Waiting for LHC

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1 Building blocks of the Universe

It would not be an exaggeration to say that a very large fraction of the physics community is waiting with a nervous excitement for August 2008 when the largest ever particle accelerator, the Large Hadron Collidor, or to name its ubiquitous acronym, LHC, is expected to start working near the city of Geneva in Switzerland. This is the largest ever experiment conducted by human beings. It will involve smashing two very high energy beams of protons. Protons together with neutrons are the building blocks of various nuclei which are at the centre of an atom. The proton and neutron are in turn made up of elementary particles called quarks and gluons. Various particle made of quarks and gluons are called hadrons. Proton being one of the hadrons, and hence the name LHC. The reason for this hugely expensive instrument and the eager anticipation of the physics world is that with it we hope to answer a very simple question: Why do the electrons and quarks have the mass that they have?

To appreciate the question, recall we believe that every thing we see around us is made of molecules, which in turn are made of atoms. All the atoms are build of three building blocks - electrons, protons and neutrons. So the extraordinary diversity that we see from the mundane paper of this magazine to the skin of your hand are just di_erent combinations of electrons, protons and neutrons. These three particles have mass. The mass of electron is negligibly small compared to the mass of the proton and neutron. As a result mass of an atom is essentially the mass of the protons and neutrons that make of that atom. The protons and nucleons combine together to form the nucleus around which the electrons are distributed. As we have noted protons and neutrons are made of quarks and gluons.

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Electron and quarks, together with their cousins, are the building blocks of the matter. They interact with themselves and with other building blocks through at least four know forces. These are the familiar gravitational and electromagnetic force, together with two unfamiliar forces called weak and strong interaction. We will be mainly concerned with the Weak force or the Weak interaction. This force is responsible for a neutron to decay into proton, electron, and another particle called anti-neutrino. As a result of Weak force many elements can transmute into other elements either by their neturons getting converted into protons, or their protons getting converted into neutrons. The strong force is responsible for holding quarks together to form protons and neutrons, and is also responsible for holding protons together in a nucleus. It was termed historically strong as the strong attractive force between the protons in a nucleus is much greater than the repulsive electric force between the protons (recall that the like charges repel each other and therefore two protons repel each other through electric force.)

With each of these forces there are associated particles. The gravitational force, in-spite of being the most familiar is the least well understood at short distances, but the expectation is that there is an particle associated with it called the graviton. Next there is particle called photon which is associated with electromagnetic force, a beam of photon, is what we call light. Similarly associated with the Weak force are three particles called W+, W_, and Z0 - Bosons and finally with strong force we associate particles called the gluons. These elementary particle together form what is referred to as the standard model of particle physics.

2 Local Symmetry

One of the remarkable facts about the Universe is that it is build of few identical particles. The key word here is identical. Each elementary particle is characterized by few numbers. Some of these numbers derive from familiar properties. For instance an electron has a definite mass, it also has a definite electric charge. All the electron in the universe have the same value of mass and charge. Another building block of our universe is a particle called the photon, this is the particle of light. Again all the photon in the universe are identical they have zero mass and zero charge, they also have an additional properly called the polarization or the helicity. A photon can either be a left-handed polarized or right-handed polarized. We can think of lefthanded photon as a particle which is spinning in the direction opposite to the direction of its motion, while the right-handed photon as a photon that is spinning in the direction of the motion of the particle. A fact which will be

Figure 1: Standard Model

of great importance for us is that for all massless particles the polarization or the helicity is an intrinsic property of the particle. By which we mean no matter who is observing that particle they all will agree that particle is, for example, left-handed. For massive particles the helicity is not an intrinsic property, di_erent people who are moving with respect to each other will in general attribute di_erent helicity to the same particle.

In order to describe our universe which is made of identical photons which can be created and destroyed we need a new type of mathematical language. This language goes under the name of Quantum Field Theory. Quantum field associated with the photon can be though of as carrying information for creating a photon at any point in the Universe at any time. This means at each point of the space, and for each moment or time, we associate a set of numbers. How many numbers do we associate with each point? In the case of photon we need two distinct numbers at each space-time point. We need two because we have two polarization of photons. Now we have one very important requirement for our description. The laws of nature that we write using quantum fields should be identical for di_erent people who may just be moving with respect to each other, this is the Principe of Relativity. It turns out, and the reasons have to do with mathematics which I cannot describe here, that even though we need two numbers at each point of space and time but for our laws to respect relativity we use a language in which there are four numbers associated with each point in space and time. Our description therefore results in a redundancy, at each point in space-time we have four

numbers but two of them can be made redundant. This redundancy implies that there is a local symmetry. What does one mean by local symmetry? By symmetry we mean that there is some thing we can do to an object such that after having done that the object still looks the same. A perfect sphere looks the same even after we rotate it, and therefore we say that a sphere is a symmetrical object. In our case the symmetry is that we can add redundant numbers to a given field and still the corresponding field would describe the same situation as the one described by the original field, further these number can be di_erent at di_erent points of space and time, and so we say that the symmetry is local.

In 1950-60s many physicist realised that one can extend the idea of local symmetry from photon field to other fields. One of the simplest such extension would describe three photon like particles, in that they are massless and have two polarizations. It turns out that the way these three particles interacted with electron and quarks could precisely describe the weak interactions between them and these, then hypothetical particles, were called Z0, W+, W_. But this description had one apparently insurmountable di_culty.

It has to do with the manner in which the force between two particles decreases with the distance. The electromagnetic interaction is what we call a long range interaction, the force between charge particles decreases rather slowly as the inverse square of the distance between them, this is the familiar Coulomb force. In Quantum Field Theory the long range nature of electromagnetic force is a direct consequence of the zero mass of the photon.

In nature we find that the Weak interaction between electrons and quarks decrease much more rapidly than the Coulomb force. A short range force, like the Weak force requires that W and Z bosons must be massive, but the local symmetry forces them to have a zero mass.

Our first though would be that one should just give up on the idea of describing Weak force using a local symmetry, but the idea was very appealing. Particularly, it suggested that Electromagnetic Force and Weak Force are both mathematically similar and therefore may physically reflect just different aspect of one fundamental force, the Electro-Weak force. At this stage a fundamental break through was made by many physicist. The intuition for this idea came from the fact that familiar Coulomb force is no longer inverse square-force when charged particles are surrounded by a medium made of other charged particles. Using this analogy physicist made a daring hypothesis that the entire Universe is immersed in a medium, or a field, which is like a charged medium for the W and the Z bosons but neutral for the photon. When the massless W and Z bosons move through this field they behave like a massive particle, and can correctly describe the Weak force including its short-range nature. But if such a medium exists then we should be able to

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make waves in this medium and these waves would have energy which would, according to quantum mechanics, come in discrete quantum. Each discrete quanta is nothing but a particle. So there must be a particle in the nature because of this field, and that particle is called the Higgs particle, and the field is called the Higgs field. One of the great triumph of these ideas was the experimental discovery of W and Z bosons which describe weak interaction and they indeed are massive, but up-till now we have not discovered the Higgs particle. This is the particle we are waiting for and we hope to discover it at LHC.

3 The Mystery of Mass

The Higgs has more magical proprieties to it, our current understanding is that not just W and Z bosons but also the electron and the quarks acquire their mass because of the Higgs field. The reason behind this is again related to symmetry. Weak-Interactions is the only force that we know that makes distinction between left and right. As we saw photon can have two polarization or helicity, similarly a massless electron or quark can have two helicity. As in the case of the photon we can visualise a left-handed electron as a massless electron which is spinning in the direction opposite to its motion, and a right-handed electron would be the one which is spinning in the direction opposite to its motion. This terminology comes, as you might have guessed, from the right-handed screws and the left-handed screw. As far as the electromagnetic and the strong forces are concerned they have leftright symmetry. What this means is that, for example, the electromagnetic interaction between two right-handed electrons is identical to the electromagnetic interaction between two left-handed electrons. In the other words electromagnetic and strong interaction do not care about the helicity of the electron or the quark.

Weak force is very di_erent. We know from experiments that the weak force between two left-handed electron is very di_erent from the weak force between two right-handed electrons. So to describeWeak-interaction we start with massless electrons and quarks, and give di_erent "weak charge" to the left-handed and the right-handed particle. This way we can describe the left-right asymmetry of the Weak force. This requires that the electrons and the quarks are massless, for helicity is an intrinsic property of only massless particles. If the electron is massive than an electron which is left-handed for me could appear as right-handed to some one who is moving with respect to me!

Thus we are in a quandary, to describe Weak force we need massless

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electrons and quarks but the real world is made of massive electron and massive quarks. Again the Higgs come to rescue! As the massless lefthanded electron travels through the Higgs field it interacts with it and gets converted into a right-handed electron and similarly the right-handed electron interacts with the Higgs field and gets converted into a left-handed electron and this process of flipping goes on. The rate of flipping depending on how strongly the electron interacts with the Higgs field. This is precisely the way a massive electron behaves in the absence of a Higgs field, it flips between the left helicity and the right helicity at a rate that depends on its mass. If the mass is zero it does not flip. In this manner we can give a mass to massless electrons and quarks and still describe the Weak interaction in a left-right asymmetrical manner. The mass of the electron and the quarks depends on how strongly they interact with the Higgs field.

Will the discovery of a Higgs particle at LHC confirm that the standardmodel of particle physics as the ultimate description of the building blocks of the Universe? Certainly not, there are too many short-comings in our present understanding. Some are aesthetic, for example, we can describe an electron of any mass using the Higgs-Mechanism. We have to put by hand the strength of electron-Higgs interaction, to get the electron mass which we know from experiments. Ideally our theory should tell us the strength of the electron-Higgs interaction. Other more glaring short-coming comes from the astronomical observations. The motion of stars in galaxies tell us that the our Universe must contain other types of particles which interact through gravity but are not part of the standard model. This is the so called "dark matter." Therefore we know that the standard-model is incomplete, there are certainly more things under the heaven than described by the standard model. What are those things? We hope LHC will provide us the with clues to them, and so we wait for LHC!