Nuclear and Particle Physics
Prof. P Poulose
Department of Physics
Indian Institute of Technology, Guwahati

Module – 07
Elementary Particles
Lecture – 01
Introduction-overview

Today discuss the basic some basic properties of the; and some basic properties of the elementary particles and fundamental forces in nature.

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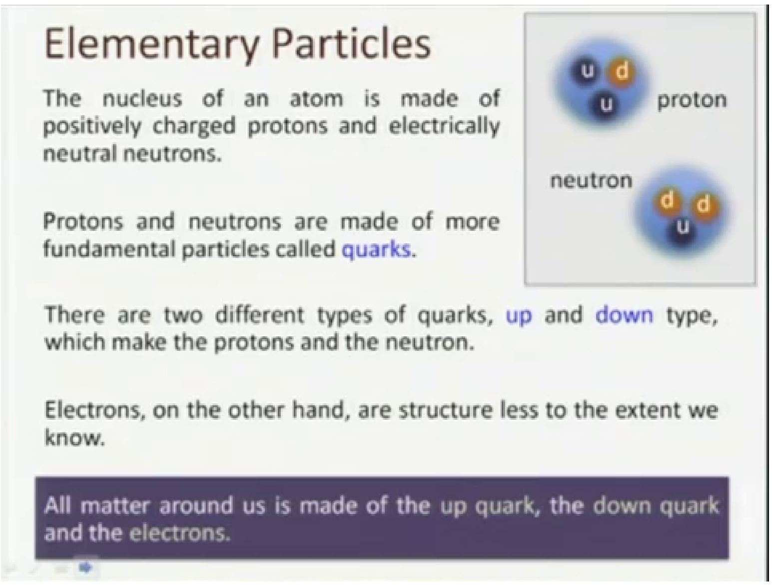

We know that the nucleus of an atom is made of protons which are positively charged and neutrons which are electrically neutral. Protons and neutrons are made of more fundamental particles called quarks. This we know from scattering experiments which tells us information about the interiors of protons.

So, there are different types of quarks, two such different quarks are called up type quark and down type quark and protons are made of 2 up type quarks and 1 down type quark. Neutrons are made of 2 down type quarks and up type quark. They are fractionally charged. The up type quark is made of I mean is minus up type quark is plus 2 by 3 times magnitude of the electronic charge e, the charge on the down type quark is minus 1 by 3 it is negatively charged and the magnitude is minus 1 by 3 one-third of the charge of the electron magnet. So, between u, two u quarks and d quarks total they have one unit positive charge in units of electronic charge.

Electrons on the other hand are found to be structure less we do not so far as the experiment goes they have no structures. Poor matter around us are made of these fundamental particles u quark, d quark and electrons.

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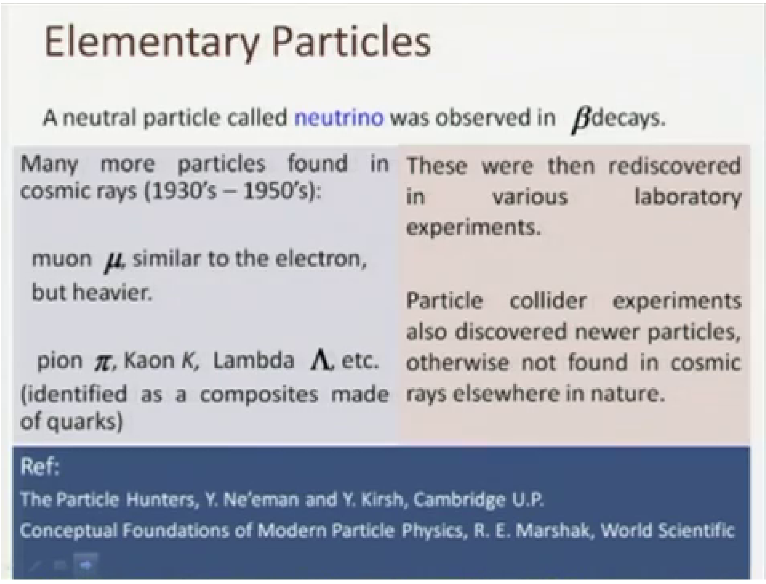

And another particle which was known this was proposed by Pauli Wolfgang, Pauli in connection with the beta decay p. In the beta decay experiments the electrons coming out of the nuclei were found to have a continuous energy spectrum which is not expected if final state had only an electron in addition to the daughter nucleus. If it was only a daughter nucleus and an observed electron beta particle in the final stage then we could have calculated the energy kinetic energy of the emitted beta particle from the mass relations between the masses of the daughter nucleus and the parent nucleus and use using the kinematic relations energy momentum relations.

But that was not the case. So, the way out was proposed to how another particle in the final state which is not observed at all. And this was supposed to be a mass less particle, charge less particle, weakly I mean a inter coming out in the or interacting with interacting with the electrons and the atomic particles I mean nuclear particles. And that was a story at that time in 1930s. And later on in the period of 30s to 50s many particles, many new particles which was otherwise not present in ordinary matter were found in what is now known as cosmic rays. The cosmic rays are basically a radiation coming from outer space outside that earths it could be partly from sun, could be from other stars or it could be from other sources astrophysical sources. These radiations it has electromagnetic radiation as well as particle content in it. There are charged particles and neutral particles some of these particles are exotic compared to the naturally available particles elements on earth.

So, there many of them which was discovered one is called muon which was later found to be very similar to the electron, but much much heavier 200 times heavier than the electrons. There were other particles called pions, kaons, lambda particles etcetera. Muons were like electrons elementary in the sense that they are not made of some finer particles or more fundamental particles whereas, the other set pion, kaon, lambda etcetera are later on found to be made of quarks like neutron and protons. So, these particles were also discovered in various laboratory experiments. So, scattering experiments were going on and then we could also produce all these particles in scattering experiments. And these experiments collider experiments also disk discovered many other particles which we are not even present in cosmic rays.

So, thus there are lot of lot many subatomic particles that were discovered in the 20th century. We will not go into the historical details or even attempt to actually give a overview of that rather. We will refer to some of these books we could take any other book, but I just mentioned 2 of them, one is particle hunters which is a very readable book for students telling this discoveries and other aspects of particles giving a very good introduction to this many times without going into the details and emphasizing sometimes on the historical aspects etcetera. So, if you are interested in it you can go through this, Particle Hunters by Neemann and Kirsh.

Another book is conceptual foundations of modern particle physics by Marshak. It is also a very good book which gives a good introduction to all these developments in the early stages and the discoveries.

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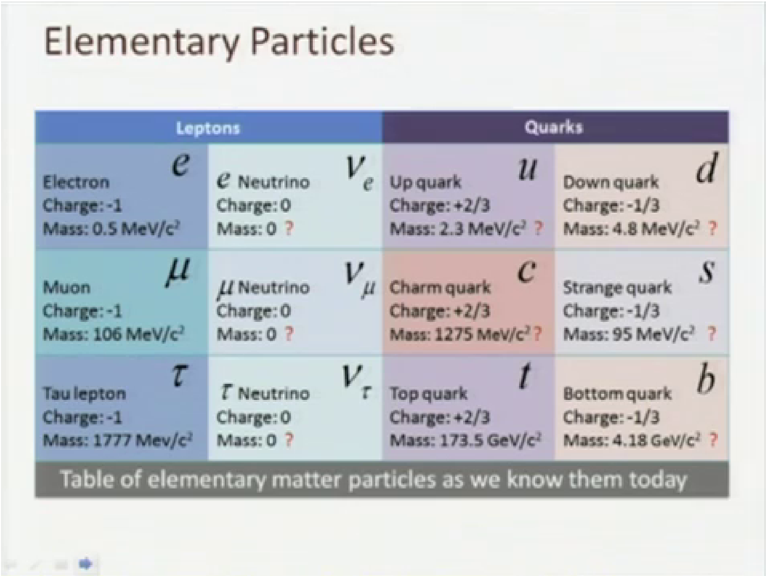

We will actually here some of the knowledge that we have now. The very elementary particles are categorized into 2 different distinct classes one is called leptons 2 which belongs electrons, muons and tau leptons all of these have something in common we will come to some of the details as we progress. All of them have one unit of negative charge again in units of electronic charge. So obviously, electron will have minus 1 charge and muon. And tau also have are found to how the same charge electric charge.

But the masses are different electron is the lightest one with mass 0.5 Mev per c square. Muon is 200 times heavier than this 106 Mev per c square and tau has 1 tau electron is much much heavier it is 1777 in Mev per c square or 1.7 or 1.8 Gb per c square. These are 3 particles under leptons 3 charged particles under leptons. Then there are 3 other a neutral particles which are called neutrinos. There are 3 of them each one linked with either electron muon or tau. All of them are neutral electrically neutral. All of them are very very light in fact, in the standard model of particle physics they are assumed to be mass less m mass is equal to 0 strictly, but recently last 10 years we know that 10 or 15 years actually we know that these particles are not really completely mass less they have some mass. We do not know yet what their masses are, we have some information about the difference of their masses but they are very light, light in the sense that they are something like of the order of a few electron volts masses.

So, I have put a question mark there just to remind you that when I say mass equal to 0 that is with all these caveats. This electron type neutrino e neutrino is the one which is produced in the beta d. Strictly speaking it is not exactly the neutrino this particle, but it is the antiparticle of this which is produced in the beta decay. We will come to what an antiparticle is at some stage. So, but it is of that type I mean and muon type neutrino or anti neutrino are not produced in beta decay they are produced only in association with mu lepton similarly tau leptons, that is one thing.

And the other part of the spectrum is called quarks. The up type and down type quarks we already saw inside the proton and inside the neutron. And as I mentioned at that time the electric charge of up type quark is plus 2 by e in units of electronic charge, mass of that is roughly 2.3 Mev per c square down type quark has a electric charge of minus 1 by 3, mass slightly heavier than u quark 4.8 Mev per c square, charm quark is similar to the u quark electronic charges 2 by 3 masses 1275 Mev by c square. There is another type quark which are called strange quark electronic charge is minus 1 by 3 heavier 95 Mev per c square, heavier compared to the d quark and u quark.

Then comes top quark which is again similar to u and c charge electronic charges plus 2 by 3 masses 173.5 Gev by c square. It is an elementary particle which is something like 200 times, 174 times heavier or 180 or more times heavier compared to the proton heavier than the proton and it is an elementary particle. It is an elementary particle in the sense that it is not made of any further finer structure and in the dynamics of elementary particles this top quark is one of the crucial components it plays a crucial role in many cases. In the 6 another quark has b quark or bottom quark charge is minus 1 by 3 mass is 4.18 Gev per c square.

So, you see that I have put a question mark on all these masses except for the top quark that is because except for the top quark all of all the other quarks are really not found in free states therefore, when we say the mass of this particle. We had to qualify that statement with various other these things. It is the mass of the particle as inferred indirectly and there again the precise definition of mass itself is somewhat hazy. So, we had to keep in mind that when I say the mass of this particle it is some notion of mass of the particle and then that is not a very precise definition, precise quantity like the mass of the particle like the mass of the top quark or proton etcetera that we can measure.

Whereas, in the case of top quark these particles are so heavy that they are not really found in bound states, they are actually there you know if you produce them and they decay immediately very unstable particle. Many of these particles are unstable top quark is also unstable, muon is unstable, you do not really see them freely moving around for edges they are produced in some reactions and then the decay in some short while. But and top quark is also like that u quark, you know they can be made into protons and which can stay for a long time and then in fact, they do not decay for a they do not decay they however, they are very very stable. And similarly you can have bound states of charm quarks bound state of strange quarks combinations of these bound states of b quark etcetera.

Many of these bound states are unstable, but they all form bound states. They do not really decay as a b quark. This is slightly different from saying that top quark decays a b quark immediately combines with some other quark, another b quark or some other quad to form bound states. But top quark actually when it is produced it decays immediately the decay time is so short that it cannot even combine with some other quark within that short time. So, they have such short decay time and therefore, from the decay products actually we can infer the mass of this particle very accurately, mass of a particle is basically can be at working definition can be that the energy of the particle the total energy of the particle in its rest frame. So, when the particle is at rest it not moving it has no momentum it has no kinetic energy. So, the only energy that it has is due to its mass.

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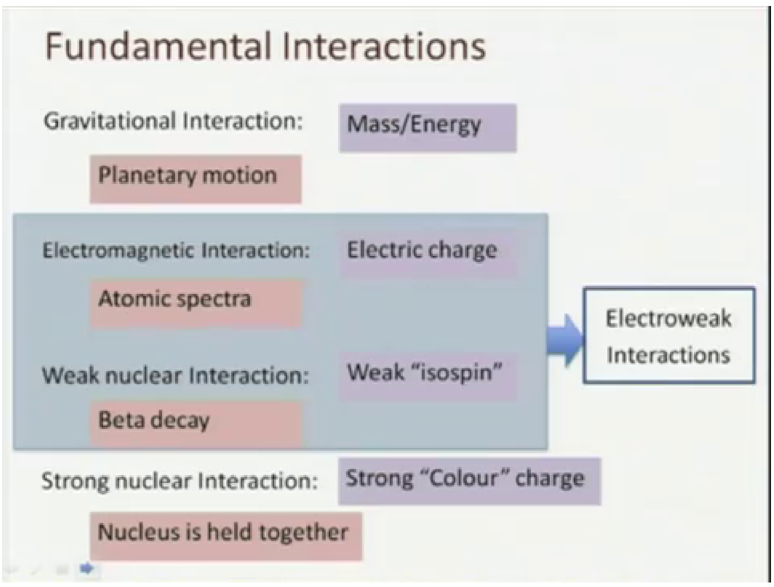

So, that is the mass of the particle say one definition. So, that is basically the picture of the elementary particles that we know of now. And the other part of this discussion is basically the fundamental interactions. Gravitational interaction is all around us and then we know a lot about them about this, planetary motion, happens falling or anything. Anything that has mass or energy can take part in or thus take part in gravitational interaction.

Then we have electromagnetic interaction which is also very well known we have it all around us light, that I see you when you see me is an example of electromagnetic interaction or I flex my muscle or I pick up something and all these forces or muscular force or anything that has to do with our body mostly is due to electromagnetic interaction, so reactor magnetic force, atomic spectra so that is another thing that you know. And any particle having electric charge has electromagnetic interaction or takes part in electromagnetic interaction.

Weak nuclear interaction, we know that there are electrons coming out of nucleus the electrons do not exist their previous prior to this, but they are produced in what is called beta decay of the nucleus and they are ejected from the nucleus. So, that is one instant of beta weak interaction, but there are other weak interactions that we will be have well understood. And, but that is not naturally you occurring we have to actually go to laboratory experiments like all other experiments and let us see experiment or lab experiment that we mentioned earlier or any other experiment that is going around and for weak interactions. And we can associate the weak interaction to charge called and called charge which is called the weak isospin of particular property of the particle which is called weak isospin.

So, if the week isospin of the particle is 0 then they will not take part in weak interaction. Then there is strong nuclear interaction; obviously, we know about that they are there because a nucleus is held together or many protons are held together in the nucleus despite their positive charge and repulsion electromagnetic repulsion. So, there has to be some strong nuclear force and the course of this can be associated with some other property which is called color charge strong color charge of the particle.

Now, we cannot at some stage at high energies separate this electromagnetic interaction and weak interaction. Instead we are first to talk about them as a combined force which is called electro weak interaction. This combining mixing of the there is a joining of these two is similar to the electromagnetic interaction which is a combination well in some sense of electric and magnetic properties of the matter I should say the other way around actually electromagnetic interaction cannot be separated into electric and magnetic forces or interactions, many cases including when the particle particle charged particle are moving are in motion. So, you cannot separate this electromagnetic interaction into electric and magnetic forces unless you go to very small non relativistic cases.

So, now, the in a similar fashion we can actually combine we have to think about a combined electromagnetic force rather than an electric electromagnetic sorry combined electro weak interaction rather than an electromagnetic and weak nuclear interaction separately.

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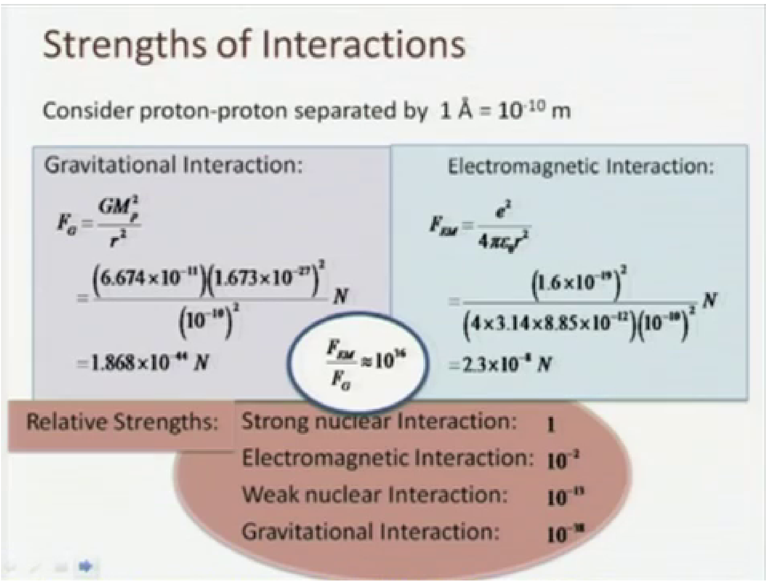

Coming to the strengths of these interactions gravitational, let us take a particular case of a proton proton, separated at say 10 power minus 10 meters or 1 astrum. What is the gravitational interaction between these? Gravitational force say is GM p square over r square, which G is the gravitational constant 6.674 into 10 power minus 11 and then mass of the proton is 1.673 into 10 power minus 27 kilogram square of that has to be multiplied with the G, divided that by the distance 10 power minus 10 square meters. This gives us something like 1.868 into 10 power minus 44 neutron.

Take the same proton and proton and combine it and find out what is the electromagnetic interaction between these two when they are separated by N by 1 anstrum. It is equal to e square over e is the charge e square over 4 pi epsilon 0 r square numerically it is e is 1.6 into 10 power minus 19 coulomb square of that divided by 4 into pi 3.14 into 8.85 into 10 power minus 12 which is epsilon 0 into r square turns out that it is equal to 2.3 into 10 power minus 8 neutron.

So, if you compare the electromagnetic force is the strength of the electromagnetic force with the strength of the gravitational force you see that it is something like 10 power 3 6 times stronger compared to electron my gravitational force which is much much very very strong compared to the gravitational force.

So, let us see how the other interactions are. If we consider the strong interaction to be of strength say 1, then electromagnetic interaction is 100 times weaker than this weak nuclear interaction is 10 power minus 3 times weaker than the strong interactions for 10 power minus 11 times weaker than the electromagnetic interaction and gravitational interaction is very very very weak 10 power minus 38 times weaker and strong interaction. So, in most of the academic elementary particle physics studies we actually neglect the effect of gravitation interaction because when we consider say proton proton collision at LHC at 70 av or 8 av centre of mass energy we have effect of strong interactions, weak interactions, electromagnetic interactions etcetera and if you consider the gravitational interaction along with that if what we are saying here is the right thing then we will not have any effect of this compared to the other 3 interactions.

So, basically we actually do not really consider this here. The other reason is that we do not still have a good theory, theory give good model for quantum gravity we do not know what is gravity like at very small scales, only what we know so far is that even at 1 Fermi scale 10 power minus 15 we do not have the effect of gravity observed so far. And Newtonian gravity is tested up to micron level, so less than millimeter level sub millimeter level we know that it is gravitational interaction is like the Newtonian gravity. So, therefore, it is very weak at that stage. Beyond that we do not really know. But if we believe we can take is a extension extend this idea of gravitational interaction that we have at larger scales then it is going to be very very weak and little we reach very high energies. All these strengths actually are again scale dependent. So, this is not strictly a constant anything at high energies at energies of Planck scale say 10 power 19 Gev we can expect the gravitational interaction to be of the at a comparable strength compared to other interactions.

So, and the other interactions also evolve with energy scale. So, the statement is taken to be taken with some caution, but by and large this is a kind of a guiding principle when we actually look at the strengths of these contractions.

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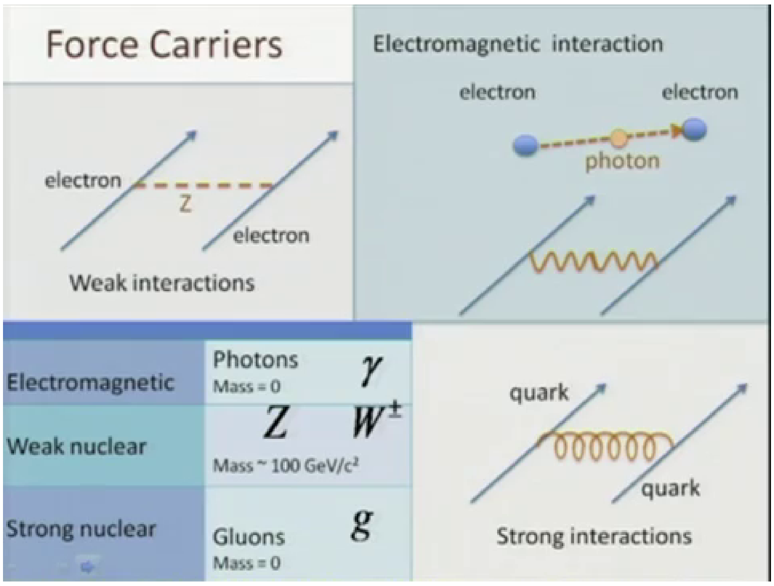

Certainly at the scales that we deal with in the normal case, but an atomic and nuclear scales, but it is also valid even to a slightly higher scale. Now, how do we understand these interactions? Let us look at electromagnetic interaction between 2 electrons say. So, if you consider an electron interacting with an electron we can think about it as see if say electron exchanging some particles some information in terms of quanta of electromagnetic which is called a photon. So, we have a an exchange of information from one electron to the other or exchange of something quondam of the electromagnetic field or exchange of photons between these electrons and that is how the interaction is a interaction happens, that is how we understand it presently. So, diagrammatically I can represent one electron by an arrow the other electron by another arrow blue arrow and exchanged photon by a wavy line, the orange wavy line.

So, they represent this particular picture then represent the electromagnetic interaction between 2 electron so say. So, we can say in some sense that the photons carry photons are the carriers of electromagnetic interaction. This is true not only between the electrons, but between any charged particle electromagnetic interaction between any charged particle this thought of happening through the force carriers photons or the exchange of the first carriers photons. And exactly similarly we can think about weak interactions between electrons right, but now the interaction is different therefore, the force field is different and therefore, the carrier is different. So, the first carrier here is called as a Z Boson, this particle is exchanged some quantum of the weak field is exchanged between the electrons and then that is basically the interaction between the electron.

And when we talk about strong interactions electrons do not take part in strong interactions we will come to the details later. So, quarks when they interact strongly they exchange some quantum of strong field which is called blue on. To sum up electromagnetic interactions are due to what are called photons we usually label it a photon by the letter, Greek letter gamma and the mass of the photon is 0 photon is strictly mass less. Weak nuclear interaction is due to the exchange of this happens via the carriers called Z Bosons and W Bosons.

Z Boson is electrically neutral and massive with mass around 100 Gev per c square. W Boson is electrically charged one unit of either plus charge there are 2 types of W's plus and negative minus. So, one of them is charged like electron the other is charged like proton and they also have similar mass about 100 Gev, well it is actually 80.4 Gev or so, for W and 99.19 Gev for the Z Boson, roughly 100 Gev. And the gluons are again massless and they are electrically neutral, but they carry strong color charge. So, they can interact base strongly between themselves and there are different types of them there are actually h such different type of quarks also gluons, gluons that we have in nature to account for the strong interaction.

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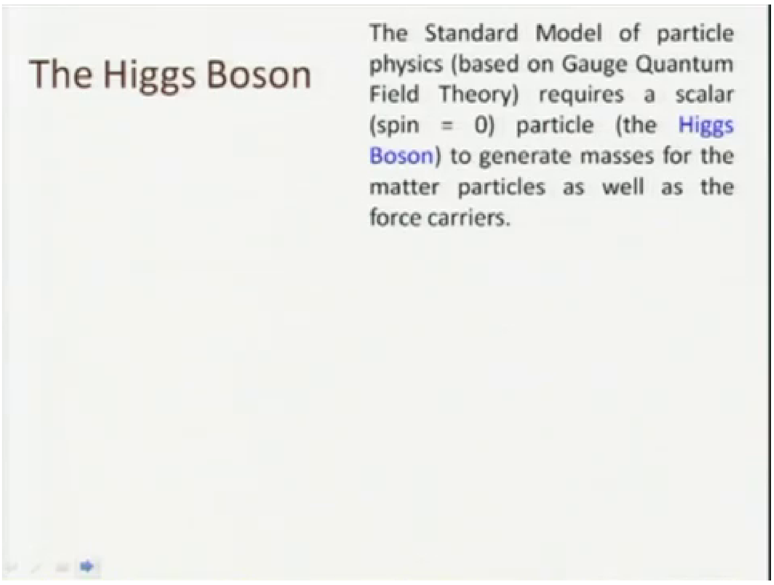

Coming to the other particle which is a totally different species on it in itself completely different from the ones that we have been talking about so far leptons and quarks this is called the Higgs Boson. The standard model particle physics requires this particle to generate masses for the matter particles as well as the gauge for somebody we said electron has mass proton, as mass resent Boson, as mass to explain this presence of the mass of the particle we need to have some mechanism by which masses are generated or generated for the particles and this in turn needs what is called the Higgs field. And consequently we have a physical particle called Higgs Boson which is a scalar particle meaning spin is spin of this particle is 0 and that particle itself has mass the mass itself is not dictated by the standard model it is not known in the standard one model. It has to be fixed from experiments like any other mass of the other particles.

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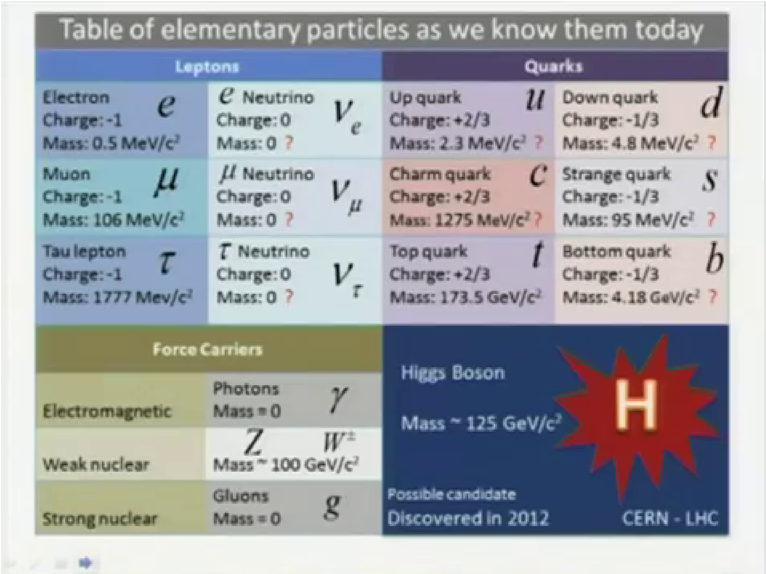

So, with the discovery of the Higgs particle, then we have the table of elementary particle here, we discuss the leptons and the quarks and that is the same as what we had seen earlier. Force carriers we discussed and then there is electromagnetic force and electromagnetic field and photons are the carriers of electromagnetic field and the weak nuclear force as Z and W plus minus as the carriers, strong nuclear forces 8 gluons in this and the Higgs field here. So, this particular chart basically combines all the known or list all the known particles and some of their properties.

So, with that I think we will stop here today and then we will continue our discussion tomorrow in the next lecture.