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The discovery of the Higgs boson opens up other puzzles in particle physics

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The Higgs boson is said to have been discovered in 2012 at the Large Hadron Collider in Geneva, Switzerland. However, the curious thing about the Higgs boson is that many people did not believe it could exist as an elementary particle until it was apparently found. Even more curious, many people still are not convinced that it exists.

We are not talking about a conspiracy on the level of fake moon landing staged in a warehouse studio in Des Moines. The issue is one of determining the “true nature” of a discovery. The particle found in Geneva walks like a duck, quacks like a duck, but it might not be a duck. In fact, many researchers hold that it cannot be a duck.

Why a Higgs boson?

Let’s first discuss why nature needs a Higgs boson at all, which at the same time will reveal its vulnerabilities. The Higgs boson was postulated in the 1960s by Peter Higgs and it was later understood to be an excellent candidate for the explanation of how all elementary particles can obtain mass. Let’s define what we mean by Higgs boson:

Higgs boson: *the Higgs boson is a spin-less elementary particle, which has, unlike any other elementary particle, a non-zero field value that spreads across the entire universe and gives mass to every massive elementary particle that we know about, and completes the “story of mass” in elementary particle physics.*

It’s difficult to understand what is meant by “non-zero field value” but for our purposes think of it analogously as a mist everywhere that all elementary particles feel, and by feeling the mist they obtain mass (see Fig.1). The photon does not feel the mist at all, and so it is massless. The top quark feels the mist the strongest and is therefore the heaviest, about 185 times heavier than a hydrogen atom.

One might ask, “Why can’t the other elementary particles just have mass without the Higgs boson? An astronaut has mass even if you take it out of the earth’s gravitational field!” Well, the problem is that as we understood better the nature of electrons, and photons, and quarks, which are the constituent elementary particles of protons and neutrons, we had a rather serious conundrum. Our understanding of quantum field theories told us that masses for elementary particles were incompatible with the fundamental symmetries that we had derived from observations, most notably the symmetry that governs the so-called “weak decays” of heavy nuclei (“weak symmetry”).

These “weak decays” happen when one nucleus decays to another and ejects an electron and neutrino in the process, for example. We see them in the laboratory: Cobalt-60 decays to Nickel-60 plus an electron and neutrino. We can’t ignore that. But our beautiful quantum field theory that described that so well had no way of allowing the elementary particles to have mass, which was a major stumbling block to progress in physics for years. The Higgs boson and its all-pervasive mist solved the problem.

They found the Higgs boson, right?

Now fast forward to 2012, and the announcement that the Higgs boson had been discovered at CERN. I was a staff physicist in the Theory Department at CERN and had the good fortune to be in the auditorium for the discovery announcement. What an event it was. What an achievement of the human intellect. Much celebration. People crying with joy. Reporters swarming. TV cameras in every hallway it seemed. The Director General Heuer said, “I think we got it!” meaning they finally collared this elusive particle. They saw it by measuring a small excess of two photons and four leptons (electrons and muons are both in the category of “leptons”) over normal backgrounds being produced in the collisions of protons at very high energies (see Fig.2). It was predicted we would find it that way. They spent decades developing the detectors to make exactly that discovery. It worked. Its mass was found to be equal to approximately 134 hydrogen atoms.

The question is, however, exactly what did they find at CERN? You must keep in mind that many physicists were not expecting the Higgs boson to be there at all. The esteemed Nobel Laureate Martinus Veltman said in 1997 that “by the time you get there [when the LHC runs] you will find something else…. I don’t believe the Higgs system … as it is advertised at this point … I really don’t believe that” [1]. He was certainly not alone. There were numerous research papers exploring “Higgsless theories” all the way up to the moment of Higgs boson discovery [2].

With significant opposition to the Higgs boson before its discovery it is not surprising that many are still loath to accept that what was found at CERN was indeed the Higgs boson elementary particle.

Why the animosity toward the Higgs boson?

Why do so many theoretical physicists really dislike the Higgs boson as a stand-alone elementary particle? One answer was from Harvard physicist Howard Georgi, who said that nature would be “malicious” if the Higgs boson were discovered since it would mean that nature would have skipped the opportunity to teach us new things [4]. Less reliant on human psychology, many theorists believed and still believe that a single Higgs boson elementary particle has a severe sickness. Let’s phrase it in the form of a conjecture:

The spin-less heavy elementary particle conjecture (SHEP conjecture): *ordinary quantum field theory suggests to us that it is extraordinarily improbable that a spin-less elementary particle, like the purported Higgs boson, can have mass much less than the Planck mass, which is 16 orders of magnitude greater than the heaviest known elementary particle (i.e., Planck mass divided by top quark mass ~* 10^{16}*).*

The Planck mass is derived from gravitational physics and it is assumed that no elementary particle can have mass above it. Its numerical value is equivalent to about 10^{19} hydrogen atoms, which is about 0.00002 grams. That sounds like a tiny and accessible mass, well below a pecan’s, so surely a particle could be that massive? But pecans are not “point-like” elementary particles, and it's the elementary particle by itself that has the Planck mass restriction inferred through quantum gravity considerations.

The SHEP conjecture is a claim based on the synthesis of hundreds of research papers on the so-called Naturalness, Hierarchy and Fine-tuning problem of the Higgs boson -- an amalgam of all the vulnerabilities perceived in the Higgs boson idea. We will not discuss the detailed reasons behind that and just go straight to its effect: Because of the SHEP conjecture few thought before the start of operations of CERN’s Large Hadron Collider that a Higgs boson would be discovered all alone, so light, trembling without an entourage of other particles or effects that would show us that the premises of the SHEP conjecture did not apply.

There had been already some evidence from previous experiments doing precision experiments on decays of the Z boson and precision mass determinations of the W boson (discovered in the 1980s) and the top quark (discovered in the 1990s) that a Higgs boson likely existed with mass less than the top quark mass (top quark mass = 186 hydrogen atoms). The research community was presented with the exciting prospect of discovery, but for those who accepted the dogma of the SHEP conjecture there was confusion and doubt about how it could exist. “I believe; help thou mine unbelief” is a pretty good summary of what most physicists felt. The resolution to the coexistence of the Higgs boson with the SHEP conjecture was that nature need only violate one or more premises of the SHEP conjecture and all would be well.

Violating the premises of the SHEP conjecture: supersymmetry

One can violate the premise of “ordinary quantum field theory” by introducing supersymmetry which is an exotic quantum field theory that has strict bindings between particles of different spins. A spin-less elementary particle, like the Higgs boson, would have to be paired with an elementary particle with spin, and that pairing immediately vacates the pressure that the spin-less particle has mass near the astronomically high Planck mass. The implications of supersymmetry is that many other particles -- superpartners to every known particle -- must exist and are discoverable if only colliders have enough energy to produce them.

Violating the premises of the SHEP conjecture: extra spatial dimensions

One can also manipulate the premise by adding extra spatial dimensions compactified into a tiny volume, which can have the effect of lowering the Planck mass from 10^{16} times the Higgs boson mass to a value nearby. In that case, we satisfy the SHEP conjecture by saying that the Higgs boson is indeed not much less than the Planck scale. These extra dimensions are discoverable in principle, but in practice we don't know how tiny the volume is for the extra spatial dimensions. The smaller this extra volume the higher energy we have to collide protons to see these dimensions unfold. (Don't worry, it's safe.)

Violating the premises of the SHEP conjecture: the Higgs boson is not elementary

Finally, one can violate the premises by assuming that the Higgs boson is simply not an elementary particle. It might be a composite particle like the proton or neutron, made up of smaller constituents [5]. Those smaller elementary particles that bind together to make the Higgs boson could be particles with spin, and then the SHEP conjecture would not apply and what we call the "Higgs boson" is a spin-less bound state of other particles whose spins cancel out, similar to what we see in superconductivity [6].

How to know if the Higgs boson is fictitious?

Each idea that we have discussed that allows the Higgs boson to exist but not violate the SHEP conjecture -- supersymmetry, new spatial dimensions, and compositeness -- implies that experiments in principle can see tiny deviations from what is otherwise expected if nature has only the pure elementary particle Higgs boson.

For example, experiments can count the number of times the Higgs boson decays into two photons. Under the assumption that the Higgs boson is strictly an elementary particle with no other additional features to support its existence, one can predict a value B for the number of times it decays into two photons. On the other hand, under the assumption that the Higgs boson exists in a more exotic way (again, supersymmetry, extra dimensions, or compositeness) the prediction will be a little different than B -- let's call it B+x, where x is a small number compared to B.

At present, no final state decay of the Higgs boson is measured to better than 10%. In other words, the value of x can be as high as 10% of the value of B without running afoul of experimental results. So a theory of composite Higgs boson, or of supersymmetry or of extra dimensions, that predicts deviations that are less than 10% different from the predictions of an elementary Higgs boson is perfectly consistent with everything we know to date. Those who agree with the SHEP conjecture believe that these tiny deviations away from the elementary Higgs boson predictions will be seen if we can one day measure the Higgs boson decays with much better precision.

So, physicists are not yet ready to call the Higgs boson a stand-alone elementary particle on the same level as we do an electron or a quark or a photon. We want to test all of the decays of the Higgs boson to better than a percent to give us more confidence ---the 10% determinations we have now are not good enough. We might be lucky and the CERN collider will discover small deviations as it collects more data starting next year. Or, more likely, we will have to wait for the proposed “Higgs factory” in Japan -- the International Linear Collider -- which has the ability to measure the Higgs boson properties to the sub-percent level and really test whether the Higgs boson can stand it alone and be a proud member of the elementary particles club like the electron, or whether it is fragile and reveals its supersymmetric, extra dimensional, or non-elementary heritage when we put it under a more powerful microscope.

References & End Notes

[1] M. Veltman. “Reflections on the Higgs system,” 17-21 March 1997, CERN. https://cds.cern.ch/record/334106

[2] J.D. Wells, “Beyond the Hypothesis: theory’s role in the genesis, opposition, and pursuit of the Higgs boson.” Stud.Hist.Phil.Sci B62, 36-44 (2018). https://www.sciencedirect.com/science/article/abs/pii/S1355219816301551?via%3Dihub

[3] P. Anderson. “Higgs, Anderson, and all that”. Nature 11, 93 (2015). https://www.nature.com/articles/nphys3247

[4] H. Georgi. “Why I would be very sad if a Higgs boson were discovered.” In *Perspective on Higgs Physics II*, ed. G.L. Kane. World Scientific, 1997.

[5] The prospect of the Higgs boson being composite is not so odd an assumption as it might appear on the surface, since there are bound states like that which already exist in nature, such as the pions. Pions are a class of particles with mass about 1/7th the mass of a hydrogen atom. They were first proposed by the Japanese physicist Hideki Yukawa in the 1930s in order to explain the strong force between protons and neutrons in the nucleus. Their experimental discovery was slow in coming, but by the 1950s they were firmly established empirically. However, it was not until the 1970s that it was understood that these pions are really just bound pairs of quarks and anti-quarks. Although the pions were spin-less, the constituent quarks that made the pions had spin that canceled out when paired. The Higgs boson could be a bound state analogous to the pion. “If nature can do it once, it can do it again,” was the rallying cry.

[6] Some materials when cooled to sufficiently low temperatures become perfect conductors of electricity -- superconductivity. The microscopic reason for why that happens is the formation of Cooper pairs, where two electrons, which have spin, bind in the material and form a spin-less boson very similar to the structure of a Higgs boson. If nature does it in superconductivity, maybe it can do the same thing for elementary particles. This line of thought led the Nobel Laureate physicist Phil Anderson, who is a condensed matter physicist that knows very little about particle physics, to declare in 2015 three years after the Higgs boson discovery that

“maybe the Higgs boson is fictitious!” [3], as though we particle physicists had never thought about that possibility.

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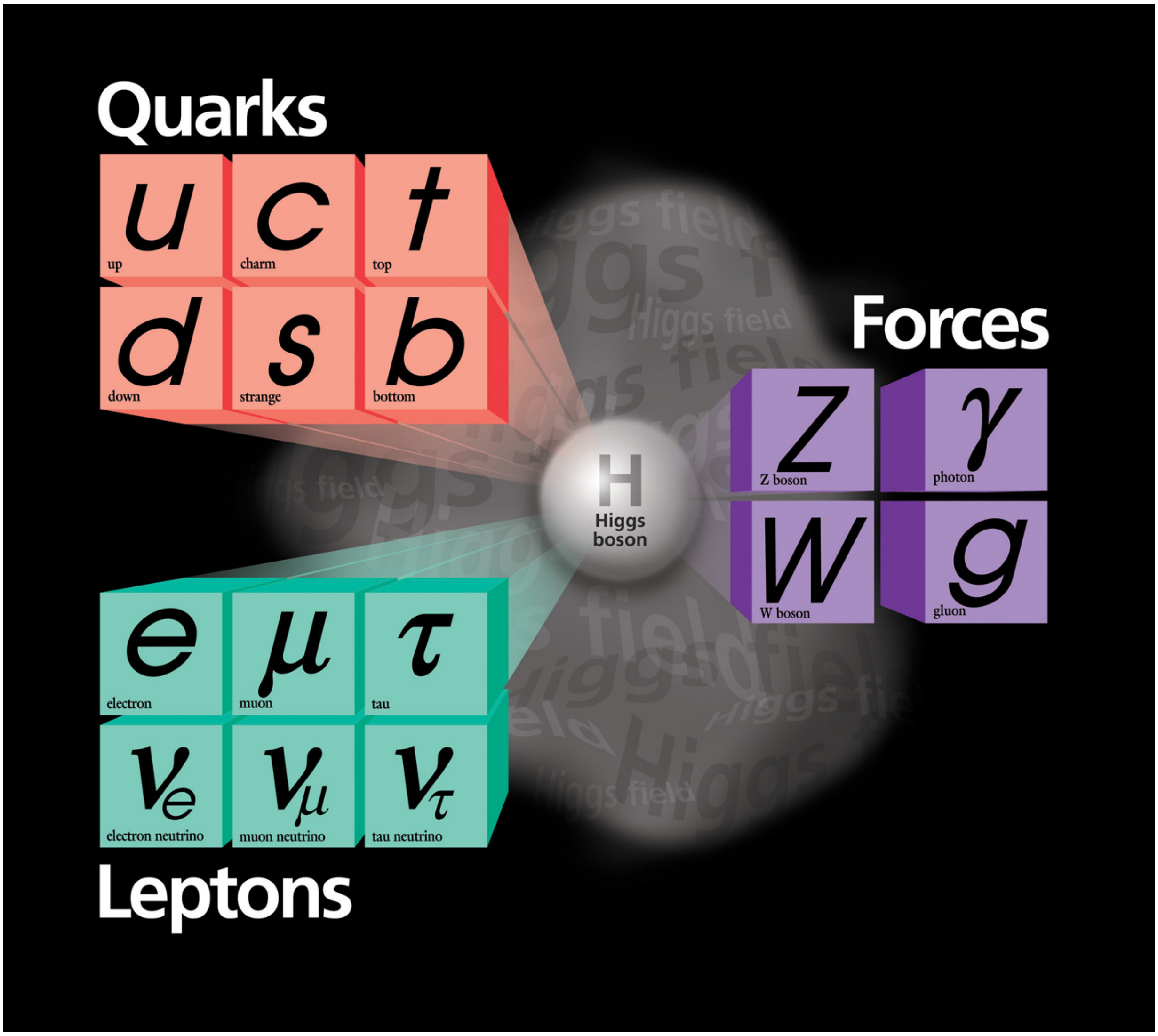

Fig. 1: Depiction of all the elementary particles, with the Higgs boson in the middle in the midst of its own generated "mist" -- the background non-zero field value -- that gives mass to other elementary particles. (Source: Fermilab communications)

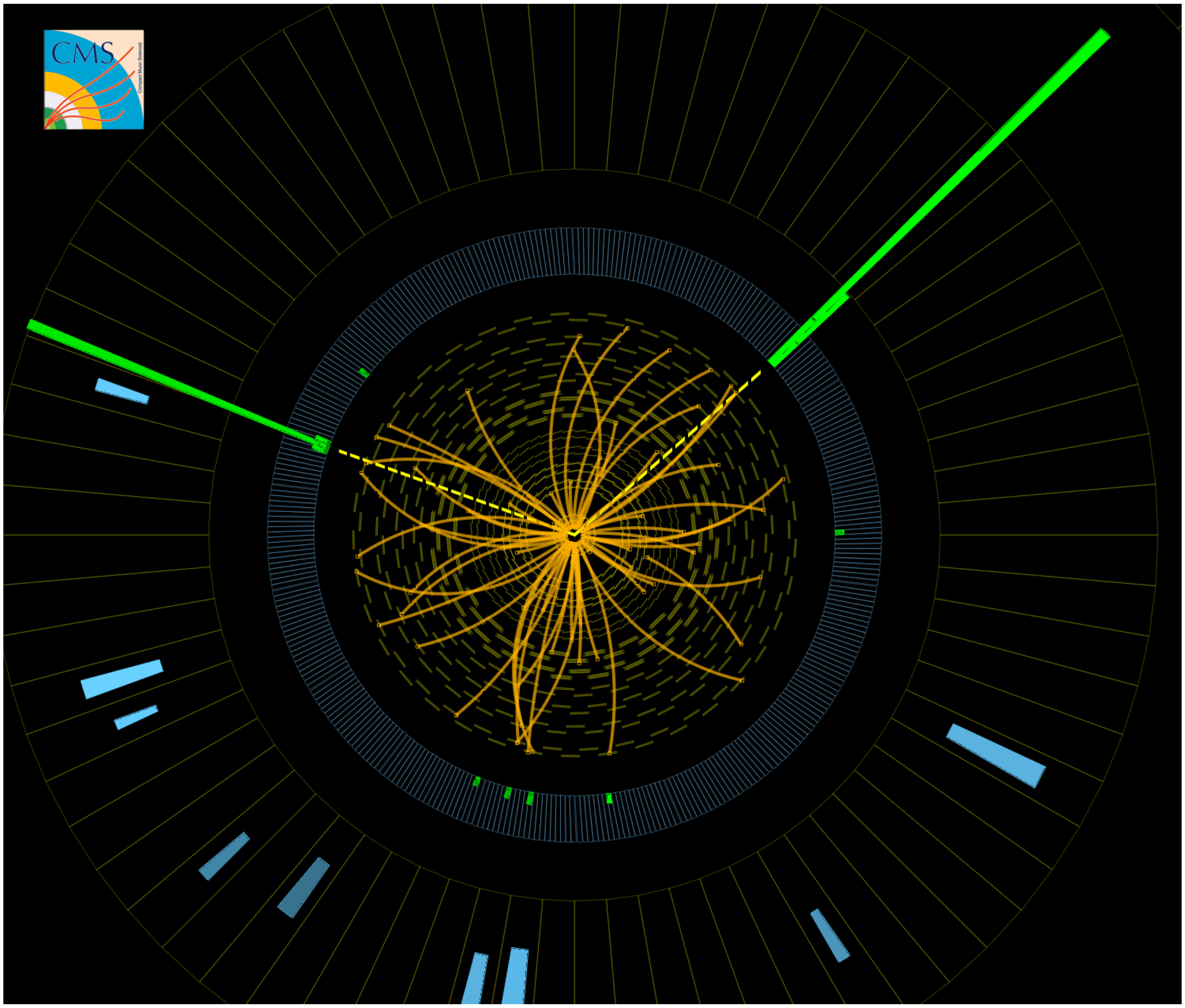

Fig. 2: Detector image of a Higgs boson decay into two photons, where the photons are the dashed yellow and green lines coming out of the center, which is where the Higgs was created and decayed. Its point of creation is extremely close to where it decays because the Higgs boson lifetime is so tiny. (Source: CMS collaboration https://cms.cern/news/world-without-higgs)