

60th Compton Lectures

The Origin of Mass in Particle Physics

Ambreesh Gupta

Lecture VII: Higgs Properties and Experimental Searches

1. Higgs Properties

The present notion is that all of space contains the Higgs field, it permeates the vacuum and has non-zero value everywhere. Other particle fields interact with the Higgs field and acquire mass. The Higgs field is a scalar field and only requires one number at each point to describe it. It does not have a direction associated with it like a vector field. If it did have a direction then the interaction of this field with other particle fields to give them masses would have a directional dependence. This is not what we observe in reality; the W boson mass or the electron mass, for example, is the same measured in any direction.

Since known particles have a large range of mass. For example, photon is of zero mass, neutrinos are expected to have very small mass ($< 1\text{eV}$), electrons are 0.511 MeV , W bosons are 81 GeV , Top quark is 175 GeV . It is a fundamental question why do the known particles in standard model have this very large mass difference. To take the example of an electron and muon, the only difference between their properties is that the latter is about 200 times heavier than the first. Other than that they have very much identical properties. What rules of interaction with the Higgs field, might attribute known particles with these vastly different masses, is not known. Also, the Higgs is massive itself, and it is believed that it gets its own mass via self-coupling.

The Higgs field serves two fold purpose; firstly it provides mathematical consistency (calculation don't become infinite) to theory and secondly it provides mass to the particles/fields in the Standard Model as discussed above. Another way to think about the problem of infinity or technically the problem of renormalization can be thought in the following. When bunches of particles collide, they interact via different forces - electric, weak and strong (also gravity but its effect is zero due to its weakness). The result of that is different kinds of particles are produced that fly in the detector. For each type of particle production there is an associated probability. For example, if out of a thousand events only 100 events produce electron and positron in the detector, then the probability of such a process is 10%. The probability can never exceed 100%, which is a meaningless thing to say. We saw in previous lectures that Fermi theory that explains radioactive beta decay is a low energy approximation to the theory of weak force involving W/Z boson as force carriers. The theory worked well when the energy involved was about 100 MeV . At high energies, 100 GeV the theory broke down and gave unrealistic probabilities of values more than 100%. Introduction of massive W/Z bosons cured that problem. In a similar fashion, the present electroweak theory will give

unrealistic probabilities at energies of about 1 TeV. Introduction of the Higgs particle cures that problem and makes the predicted probabilities sensible. This 1 TeV energy is called as the Unitarity limit (probabilities cannot be larger than one) and the Higgs is expected to have mass smaller than 1 TeV.

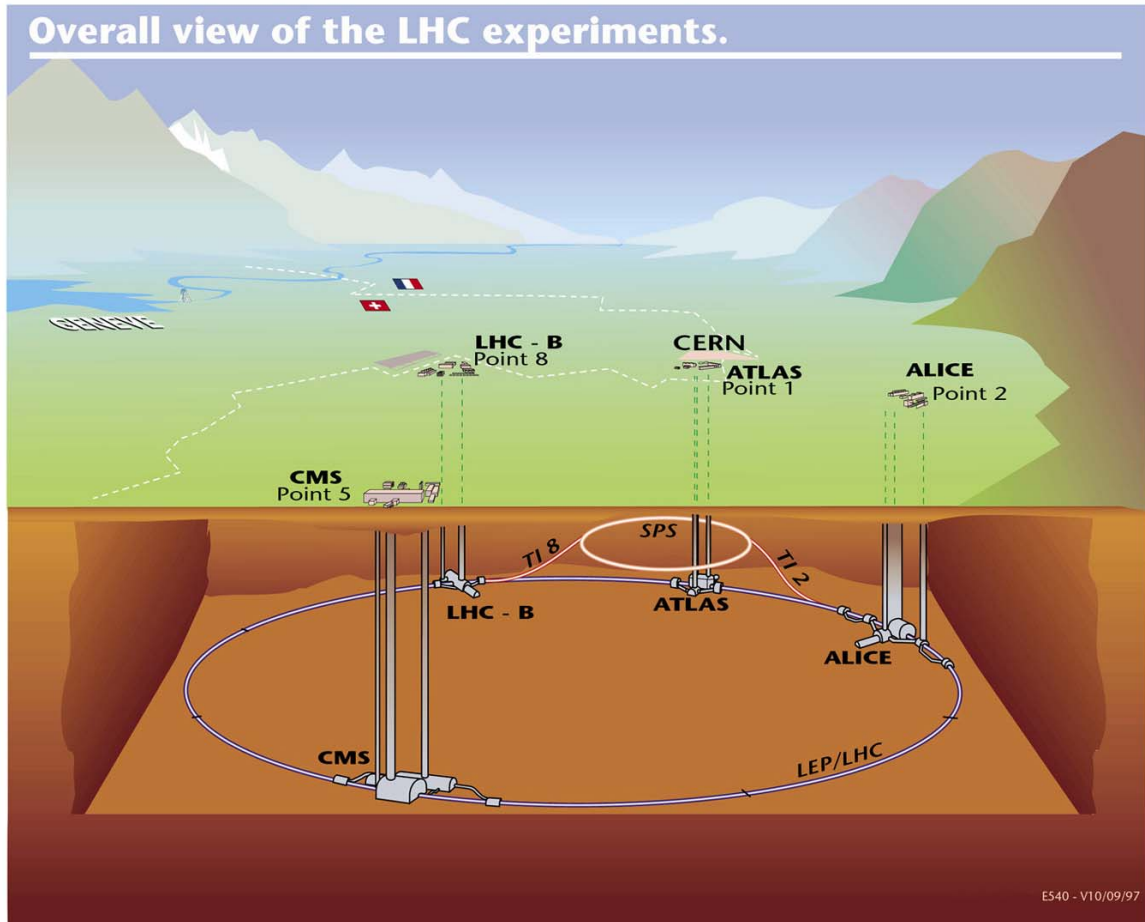
What do we know about the existence of the Higgs boson? Intense experimental searches, so far, have failed to show clear evidence of the Higgs boson. The Standard Model of particle physics has about 20 unknown parameters (the particle masses, the force couplings etc.) that are measured directly through experiments. It also predicts relationships between these parameters. Out of these 20, all except the Higgs mass is measured directly in experiments. Since Higgs is the only unknown, its mass can be inferred by plugging in the rest of the parameters in the Standard Model relationships. This gives an indirect evidence of the Higgs boson and it predicts that the mass of the Higgs boson should be smaller than 200 GeV. The Large electron positron (LEP) collider experiments at the end of their run in 2000, seemed to have seen a hint of Higgs boson directly. At the high energy runs of LEP there were events suggesting a particle in nature similar to the Higgs boson with a mass of 115 GeV. But, the smallness in the number of such events did not provide a robust statistical test about the trueness of the signal. So, all we know about the Higgs boson, if it exists, it should have a mass with 115 GeV and 200 GeV.

2. The Large Hadron Collider (LHC)

It is believed, unless something spectacular happens at the Tevatron at Fermilab, the saga of Higgs search will finally culminate at the LHC. The LHC which will become functional in 2007, will collide one bunch of protons with another bunch of protons traveling in opposite directions in the 27 kilometers accelerator ring at an energy of 14 TeV. (The energy stored in a proton is about 1 GeV and 1000 GeV makes 1 TeV). At that energy the protons will be traveling at a velocity very close to that of light: 99.999999 % of light speed. Such high-energy collision will make LHC the finest microscope to probe the deeper structure of nature. The constituents a proton is made of, the quarks and the gluons, share this high energy. When the protons collide, these high-energy quarks and gluons interact. In most collision, the energy is squandered because the quarks and gluons give only tangential blow to each other and produce a spray of particles that have been known and catalogued for long time. But, once in a while two quarks will collide head on with each other at energy has high as 2 TeV or more. At such high-energy collision of quarks, interactions, which were not possible at low energies, become possible, including the possibility of producing the Higgs boson.

The vast and technologically challenging project, coordinated by the European high-energy physics laboratory CERN, is well under way. The LHC will use the ring of LEP collider, which worked at energy of about 1% of LHC energy and used to collide electron on positron. By using the LEP ring, LHC avoids the large expense of siting and building a new larger accelerator ring. Bending the protons at such high energies will require very strong magnetic field; higher than any used in accelerator experiments. The magnetic fields will be produced by 1232 fifteen meter long dipole magnets installed along 85% of LHC ring circumference. Superconducting cables carrying currents of 12,000 amperes

will power the magnets. The cables are cooled by superfluid helium to -271 degrees Celsius, just two degrees above absolute zero. The picture below shows the view of the LHC ring and the experiments that will function.



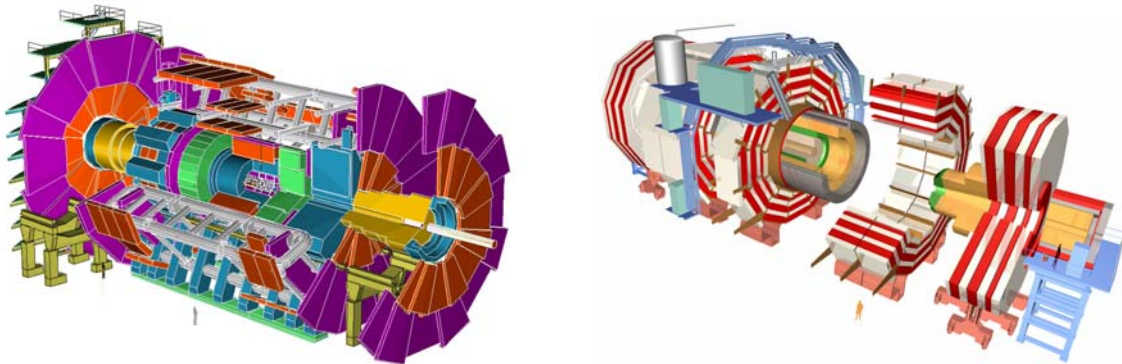
Since the energy of the protons is shared by the quarks and gluons, and they are the ones that interact, it is necessary that they get chance to have a large fraction of the proton energy. This is a probabilistic thing, and to increase the chances of high-energy collision between the quarks, a large number of collisions need to be performed. To achieve this, the LHC will collide particles at very high intensity i.e., a large number of proton will be bunched tightly to make an intense beam and collided at very short time interval. The LHC intensity or “luminosity” will be 100 times that of the Tevatron at Fermilab.

The proton and proton bunches collide at a short time interval of 25 nano second, or 40 million times every second. In every bunch crossing, there will be about 20 (out of 10^{11} protons per bunch) proton and proton collision. This makes 800 million collisions per second. Although, this might sound like a lot, but only in about one in a billion collision we get an interesting head on quark collisions. In general, about a 100 secondary particles are produced in each collision. The enormous LHC detectors, ATLAS and

CMS, which are about the size of six-storied buildings, detect the secondary particles. They are packed with sophisticated detector technology and electronics readout and they track all the debris that comes from the proton-proton collision. Once functioning, the LHC experiments will probe matter to a very small size of about 10^{-19} meter. These high energies will emulate the conditions about a trillionth of a second after the big bang and the beginning of the Universe. To hold such high-energy proton beams of 7 TeV, the LHC ring will need a magnetic field of 8.3 Tesla, which is about 100,000 times the earth's magnetic field. They will rely on superconducting wires, resulting in compact magnets that can generate magnetic field strengths that are unobtainable with conventional magnets with copper wire.

3. The LHC detectors

There will be four detectors at LHC, two general-purpose giant of detectors ATLAS and CMS and two smaller detectors for specific physics, ALICE and LHCb. The figure below shows the ATLAS (left) and CMS (right) detectors. The size of these detectors can be appreciated by the almost invisible human size at the bottom of these detectors.



The deal with the furious rate of collision requires sophisticated handling in the data readout chain. At the first step, event data is send in an electronics pipeline that can hold data for about a thousand events. This gives the downstream electronics enough time to make a decision whether to keep the event or throw it away. LHC detectors will have tens of millions of electronics readout channels. Matching up all the pipelined signals that originate from the same proton-proton collision will be a mind-boggling task.

Both ATLAS and CMS are optimized to detect energetic muons, electrons, photons and jets of particles coming from quarks. The presence of these particles, their energy and topology of distribution in the detectors, can lead to the signature such as that of a Higgs boson.