Today we are going back to Einstein’s most famous equation, \( E = mc^2 \), or more accurately, \( E^2 = m^2c^4 + p^2c^2 \). When we first discussed it, we focused on the implication that energy was equivalent to mass, which allows the LHC to make Higgs bosons out of ordinary protons. Einstein arrived at this equation through his development of the theory of Special Relativity, which states that the laws of physics are the same in any frame of reference traveling at constant velocity with respect to another frame of reference. This rule necessitates the concept of invariant quantities, or quantities which are the same in all reference frames. If we produce a Higgs boson, we can always be in the reference frame where it is at rest. If it decays, then the decay products have to respect energy and momentum conservation, therefore they have to have the same total energy as the Higgs and have the equal and opposite momentum since the Higgs was at rest in this reference frame. However, as experimentalists, we can’t be in the Higgs reference frame for every event since the Higgs is produced in our detector with some momentum. So, we would like to construct a quantity which tells us about the Higgs, but is the same in all reference frames. A particle’s rest mass is one such quantity and

---

1 A reference frame is defined by the coordinate system that an observer stationary in that frame would use. If I am standing on the street and see an El train go by, my reference frame and the passengers reference frames are moving at the speed of the train with respect to each other but we are each stationary in our respective frames. For more information about special relativity, see “Relativity: A Very Short Introduction” by Russell Stannard.

http://hep.uchicago.edu/~tompkins/
is defined by: $E^2 - p^2c^2 = m^2c^4$. If this quantity is in variant, then our decay products, particles 1 and 2 satisfy, $(E_1 + E_2)^2 - (p_1 + p_2)^2c^2 = m_1^2 c^4$, in any reference frame. So by measuring the energy and momentum of the decay products of the Higgs, we can reconstruct its mass!

The second topic covered in today’s lecture is how we reconstruct quarks and gluons in our detector. Because the strong force does not allow quarks and gluons to exist alone, as soon as they are produced in the detector they start radiating other quarks and gluons. Once they radiate enough such that energy of the original quark or gluon is divided into many low energy quarks or gluons, those quarks and gluons start forming hadrons, or bound states of quarks. Those hadrons then deposit energy in the electromagnetic and hadronic calorimeters. We then look for many tracks and calorimeter depositions in a narrow cone, and by summing up all of the energy in this cone, we can reconstruct the energy of the initial quark or gluon. We call these cones of energy jets.

Higgs decay into quarks or gluons approximately 70% of the time but it is very hard to find them in this decay mode because jets are ubiquitous in LHC events. The most common process is the production of a pair of quarks, or a quark and a gluon, and they are produced with a wide range of invariant masses because the intermediate particle can be a virtual gluon with any mass. There are about 10,000 high energy jets events produced for every Higgs event. It would be impossible to find the Higgs decaying to jets if it weren’t for the fact that Higgs preferentially decay to b-quarks, the most massive quark other than the top quark, and jets from b-quarks look a little bit different than jets from other quarks or gluons. b-quarks form B-hadrons, which have the peculiar property that they live for a little while and then decay. They live long enough to travel a few millimeters in our detector, then decay into several charged particles. We can look for that decay, which is a few millimeters from where the protons interacted, as a signature of the b-quark. Luckily, there are less processes which produce two b-quarks, so Fermilab was able to see the Higgs using b-quarks.

http://hep.uchicago.edu/~tompkins/