Can a light Higgs particle have escaped detection?

2 July 2010

Abstract

The standard model of elementary particle physics (SM) demands the existence of a neutral and spinless so-called Higgs particle. Unlike the neutral spin-$\frac{1}{2}$ neutrino, which theoretically may or may not have a small mass, the Higgs is required by SM theory to possess nonzero mass. However, SM does not predict the value of this mass. Experimental physicists have long been searching for Higgs particles in the GeV region of the energy spectrum without success. This failure suggests that one should also investigate the possibility that the Higgs is very light—not much heavier than the neutrino—before SM is declared wrong and all interest is focused on the hunt for "new physics."

[Comment: It has been shown that a very heavy (above 100 GeV) Higgs causes a discrepancy between theoretical predictions and high-precision measurements of the muon anomalous magnetic moment (sometimes referred to as "muon g-2" or "the muon's g-factor"). This discrepancy in combination with a conviction that the Higgs is very heavy has led many physicists to conclude that SM is wrong or incomplete. See *New Scientist* 22 May 2010.]

Matter-building particles: quarks and charged leptons

Ordinary matter—the atomic elements ranging from hydrogen to uranium and beyond—is built from fractionally charged d and u quarks (uud forming a proton and ddu a neutron) and electrons. Heavier quarks (s and c, b and t) and charged leptons (muon, tauon) decay rapidly and do not form stable matter.

[Comment on terminology: Because the neutrino is said to be a lepton, one must distinguish between electrically charged (e, μ, τ) and neutral (ν_e, ν_μ, ν_τ) leptons. In contrast, the word quark is unambiguous, since there are no neutral quarks.]

Forces known to act in the microscopic quantum world

Three forces—strong, electromagnetic, and weak—govern all observed interactions between elementary particles in the microscopic quantum world.

The strong force is mediated by eight massless spin-1 gluons ($g_1, \ldots, g_8$) and only acts on quarks.

The electromagnetic force is mediated by the massless spin-1 photon (γ) and acts on all types of electrically charged particles. Thus, the photon provides a link between the charged leptons and the (fractionally charged) quarks.

The weak force acts on both charged leptons and (fractionally charged) quarks. Thus, the neutral Higgs, neutrino, and Z particles and the charged W particle provide another, weak link between the two types of matter-building particles—quarks and charged leptons.

Unlike the carriers of the strong and electromagnetic forces, which are massless spin-1 particles, the weakly interacting particles have nonzero mass and three types of spin:

The neutral spin-0 Higgs couples graphically to quarks and charged leptons in the same way as the spin-1 photon does. [See Martinus Veltman, *Diagrammatica: The Path to Feynman Diagrams*, pp. 269-271, where the photon is denoted by A.] Therefore, since a spin-0 particle is unable to carry polarization, the Higgs may be looked upon as a massive photon stripped of its electromagnetic clothing.

The neutral spin-$\frac{1}{2}$ neutrino is known to be lighter than the electron (that is, lighter than 0.511 MeV) and has no analogue among the rest of the particles.

The neutral spin-1 Z particle couples graphically to quarks and charged leptons in the same way as the the photon and Higgs do. [See *Diagrammatica*, pp. 269-271.] It may be looked upon as a massive photon that is much heavier than a proton (91.2 GeV versus 0.938 GeV).

The electrically charged spin-1 W is a heavy particle (80.4 GeV) that has no analogue among the rest of the particles.

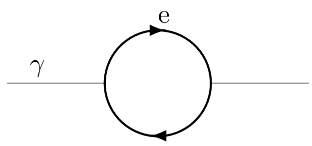
The masses of the Z and W particles determine the strength of the weak force. Alternatively, the strength of the weak force determines the Z and W masses. Thus, M_W is obtained from the Fermi coupling constant G_F via $M_W^2 = \pi\alpha(\hbar c)^3/\sqrt{2}G_F c^4 \sin^2\theta_W$ and M_Z from the relation $M_W/M_Z = \cos\theta_W$ after the theoretically unknown value of the so-called Weinberg angle θ_W has been experimentally determined.

The spin-0 Higgs and spin-$\frac{1}{2}$ neutrino are similar in the sense that SM theory does not predict their masses. Thus, the neutrino was long thought to be massless, but has recently been found to have a small mass and being able to exist in—and oscillate between—three different mass states. SM predicts that the Higgs should have nonzero mass, but nothing in SM theory—that is, in electromagnetic (QED), weak, or strong (QCD) theories—demands it to be very much heavier than the neutrino. Also, SM theory does not exclude the possibility that, like the neutrino, the Higgs may exist in three mass states—one associated with the electron, another with the muon, and a third with the tauon.

[Comment: The generally accepted belief that the Higgs is about as heavy as (or maybe even much heavier than) the Z and W particles derives from cosmological considerations and is not anchored in the experimentally well-established standard model of elementary particle physics. That is, SM theory does not exclude the possibility of a very light Higgs particle.]

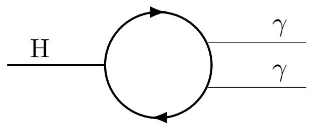
The photon propagator

For a fleeting moment, the photon may disintegrate into a virtual electron-positron pair and form an electron loop graphically described by a two-vertex—that is, a second-order—so-called photon-energy diagram:

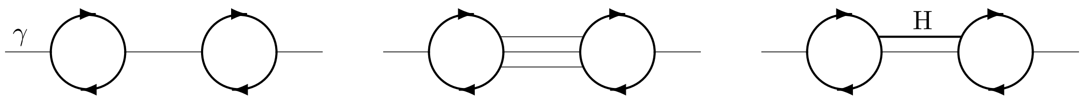


An identical-looking diagram holds for the Higgs particle. Not only the electron, but all charged elementary particles (e, μ, τ, d, u, s, c, b, t, and W) form shortlived virtual pairs or loops in the photon and Higgs propagators.

Conservation of its polarization forbids a photon from transforming into one or more Higgs particles. In contrast, the Higgs is unstable and may decay into a pair of photons:

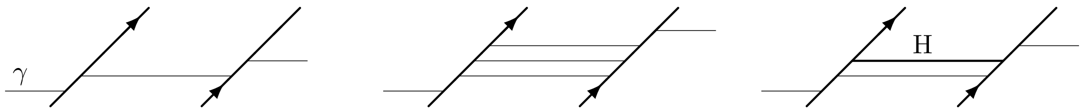


According to Furry's theorem, only loops with an even number of external (incoming or outgoing) photon lines contribute to physical processes. Thus, if a pair of photon lines are added between two loops in a so-called reducible or improper photon self-energy graph (left), the loops become connected, and an irreducible or proper graph of eighth order is formed (middle):



Alternatively, two unconnected loops may be combined into one irreducible, sixth-order Feynman diagram via the addition of a single Higgs line (right).

The appearance of a Higgs or other massive particle in the photon propagator does not reduce the speed of a free photon whose speed is always c. But the picture changes if the virtual-particle loops are replaced by real particles that are sufficiently near each other to allow them to exchange virtual particles:



The time delay between absorption and reemission of a photon by a real particle (electron or proton, say) has the effect that light rays travel slower than c in transparent media. The difference between the time a Higgs remains absorbed in a particle (right) and the time a photon pair does so (middle) introduces an anomaly in the signal speed. This "Higgs anomaly" may be too small to be experimentally demonstrable.

The massive Higgs particle is slower than the massless photon which always travels with the speed of light, c, if one ignores quantum fluctuations that are smoothed out in macroscopic time-of-flight measurements. [See Richard P. Feynman, *QED: The Strange Theory of Light and Matter*, p. 89.]

If the energy of the photon is much lower than the rest energy of the Higgs, the probability for a virtual Higgs particle to accompany the photon in its jump between two adjacent real particles (right in the figure) is very small, and no slowing down of the signal speed will be observed.

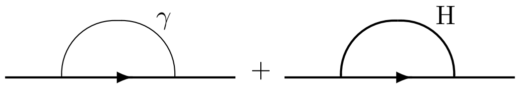
Likewise, if the energy of the photon is much higher than the rest energy of the Higgs, virtual Higgs particles will move with speeds very close to c, which means that they won't cause any noticeable signal delay.

However, when the energy of the photon is in the vicinity of the Higgs rest energy, the virtual Higgs particle that occasionally accompanies the massless photon in its jump between two real particles may be only slightly off mass-shell and have an energy that approximately equals its rest energy. When this happens, the Higgs has low kinetic energy and moves with a speed that may be much lower than the speed of light, c.

The result is that signals passing through a thin plasma may travel noticeably slower than they would do so in the absence of the Higgs effect. In practice, this means that the signal speed's dependence on photon frequency and plasma density may measurably differ from what it would be if no virtual Higgs particles were present in the photon propagator.

SM-based calculation of Higgs masses

According to QED theory, the mass m of a charged lepton (with m standing for m_e, m_μ, or m_τ) is the sum of the lepton's bare mass, m_0, and its self-mass, δm: $m = m_0 + \delta m$, where the value of m_0 is undetermined and δm is infinite.



The figure shows the lowest-order (that is, second-order) lepton self-mass diagrams involving a virtual photon and a virtual Higgs, respectively.

Ignoring other contributions to the lepton mass, one obtains from standard electroweak theory the expression

$$\begin{aligned} m &= m_0 + \delta m^{(2)}(\gamma) + \delta m^{(2)}(H) \\ &= m_0 + \frac{3}{2}\left(\frac{\alpha}{\pi}\right) \ln \frac{\Lambda}{m} \left[1 - \frac{G_F (mc^2)^2/(\hbar c)^3}{4\sqrt{2}\pi\alpha}\right] m, \end{aligned} \tag{1}$$

for the renormalized mass m of the charged lepton. In the equation, Λ is a UV cutoff mass introduced to make the mathematics finite. With m_0 unknown and δm divergent, Eq. (1) appears to be void of physical content.

Now, the self-mass term is one of four infinite renormalization constants (δm, Z_1, Z_2, and Z_3) appearing in QED theory. In the 1960s, the so-called pure QED or JBW hypothesis was developed by Kenneth Johnson, Marshall Baker, and Ray Willey [*Phys. Rev.* 136 B1111 (1964)]. They managed to show that if Z_3 is nonzero, a suitable choice of gauge eliminates the divergence in $Z_1 = Z_2$. Also, they found that avoidance of perturbation theory eliminates the divergences in δm, which implies that m equals δm and the bare mass m_0 is zero.

Even if it has not been rigorously proven, the JBW hypothesis is appealing because it turns QED into a self-contained finite theory. When considering the present calculation involving lepton masses, one has two options. The first option is to believe that the JBW hypothesis is wrong and conclude that the lepton self-mass is in principle incalculable. Alternatively, one may note that, even if nobody has been able to prove that the JBW hypothesis holds true, no one has proved it wrong, either.

However, if one wants to adhere to the scientific method, there is but one choice. One must tentatively assume that nature is predictable and, consequently, attempt the calculation relying on the JBW hypothesis. Doing so (that is, setting $m_0 = 0$), one immediately obtains from Eq. (1) the ratio

$$\frac{\delta m^{(2)}(H)}{\delta m^{(2)}(\gamma)} = -\frac{G_F (mc^2)^2/(\hbar c)^3}{4\sqrt{2}\pi\alpha} \tag{2}$$

between the two contributions to the mass of the charged lepton.

In elementary-particle perturbation theory (PT), the Higgs-lepton diagrams exactly parallel the photon-lepton diagrams. Therefore, one may expect that the ratio between the Higgs and photon contributions to the lepton mass should remain the same as in Eq. (2) also when higher-order self-mass diagrams are considered. In other words,

$$\frac{\delta m(H)}{\delta m(\gamma)} = -\frac{G_F(mc^2)^2/(\hbar c)^3}{4\sqrt{2}\pi\alpha} \tag{3}$$

is expected to hold true.

The Higgs and other possible corrections are small in comparison with the photon's contribution to the lepton mass. Therefore, one may set $\delta m(\gamma)$ equal to m in the left denominator of Eq. (3) and obtain as a good approximation

$$\delta m(H) = -(4\sqrt{2}\pi\alpha)^{-1}G_F(\hbar c)^{-3}(mc^2)^2 m \tag{4}$$

for the contribution of the Higgs particle to the lepton mass.

This result does not say anything definite about the mass of the Higgs particle itself. However, when speculating about what events might have taken place in the newborn universe, it is natural to ask: What happened to the mass that was pulled from the lepton when the Higgs particle appeared for the first time? If the Higgs is going to have a theoretically calculable mass, there can be but one answer to this question: The lepton was forced to hand over the now missing part of its mass to the Higgs particle itself.

Again, the scientific method demands that one investigates this very simple proposition before dismissing it by referring to cosmological hypotheses that are experimentally unverified add-ons to the experimentally well-established standard model of elementary particle physics. In other words, one must tentatively assume that the Higgs mass is directly calculable using standard SM methods, and that its value to a good approximation is given by

$$m_H = (4\sqrt{2}\pi\alpha)^{-1}G_F(\hbar c)^{-3}(mc^2)^2 m, \tag{5}$$

where m represents the lepton mass of m_e, m_μ, or m_τ, and m_H is the corresponding Higgs mass associated with each type of lepton.

For a Higgs particle emitted by an electron, muon, and tauon, respectively, one obtains from Eq. (5)

$m_{H_e}/m_e = 2.348\ 476(20)\times10^{-11}$	$m_{H_e} = 12.000\ 69(10)\ \mu\text{eV}/c^2$	$\nu_{H_e} = 2.901\ 753(25)\times10^{9}\ \text{s}^{-1}$
$m_{H_\mu}/m_\mu = 1.004\ 047(9)\times10^{-6}$	$m_{H_\mu} = 106.0859(9)\ \text{eV}/c^2$	$\nu_{H_\mu} = 2.565\ 147(22)\times10^{16}\ \text{s}^{-1}$
$m_{H_\tau}/m_\tau = 2.8400(6)\times10^{-4}$	$m_{H_\tau} = 0.504\ 67(14)\ \text{MeV}/c^2$	$\nu_{H_\tau} = 1.220\ 28(34)\times10^{20}\ \text{s}^{-1}$

A photon possessing the same energy as a Higgs particle at rest has frequency $\nu = m_H c^2/h$. This photon frequency is shown in the third column. It is seen that the predicted mass of a Higgs particle emitted by an electron corresponds to a microwave photon of frequency 2.9018 GHz, which lies near the upper end of the ultrahigh radio-frequency band (UHF, ranging from 0.3 to 3 GHz).

Higgs delay in radio communications

Because the ionosphere is transparent to high-frequency radio waves, microwaves are often used in communication with satellites. In general, the speed of microwave signals traveling through plasma increases with frequency. However, for frequencies approaching 2.9018 GHz, the speed should slow down owing to the appearance in the photon ray of virtual Higgs particles that are only slightly off mass-shell.

This "Higgs delay" might be large enough to be experimentally detectable and may already have revealed itself through the so-called Pioneer anomaly.

Nature and origin of the lepton mass

The history of the present phase of the universe begins with the birth of the electron, muon, and tauon. These spinning charged leptons first appear in the form of "frozen," not yet interacting particles. That is, at the instant of their birth, they are described by a stationary ($\partial/\partial t = 0$) differential equation. Also, they are the only particles in the universe. The lepton's mass is identical with its so-called bare mass: $m = m_0$.

Immediately upon the birth of the three spinning leptons (e, μ, τ), the photon (γ) appears and the leptons transform from noninteracting to dynamically interacting particles by handing over their initial, bare mass to virtual photons. Pure QED becomes the theory of everything (TOE). Compare with the JBW hypothesis. With $m_0 = 0$ and δm denoting the lepton's so-called self-mass, $m = \delta m(\gamma)$.

Conservation of energy forbids the existence of an expanding universe void of matter. Therefore, after all matter-carrying real electrons and positrons have annihilated each other forming massless photons ($e^- e^+ \rightarrow \gamma$), matter is recreated in the form of today's matter-carrying electrons and protons.

This creation of stable matter (and formation of a viable universe) proceeds through a series of symmetry-breaking, particle-creating events in which the strongly and weakly interacting particles appear. The value of the lepton mass m changes in three steps:

1. The leptons give a small part of their initial mass to Higgs particles for delivery to quarks that build two real pion-antipion pairs ($\pi^+\pi^-\ \pi^+\pi^-$). With $\delta m(H) = -m_H$ being the Higgs particle's negative contribution to the lepton self-mass, $m = \delta m(\gamma) - m_H$.

2. The leptons give a small part of their remaining mass to Higgs triplets—nonviable particles that today are perceived by theorists as unobservable, so-called Higgs ghosts—for delivery to quarks that transform a real pion-antipion pair ($\pi^+\pi^-$) into a real proton-antiproton pair ($p\bar{p}$): $m = \delta m(\gamma) - 4\,m_H$.

3. The quarks give the surplus mass they have no use for to neutrinos for delivery back to the leptons (a delivery that, due to incompatible sender and receiver protocols, necessitates neutrino oscillation). With $\delta m(\nu) = m_\nu$ being the neutrino's positive contribution to the lepton self-mass, $m = \delta m(\gamma) - 4\,m_H + m_\nu$.