Introduction to Elementary Particles

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Abstract: *Dramatic progress has been made in particle physics during the last two decades. A series of important experimental discoveries has firmly established the existence of a sub nuclear world of quarks and leptons. This article gives a basic introduction to elementary particle physics and its latest advancements.*

Key words:*Quarks, Leptons, Feynman Diagram, QED, QCD, Weak Interaction, Higgs Boson, Deep Inelastic Scattering, GUT, String Theory*

1 Introduction

1.1 Fundamental Constituents

Particle physics is concerned with the fundamental constituents of matter and the fundamental forces through which the fundamental constituents interact among themselves. The very word fundamental needs explanation. When we say a particle is fundamental, in the language of quantum mechanics, it has no spectra. It is important to note that electron is a fundamental particle to the energy scale we have reached so far. It is because, experimentally the transition $e^{-*} \rightarrow e^{-} + \gamma$ has never been seen. So we can safely say, to the energy scale reached so far electron has remained a fundamental particle. Important aspect to be noted here is, if you want to probe a particle, the wave length of the probe has to be of the order of the size of the particle. To probe small distances, we need high energy particle. Till 1900, only two forces were known gravitational and electromagnetic. Atom was thought to be a fundamental particle since there were no probes which could probe inside the atom. But, the Rutherford's scattering experiment (the large back angle scattering of α particles by gold foil) confirmed that atom has a sub structure. Hence, accelerators were developed to probe the ultimate constituents of matter. In the early decades of the 20^{th} century, the particle beam energies reached only a few MeV (10^6 eV), and the resolution was so poor that protons and neutrons were regarded as fundamental particles. In all these experiments, projectiles were accelerated and were to hit the target which was stationary. Now a days, all the accelerators built are colliders (collide two high energy particles head-on, as opposed to firing one particle on a stationary target).

Suppose an incident particle of mass M_A, total momentum P_A and total energy E_A collide with a particle of mass M_B, momentum P_B and energy E_B, for a fixed target machine ($P_B = 0$), the total available energy rises as the square root of the incident energy $E_{FIXED} \approx (2M_B E_A)^{1/2}$, where as for the collider the energy available is $E^2_{CM} = (E_A + E_B)^2$. Obviously, therefore, the highest possible energies for creating new particles are to be found at colliding-beam accelerators.

1.2 Birth of the Strong Force

Rutherford's scattering experiment established that, an atom has a sub structure that is the nucleus. Nucleus consists of protons and neutrons. But Rutherford's model did not address the question: what holds the nucleus together? After all, the positively charged proton should repel one another. Hence, it must be some other force and named it as strong force or nuclear force. From the nucleon-nucleon scattering experiments and from the study of deuteron it was established that nuclear forces are of short range, spin dependent, charge independent and have saturation property. Hence the fundamental forces rose to three in number.

In 1930, the fourth fundamental force was discovered in nuclear beta decay and was termed as weak interaction. It was found that a free neutron decays to a proton and an electron. But, the beta decay spectrum was continuous. By the conservation of energy and momentum it was clear that if it is a two-body decay then the beta spectrum cannot be continuous. Also, the interaction violated the conservation of energy and angular momentum. To explain the beta decay spectrum Pauli (Wolfgang Pauli, Noble Prize 1945) proposed that there should be a third particle which is spin $\frac{1}{2}$, chargeless massless. It was called as neutrino (ν) (in beta decay it is in fact anti neutrino $\bar{\nu}$).

The advancement in particle physics was in identifying the **conserved quantities** in a physical system which is based on Noether's theorem. According to Noethers theorem, "for every continuous symmetry of the laws of physics, there must exist a conservation law". For every conservation law, there must exist a continuous symmetry. The invariance under time translation leads to conservation of energy and invariance under space translation leads to conservation of linear momentum and invariance under rotation leads to conservation of angular momentum. Quantum field theory exploits these conservation laws.

1.3 Development of Quantum Field Theory

In the mean time, the quantum field theory (QFT) was developed (Sin-Itiro Tomo Naga, Julian Schwinger and Richard P. Feynman, Noble Prize 1965). According to QFT, i) all forces are of exchange type, i.e., particle interact through the exchange of a mediating particle which are virtual particles (for a real particle $E^2 - P^2C^2 = M_0^2C^4$, for a virtual particle it can take any value, in other words virtual particle exists for a time allowed by the uncertainty principle). This was a revolutionary concept, since in classical physics, no mediating particles are present. ii) The range of the interaction is inversely proportional to the mass of the particle being exchanged. In electrodynamics, the electromagnetic force has infinite range and hence is mediated by a massless particle which is the photon.

Yukawa (Hideki Yukawa, Noble Prize 1949) applied the QFT to the strong interaction. Since the range of the strong interaction was known, Yukawa predicted the mass of the mediating particle to be around 140 MeV. In the mean time, Powell (Cecil Frank Powell, Noble Prize 1950) and his workers discovered that there are actually three middle weight particles in cosmic rays, which were named as π (pion). It had the mass as predicted by Yukawa. Hence, QFT had its biggest success. Now we know that all the forces of nature (strong, electromagnetic and weak) are governed by the application of QFT.

In 1936, the positron (e^+) the anti-particle of e^- was discovered by C.D. Anderson (Carl Anderson, Noble Prize 1936). Anderson took the photograph of the track left in a cloud chamber by a cosmic ray particle. The chamber was placed in a magnetic field. From the curvature of the track and from its texture, Anderson showed that the mass of the particle was close to the mass of the electron. In 1960's most of the elementary particles were discovered in the following manner. When a high energy particle passes through matter they ionise the atoms along their path. The ions act as 'seeds' in the formation of a droplet (cloud chamber) or bubble (bubble chamber) or sparks (spark chamber). For example, in bubble chamber neutral particles will be 'invisible', their paths have to be reconstructed by analysing the tracks of the charged particles in the picture and invoking conservation of energy and momentum at each vertex. In a magnetic field, a particle of charge q and momentum p will move in a circle of radius R given by the cyclotron formula R= (pv/qB). Knowing the curvature and the track in a known B, the particle momentum can be measured. The sign of the charge is inferred from the direction of the curve.

The concept of anti particles was introduced by Dirac (Paul Anderson Dirac, Nobel Prize 1933) in his theory to explain the negative energy solution of a relativistic spin $\frac{1}{2}$ particle. According to QFT, for every particle there must be an anti-particle with the same mass, life time and spin but with opposite electric charge and opposite magnetic moment. The negatively charged anti proton was observed at Berkeley Bevatron in 1955 by Segre and his collaborators (Emilio Gino Segre and Owen Chamberlain, Noble Prize, 1959). The neutral anti neutron was discovered a year later. Several more particles were discovered. Some of them were produced in strong interaction but decayed via weak interaction (decaying only after a considerable time) and such particles were termed as strange particles (were produced in pairs). In 1947, G.D. Rochester and C.C. Butler obtained a cloud chamber picture of cosmic rays that indicated existence of a new particle. 'V' track was seen indicating that a new neutral particle had decayed into two charged particles. In cloud chamber, bubble chamber and emulsion chamber, such par-

Table 1: The Properties of the Four Forces

Force	**Srength**	**Range**	**Theory**	**Mediating Particle**	**Life Time (τ)in Sec.**
Strong	1	$10^{-13}cm$	Yukawa theory	$\pi^{\pm}, \pi^{0}$ (spin 0)	10^{-23}
Electro mag-netic	10^{-2}	∞	Quantum Electro-dynam-ics	Photon(spin 1 massless)	Infinite
Weak	10^{-7}	$10^{-16}cm$	Fermi theory	Not known	Unknown
Gravi-tation	10^{-39}	∞	General theory	Graviton (spin 2)	Unknown

ticles were discovered at a faster rate. It was clear by 1960, that there are four fundamental forces. The decay of unstable particles through strong, electromagnetic and weak was established (the uncertainty principle relates the life time and the uncertainty in the energy of a state). An unstable particle does not have a unique mass, but a distribution width $\Gamma' = h/\tau$. So, when τ is very short, its value can be inferred from the measured width Γ'. The quantum electrodynamics (QED) was recognised as the theory of electromagnetic interaction. The properties of the four forces around 1960 are listed below.

By 1960, there were many more elementary particles. The question was whether all these particles can be termed elementary or fundamental particles? Table 1 lists the fundamental interactions as we understand today.

1.4 Production and Detection of Elementary Particles

Most of the elementary particles were produced in cosmic rays, nuclear reactors and particle accelerators. Electrons are produced by simply heating up a metal piece. Protons are produced by ionizing the hydrogen atom. The electrons and protons are stable particles. More exotic particles were discovered in cosmic rays which are high energy particles which constantly bombarded earth from outer space and their origin still remains a mystery. When high energy particles hit the atoms in upper atmosphere they produce showers of secondary particles (mostly muons when they reach the ground). The nuclear reactors are another source of elementary particles. When a radioactive nucleus disintegrates, it emits variety of particles - such as neutrons and neutrinos and alpha particles (bound state of two protons and two neutrons), beta rays (electrons or positrons) and gamma rays (photons). In present day accelerators, electrons or protons are accelerated to very high energy and smash them to a target, using electric fields to accelerate particles, magnetic fields to steer and focus the beams. Three major types of accelerators are 1) linear accelerators, 2) cyclotrons and 3) synchrotrons. The increasing energy requires increasing sophistication of tools to detect particles.

In modern accelerators, it is possible to generate intense secondary beams of positrons, muons, pions, kaons and antiprotons which can be fired at another target. The stable particles such as electrons, positrons and antiprotons can be fed into giant storage rings which

guided by the powerful magnets circulate at high speed and can be used at the required moment. It should be noted that the heavier the particle to be produced the higher must be the energy of the collision. Hence, the light particles are produced first. In general, higher the energy of the particle (hence higher is the momenta) the smaller is the wave length and hence can probe a smaller distance. Hence, to probe a small distance higher energies are required. The accelerator at CERN (European Organisation for Nuclear research), is the large hadron collider (LHC) collides proton on protons each of 7 TeV to produce centre of mass energy of 14 TeV. Two protons colliding at high energy can produce various hadrons plus very high mass particles such as z bosons. The Higgs boson was discovered in LHC. LHC is the largest and highest particle collider with CM energy of 14 TeV. Its length is 27 km in circumference and it is 175 meters beneath the ground. The other important collider is the relativistic heavy ion collider (RHIC) at Brookhaven National Laboratory (BNL), Upton, New York, USA. In RHIC, two gold nuclei of 200 GeV collide to produce centre of mass energy of 400 GeV. Its length is 2.4 miles and temperature achieved is about 10^{12} K (for detecting quark-gluon plasma, believed to be formed during the big bang). RHIC collisions occur thousands of times per second. The high energy accelerators developed in last twenty five years are listed below.
1) LEP-I e^+e^- collider, CERN 91 GeV (1989 1994)
2) LEP-II e^+e^- collider, CERN 209 GeV (1995 2000)
3) HERA-I ep (electron-proton collider), DESY 27 + 800 GeV (1992 2000)
4) HERA-II ep collider, DESY 27 + 920 GeV (2002 2007)
5) TeVatron Run I ppbar collider, (proton-anti proton) Fermilab 1.8 TeV(1987 -1996)
6) TeVatron Run II ppbar collider, Fermilab 1.96 TeV (2002 2011)
7) LHC, phase I pp collider, CERN 7 TeV (2010- 2012)

8) LHC, phase II pp collider, CERN 14 TeV (2014 onwards)

The early particle detectors were Geiger counters, cloud chambers, bubble chambers, spark chambers, photographic emulsions, Cerenkov counters, scintillators, photo multipliers etc. The present day modern detectors have whole array of these devices connected to a computer that tracks the particles and displays the trajectories on the computer screen. The most of the detectors rely on the fact that when a high energy charged particles pass through matter they ionize atoms along their path. The ion then acts as 'seeds' in the formation of droplets (cloud chamber) or bubbles (bubble chamber) or sparks (spark chamber). It should be noted that neutral particles do not cause ionization and leaves no track. These detectors were placed in magnetic field. From the curvature of the track in a known magnetic field, particle momentum can be measured and from the direction of the curve the sign of the particle can be determined.

1.5 Classification of Elementary Particles (1960)

All the known elementary particles were classified as hadrons (heavy) and leptons (light) depending on their mass. But, now this nomenclature has lost its meaning. After the discovery of the τ^- particle (Mass 1777 MeV) and its corresponding neutrino ν_τ ($m_{\nu_\tau} \leq$ 18 MeV) (discovered by Martin Perl and Frederick Reines (Noble Prize 1995)). The earlier classification still holds but with a definition that hadrons under go all interactions (strong, electromagnetic and weak) where as leptons undergo only electromagnetic and weak interaction. The hadrons were classified into baryons (odd integral spin particles) and mesons (integral spin particles) based on the statistics. Baryons obey Fermi-Dirac (FD) statistics and mesons obey Bose-Einstein (BE) statistics. The complete list of leptons is given in table 3.

2 Quark Model (1964)

2.1 SU(3) Symmetry

With the growing number of strongly interacting particles, it was difficult to believe that they are all fundamental building blocks of nature, and so there were attempts to look for symmetries. Finally, in 1961 M. Gell-Mann and Y Ne'eman proposed the eight-fold way, an SU(3) symmetry scheme for the classification of hadrons, the baryons and mesons. The eightfold way arranged the baryons and mesons into weird geometrical patterns, according to their charge and strangeness. It was found that all observed baryons fall into the representations 1,8 and 10 of the group SU(3) of transformations whereas all mesons are grouped into the representations 1 and 8 of SU(3) (SU(3) is a Lie Group which consists of 3x3 unitary matrices with determinant = +1). This observation served as a basis for the quark model, which was independently suggested by M. Gell-Mann and G. Zweig in 1964. According to the quark model, baryons are made of three quarks up (u), down (d) and strange (s). While mesons are bound state of quark-anti-quark. Quarks are spin $\frac{1}{2}$ particles and so obey Fermi-Dirac statistics. All the quarks carry addition quantum number known as baryon number whose value is 1/3. The three quarks u, d and s form the fundamental representation of the SU(3) group. With this classification all the observed baryons and mesons of same spin and parity form the higher dimensional representations of the SU(3) group. All observed baryons ($J^p = 1/2^+$) are of octet representation and baryons of $J^p = 3/2^+$ form the 10 dimensional representation of the SU(3) group. Out of the 10 ($J^p = 3/2^+$) baryons predicted by the quark model only nine were known experimentally at that time. The greatest triumph of the quark model was the 10th baryons predicted by the quark model (the famous omega particle (Ω^-) with a mass of 1672 MeV and charge -1 with three s quark content) was experimentally found (V.E.Barnes et al., Phys. Rev.Lett. 12, 204 (1964)) precisely as predicted by Gell-Mann (Noble prize for Gell-Mann in 1969) (appendix I). Also, the quark model could successfully account for the masses, magnetic moments, and lifetime and could predict the principal decays of hadrons. One of the biggest successes of the quark model was its prediction of the neutron magnetic moment (which could not be explained in nuclear physics since the charge of the neutron is zero). The quark model was accepted by the scientific community partially. The rest mass of an individual quark is not well-defined, given that individual quarks don't exist. The proton and neutron have masses $\approx$ 1836 times that of the electron,but this doesn't mean that up and down quarks have masses of roughly one-third of the proton. The strong force is so powerful inside a triplet that the energy which binds them together (think of it as "strong-force potential energy", analogous to gravitational potential energy) is by far the largest contributor to the mass of the proton. That is, the quarks potential energy far exceeds the energy $E = mc^2$ that their masses represent, so the mass of a proton may consist of $5\% - 20\%$ quark mass (it's hard to tell), and the rest is the nuclear binding energy.

2.2 Introduction of the Colour

In spite of great success of the quark model, it had one very big draw back. It violates Paulis exclusion principle. Since quarks are fermions the wave function of the baryon has to be antisymmetric. But the Δ^{++} particle (and also the Δ^{--} and the Ω^{-}) total wave function turns out to be symmetric. Hence, there was a danger of quark model being abandoned. To save the Pauli Exclusion Principle, O.W. Greenberg (O.W. Greenberg, Phys. Rev.Lett. **13**, 598 (1964)) proposed that each flavour quark comes in three colours, red, green and blue. Baryon wave functions are products of a symmetric space-spin-flavour wave function, and an antisymmetric colour wave function. Hence the total wave function is antisymmetric. It is to be noted that the term colour here has absolutely no connection with the ordinary meaning of the word. Redness, blueness and greenness are simply additional quantum numbers used to denote quarks in addition to the charge and the strangeness. With the introduction of the colour, quark model was saved. Since it was clear that none of the baryons or mesons are fundamental particles, attempts were made to explain the baryon and meson spectra from the quark models. That is to describe the excited states which one observes when protons or neutrons are bombarded with particles having energies higher than several hundred MeV. Under such circumstances the nucleon can assume different properties that can be described as an excitation of the nucleon, analogous to the excitation of atoms or nuclei. Many excited states of the nucleon have been discovered. The nucleon is merely the ground state of a complex spectrum. Since all baryons levels have half-integral spin, any such transition requires an integer change of angular momentum. Consequently, the system that is emitted or absorbed by the baryon during such a transition can consist of any number of bosons, or of an even number of fermions, or of both. As in atoms and nuclei, one observes the emission and absorption of photons in transition between baryon sates. These occur only between states of the same strangeness, and this tells us that there is a selection rule $\Delta S = 0$ for electromagnetic transactions. In baryon transition, yet another transition mode appeared: the absorption or emission of particles belonging to a new species, the mesons. As mesons can be absorbed or emitted singly, it is clear that mesons are bosons. The characteristic energy differences are of the order of several hundred MeV (for recent excited states of hadrons see Particle data group (2016). The baryon spectrum is the third level at which nature offers us a series of well defined quantum states: the first were the atomic and molecular spectra, the second the nuclear spectra. The typical excitation energies are higher with each step: of the order of eV in the first, MeV in the second, and GeV in the third. In an analogous manner, the π's are the lowest-lying members of the meson spectrum. Each of the meson octet's have a rich spectra. All these mesons are interconnected by some combinations of strong, electromagnetic, or weak decays, and can be viewed as the excitation of a single system, the meson. The Table 4 lists the mediating particles of the strong, electromagnetic and weak interactions. Table 5 lists the conservation laws for strong, electromagnetic and weak interactions.

But, it should be noted that all naturally occurring particles (baryons and mesons) are colourless. The colourless means that the total amount of each colour is zero or all three colours are present in equal amounts. The only colourless combinations you can make are $q\bar{q}$ (the mesons), qqq (the baryons) and $\bar{q}\bar{q}\bar{q}$ (the antibaryons).

2.3 Evidence of Quarks, Deep Inelastic Scattering (DIS) Experiments

The quark model suffered from one profound embarrassment. In spite of the most diligent search over the years, no one has ever seen an individual quark. Now, if a proton is really made out of three quarks, the quarks should come out when hit by a projectile of sufficient energy. Also, one of the quarks should be absolutely stable. Since it can not decay into any lighter particle of fractional charge.

Though no free quarks were seen, one can probe inside the proton in much the same way as Rutherford probed inside of an atom. Sixty years later, history repeated itself when a SLAC (Stanford Linear Accelerator Centre) team of scientists performed (Breiden bach et al., Phys. Rev.Lett.23, 935, (1969)) inelastic electron-proton scattering with incident electron energies between 7 GeV to 17 GeV. In the reaction e + p $\longrightarrow$ e'+ X, they only counted the number of outgoing electrons at various angles, leaving the debris X unobserved. Such cross-sections are termed 'inclusive' cross sections. The results of these experiments are called 'deep inelastic scattering (DIS)' experiments. When the momentum transfer is much larger than the average internal momentum of the nucleon in the ground state, the process is referred to as DIS. In a DIS process, large amount of energy and momentum is transferred to the target. The results of the DIS experiments were striking similar to the Rutherfords scatter results of the DIS experiments were striking similar to the Rutherford's scattering experiment. Most of the incident particles pass right through, whereas a small number bounces back sharply. This means that the charge of the proton is concentrated in small lumps, just as Rutherfords results indicated that the positive charge in an atom is concentrated at the nucleus. However, in the case of the proton the evidence suggests three lumps, instead of one. This is a strong support for the quark model. The Nobel prize was awarded to Jerome.I. Friedman, Henry W. Kendall and Richard E. Taylor for their pioneering work on DIS experiments.

3 Quantum Chromo Dynamics (QCD)

3.1 The Theory of Strong Interactions

The experimental confirmation that quarks come in three colours came from the ratio of the cross sections of the process of $e^+ + e^-$ hadrons to $\longrightarrow \ \mu^+ + \mu^-$. Also, in the e^+e^- collider as beam energy was cranked up one encountered a succession of such thresholds. First the muon and the light quarks, later (at about 1500 MeV) the charm quark, was found. C.C Ting in the summer of 1974 at

SLAC found an electrically neutral, extremely heavy meson more than three times the mass of the proton. It had an extraordinary long life time (10^{-20} seconds). The new particle was named $\mathbf{J/\Psi}$ (Samuel C.C. Ting and Burton Richter Noble Prize, 1976) which has a mass of 3097 MeV with a charge 0 and the quark content ($c\bar{c}$) (Charmonium is the bound state of charm quark and anti-charm quark) and subsequently another new meson known as upsilon (γ) (Bottomonium is the bound state of bottom quark and anti-bottom quark) was discovered (Herb et al., Phys. Rev. Lett.39, 252 (1977)) and it was quickly recognized as the carrier of a fifth quark, b (for bottom). The γ(b$\bar{b}$) has a mass of 9.460 GeV. Many more charmed and bottom baryons and mesons were discovered which led to the study of heavy quark spectroscopy. One more quark named top quark, the sixth member was observed in 1995, almost 20 years after the discovery in 1977 of the previously heaviest quark, the bottom quark. The top quark (t) has a mass of 175 GeV. It was discovered at the Fermi lab in proton- anti proton collider with 1.8 GeV center of mass energy. The system is so short-lived that no discrete bound states have been found so far. Table 2 gives the complete list of quarks.

The nuclear force is also taken into account by QCD. At distances large compared to the size of hadrons there is no strong force between hadrons, since they are colour neutral. The nucleon-nucleon interaction is described by the exchange of and mesons when the two nucleons do not over lap. But, the region where the two nucleons overlap (around 0.5 Fermi) is described by the six quark system and the quark models have been reasonably successful in explaining the short range repulsion.

With these developments QCD was developed. The QCD is the formal theory of the strong colour interactions between the quarks. The quarks which come in 3 colours form the fundamental representation of the SU(3) colour group. The SU(3) group is an infinite set of 3x3 unitary matrices with determinant +1. The SU(3) group has 8 generators. The anti-quarks carry anticolours. The quarks interact via exchange of gluons. The gluons are the mediators of the quark interaction. The colour charge of the strong interactions is analogous to the electric charge in electromagnetic interactions. A gluon is a very complicated thing. It has no rest mass, and so moves at the speed of light, yet the strong force is still very short-ranged. The reason is, the gluon itself carries strong charge, and thus it can interact with itself! This would be equivalent to the photon carrying electric charge instead of being neutral (except that the strong force is always attractive, never repulsive). Rather than just streaming away from a light source, electrically charged photons would tend to electro statically pull themselves back together. So the gluon has a very limited range, despite being massless. Both forces are mediated by a massless vector particle (a gluon or a photon). But, in QCD there are six types of charges (colour and anticolour) and a charged (i.e. coloured) mediating gluon. Also the gluons interact among themselves to form glue balls. Gluons have a combination of a color and an anti color of a different kind of a superposition of states which are equivalent to the Gell-Mann matrices. Unlike the single photon of QED or the three mediating particle of the weak interaction (W^+, W^- and Z^0) bosons, there are evidently eight kinds of gluons in QCD listed as follows:

$$R\bar{B}, R\bar{G}, G\bar{R}, G\bar{B}, B\bar{R}, B\bar{G}, \frac{(R\bar{R} - G\bar{G})}{\sqrt{2}}, \frac{(R\bar{R} - G\bar{G} - 2B\bar{B})}{\sqrt{6}}$$

In other words, gluons belong to a SU(3) octet. The remaining combination, the SU(3) color singlet,

$$\frac{(R\bar{R} + G\bar{G} + B\bar{B})}{\sqrt{3}}$$

does not take part in the interaction and is a color single and if it exists as a mediator, it should also occur as a free particle and hence

could be exchanged between color singlets (say between mesons or a proton and a neutron) giving rise to a long range force with a strong coupling, but the strong force is of short range. Since gluons are massless, like photons they should mediate a force which is of long range. However, confinement and absence of single gluon, makes strong force short range. In language of group theory, the symmetry of QCD is not U(3), since it requires 9 gluons. But, the experiments resolve the question in favour of SU(3) symmetry.
The equation for QCD is known as Yang-Mills equation which is a coupled partial differential equation. To this day, there is no analytical solution to the Yang-Mills equation. Hence, QCD is the least understood of the three forces. The current topic of interest in low energy QCD is the chiral perturbation theory. Chiral symmetry is the symmetry of the massless fermions. Chiral symmetry is employed to predict the masses of hadrons in the low energy sector. Another field of current interest is heavy-quark spectroscopy.

3.2 Experimental Evidence of Gluons

In the process $e^{+}+e^{-} \longrightarrow \gamma \longrightarrow q\bar{q} \longrightarrow$ hadrons, for a brief moment the quarks fly apart as free particles, but when they reach a separation distance of around 10^{-15} meters (the diameter of the hadron), their strong interaction is so great that new quark-antiquark pairs are produced mainly by the gluons. These quarks and antiquarks join together to make the baryons that are actually recorded at the detector. In all the debris there is one unmistakable footprint left behind by the original quark-antiquark pair: the hadrons emerge in two back-to-back 'jets', one along the direction of the primordial quark, the other marking the direction of the antiquark. But, in addition to two jet events three jet events are also observed, indicating that a gluon carry a substantial fraction of the total energy. The observation of the three-jet event is generally regarded as the most direct evidence for the existence of the gluons.

3.3 Two Important Features of the QCD

The two important features of the QCD are the asymptotic freedom and the infrared slavery. From DIS experiments it was clear that interaction strength between quarks given by the strong coupling constant (α_s) decreases at very large momentum transfers or at short distances. This is termed in literature as asymptotic freedom but at large distances or at low momentum transfers the coupling constant α_s grows in strength and is so large that no free quarks have ever been seen outside the hadron, this is termed as infrared slavery. But, this is the region which is of importance in nuclear physics where quarks condensate to form baryons and mesons. Hence, in quark models, the confinement is imposed by a linear or quadratic potential. Attempts have been made to solve Yang-Mills equation using numerical techniques (known as lattice gauge theories). It is important to note that α_s is in fact not a constant at all, but depends on the separation distance between the interacting particles (hence is termed as running coupling constant). The perturbative analysis of QCD is well grounded based on the fact that the theory is asymptotically free. The coupling constant which is a measure of the effectiveness of the strong force that holds quarks and gluons together into composite particles introduces a dependence on the absolute scale, implying more radiations at low scales than at high ones and it is usually referred to as running coupling constant. The running is logarithmic with energy is given by,

$$\alpha_s(Q^2) = \frac{\alpha_s(\mu^2)}{1 + \alpha_s(\mu^2)\beta_0 \; ln\frac{Q^2}{\mu^2} + 0(\alpha_s^2)}$$

Numerically, the value of the strong coupling constant is specified by two parameters, the renormalization scale (μ) and the corresponding value of the coupling at that point. These two parameters can be replaced by a single parameter Λ so that the running coupling can be expressed as

$$\alpha_s(Q^2) = \frac{1}{\beta_0 \; ln\frac{Q^2}{\Lambda^2}}$$

The coupling would clearly diverge at the scale Λ, called the Landau pole, which specifies the energy scale at which the perturbative coupling constant would become infinite. Its value is experimentally found to be $\Lambda \approx 200$ MeV. This implies that the perturbative calculations are allowed only at energy scales of or higher than one GeV.

Qualitatively we do understand the reason for asymptotic freedom. According to QFT, for example in QED, an electron is just not an electron: it can suddenly emit a photon or it can emit a photon that subsequently annihilates into an electron-positron pair, and so on. Since the original electron is surrounded by e^-e^+ pairs and, because opposite charges attract, the positrons will be preferentially closer to the electron. Therefore, the electron is surrounded by a cloud of charges which is polarized in such a way that the positive charges are closer to the electron. The negative charge of the electron is thus screened. Hence, if we want to determine the charge of the electron by measuring the Coulomb force experienced by a test charge, the result depends on where we place the test charge: when moving the test charge closer to the electron, we penetrate the cloud of positrons that screens the electron's charge. Therefore, the closer one approaches the electron, the larger is the charge one measures. Hence the coupling constant (α) in QED increases at short distances or at large momentum transfers, but decreases at low momentum transfers. If the same analogy is carried to QCD, it is the colour screening of the quark charge. But, there is a basic difference here. The gluons, themselves are carriers of colour, also spread out the effective colour charge of the quark. A red charge is preferentially surrounded by other red charges. By moving the test probe closer to the original red quark, the probe penetrates a

Table 2: Comparison of QED and QCD

S.N.	**QED**	**QCD**
1	It is an abelian Gauge theory.	Non-abelian Gauge theory.
2	Mediated by photon which is massless spin 1 particle which carries no electric charge	Mediated by 8 gluons which is a massless spin 1 particle which carries colour charge.
3	The QED coupling constant due to radiative corrections (α) (emission and absorption of virtual photons)increases at short distance but decreases at large distances.	The QCD coupling constant due to radiative corrections (α_s) (emission and absorption of virtual gluons) decreases at short distance but increases at large distances.

sphere of predominantly red charge and the amount of red charge measured decreases. This in literature is termed as ”anti screening” of the red colour and is referred to as asymptotic freedom. Below we compare QED and QCD. QED is the synthesis of quantum theory, electrodynamics and relativity. The fundamental constants representing these theories are , e and c respectively. In QED they come together as the fine structure constant $\alpha = (e^2/\hbar c) = 1/137$.

4 Gauge Theories

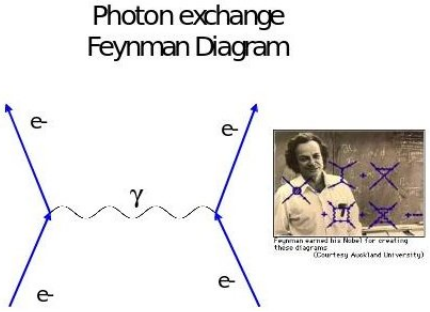
4.1 Theory of Strong, Electromagnetic and Weak.

It is now clear that gauge theories are the underlying theories of the strong, electromagnetic and weak interactions. The basic postulate of gauge theories is that it is not possible to measure the absolute phase of a wave in any experiment. If a lagrangian is invariant under gauge transformation in which the phase is dependent on space-time then such theories are known as local gauge theories. If the Lagrangian is locally gauge invariant under the particular symmetry transformation, it automatically gives the interaction of the lagrangian with the external field. This is the crux and most important aspect of the gauge theories. The biggest boost to the gauge theories came from the work of Gerardus ‘t Hooft and Martinus J.G. Veltman (Nobel prize 1999) who showed that all gauge theories are renormalisable. The term renormalization needs some explanation.

From the basic interaction of the theory for a particular process, one can write down the Feynman diagrams (FD) which gives the scattering amplitude (M_{fi}) for a given process. The FD are purely symbolic; they do not correspond to particle trajectories (as you might see them in, say, bubble chamber photograph). In FD the vertical dimension is time, and the horizontal spacings do not correspond to physical dimensions (see figure below). In the figure below, photon is the Feynman propagator internal line. It represents creation of the particle (virtual) at one vertex, its propagation to other vertex and its annihilation. For instance, in the diagram below, all that the FD says is once there was an electron and a positron; they exchanged a photon; then there was an electron and an electron again. Each FD actually stands for a number, which can be calculated using the so-called Feynman rules. First analyse a given process say, the electron-electron scattering (figure below).

Here, one writes down all the diagrams that have the appropriate external lines (the one with two vertices, all the ones with four vertices, and so on), then evaluate the contribution of each diagram, using Feynman rules, and add it all up. The sum total of all the FD for any particular process with the external lines represents the physical process. The Feynman rules enforce conservation of energy and momentum at each vertex (the point of interaction). But, some of the diagrams become infinite and hence needs to be renormalized (made finite). Once the Mfi is written down, one can compute cross section or the lifetime for a given process. QED is a U(1) abelian gauge theory. Here, we demand QED lagrangian to be invariant under local U(1) gauge transformation. The QCD is an SU(3) non-abelian gauge theory (non-abelian since the generators of the group do not commute). Here, the QCD Lagrangian is to be invariant under local SU(3) gauge transformation. Each flavour quark comes in three colors, red, blue and green. Although the various flavours carry different masses, the three colors of a given flavour weigh the same. Invariance of the Lagrangian under local $SU(3)_{color}$ transformation leads to Yang-Mills equation which gives interaction between the quarks and gluons and the self interaction of the gluons.

Figure 1: Electron-Electron Scattering



4.2 Quark Gluon Plasma (QGP)

The concept of asymptotic freedom suggests a phase transition of hadronic, the QCD matter at low temperature (T) and low baryon density (n_B) in which quarks and gluons are confined, into a new deconfined phase of matter called quark gluon plasma, at high temperature and high density. Plasma by definition, are quasi neutral gas of charged and neutral particles that exhibits collective behaviour. Quarks are the constituents of nucleons. Usually they are confined in groups of three to form a nucleon. Under certain conditions there should exist a new phase where the nucleons get close to each other such that the quarks can fly around freely in a so called quark gluon plasma. This transition from hadrons to QGP leads to the change in degrees of freedom in a strongly interacting medium. Lattice QCD suggests the existence of such a phase transition at critical temperature T_c of about 150-200 MeV, which corresponds to a critical density ϵ_c= 1GeV/fm^3 (depends on the quark flavour N_f). Lattice gauge theory was developed by K. G. Wilson in 1974.

Lattice gauge theory is a tool to study non-perturbative QCD from the first principle by numerical computation. Lattice theory treats the four dimensional space-time as a lattice like in crystals, in which quarks occupy lattice points or lattice sites while gluon field occupies lattice links. The lattice approximation approaches continuum QCD as the spacing between lattice sites is reduced to zero. Using lattice technique, QCD may be solved using Monte-Carlo method.

4.3 Big-Bang Theory

The big bang model says that the universe began about 13.7 billion years ago as a tiny point of infinite density and zero size. This spot and after the explosion, all the particles of matter and anti-matter rushed outward, away from each other. According to the Big-Bang theory evolution of the Universe took place in the following manner. At the time of big bang matter and anti matter were supposed to be in equal quantities. 1) QGP was supposed to have been formed 10^{-9} seconds after the Big-bang 2) After 0.01 sec protons and neutrons were formed 3) After 100 sec. formation of the Helium Nuclei 4) After 105 years first atom was formed. Big-bang predicts 1) 75% of the visible matter is hydrogen and 25% of the matter is Helium 2) Presence of background microwave radiation.

4.4 Neutrinos

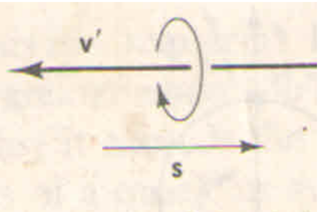
The neutrinos were postulated by Fermi in 1930 to explain β spectra on purely theoretical grounds. Believed to have zero mass, no charge and undergo only weak interaction. Important property is all neutrino's are left handed (direction of the momentum is opposite to the direction of the spin) and anti-neutrino's are right handed (direction of the momentum is opposite to the direction of the spin) (see figure below) and it comes in three flavors ν_e, ν_μ and

ν_τ. The electrons on the other hand are both left and right handed. The neutrinos are massless and travel with the speed of light.

In fact, electron, proton and neutrons are rarities for each of them in the universe, there is 1 billion neutrinos. Neutrinos are the most abundant matter-particles in the universe. Neutrinos are found everywhere in the outer space, on earth and in our bodies. The number of neutrinos from the Sun that are passing through the fingernail in one second is about 40 billion.

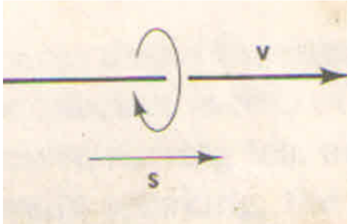
The most intriguing aspect of weak interactions is, it violates parity (Parity is a valid symmetry of strong and electromagnetic interaction). This was theoretically predicted by Yang and Lee in 1956 (Chen Ning Yang and Tsung Dao Lee, Noble prize 1957). It was experimentally verified by C.S. Wu (C.S. Wu et al., Phys. Rev. 104, 254, (1956)). The parity is the space inversion operator (reflection in X-Z plane + rotation by π degrees about Y-axis, in Cartesian coordinate system). Parity is a Hermitian and unitary operator. Parity of a particle is the product of intrinsic parity and the parity of the orbital angular momentum. Fermion and anti-fermions have opposite parity where as bosons have same parity. For mesons parity is $(-1)^{L+1}$ (L is the orbital angular momentum) and for photons parity is $(-1)^{N}$, where N is the number of photons. Physicists thought that the mirror image of an object or a process was indistinguishable from the object or process itself. Let us take a simple example which violates parity. Suppose you were holding a ball in your right hand and allowed it to fall. Obviously the ball would fall on the floor. In the mirror it would be a left hand which drops the ball. The image ball would also drop on the floor. Here the mirror image corresponds to reality. However, if you had a special ball discovered by someone, which falls down whenever it is dropped from right hand, but goes up when dropped from the left hand then the mirror symmetry would be broken. This is because the mirror image of this special ball falling down from the right hand would be a ball falling down from the left hand, a situation contradicting reality. Further, weak interactions are not invariant under Charge conjugation(C) and also under the combined operation of both C and Parity (CP). Also it was observed that the neutrinos which are present in all weak interactions (in fact it is the signature of the weak interactions) are left handed (the direction of the spin is opposite to the direction of momentum) and all antineutrinos are right handed (the direction of the spin is along the direction of momentum),

Figure 2: Neutrinos (Left-handed)



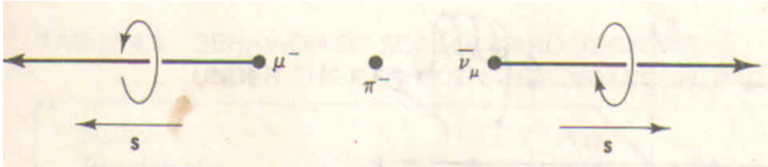
In the decay of $\pi^- \longrightarrow \mu^- + \bar{\nu}_\mu$, if pions were to be at rest, the muon and the anti neutrino should come out back to back and also since the pion has spin zero, the muon and antineutrino spin must be oppositely aligned (see figure below). Hence, the anti neutrino must be right handed in the rest frame of the pion and this was observed experimentally. Hence, measurement of the muon helicity enables to determine the helicity of the antineutrino. Hence the

Figure 3: Anti-neutrinos (Right-handed)



mirror image of the neutrino does exist. The following figure shows the decay of π^- at rest.

Figure 4: The decay of π^- at rest



4.5 Experimental Evidence of Parity Violation

In 1956, Lee and Yang discovered that parity is not conserved in weak interaction. They proposed a test, which was carried out by C.S Wu. In the experiment, radioactive Cobalt 60 nuclei were aligned such that their spins were along the direction of the magnetic field (see figure below). Cobalt undergoes beta decay

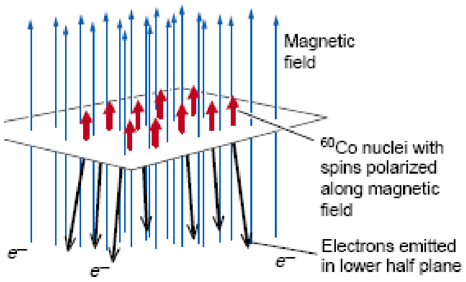
$$^{60}_{26}Co \longrightarrow ^{60}_{27}Ni + \ e^- + \bar{\nu}_e$$

and Wu recorded the direction of the emitted electron and found that there were along the direction of the nuclear spin. If one examines the mirror image of the same process, the image nucleus rotates in the opposite direction and its spin is downwards. But, the electrons in the mirror still came in the upward direction. This implies that, in the mirror, electrons are emitted preferentially in the direction opposite to the nuclear spin. Hence, the mirror image of the process does not occur in nature. Hence, parity is not an invariance of the weak interaction. If it were, the electrons should have come out in equal distribution. For example, in the decay of neutral pion $\pi^0 \longrightarrow \gamma + \gamma$, which is an electromagnetic process and hence respects parity. The number of emitted right handed pairs is equal to the number of left handed photon pairs.

4.6 Double Beta Decay

Double beta decay is a radioactive decay process where a nucleus releases two beta rays as a single process. Here two neutrons in the nucleus are converted to two protons and two electrons and two antineutrinos. In order to the beta decay to be possible the final nucleus must have larger binding energy than the original nucleus. Double beta decay is difficult to study since both beta decay and double beta decay are possible and the probability favouring beta decay. Hence, the double beta decay is studied only for beta stable nuclei. Like single beta decay, double beta decay does not change the mass number. In fact, it is a second order weak process in

Figure 5: Radioactive Cobalt 60 nuclei were aligned such that their spins were along the direction of the magnetic field



which two neutrons inside a nucleus spontaneously transform into two protons. The double beta decay can be broadly classified into four categories. They are 1) Two neutrino double beta decay 2) Neutrinoless double beta decay 3) Single Majorana accompanied neutrinoless double beta decay and 4) Double Majorana accompanied neutrinoless double beta decay. The decay modes can occur via 1) Emission of two electrons 2) Emission of two positrons, 3) Electron-positron conversion and 4) Double electron capture. Majorana particles are identical with their own anti particles unlike the Dirac particles which can be distinguished from their anti particles.

5 Weak Interactions

5.1 Weak Interaction and Unification with the Electromagnetic Interaction (Electroweak Unification:SU(2)$_L$ x U(1)$_Y$ Theory)

To explain beta decay, Fermi treated the weak interaction process as a contact interaction, occurring at a single point, and therefore requiring no mediating particle. It works well at low energies but fails completely at high energies. Also, it is not a renormalisable theory. The weak interactions have a very short range of the order of 10-16cms and hence according to the QFT should be mediated by very massive particles. Weak interactions take place between all quark and leptons constituents: each of them has to be assigned a weak charge g which is related to the electric charge. But, with the emergence of the electroweak theory of Glasow, Weinberg and Salam (GWS) (Nobel Prize 1979) predicted that weak interactions are mediated by three spin 1 bosons two of them charged (known as $W^{\pm}$ with a mass of 82 GeV) and Z boson (with a charge = 0 and mass 92 GeV). In the late seventies, CERN began construction of a proton-antiproton collider designed specifically to produce these extremely heavy particles. In January 1983 $W^{\pm}$ and Z bosons were experimentally detected by Carlo Rubbia's group (Carlo Rubbia and Simon Van Der Meer, Nobel Prize 1984), and George Charpak (Nobel Prize 1992 for his invention and development of particle detectors). So, weak interaction was placed on a firm footing. It is important to know the following aspects of the weak interactions.

5.1.1) The weak coupling constant α_w= 1/29 and hence is much larger than the electromagnetic coupling constant $\alpha = 1/137$, by a factor of nearly 5. It should be noted that weak interactions are not weak because the intrinsic coupling is small, but because the mediating particles are very massive. Since we work typically at energies so far below the W mass that the denominator in the propagator is extremely large. But in e^-e^+ collider at Z^0 resonance weak interactions simply dominate over the electromagnetic interaction.

5.1.2) There are two types of weak interactions. The neutral current interaction (mediated by Z^0 particle) and charged current interaction (mediated by $W^{\pm}$, typical example is the beta decay). In the neutral current interaction, for example,

$$e^- + e^+ \longrightarrow \mu^+ + \mu^-$$

can occur either by a virtual Z^0 or by a virtual photon. At low energies the photon mechanism overwhelmingly dominates. But, in the neighbourhood of the Z^0 mass, where the denominator of the Z^0 propagator is small the weak interaction cross sections are very large compared to the electromagnetic cross sections. One of the biggest successes of the GWS theory was the prediction of the weak neutral current interaction. It is important to note that every electromagnetic process is contaminated by weak neutral process leaving a foot print of parity violation.

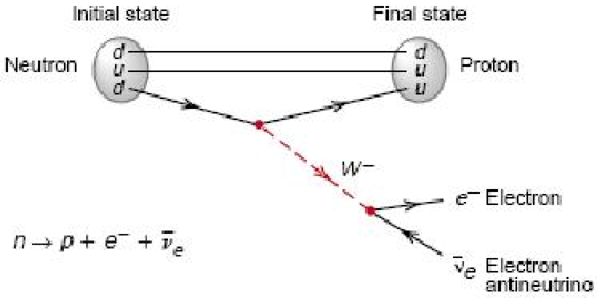
5.1.3) The leptons carry no colour, and they do not undergo strong interactions. Neutrinos have no charge and do not participate in electromagnetic interaction. But all of them undergo weak interactions.

The basic problem with the Fermi theory is that, it is a Vector-Vector (V-V) theory (for example **P** the momentum is a vector and changes sign under parity whereas, **L** the angular momentum is an axial vector and does not change sign under parity) and hence is invariant under parity. Further, it was based on contact interaction. Based on experimental observations (violation of parity) and in consistency with the QFT, it was boldly proposed by Sudharshan and Marshak and independently by Feynman and Gillmann, that the weak interactions are Vector-Axial vector type (V-A). The input came from the experiments. To incorporate weak neutral current (J^{NC}) and weak charged current J±, the group was chosen as SU $(2)_L$ x U $(1)_Y$. Here, L stands for left-handed and Y stands for hypercharge. SU(2) has 3 generators. Out of the 3 generators two $T^+$and T^- corresponds to charged currents. But, J^{NC} is not purely left handed. Therefore there was need to enlarge the group. Y, the hypercharge is the generator of U(1)Y group. Since the electromagnetic current J^{EM} is both left handed as well as right handed, J^{EM} was included in the theory so as to save the $SU(2)_L$ symmetry (J^{EM} = J_3 + Y/2). Thus, the electromagnetic interaction was incorporated into the theory. That is, we have two groups each with an independent coupling strength. So, in addition to e, we need another coupling to fully specify electroweak interaction. In the standard mode, the three weak currents couple, with strength gw, to a weak isotriplet of intermediate vector bosons W, and the weak hypercharge current

$$Q = I_3 + \frac{Y}{2}; j_\mu^Y = 2\ j_Y^{EM} - 2\ j_\mu^3$$

couples with strength g'/2 to an isosinglet intermediate vector boson B. The standard model for the weak and electromagnetic interaction is constructed from a gauge theory mediated by four gauge bosons, (the photon, $W^\pm$ and Z^0). The masses for $W^\pm$ and Z^0 are generated by spontaneous symmetry breaking (SSB). Our present understanding of the neutron decay is illustrated in the figure below.

Figure 6: Neutron decay



5.2 Basic Idea of SSB and Higgs Mechanism

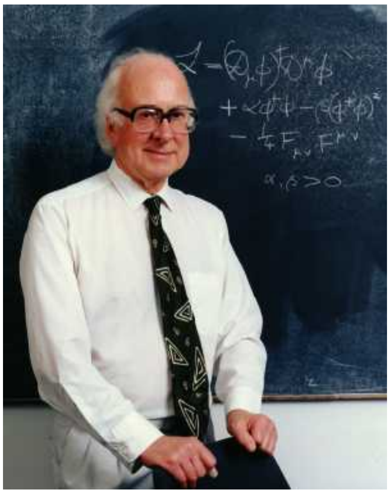
For the gauge invariance, the gauge boson has to be massless. It is not a problem in QED and QCD since both photons and gluons are massless. But, weak interactions are mediated by $W^{\pm}$ and Z^0 which are massive particles. To generate the masses from a massless theory is achieved through SSB. To start write down the Lagrangian which is invariant under the gauge group (here $SU(2)_L$x $U(1)_Y$). The Lagrangian is invariant, but the ground state (vacuum) is not. If one of the ground state is singled out as the physical state of the system (the others being unphysical), the symmetry is lost and the theory is said to be spontaneously broken i.e. the ground state is no more invariant under the symmetry transformation but the Lagrangian is still invariant. If symmetry is broken spontaneously globally, then there will be one or more massless (spin 0) particles called Goldstone bosons. This in literature is termed as Goldstone theorem. But, if the symmetry is broken locally then these massless bosons acquire mass and this mechanism is known as Higgs mechanism. In standard model, the Higgs mechanism is responsible for the masses of all the particles. The gauge principle is responsible for the masses of all the particle interaction in electroweak theory. The Higgs particle couples to leptons, quarks and to the gauge bosons. Higgs boson was first proposed by a group of six theoretical physicists, who worked independently, most notably by Peter Higgs. Higgs boson and its corresponding field is responsible for the spontaneous symmetry breaking mechanism through which the fermions and the W^+, W^- and Z bosons acquire mass. The more a particle interacts with this field, the heavier it is. Particles like photons and gluons do not interact with the Higgs field and hence do not acquire mass. The Higgs boson are the only scalar particles (spin zero). In the 'Standard Model' the origin of mass is addressed using a mechanism named after the British physicist Peter Higgs. This predicts a new particle: The Higgs boson.

The Nobel Prize for Physics in 2013 has been awarded to Peter Higgs and Francois Englert, a Briton and a Belgian, 'for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider'.

Almost 50 years ago in 1964, Englert and Robert Brout, who died in 2011, and Peter Higgs independently published their work in the span of a few days. They had described a mechanism making use of what was known about particle physics at that time to try to answer a perplexing problem: How do particles acquire mass?

Higgs and Englert hypothesized a quantum field, which is a distribution of some energy, throughout the universe. When the field is disturbed, waves travel through it. The dimmest possible wave is

Figure 7: Peter Higgs



called a particle. In this field, since called a Higgs field, the associated particle is called the Higgs boson.

For physicists, finding the Higgs boson meant that the Higgs field exists. And because of the Higgs field and its properties, any fundamental particles that made through it cause Higgs bosons to clump around the particles. This clumping causes the particle to acquire energy and, therefore, mass.

The existence of the Higgs boson was confirmed at the Large Hadron Collider, near Geneva, Switzerland, over the last year. On July 4, 2012, first hints of the boson's existence were spotted at the collider. Ever since, a series of tests on the particle have yielded confirmation, establishing Higgs's and Englert's work as a cornerstone of modern particle physics.

Through an Edinburgh University statement, where Higgs is an emeritus professor, he said he was overwhelmed to receive the award and congratulated ‘all those who have contributed to the discovery of this new particle and to thank my family, friends and colleagues for their support. I hope this recognition of fundamental science will help raise awareness of the value of blue-sky research’.

6 Solar Neutrinos

6.1 Solar Neutrinos Problem

The observed ν_e on the earth is about $1/3\ ^{rd}$ of the theoretically predicted ν_e’s produced by the sun.
6.1.1 There is a major discrepancy between measurements of the numbers of neutriono’s and observed number of neutrinos predicted by Standard Model (SM).
6.1.2 In SM neutrino’s are massless
The solar neutrino problem was a major discrepancy between measurements of the numbers of neutrinos flowing through the earth and theoretical models of the solar interior, lasting from the mid-1960s to about 2002. The discrepancy has since been resolved by new understanding of neutrino physics, requiring a modification of the Standard Model of particle physics specifically, neutrino oscillation. Essentially, as neutrinos have mass, they can change from the type that had been expected to be produced in the Sun’s interior into two types that would not be caught by the detectors in use at the time late 1960s.
Measurements: In the late 1960s, Ray Davis’s and John N. Bahcall’s Homestake Experiment was the first to measure the flux of neutrinos from the Sun and detect a deficit. The experiment used a chlorine-based detector. Many subsequent radiochemical and water Cherenkov detectors confirmed the deficit, including the Sudbury Neutrino Observatory.

The expected number of solar neutrinos had been computed based on the standard solar model which Bahcall had helped to establish and which gives a detailed account of the Sun's internal operation. In 2002 Ray Davis and Masatoshi Koshiba won part of the Nobel Prize in Physics for experimental work that found the number of solar neutrinos was around a third of the number predicted by the standard solar model.

6.2 Resolution of the Solar-neutrino Problem

The solar neutrino problem was resolved with an improved understanding of the properties of neutrinos. As discussed already, according to the Standard Model of particle physics, there are three different kinds of neutrinos 1) electron neutrinos ((ν_e) (which are the ones produced in the Sun and the ones detected by the abovementioned experiments, in particular the chlorine-detector Homestake Mine experiment), 2) muon neutrinos (ν_μ) and 3) tau neutrinos (ν_τ) . Through the 1970s, it was widely believed that neutrinos were massless and their types were invariant. However, in 1968 Pontecorvo proposed that if neutrinos had mass, then they could change from one type to another. Thus, the 'missing' solar neutrinos could be electron neutrinos which changed into other types along the way to Earth and therefore were not seen by the detectors in the Homestake Mine and contemporary neutrino observatories. The supernova 1987A produced an indication that neutrinos might have mass, because of the difference in time of arrival of the neutrinos detected at Kamiokande and IMB. However, because very few neutrino events were detected it was difficult to draw any conclusions with certainty. The first strong evidence for neutrino oscillation came in 1998 from the Super-Kamiokande collaboration in Japan. It produced observations consistent with muon-neutrinos (produced in the upper atmosphere by cosmic rays) changing into tau-neutrinos. What was proved was that fewer neutrinos were detected coming through the Earth than could be detected coming directly above the detector. Not only that, their observations only concerned muon neutrinos coming from the interaction of cosmic rays with the Earth's atmosphere. No tau neutrinos were observed at Super-Kamiokande. The convincing evidence for solar neutrino oscillation came in 2001 from the Sudbury Neutrino Observatory (SNO) in Canada. It detected all types of neutrinos coming from the Sun and was able to distinguish between electron-neutrinos and the other two flavors (but could not distinguish the muon and tau flavours), by uniquely using heavy water as the detection medium. After extensive statistical analysis, it was found that about 35% of the arriving solar neutrinos are electron-neutrinos, with the others being muon- or tau-neutrinos. The total number of detected neutrinos agrees quite well with the earlier predictions from nuclear physics, based on the fusion reactions inside the Sun. In particle physics, neutral particle oscillation is the transmutation of a particle with zero electric charge into another neutral particle due to a change of a non-zero internal quantum number via an interaction that does not conserve that quantum number. For example, a neutron cannot transmute into an antineutron as that would violate the conservation of baryon number.

6.3 India-based Neutrino Observatory

India-based Neutrino Observatory (INO) is a Particle Physics Research Project under construction to study primarily, the atmospheric neutrinos in a 1,300 meters (4,300 ft) deep cave under Ino Peak near Theni, Tamil Nadu, India. This project is notable in that, it is anticipated to provide a precise measurement of neutrino mixing parameters. The project is a multi-institute collaboration and one of the biggest experimental Particle Physics projects undertaken in India. The project was originally to be completed in 2015 at an estimated cost of 1,500 crores, has been cleared by the

Ministry of Environment (India) for construction in the Bodi West Hills Reserved Forest in the Theni district of Tamil Nadu. Although delayed, the project is underway. When completed, the main magnetized iron calorimeter (ICAL) experiment include the world's most massive magnet, four times larger than the 12,500-tonne magnet in the Compact Muon Solenoid detector at CERN in Geneva, Switzerland.

The Primary goals of the INO are the following.

6.3.1 Unambiguous and more precise determination of Neutrino oscillation parameters using atmospheric neutrinos.

6.3.2 Study of matter effects through electric charge identification, that may lead to the determination of the unknown sign of one of the mass differences.

6.3.3 Study of charge-conjugation and charge parity (CP) violation in the leptonic sector as well as possible charge-conjugation, parity, time-reversal (CPT) violation studies.

6.3.4 Study of Kolar events, possible identification of very-high energy neutrinos and multi-muon events.

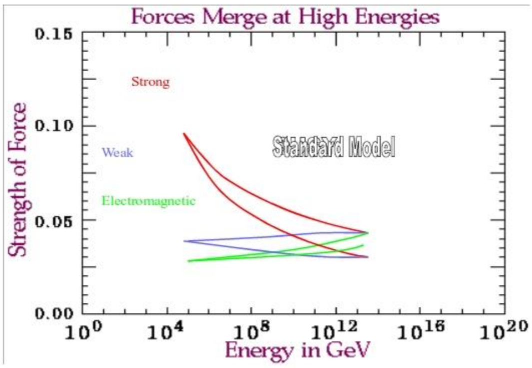
The Nobel Prize in physics has been awarded to Takaaki Kajita and Arthur McDonald for discovering that elusive subatomic particles called neutrinos weigh something more than nothing. Named after the Italian for 'little neutral one', neutrinos have no electric charge and were long thought to have zero mass, but Kajita at the University of Tokyo and McDonald at Queen's University in Kingston, Canada, showed otherwise. With two separate detectors built deep underground, one a kilometer beneath a mountain in Gifu prefecture, and the other 2 km down an old nickel mine in Ontario, the scientists discovered that neutrinos can flip from one form to another as they hurtle through space a chameleon-like behavior that proves they have mass. The Nobel committee said, the discovery had 'changed our understanding of the innermost workings of matter and can prove crucial to our view of the universe'. Asked by reporters in a call following the Nobel announcement how it felt to have won the prize, McDonald described the discovery as a 'eureka moment' and said, 'It's a very daunting experience needless to say. Fortunately, I have many colleagues as well who share this prize with me'.

7 Grand Unification Theory (GUT)

GUT is the basic theory developed to unify the strong with the electroweak theory. Beginning in the early seventies, many people have been working on the obvious next step, combining the strong force with the electroweak force. Several different schemes for implementing this grand unification are now on the table, and although it is too soon to draw any definitive conclusions, some of the early results are promising. In QCD strong coupling decreases at short distances so do the weak coupling (α_w). Also, the electromagnetic coupling (α) which is smallest of the three, increases. The question addressed is: Will all these couplings converge to a common limiting value at extremely high energies. From the functional form of the coupling constants it is estimated that at 10^{15} GeV the three forces coupling constant should be the same (see figure below). In the simplest version of the GUT the gauge group describing all interactions is SU(5) which contains as its subgroup the gauge group SU(3) x SU(2) x U(1). The quarks and leptons are put in the same representations of the group. There are 24 gauge bosons. One of the important predictions of the GUT is that proton is not a stable particle, although its half-life is 10^{31} years (at least 10^{20} times the age of the universe). The hectic search for the decay of proton has met with negative result. If grand unification works, all the elementary particle physics will be reduced to the action of a single force. The final step then will be to bring in gravity, the dream of

Einstein. Many theorists are already working in this direction.

Figure 8: Forces Merge at High Energies



8 Beyond the Standard Model

8.1 Short Comings in Standard Model

There are many short comings in the standard model such as the strong CP problem, neutrino oscillations, matter-anti matter symmetry, and the dark matter and dark energy etc. Another problem with the standard model is that it incorporates only three of the four fundamental forces, omitting gravity. The model is also unsuccessful in explaining why gravity is so much weaker than the electromagnetic force or strong forces. Also, SM cannot provide justification for the three generations of quarks and leptons with such a diverse mass scale. The hierarchy problem is also associated with the Higgs boson mass. Another problem with the SM is it describes only visible matter, and cannot explain the nature of the dark matter and dark energy. Many attempts in the theoretical and experimental physics are going on to extend the SM through super symmetry or new theories like Minimal Supersymetric Standard Model (MSSM), string theory and extra dimensions. In spite of these deficiencies, the SM is the most successful theory of particle physics to date.

8.2 Dark Matter and Dark Energy

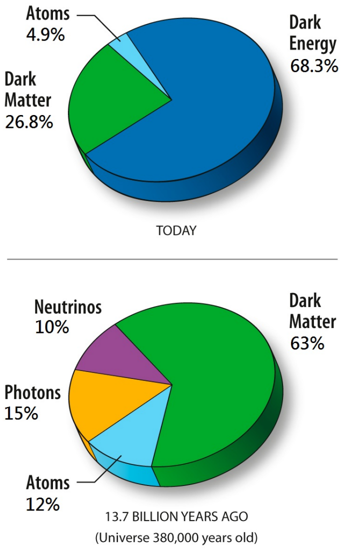
Dark matter is a hypothetical kind of matter that cannot be seen with telescopes but would account for most of the matter in the universe. The existence and properties of dark matter are inferred from its gravitational effects on visible matter, on radiation, and on the large-scale structure of the universe. Dark matter has not been detected directly, making it one of the greatest mysteries in modern astrophysics. Hence, dark matter refers to the invisible non luminous matter in the universe which does not interact with the electromagnetic radiation. This is held as a direct evidence of the existence of the dark matter. According to the Virial Theorem, the total energy should be half of the potential energy. But, experimentally the total kinetic energy is found to be much greater than the total gravitational binding energy of the galaxies. It is said that dark matter is able to bend the light. The Swiss astrophysicist Fritz Zwicky, of the CIT in 1933 applied the virial theorem to the Coma cluster of galaxies and obtained evidence for unseen mass. The 4.9% of the matter of the universe is ordinary matter and 26.8 % is composed of dark matter and 68.3 % is thought to consist of Dark energy. Many Particle Physics candidates for Dark Matter have been proposed and several projects to detect them directly or under way. The probable candidates for the dark Matter are 1) exotic new particles 2) black holes and 3) neutrinos (likely to be verified at LHC).

The 2011 Nobel prize in Physics was awarded for the accelerating expansion of the Universe to Saul Perlmutter of Lawrence Berkeley National Laboratory and the university of California, Berkeley, Brian Schmidt of the Australian National University and Adam Riess of Johns Hopkins University and the Space Telescope Science Institute, Baltimore ‘for the discovery of the accelerating expansion of the Universe through observations of distant supernovae’, a discovery has reshaped our understanding of the cosmos and the ultimate fate of the universe. The work constrains the ultimate fate of the universe, addresses Einstein’s cosmological constant, an element of the theory of relativity. It provides the frame work for the concept of dark energy which makes up approximately 75% of the matter and energy in the universe

8.3 Super Symmetry

The Electroweak Theory and the GUT are incomplete. Super symmetry relates fermions to bosons. This is a symmetry which tells us that if we have a boson we must have a fermion partner and vice versa. Thus, every fermion (quark or lepton) will have a super symmetric (SUSY) spin zero partner (squark, slepton) while every boson (photon, gluon, W, Z and Higgs) has a spin 1/2 partner. The quantum of gravitational force, the gravitation, which has spin 2, will have super symmetric partner graviton with spin 3/2. In the super symmetric limit, the particles and their super symmetric partners should have equal masses. The discovery of super particles would certainly be a triumph of symmetry ideas. At present, super symmetry is only an attractive idea.

Figure 9: Dark Matter and Dark Energy



8.4 Superstring Theories

Superstring theories combine the interaction of particle physics with gravity and are essentially a geometric theory. In string theories the elementary constituents are not points in space but curves (or strings) in a D-dimensional space, where D is considerably greater than 4, with D =10 being the value the current theory requires. The elementary particles are different vibrational modes of the string. Since the gravity becomes important at the Planck's scale (10^{19}GeV or 10^{-33} cm). The superstring theories can be tested only at this energy, and hence are still far from verification.

Summary of the Elementary Particles and Their Interaction

Table 3: Fundamental Interactions (Mc^2 = 1 GeV)

	Gravitational	**Electromagnetic**	**Weak**	**Strong**
Field Bosons	Graviton (?)	Photon	W+, W- , Z	Gluons
Spin-parity	2+	1-	1-,1+	1-
Mass(GeV)	0(?)	0	M_W= 80.2 GeV M_Z = 91.2 GeV	0
Range	∞	∞	10^{-16} cm	10^{-13} cm
Source	Mass	Electric Charge	Weak Charge	Colour Charge
Coupling Constant	5×10^{-40}	1/137	1.17×10^{-5}	$\alpha_s \leq 1$
Typical cross section, m^2	-	10^{-33}	10^{-39}	10^{-30}
Typical Life Time , sec.	-	10^{-20}	10^{-10}	10^{-23}

Table 4: Quantum Numbers of the Quarks, $Q = I_3 + \frac{1}{2}(B + S + C + B^* + T)$ (Here B denotes the Baryon Number and B^* denotes the Bottom Quantum Number)

Flavour	I	I_3	B	S	C	B^*	T	Q	Effective Mass in Baryons MeV/C^2	Bare Mass MeV/C^2
u	1/2	1/2	1/3	0	0	0	0	2/3	363	4.2
d	1/2	-1/2	1/3	0	0	0	0	-1/3	363	7.5
s	0	0	1/3	-1	0	0	0	-1/3	538	150
c	0	0	1/3	0	1	0	0	2/3	1500	1100
b	0	0	1/3	0	0	-1	0	-1/3	4700	4200
t	0	0	1/3	0	0	0	1	2/3	1,74,000	1,74,000

Table 5: Fundamental Leptons

Leptons	J	Mass MeV/c^2	Lifetime
e^-	1/2	0.511099907	Stable
μ^-	1/2	105.658389	2.197×10^{-6} s
τ^-	1/2	1777.0 0.3	(291 + 1.5) x 10^{-15} s
ν_e	1/2	$<$ 10 eV	Stable
ν_μ	1/2	$<$ 0.16 MeV	Stable
ν_τ	1/2	$<$ 18 MeV	Stable

9 Conclusion

The field of elementary-particle physics has made dramatic progress over the past 25 years in understanding the fundamental structure

Table 6: Fundamental Bosons

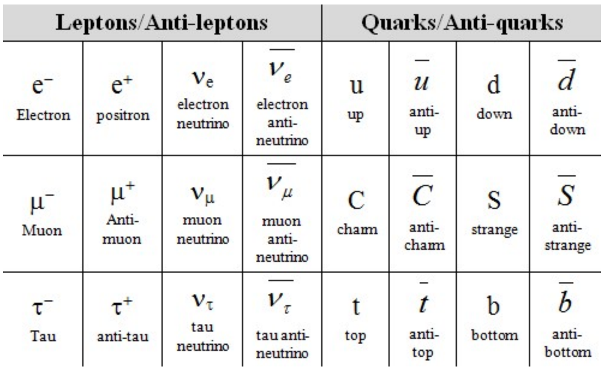
Gauge bosons	J^{PC}	**Mass (GeV/c^2)**	**Width** GeV
Photon	1^{--}	$< 10^{-26}$	Stable
Gluon	1^{-}	0	Stable
Weak bosons			
W$^{\pm}$	$1^{\pm}$	80.33±0.15	$\acute{\Gamma}$=2.07±0.06
Z	$1^{\pm}$	91.187±0.007	$\acute{\Gamma}$=2.49±0.01

Table 7: Conservation Laws

Sl.No	**Conservation Law**	**Strong**	**Electromagnetic**	**Weak**
1	Baryon Number (B)	Yes	Yes	Yes
2	Lepton Number (L_e,L_μ, and L_τ) are Separately conserved	Yes	Yes	Yes
3	Iso-spin (I)	Yes	No	No
4	Third Component of Iso-spin (I_3)	Yes	Yes	No
5	Strangness (S)	Yes	Yes	No
6	Electric Charge (Q)	Yes	Yes	Yes
7	Parity (P)	Yes	Yes	No
8	Charge Conjugation (C)	Yes	Yes	No
9	CP	Yes	Yes	No
10	CPT	Yes	Yes	Yes
11	Energy, Momentum and Angular Momentum	Yes	Yes	Yes

of matter. Recent discoveries and technological advances are en-

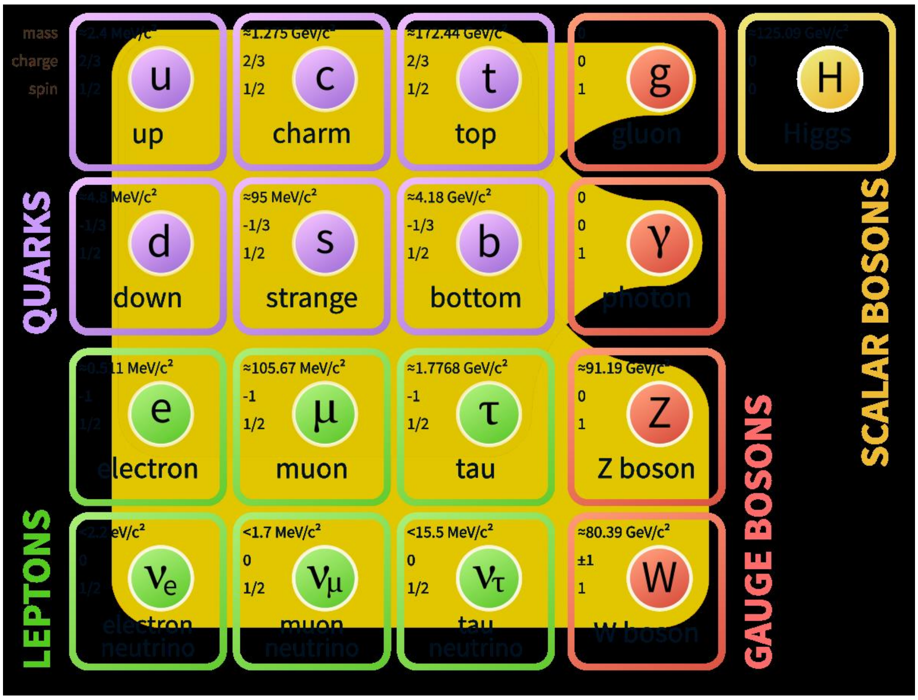
Figure 10: Leptons:List of the Fundamental Particles Leptons and corresponding anti particles; Total (6 x 2=12),Qurks: Quarks and corresponding anti-particles; Total (6x3x2=36);(Each quark comes in three colors)



Leptons/Anti-leptons				Quarks/Anti-quarks			
e^- Electron	e^+ positron	ν_e electron neutrino	$\overline{\nu_e}$ electron anti-neutrino	u up	$\overline{u}$ anti-up	d down	$\overline{d}$ anti-down
μ^- Muon	μ^+ Anti-muon	ν_μ muon neutrino	$\overline{\nu_\mu}$ muon anti-neutrino	C charm	$\overline{C}$ anti-charm	S strange	$\overline{S}$ anti-strange
τ^- Tau	τ^+ anti-tau	ν_τ tau neutrino	$\overline{\nu_\tau}$ tau anti-neutrino	t top	$\overline{t}$ anti-top	b bottom	$\overline{b}$ anti-bottom

abling high-energy physicists to address such compelling scientific issues as why elementary particles have mass, the excess of matter over antimatter in our universe, and the fundamental nature of the breaking of electroweak symmetry. In this article an attempt has been made to explain the fundamental particles, fundamental forces and their interactions. The article also gives information about the current experimental facilities to detect elementary particles. The complete list of our understanding of the elementary particles, and their interactions and the conservation laws obeyed by them are listed in Tables 3-7, Figure 10 and Figure 11.

Figure 11: Leptons: Leptons and corresponding anti particles; Total (6 x 2=12),Qurks: Quarks and corresponding anti-particles; Total (6x3x2=36);(Each quark comes in three colors),Gauge bosons: Photons, Gluons (8), $W^{\pm}$, Z and the Higgs particle; Total 13,
Total number of fundamental particles 61



References

David Griffiths, (1987). *Introduction to Elementary Particles*, John Wiley and Sons, Inc., (ISBN 0-471- 43132-X).

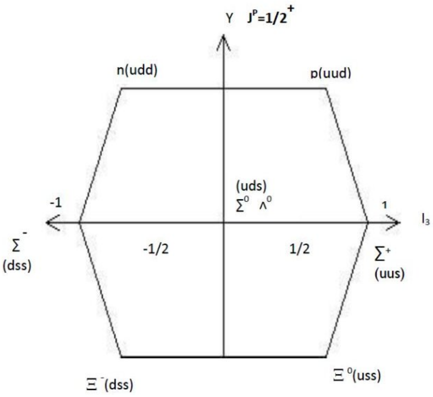
Donald H. Perkins, (2000). *Introduction to High Energy Physics*, fourth edition, Cambridge University Press, (ISBN 0-521-62196-8)

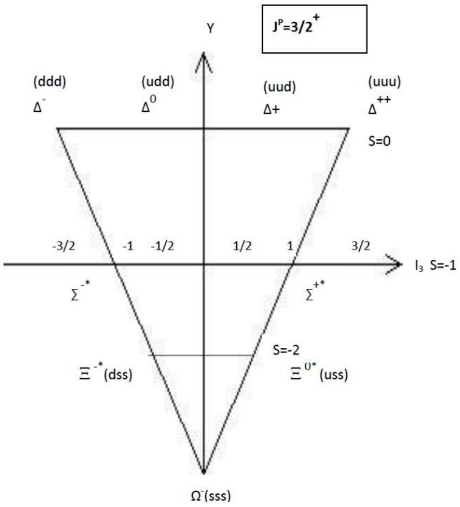
Kurt Gottfried, Victor F. Weisskopf, (1986).
Concepts of Particle Physics, Volume I, Oxford University Press, (ISBN 0-19-504373).

Leon M. Lederman, David N. Schramm, (1989),
From Quarks to the Cosmos: Tools of Discovery, Scientific American Library,(ISBN 0-7167-6012-6).

Appendix I

SU(3) Quark Model Baryons
Baryon Octets and Decouplets





SU(3) Quark Model Mesons

Meson Nonets