The Higgs Boson

Abstract

{In our final segment, we cover the Higgs Boson starting with force fields and their particles.

First, we cover Quantum Electrodynamics - QED. We note that a disturbance in the electric field can create a particle – the photon. We show how the virtual photon mediates the electromagnetic force with virtual photons that are actually not particles. We also introduce coupling constants and Feynman Diagrams. We then extend this 'force particle from a force field' concept to include a matter particle from a matter field. In electromagnetic quantum field theory, this is the electron.

Next, we cover Quantum Chromo Dynamics – QCD. We show how the electromagnetic force is used as the model for the strong nuclear force that holds quarks together in protons and neutrons and holds protons and neutrons together in the atomic nucleus. We introduce color charge, gluons, virtual gluons, quark containment, and pion exchange between nucleons (the residual strong force). We also highlight the origin of mass for the proton. We then fill out the Standard Model of particle physics with the weak nuclear force and its force particles - the W and Z bosons. Using Beta Decay, we show how this force can change the actual particle in an interaction, not just accelerate it.

Next, we discuss spin oscillation as the origin of mass for elementary particles that lead to the Higgs Field and the Higgs Mechanism, and, as with all other fields, a disturbance in the Higgs Filed should create a particle – the Higgs boson. We show how the Large Hadron Collider (LHC) at CERN works and how the Higgs particle was discovered.

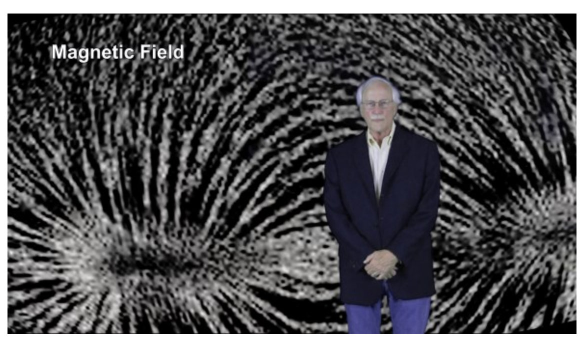
We'll conclude with a brief look at what the standard model doesn't cover (like gravity) and some of the theories in development that may very well take physics to the next level (like Super Symmetry). We end with a description of Planck's Length (the shortest distance that can exist) and its implications for the next generation of physicists.}

Introduction

[**Music**: Albinoni - Concerto for Oboe and Strings No 2 II]

Hello. And welcome to our segment on the Higgs Boson. I remember back in high school, a long time ago, when we were learning about magnetism. I was particularly impressed by what could be going on at a point here - far from the actual magnet that could move an object like an iron filing. It was back in 1894 that Michael Faraday first studied magnetic fields. He coined the phrase force field. And it was Maxwell a few years later who developed the first physics of fields - electric fields magnetic fields.

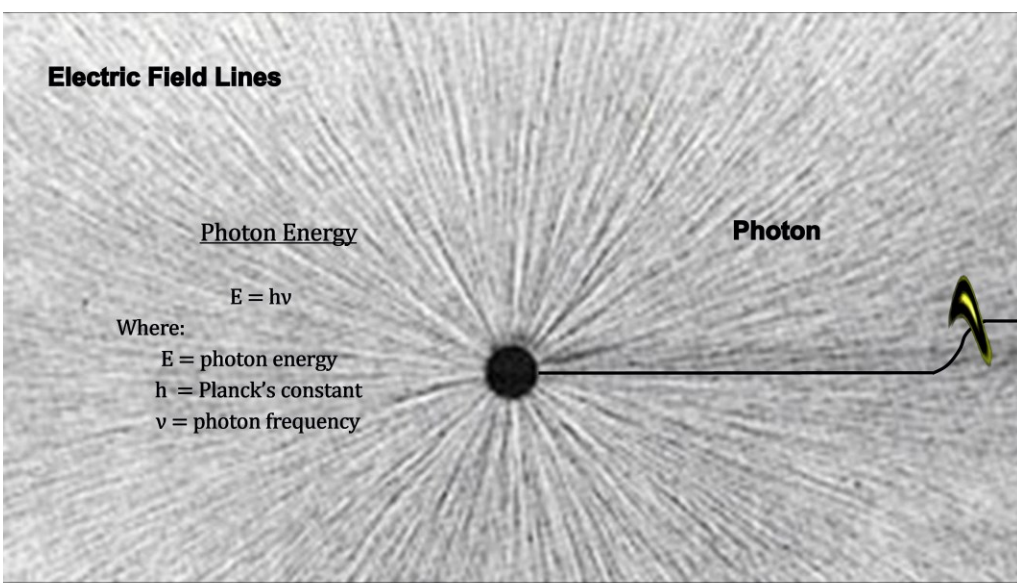
I think it was my curiosity back then that led me to the math institute at oxford where I studied the mathematical foundations for quantum field theory. Which is the theory of what's going on in this so-called empty space. If we can get a deeper understanding of the nature of force in space distant from a particle. We'll have what we need to know in order to get an understanding of the Higgs boson.



Quantized Electromagnetic Field

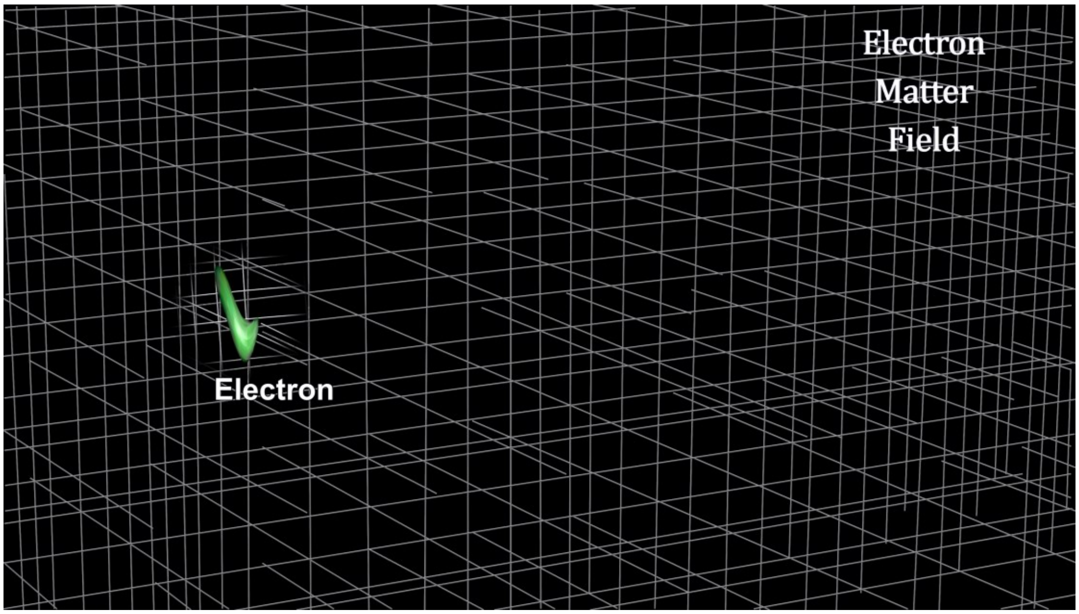
We saw in our first segment that particles with electric charge create an electromagnetic field around themselves that stretches out in all directions. This field is attached to the particle. It will go where the particle goes. In quantum field theory, fields like this are quantized. That is, they contain tiny massless energyless bits of the field.

We have seen that the photon is a certain type of disturbance (an excitation or vibration) in the electromagnetic field. We'll call these a localized vibrating ripple. It moves with a life of its own. It is not attached to the particle that created and sustains the field. The photon has no mass, no charge, a spin of 1 (a boson) and travels at the speed of light in a vacuum. In our segment on the atom, we saw that energy was quantized, and equal to Planck's constant times the photon's frequency.

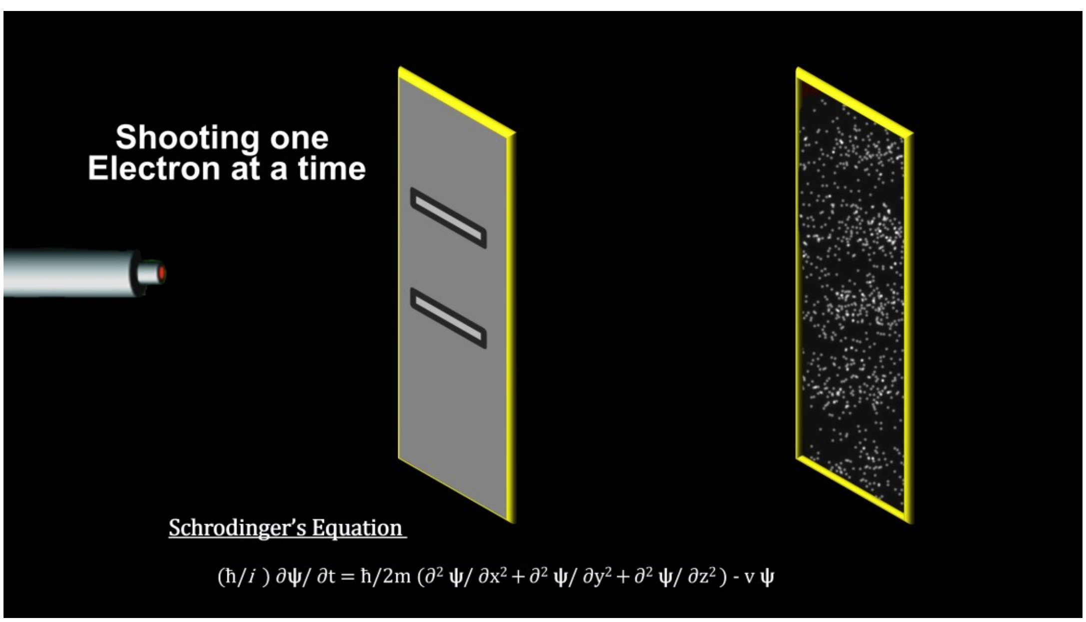


Matter Fields

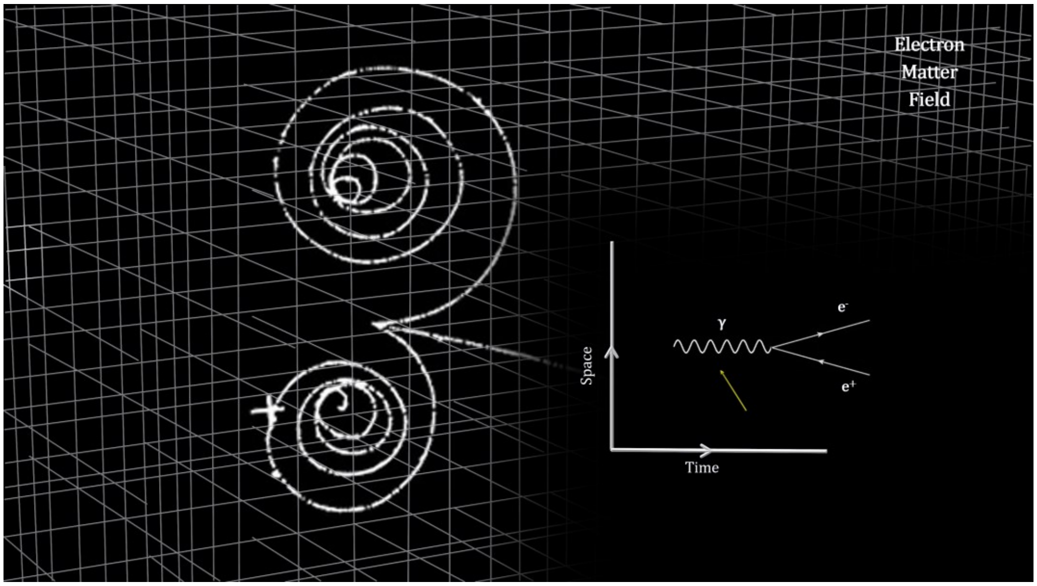
Now we take a leap. If a photon is actually a localized vibrating ripple in the quantized EM field, why not consider the electron to be a localized vibrating ripple in a quantized matter field – a field that permeates all the space in the universe.



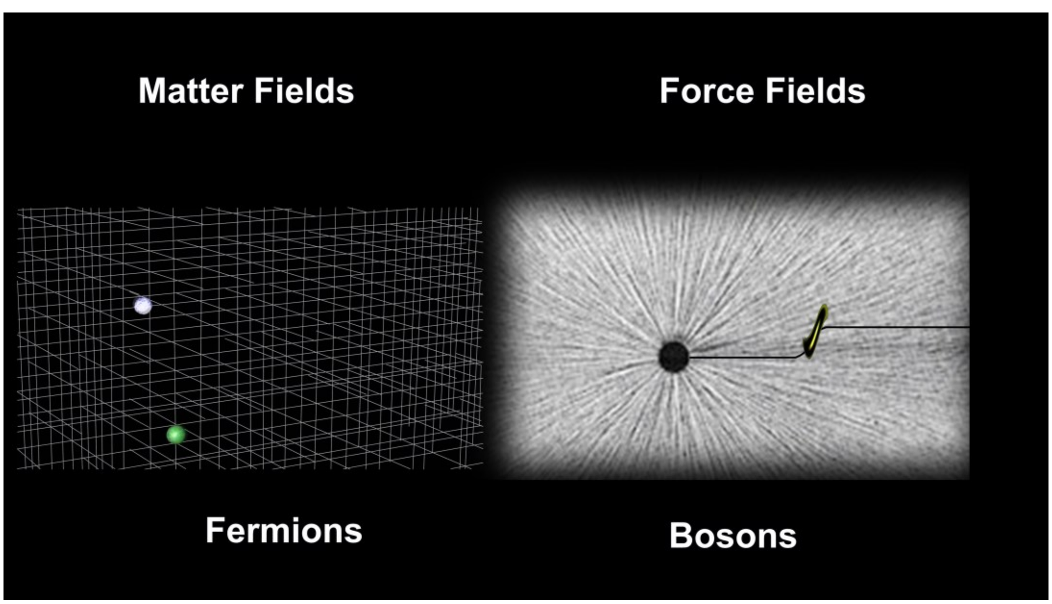
This is not as odd as it might look. In our first segment on the microscopic, we saw the wave properties of the electron. And in our second segment on the atom, we saw that its behavior is described by the Schrodinger Wave Equation.



And in our third segment on elementary particles, we saw how electrons and positrons can materialize at any point in space. What's happening is that the photon has disturbed the electron field to the point that it generates the kinds of waves that constitute electrons. A convenient way to illustrate elementary particle interactions is to use Feynman Diagrams invented by Richard Feynman in 1948. Straight lines are for fermions, squiggly lines are for force particle bosons, and the back arrow on a fermion indicate an anti-particle.

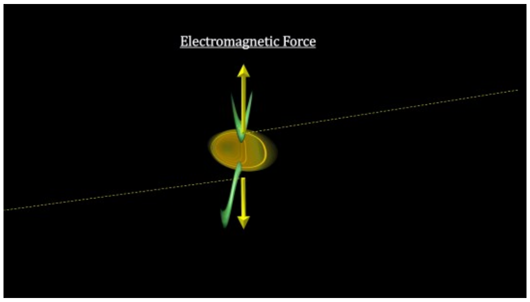


This is what Quantum Field Theory is all about. These fields generate particles. You can't have a particle without a field. And every filed will have its particle. Elementary bosons (force particles) require force fields. Elementary Fermions (matter particles) require matter fields. In modern physics, there is no such thing as empty space. Fields pervade space; they are a condition or property of space; you can't have space without fields.

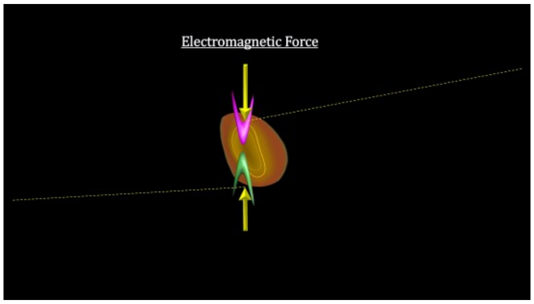


Quantum Electrodynamics QED

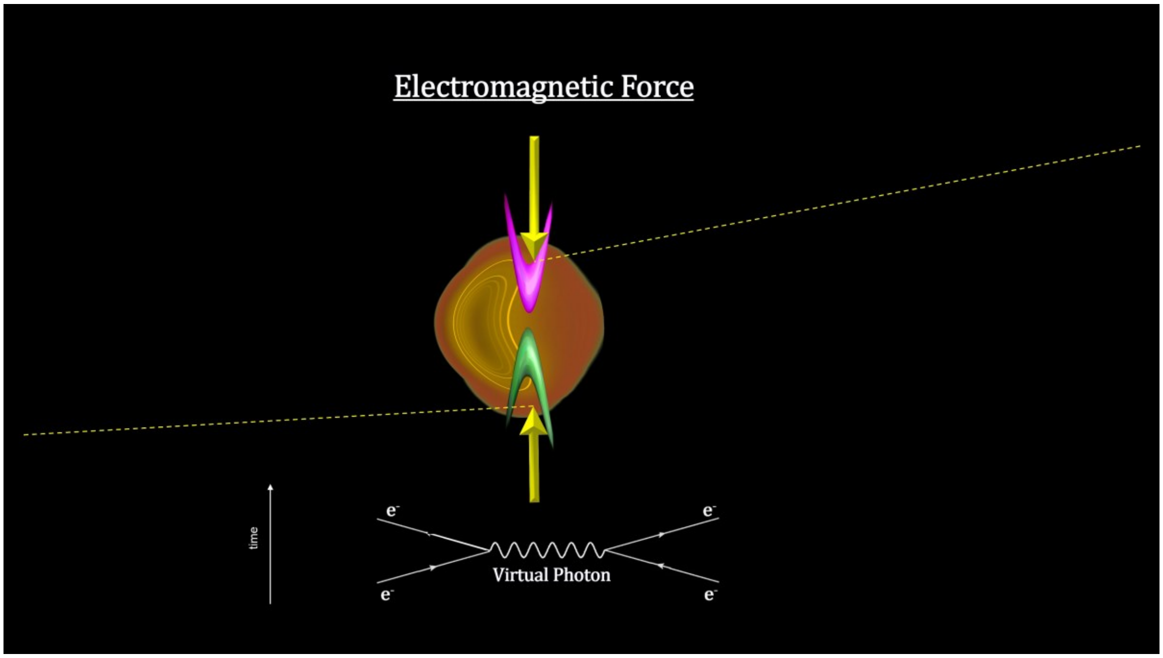
Here's a couple of examples of how this electromagnetic force works. When two electrons approach each other, their charge generates a disturbance in the electromagnetic field; this disturbance pushes them apart, and their paths are bent outward.



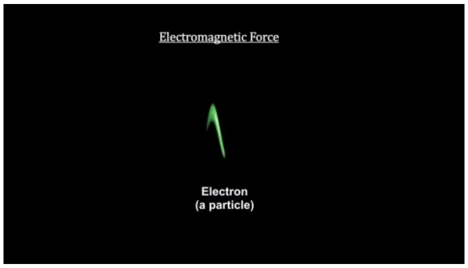
The same is true if an electron and a positron pass near each other. The disturbance in this case is similar in type but different in its details, with the result that the oppositely charged electron and positron are attracted to each other. Their paths are bent inward.



Here's the Feynman Diagram of an electron-electron interaction where the photon field 'mediates' the force that changes the momentum of the two electrons.

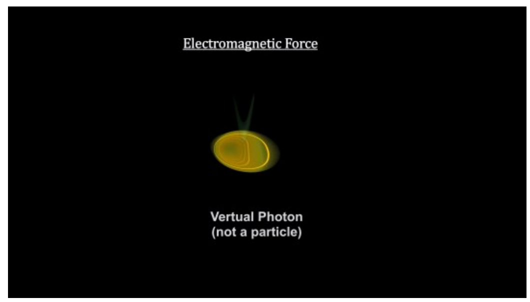


One says they "exchange virtual photons", but this is just jargon. The diagram is used for convenience. A virtual particle is not a particle at all.

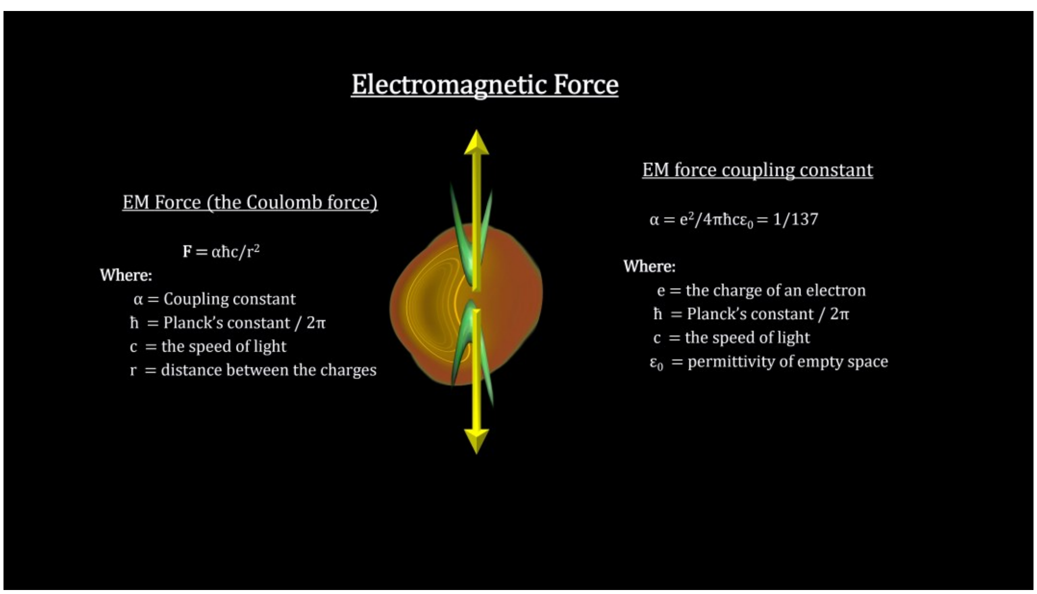


A particle is a nice, regular ripple in a field, one that can travel smoothly and effortlessly through space.

This disturbance is not a photon. It doesn't have the energy to become a well-formed ripple moving through space. This "virtual particle" is a disturbance in a field that will never be found on its own, but instead is something that is caused by the presence of other particles, often of other fields. This kind of disturbance will decay, or break apart, once its cause is gone.



This kind of interaction between the electromagnetic field and the electron field is important because the force that the two charged particles exert on each other (the coulomb force) is generated by this interaction. This force is the first of four fundamental forces in nature. They are characterized by a 'coupling constant'. The coupling constant for the electromagnetic force is 1/137. We will use the electromagnetic force as a model for the strong and weak nuclear forces. The complete picture of what is going on is still an area of active research called Quantum Electrodynamics or QED for short.

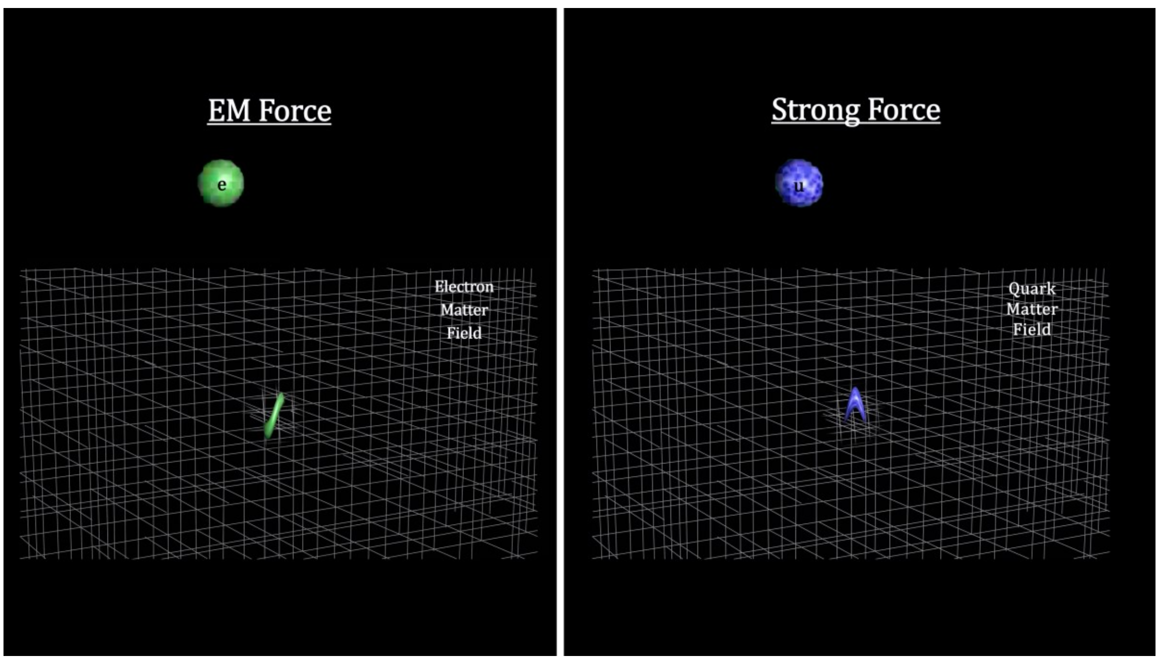


[Steven Weinberg, a theoretical physicist, summed up what we learned from QED very nicely:

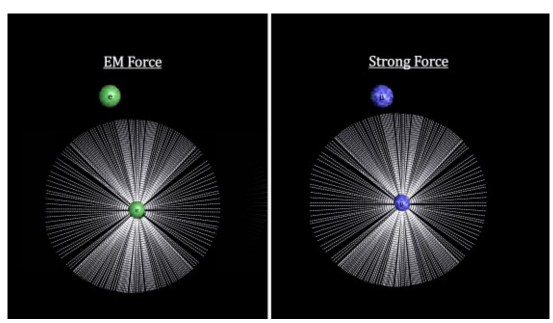
> "Just as there is an electromagnetic field, whose energy and momentum come in tiny bundles called photons, so there is also an electron field, whose energy and momentum and electric charge are found in the bundles we call electrons, and likewise for every species of elementary particle. The basic ingredients of nature are fields; particles are derivative phenomena."**]**

The Strong Nuclear Force – Quarks [**Music**: Rachmaninoff - Symphony No. 2 Adagio]

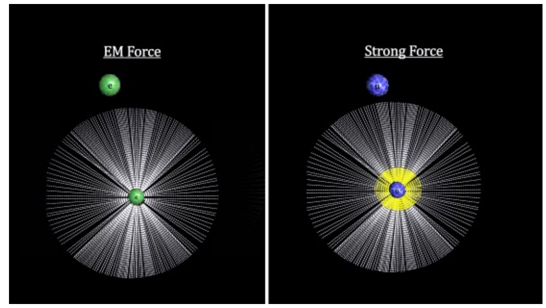
In Quantum Electro Dynamics, electrons are the central matter particle for the electromagnetic force. Using this as the model, and data from thousands of high energy scattering and collision experiments over the past twenty-five years, we have come to understand that quarks are the central matter particle for the strong nuclear force. -We have seen that an electron is a vibrating ripple in the electron matter field. Similarly, a quark is a vibrating ripple in the quark matter field.



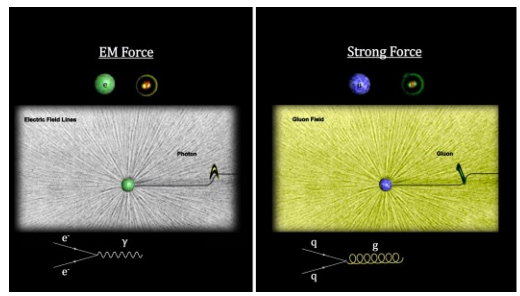
Electrons carry the electric charge that generates an electromagnetic force field. Quarks also carry electric charge so they too generate an electromagnetic force field, although, with only 1/3 or 2/3s of a charge, their electromagnetic force field is weaker than the electron's.

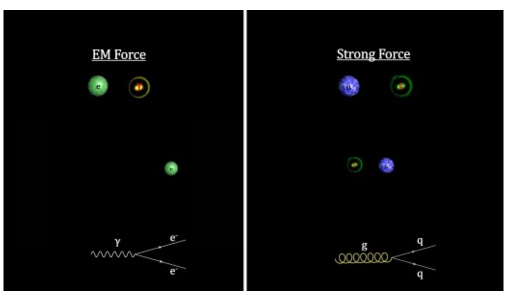


It turns out that they also carry a different kind of charge we call 'color charge'. This charge generates a gluon force field. This is a significant difference and we'll cover it in more detail shortly.



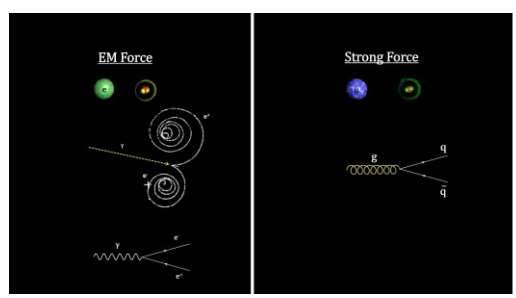
We have seen that an accelerating electron creates a vibrating ripple in its electromagnetic field called a photon. Similarly, an accelerating quark creates a vibrating ripple in its gluon field called a gluon. And like photons, gluons are massless spin 1 particles making them bosons.



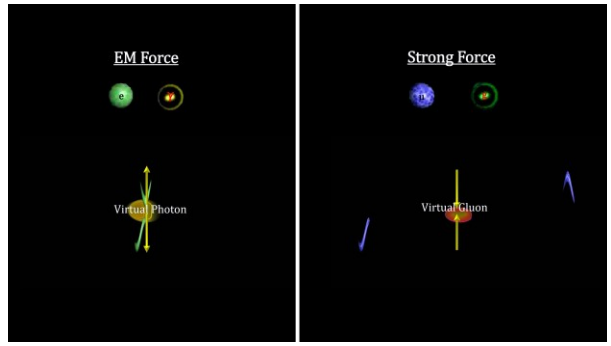


And where photons can accelerate electrons, gluons can accelerate quarks.

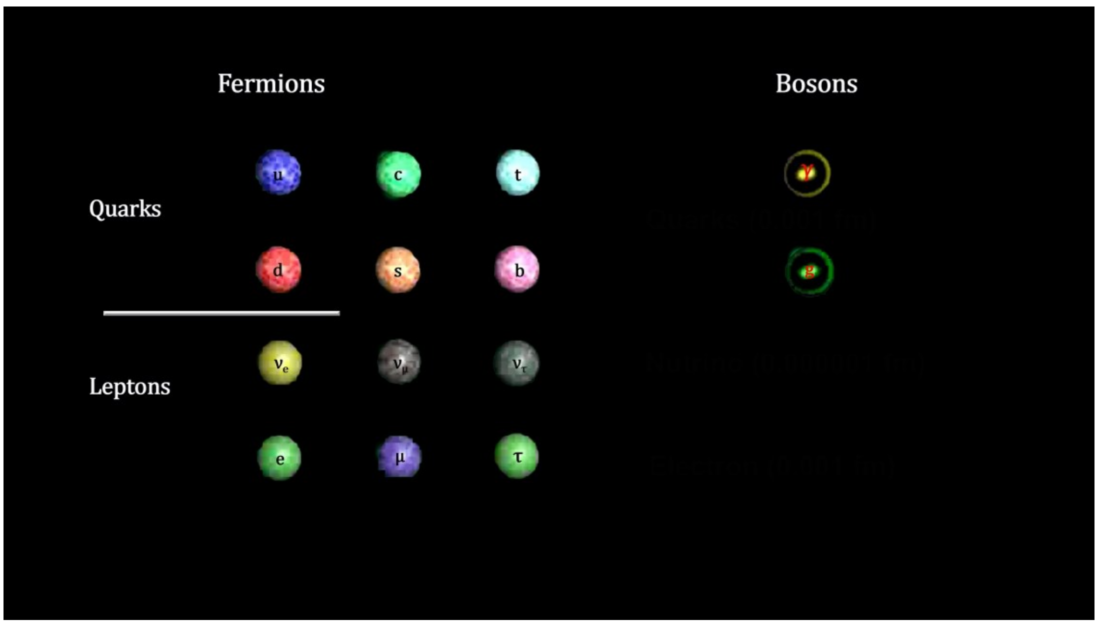
And where an energetic photon can create electron anti-electron (positron) pairs, an energetic gluon can create a quark antiquark pair.



And where interacting electrons disturb the electric field in a way that creates virtual photons that exert the force of the Electromagnetic field – the EM force, interacting quarks disturb the gluon field in a way that creates virtual gluons that exert the force of the gluon field – the strong nuclear force. Note that the EM force can be attractive or repulsive depending on the charge. But the strong force is always attractive.

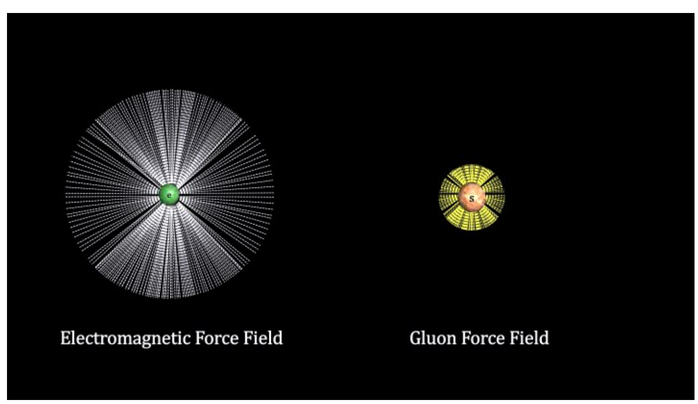


So, we can now add gluons to our standard model of particle physics.

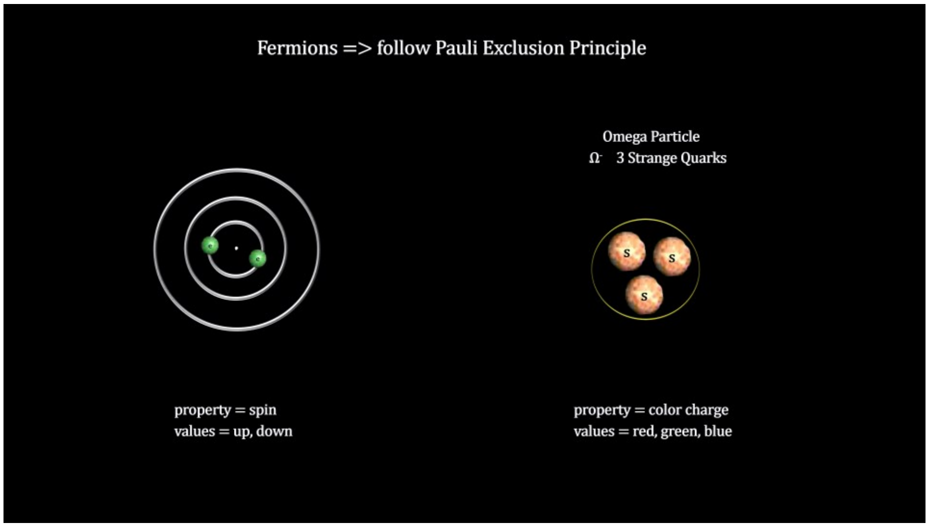


Color Charge

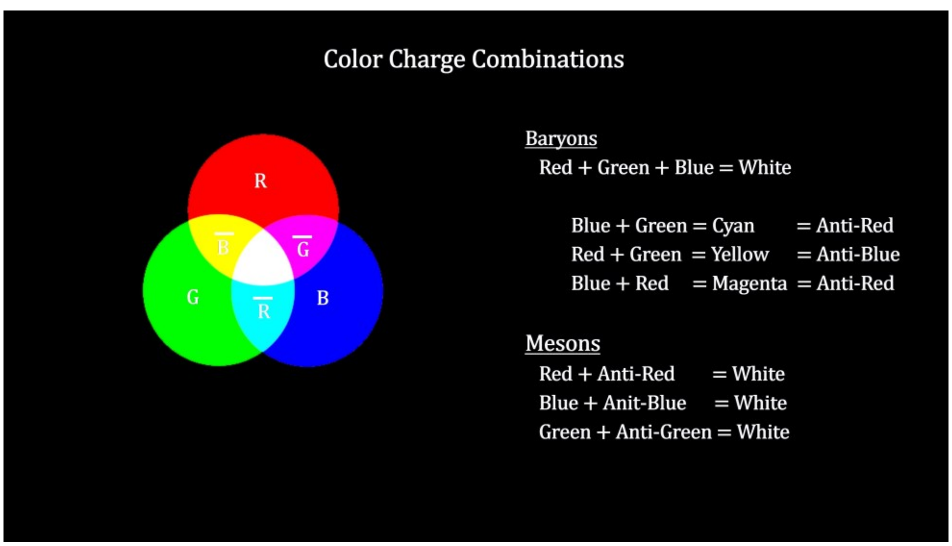
One of the key differences between the EM force and the Strong force is that the EM force involves an electromagnetic force field, whereas the Strong force involves a gluon force field.



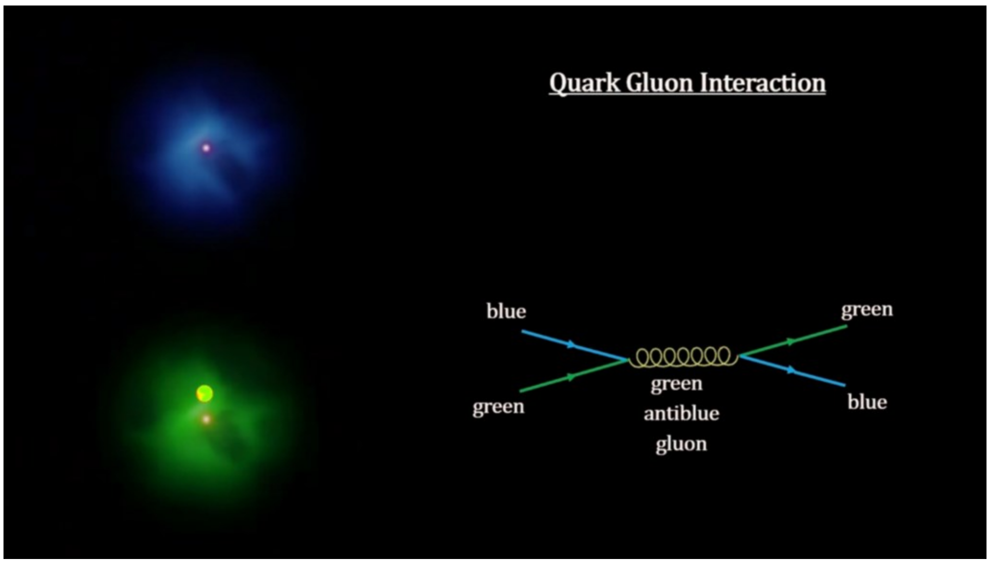
You'll recall from our previous chapter on elementary particles, that quark theory predicted the existence of the Omega particle - which was eventually discovered. One of the particle configurations turn out to have 3 strange quarks. Like 2 electrons in the ground state orbital for atoms, this presented a problem. These are fermions and follow the Pauli Exclusion principle. So, an extra quantum number was needed to explain the combinations. For electrons, it was spin with two values – up or down. For quarks it was color charge with 3 values – red, blue or green.



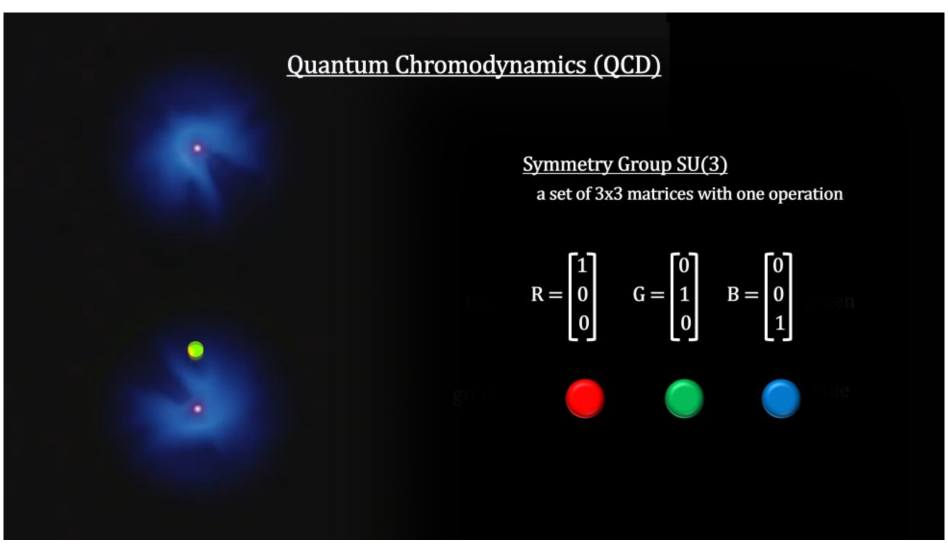
The fact that no such charge has ever been seen in the mesons and hadrons made from quarks indicates that the three charge colors neutralize each other in these configurations. This led to the idea to use red green and blue because they neutralize each other when combined. Our rule for allowed quark combinations was that they had to add up to a whole unit of electric charge. We can now add the rule that they also have to add up to no color charge at all.



Another even more dramatic difference is that gluons carry color charge as well as quarks, whereas photons do not carry the electric charge. Where quarks carry a red, green, or blue charge, gluons carry two charges one is a color and the other is an anti-color. Here's an example of how this works. We have two quarks. One with a green charge and another with a blue charge. When the green quark disturbs the gluon field, it creates a gluon. This gluon carries away a green charge and an anti-blue charge. This turns the green quark blue. When the gluon encounters a blue quark, it is absorbed and the gluon's anti-blue and green charge turns the quark green.

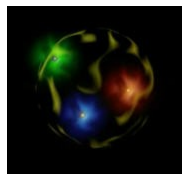


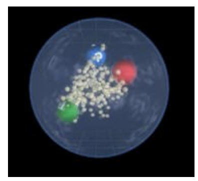
The actual functioning of the quark-gluon relationship follows the mathematical model called SU(3). The math was invented in the late1800s and was the foundation for today's abstract algebra. A hundred years later, it turned out to be very useful for particle physics. But using color is quite helpful. In fact, the study of quarks, gluons, and their color charges is called Quantum Chromodynamics or QCD for short. It is a very active area of research and changes in our understanding are expected as we learn more.



[It turns out that the nucleons (protons and neutrons) contain a sea of gluons, virtual gluons, photons, quarks, and quark-antiquark pairs being created and annihilated in the space of millionths of a second with standing waves and particles moving around near the speed of light in a ball of energy squeezed into the tinny volume of a proton.]

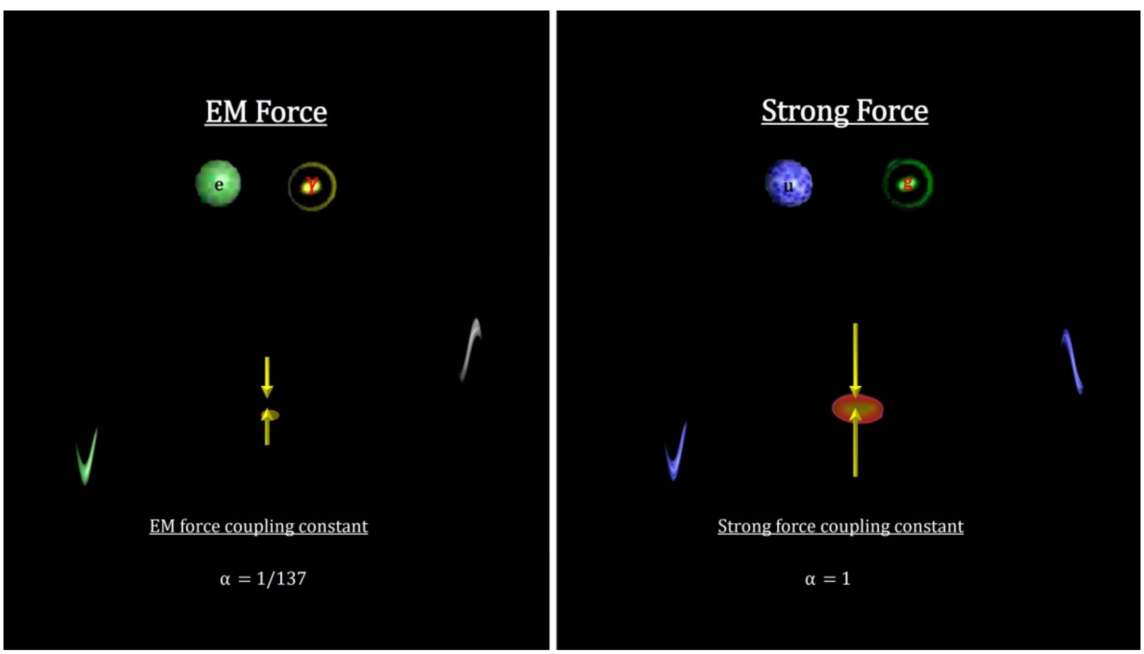
Our very idea of what a proton looks like has now shifted from a point particle to a three-part particle to a whirlwind of elementary particle activity. In fact, it is very difficult to distinguish between the disturbances that represent virtual particles and disturbances that represent actual particles in a plasma like this. But for our purposes, we can view a proton as a cloud of gluons holding three quarks together.



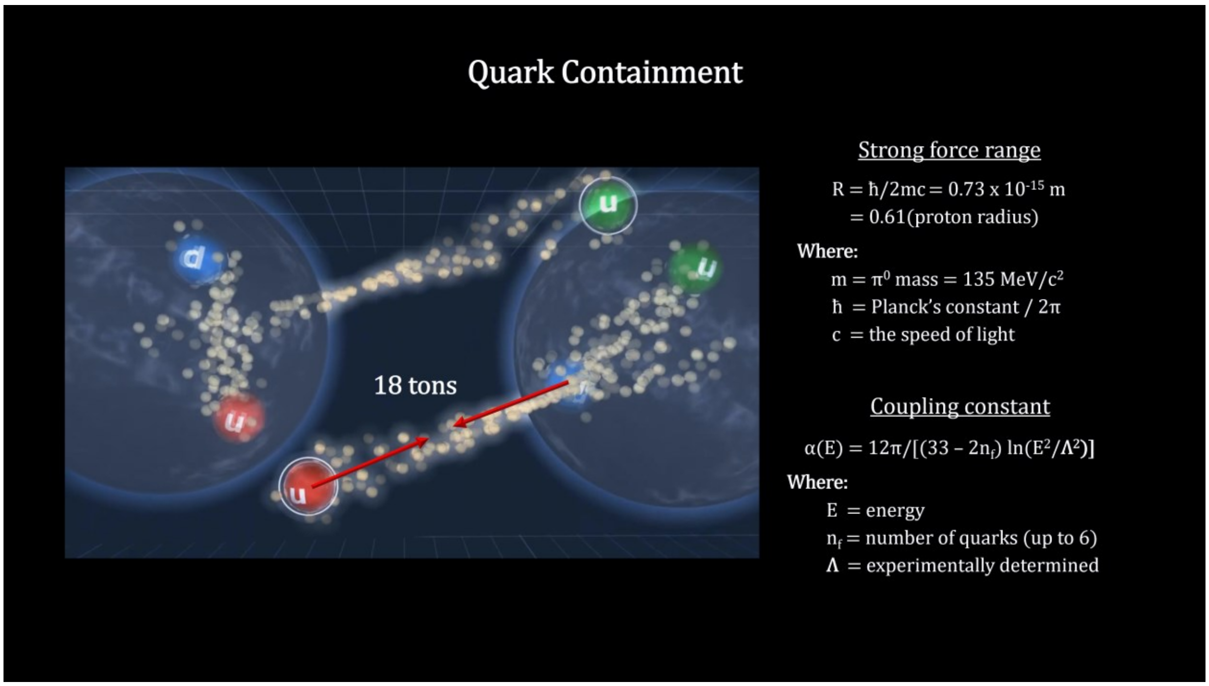


Quark Containment

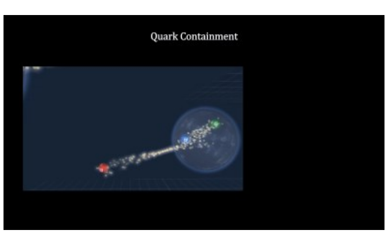
Another significant difference between the EM force and the Strong force is that the coupling constant for the strong force is 137 times stronger. And most importantly, were the EM force decreases with distance, the strong force increases with distance.

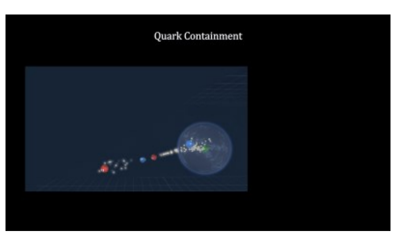


As the distance between quarks grows to the diameter of a proton, the strength of the force approaches 18 tons! Imagine 18 tons focused on such a tiny spot. This makes it virtually impossible to separate quarks.

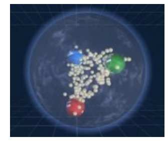


In fact, with a force that strong, the energy it takes to separate two quarks in a hadron is greater than the energy it takes to create two new quarks! So, before we reach separation energies, new quarks are created instead. These new quarks immediately combine to create new hadrons. This is called Quark Confinement or Color confinement and it explains why we can never see a quark or a gluon or a color charge on its own.

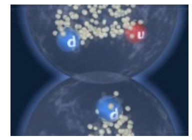




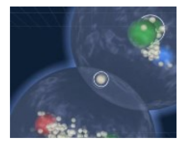
[Let's take a look at a proton-proton collision to see how this happens. Here we see a proton with its three quarks and a bevy of gluons interacting with the quarks and holding them together.



When the colliding protons get very close, they overlap.

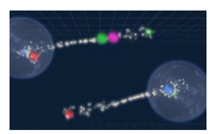


An energetic gluon finds its way to a quark in the other proton.



Now, as the protons separate, the two quarks that exchanged the high energy gluon are pulled out of their respective protons.

The gluon train is also called a gluon flux tube. As the energy of the tube reaches the amount needed to create quarks, the gluon field breaks and a quark-antiquark pair is created instead of the quarks getting further apart.



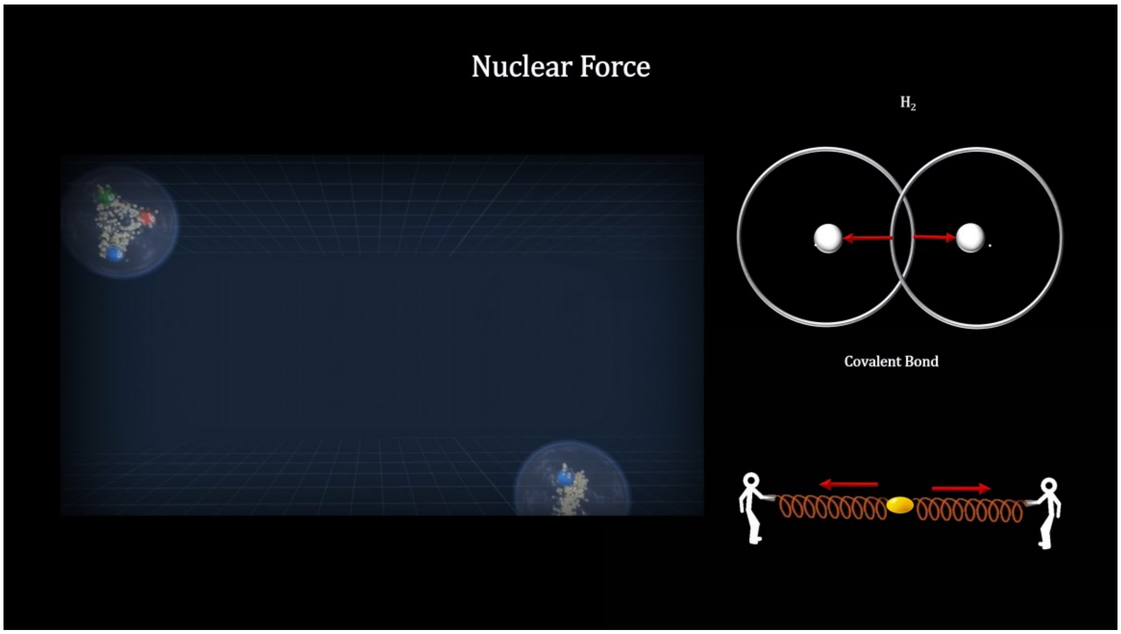
This stretching-breaking-pair production process continues until the gluon field energy is used up and separation stops. Meanwhile, the created quark-antiquark pairs are combining to form their own hadrons.

The end result is four or more jets of hadrons flying out with the remains of the colliding protons which may or may not recapture a quark. No quark is released to travel on its own and be detected.]

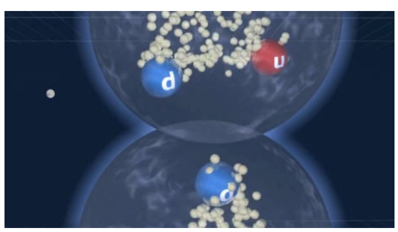
Residual Strong Force (aka Nuclear Force)

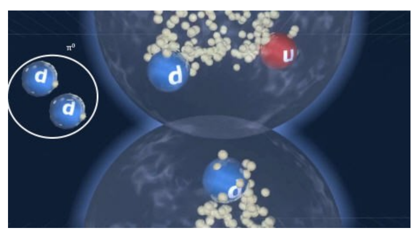
One last item on the strong force answers the question I raised at the end of our segment on the atom: 'what holds the protons together in the nucleus?'

In 1934, a Japanese physicist Hideki Yukawa made the earliest attempt to explain the nature of the nuclear force. According to his theory, a particle was being shared between nucleons like molecules share electrons between atoms to bind them together. He even calculated the mass of this particle we now know as a pion. The shared particle is attracted to both protons. The situation is similar to two people pulling on a ball. Each person exerts a force on the ball, and the effect is as if each exerted a force on the other.

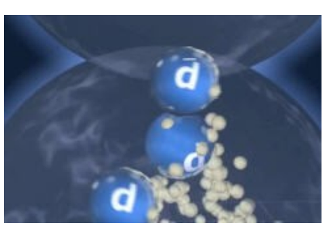


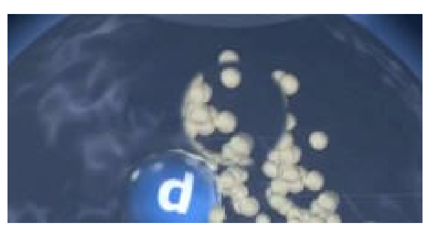
Here's a two-proton example of how we think it works. First, in one of the protons, an energetic gluon spontaneously creates a down quark – antidown quark pair. This is a neutral pion. [You'll remember the discovery of the pion in 1947 that we covered in the Elementary Particles segment.]





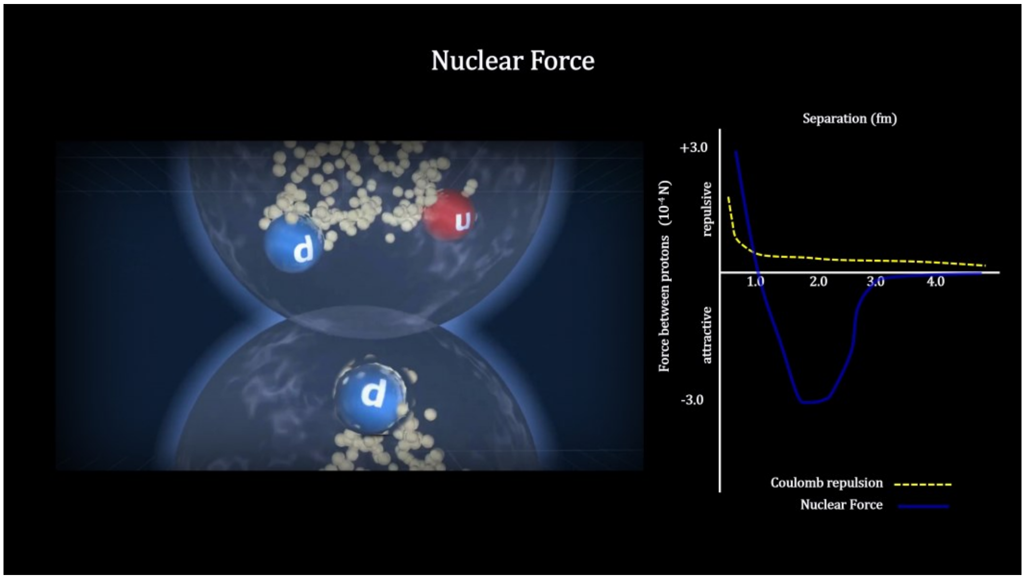
Next, the pion drifts into the other proton, and the antidown quark annihilates a down quark, leaving the other down quark to take its place.





The diameter of the proton is 1.662 fm. At a separation of less than a half a fm the nuclear force is repulsive. This prevents nucleon collapse. It then becomes attractive over a short range, peaking at

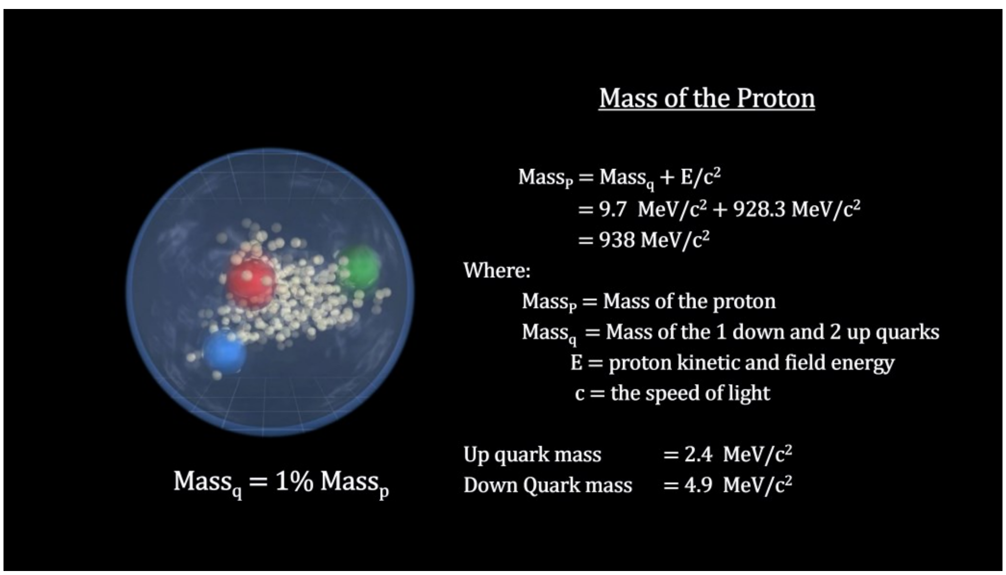
1.3 fm with a force much stronger than the electromagnetic repulsion. And it becomes negligible by around 3 fm separation where the electromagnetic repulsion takes over.



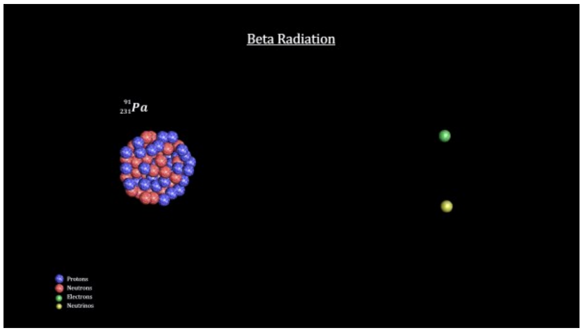
[This range for the nuclear force, given the mass of the pion, is around the diameter of an iron nucleus. This is the dividing line between the energy needed for fusion (joining nucleons) and the energy achieved through fission (the separation of nucleons).]

Proton Mass

The proton is a key to helping us understand "the origin of mass". The only stable elementary particles in the proton with mass are the two up quarks and one down quark. Their tiny masses constitute only 1% of the mass of the proton. 99% comes from the energy of the fields and motion the moving parts following the famous $E = mc^2$ formula. So, it is quite accurate to say that "confined Energy is the origin of mass." We'll bring this point home when we get to the Higgs boson.

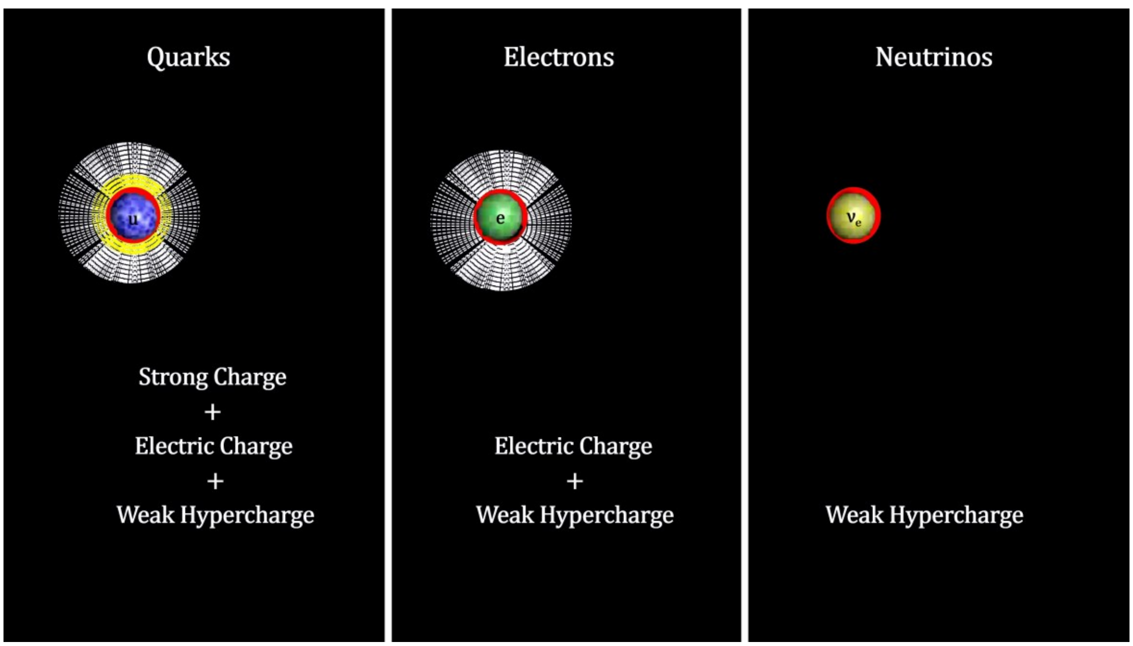


Weak Nuclear Force



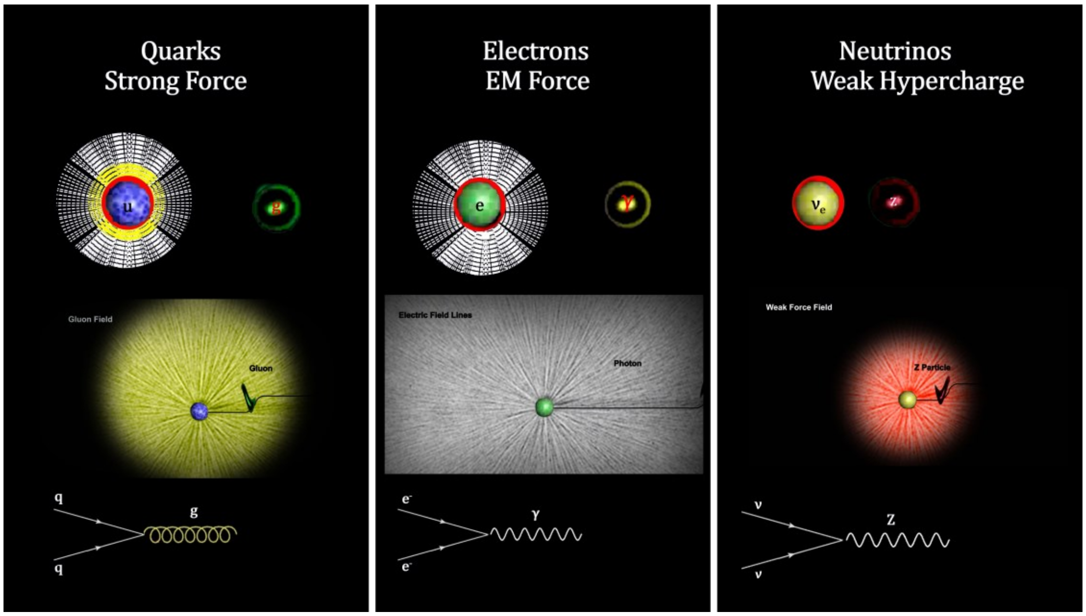
The Weak nuclear force or weak interaction is responsible for radioactivity (for example Beta radiation ejecting electrons and neutrinos). It's the force that turns a neutron into a proton.

Unlike QED and QCD, there is no separate matter field that creates a particle with a Weak Force Charge – sometimes called weak isospin or weak hypercharge. Instead, all fermions already have this charge including electrons, quarks, and neutrinos.

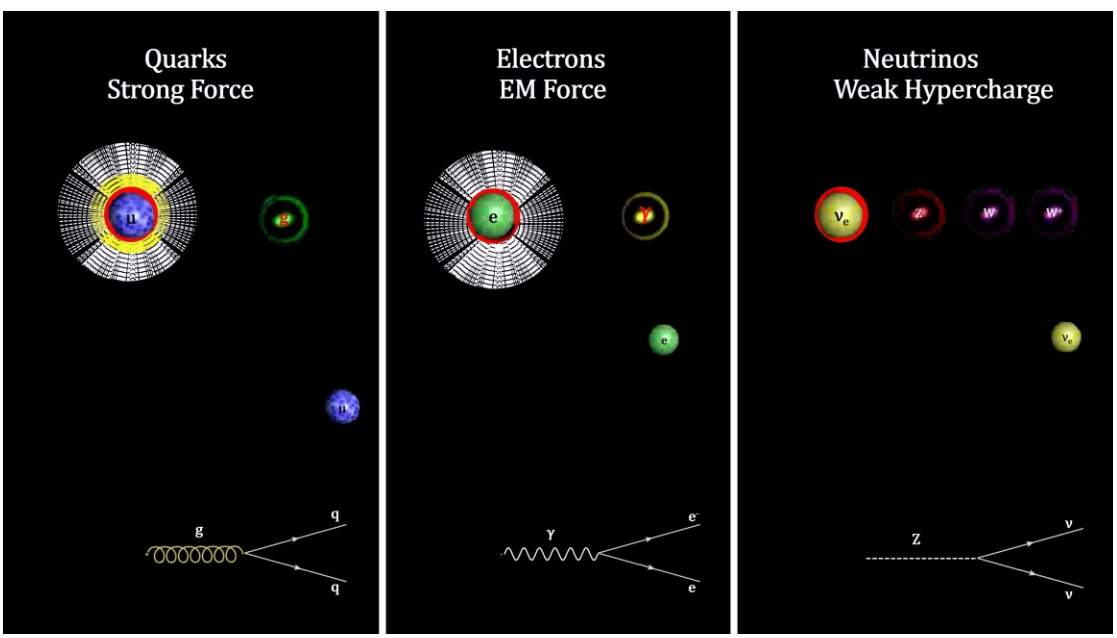


[For this reason, it is most often included in theories that combine it with the electromagnetic force into a theory called the electroweak interaction developed by Steven Weinberg along with Abdus Salam and Sheldon Glashow.]

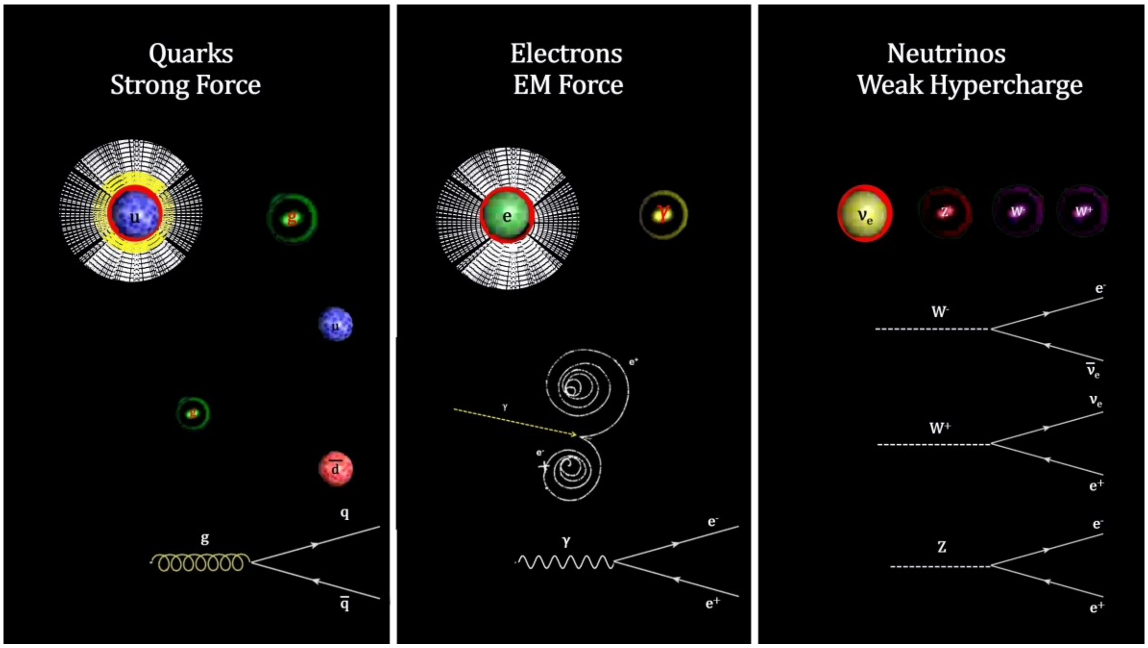
Like accelerating electrons and quarks create vibrating ripples in their respective force fields called photon and gluons, accelerating electrons, quarks, and neutrinos can create vibrating ripples in the weak hypercharge field called Z particles.



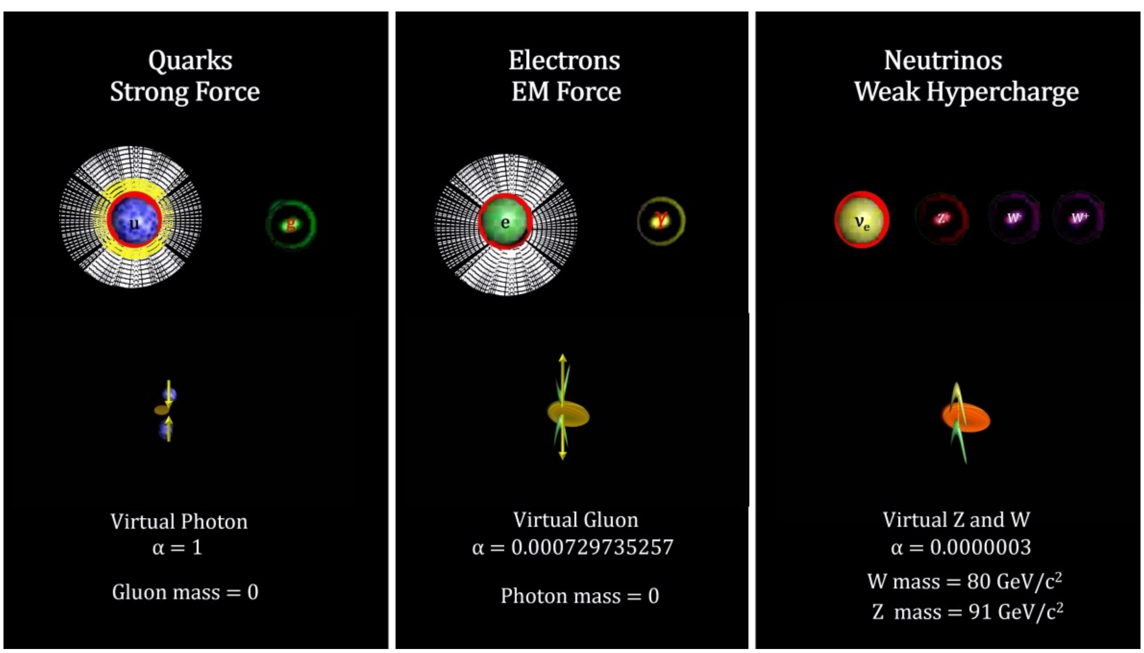
And where photons can accelerate electrons, and gluons can accelerate quarks, Z particles can accelerate neutrinos and electrons and quarks, because they all carry the weak charge. But for the weak hypercharge, there are 2 additional particles called W^- and W^+. Like the gluon caries color charge, W^- caries a negative electric charge equal to the charge of an electron, and W^+ carries a positive electric charge equal to the charge of a positron. The Z particle has no charge at all. They are all spin 1 particles, making them bosons. They are the force particles for the weak interaction.



Like photons and gluons can create matter anti-matter particle pairs, the W and Z bosons can create matter anti-matter particle pairs.

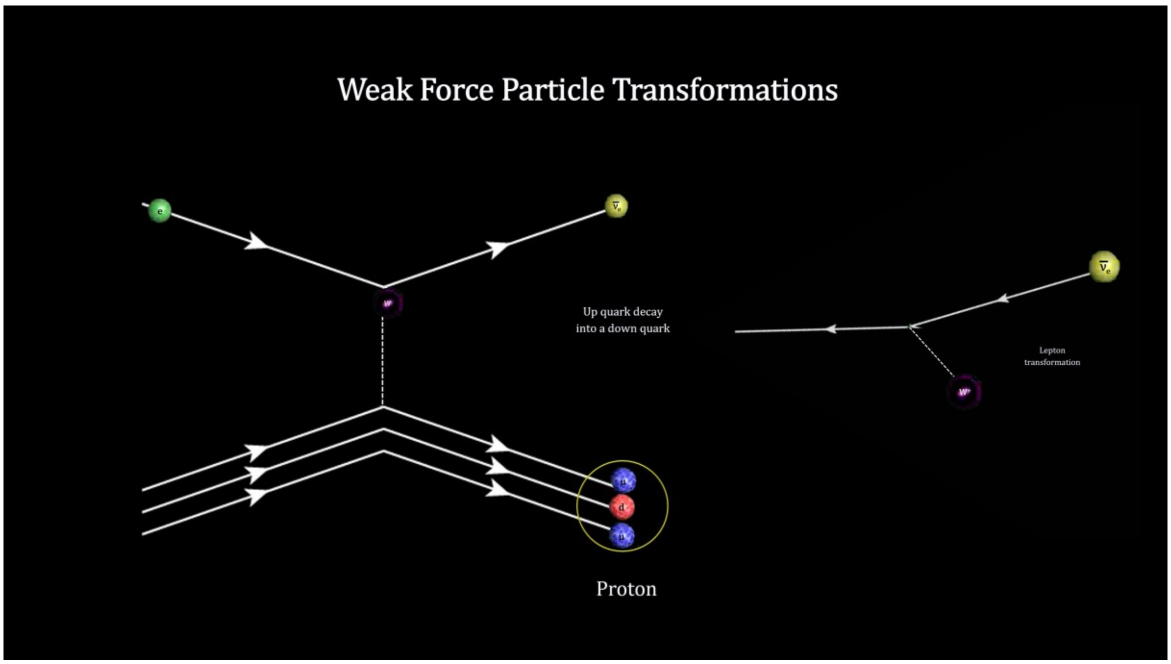


And like interacting electrons and quarks disturb their respective force fields creating virtual photons and gluons that exert the force of the field, interacting particles carrying the weak hypercharge disturb the weak hypercharge field creating virtual W and Z bosons that exert the force of the field. The force can be attractive or repulsive depending on a variety of circumstances.

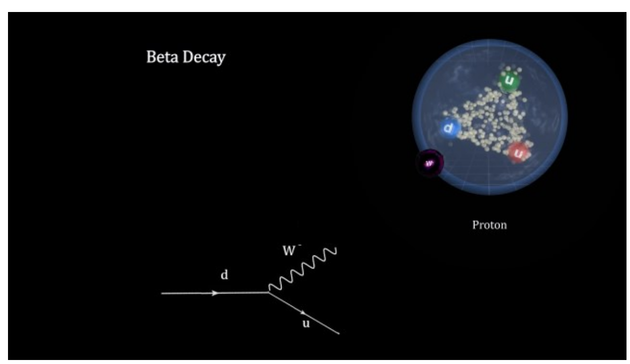


We call it the weak force because its coupling constant is 3.3 million times smaller than the strong force coupling constant. And, unlike massless photons and gluons, these particles are massive – around 53 times more massive than an up quark, and 160 thousand times more massive than an electron. This makes its range incredibly short – around 0.1% of the diameter of a proton.

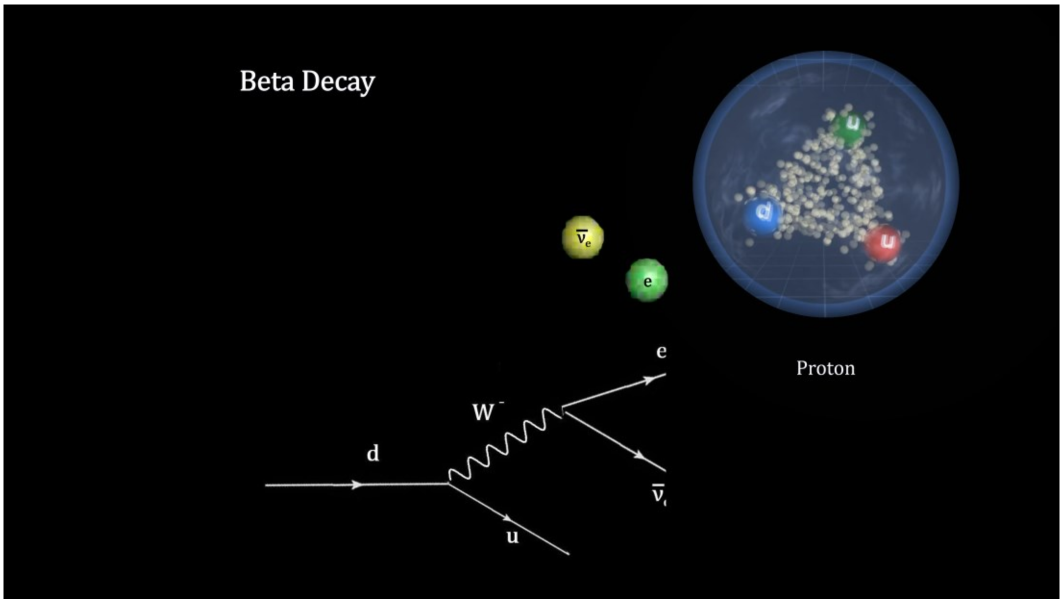
All the force particles actually exert a force on their respective matter particles. But the weak force has a unique additional capability: it can change one flavor of quark into another, or one type of lepton into another. The idea that a force field particle can cause a matter field particle to decay, i.e., transform into another particle was a new one.



We'll use beta decay from our Radium to Polonium energy experiment to help illustrate how this works. The process consists of two phases. The first phase is similar to the way an electron emits a photon when it drops to a lower energy state in an atom. Here a down quark drops to the lower energy up quark and emits a W boson that carries away the energy and a full unit of electric charge. The remaining quark's charge has gone from -1/3s to +2/3 making it an up quark.



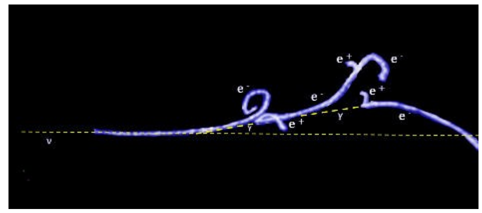
However, the mass of the weak field quantum is so large that there is not enough energy in a down quark quantum leap to an up quark to create a fully independent W boson. Instead, what is created is a virtual W Boson. However, in the second phase, because there **is** enough energy in the virtual boson to create an electron and a neutrino, it decays into these particles. This is possible because both the electron and neutrino carry the weak hypercharge. This is how our Radium turned into Polonium in our segment on the atom.



Because of the significant amount of energy needed to produce these massive Z and W weak force bosons, it wasn't until 1972 that the first evidence for Erico Firme's Weak Interaction theory was found. This event shows a neutrino–electron interaction that would require a Z boson. It was recorded by the Gargamelle bubble chamber at CERN. Final proof came for Z and W bosons when the proton anti-proton collider was built at CERN in 1983.

[The neutrino, which leaves no track because it has no electric charge, entered the bubble chamber from the left of this image and hit an electron. Unlike all other neutrino events seen before, this collision did not transform the incoming neutrino into another type of particle. Instead, the neutrino remained a neutrino and continued on its way.

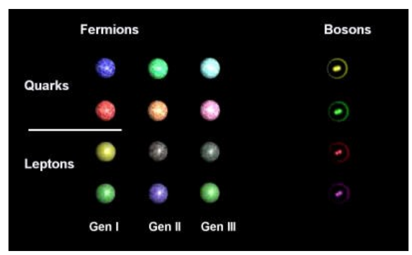
The impacted electron on the other hand was propelled forward at a high speed. Moving through the liquid, the electron slowed down and emitted a powerful photon. This photon, in turn, created an electron-positron pair visible in the photo, making the initial electron identifiable. This was followed by additional particle pair creations.



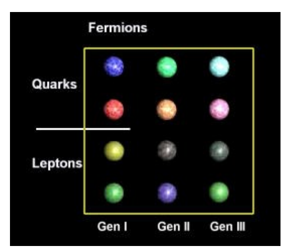
The interaction between the neutrino and the electron did not involve the charged W boson, so it must have been done by a weak force boson without a charge. This boson was named the Z boson. These results firmly established the mathematical framework that predicted the weak neutral current and this Z boson. The framework became known as the Standard Model of particle physics.**]**

Standard Model of Particle Physics Summary [**Music**: Ravel – Boléro]

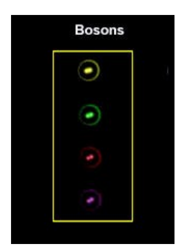
Here's the Standard Model with all the stable fermions. If we add the excited state versions of these fermions, we get the full view.



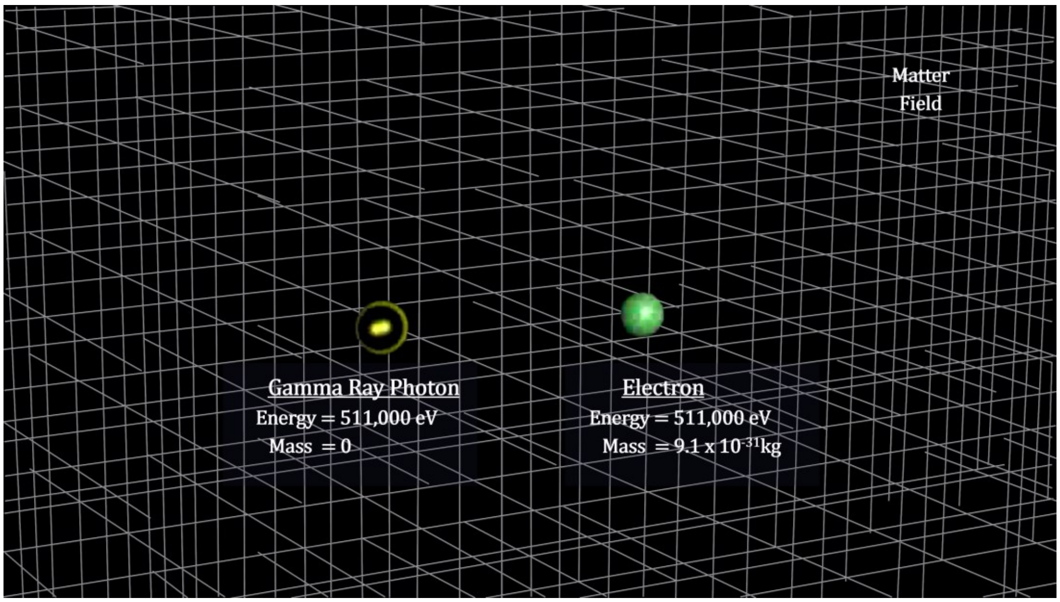
In summary, all of space is filled with matter fields that can spawn fermion particles as waves in the elements of their respective fields. This includes all the Leptons and the Quarks.



These particles carry one or more charges: Color charge, Electromagnetic charge, and weak hypercharge. Particles with a charge fill the space around them with a force field that can spawn force particles when excited by particles that carry their charge. These are the bosons. The bosons are the force carriers or mediators for all fermion particle interactions.

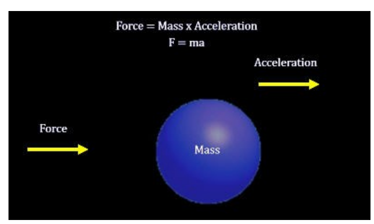


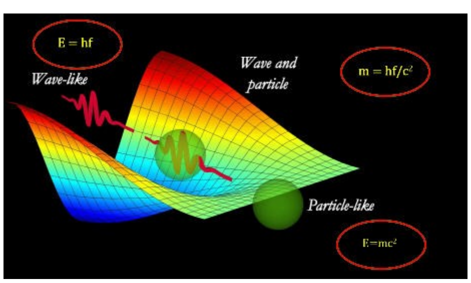
This model has had great success in explaining observed natural behavior at the quantum level. But there was one serious problem that had to do with the mass of the particles. One way to look at it is that it didn't explain how elementary particles acquire mass. Or, given that we know that confined energy generates mass, another way to look at the problem is that the standard model did not explain how photons, no matter how much energy they have confined, do **not** have mass.



The Origin of Elementary Particle Mass

In classical physics, mass is a measure of the inertia of a body. The mass of an object causes it to resist a change in its speed or direction. The greater the mass, the greater the resistance. This is codified as Force = Mass times Acceleration.





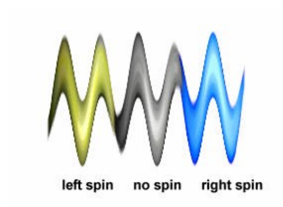
In QFT, on the other hand, the energy of a quantum is represented by oscillations in its field. Since both mass and energy are associated with oscillations in the particle field, we can simply combine Einstein's equation for mass energy and Planck's equation for wave energy to calculate the mass of a wave.

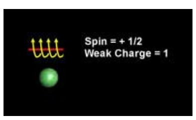
The faster a particle is oscillating, the harder it is to change its direction or speed. So, this fits our common understanding of mass.

Paul Dirac identified the oscillation of a particle between its right-handed incarnations and its left-handed incarnations as the mechanism for fermion mass.

The faster the oscillation, the more energetic the particle, the more massive it is. [With these oscillations as the key to a particle's mass, we need to take a closer look at the nature of left-handed and right-handed spins.]

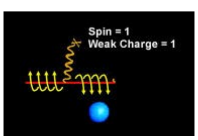
It might seem strange – a particle changing its spin on the fly. But if you recall that particles travel as waves, and spin can be viewed as a phase shift in the wave, it's not too hard to visualize.





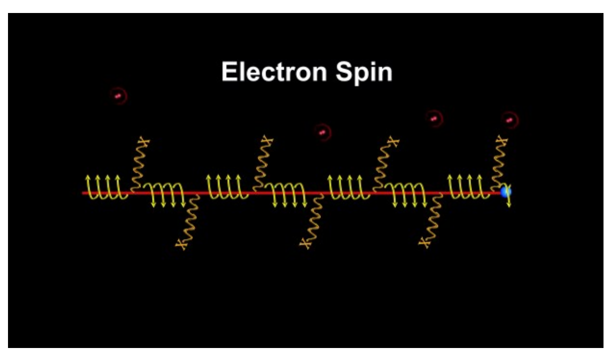
We'll use electrons for an example. A left-handed spinning electron has a spin of ½ and carries a weak hypercharge.

A right-handed spinning electron has a spin of – ½ and carries 0 weak hypercharge.



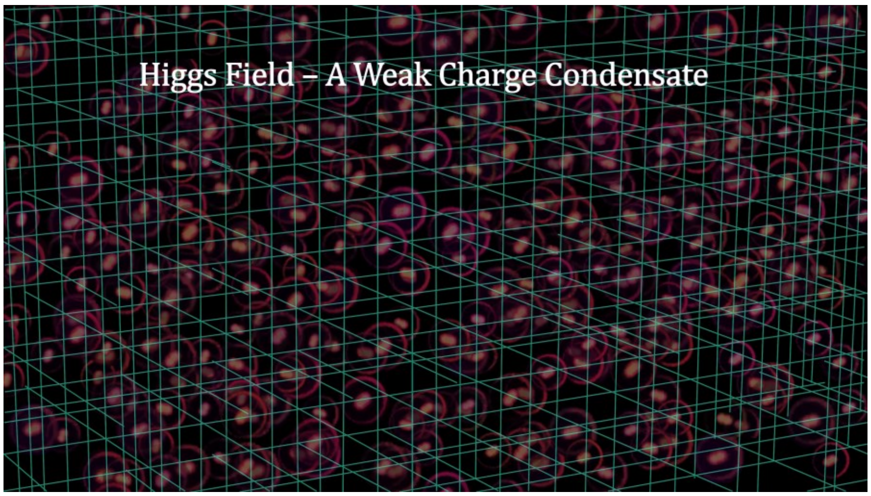
So, for an electron to switch from left to right, it must emit a quantum of weak charge and lose a full unit of spin. And for it to switch back, it must absorb a quantum of weak charge and gain a full unit of spin.

Now here we had a very large problem for particle physics. It was understood that a derivative of the Z boson was a candidate for the electron's spin and charge transition, but there was no standard model mechanism for ejecting and absorbing weak hypercharge out of the blue. Where did the charge go? And where did it come from?



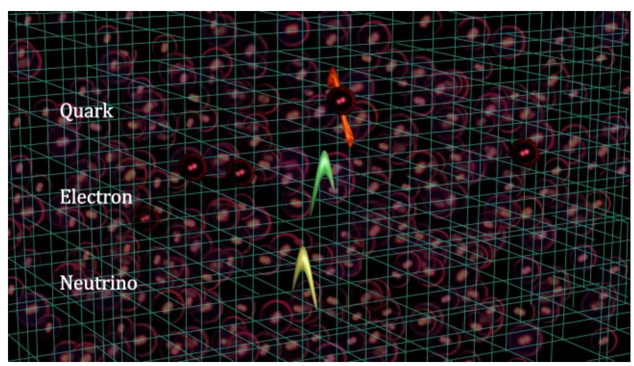
The Higgs Field

In 1964, in order to resolve this problem, François Englert, Robert Brout, Peter Higgs and others proposed a new field that permeated all of space – now called the Higgs field. They proposed that this field contained a condensate of weak charge. A condensate has the property that adding to it or subtracting from it leaves it the same.



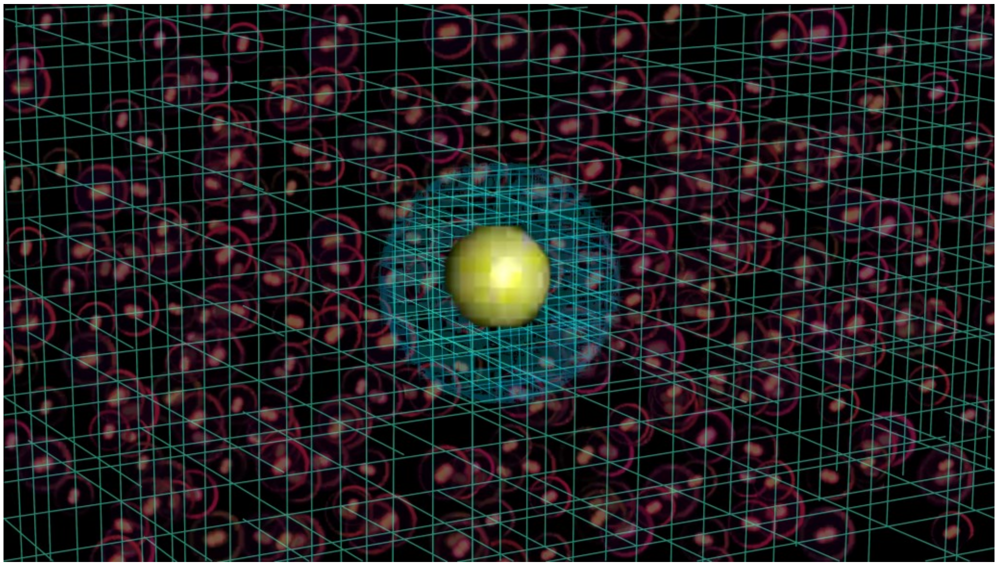
A particle carrying weak charge could use a weak charged virtual Z Boson to move the charge to this condensate without noticeably changing the field, and it could use the same Z Boson mechanism to absorb a weak charge from the condensate without noticeably changing the field. This was called the Higgs mechanism. With the Higgs mechanism, an elementary particle that carries the weak hypercharge can oscillate and therefore has mass. Electrons, Neutrinos and Quarks all carry this charge and interact with the Higgs field. So, they can oscillate and therefor they have mass.

Photons don't carry weak hypercharge and therefore, they cannot interact with the Higgs field, and therefor they cannot oscillate and therefore, no matter how much energy they have, they have no mass. The process is a little different from particle to particle, and physicists use subtler concepts of chirality, gauge symmetry and symmetry breaking, but this is the basic idea.

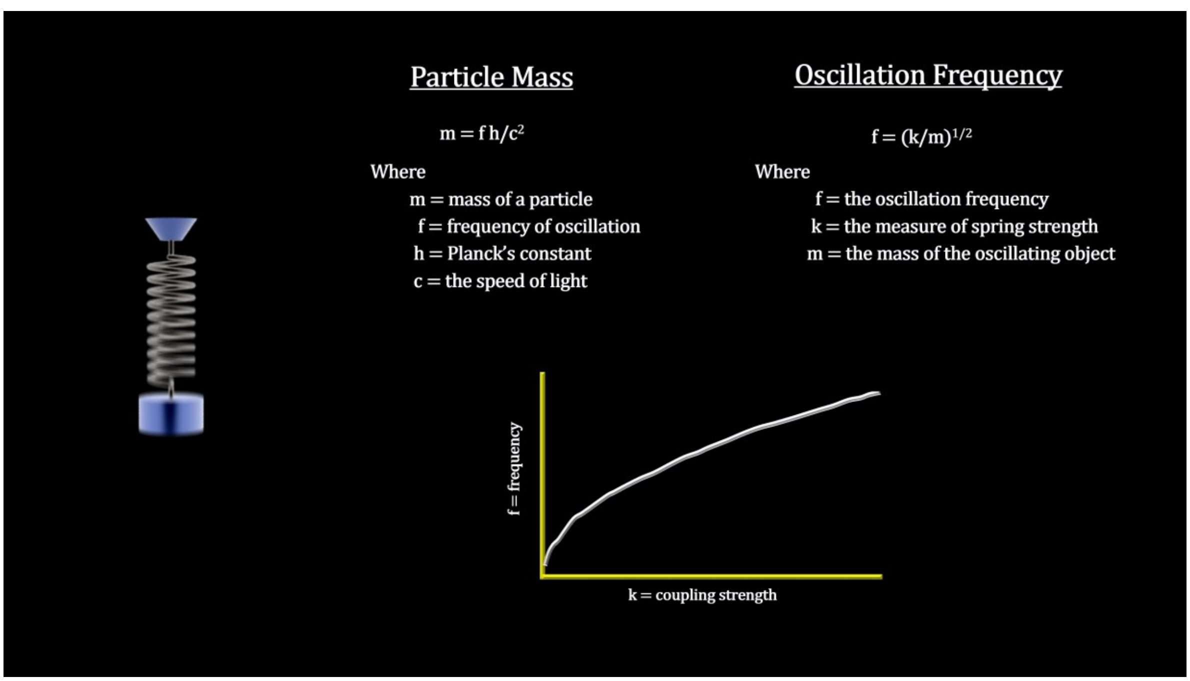


[Earlier we determined that "confined Energy is the origin of mass." So, from one point of view, we can see that the Higgs mechanism provides a Standard Model vehicle for elementary particles to acquire the mass their energy content predicts they should have. But from another point of view, we see that Higgs explains the more mysterious question about why photons, no matter how energetic they may be, do not have mass.]

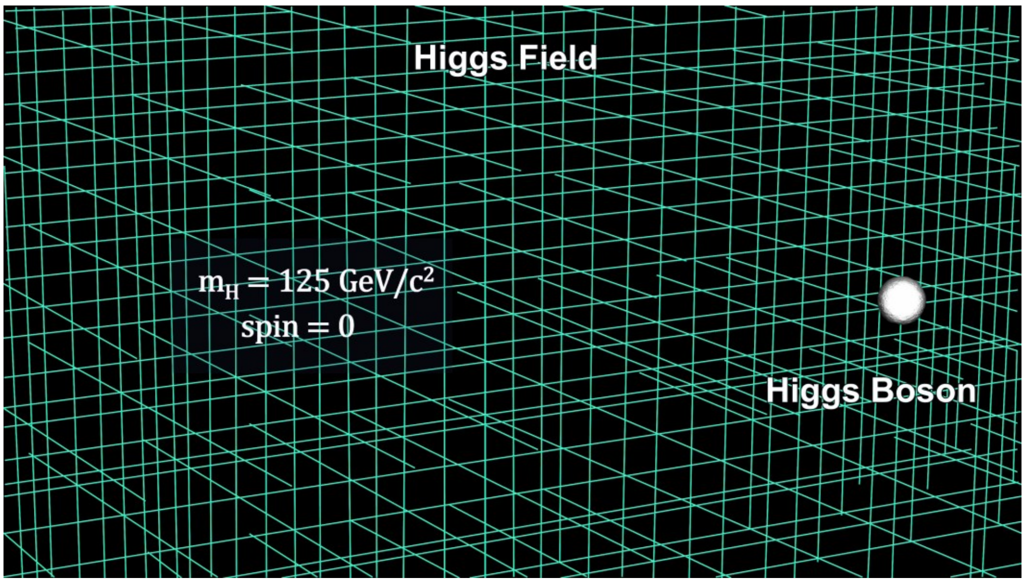
You'll note that the particles that interact with the Higgs field are not slowed down. The Higgs field is not like molasses. If the Higgs field slowed particles down in any way, objects in motion would no longer remain in motion. This is not what we see in the real world.



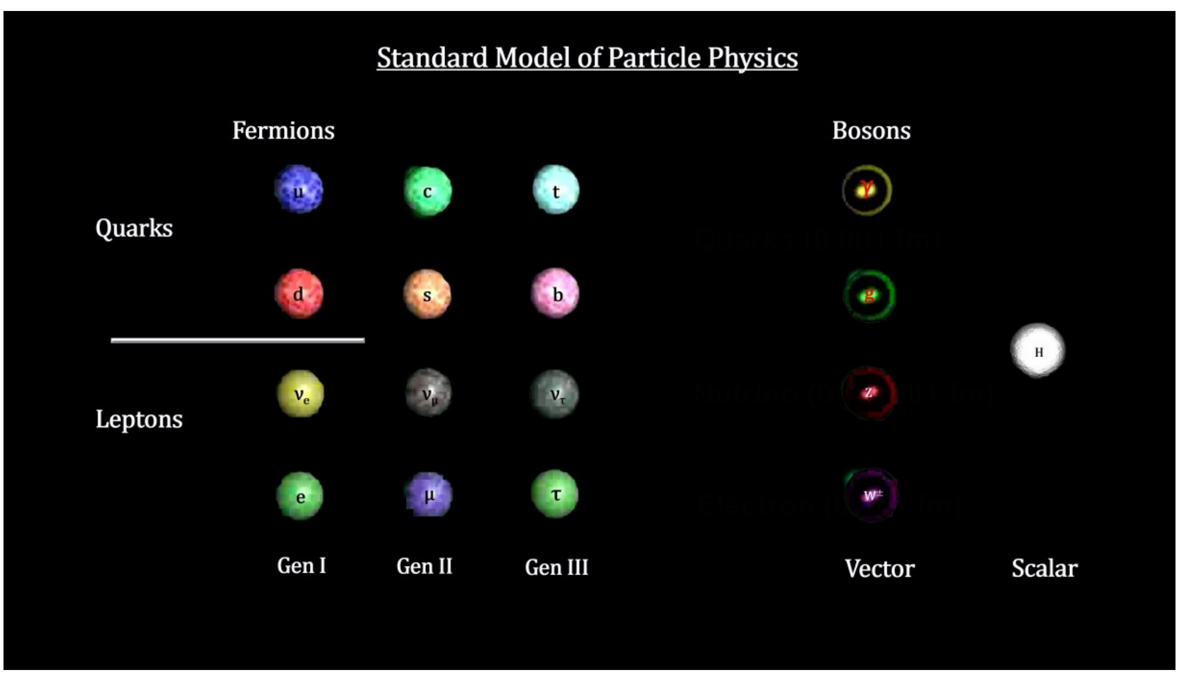
Here's one more important idea about mass. The reason the masses are different for different particles, is that the coupling strength of the interaction with the Higgs field is stronger for some particles than others. Increasing the coupling strength is like increasing the stiffness of the spring in a harmonic oscillator. It has the effect of increasing the oscillator's frequency. And we have already determined, that if we increase a particle's oscillation frequency, we increase its mass.



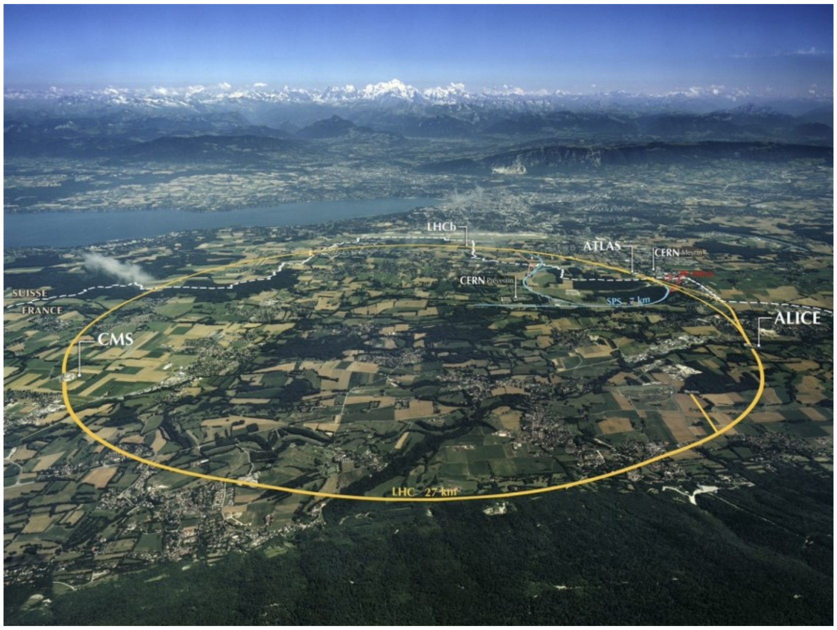
Now we can ask: "What is a Higgs boson?" We have learned that, under the right circumstances, excited fields generate particles. This also applies to the Higgs field. If it exists, it has an associated particle – that particle is called the Higgs boson. So, working in reverse, if we can find the Higgs boson, we'll have strong evidence that the Higgs field exists and the Higgs mechanism is real, and the Standard Model of Particle Physics, is correct. Quantum filed theory predicts that this particle's mass should be around 125 GeV/c^2 with zero spin called a scalar boson.



Note that all the other force particle bosons (photon, gluon, W and Z) had a spin of 1 and are called vector bosons.

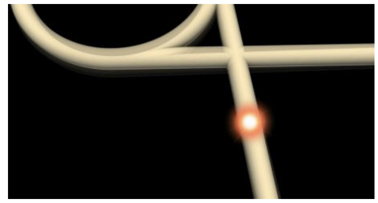


This large mass - around 133 times more massive than a proton - makes it difficult to form one. It takes a great deal of energy. At the time the Higgs boson was proposed, no existing accelerator could do the job. This is why the Large Hadron Collider at CERN was built.

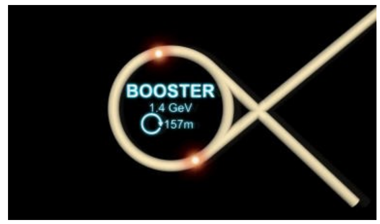


Large Hadron Collider
This Large Hadron Collider or LHC for short is the world's largest and most powerful particle accelerator. [Inside the accelerator, two high-energy particle beams travel at close to the speed of light before they are made to collide. The beams travel in opposite directions in separate beam pipes – two tubes kept at an ultrahigh vacuum (a vacuum as empty as interplanetary space). They are guided around the accelerator ring by a strong magnetic field maintained by superconducting electromagnets. This requires chilling the magnets to -271°C – a temperature colder than outer space. It uses a system of liquid helium to cool the magnets.]

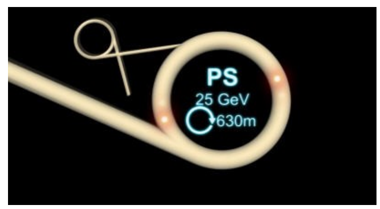
Here's how it works. Using hydrogen with the electrons removed, proton packets containing billions of protons are accelerated down a linear accelerator like we saw at SLAC. By the time the protons reach the first cyclotron, they are traveling at 1/3 the speed of light.



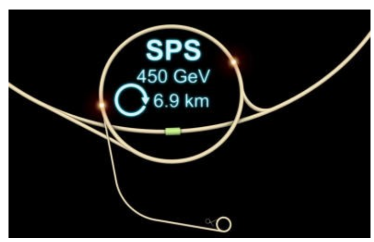
The first booster is 157 meters in circumference and accelerates the protons to 91.6% of the speed of light.



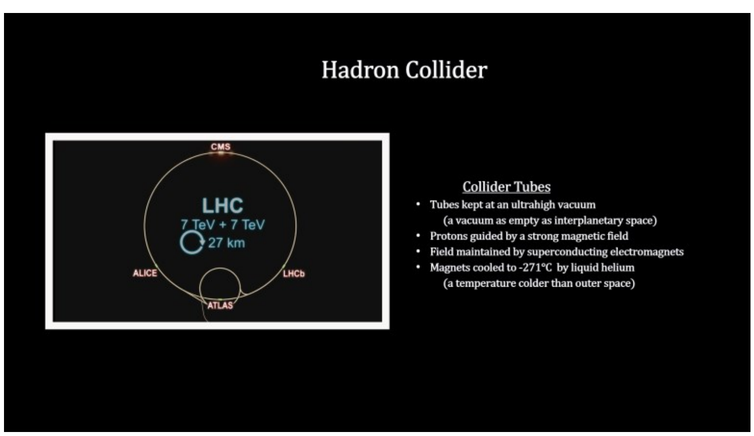
The protons are then flung into the proton synchrotron. They circulate here for 1.2 seconds reaching 99.9 % of the speed of light.



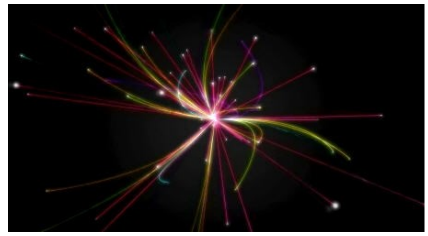
The protons are then channeled into the Super Proton Synchrotron. This is a huge ring, almost 7 kilometers in circumference. Here they are accelerated to the point where they can enter the LHC.



Here there are two pipes that carry the proton beams in opposite directions. Each stream is accelerated to 7 TeV – that's 7 trillion electron volts. And because they are traveling at each other, the total energy of a collision is 14 trillion electron volts. This ought to be enough to kick the Higgs field into producing a Higgs boson. As the protons approach each other, they are traveling at 99.999999% of the speed of light.



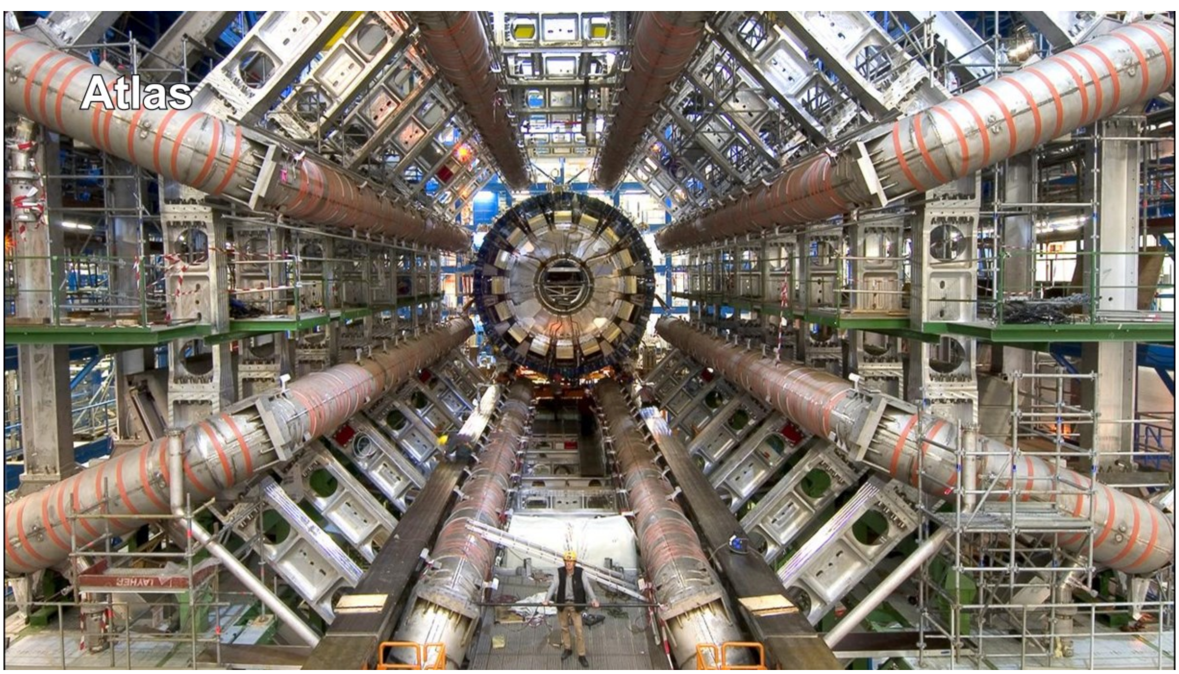
The actual collision creates hundreds of particles that scatter out in all directions. Detecting, and measuring the trajectories, momentum, and energy of each of these particles is the next big step.



CERN Particle Detectors – CMS and ATLAS [**Music**: Vaughan Williams - The Lark Ascending]

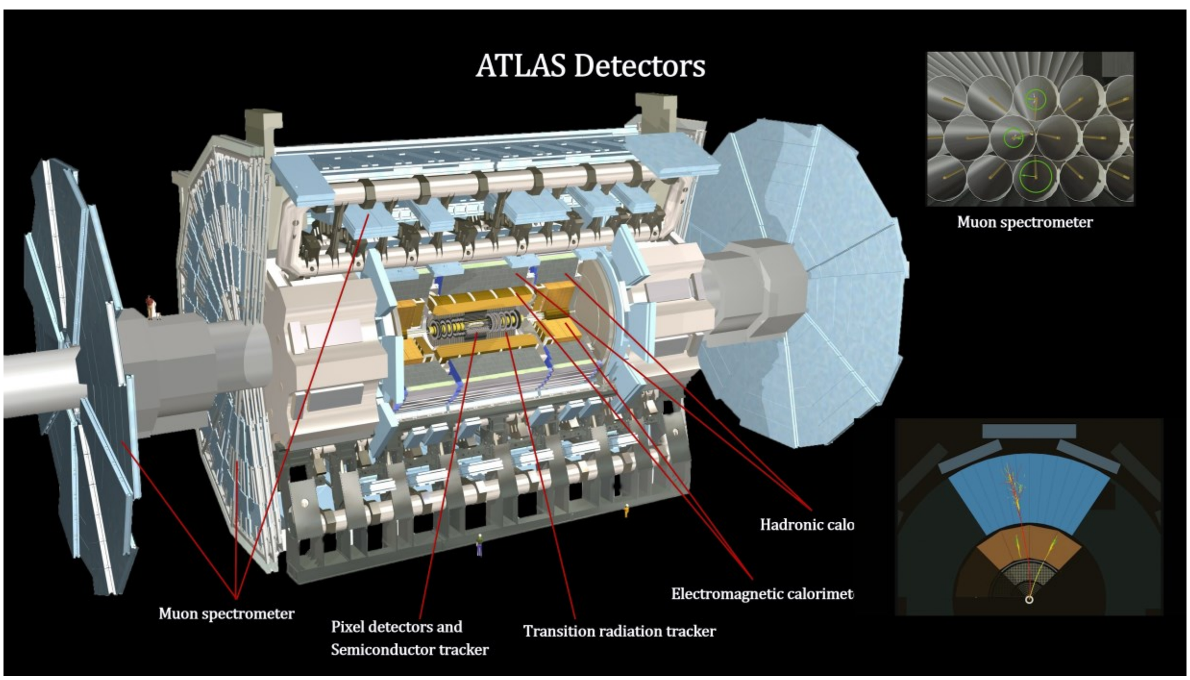
For crosschecking purposes, CERN uses two main detectors. One of them is the Compact Muon Solenoid or CMS for short. It was designed to search for the Higgs boson, and dark matter, [CMS is 21.6 meters long, 15 meters wide, and weighs around 14,000 tons.]

The second detector called ATLAS uses different technical solutions and a different magnet-system design than CMS. It is 7 stories high. We'll take a closer look at this one.



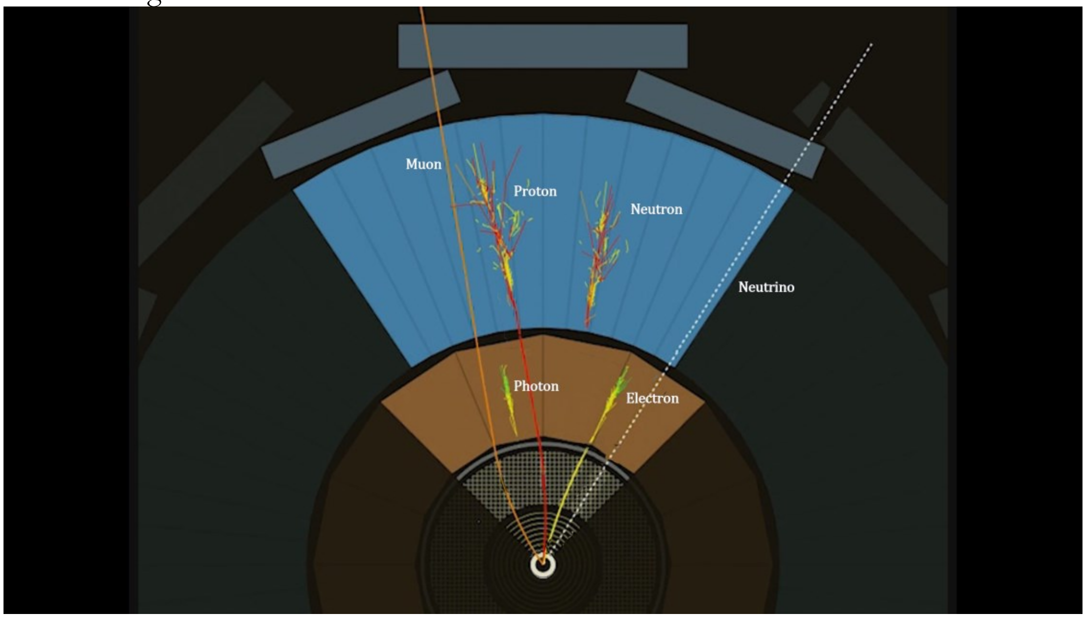
The detecting components in ATLAS are each designed to detect different kinds of particles. The pixel detector and semiconductor tracker contain layer of silicon. Charged particles passing through the silicon release electrons that flow to millions of microscopic metallic spheres under the silicon layer. These are all electronically connected to the computer that keeps track of their path. The Transition Radiation Tracker can distinguish between different types of charged particles. It contains a large number of tubes filled with gas. Passing charged particles produce electrons that flow down a wire in each tube. Different particles produce different currents. A strong magnetic field is created around these inner trackers. The generated curves in particle paths enable us to calculate the particles momentum, like we did at SLAC.

ATLAS has two calorimeters. Like the calorimeter used in the Beta Decay experiment, they are used to measure the energy of transiting particles. But these two don't use heating water. That would take forever. The Electromagnetic Calorimeter measures the energy of photons and leptons like electrons and positrons. It contains many layers of lead and stainless steel that absorb the particles. Between the layers is liquid argon at -180 degrees C. Immersed in the liquid argon is a copper grid. Passing particles drive electrons to the copper and measuring their number gives us the energy of the particle. The Hadronic Calorimeter measures the same for hadrons like protons, neutrons and mesons. It is a large array of steel and scintillator sheets that create photons when struck by a charged particle. Light fibers carry the light to intensity measuring devices. The light intensity gives us a measure of the energy of the hadrons entering the calorimeter. At the outer layer there is a Muon Spectrometer with a surface area the size of several football fields. In the attached chambers there are tubes also filled with gas. The electrons that are generated by the passing muon drift to the center. This enables the system to determine its track.



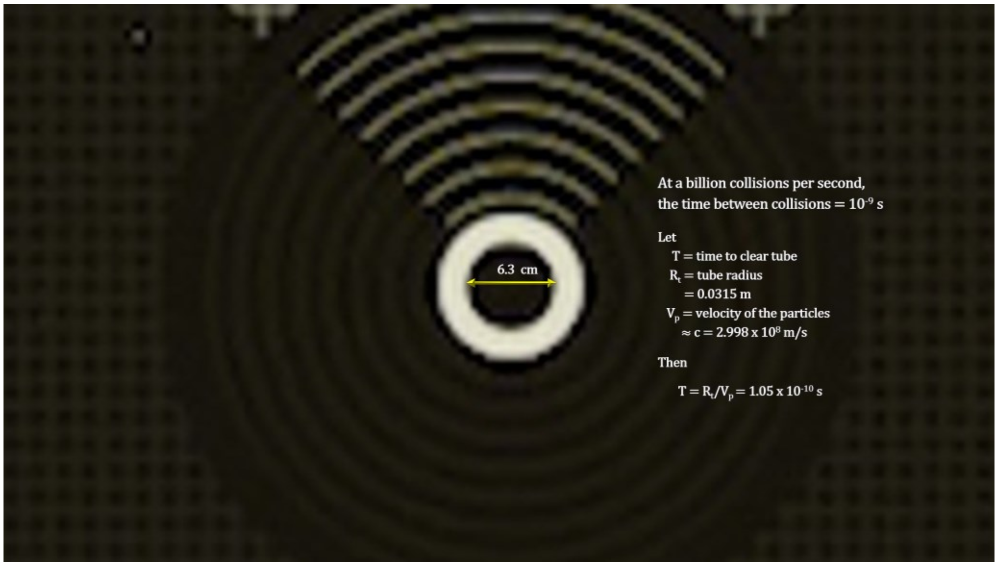
Here are a few examples.

Photons will act the same way in the calorimeter, but they do not leave any track through the inner detector since they have no charge. Protons leave a track, but will most likely pass through the electromagnetic calorimeter into the hadronic calorimeter. Neutrons behave in a similar way, but leave no track through the inner detector. Muons passe all the way through Atlas leaving tracks behind in every layer. And as was the case with beta radiation, neutrinos passe all the way through Atlas without being detected.



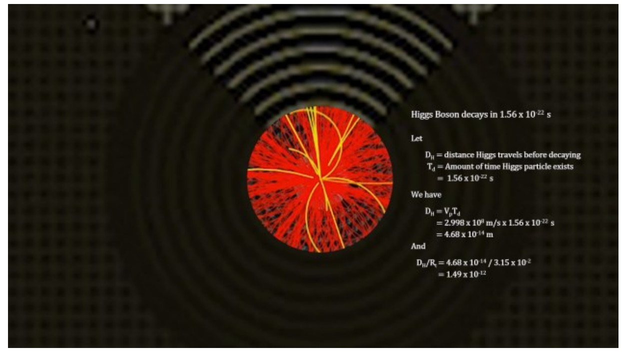
The Higgs Boson Discovery [Music: Brahms - Violin Concerto, Op 77 II Adagio]

The LHC produces a billion collisions per second. That gives the particles produced by any one collision less than a billionth of a second to clear the tunnel and pass into the detectors. But with particles traveling near the speed of light and the radius of the tube being just over 3 cm, they are all clear in 10^{-10} seconds.

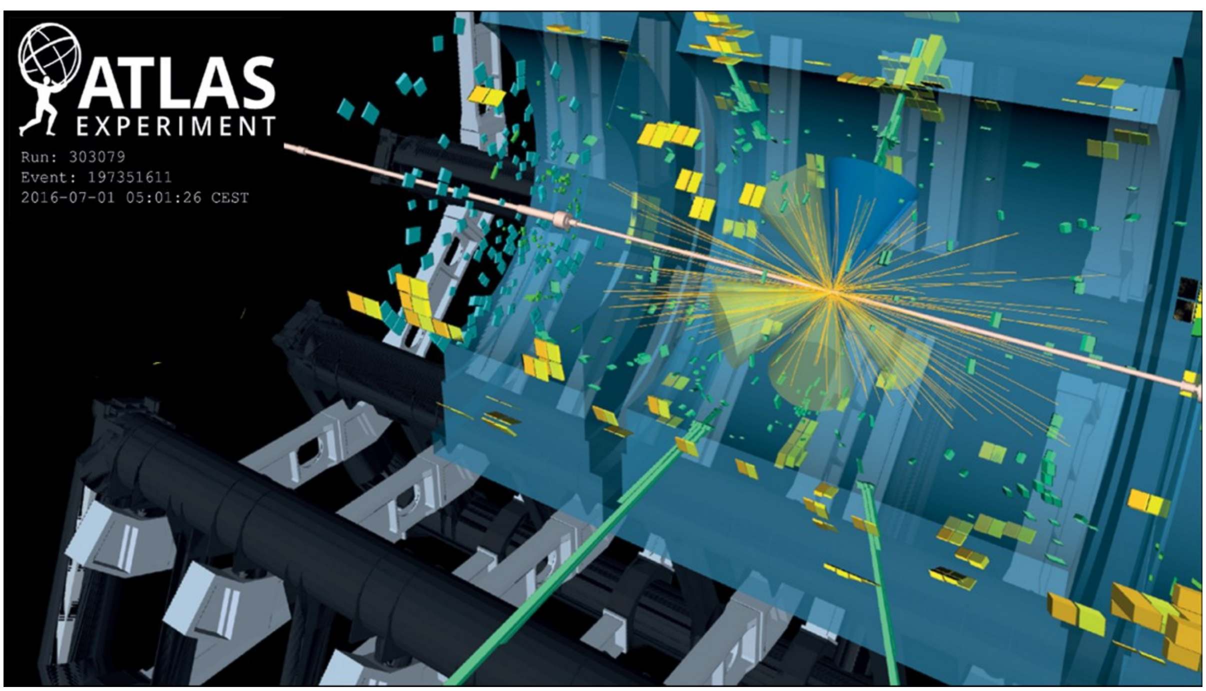


Out of hundreds of billions of particles created by a few seconds worth of collisions, only a few are massive enough to be interesting.

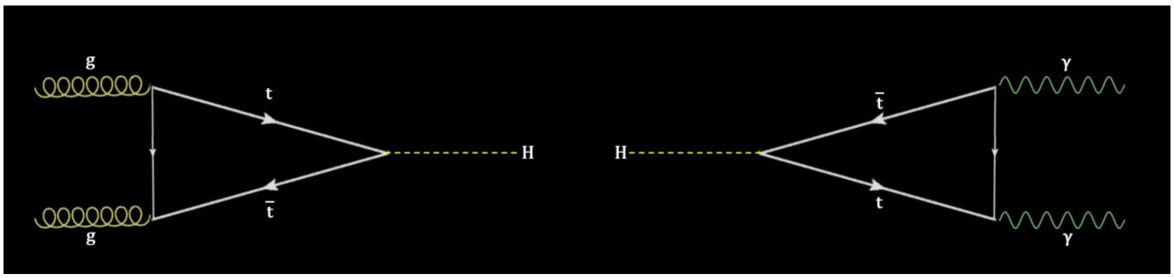
Massive particles like the Higgs Boson itself will decay into lighter particles so rapidly that they never reach the detectors. It's gone before it reaches 2 trillionths of the way out. We cannot see them directly. But we can detect the lighter particles created by their decay. We can then deduce the originating particles by their decay signatures just like we did with the kaon in a cloud chamber.



On July 4, 2012, 45 years after Peter Higgs proposed its existence, CERN announced that one of these interesting particles created in a 2011 collision turned out to fit the decay signature for the Higgs Boson. Here's a Higgs Boson decay into two photons event recorded by ATLAS in 2016 that illustrates the decay mode for Higgs found in the 2011 event. Orange lines show the trajectories of charged particles as they passed through the inner tracking systems. The green and blue cones show jets of particles produced in the collision. The green boxes show the energy deposits in the electromagnetic calorimeter. The yellow boxes show the energy deposits in the hadronic calorimeter. The longer the box, the greater the energy deposited. The extremely long green boxes out the bottom represent the energy deposited by the 2 photons created by the Higgs boson decay.

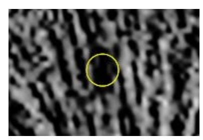


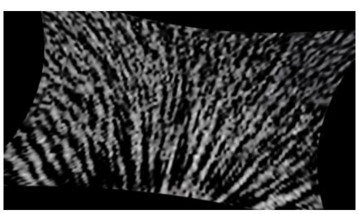
According to the Standard Model of particle physics, there are several ways for a Higgs particle to form and to decay through W, Z and quark particles. Here is a 2 photon one. It's rare, but easily identified when it happens. As two colliding protons approach each other, they overlap. Then two highly energetic gluons collide, creating a virtual top quark and anti-top quark pair. This is called gluon-gluon fusion. These unstable quarks quickly decay into a Higgs boson. The Higgs boson in turn decays into a virtual top quark and an anti-top quark that quickly decay into two high energy photons. It is the photons that were detected by Atlas.



Conclusion

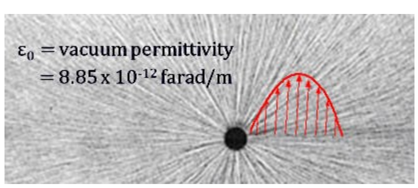
In our search to find out what is actually happening at that point in 'empty' space outside the magnet, we have learned a lot.

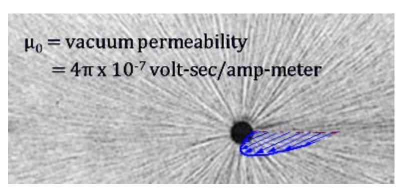




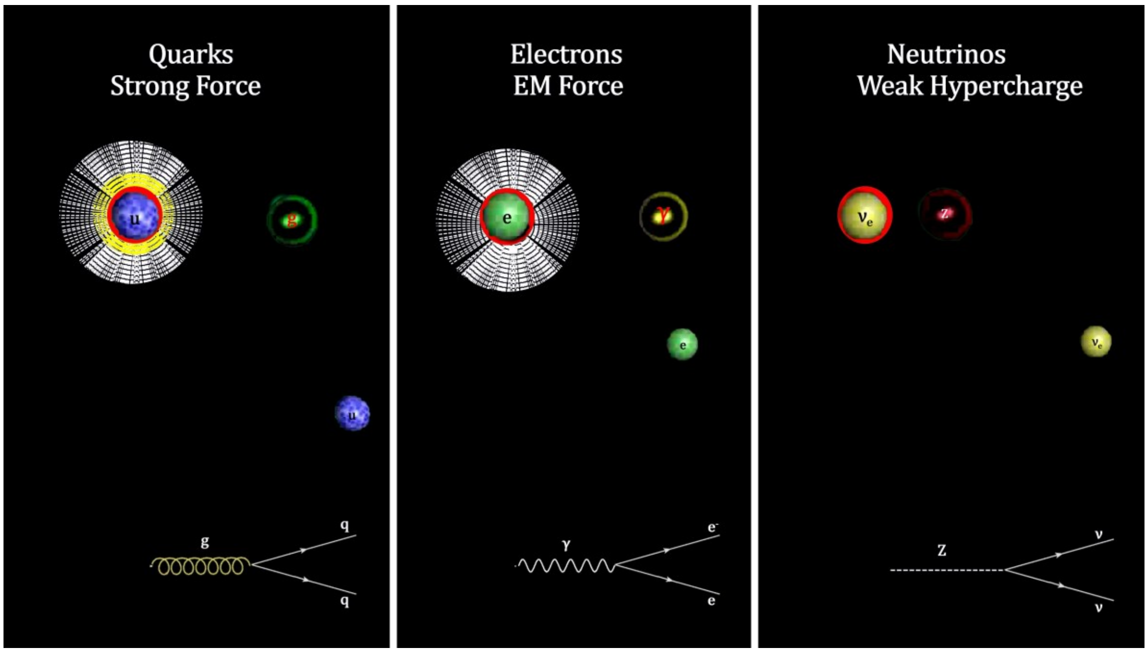
What we have discovered is that "empty space" is a complex entity. It can be stretched (as seen in the expanding universe). It can be bent (as understood by general relativity).

It's filled with various types of matter fields, force fields and the Higgs field (according to the Standard Model). The elements of these fields are quantized, massless, and almost energyless. And we know that empty space offers resistance to changes in these fields (e.g., permittivity and permeability).

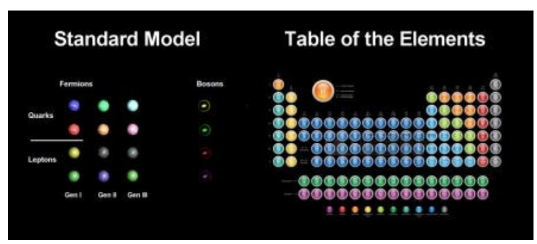


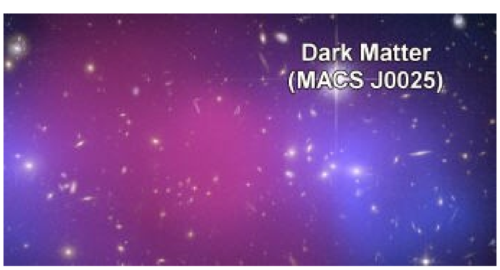


We know that, with enough energy, the elements of a field can bunch up into localized particles with properties like mass, spin, and various types of charges that spew out their own field elements into the empty space around them.



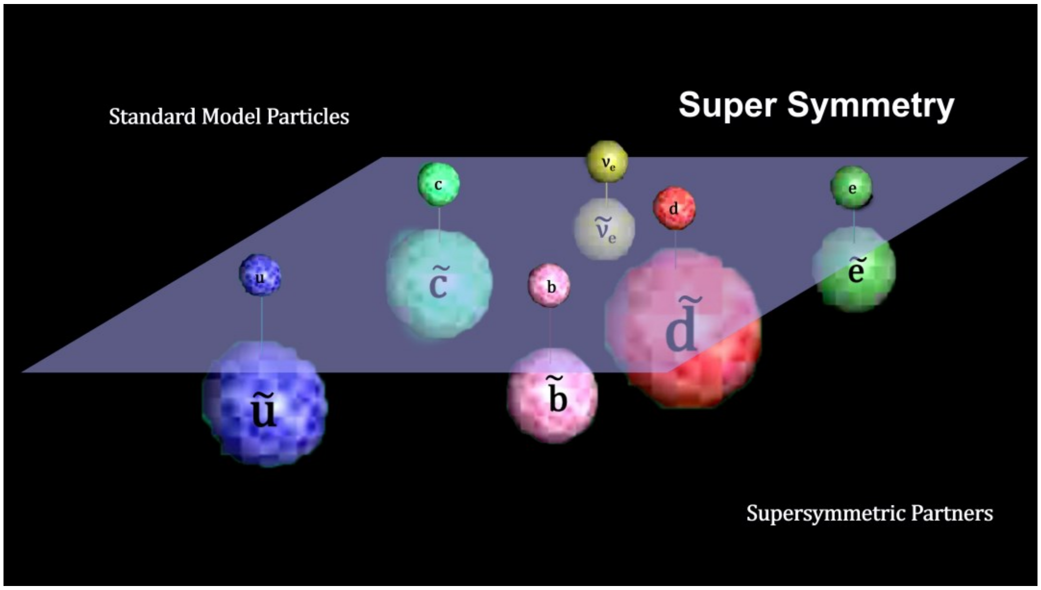
But as much as we've discovered, it feels like we're still just scratching the surface. The order in the Standard Model, like the order in the Periodic Table of the Elements, lends itself to the theory that there is an underlying structure yet to be discovered.



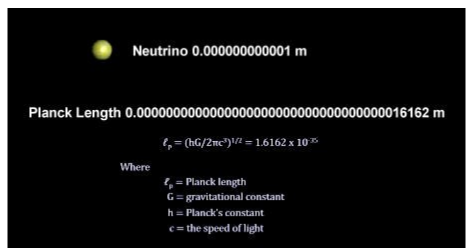


This, along with the mysteries of dark matter and dark energy plus the fundamental incompatibilities with general relativity also speak to a deeper reality.

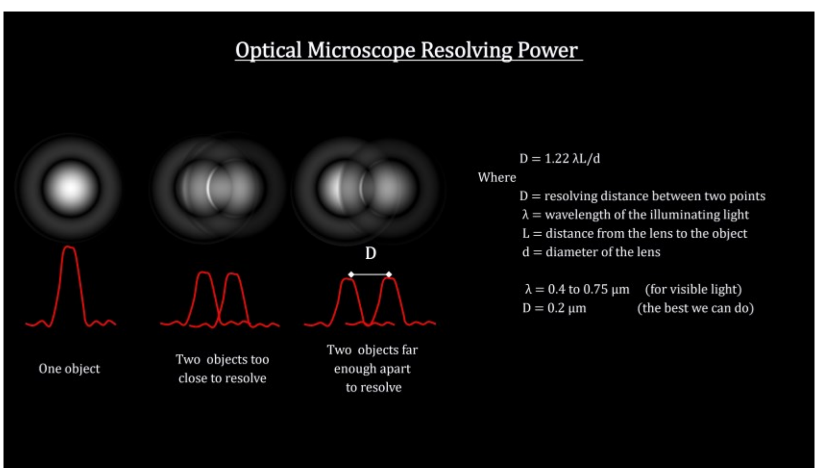
String theory, super symmetry, and loop quantum gravity are just a few of the candidate theories currently being explored.



In that vein, as we approach the end of our "How Small Is It" video book, we'll take a look at the smallest that small can get. In quantum mechanics, there is a minimum length called the Planck length. It is over 62 trillion times smaller than a neutrino – our smallest elementary particle!



This Planck length is as many times smaller than this dot ".", as this dot is smaller than the visible universe! Theoretically, it is impossible to determine the difference between two locations less than one Planck length apart. This idea takes us back to our first segment on the microscopic where we saw how light diffraction created the same problem for optical microscopes.



As we pointed out at the start of our story, you can't probe a grain of sand with your finger. How are we going to find out what's happening at this level – the level where the quantized field elements operate? This is just one of the many challenges for the physicists of tomorrow. It should be interesting.

Please take a look at the credits segment. It will point you to resources for additional research.

Thank you for watching.

Music:

@00:00 Albinoni - Concerto for Oboe and Strings No 2 II: Frank Berger, Hans-Dieter Weber; from the album "50 Must-Have Adagio Masterpieces" 2013

@06:59 Rachmaninoff - Symphony No. 2 Adagio: Sofia Philharmonic Orchestra; Emil Tabakov; from the album "Sergei Rachmaninoff: Symphony No. 2 in E Minor, Op. 27" 2011

@23:02 Ravel – Boléro: The London Symphony Orchestra; from the album "Classical Masterminds - Ravel" 2007

@33:22 Vaughan Williams - The Lark Ascending: Hugh Bean; New Philharmonia Orchestra; Sir Adrian Boult; from the album "Essential Adagios" 2010

@37:43 Brahms - Violin Concerto, Op 77 II Adagio: Sofia Philharmonic Orchestra, Vesselin Eshkenasi; from the album "50 Must-Have Adagio Masterpiece" 2013

Greek letters:
- α β γ δ ε ζ η θ ι κ λ μ ν ξ ο π ρ σ τ υ φ χ ψ ω
- Α Β Γ Δ Ε Ζ Η Θ Ι Κ Λ Μ Ν Ξ Ο Π Ρ Σ Τ Υ Φ Χ Ψ Ω

⇒ → ± ⊙ ∞ ↛ ∃ ∄ ∈ ∉ ∬ ∫ ≅ ≥ ≤ ≈ ≠ ≡ √ ∛ ~ ∝ ℏ ÷ ∂