Triumph, Window,

The Higgs Particle in Context

The discovery, after years of search, of the Higgs particle is a many-splendored triumph for physics.

IT IS A TRIUMPH OF IMAGINATION. Physicists imagined, in their equations, a simpler and more coherent world than the one we observe. They ascribed the difference to a space-filling material. And then they imagined a new particle, the Higgs particle, to make that material. With the discovery, we find that esthetic intuition has not led us astray. The audacity to trust in equations "too beautiful for this world" has paid off.

It is a triumph of technique. The Higgs particle is a rare and fleeting physical phenomenon. Even at the Large Hadron Collider (LHC) the Higgs particle H is produced in less than a billionth of the collisions, and it is highly unstable (its lifetime is too short to be measured directly, but is inferred to be $\sim 10^{-22}$ sec.) Even if the Higgs particle were produced in isolation, in a clean environment, it would be challenging to study. High-energy proton-proton collisions, however, are far from that ideal: The final states typically contain dozens of particles, very few of which have anything to do with the Higgs particle. Tremendous effort, both theoretical and experimental, has gone into understanding those "backgrounds," which themselves reflect fundamental processes. "Yesterday's sensation is today's calibration," the saying goes, but it should be noted that successful anticipation of what happens 99.9999999% of the time, in these extraordinary conditions, is as remarkable as the new information contained in the remaining .0000001%.

Most profoundly, it is a triumph of moral commitment to intellectual honesty and curiosity. With the overwhelming practical success of the Standard Model,

Clue, and Inspiration

by Frank Wilczek

physicists might have declared victory, and declined to press their luck. Instead they strove to test the foundational ideas of that model rigorously. Humanity at large, in a shining example of international collaboration, supported their effort generously. Thus the discovery forms a monument to our modern scientific culture.

Here I'll describe what has been achieved so far, mention some important questions that further work should soon address, and offer a perspective on what it means.

"The Origin of Mass" — a reality check

But first, a reality check is in order. The Higgs particle is sometimes said to provide "the origin of mass" or, along the same lines, to be "the God particle". These are very misleading statements, especially the first. (It's hard to assess where the other leads.)

One hundred twenty years ago, Hendrik Lorentz proposed an electromagnetic theory of the origin of the (then yet to be discovered!) electron's mass. According to Lorentz's theory, back-reaction of electric and magnetic fields resists accelerated motion of electric charges, giving rise dynamically to the effect we call mass. In other words, the forces generated by an electron's own electric and magnetic fields, acting on that electron itself, resist changes in its velocity.

The details of Lorentz's theory did not survive the subsequent revolutions in physics, relativity and quantum mechanics. But quantum chromodynamics (QCD) realizes the vision of Lorentz in a modified form. Back-reaction of color fields, which resist the acceleration of quarks, is responsible for more than 95% of the mass of protons and neutrons. Those masses in turn supply better than 99% of the mass of normal baryonic matter—the kind of matter we study in chemistry, biology, and most of physics, and of course the kind of matter we're made of.

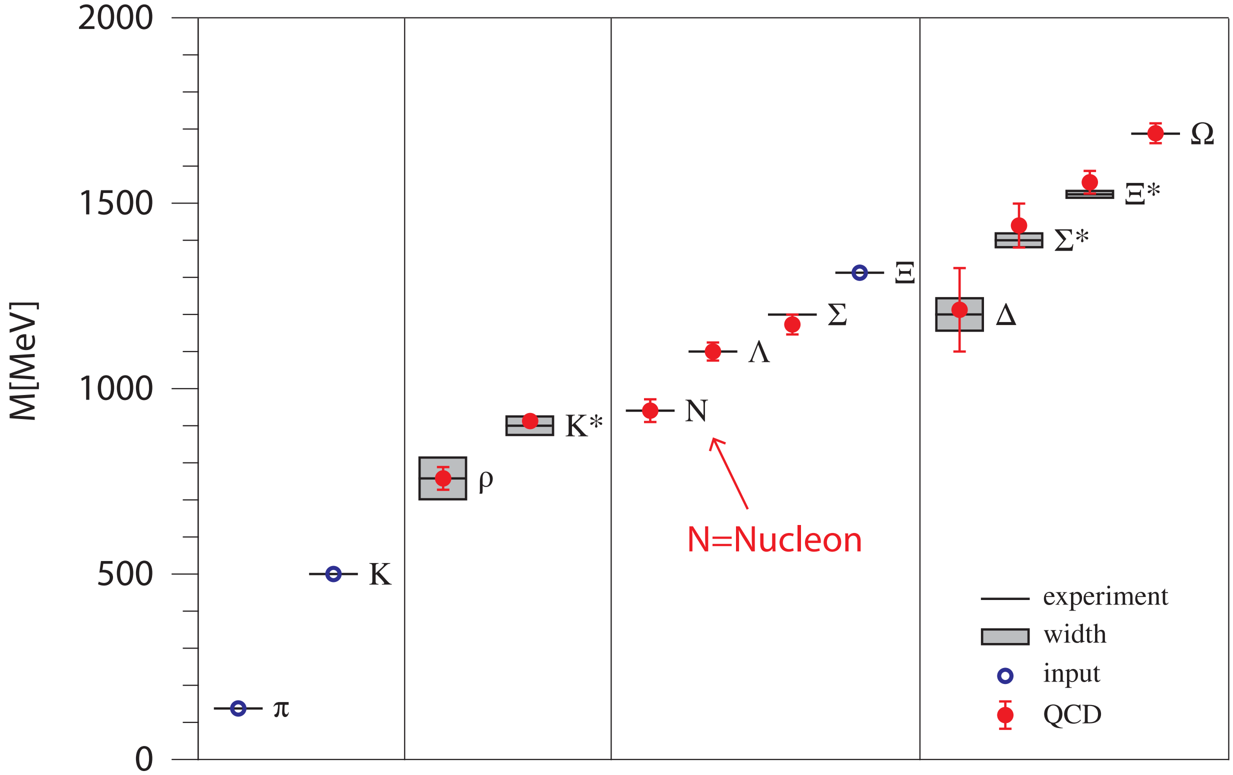


FIGURE 1

Numerical calculation of the masses *of many strongly interacting particles ("hadrons"), including nucleons (protons and neutrons), based rigorously on QCD. The π and K are spin 0 mesons; the ρ and K are spin 1 mesons; the nucleon N as well as Δ, Σ, Ξ, Ω are spin ½ baryons; and Δ, Σ*, Ξ*, Ω are spin 3⁄2 baryons. Since the theory provides an accurate, vastly over-constrained account of these masses, it accounts for their origin. But QCD makes no mention whatsoever of the Higgs particle. (Budapest-Marseille-Wuppertal collaboration)*

Very detailed and impressive calculations stand behind those words, as illustrated in *Figure 1*.

An alternative perspective on this origin of mass is also illuminating, and quite beautiful. Einstein's famous relation $E = mc^2$, relating the energy of a particle at rest to its mass, can also be read the opposite way:

$$m = E/c^2$$

In this way, we see that a region of space where a stable, confined disturbance with energy E is contained will appear to be a particle of mass E/c^2. A proton is a confined disturbance in quark and gluon fields, and the energy of their oscillations is responsible for the proton's mass.

Mass from medium

As I mentioned before, the Higgs particle is a rare and fleeting presence, neither impressive nor important purely as a physical phenomenon. To appreciate the significance of the Higgs *particle*, we must put that particle in its proper context, the Higgs *mechanism*.

The equations for particles with zero mass, including the Maxwell equations, the Yang-Mills equations, and Einstein's equations in general relativity, are especially beautiful. They can support an enormous amount of symmetry, so-called gauge symmetry. Photons have zero mass, as do the color gluons of quantum chromodynamics and the gravitons of gravity. (Neither color gluons nor gravitons can be observed directly, as individual particles, but the transverse nature of radiation in QCD and the long-range nature of gravitation, respectively, show that they have zero mass.) Both to have beautiful equations, and to have uniformity in our description of nature, we'd like to build the world from zero mass building blocks.

Unfortunately, several kinds of elementary particles refuse to cooperate with our wishes. Specifically, the *W* and *Z* bosons, which mediate the weak interactions, have quite substantial masses. (That is why the weak interactions are short-ranged, and act feebly at low energies.) This is especially vexing, because in other respects the *W* and *Z* bosons appear remarkably photon-like—they are spin-1 particles—and the way they interact with other forms of matter (for experts: through conserved currents) is remarkably similar to the way photons respond to electric charges and currents.

FIGURE 2
Fish discover water.

A possible resolution to this difficulty appears, when we consider that the behavior of photons can be affected by the properties of material they move through. A familiar example is that light slows down in refractive media, such as glass or water. That phenomenon, whereby light becomes more sluggish than usual, is very roughly analogous to light acquiring inertia. Less familiar, but for present purposes more profound, is the behavior of photons inside superconductors. The equations that describe photons in superconductors are *mathematically identical* to the equations for a massive particle. Within a superconductor, photons effectively become particles with non-zero mass.

The essence of the Higgs mechanism is the idea that "empty space"—that is, space devoid of particles and radiation—is in fact filled with a material medium that renders the *W* and *Z* bosons massive. This idea lets us keep the beautiful equations for massless particles, while observing a decent respect for the opinion of reality.

We need a material that does, for *W* and *Z* bosons, what superconductors do for photons. Indeed, the hypothetical cosmic medium must produce masses on a much larger scale: the masses of *W* and *Z* in (not) empty space are roughly 10^{16} times those of photons in superconductors.

The search for appropriate metaphors has occupied science writers and journalists, and yours truly, for some time. Early on I suggested *cosmic molasses*, which became inordinately popular. My motivation was primarily poetic: I wanted to used the title "Cosmic Molasses for Particle Masses" for a piece in *New Scientist*. They mangled my title to "Masses and Molasses" (with the lame excuse of space constraints), but the idea stuck. Molasses is that way.

I much prefer a different metaphor, which comes with a little story. On a water-covered planet in a galaxy far, far away, fish have evolved to become intelligent—so intelligent, that some of them become physicists, and begin to study the ways things move. At first the fish-physicists derive very complicated laws of motion, because (as *we* know) the motion of bodies through water is complicated. But one day a fish genius—Fish Newton—proposes that the basic laws of motion are much simpler and more beautiful: in fact, they are Newton's Laws of Motion *(Figure 2)*. She proposes that the observed motions look complicated due to the

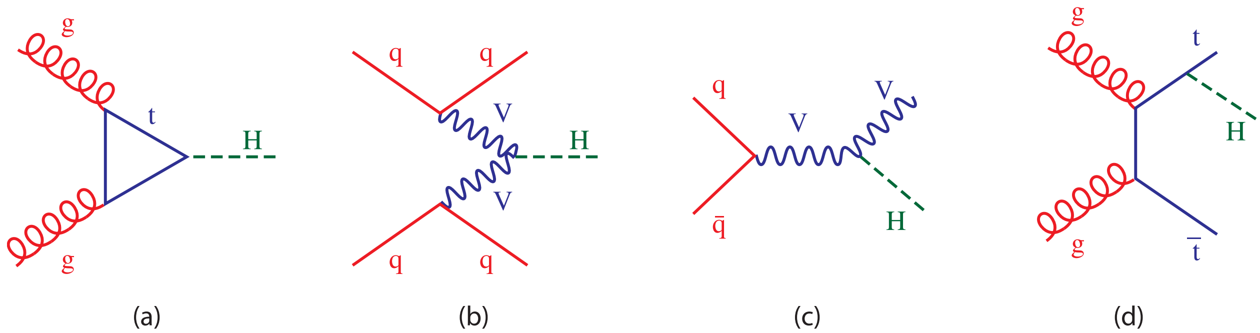


FIGURE 3

Different ways to produce the Higgs particle. *The reactions develop from left to right.*
(a) *Gluon fusion: 87%. Gluons* g *inside the two colliding protons do not couple directly to the Higgs particle, but produce it indirectly, through a remarkable quantum process. The gluons fluctuate into a virtual top-antitop quark pair* t. *The top quarks have a robust coupling to the Higgs particle* H, *and recombine to produce it.*
(b) *Vector boson fusion: 7%. Quarks* q *inside the proton radiate W or Z vector bosons* V, *which fuse into* H. *The final state contains two energetic quarks, which materialize as jets, in addition to the Higgs particle.*
(c) *Vector boson radiation: 5%. A quark and antiquark combine into a* W *or* Z *boson, which radiates* H. *The final state contains an additional* W *or* Z.
(d) *Top radiation: 1%. The dynamics resemble* a, *but here the top quarks have enough energy to materialize, and are visible in the final state.*

influence of a material—call it "water"—that fills the world. After a lot of work, the fish manage to confirm Fish Newton's theory by isolating molecules of water.

According to the Higgs mechanism, we are like those fish. We are immersed in a cosmic ocean, which complicates the observed laws of physics.

Physicists have been invoking the Higgs mechanism for many years, and with its use have gone from success to success. Many aspects of the interactions of W and Z bosons, besides their masses, were predicted accurately by using the beautiful equations of massless particles and gauge symmetry, with their consequences suitably modified by a space-filling material. In this way, we built up a convincing case for the existence of our cosmic ocean. But ultimately that case rested on circumstantial evidence. There was no clear answer to an obvious question:

What's it made from?

A portrait of the suspect

No known substance could provide the cosmic ocean. No combination of the known quarks, leptons, gluons, or other particles has the right properties to make it. Something new was required.

In principle the cosmic ocean could have been a composite of several substances, and the substances themselves could be complicated. The literature of theoretical particle physics contains hundreds, if not thousands, of proposals of that kind. But among all the logical possibilities, there is a simplest and most economical, which defines the so-called *minimal* Standard Model. In that minimal model, the cosmic material is made from just one ingredient. Though the terminology in this subject is both confused and changing, here when I refer to the "Higgs particle" I will mean the unique new particle that is introduced to complete the minimal Standard Model.

We can infer a lot about how the Higgs particle interacts with other forms of matter. After all (since we're embedded in the cosmic ocean) we've been observing the properties of Higgs particles *en masse* since time immemorial. In fact all the properties of that particle are predicted uniquely, once its mass is known. For instance, both its spin and its electric charge must be zero, since it has got to look like "nothing."

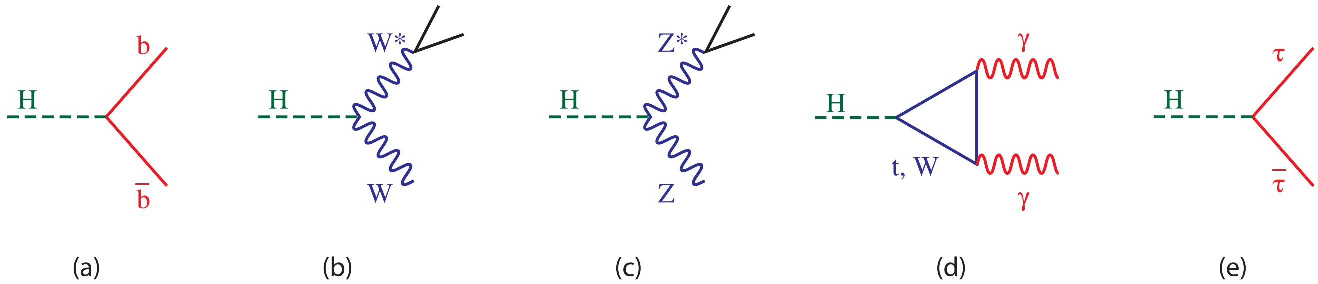


FIGURE 4

Decay modes of the Higgs particle.
(a) *Bottom quark-antiquark pairs: 57.7%.*
(b) W *boson pairs: 21.5%.* H *is not heavy enough to decay into two* W *bosons, so one (*W**) never materializes as such, but "decays" virtually before it is actually produced! The other decays normally.*
(c) Z *bosons pairs: 2.6%. Similar to* W *boson pairs, conceptually, but this channel has important experimental advantages.*
(d) *Photon pairs: .23%. Since photons, like gluons, do not couple directly to the Higgs particle, this decay proceeds by a mechanism similar to gluon fusion* (Figure 3a.) *Not only top-antitop, but also* W *boson pairs contribute significantly. This decay mode is quite rare, but offers exceptional experimental advantages, and has been the primary discovery channel.*
(e) *Tau lepton-antilepton pairs: 6.3%. Other decay channels are possible, notably gluon pairs and charm quark-antiquark pairs, but are more challenging to access experimentally, because energetic gluons and charm quarks are easily produced by other means, raising severe signal/noise issues.*

As I already mentioned, the Higgs particle is a rare and fleeting phenomenon. To hunt it down required deep consideration of the traces it leaves, and strategic planning to look for them amidst the debris of proton-proton collisions.

Figures 3 and *4* summarize the most important production mechanisms and decay modes.

Gathering evidence

The dominant production mechanism is especially remarkable. Ordinary matter couples very feebly to H. (That's a big reason why electrons and protons can be much lighter than W and Z—they don't feel its drag.) In fact the dominant coupling arises through an indirect process, "gluon fusion", that I discovered in 1976. It is displayed in *Figure 3a*.

Gluons don't couple to the Higgs particle directly at all. The coupling is a purely quantum effect. It is characteristic of quantum mechanics that spontaneous fluctuations, or "virtual particles", occur. Usually these fluctuations come to be and pass away without discernable effect, but they also influence the behavior of nearby real particles. In the most important gluon fusion process, quantitatively, gluons inject energy into a virtual pair consisting of a top quark t and an antitop antiquark $\bar{t}$. t and $\bar{t}$ couple powerfully to the Higgs particle—that's a big reason why they are very heavy—so there's a fair chance that they will bring forth that particle before expiring.

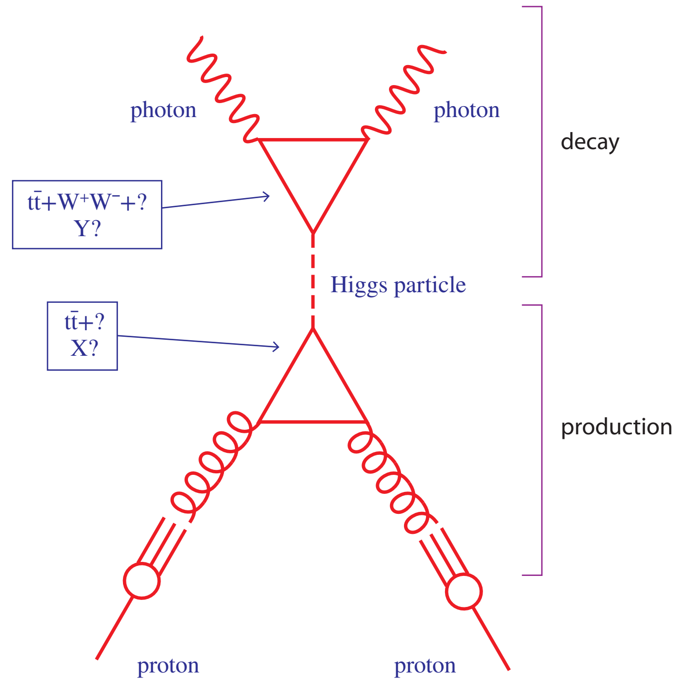
H decay into two photons, $H \rightarrow \gamma\gamma$, shown in *Figure 4d*, arises through a similar dynamics. Photons do not couple directly to the Higgs particle, but communicate with it through virtual $\bar{t}t$, and W^+W^- pairs. Although this is quite a rare decay mode, it was the primary discovery mode for H, because it has two big advantages from an experimental point of view.

The first is, that the energy and momentum of high-energy photons can be measured quite accurately. We can combine these, according to the kinematics of special relativity, to determine the "effective mass" of a photon pair. If the photons result from decay of a particle with mass M, then their effective mass will be M.

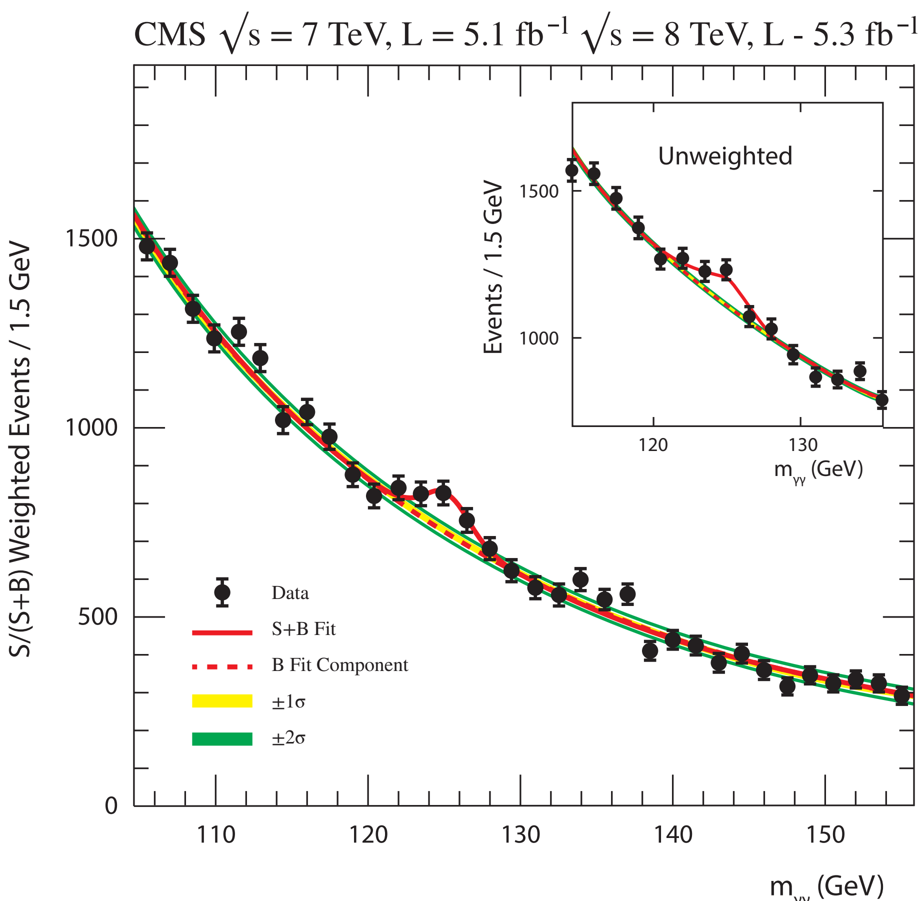
The second is that energetic photon pairs are rather difficult to produce by ordinary (non-Higgs) Standard Model processes, so that the background is suppressed.

FIGURE 5

(a) *The discovery mode for the Higgs particle H. Gluons within the colliding protons communicate with H through virtual top-antitop $t\bar{t}$ quark pairs, and then H decays through virtual particles into two photons, which are the observable particles. Many other processes can produce photons, but the effective mass of pairs produced this way must add up to a specific value, namely the H mass. So the signature of H is an enhancement in the production rate of pairs for pairs with a specific effective mass, compared to nearby values of the mass.*
(b) *Experimental measurements indicate just such an enhancement, at M_H ~ 125 GeV (Courtesy of CMS experiment/CERN)*



(a)



(b)

Exploiting both these advantages, experimentalists designed their search strategy: Measure the effective masses of many photon pairs, and look for an enhancement at one particular value, relative to nearby ones. The overall process makes a pretty picture, shown in *Figure 5a*.

There's a bonus: Since the background can be calculated reliably, the size of the enhancement, relative to background, gives a measurement of the production rate of H, times its branching ratio into $\gamma\gamma$. One can then check, whether the measured enhancement agrees the predictions for the minimal H. This is especially interesting, because those rates open a new window on the unknown. Specifically: There might well be other heavy particles, yet unobserved, contributing in their virtual form! So far the observations are consistent with the unembellished minimal model, but greater accuracy is both attainable, and highly desirable.

Many combinations of production and decay modes are possible. This enables a program of detailed, stringent testing of the minimal Standard Model, by measuring as many combinations as possible as accurately as possible. That program, though still in its early stages, is now well launched.

The analysis of H decay into ZZ pairs is especially advanced, because the decay of the Zs into four leptons allows full kinematic reconstruction. This has allowed experimentalists to verify that the spin of H is indeed 0 (for experts: and that its parity is even).

So far these observations, and all others, are consistent with the predictions of the minimal Standard Model. That model is unlikely to be the final word on H, but it has provided an excellent first draft.

Winning a bet, upping the ante

Up to now I have described the Higgs particle in its role as triumph and window—corresponding to the recent past and the present. Now I'd like to discuss its significance for the future.

To establish my credibility as an oracle, and to show I've got skin in the game, I'll start with the story of my 2005 bet with Janet Conrad (then a professor at Columbia, now at MIT), and two recent follow-ups.

Let's set the scene. Janet and I were at an important international conference in Uppsala, Sweden. The conference banquet was held in the great hall of Uppsala Castle. I sat next to Janet, and eventually we got to talking about the Higgs particle. Like the good experimentalist she is, Janet was extremely skeptical about everything I said. After a glass or two of wine her trash talk got under my skin, and I proposed a bet. To appreciate the rashness of my bet, a little background is in order.

Within the framework of the minimal Standard Model, neither the origin nor the value of the mass of the Higgs particle itself is explained. M_H appears simply as a free parameter, to be determined experimentally.

(By the way, that is another reason why it is comically absurd to say that the Higgs particle explains "the origin of mass": Its very own mass arises as a *deus ex machina*. And sorry, but no, that fact does not make it the God particle.)

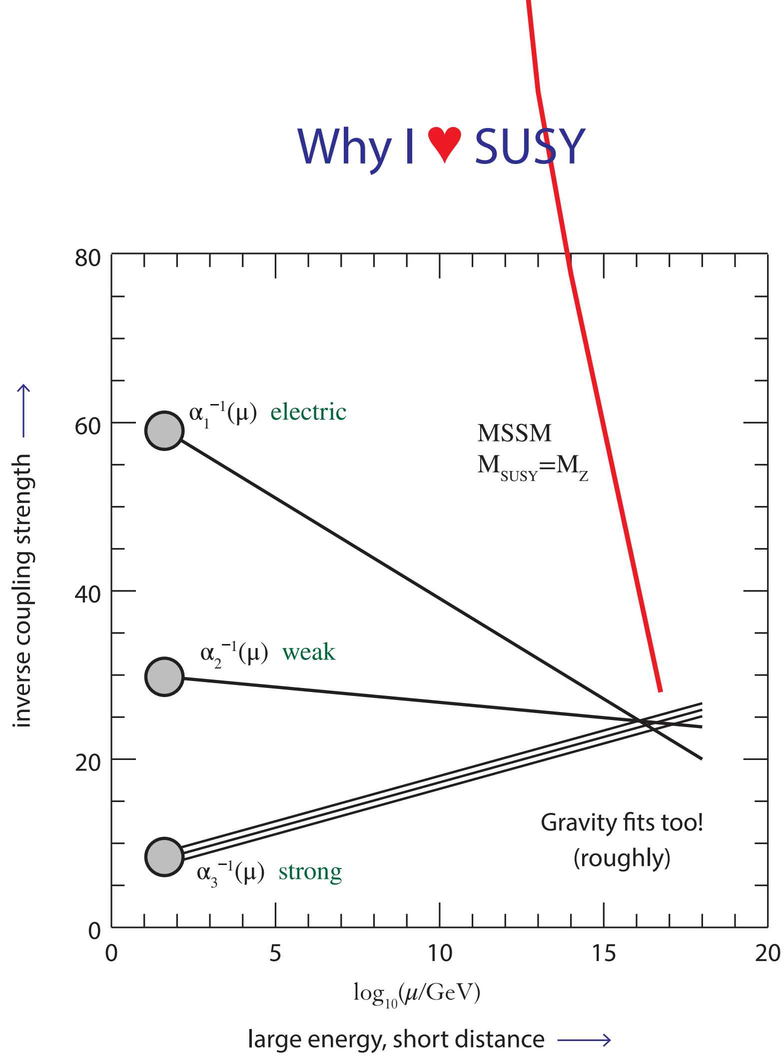


FIGURE 6

Quantitative unification. *At the (relatively) low energies and (relatively) large distances we have accessed experimentally, the four fundamental forces—strong, weak, electromagnetic, and gravitational—have significantly different strengths. Theoretically, however, those measured values are not the most basic ones, since the measurements are complicated by the effects of quantum fluctuations (virtual particles) and by the cosmic ocean we discussed above. We can strip those complications away, theoretically, by calculation. We can estimate what measurements would reveal, were they to be carried out at shorter distances. The quantitative predictions we obtain depend, of course, on what we assume about the virtual particles and the ocean. If we extend the minimal Standard Model to the minimal Supersymmetric Standard Model, and use that extension in our calculations, we find that the non-gravitational forces unify accurately, and even gravity (the red line), which starts out hopelessly feebler than the other forces, comes close.*

In 2005, the value of the Higgs particle mass was very poorly constrained—if indeed the Higgs particle existed at all. Searches up to 115 GeV had come up empty, and the theory starts to self-destruct for masses greater than about 900 GeV. Anything in between was fair game, even within the minimal Standard Model—and besides, that whole framework was in question. Other than that, nothing was known for sure.

Yet I bet, *at 10-1 odds*, that a particle with the properties predicted for the Higgs particle would be discovered at the LHC, within the small window of mass below 150 GeV. If no such particle were found, I would have to give 100 chocolate replica Nobel medals to Janet; were it found, she would give me 10.

Why was I so cocky? Because I trust in Nature's wonderful revelation, the unification of forces, displayed in *Figure 6* and explained in its caption.

The message is simple and clear: If we enhance the symmetry of the Minimal Standard Model (MSM) in a minimal way, so that it becomes the Minimal Supersymmetric Standard Model (MSSM), then unification of forces is a qualitatively gorgeous, quantitatively precise consequence. On the other hand, if we stick to the Minimal Standard Model, without supersymmetry (SUSY), it doesn't work nearly as well. Other shenanigans—that is, other people's speculations—in Beyond the Standard Model (BSM) physics, such as new strongly interacting sectors ("technicolor") or new spatial dimensions ("large volume compactifications" or "brane worlds") also tend to ruin it. That's why I ♥ SUSY.

But SUSY has another, most relevant consequence: It constrains the Higgs particle and its mass. It turns out that in any minimal or near-minimal model with low energy supersymmetry, i.e. in the kind of model that supports *Figure 6*, there is a particle that closely resembles the Higgs particle of the standard model, and furthermore we find that its mass is < 150 GeV.

In September of 2012, I got my reward, at a gala Higgs celebration in Uppsala Castle, before an audience of several hundreds packed into the great hall *(Figure 7)*.

In the aftermath, another fine experimentalist, Tord Ekelöf of Uppsala University, has taken up the gauntlet. I've bet him that some of the other new particles predicted by SUSY will be discovered at the LHC by 2020. This time I got even odds, for 100 Nobel chocolates.

Philosophical implications

The discovery of the Higgs particle, through its vindication of the Higgs mechanism, has important philosophical implications, both for fundamental physics and for cosmology.

We have learned that we live in a cosmic ocean that obscures, but does not abolish, the symmetry and beauty of the fundamental laws. We are inspired to take symmetry further.

Could *all* the apparent distinctions among different elementary particles arise from the influence of space-filling materials? Detailed investigations answer: Very possibly. The unification of *strengths* of forces, discussed above, provides a concrete test of this vision. In this way, Einstein's dream of unification has evolved from mystic faith to quantitative science.

FIGURE 7

The rewards of right thinking. *You can re-live the presentation at* www.uu.se/en/research/higgs-fest/. *These coins, by the way, are not so easy to come by. They're on sale at the Nobel Museum in Stockholm. Alternatively, you might arrange to have a friend grab leftovers at the Nobel Prize banquet, where they are sprinkled in abundance at every table. (Photo by Betsy Devine)*

Since space is—or, more flexibly, since space is filled with—a material, it is natural to think that the properties of that material, like the properties of other materials, are negotiable. Its properties might change in time, triggering episodes of cosmic reorganization, including Alan Guth's inflation. Its properties might be different far away, leading to a "multiverse" effectively governed by disparate physical laws. These concepts, which might once have seemed fanciful, now appear unavoidable.

PROFESSOR FRANK WILCZEK *is one of the most eminent theoretical physicists at work today. When only 21-years old and a graduate student at Princeton University, in collaboration with David Gross he discovered the fundamental equations for one of the four basic forces of nature: the strong force. That work led to a Nobel Prize. He is also known, among other things, for the development of unified field theories, the invention of axions, and the discovery and exploitation of new forms of quantum statistics (anyons).*

Professor Wilczek is a second-generation American and a graduate of New York City's public schools. Presently he is the Herman Feshbach Professor of Physics at MIT.

Professor Wilczek has received many honors. Notably, he was among the earliest MacArthur Fellows (1982-87) and in 2004 he received the Nobel Prize in Physics. He contributes regularly to Physics Today *and to* Nature*, explaining topics at the frontiers of physics to wider scientific audiences, and is much in demand as a public lecturer.*