactions, were inherently massless. The Model would then have to provide for some mechanism to account for their 'observed' masses (see **Box 5**).



	I	II	III		
mass charge spin	≈2.2 MeV/c^2 ⅔ ½ u up	≈1.28 GeV/c^2 ⅔ ½ c charm	≈173.1 GeV/c^2 ⅔ ½ t top	0 0 1 g gluon	≈124.97 GeV/c^2 0 0 H higgs
	≈4.7 MeV/c^2 −⅓ ½ d down	≈96 MeV/c^2 −⅓ ½ s strange	≈4.18 GeV/c^2 −⅓ ½ b bottom	0 0 1 γ photon	
	≈0.511 MeV/c^2 −1 ½ e electron	≈105.66 MeV/c^2 −1 ½ μ muon	≈1.7768 GeV/c^2 −1 ½ τ tau	≈91.19 GeV/c^2 0 1 Z Z boson	
	<2.2 eV/c^2 0 ½ νe electron neutrino	<0.17 MeV/c^2 0 ½ νμ muon neutrino	<18.2 MeV/c^2 0 ½ ντ tau neutrino	≈80.39 GeV/c^2 ±1 1 W W boson	

Fig. 2. The Standard Model offers a framework to order and classify elementary particles.

Credits: MissMJ, PBS NOVA, Fermilab, Office of Science, United States Department of Energy, Particle Data Group, Wikimedia Commons. URL: https://en.wikipedia.org/wiki/File:Standard_Model_of_Elementary_Particles.svg. License: CC-BY.

Box 1. Elementary particles are 'indivisible' building blocks of matter:

Originally believed to be indivisible, atoms are known to consist of electrons, neutrons and protons. By the late 1940's, many other such particles had been discovered. In 1964, the physicists Murray Gell-Mann and George Zweig independently suggested that this zoo of subatomic particles, called hadrons, were not 'elementary' particles. Instead, they were often composed of combinations of smaller subatomic particles, called quarks.

Since all matter consists of atoms, three subatomic particles may be sufficient to build the physical universe – electrons, along with up and down quarks (two of the six flavors of quarks, which together make protons and neutrons). But, by this time, physicists knew of 12 subatomic particles and were uncertain of how many other such particles awaited discovery. The obvious question to ask was – what did these other particles do?

You can think of the Standard Model as the periodic table for elementary particles. It offers a framework to order and classify them based on their spin – an intrinsic form of angular momentum that all elementary particles are believed to possess. The spin of an elementary particle is a dimensionless number calculated as the ratio of its angular momentum to the reduced Plank's constant ħ (or, h divided by 2π).

According to the current version of the Standard Model, all elementary particles are of two kinds – fermions (with half-integral spin) and bosons (with zero, or integral spins). While fermions are described as 'matter particles', bosons are described as 'force particles'. In other words, while all matter is made up of fermions, bosons mediate the forces between matter particles. Fermions are believed to be of 12 kinds – six leptons (that do not participate in strong nuclear interactions) and six quarks (that participate in nuclear interactions). In addition, each fermion has an anti-particle with the same mass, but an equal and opposite charge. On the other hand, bosons are believed to be of five kinds – one boson (the photon) mediates electromagnetic fermion interactions, three bosons (known as W-plus, W-minus and Z-naught) mediate weak interactions, and eight bosons (called gluons) mediate strong nuclear interactions.

Much like the periodic table, the Standard model also allows the prediction of some yet undiscovered elementary particles. For e.g., it predicts the existence of a graviton, a boson that is believed to mediate gravitational interactions.

Box 2. Fundamental forces shape interactions between elementary particles:

All matter, whether at the sub-nuclear or at the astronomical scale, arises from interactions of building blocks like quarks and leptons. These interactions are mediated by four fundamental forces:

- **Strong nuclear force:** acts only on quarks, binding them together to form protons and neutrons. It also binds protons and neutrons within atomic nuclei.
- **Electromagnetic force:** is the best understood of all forces. It binds the negatively charged electrons to the positively charged nuclei within atoms. It also mediates bonding among atoms to form matter in bulk.
- **Weak force:** acts on quarks and leptons. It is responsible for the beta decay of neutrons into protons as well as the many nuclear reactions that fuel the sun and other stars.
- **Gravity:** is the most dominant force at the largest scales of matter. It governs the aggregation of matter into stars and galaxies, and has influenced the way the universe has evolved since its origins.

While electromagnetic force and gravity are well known for their effects at the macroscopic level, strong and weak forces operate only at subnuclear scales.

Box 3. Gravity is explained by the General Theory of Relativity:

First published by Albert Einstein in 1915, this theory describes gravity as a manifestation of spacetime curvature that is directly determined by the distribution of matter and energy contained within it. Many different observations have shown this theory to be remarkably accurate. For e.g., in September 2015, gravitational waves were directly observed for the first time – exactly 100 years after the General Theory of Relativity predicted their existence. Similarly, the image capture of a black hole in 2019 by a planet-scale array of eight ground-based radio telescopes supports this theory's prediction of their existence as end-states of massive stars.

By the early 1960's, physicists like Yoichiro Nambu and Philip Anderson had suggested that it may be possible for 'some' elementary particles to 'acquire' mass under certain conditions. The fledgling Standard Model was, however, saved by the work of three independent groups of researchers – Robert Brout and Francois Englert; Peter Higgs; and, Gerald Guralnik, Carl Hagen, and Tom Kibble. In papers published (almost simultaneously) in 1964, these groups postulated that fundamental particles were created massless. These particles could, however, acquire their 'observed' masses if they happened to interact with a hypothetical, ubiquitous 'field', called the **Higgs field**, that was believed to permeate the universe (see **Box 6**). These researchers also suggested a mechanism, called **Higgs mechanism** after Peter Higgs, that could give fundamental particles their observed masses (see **Box 7**).

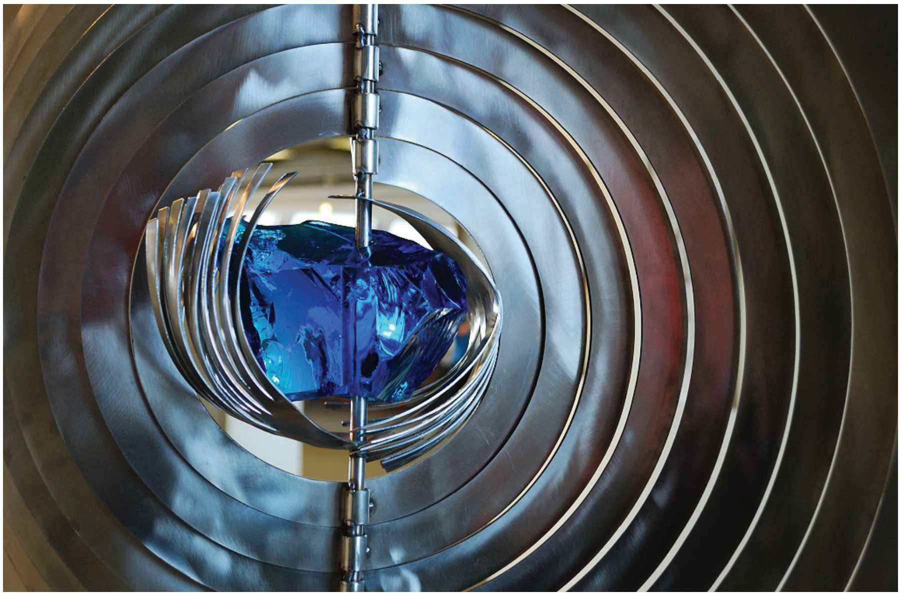
According to the concept of wave-particle duality (see **Box 8**), all fields must have a fundamental particle associated with them. Thus, the scheme offered by the Standard Model necessitates the existence of a special boson – the Higgs boson (see **Box 9**). In other words, the Higgs boson can be described as the manifestation of the quantum excitation of the Higgs field. The existence of this field can, therefore, be proved only by detecting the Higgs boson.

Finding the Higgs boson

In 2008, the Large Hadron Collider (LHC) was constructed at CERN France. One of its important goals was to find out if the Higgs boson existed, and to detect

Box 4. What does it mean when we say that something as small as an elementary particle has mass?

The intrinsic mass of a fundamental particle is known as its **rest mass**. Particles having zero rest mass are called massless. The mass of a compound particle, like that of a proton (which is composed of quarks), can be calculated using the rest mass of each of its constituents, their kinetic energy of motion, and their potential energy of interaction. However, how a truly elementary particle, like an electron, acquires its rest mass is the main problem of the origin of mass.[2] It is this mass that is ascribed to the interaction of elementary particles with the all-pervading Higgs field.



Box 5. Not all elementary particles are 'observed' to act as if they possess intrinsic mass:

All fermions (mass particles) as well as bosons that mediate weak interactions act as if they possess intrinsic mass. However, bosons like photons, gluons, and (the still hypothetical) gravitons behave as if they are massless.

Box 6. What is the Higgs field?

The Higgs field is an all-pervading field, present throughout the Universe. In physics, a 'field' is defined as a region in spacetime where each point is affected by an interaction of a certain kind. Thus, every particle in a Higgs field is affected by interactions with it.

Particles that interact with this field acquire mass; those that don't, remain massless. The stronger the interaction, the heavier the mass acquired by the particle. However, the strength of this interaction does not seem to depend on the size or shape of the elementary particle. For e.g., the top quark interacts very strongly with the Higgs field, thus acquiring a massive intrinsic mass.

it if it does. In the LHC, two beams of hadrons (like protons) are forced to collide with each other while traveling at speeds close to that of light, releasing enormous amounts of energy. This energy is quickly used up to form an array of fundamental particles, the exact nature of which may vary with each collision (see **Fig. 3**).

Since the Higgs boson is fairly heavy (~130 times heavier than a proton), only the latest generation of colliders, such as the LHC, would be energetic enough to produce it. Scientists hoped that the higher the speed of the colliding protons, the greater would be the amount of energy released on collision and, therefore, the higher the probability of it throwing out a Higgs boson. They were aware, however, that even if a Higgs boson were produced, detecting it would be very difficult. Firstly, the probability of a Higgs boson being produced by the collision of two hadrons is extremely small — roughly 1 out of every 10^{12} (trillion) events. This means that a very large number of collisions would be needed before the Higgs boson could be expected to be produced with any reliability. Secondly, given its high energy, a Higgs boson was predicted to be extremely unstable in nature. If produced, it would decay almost immediately into other types of elementary particles, including photons (electromagnetic force), W bosons

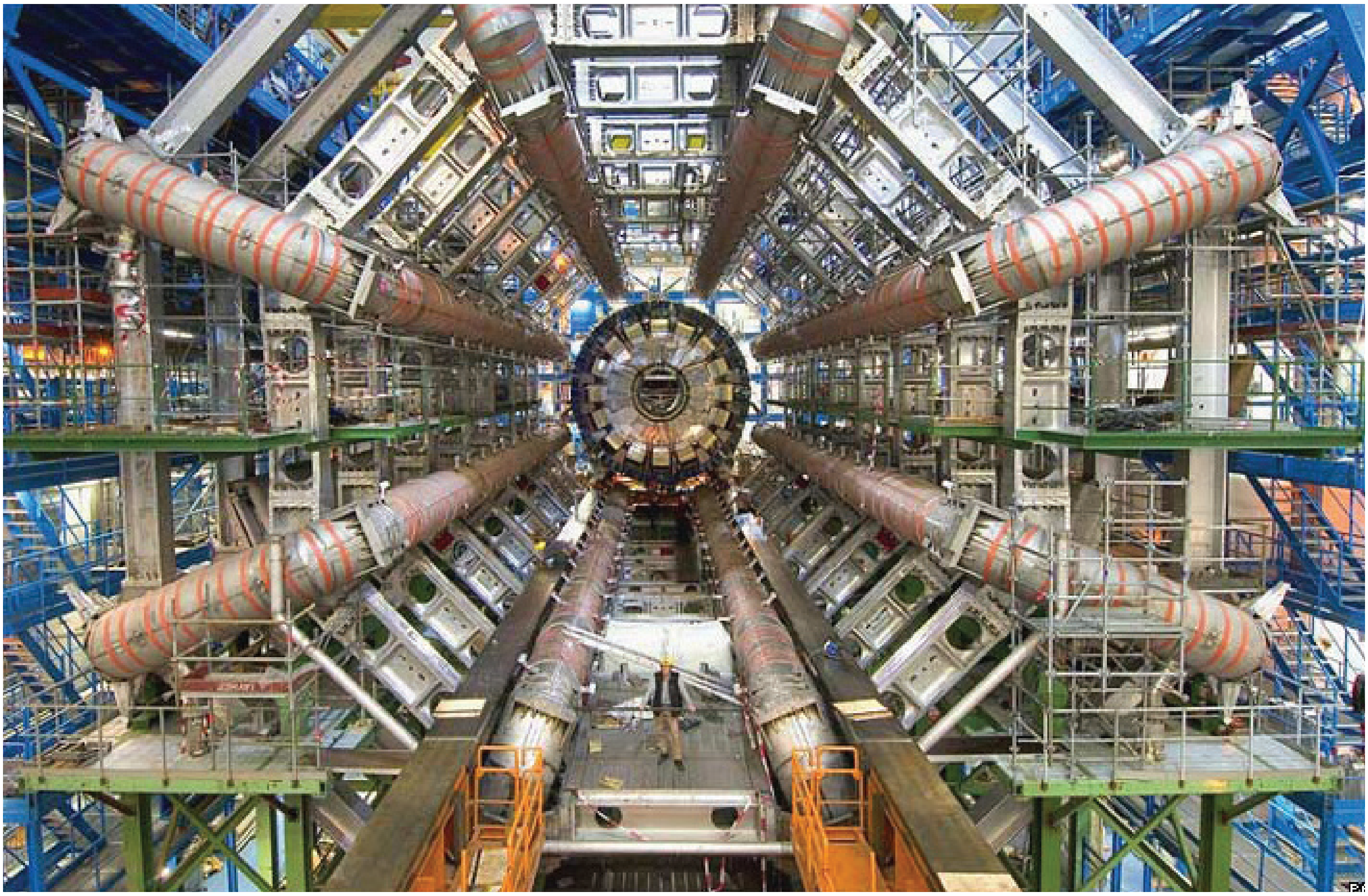


Fig. 3. The Large Hadron Collider at CERN.

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Box 7. The 'Higgs' mechanism is known by many names:

The three groups of researchers who suggested the existence of the Higgs field and Higgs mechanism built upon previous work by Anderson, but used three different approaches to arriving at it. While Brout and Englert published their paper first, Peter Higgs's model offered the simplest and most direct argument. Thus, the Higgs mechanism is also called the Brout-Englert-Higgs mechanism, or the Englert-Brout-Higgs-Guralnik-Hagen-Kibble mechanism. Peter Higgs, however, refers to it as the ABEGHHK'tH mechanism to reflect the work of the many physicists — Anderson, Brout, Englert, Guralnik, Hagen, Higgs, Kibble, and 't Hooft — who have contributed to it. Gerardus 't Hooft was a Dutch theoretical physicist who was awarded the Nobel prize in Physics in 1999 for his contribution to our understanding of electroweak interactions.

Fig. 4. More than 200 Fermilab researchers and staffers (of the 1,700 scientists, engineers, technicians and graduate students from the United States that helped design, build and operate the LHC accelerator and particle detectors, and analyze the data from the collisions) assembled in an auditorium at 2 a.m. EDT on 4th July, 2012 to await the announcement that a Higgs boson-like particle had been detected.

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(weak force), and leptons (strong force). This means that we'd only be able to deduce the presence of a Higgs boson indirectly through measurements of its decay products. Thirdly, even detecting the presence of the Higgs boson from its decay products would be a challenge unless it showed a distinctive decay pattern. If the decay products of the Higgs boson were similar to those arising from the decay of other known unstable particles, it would be very hard to ascertain the actual source of these products (see **Box 10**).

In 2012, ATLAS and CMS — the two teams looking for the Higgs boson at CERN's LHC, announced the discovery of a particle 'compatible' with it, with an error margin of less than one in a million (see **Fig. 3**).[4, 5] For the next several months, scientists continued to examine this particle and its attributes. Their measurements have shown that the particle behaves, interacts, and decays in many of the ways that the Standard Model predicts for Higgs particles.

To conclude

With the detection of the Higgs boson, we've found all the fundamental particles predicted by the Standard Model. While this strengthens the case for this model as the theoretical

Box 8. Wave-particle duality is a fundamental concept in quantum mechanics:

Max Planck, Louis de Broglie, Albert Einstein, Arthur Compton, Niels Bohr, and many others have shown that all matter (or, each particle) exhibits wave nature and vice versa. For e.g., the motion of an electron in a cathode ray tube could be best described by considering its particle-nature. In contrast, its motion inside an atom is best described in terms of its wave-nature. Thus, a complete description of an electron's behavior (or that of any quantum-scale object) is possible only by bringing together both ('particle' and 'wave') classical concepts.

Box 9. Why is the Higgs boson called the God particle?

In mainstream media, the Higgs boson is often called the 'God particle'. This epithet originated in 1993, from a book titled 'The God Particle: If the Universe Is the Answer, What Is the Question?'.[3] Frustrated with the continuing difficulties of detecting this particle, its author Leon Lederman (Nobel laureate and former director of Fermi Lab) referred to the Higgs boson as 'The Goddamn Particle'. The publishers of the book suggested replacing this with the epithet 'God particle' to emphasize the particle's elusiveness as well as its significance in our understanding of the structure of matter. The epithet stuck. It remains hugely popular in spite of the many physicists, including Higgs, who reject it as being sensationalistic. The name is, of course, pure invention — there's nothing in the mathematical equations or in any religious texts/traditions that connects the Higgs particle or the Higgs field with any notion of religion or divinity.

Box 10. Detecting a novel particle by its decay products is a question of signal vs. background:

The signal, in this case, would be the potential decay signatures of the Higgs boson – each consisting of a characteristic set of particles that can be used to identify its presence conclusively. The background would consist of every ordinary type of event that can mimic the same signatures. For e.g., a Higgs boson formed in the LHC is predicted to decay into a pair of bottom quarks 60% of the time. Since a pair of quarks can result from many other events, the background for this decay signature of a Higgs boson is enormous – about 10,000 times the signal.

One way of differentiating between the signal and background is by calculating the amount of energy released in every collision. At higher energies, the probability of formation of Higgs bosons increases dramatically, and the ratio of Higgs signal to the background (due to already known particles) improves. Given that the probability of a Higgs boson being formed is itself very small, its existence can only be detected by acquiring data for a very huge number of collisions. To obtain such large data sets, collisions in the LHC are conducted 40 million times per second, all day, every day of the year! In order to improve the probability of detecting signs of this elusive particle, the LHC has been upgraded with improved detectors, and its voluminous decay signals are analyzed by computer resources drawn from all over the world.

edifice of particle physics, it has had remarkably little impact on the discipline *per se*. This is because the Higgs field has been part of the Standard Model for many years before its detection.

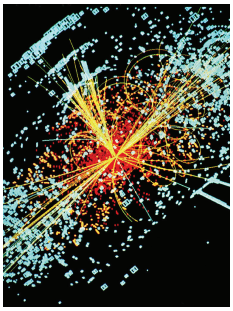
The current focus of particle physics is on determining the existence of elementary particles that are not in the Standard Model, and measuring effects of known fundamental particles that this model gets wrong. For e.g., meticulous experiments and analyses of measurements are being carried out at the LHC and elsewhere to determine if different types of Higgs bosons exist.[6] If they do, their discovery may lead us into realms of physics that go beyond our current understanding of the Standard Model.

While the quest for the Higgs boson has furthered technological progress of widespread importance (see **Box 11**), its discovery does not seem to have had any direct technological benefits. Given that all fundamental discoveries tend to yield practical applications on exploration, this may just be a matter of time. No wonder, then, that the whole world is excited – we now believe we know how elementary particles and everything they build (including ourselves) possess the property that we call mass!

Box 11. Did you know?

The World Wide Web (www) began as a project to improve CERN's communication system. Similarly, CERN's requirement to process the massive amounts of data produced by the LHC has led to significant developments in the fields of distributed and cloud computing!

Key takeaways



- The Standard Model of particle physics predicts the existence of a hypothetical, ubiquitous 'field' called the 'Higgs field'.
- This field is believed to impart mass to fundamental particles through a mechanism called the 'Higgs mechanism'.
- The Higgs boson is a hypothetical particle associated with the Higgs field.
- This particle gets its popular name 'God particle' from a book by the Nobel laureate Leon Lederman.
- Experiments to find the Higgs boson are conducted at the Large Hadron Collider, CERN, France.
- On 4th July, 2012, scientists at CERN announced the discovery of a particle with properties similar to those predicted for the elusive Higgs boson.

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Note: Image used in the background of the article title – A Higgs-event. Credits: Lucas Taylor/CERN, Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:CMS_Higgs-event.jpg. License: CC-BY-SA.

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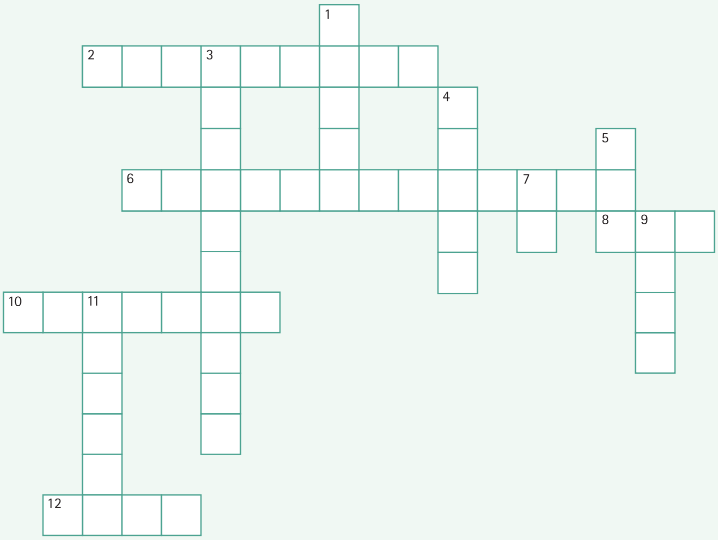
EVOLUTION CROSSWORD



Across

2. Choosing and fixing certain species or traits by natural or artificial forces acting on it. (9)
6. The English naturalist who is known for his theory of evolution. (13)
8. Any of the large, tailless, semi-erect primates of Africa and Southeast Asia. (3)
10. A group of individuals that can interbreed and produce viable offspring. (7)
12. A type of fertilization that occurs within the same organism: ________ fertilization. (4)

Down

1. A term to describe an organism's role in its environment. (5)
3. A species which is at high risk of extinction. (10)
4. Adjust to changing environments. (5)
5. The 'Molecule of Life' that carries genetic information between generations. (3)
7. Sex chromosomes in birds and snakes. (2)
9. Prefix to the number of times a woman has given birth or the number of children. (4)
11. To undergo a gradual change of characteristics in successive generations. (6)

Answers on page 93.

Rohini Chintha is an Assistant Professor (C) at the Department of Genetics and Biotechnology, University College for Women, Hyderabad. She is passionate about writing for children, and believes that 'A Happy Childhood builds a Happy Society'. About 85 of her stories for children have been published in various magazines.