First LHC School
Lecture#1

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What are the fundamental constituents of matter? What are the fundamental "forces" through which the fundamental constituents interact? These two questions are fundamental to physics. The physicists are trying to find answers to these questions. They have achieved a considerable understanding of the structure of matter and the basic forces in the universe.

Until about 1932, only four particles namely the proton (p), the neutron (n), the electron (e) and the neutrino (ν) were regarded as the ultimate constituents of matter.

Of these four particles, two, the proton and the electron are electrically charged. The other two are electrically neutral. The neutrons and protons form an atomic nucleus; the electron and the nucleus form an atom while the neutrino comes out in radioactivity, i.e. the neutron decays into a proton, an electron and a neutrino.

$$n \rightarrow p + e^{-} + \bar{\nu}_e$$

$$^{14}_{8}O \rightarrow ^{14}_{7}N + e^{+} + \nu_e$$

Each of these particles, (called a fermion), spins and exists in two spin (or polarization) states called left-handed (i.e. appears to be spinning clockwise as viewed by an observer that it is approaching) and right-handed (i.e. spinning anti-clockwise) spin states. One may add a fifth particle, the photon to this list.

The photon is a quantum of electromagnetic field. It carries spin 1 (boson), but due to its zero mass, has only two spin directions or it has only transverse polarization. It is a mediator of electromagnetic force. It is a general feature of quantum theory that each particle has its own antiparticle with opposite charge but with same mass and spin.

Accordingly we have four antiparticles viz, the antiproton ($\overline{p}$), the positron (e^+), the antineutron ($\overline{n}$) and antineutrino ($\overline{\nu}$).

The four particles experience four types of forces.

The Gravitational Force

This is the force of attraction between two particles and is proportional to their masses and inversely proportional to the square of distance between them. It controls the motion of planets and galaxies and also governs the law of falling bodies. It is a long range force. It determines the overall structure of the universe.

Weak Nuclear Force

It is responsible for radioactivity [e.g., a radioactive isotope of oxygen: decays into nitrogen, the electron and neutrino with a half life of 71.4 sec]. The strength of this force is characterized by a constant called Fermi constant $G_F \approx 10^{-5} / m^2{}_p$ where the mass of proton is 1GeV. (MeV: million electron volt i.e.the energy attained by a proton when accelerated in a potential of one million volts). It is a short range force effective over a distance of order of 10^{-16} cm. The weak nuclear force can distinguish between left-handedness and right-handedness.

The Electromagnetic Force

It acts between two electrically charged particles, e.g. a negatively charged electron and a positively charged proton attract each other with a force which is proportional to their electric charges and inversely proportional to square of distance between them. But according to the concept of electromagnetic field introduced by Faraday and Maxwell ; presence of a charged particle produces an electric field and when moving it also produces a magnetic field. This field manifests itself in a force between charged particles. It is responsible for binding atoms. The interatomic and intermolecular forces are all electrical in nature.

Thus it mainly governs all known phenomena on earth, including life. This force also manifests itself through electromagnetic radiation in the form of light, radio waves and X-rays. Electromagnetic radiation is a carrier of electromagnetic force. It is a long range force. The strength of electromagnetic interaction is determined by the dimensionless number $\alpha = \frac{1}{137}$

The Strong Nuclear Force

It is responsible for the binding of protons and neutrons in a nucleus. It is a strong force and is about 100 times stronger than the electromagnetic force. It is a short range force effective over the nuclear dimension of the order of 10^{-13} cm. The relative strengths of four forces are in the order of $10^{-40} : 10^{-7} : 10^{-2} : 1$

Is it possible to unify all these diverse forces into a single universal force? The physicists are trying to do exactly that. They have attained a partial success in this respect. They have succeeded in unifying the weak nuclear force with electromagnetic force as we will see

Classification of Matter

We know that electron and neutrino are just two members of a family called leptons (leptons do not experience strong nuclear force) of which six are presently known to exist. Similarly, the neutron and proton are members of a much larger family called hadrons (hadrons also experience strong nuclear force).

Hadrons exist in two classes, baryons and mesons; the former carry half integral spin and a quantum number called baryon number while the latter carry zero or integral spin and no baryon number.

It was found experimently that the proton or the neutron has a structure; they are not the elementary constituents of matter. The mass spectrum, production and decay characteristics of hadrons can be understood in a much simpler picture if one assumes that the baryons are made up of three constituents called quarks and mesons are made up of quark and antiquark.

The quark carries fractional charges 2/3 or -1/3. They have spin one half and carry different flavors to distinguish them. At present six flavors are known to exist. Quarks play the same role in hadron spectroscopy as neutrons and protons in nuclear spectroscopy and electrons and nuclei in atomic spectroscopy.

There are three layers or generations of matter. The first generation

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}, \begin{pmatrix} u \\ d \end{pmatrix}$$

[u, d called up and down quarks are constituents of proton (*uud*) and neutron (*uud*)]

is relevant for the visible universe and the life on earth. The second and third generations i.e. middle and top layers of matter

$$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}, \begin{pmatrix} c \\ s \end{pmatrix} and \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}, \begin{pmatrix} t \\ b \end{pmatrix}$$

do exist and are produced either in laboratory or in cosmic rays by a collision of particles of first generation.

To sum this up according to present view, the six quarks and six leptons form the fundamental constituents of matter. They experience the four forces listed above. The relative strengths of these forces are found to be independent of generation (Universality).

These forces vary with energy; they are characterized here at energy of $1 GeV$. However, the weak force is as strong as electromagnetic force at 300 GeV i.e. the scale at which weak and electromagnetic forces are unified is 300 GeV . However for the gravitational force which is characterized by Newton constant $\alpha_{G_N} \approx 10^{-40}$ (compare with $\alpha = \frac{1}{137}$) the unification scale would be at Planck mass $M_P \approx 10^{19} GeV$.

The relative strength of these interactions are found to be independent of generation number (Universality): Characteristic of gauge forces. These interaction vary with energy, they are characterized here at a scale of 1 GeV.

For instance

$$m_Z = 90\text{GeV}, \qquad \alpha(1\text{GeV}) = \frac{1}{137.5}$$

$$\alpha(m_Z) \approx \frac{1}{128}, \qquad \alpha_s(1.7\text{GeV}) \approx 0.328$$

$$\alpha_s(m_Z) \approx 0.1185, \qquad \frac{G_N}{\hbar c} \approx 6.71 \times 10^{-39} \left(\text{GeV}/c^2\right)^{-2}$$

$$M_P = \sqrt{\frac{\hbar c}{G_N}} \approx 10^{19}\ \text{GeV}$$

$$\alpha_{G_N} = \frac{(1\text{GeV})^2}{M_P^2}\alpha \approx 10^{-38}\alpha \approx 10^{-40}$$

$$\frac{G_F}{(\hbar c)^3} \approx 1.166 \times 10^{-5}(\text{GeV})^{-2}$$

$$\sqrt{\frac{(\hbar c)^3}{G_F}} \approx 300\ \text{GeV} \qquad \alpha_W = \frac{(1\text{GeV})^2}{(300\text{GeV})^2}\alpha = 10^{-7}$$

Universality implies that the fundamental forces are gauge forces. A prototype of gauge force is electromagnetic force. Electromagnetic interaction is mediated by a photon the quantum of electromagnetic field and its strength is determined by electric charge

$$eJ^{\mu}_{em}A_{\mu} \qquad\qquad \partial_{\mu}J^{\mu}_{em} = 0$$

Photon is massless spin-1 particle which has no longitudinal polarization. The underlying gauge group is U(1). Thus understanding of the elementary interactions lies in discovering a gauge symmetry group: the fundamental representation of which gives the content of elementary fermions and adjoint representation

of the group gives the mediators. The strength of interaction is determined by gauge coupling constant.

Edifice of particle physics is based on the following principles

- Chiral Fermions: Left right fermions belong to different representations of gauge symmetry group, to take into account the fact that weak interactions distinguish between left and right
- Local Gauge invariance: To find appropriate gauge symmetry group
- Spontaneous breaking of gauge symmetry
- Renormalizability

This is what one would expect : A charged particle produces an electromagnetic field; in quantum mechanics the presence of electromagnetic field would manifest itself by emission and reabsorption of the photon (uncertainty principle allows this; this is called quantum fluctuations). Whenever another charged particle is present, the photon emitted by the first particle may be absorbed by the second particle giving rise to electromagnetic interaction between them mediated by a photon whose strength is given by the product of charges Q_e and Q_q of two particles e and q.

This is generalized: All fundamental forces are gauge forces describable in terms of ``charges'' and mediated by vector bosons similar to photon. According to these ideas, the weak nuclear force is a gauge force mediated by two electrically charged vector bosons W^+ and W^- and describable in terms of two weak charges Q_{W^+}, Q_{W^-} similar to electric charge Q.

Attempts were made to unify these forces; it was found that this can be done only if the fourth vector boson Z (electrically neutral) and corresponding weak charge Q_Z exist.

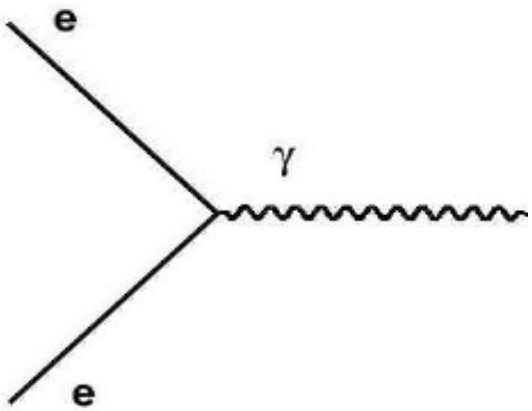
This theory was formulated in late 1960's by Salam, Weinberg and Glashow but full implication of it was realized in the 1970's.

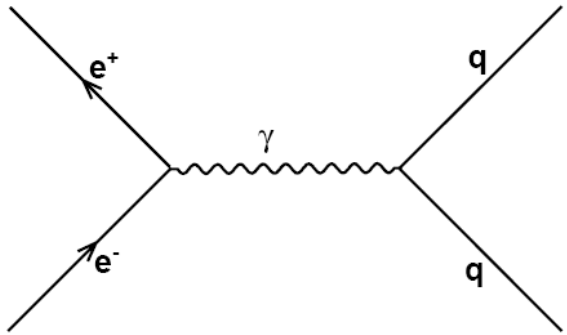
According to this theory, the weak nuclear force is nothing but a different facet of a basic force whose other facet is electromagnetism. The unification of two seemingly different forces, namely, weak and electromagnetic is analogous to the 19th century unification of electricity with magnetism.

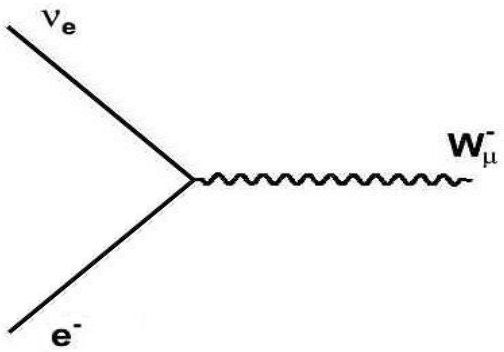
The theory referred to the above predicted: The existence of a new type of neutral weak interaction (or force) mediated by *Z*-boson. The four vector bosons namely $\gamma, W^{\pm}$ *and* Z belong to a family or a group.

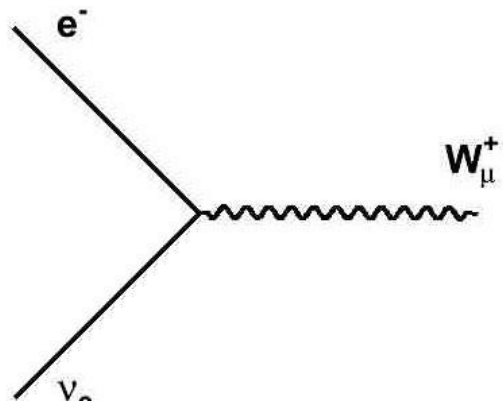
The vector bosons W, Z must be massive since weak interactions are of short range while the photon is massless. Their masses are generated by a mechanism called the spontaneous breaking of gauge symmetry to which four vector bosons belong.

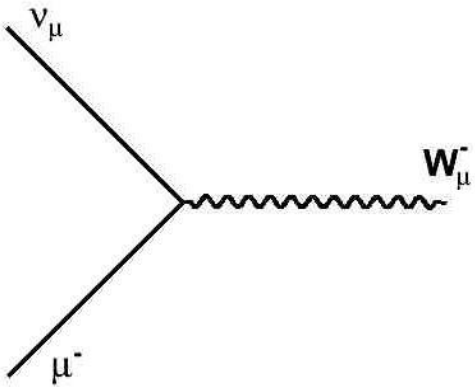
			$SU_L(2)$	I_{3L}	Y
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	2	$\frac{1}{2}, -\frac{1}{2}$	-1
$\begin{pmatrix} u \\ d' \end{pmatrix}_L$	$\begin{pmatrix} c \\ s' \end{pmatrix}_L$	$\begin{pmatrix} t \\ b' \end{pmatrix}_L$	2	$\frac{1}{2}, -\frac{1}{2}$	$\frac{1}{3}$
e_R u_R d_R	μ_R c_R s_R	τ_R t_R b_R	1 1 1	0 0 0	-2 $\frac{4}{3}$ $-\frac{2}{3}$

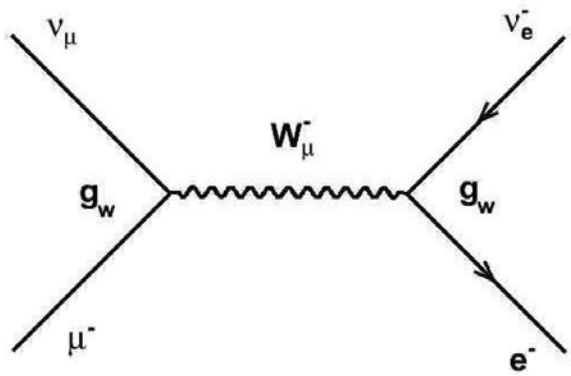

e
γ
e


e+
q
γ
e-
q


νe
W-μ
e-


e-
W+μ
νe


νμ
W-μ
μ-


νμ
ν-e
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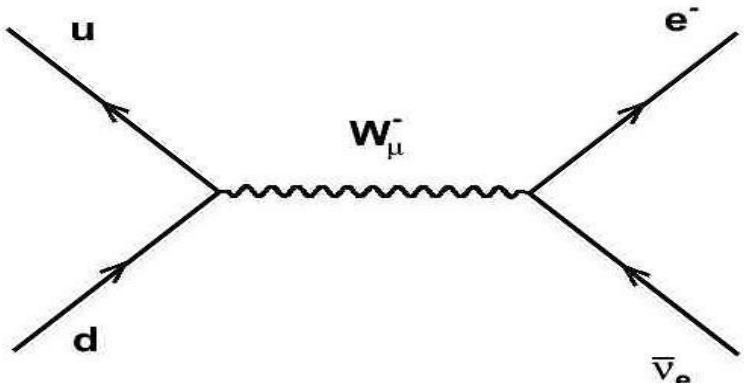
u
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d
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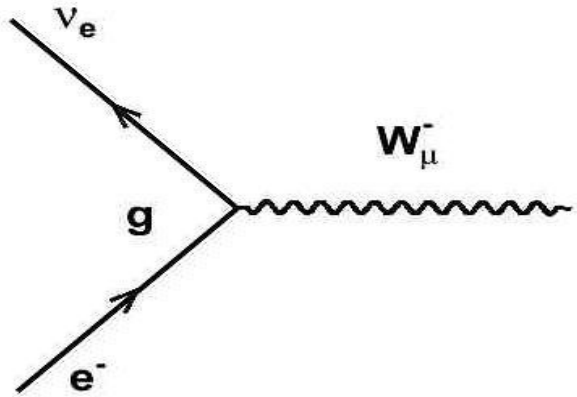
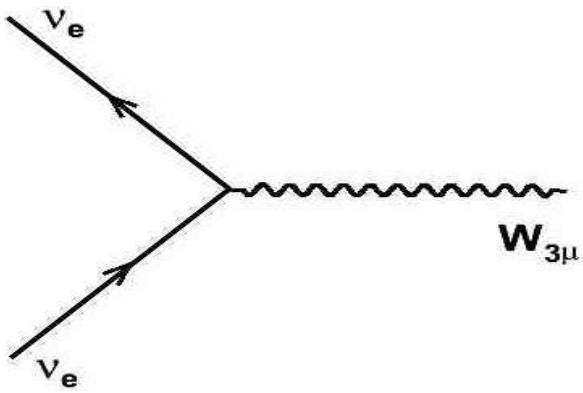
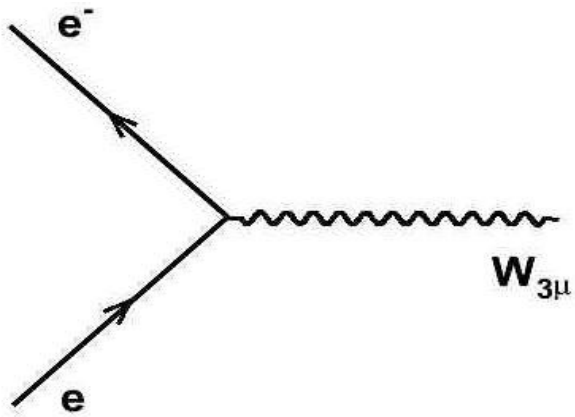
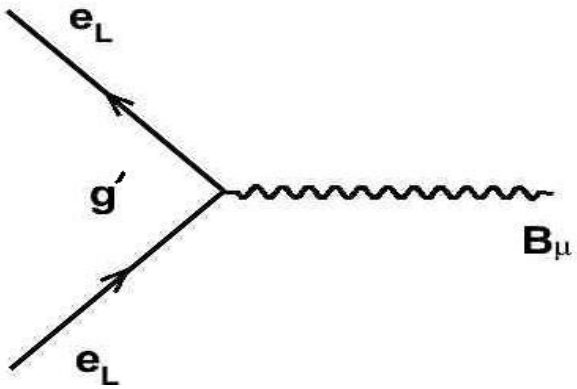
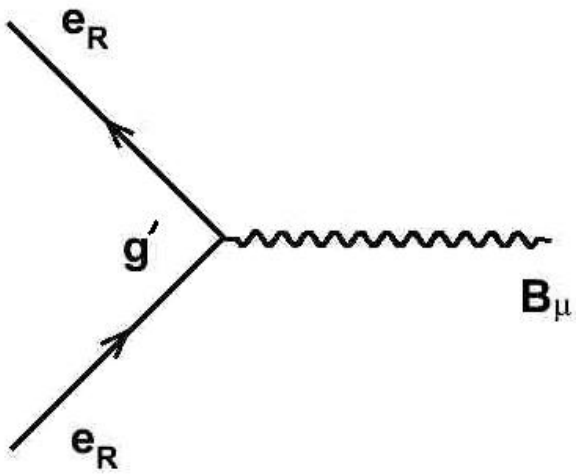
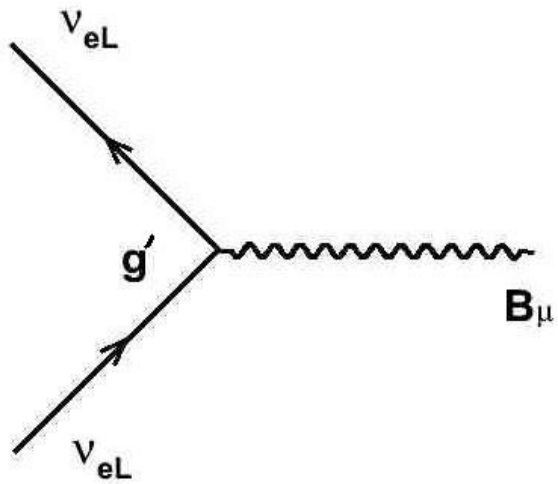

νe
W-μ
g
e-

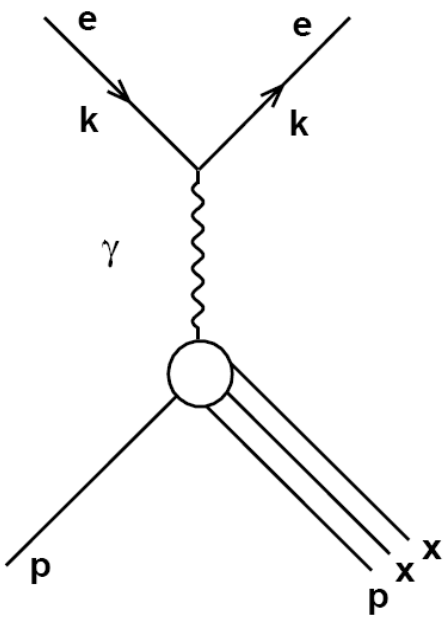

νe
W3μ
νe


e-
W3μ
e


eL
g′
Bμ
eL


e_R
g′
B_μ
e_R


ν_{eL}
g′
B_μ
ν_{eL}


e
e
k
k
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p
p
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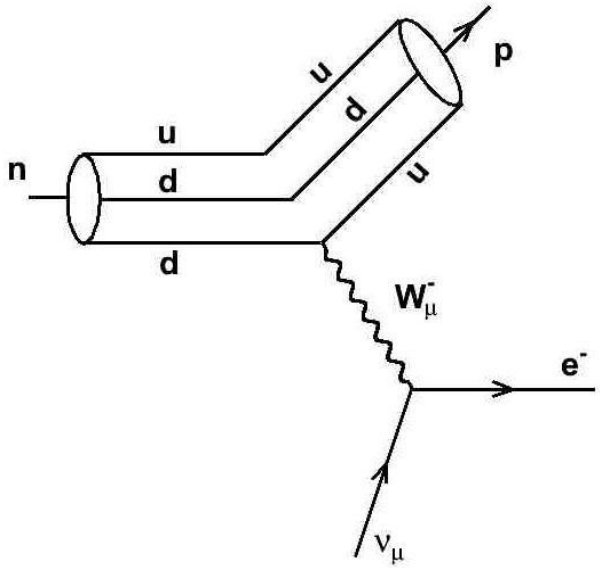

n
u
d
d
u
d
u
p
W$_\mu^-$
e$^-$
ν$_\mu$

$$Q = I_{3L} + \frac{1}{2}Y$$

Mediators of the weak interactions are put in the: adjoint representation of $SU_L(2)$

$$W_\mu^+,\ W_\mu^-,\ W_\mu^0 : SU_L(2) \quad \text{isospin}$$

$$B_\mu : U(1) \quad \text{Hypercharge}$$

Since weak forces are short range, the gauge group SU(2) x U(1) is spontaneously broken:

$$SU_L(2) \times U(1) \rightarrow U_{em}(1)$$

The mass eigenstates are

$$Z_\mu = -\sin\theta_w B_\mu + \cos\theta_w W_\mu^0$$

$$A_\mu = \cos\theta_w B_\mu - \sin\theta_w W_\mu^0$$

W^+, W^-, Z_μ are mediators of weak interactions.

A_μ: Photon mediator of electromagnetic interaction.

$$m_A = 0, \quad m_W^2 = \frac{\pi\alpha}{\sqrt{2}\, G_F \sin^2\theta_w}$$

$$\sin^2\theta_w = 0.33$$

$$m_Z = \frac{m_W}{\cos\theta_w}$$

After radiative corrections mass of $m_W = 80.39$ GeV, $m_Z = 91.18$ GeV is a remarkable agreement with the experimental values.

The year 1978 saw a remarkable set of experiments, confirming the existence of neutral weak interaction as predicted by the electroweak theory.

Since the weak and electromagnetic interactions are different manifestation of the same force and since weak interactions can distinguish between left and right; one should be able to see this minute effect in the scattering of polarized electrons on nuclei.

This effect was detected experimentally; further confirming the theory. The crowning verification of electroweak theory was achieved in 1980's, when three spin1 particles W , Z with mass 80-90 times proton mass were discovered at CERN collider experiments in Geneva.

Quarks and Strong Quark Gluon Force

Are quarks real or merely conceptual entities introduced to understand the mass spectrum, production and decay characteristics of hadrons? To answer this question, the structure of proton or neutron should be experimentally probed. Electron-proton scattering is a very direct means of probing the proton structure. In Particular electron-proton scattering serves to produce a virtual photon of mass Q^2 which probes the proton structure in a very clean way. In the elastic scattering of electrons of proton target, proton recoils elastically; the photon interacts with the proton constituents in a coherent manner.

The scattering crossection is the product of Rutherford scattering for a point particle multiplied by form factors $F(Q^2)$ and $G(Q^2)$ which are functions of virtual photon mass Q^2 . These form factors are related roughly to average shape of a proton. For a particle with no structure the crossection would be given by the Rutherford scattering only. On the other hand, in the inelastic process, the photon interacts in an incoherent manner and it probes, roughly, the instantaneous construction of the proton, rather than the average shape found in the elastic scattering experiments.

Thus the study of deep inelastic electron-hadron scattering at high energy (ν) and large momentum transfer Q^2 [ν and Q^2 are the energy and mass of virtual photon] may give information about the structure pertaining to any fundamental constituents of hadrons.

These experiments have established without any doubet that fractionally charged quarks are indeed the fundamental constituents of a proton (hadron) and that in the deep inelastic regime they are almost free i.e. they interact weakly at high momentum transfer or at short distance.

These experiments clearly show that the structure of proton (hadron) has a different character in the sense that a proton cannot be split into its constituents viz quarks. While an atom (a nucleus) can be split into its constituents viz electrons and nucleus (protons and neutrons) in high energy collision, a hadron-hadron collision always produces hadrons. This leads us to the hypothesis of quark confinement i.e. quarks are always confined in a hadron.

The strong force which keeps the quarks glued together in a hadron is a fundamental force on the same level as electromagnetic and weak nuclear forces which are two other fundamental forces in nature. Hence like electroweak forces, it is a gauge force mediated by vector bosons coupled to the quarks with a universal coupling characterized by a dimensionless coupling constant α_s =0.5 at present energies. Such bosons are called gluons. This force should be attractive between quarks and also between a quark and antiquark. Note that electromagnetic force is repulsive between two electrons but attractive between an electron and a positron.

Another crucial difference is that α_s decreases at short distances or large momentum transfers, whereas α increases with increasing momentum transfer.

This property is in accord with the deep inelastic scattering experiments which show that at short distances quarks are almost free. This property is called the asymptotic freedom of inter quark force.

The other feature of a gauge force is that there are charges associated with this force. For this purpose, we note that a hadron is a bound state of quarks (a baryon is a bound state of three quarks qqq, whereas a meson is a bound state of quark antiquark $q\bar{q}$. Since quarks carry spin ½ like electron, they must satisfy Fermi statistics. This is only possible if another degree of freedom (called color) is introduced: each quark flavors carry three different strong color charges, red (r), yellow (y) and blue (b) [Leptons don't carry color and that's why they don't take part in strong interactions].

All hadrons are color singlet. Thus the color quantum number is hidden. This is the postulate of color confinement mentioned earlier and explains non-existence of free quark. Strong color charges are the sources of inter-quark force. Corresponding to three color charges of a quark, there are eight color carrying gluons. This theory is called quantum chromodynamics (QCD) in analogy with quantum electrodynamics (QED). To summarize the important physical properties of QCD are (i) the gluons, being mediators of strong interaction between quarks, are vector particles and carry color; both of these properties are supported by hadron spectroscopy, (ii) the asymptotic freedom which implies that the effective coupling constant decreases at short distances or high momentum transfer, a property which has a rigorous theoretical basis.

Asymptotic freedom is essentially a consequence of self interaction of gluons, since gluons themselves carry color unlike photon which carries no electric charge. (iii) Confinement which implies that the potential energy between color charges increases linearly at large distances so that only color singlet states exist.

Phenomenologically, a potential of the form

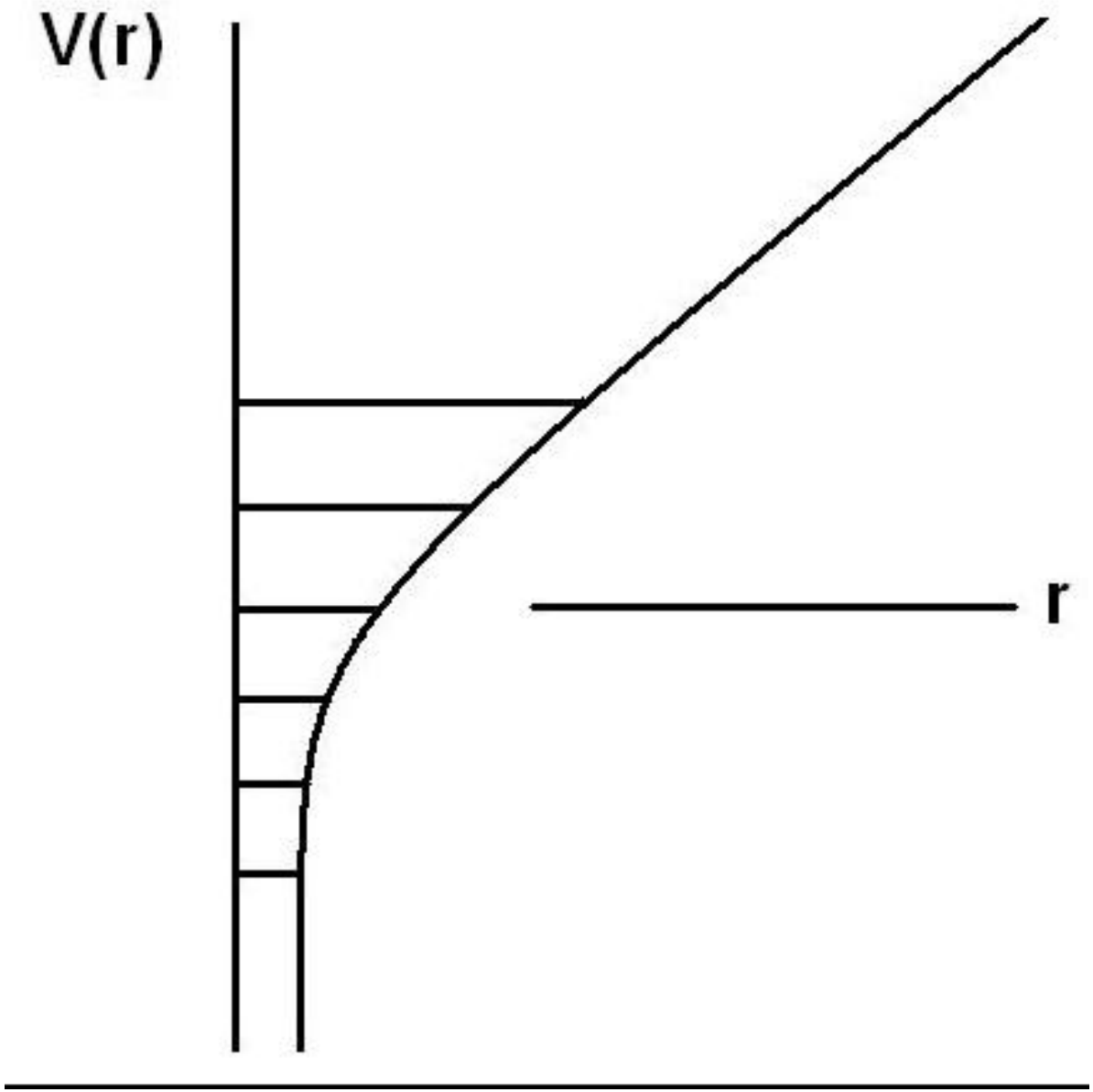
$$V(r) = -\frac{\alpha_s}{r} + kr$$

where the first term is the coulomb like potential whereas the second term give the confining potential has been used in hadron spectroscopy with good success.

Lattice gauge theories suggest a linear confining inter quark potential. Note that as r increases $V(r)$ increases; so it requires an infinite energy to release the quarks from a hadron. However quarks can be produced for example in electron-positron annihilation

$$e^+e^- \rightarrow \gamma \longrightarrow q\bar{q}$$

In this process, the photon emitted from the electron-positron pair lifts the quark and antiquark pair from the vacuum. The $q\bar{q}$ in a very short time hadronize themselves into hadrons. In the process of hadronization , the foot prints left by quarks provide us the information about them.


V(r)
r

$$\sigma_{hadron} = \frac{16\pi^3\alpha^2}{s}\rho(s)$$

$$\sigma_{hadron} = \frac{4\pi\alpha^2}{3s}\sum_i Q_i^2$$

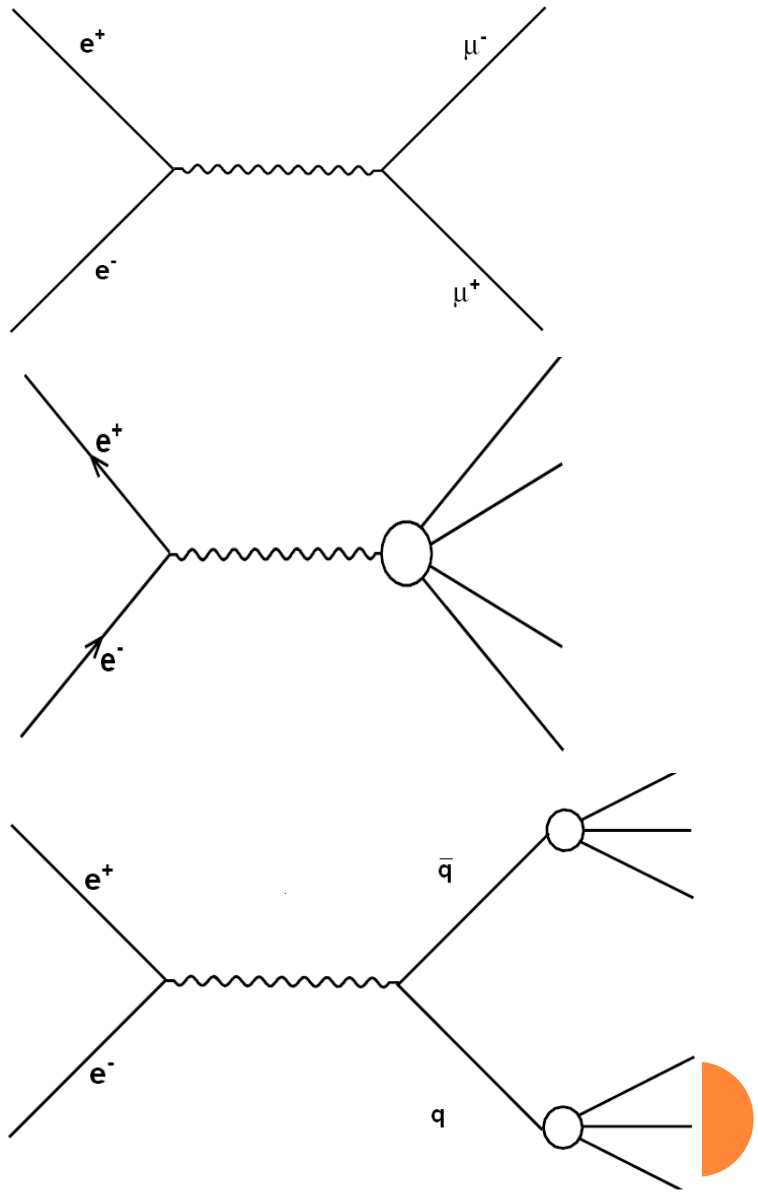
$$\rho(s) = \frac{1}{12\pi^2}\sum_i Q_i^2$$

$$R = \frac{\sigma_{hadron}}{\sigma_{e^+e^-\to\mu^+\mu^-}} = \sum_i Q_i^2 = \frac{10}{3}$$

$$R = \frac{11}{3}\left[1 + \frac{\alpha(s)}{\pi}\right]$$

$$\alpha(34\text{GeV}) = 0.142 \pm 0.03$$

$$\alpha_s(m_z = 80\text{GeV}) = 0.119 \pm 0.002$$



TO CONCLUDE

There are three generations of elementary fermions (leptons and quarks); $(\nu_i, e_i); (u_i, d_i)$ ($i=1,2,3$ generation index). The left handed fermions form a doublet i.e. they belong to fundamental representation of the group $SU(2)_L$. The right handed fermions except neutrinos (neutrinos are only left handed) belong to singlet representation of $SU_L(2)$.

For electroweak unification it is essential to extend the group to $SU_L(2)\times U(1)$. Thus there are 4-vector bosons W^+, W^-, Z and γ which are mediators of electroweak forces. Since each quark flavor carries three colors, quarks belong to a triplet representation of the group $SU_C(3)$. The eight color carrying gluons (which belong to adjoint representation of $SU_C(3)$) are mediators of interquark force

which keeps the quark confined in a hadron (a hadron is a color singlet i.e. color is a hidden quantum number). The group $SU(2)_L \times U(1) \times SU(3)_C$ which is the direct product of electroweak group and strong color group is the gauge group of standard model of elementary constituents of matter and interactions between them.

To unify the electroweak and strong quark gluon forces, it is essential to find a gauge group G which contains the group $SU(2)_L \times U(1) \times SU(3)_C$ as its subgroup. The quark and leptons are in general members of the same multiplets of the group G.

Any viable grand unified model is not possible without proliferation of quarks and leptons content of standard model.

The grand unification has met with only partial success. To unify gravity with electroweak and strong quark- gluon forces is not possible within quantum field theory framework because the underlying theory of gravity viz general theory of relativity is in conflict with quantum mechanics. The basic principle of quantum theory is principle of superposition

which the general theory of relativity does not satisfy. To unify gravity with other basic interactions one has to go beyond quantum field theory of point particles in the domain of string theory.

Thanks