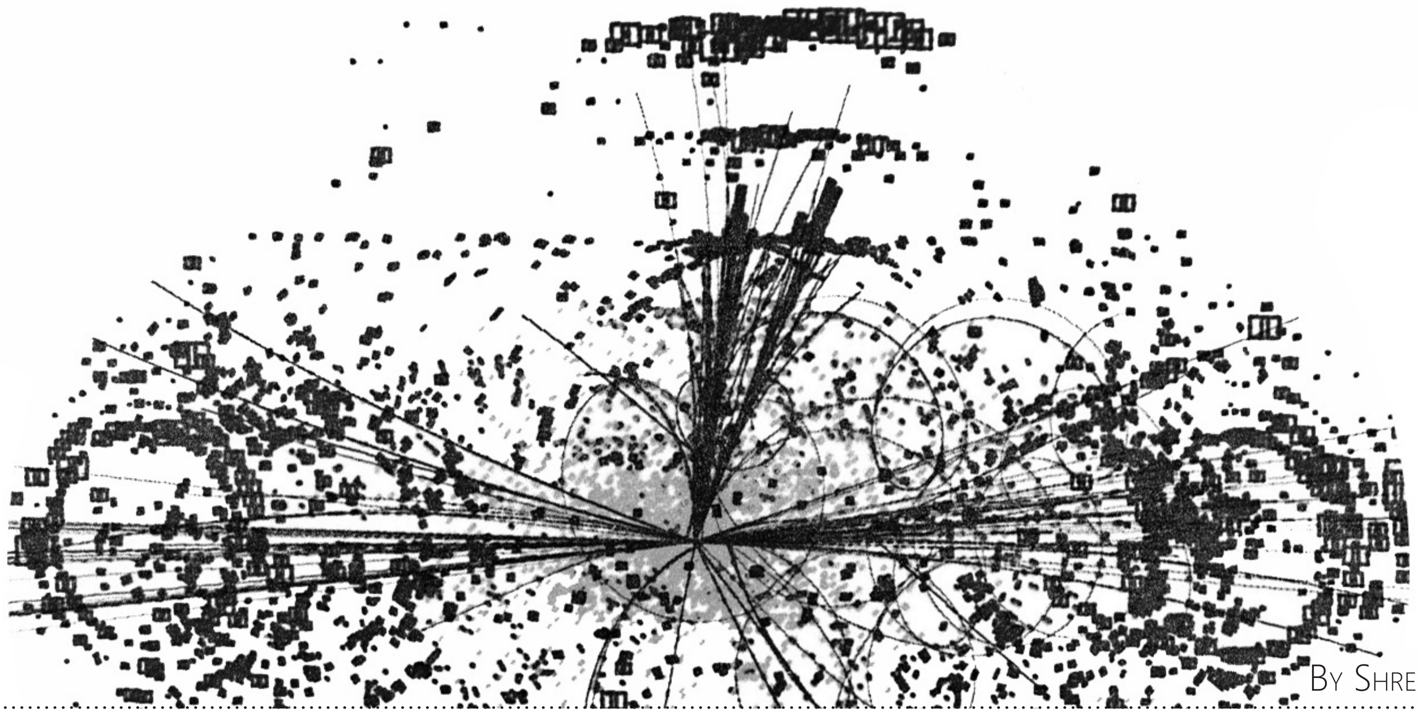
DISCOVERING THE HIGGS

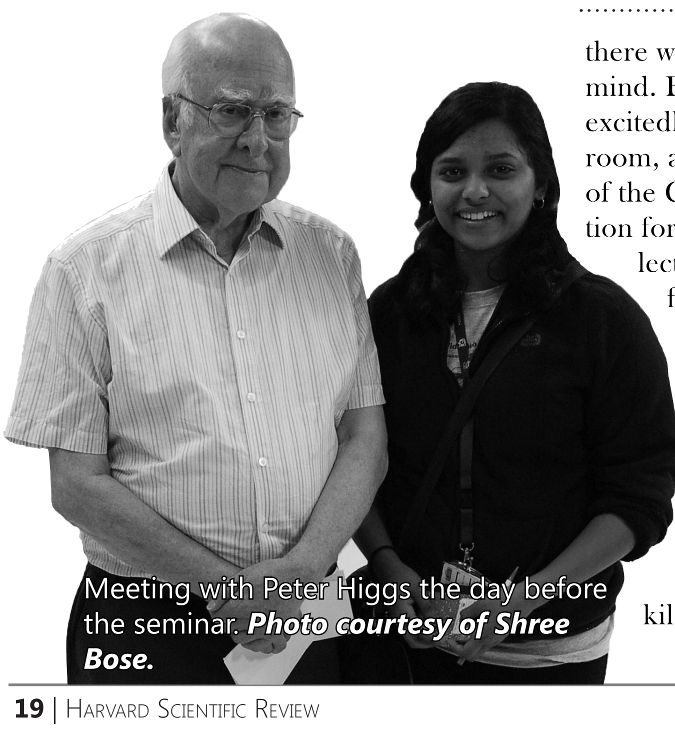
Inside the Discovery of the Higgs Boson and Understanding What it Means for Us



By Shree Bose

July 4, 2012. Geneva, Switzerland. I was near the back of the room, next to a girl who had her phone out frantically texting. I remember looking over at her phone to see a long string of French interjected with the words "Higgs," and I knew that there was nothing else on everyone's mind. Everyone around me whispered excitedly, and as I looked around the room, a small auditorium in the heart of the CERN, the European Organization for Nuclear Research, I saw a collection of people who had worked for years to hear the results of what this seminar would reveal. There were old, wizened men and women who had been there for the very beginnings of the particle physics research, for when the giant detectors had been conceived and built into the massive 27 kilometer underground ring on the border of France and Switzerland, a testament to the cooperation of the countries who had agreed to be a part of the Conseil Européen pour la Recherche Nucléaire. There was Peter Higgs, the renowned British theoretical physicist who had traveled in from the University of Edinburgh to be here for this seminar. When I had met him the day before and asked about what he believed would be discussed at the seminar, he had responded with a simple "I can't believe I'm alive to see this." There were the young men and women, some of whom had just graduated with their degrees in physics and were living out their dream careers, all seemingly trembling with excitement. And there were the millions of people all over the world tuning into the webcast of the event. Something big was in the air.

> "I can't believe I'm alive to see this."
>
> **Peter Higgs**
> *Physicist, Univeristy of Edinburgh*
> *Proponent of the Higgs Boson*



Meeting with Peter Higgs the day before the seminar. ***Photo courtesy of Shree Bose.***

The Director General of CERN, Dr. Rolf Heuer took the stage, and within moments the room was completely silent. He went through the basics, how theoretical physicists over the years had developed a model to explain strong, weak, and electromagnetic nuclear interactions of fundamental particles in our universe - a model which had come to be known as the Standard Model of physics. It was the theory of almost everything (1).

The world of modern particle physics currently has consolidated a vast amount of knowledge and experimental evidence into a set of laws and theories which explain concepts throughout all of physics, from the quantum field theory to symmetry breaking, and even extra dimensions. However, the ultimate aim is, of course, to have a theory which works for everything, what physicists all over the world have strived for - the Grand Unified Theory. However, at the subatomic level, the Standard Model is not perfect, regarding gravitational forces as negligible and, until July 2012, not being able to explain the role of mass (2).

But the Standard Model is what the physics world, and indeed many other fields and applications beyond, have built on, and what has been revalidated by experimental results time and time again. The Standard Model has been our way of understanding the world around us on an almost infinitesimally small scale.

The Standard Model is based on elementary particles – smaller than the atoms that used to be the smallest particles we understood in middle school and even smaller than the electrons, protons, and neutrons we understood in high school. Instead the Standard Model is based on fundamental particles which make up the electrons, protons, and neutrons we know – namely quarks, leptons, gluons, W and Z particles, and photons. Quarks, one of the fundamental particles, come in six different "flavors" – up, down, charm, strange, bottom, and top. Combinations of quarks with the correct charges create the protons and neutrons of atoms; however, electrons are elementary particles themselves. In fact, electrons are a class of the six types of leptons, along with muons, tau particles, electron neutrinos, muon neutrinos, tau neutrons (3). During

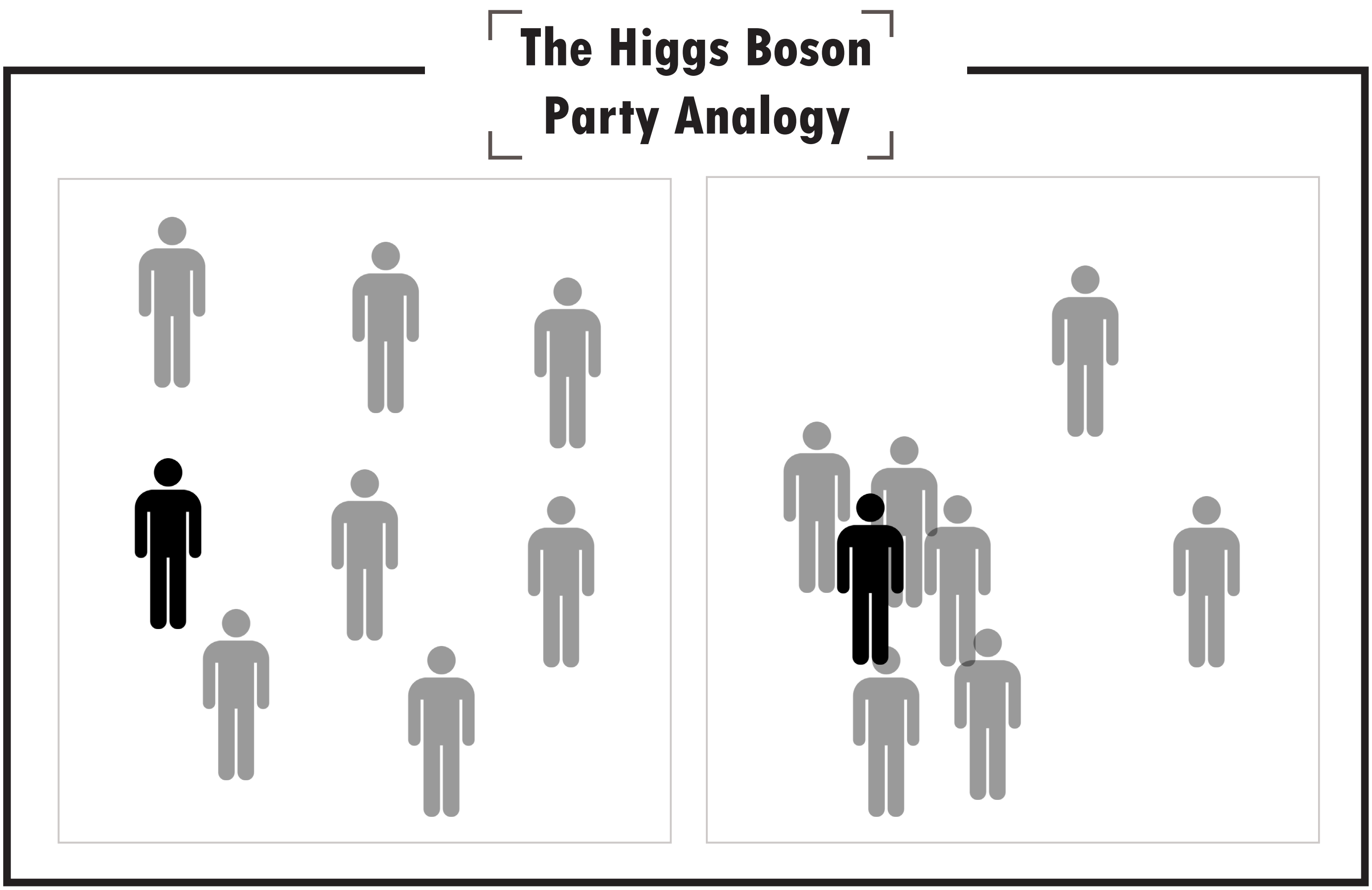


Figure 1: The Higgs field is comparable to a crowd of reporters; when someone who is not as notable walks by, they can pass through the field with little interaction with it (see left). However if a celebrity like Justin Bieber walks, the reporters would congregate around him, and he would have more interaction with the field. If each of the reporters was a Higgs boson, then the celebrity would have more interaction with the Higgs Field and therefore a much higher mass.
Graphic created by Shree Bose.

Figure 2: Decay modes that were predicted by the Standard Model Higgs at the mass observed. ***Graphic created by Shree Bose.***

particle decay, muons, tau particles, and electrons all decay into their complementary neutrinos.

Together leptons and quarks make up a class of particles known as fermions. However, fermions themselves cannot be responsible for their interactions with one another. Instead, another class of particles, known as bosons is responsible for the forces associated with each interaction. Bosons include W and Z particles, photons, and gluons, and, when paired with fermions, can create completely distinct subatomic particles. For example quarks held together by gluons create hadrons (4).

Now, based the calculations of the interactions of these different particles and their arrangements in our universe, six physicists including Peter Higgs had formulated a hypothesis for the origin of mass in 1964. Together, they proposed a so-called "Higgs field" made up of a new class of leptons, known as the Higgs Boson. But for almost 50 years and after even attracting the attention of the mainstream media as the subject of physicist, Leon Lederman's, book, The God Particle, evidence for this elusive particle of mass had not been found (5). Yet.

At the physics powerhouse of the world at CERN, theoretical and experimental physicists came together to find conclusive evidence for the existence of the Higgs field. To understand this field, imagine a mob of reporters. As some relatively unknown person walks through the mob, they could pass through with relatively little interaction with the reporters, and would not be slowed down. Now if we were to imagine Justin Bieber walking into this crowd of reporters, he would probably be mobbed and would have much more interaction and would not get through as fast. In this case, Biebs would have a much higher mass in this field than our initial unknown person, and collectively the mob of reporters would be a Higgs field made up of individual Higgs bosons (each of the reporters). The more the particles interact with the Higgs field, the higher their mass is (6). This idea of Higgs field interaction endowing particles with mass was one of the keystones of the Standard Model, without which the entire model would fall apart, and particles would fly around at the speed of light, not slowed enough by their size to bind to anything else and hold our universe together.

At CERN, in a 27 kilometer underground circular tunnel across the border of France and Switzerland, scientists accelerated protons to near the speed of light and induced collisions within huge detectors. These detectors were designed of layers of impact sensitive material to sense subatomic particles produced in the collisions. However, the principles of quantum mechanics predicate that heavier particles will, if possible, decay into lighter ones. In accordance with these principles, physicists at CERN structured their expectations around detecting the standard model predictions of the products of the Higgs Boson decay, rather the particle itself.

The Higgs Boson is expected to decay into various fermions based on its mass (7). At higher masses for the Higgs Boson, the decay patterns would be expected to favor heavier particles like top-antitop quark pairs in a higher proportion than quark-antiquark pairs. At two of the major detectors at CERN, ATLAS and CMS (compact muon solenoid), scientists used different channels to detect either photons or leptons released in the decay of the Higgs. In both channels, they found a bump in the energy at around 125 gigaelectronvolts (GeV), almost 125 times more than a proton, a mass inconsistent with any other known particle, leading them to speculate that this bump in the data was actually indicative of the mass of the

Higgs (8,9).

Using the calculations of the Standard Model using this mass, physicists were able to predict certain proportions of the decay products expected from a Higgs Boson (10). However, the particle they found had much different decay patterns than what was expected from a standard model Higgs, not consistent with those proportions that had been initially proposed. In the experimental results from CMS and ATLAS, the probabilities for the bottom quark and tau lepton decay modes were smaller in observations of the new particle and the probability of decay to two photons was almost 50% larger than the predicted (8,9).

Only one or at most a few Higgs bosons were produced at the Large Hadron Collider with every proton-proton collision. Each of the particles then decayed within fractions of a second into the unique combinations of products detected by the massive underground structures and then analyzed by a network of computers all over the world. To confirm the existence of the small bump seen in the data, trillions of collisions were necessary to get a statistical significance of 5 standard deviations. Together, using the results of ATLAS and CMS to confirm one another, CERN physicists were able to reach this level of significance – to prove that this new particle wasn't a glitch from background interference but rather a new particle decaying at that precise mass. This new particle is what is believed to the Higgs Boson, despite the fact that other properties of the particle remain to be analyzed.

So what does this momentous discovery of the physics world imply? In addition to explaining much of the origin of the mass that our universe, the existence of the Higgs Boson validates a part of the Standard Model which had previously been unproven. All of the particles of the Standard Model except for the Higgs Boson had been found before July 4, 2012. Without evidence for the Higgs Boson, much of the model would have been invalidated, and the physics world would have been back to the drawing board in developing their hypotheses.

In addition, this discovery provides some insight into the electroweak force, a combination of the electromagnetic force between charged particles and the weak force dealing with radioactive decay. The Higgs mechanism can actually explain how W and Z bosons responsible for the weak force obtain mass and interact with the massless photon responsible for the electromagnetic force. With more analysis, this interaction may explain the unification of these two fundamental forces as the electroweak force. In addition, since the mass of the boson was found to be low, the model still allows for possibility of supersymmetry, a theory which suggests that each particle has a "superpartner" particle with higher mass and slightly different characteristics (11,12).

For the physics world, as Nima Arkani-Hamed, a physicist at the Institute for Advanced Study in Princeton put it, "now some fun begins" (13).

So far, the masses and much of the behavior predicted by the Standard Model has held true for this new subatomic particle, bringing together one of the major missing pieces of the Standard Model and validating much of what the physics world had accepted to be true. This is a huge step to be made for human knowledge – a huge step which may be used in ways in the future to do things we could have never even imagined.

July 4, 2012. What could very possibly be the last subatomic particle left to be found had been discovered (14). History was being made in front of my eyes. And as the Director General said those three words we had all been waiting to hear, the auditorium, and probably so many more all over the world burst into applause.

"We got it."

- Shree Bose is a freshman in Struus from Fort Worth, Texas.

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