From spontaneous symmetry breaking to the Higgs discovery

Gordon J. Aubrecht, II
The Ohio State University

In the mid-1960s, the Higgs mechanism of spontaneous symmetry breaking emerged from several theorists. In the late 1960s, the idea of spontaneous symmetry breaking of a scalar field (the Higgs field) was engaged as part of the ultimately successful attempt to unify the weak and electromagnetic interactions. Despite extensive searches, the Higgs particle remained undiscovered until July 4, 2012. This article recounts the journey from idea to discovery from a personal perspective.

Princeton, 1967-68

It's hard to remember when some things occur, but it probably was sometime in the fall of 1967 that I attended a seminar by a brash young physicist from MIT. From the way the senior physicists at Princeton (where I was a graduate student at the time) treated Steven Weinberg, it was clear that this was someone who had a future in theoretical physics. We graduate students had no idea that Weinberg would go on to win the Nobel Prize (in 1979, with Abdus Salam) for his contributions to building what is now called the Standard Model, but we definitely knew he was considered special by the faculty members there at the seminar. A piece of evidence supporting the year being 1967 is the publication of a paper by Weinberg referring to spontaneous symmetry breaking published in November, 1967 (1).

That afternoon, I learned about spontaneous symmetry breaking. I recall Weinberg talking about a scalar particle and how this scalar particle could give mass to the vector bosons (his diagram looked like Fig. 1). I remember him doing calculations on the blackboard and coming out with a mass parameter μ from the symmetry breaking. The idea is that the ground state equilibrium is unstable, and any perturbation results in the particle falling to the lower potential energy. It was my first introduction to what has been called the "wine-bottle" or "Mexican-hat" potential.

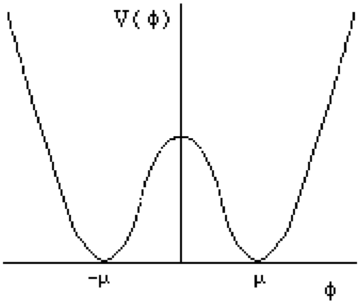


Fig.1. The particle disappears as the symmetry breaks. The particle moves from $\phi = 0$ to $\phi = \mu$.

Symmetry is a powerful tool that physicists use in many different ways. For example, four identical charges at the corners of a square produce an electric field that is zero at the center of the square (the idea works for identical charges placed at the vertices of any polygon). If one of the charges is different from the others, the electric field at the center depends on the difference in the charges and is very easy to calculate. In the early twentieth century, Noether showed that every symmetry corresponded to a conserved current, and this subsequently became the basis of much theoretical work (2). In fact, in particle physics there interest in using current algebra based on entities called Lagrangians theoretically, to which I myself later contributed. Particles that express the symmetry are known as gauge particles.

The frantic 1970s

Going back to the 1930s, there was a weak interaction theory (the theory of decay of particles such as electrons into muons and other particles) that was originally developed by Enrico Fermi for beta decay (an example is nuclear beta decay, the decay of a neutron into a proton, an electron and another elusive particle, the electron antineutrino). In fact, this approach is still known to physics students as Fermi's Golden Rule: that the probability of a transition from initial to final state depends on the density of states and the square of the interaction matrix element between initial and final states (this matrix element describes the details of the interaction). Of course, in 1934 people didn't know the matrix element; it would take until the 1950s to develop the ideas that led to the proper beta-decay spectrum. The Fermi model of weak interactions had problems when applied beyond relatively low energies—the prediction extrapolated more generally led to a growing transition probability because before and during the 1950s the matrix element was taken to be a constant and the growing density of states made the result grow too large to describe the result at higher energies (this was termed "violating the unitarity limit"). The matrix element, as we have since learned, is simply a low-energy approximation in the more complete model.

The Salam-Weinberg model for electroweak unification has been incredibly stimulating for physicists. Old ideas have been reevaluated one after the other. By the advent of the 1980s, the combined work of Howard Georgi, Sheldon Glashow, Ben Lee, Abdus Salam, Gerard 't Hooft, Martinus Veltman, Steven Weinberg, and many, many others rescued a theory of the weak interactions that violated unitarity and showed that one could calculate real values through a process of renormalization reminiscent of Richard Feynman, Julian Schwinger, Sin-Itiro Tomonaga and many others' work on quantum electrodynamics (QED).

The development of QED during the 1940s showed how renormalization could work to eliminate the infinities in electromagnetism. Electromagnetism can be explained in terms of exchange of photons. Of course, photons are massless and their exchange—through matrix elements that involved propagators that are the inverse of the square of the four-momentum, $1/p^2$—led to calculations that found infinite values for physical parameters. (On an amusing note, I once attended a colloquium during which the speaker explained renormalization by saying that the weak interaction infinities couldn't be physical, so the net result of the apparently infinite integrals must somehow be zero, from which the remainder of his talk unfolded.)

The way to get rid of the pesky infinities in theories of interactions is to realize that interactions are mediated by exchange of gauge particles that do not exist as real particles. The idea of a virtual particle is that one form of the Heisenberg Uncertainty Principle may be written $\Delta E\ \Delta t \geq ½\ \hbar$, so we can estimate the time that ΔE can violate the Uncertainty Principle to be less than $\Delta t\ /2\Delta E$, because then it does not have to become real and satisfy the Uncertainty Principle. If it really existed, it would have to violate the Uncertainty Principle, which it cannot, but if it is absorbed again before it can become a real particle, it is allowed to violate the Uncertainty Principle during that minuscule time interval it exists.

This exchange of virtual particles is an old idea in particle physics. In the late 1940s, physicists discovered particles they called pions (π^+, π^-, and π^0) in experiments looking at cosmic rays. Then they saw these same π particles in accelerator experiments in association with protons and neutrons in the 1950s. Nuclear physicists considered exchange of virtual (massive) pions and other virtual particles as the way the strong interaction worked inside nuclei (Fig. 3 shows an example of how this exchange could work to exchange a neutron for a proton).

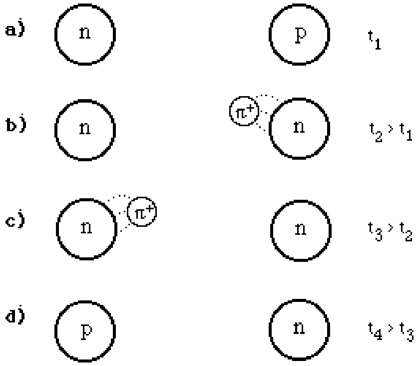


Fig. 3. a) A neutron and a proton at time t_1. b) At time $t_2 > t_1$, the proton emits a virtual positively charged pion and becomes a neutron. c) At time $t_3 > t_2$, the neutron absorbs the pion, becoming a proton. d) At time $t_4 > t_3$, there is again a neutron and a proton.

For pion exchange, the pion mass is $m_\pi c^2 = 140$ MeV, so to produce a pion of energy 140 MeV means $\Delta E \sim 140$ MeV. Therefore, the pion can exist for a time $\Delta t \sim \frac{6.58 \times 10^{-16}\text{ eV s}}{140\text{ MeV}} = 4.7 \times 10^{-24}\text{s}$ and not violate the Uncertainty Principle (The electronvolt, the eV, is a convenient unit for electron energies in atoms. The electronvolt is the energy gained by an electron accelerating through a potential difference of one volt. Mass energies of many particles are in the megaelectronvolt—MeV, 10^6 eV—and gigaelectronvolt—GeV, 10^9 eV—range).

As one of Feynman's contribution to the development of QED, he created Feynman diagrams, which allow calculations to be written down easily at the same time they allow visualization of what is happening. The diagrams serve as a picture and a guide to the formalism. The Feynman diagram for the interaction of Fig. 3, exchange of a π^+ to change the identity of a nucleon, is shown in Fig. 4. The π^+ in this diagram is virtual, because it exists for too short a time for the Uncertainty Principle to apply.

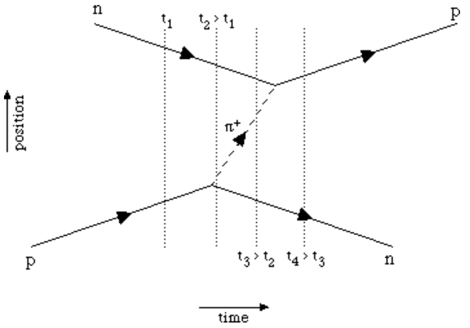


Fig. 4. This Feynman diagram corresponds to the process shown in Fig. 3. The times shown there are labeled here as well.

The idea that interactions could proceed by exchange of virtual particles that were massive was applied to the weak interactions. Simplifying the situation immensely, if there were massive gauge particles similar to the photon, the infinities would go away because the exchanged virtual particles' propagators (descriptions of a particle's travel between two points) would be of the form $1/(p_\mu p^\mu – m^2)$, and the m^2 term would mean approximately constant matrix elements at low energy (compared to the m^2), while the p^2 part of term would make them vanishingly small at high energy by tending the denominator toward zero.

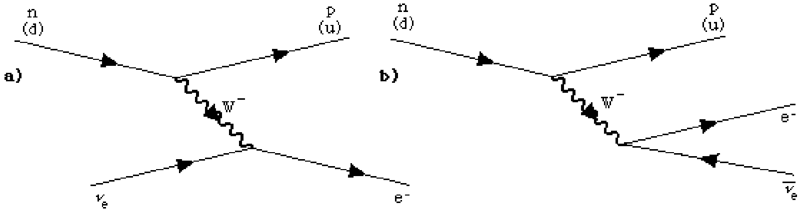


Fig. 5. a) The Feynman diagram describes the process by which a neutron (symbolized by d) and a neutrino scatter through the weak interaction producing a proton and an electron. b) The Feynman diagram for nucleon beta decay, in which a constituent of the neutron (d) is changed by the weak interaction into a constituent of a proton (u) and produces a W^-, which then decays into an electron and an antineutrino (note that the antineutrino line points to the right). The u and d are quark constituents of the nucleons. There is a propagator for the W^- and there are two vertices (u-d-W- and e--ν_e-W^-) included in each of these Feynman diagrams.

If this idea were to work, for example in the case of the 1930s "poster child" for the weak interaction, nuclear beta decay, this would mean that nuclear beta decay and scattering of a neutrino from a neutron to produce a proton and an electron would be related, as shown in Fig. 5. In the 1970s, such an interaction would be labeled a charged-current interaction (the W^- being charged and being exchanged; we could instead have drawn the diagrams for electron plus proton to neutron and electron neutrino and for positron emission, which also proceeds through exchange of the W^+).

In nuclear virtual particle exchange, the virtual particle was a single sort of charged pion in Figs. 3 and 4; however, in nature there are three pi particles—π^+, π^-, and π^0. It is easy to suggest analogously that there could be positive, negative, and neutral gauge bosons. In addition to the W^-, there should be another charged particle (by charge symmetry invariance, expected to have the same mass), that is, a W^+. Both W^+ and W^- are charged-current interactions. This raises the natural followup question: Is there that neutral gauge boson (at that time it would have been characterized as a neutral current interaction)? The gauge boson would have to be similar to the photon in its lack of electric charge, but analogous to $W^\pm$ in having a nonzero mass.

Such a neutral particle could be produced by sending electrons and positrons colliding together and seeing, for example, μ^+-μ^- pairs emerge or scattering an electron neutrino from an electron and producing the same thing or producing a μ^- and ν_μ. The first experimental evidence for the electroweak theory was the discovery of weak neutral currents, first seen in 1973 in by the Gargamelle collaboration at CERN (3) in ν_μ–nucleon scattering and anti-muon-neutrino-electron scattering, and immediately thereafter by the Harvard-Penn-Wisconsin collaboration at Fermilab (4). The exchanged gauge particle—corresponding to the current—is known as the Z.

Thus, the experimental result supported electroweak theory, in which the photon, the $W^\pm$, and the Z are the gauge bosons. The mystery was why the photon was massless, while the $W^\pm$ and Z had masses. This is where the spontaneous symmetry breaking comes in. Massless particles have two states of polarization, which we usually label clockwise and counterclockwise. Massive particles also have a longitudinal polarization, for a total of three states of polarization.

Consider a field ϕ for a particle whose original value puts it on an extremum of the potential (Fig. 1 shows the relation between the field parameter ϕ and the potential in such a case, and Fig. 6 shows a three-dimensional representation). We named particles like these *Higgs particles,* which are represented by the fields, spontaneously move away from their original wavefunction to a new wavefunction at $\phi = \mu$ having a lower potential energy. The original mechanism was presented by Peter Higgs (5) and elaborated by others (it's sometimes called the Brout–Englert–Higgs mechanism, and sometimes even more names are added). The original symmetry—each direction looks the same from the top of the "mountain" in the diagram—is broken when the field "rolls" down the potential into the trough.

In this process, known as the Higgs mechanism, the fields representing the Higgs particle disappear when they "fall" into the region of lower potential. Through their disappearance they become responsible for creating the masses and thus the longitudinal polarizations of the gauge bosons. Thus, a key part of verification of electroweak unification is the appearance of Higgs bosons in experiments. From the 1970s to now, the Higgs was a "holy grail" of experimental searches. Up until Independence Day 2012, no such scalar particle had been found.

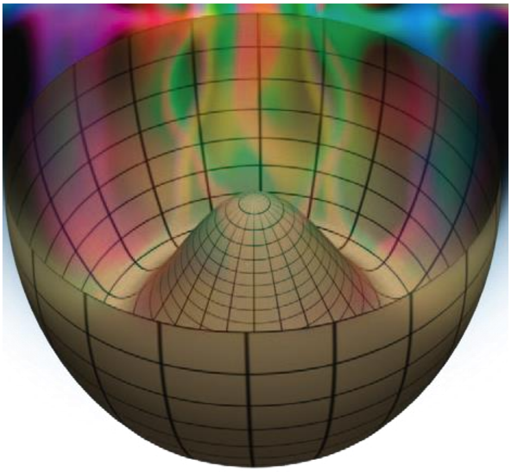


Fig. 6. The potential leading to spontaneous symmetry breaking as a three-dimensional representation. Source: Contemporary Physics Education Project.

The “normal” massive particles’ masses arise largely through the kinetic energy of the bound constituent quarks. For example, the proton is made of three quarks, two ups and a down. The intrinsic quark masses are quite small ($m_u c^2$ ~ 2 MeV, $m_d c^2$ ~ 5 MeV) compared to the proton mass, ~ 940 MeV/c^2. Therefore, if the proton is truly made of three quarks 940 MeV/c^2 of the proton mass must come from elsewhere—it must be from the kinetic energy of the particle constituents. This is very different from the idea of the Higgs mechanism described above. (Another basic question about mass that must yet be answered is where the small quark masses arise. In string theory, it would come from vibrating strings.)

What’s it all about? The Standard Model

The electroweak theory is really known by the (somewhat opaque) name of $SU(2)_L$U(1). This designates the groups involved in the approximate symmetries described by the model. They are SU(2), the special unitary group in two dimensions, and the one-parameter group U(1). (Isospin is an example of a symmetry associated with an SU(2) group.) SU(2)U(1) has been very successful at describing nature. In electromagnetism, charges surround themselves with charges of predominantly the opposite charge, so that a particle far away from a charge does not “feel” its influence, which is called *screening*. Quarks surround themselves (because of the gluons, which are gauge bosons of the strong interactions and which possess a charge called *color* that has three values—red, green, and blue) with replicas of themselves, that is, the same color charge; this is known as *antiscreening*.

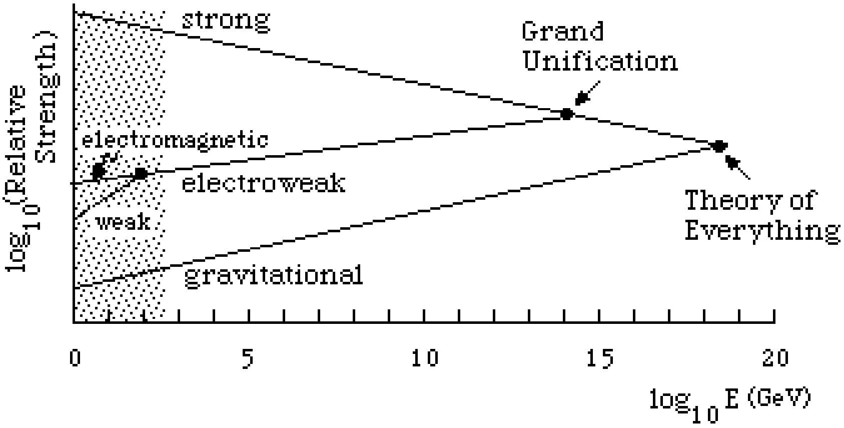


Fig 7. The number of independent coupling constants decreases with energy as symmetry increases. Note that both axes are logarithmic in character. At high enough energy, all masses are effectively zero, and all particles should be the same; this would be the realm of a theory of everything. The shaded area, up to around 7 TeV, is the regime currently being studied. Electroweak unification occurs at ~ 100 Gev, grand unification at about 10^{14} GeV, and GUT plus gravitation at about 10^{19} GeV, The grand unification theories are characterized as GUTs.

As we get near the color charge, the amount of color charge that can be seen decreases. In order to get close, we must use high energies. Thus, at high energies, the quarks act almost as if they are free particles. At asymptotically high energy, they are asymptotically free. This means that the strength of the interactions changes, the strong interaction becoming weaker as energy increases (while the opposite occurs for the electroweak interaction). This means that the interaction strengths of the strong and electroweak interactions get closer to one another as energy increases and their mass-energy is negligible compared to their energy. Therefore, we predict that a hidden symmetry in the equations will emerge at sufficiently high energy as the interaction strengths become identical (at about 1000 GeV = 1 TeV). At that energy, the weak interaction and the electric interaction are expected to be equivalent in their effects (the dot connecting weak and electromagnetic interactions in Fig. 7).

Down to the smallest scales probed experimentally, about 10^{-18} m, the constitution of material particles can be explained by the theory called “the Standard Model,” or, more technically, $SU(2)_L \otimes U(1)$, which is denoted as “grand unification” in Fig. 7, the place where the strong and electroweak interaction strengths are the same. The SU(3) part is the group that describes the strong color interactions. This does not mean that this is integrated wholly into the theory, merely that quarks are taken into account as a separate part of the theory. One key part of the electroweak unification ($SU(2)_L \otimes U(1)$) encapsulated in the Standard Model is the explanation of how the W and Z particles get mass, as we discussed above. Originally, when the symmetry is there, all gauge bosons must be massless, just as the photon is massless. Where did the mass of the other gauge bosons arise? From that Higgs particle when it breaks the symmetry spontaneously, as found in the preceding section.

From the strength of the weak interaction at lower energy, where the virtual W and Z exchange act, physicists could guess about how large the masses of these particles would have to be somewhere around 80 to 90 GeV/c^2. After Herculean work constructing and designing the CERN proton accelerator, two experiments in 1983 verified the theory with a vengeance. Italian physicist Carlo Rubbia helped redesign the CERN Super Proton Synchrotron so it could produce counter-rotating antiprotons and led the group UA 1, which discovered the W and Z particles and measured their masses, which were just about where they were expected to be (6). This result was confirmed by a second CERN experimental group, UA 2 (7).

The two results were the clear signal that the theory was basically correct. Rubbia shared the 1984 Nobel Prize with the Dutch accelerator physicist Simon van der Meer, who designed the accelerator used in the experiment (The technique allowed more precise energy measurements in the events that were detected in an almost-4 detector).

It was in the mid-1980s that I helped organize a conference on the teaching of particle physics at Fermilab. The idea that a comprehensive model of interactions involving quarks and leptons was becoming acknowledged in the particle physics community. One outcome of the conference was the formation of the Contemporary Physics Education Project (CPEP), a collaboration of particle physicists and high school and college teachers, whose first project was creation of a large chart of the Standard Model of particles and interactions (8). Most physics departments in the country have one or more CPEP charts hanging in their halls and many high school classrooms feature them as well. The charts have been featured in movies and in the TV show The Big Bang. I was a founding member of CPEP and later served as secretary and as chair. I am currently chair emeritus and a Board member.

The Standard Model, sans finding the Higgs, had come into being. This set the stage for construction of the defunct superconducting supercollider in Texas and the large hadron collider (LHC) from which the discovery was so recently announced. In the beginning, some theorists such as Weinberg suggested that fermion masses could be partly due to the Higgs mechanism as well (1).

A good review of what was known of the Higgs as of early 2012 may be found in Ref. 9.

World Conference on Physics Education, Bahçeşehir Üniversitesi, İstanbul, July 2012

Fast forward to Wednesday, 4 July 2012. I was sitting in sessions of the World Conference on Physics Education in Istanbul. Because I was listening to talks, I could not watch the seminars at CERN describing the discovery of "a Higgs-like particle," but I could surreptitiously keep following the live blog at the Guardian newspaper website (10).

At around 9:30 Istanbul time, I read a posting of a tweet from Brian Cox that was re-posted on the Guardian blog: "And combined - 5 sigma. Round of applause. That's a discovery of a Higgs - like particle at CMS. They thank LHC for the data!"

> "9.44am: Rolf Heuer, Director General of CERN, offers this verdict:
> As a layman I would say: I think we have it. You agree?
> The audience claps. I think that's a yes.
>
> "9.46am: Heuer flashes up on screen a slide that says Cern have discovered 'a particle consistent with the Higgs boson - but which one?'
>
> "So, while this is undoubtedly a milestone with 'global implications', he says, it is also the beginning of a lot more research and investigation. But, he adds, 'I think we can be very, very optimistic'."

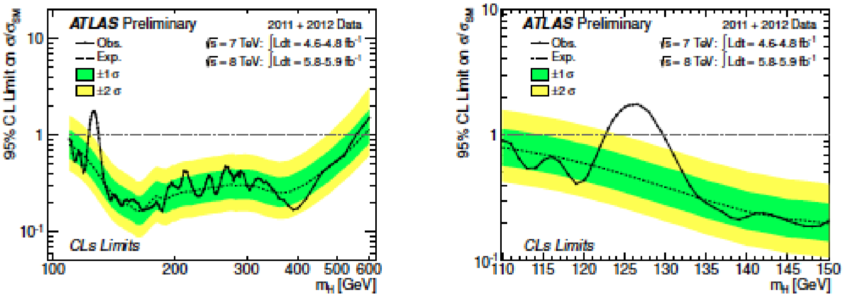
At around 10:30, the ATLAS result was reported: "ATLAS - round of applause + cheers. 5 sigma discovery at 126.5 GeV."

I lost my concentration on the speaker in the session at the conference. My particle theorist (and experimentalist) colleagues had been waiting for this news since the 1960s; we'd had hints in December, 2011 that the particle was there (only at the two sigma level) and here it was at the five sigma level—the criterion for identification of an effect in particle physics—in two independent experiments.

Why five sigma?

Toss a coin and sometimes a head (H) will be followed by a tail (T), but not always. If I toss a coin six times, I expect to get three heads and three tails because it is a random event and both possibilities are equally likely to occur. However, I could get 6 H, 5 H and 1 T, 4 H and 2 T, etc. There is just one way to get 6 H, but there are six possible different ways to get 5 H and 1 T (the sole tail could be thrown first, second, etc.), fifteen ways to get 4 H and 2 T (the first two tosses tails, etc.), twenty ways to get 3 H and 3 T, fifteen ways to get 2 H and 4 T, six ways to get 1 H and 5 T, and one way to get 6 T. We have essentially a normal distribution of the results. The probability of tossing 6 heads in a row is 1 (the number of ways to toss six heads) divided by all possible results: 1 + 6 +15 +20+15 +6 +1 = 64, or about 1.6%. The probability of tossing three heads and three tails is 20/64 = 31.25%. About one-third of the time, we will have equal numbers of heads and tails.

The sigma in “five sigma” refers to the symbol for standard deviation, σ. As we know, collision events occur at random and if there are enough of them, they fit on a normal curve, just as the tossed coins do. One standard deviation from the center would give a probability of 68% of all data (~ 1 in 3). About 95.5% of the data will be inside two standard deviations (~ 1 in 22); about 99.7% lie within three standard deviations (~ 1 in 370), four standard deviation events occur 1 in 15,787 times; and five standard deviation events occur 1 in every 1,744, 278 times. So a five sigma effect means that such a thing would be observed by chance with a probability of 1/1,744, 278 = 5.7 x 10^{-7}. This is so unlikely that this is the criterion for accepting an effect as real in particle physics when it is corroborated by another experiment, as in this case.



(a) (b)

Fig. 8. a, b. ATLAS: The observed (full line) and expected (dashed line) 95% CL combined upper limits on the SM Higgs boson production cross section divided by the Standard Model expectation as a function of m_H in the full mass range considered in this analysis (a) and in the low mass range (b). The dashed curves show the median expected limit in the absence of a signal and the green and yellow bands indicate the corresponding 68% and 95% intervals (Ref. 11, Fig. 1).

Figures 8 and 9 show the ATLAS and CMS results for the mass of the Higgs particle, m_H, respectively, as of the CERN announcement. The two experiments investigated the possible Higgs mass by exploring different interactions. ATLAS searched for interactions producing tau plus jets, in pairs of leptons with their neutrinos, three leptons and associated neutrinos, four leptons and two neutrinos, two bottom quarks, two photons, etc. (examples in Fig. 8). CMS looked for interactions producing γγ, Zγ, ZZ, and WW (example in Fig. 9).

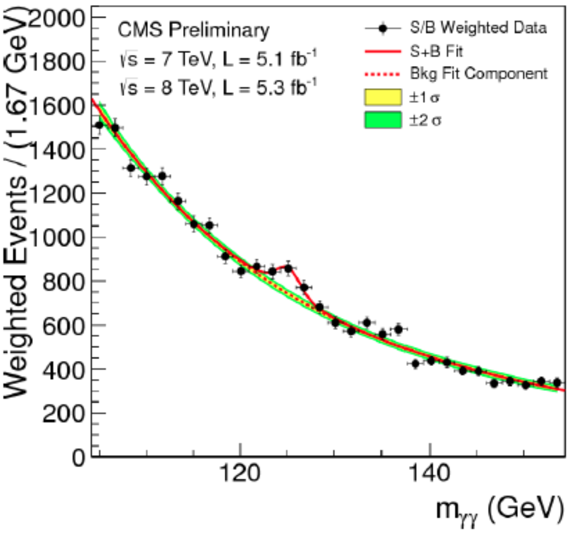
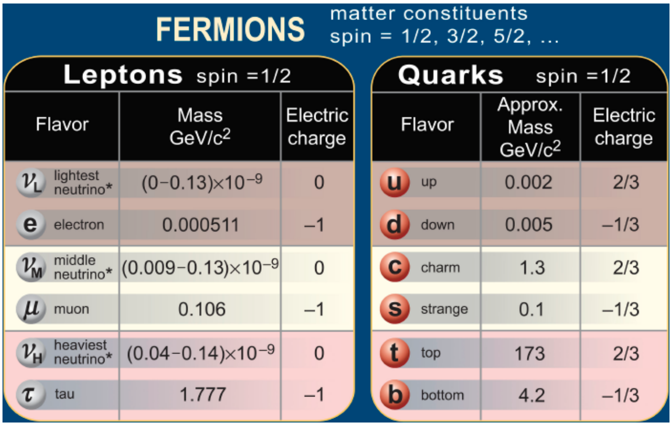


Fig. 9 CMS: Di-photon (γγ) invariant mass distribution for the CMS data of 2011 and 2012 (black points with error bars). The data are weighted by the signal to background ratio for each sub-category of events. The solid red line shows the fit result for signal plus background; the dashed red line shows only the background (Ref. 12, Fig. 3).

Beyond the Standard Model

Each generation of leptons has a distinct "flavor" – called electron type, muon type, etc. Each lepton flavor type is conserved. Neutrinos are nearly-zero-mass particles. The repeating pattern of the three generations and the pattern of the masses of quarks and leptons (Fig. 10) are *completely unexplained* by the Standard Model.



FERMIONS matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	(0−0.13)×10^{-9}	0
e electron	0.000511	−1
ν_M middle neutrino*	(0.009−0.13)×10^{-9}	0
μ muon	0.106	−1
ν_H heaviest neutrino*	(0.04−0.14)×10^{-9}	0
τ tau	1.777	−1

Quarks spin =1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	173	2/3
b bottom	4.2	−1/3

Fig. 10. The fundamental fermions. Source: Contemporary Physics Education Project, Ref. 13.

Physicists do know the Standard Model is not the final story, because of the many masses and couplings that must be put into the model, but so far we have not found anywhere the model breaks down—the only missing piece was this Higgs particle discovered in July, 2012. While the Standard Model has greatly simplified the conceptual framework of the proliferation of particles, it still has many adjustable parameters (numbers). There are over twenty numbers overall that go into building the theory. While such a theory is obviously useful, it cannot be the end theory. That end theory should be expected to have no freely chosen parameters.

Reducing the number of parameters (numbers put in ad hoc to fit data) is important: By the time Niels Bohr was awarded the Nobel Prize for the Bohr model of the atom, it was known that it was at least incomplete (after the invention of quantum mechanics, we knew the Bohr model was incorrect). Nevertheless, the prize was given because in Bohr's model, it was possible to calculate the so-called Rydberg constant (a fitted parameter that allowed physicists and chemists to reproduce frequency values of light emitted by excited hydrogen atoms in experiments) in terms of physical quantities such as mass, charge, and Planck's constant. There were only two remaining parameters, integers n = 1, 2, 3, etc. and m = 1, 2, 3, etc., that described all the observed frequencies and energies of light emitted by excited hydrogen atoms. In quantum mechanics, these integers are the so-called principal quantum numbers available to electrons in different states in hydrogen atoms, and a transition of an electron from m → n produces light with a frequency that depends on m and n just as Bohr calculated and scientists had found phenomenologically in terms of the Rydberg constant.

The physicist's ultimate goal is to search for simplicity and universal applicability, similar to Bohr's achievement. It is clearly not yet within reach for particle physics—there are too many unanswered questions. Given the attention paid by the media some years ago to the proposition that we were approaching "the end of science" (14), this confirms again for me and other scientists that obtaining an answer engenders still more questions to which we would like to have answers.

The prediction on the basis of the picture of the interaction unification is that there is a possibility of unification of the GUTs and gravity at an energy around 10^{19} GeV, as we saw in Fig. 7. The question is exactly how to get there and what sort of theory the Theory of Everything would be.

Physicists have been toying with such "Theories of Everything" for years. John Schwartz (who is my Ph.D. thesis adviser) and Michael Green were early enthusiasts for superstring models, and were able to show that so-called superstring theories could be renormalizable, that is, they might actually be able to describe nature by producing finite results instead of infinities (15). The "supergravity" theories originally proposed in the 1970s by Julius Wess and Bruno Zumino (16) have been revived and renewed by this Higgs discovery (people now speak of the Wess–Zumino–Novikov–Witten model (17)). The “super” part of their supposition is that there is an underlying symmetry between bosons (particles having integer spin in terms of ħ) and fermions (particles having half-integer spin in terms of ħ). That leads to pairs of particles – fermions are paired with bosons, particles with sparticles (supersymmetric analogs to regular particles). Unfortunately, there is so far no experimental evidence of the supersymmetric partners to “ordinary” particles.

In superstring models, which exist naturally in a multi-dimensional space, many dimensions are automatically eliminated. The ten-dimensional remnant is supposed to have six of the dimensions contract into tiny tubes (or “strings”) that leave the four dimensions of spacetime to describe all physics. At this time, I view these elegant theories as metaphysics. There is still hope that, despite the difficulties with the superstring theory, this theory will ultimately lead to a correct description of nature in terms of physical quantities with no free parameters and transition from metaphysics to physics.

Conclusion

I am grateful to have played a minor role in this quest over my years as a particle physicist and as a member of the Contemporary Physics Education Project, which makes me so excited to learn about and want to share the excitement of these experimental results.

I have tried to give non-physicists some idea about the importance and theoretical power of symmetry and symmetry breaking in physics, the idea that conserved currents (and gauge particles, virtual particles that exchange interactions) arise from symmetries in the Lagrangian is pregnant with consequences. The use of these ideas led to creation of the Standard Model, which in turn led to the prediction of the Higgs particle. The discovery of the existence of the Higgs particle makes the Standard Model, incomplete as it is because of all the arbitrary parameters, a whole that encompasses all known factors (as of the present, of course; we hope to discover physics beyond the Standard Model). It is a tribute to our human ability to

Hats off to all the dedicated work of the many theorists and experimentalists who made the Independence Day 2012 Higgs announcement possible. And a huge thank you to the countries that contributed to building the Large Hadron Collider and the many-tonne detectors necessary all of which working together allowed the identification of the Higgs particle.

Acknowledgments

I would like to thank the anonymous referees, who helped make this account of my adventures in particle physics more accessible to the reader. Any remaining mistakes remain my responsibility.

References

1. S. Weinberg, “A model of leptons,” *Phys. Rev. Lett.* **19**, 1264–1266 (1967).
2. E. Noether, "Invariante Varlationsprobleme", *Nachr. d. König. Gesellsch. d. Wiss. zu Göttingen, Math-phys. Klasse* 235-257 (1918); English translation M. A. Travel, *Transport Theory and Statistical Physics* **1**(3) 183-207 (1971).
3. F. J. Hasert *et al.*, “Search for elastic muon neutrino electron scattering,” ***Phys. Lett. B*** **46**, 121 (1973); ibid., “Observation of neutrino-like interactions without muon or electron in the Gargamelle neutrino experiment,” *Phys. Lett. B* **46**, 138 −140 (1973).
4. A. Benvenuti et al., “Observation of muonless neutrino-induced inelastic interactions.” *Phys. Rev. Lett.*, **32**, 800-803 (1974).
5. P. W. Higgs, “Broken symmetries and the masses of gauge bosons,” *Phys. Rev. Lett.* **13**, 508–509 (1964).
6. UA 1 Collaboration, “Experimental observation of isolated large transverse energy electrons with associated missing energy at **p**s = 540 GeV.” *Phys. Lett. B*, **122**, 103-116 (1983).
7. UA 2 Collaboration, “Observation of single isolated electrons of high transverse momentum in events with missing transverse energy at the CERN pp Collider.” *Phys. Lett. B*, **122**, 476-485 (1983).
8. The CPEP website is found at http://www.cpepphysics.org/.
9. J. Ellis, M. K. Gaillard**,** and D. V. Nanopoulos, “A historical profile of the Higgs boson,” preprint KCL-PH-TH/2012-04, LCTS/2012-01, CERN-PH-TH/2012-009, LBNL-UCB-PTH-12/01, ACT-1-12, MIFPA-12-01, January 2012.
10. L. Davies. “Scientists gather for a major announcement in Cern, home of the Large Hadron Collider,” http://www.guardian.co.uk/science/blog/2012/jul/04/higgs-boson-discovered-live-coverage-cern, retrieved 4 July 2012.
11. The ATLAS Collaboration, “Observation of an excess of events in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC,” ATLAS-CONF-2012-093, July 5, 2012.
12. The Compact Muon Solenoid (CMS) Collaboration, “Observation of a new particle with a mass of 125 GeV,” talk presented at CERN and the 36th International Conference on High Energy Physics, Melbourne, Australia, 4 July 2012.
13. The figure is taken from the Contemporary Physics Education Project chart; see www.cpepphysics.org for more information. Also, I can recommend our Particle Adventure website, http://www.particleadventure.org/, and a book with contributions from many CPEP members, R. M. Barnett et al., *The Charm of Strange Quarks: Mysteries and Revolutions of Particle Physics* (New York: Springer, 2000).

14. John Horgan, *The End Of Science: Facing The Limits Of Knowledge In The Twilight Of The Scientific Age* (New York: Broadway Books, 1997).
15. M. B. Green and J. H. Schwarz, "Anomaly cancellations in supersymmetric D = 10 gauge theory and superstring theory," *Phys. Lett. B* **149**, 117–122 (1984).
16. J. Wess, and B. Zumino, "Consequences of anomalous Ward identities," *Phys. Lett. B* **37**, 95–97 (1971).
17. E. Witten, "Global aspects of current algebra," *Nucl. Phys. B* **223**, 422–432 (1983); "Non-abelian bosonization in two dimensions," *Comm. Math. Phys.* **92**, 455–472 (1984).

Personal Biography

Gordon J. Aubrecht, II is emeritus professor of physics and a research scientist at OSU Marion. He graduated from Rutgers University summa cum laude and earned his graduate degree at Princeton University. His original research interest was theoretical particle physics, but he is currently studying how students understand atoms, nuclei, and the interaction of light and matter as well as how useful and effective physics by inquiry is. He was awarded the Distinguished Service Citation of the American Association of Physics Teachers in 1994, was elected a Fellow of the American Physical Society in 2000, and was presented with the John B. Hart Award for distinguished service from the Southern Ohio Section of the American Association of Physics Teachers in 2002. He received the AURCO Distinguished Service Award in 2004. Also in 2004, Aubrecht received the Howard Maxwell Award for Distinguished Service from the Ohio Section of the American Physical Society and the Louis Nemzer Award from the Ohio State Chapter of the American Association of University Professors for his defense of academic freedom. He is a past president of AURCO.

NOTE: *This version has been corrected from the initial published article due to a copy editing error. It was designated the* ***Editor's Choice Award*** *by the editors*.