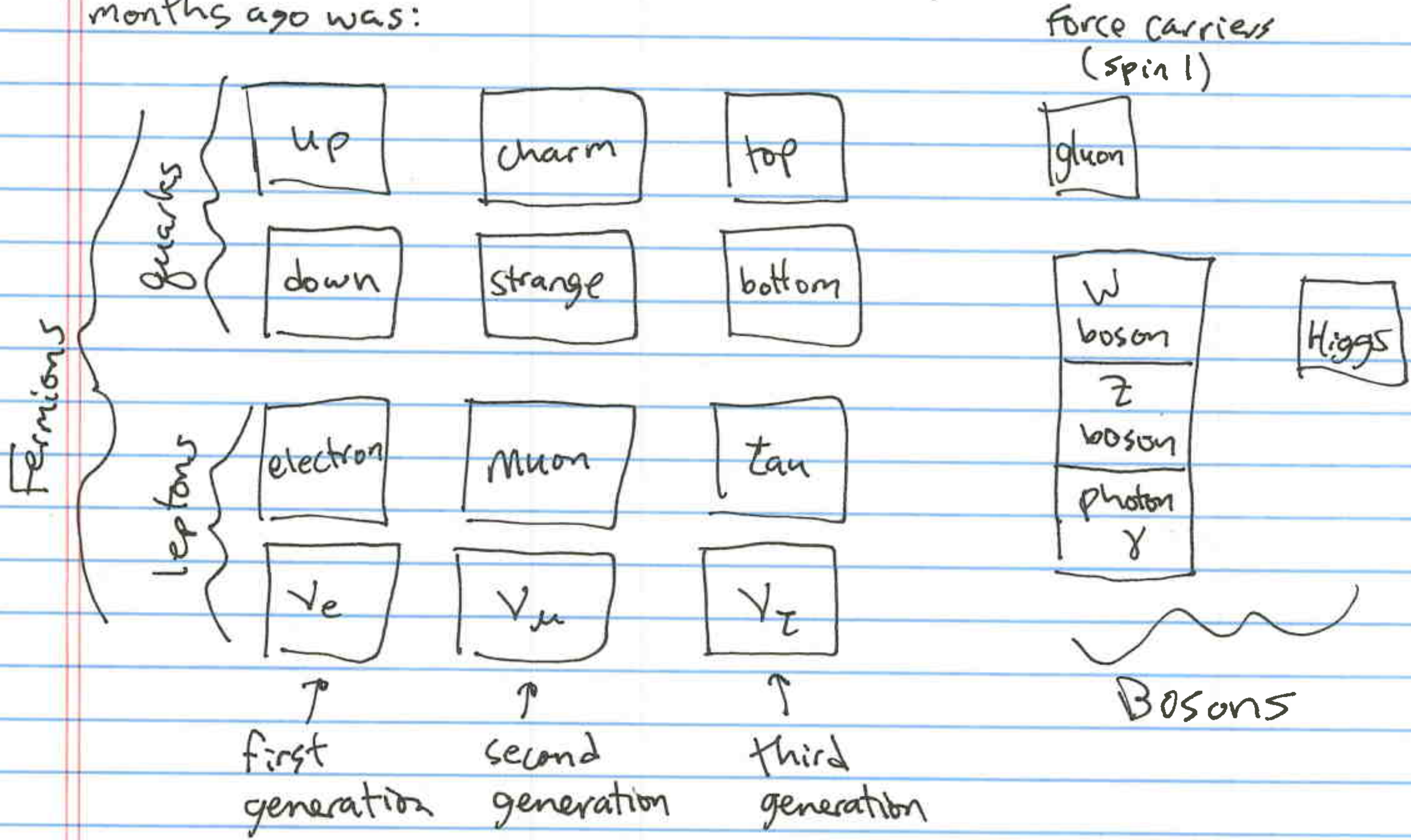
- Daily Show segment
- Typing up notes
- Final Exam ⇒ Assigned on Thursday
- Oral Exam

The Higgs Boson   Lecture 24

We've come a long way in this class. In the first lecture, I drew a sketch of the Standard Model of Particle Physics, which pointed the way for what we would cover in this class. With just a couple lectures to go, I want to revisit it, and review what we have covered in this class. This will be the segue into the most recently discovered particle of the Standard Model: the Higgs Boson.

The drawing of the Standard Model I presented three months ago was:



Our entry into particle physics was studying the properties of electron-muon scattering via electromagnetism. This was our jumping off point for studying the strong force. From $e^+e^- \to$ hadrons, we learned that quarks are spin-½ particles; we also learned that we needed three quarks for every lepton. This factor of three lead us down the rich path of postulating a new symmetry of nature that mixed these three colours of quarks, consistent with quantum mechanics. Following this to its logical conclusion resulted in the theory of quantum chronodynamics, or the strong force, and its interactions described by the properties of the gluon. With QCD in hand, we then predicted crazy phenomena of the running coupling with asymptotic freedom, and high energy collimated streams of particles called jets.

Just when we thought we were getting the hang of the subatomic world, then we attempted to understand neutron decays. Out of left-field, whatever governs neutron decays violates parity, one of our formerly sacred ideals. Not only does this force violate parity, unlike electromagnetism and QCD, its force carrier is massive. Somehow we have to give force carriers a mass, while at the same time maintaining gauge invariance to ensure that our symmetry ⇔ conservation law guiding principle from Noether's theorem holds. We were able to do this with the Higgs mechanism, where we couple a spin-0 scalar field to the force carriers, and give the scalar a vacuum expectation value. This spontaneously breaks the gauge symmetry while giving a mass to the force carriers. These force carriers, the W and Z bosons, turn out to be intimately related to the photon, and form a unified electroweak force. All particles of the standard Model interact via the weak force, save the gluon.

Last week, we studied consequences of weak interactions.

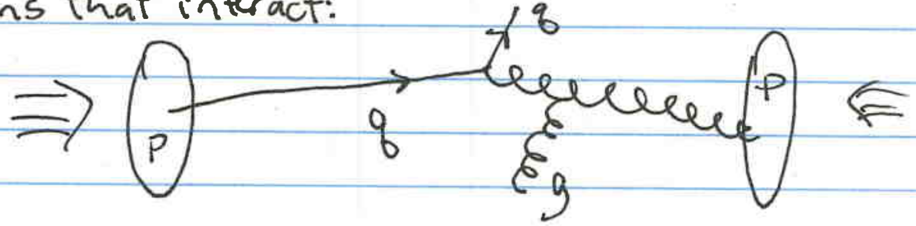
Unlike QCD or electromagnetism, the weak interactions turn leptons into different leptons or quarks into different quarks. This lead to issues when we tried to consistently describe our system. Quarks, which have mass and interact via the weak force mix into one another because the eigenstates of weak interactions are not the same as the eigenstates of mass. Beyond the standard parity violation, this mixing introduced a new CP violation because there are three generations of quarks. Quarks interact with W bosons differently than anti-quarks, apparently.

Finally, last lecture, we discussed how this mixing extends to neutrinos, though they are massless in the Standard Model. Because neutrinos can mix, or oscillate into one another, they necessarily have mass, that cannot be described by the properties of the Standard Model.

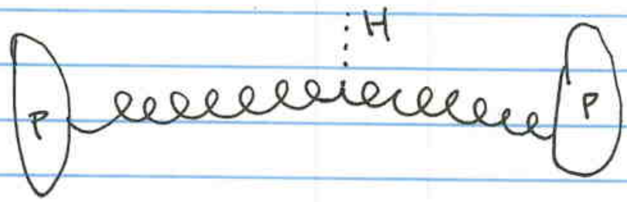
Thus, every particle and interaction of the standard Model has been observed and verified, and even some mysteries identified. well, all except for one particle: the Higgs boson. While the Higgs boson seems to be a requirement for the consistency of the theory of the weak force, it was predicted in the early 1960s and wasn't observed through many generations of experiments. Its lack of observation stumped physicists over and over again. If it were to exist, we know all of its interactions by the structure of the weak force. However, we do not know its mass, as that is not constrained by any properties of the weak force. Scientists looked and looked, in new experiments and higher energies, but no Higgs was found. A now-classic book, "The Higgs Hunter's Guide" was published in the late 1980s as a compendium of properties of the Higgs boson. It wasn't until 2012 that these hunters caught their quarry, in the experiments of the Large Hadron Collider.

The discovery of the Higgs boson at the LHC is our topic for today. The Higgs boson, as an elementary scalar (spin-0) particle, is like no other we have observed. Within the Standard Model, the Higgs mechanism is responsible for non-zero particle masses, due to the non-zero vev. (This should not be interpreted as explanation, however. The Higgs mechanism doesn't explain why the masses of the fermions or gauge bosons are what they are.) More importantly, especially for discovery, is that the Higgs boson couples to particles with a strength proportional to the particle mass. The Higgs boson couples strongly to heavy particles like the top quark or W and Z bosons, but very weakly to less massive particles, like electrons or muons. In fact, because they are massless, the Higgs doesn't couple to photons or gluons at all! This is a bit problematic, and we will have to think carefully about how to produce and therefore discover the Higgs boson at the LHC.

Let's recall what happens in proton collisions to see how we might create a Higgs boson. When protons collide at the LHC, it is actually their constituent quarks and gluons that interact:

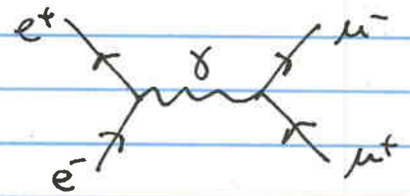


So, if we want to create a Higgs boson, we have to do so from quarks and gluons. This is a problem. There is no diagram we can write down that produces the Higgs from gluon collision:



This is not allowed because the gluon is massless and so there is no gluon-gluon-Higgs vertex in the Standard model. Similarly, the quarks that are dominantly in the proton (up, down, strange) have masses that are tens of thousands of times smaller than the W or Z bosons and therefore the cross-section for Higgs production from quark-anti-quark scattering is suppressed by a factor of something like 10^{-8}! How are we ever going to make and observe Higgs bosons?

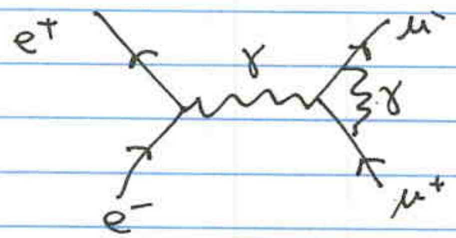
The tactic, and in fact dominant production mechanism, is to let quantum mechanics work for us. In this class, we have only discussed what are called tree diagrams for calculation of cross sections or decay rates. That is, the diagram we drew for $e^+e^- \to \mu^+\mu^-$ was tree-like, with a definite branching structure:



Topologically, such a diagram has no holes, or loops, in which you can be inside of.

It turns out that these tree diagrams are proportional to $\hbar^0$, when you re-instate $\hbar$ and c factors. That is, in the classical limit, when $\hbar \to 0$, tree diagrams remain, and are non-zero. Tree diagrams in quantum electrodynamics corresponds to Maxwell's equations.

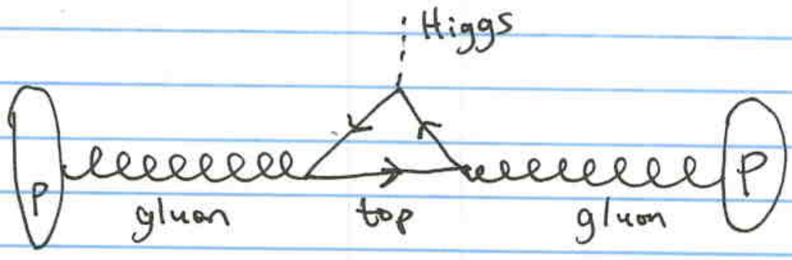
Thus, applying this to the Higgs boson, our conclusion from earlier that it is hard / impossible to produce the Higgs boson in proton collisions is true classically; at tree-level. However, our world is quantum mechanical and quantum mechanics says that anything that is not forbidden is mandatory. In quantum field theory, with Feynman diagrams, it turns out that diagrams with topological loops in them are quantum mechanical; that is, proportional to a positive power of $\hbar$. For example, in $e^+e^- \to \mu^+\mu^-$, the following diagram describes one part of quantum mechanical corrections to it:



Note that there is a $\mu^+\mu^-\gamma$ loop in this diagram; its value happens to be proportional to $\hbar$. Thus, it is honestly quantum mechanical. Whatever phenomena this diagram represents does not follow from Maxwell's equations.

So, how can this help us produce a Higgs boson? Well, let's work backwards. Because the top quark is the most massive particle of the standard Model, it couples to the Higgs boson with the greatest strength. The problem with this is that the top quark is about 175 times the mass of the proton, and so there is no way that you would be able to "find" a top quark in a proton. That is, the parton distribution function of the top quark is 0. (This is not quite true, but good enough.) So, there's no hope of tree-level production via top quarks.

However, the proton contains a copious number of gluons and as quarks, gluons couple to top quarks. So, we can extract gluons out of the protons, have them create top quarks, and the the top quarks combine to produce a Higgs boson! The simplest diagram that accomplishes this is the so-called triangle diagram:

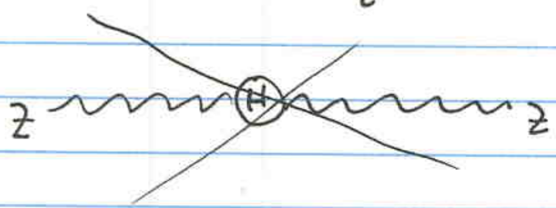


Note that this diagram contains a loop: it is honestly quantum mechanical. Its interpretation is that gluons collide and produce virtual top quarks, which exist for a time/distance as defined by the Heisenberg uncertainty principle. This is long enough, however, for the top quarks to emit a Higgs boson.

Such a diagram, that provides the first non-zero contribution to a cross-section of interest with the fewest number of loops is called a "leading-order" diagram. For many processes, leading order diagrams are tree-level diagrams. For Higgs production, however, the leading-order diagram has one loop. As more loops are added, one builds up a better and better approximation to the desired result.

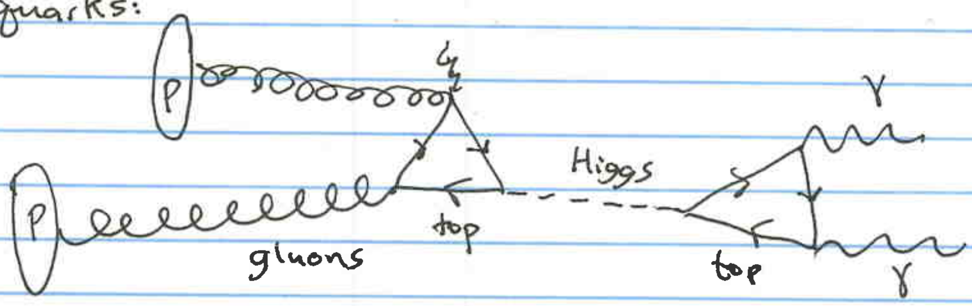
One refers to diagrams with more loops as next-to-leading order (one more loop), next-to-next-to-leading order (one further loop, NNLO for short), etc. The state of the art high precision calculations are now being performed at next-to-next-to-next-to-leading order (N^3LO; read "N-three-ell-Oh"), which adds three (!) loops to the leading order diagram. These are Herculean calculations that require large teams to complete. The first N^3LO calculation was presented about 2 years ago in 2015.

Okay, that's how to produce the Higgs boson; how do we observe it? Like the other very massive particles of the Standard Model, the Higgs boson decays almost immediately. So, we need to identify the Higgs boson by its decay products. So, we need to know what the Higgs boson can decay to. The mass of the Higgs boson is 125 GeV, which is right between the masses of the W and Z bosons (at 80 and 91 GeV, respectively) and the mass of the top quark (at about 173 GeV). Even though the Higgs boson would like to decay to these particles because they have large couplings/large masses, this is precisely the reason they cannot. A Higgs boson can't decay to ~~two~~ on-shell Z bosons, for example because $m_H \not> 2m_Z$:



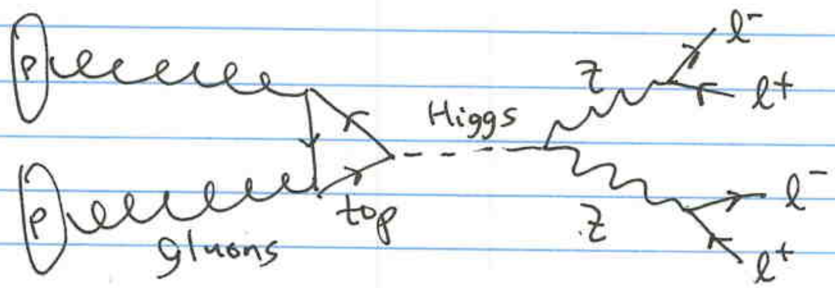
There is no allowed phase space volume for this decay. The heaviest particle of the Standard model to which the Higgs boson can directly decay is the bottom quark. The bottom quark has a mass of about 4.5 GeV, and so $m_H > 2m_b$. While the Higgs decays to bottom quarks about 60% of the time, identifying those bottom quarks is actually exceptionally challenging. These bottom quarks will just look like two jets in the detector, and have very large probability to have been produced by standard QCD processes. In fact, as of these notes, this decay of the Higgs is so challenging that it has not yet been observed.

To discover the Higgs boson, we need to identify those decays that are very easy to observe, first and foremost. The easiest particles to observe in the experiments at the LHC are photons and charged leptons: charged particles leave clear tracks, and both deposit their energy in the electromagnetic calorimetry. As discussed earlier, because photons, electrons, and muons are massless or have very small masses, they don't directly couple to the Higgs, or only very weakly. For the Higgs decaying to photons, we do the same trick as for its production: we let quantum mechanics do the heavy lifting. So, both the production and decay of the Higgs boson occurs via top quarks:



To discover the Higgs boson, we then plot the invariant mass of pairs of photons produced at the LHC and look for a bump over a smoothly falling background.

The trick to find the Higgs boson via charged leptons is a bit different. By conservation of angular momentum, we can't have the Higgs couple to top quarks that then couple to leptons. We can, however, have the Higgs boson decay to off-shell Z bosons ($m_Z^2 \neq p_Z^2$) that subsequently emit charged leptons. The diagram for this is:

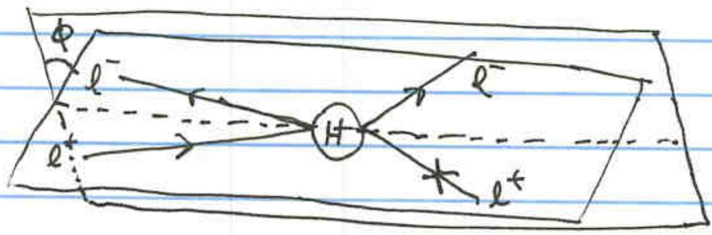


Note again that the Z bosons cannot (both) be on-shell because $m_H \not> 2m_Z$. In our detector, we look for four charged leptons, two each positively and negatively charged and calculate their invariant mass. As with photons, we look for a peak in the mass distribution over a smooth background.

So, this is the program. We smash together lots and lots of protons. If we see two photons or four charged leptons from the collision, we measure their invariant mass and add it to a histogram. After we have collected enough data, we then look at the histograms and see if there is any deviation from our background (= null hypothesis) prediction. To viscerally see what is going on, the ATLAS experiment made animations of this process, that adds events into a histogram over the data collection period. I have provided links to the animations on the class website, and we'll look at them now.

Another thing that we would like to verify with this data is that the Higgs boson is spin-0; that is, is a scalar particle. We observe it decay to photons and 4 spin-1/2 particles (the leptons), so it must be a boson. There is a result in quantum field theory called the Landau-Yang theorem that states that a spin-1 particle cannot decay to massless spin-1 particles. Therefore, because we observe the Higgs decay to photons, the Higgs itself cannot be spin-1. How do we nail down spin-0? Just like we found evidence for the spin-1/2 nature of muons and quarks, we look at (relative) angular distributions. In a proton collider, it is extremely challenging to determine spin information from relative angles from the proton beam. The biggest reason for this is that you do not know the frame in which the partons collided.

However, from the $H \to 4$ leptons decay, we can measure the relative angle between the planes defined by appropriate pairs of leptons. A picture of the angle that we measure is:



Note that the angle ϕ is measured in the rest frame of the Higgs boson. This angle will have a different distribution depending on the spin of the Higgs boson. Comparing this distribution of the angle ϕ to predictions suggests that the Higgs is a spin-0 particle with high significance. So, we got it!