The standard model of fundamental particles

D. P. Roy

Theoretical Physics Group, Tata Institute of Fundamental Research, Homi Bhabha Road, Colaba, Bombay 400 005, India

This is an overview of our current understanding of the fundamental particles and their interactions, which is commonly called the Standard Model. The major developments in this field are outlined along with the major issues that remain to be settled. Important Indian contributions to these developments are underlined.

OUR concept of fundamental particles has undergone two revolutionary changes during this century. The first was the Rutherford scattering experiment of 1911 bombarding α particles on gold atom; while most of them passed through straight, occasionally, a few were found to scatter off at a large angle. This showed that the atom is not a solid compact object, but is largely hollow with a solid compact nucleus (made up of protons and neutrons) surrounded by the tiny revolving electrons. The second was the electron–proton scattering experiment of 1968 at Stanford, which was essentially a repeat of the Rutherford scattering type experiment, but at a much higher energy. The result was also very similar as illustrated in Figure 1. It was again clear from the scattering pattern that the proton is not a solid compact object itself, but is largely hollow with three solid compact cores called quarks. Indeed we know now from many such experiments, that all the nuclear particles (proton, neutron and mesons) are made up of quarks, i.e. they are quark atoms.

The reason it takes a much higher beam energy to probe the structure of the nuclear particles is their small size relative to the atom, about 1 fm (10^{-15} m) against 1 Å (10^{-10} m). It follows from the famous Uncertainty Principle that the uncertainties in distance and energy are related by

$$\Delta x \Delta E > \hbar c \sim 0.2 \text{ GeV} \cdot \text{fm}, \qquad (1)$$

i.e. probing a distance scale $x << 1$ fm requires a beam energy $E >> 1$ GeV, where a Giga electron volt (GeV = 10^9 eV) is the energy acquired by an electron on passing through a billion volts. It is this multi-billion volt accelerator technology that is responsible for the half a century gap between the two experiments. The Stanford experiment got the Nobel Prize in 1990.

In particle physics one normally uses the so-called natural units

$$\hbar = c = 1, \text{ i.e. } m = mc^2. \qquad (2)$$

That means the mass of a particle is same as its rest mass energy. The GeV is the most commonly used unit of mass, energy and momentum. The mass of proton $m_p \simeq 1$ GeV.

Basic constituents of matter

According to our present understanding the basic constituents of matter are a dozen of spin-1/2 particles (fermions) along with their antiparticles. These are the 6 leptons (electron, muon, tau and their associated neutrinos) and the 6 quarks (up, down, strange, charm, bottom and top). Each can be organized into 3 pairs, in increasing order of mass (Table 1). Members of each pair differ by 1 unit of electric charge as shown in the last column, i.e., charge 0 and –1 for the neutrinos and the charged leptons and 2/3 and –1/3 for the upper and lower quarks. This is relevant for their weak interaction. Apart from the electric charge the quarks possess a new kind of charge called colour charge. This is relevant for their strong interaction, which binds them together inside the nuclear particles (hadrons).

Basic interactions

There are 4 basic interactions among these particles – strong, electromagnetic, weak and gravitational. Apart

Table 1. Basic constituents of matter

Leptons	ν_e	ν_μ	ν_τ	0
	e	μ	τ	–1
Quarks	u	c	t	2/3
	d	s	b	–1/3

ν, neutrino; u, up quark; d, down quark; c, charm quark; t, top quark; s, strange quark; b, bottom quark.

Table 2. Basic interactions

Interaction	Strong	EM	Weak
Carrier	g	γ	$W^\pm$ & Z^0
		$U(1)$	$SU(2)$
Gauge group	$SU(3)$	$SU(2) \times U(1)$	

g, gluon; γ, photon; W, charged weak boson; Z, neutral weak boson.

from gravity, which is too weak to have any perceptible effect in particle physics, the other three are all gauge interactions. They are all mediated by spin-1 (vector) particles called gauge bosons, whose interactions are completely specified by the corresponding gauge groups (Table 2).

The three basic interactions are illustrated by Feynman diagrams shown in Figure 2. They are simple space–time pictures, where the arrows indicate the direction of time. It may be noted here that a particle line is equivalent to the corresponding antiparticle with the direction of the time arrow reversed. Thus the same Feynman diagram represents the scattering process

$$\text{(a) } qq \to qq, \quad \text{(b) } q\ell \to q\ell, \quad \text{(c) } d\nu_e \to ue^-, \tag{3}$$

as well as the corresponding annihilation process

$$\text{(a) } q\bar{q} \to q\bar{q}, \quad \text{(b) } \ell\bar{\ell} \to q\bar{q}, \quad \text{(c) } d\bar{u} \to e^-\bar{\nu}_e, \tag{4}$$

where the bar denotes the antiparticle. The last diagram also represents the decay process

$$\mu^- \to \nu_\mu e^- \bar{\nu}_e \text{ or } d \to ue^-\bar{\nu}_e, \tag{5}$$

the latter being responsible for neutron decay. The rate of the scattering, annihilation or decay is simply given by the square of the corresponding Feynman amplitude given below each diagram, where Q^2 denotes the 4-momentum square transferred.

The quarks interact strongly by the exchange of a massless vector particle called gluon, whose couplings are proportional to their colour charge C (Figure 2 *a*). This is analogous to the electromagnetic interaction between quarks and charged leptons by the exchange of the massless photon, whose couplings are proportional to their electric charge e (Figure 2 *b*). The constant of proportionality for the strong interaction is called α_s in analogy with the fine structure constant α ($\simeq 1/137$) for the electromagnetic interaction. And in analogy with Quantum Electro-Dynamics the theory of strong interaction is called Quantum Chromo-Dynamics (QCD). There is an important distinction between the two interactions, however, which follows from the non-abelian nature of the strong interaction gauge group $SU(3)$. Unlike the photon which does not carry electric charge, the gluon carries a colour charge and hence has self-interaction. This is responsible for the most distinctive property of strong interaction called confinement, i.e. the quarks and gluons are perpetually confined inside the nuclear particles (hadrons); they cannot be pulled apart! The weak interaction between the quarks and leptons is mediated by massive vector particles called $W^\pm$ and Z^0 bosons. The charged W boson couples to the above pairs of quarks and leptons with a universal coupling α_W (Figure 2 *c*), since they all belong to the doublet representation of the weak gauge group $SU(2)$, i.e. they carry the same gauge charge. This is called the charged current weak interaction. The neutral Z boson couples to each quark and lepton, mediating the neutral current weak interaction, e.g.

$$q\nu \xrightarrow{Z} q\nu. \tag{6}$$

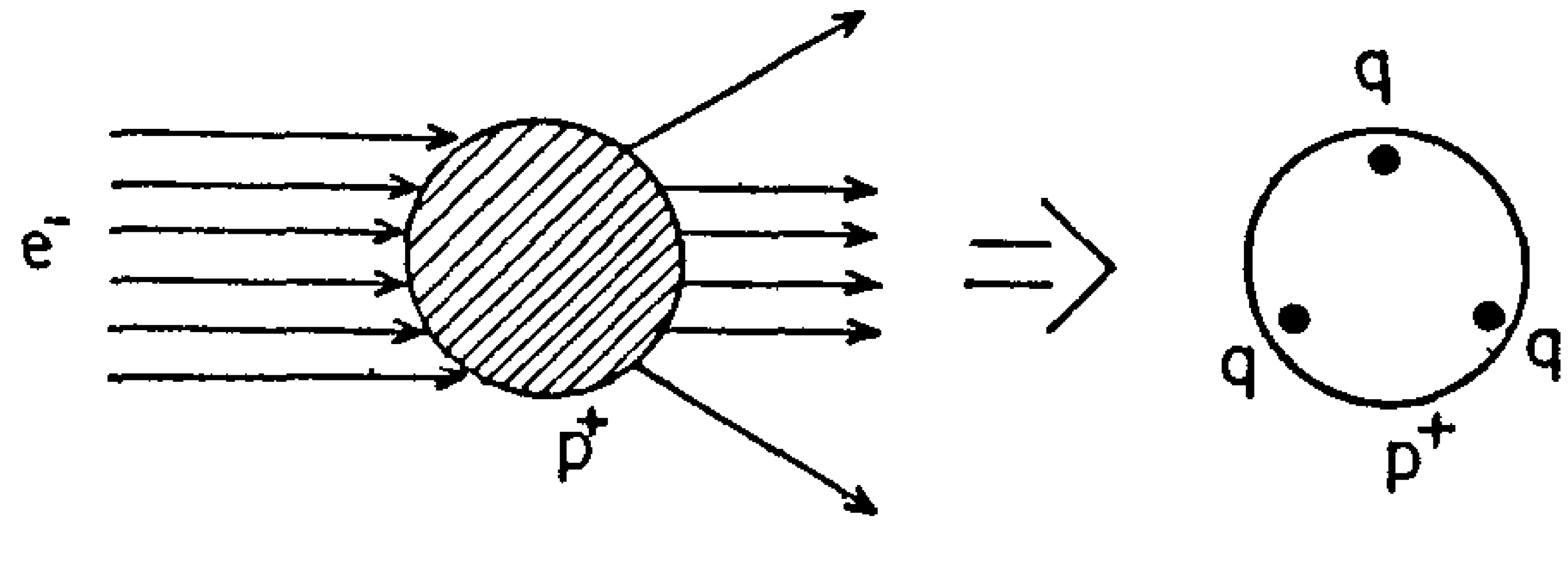
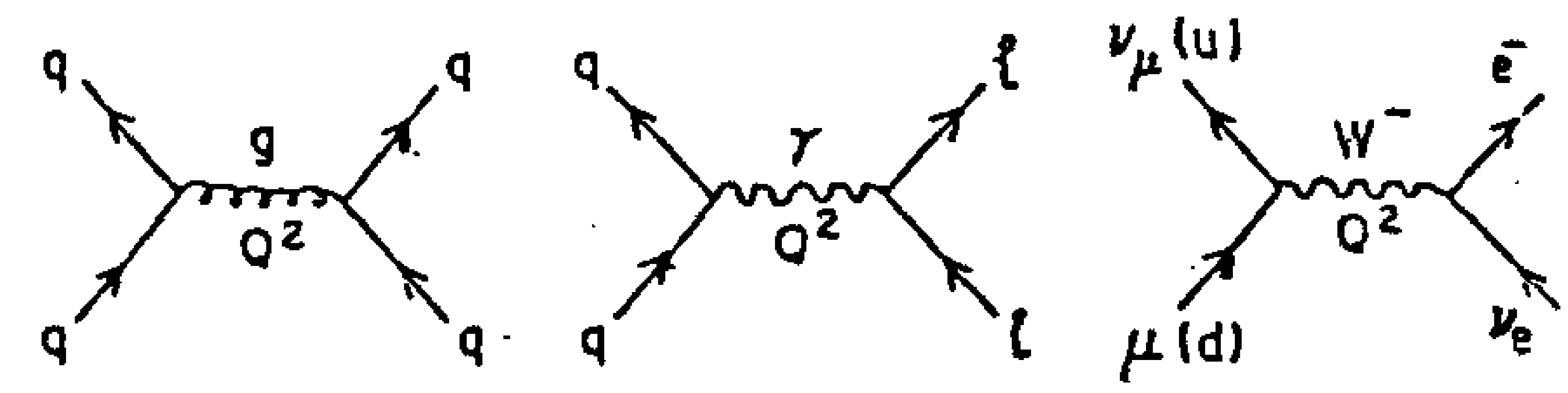


Figure 1. The Stanford electron–proton scattering experiment.



$$\frac{C_q^2\,\alpha_s}{Q^2} \qquad \frac{e_q e_\ell\,\alpha}{Q^2} \qquad \frac{\alpha_W}{Q^2 + M_W^2}$$

a *b* *c*

Figure 2. Feynmann diagrams for (*a*) strong, (*b*) electromagnetic and (*c*) weak processes.

Electro–weak unification

The weak and the electromagnetic interactions have been successfully unified in terms of a $SU(2) \times U(1)$ gauge theory, for which Glashow, Salam and Weinberg were awarded the Nobel Prize in 1979. Being a product group it contains two independent gauge couplings, whose relative magnitude is defined in terms of a parameter called the weak mixing angle θ_W. The weak couplings α_W and α_Z are related to the electromagnetic coupling α in terms of this parameter. Following the discovery of the neutral current weak interaction[1], the parameter θ_W was estimated[2] from the relative rates of the charged and neutral current weak interactions (3c) and (6). The present value of this parameter is

$$\sin^2\theta_W \simeq 0.23. \tag{7}$$

Thus

$$\alpha_W = \alpha/\sin^2\theta_W \simeq 4\alpha \simeq 1/30, \tag{8}$$

i.e. the weak coupling is in fact stronger than the electromagnetic. The rate of the weak process (Figure 2 *c*) is weaker than the electromagnetic (Figure 2 *b*) due to the extra suppression factor coming from the large W mass. Note that this is only a low-energy phenomenon, occurring at $Q^2 \ll M_W^2$. The two rates are predicted to become comparable at $Q^2 \geq M_W^2$, as indeed they do. In other words the electro–weak unification takes place at the energy scale of the W boson mass. One can also predict the W boson mass from the observed rate of a low energy weak process like μ decay (Figure 2 c). One gets

$$M_W \simeq 80 \text{ GeV and } M_Z = M_W/\cos\theta_W \simeq 91 \text{ GeV}, \quad (9)$$

i.e. they are about 100 times heavier than the proton.

Discovery of the fundamental particles

The list of fundamental particles consists of the above-mentioned quarks, leptons and gauge bosons. The up and down quarks are the constitutents of proton $p(uud)$ and neutron $n(udd)$. So together with the electron they constitute all the visible matter around us. The heavier quarks and leptons are unstable and hence not freely occurring in nature. But one can produce them in the laboratory experiments or detect them in the cosmic rays. The muon and the strange quark were discovered in cosmic ray experiments in the late forties, the latter in the form of the K-meson $(s\bar{d})$. The neutrinos are massless and stable, but hard to detect because of their weak interaction with matter. The ν_e was discovered in an atomic reactor experiment in the mid-fifties and awarded Nobel Prize this year (1995), while the ν_μ was detected at the Brookhaven proton accelerator in 1962 and awarded Nobel Prize in 1988. The first cosmic ray observation of neutrino (ν_μ) was made in the Kolar Gold Mine experiment in 1965 (ref. 3).

The remaining constituents of matter as well as the carriers of the basic forces have all been discovered during the last two decades, thanks mainly to the electron–positron and proton–antiproton colliders. In fact, over half of these discoveries were made during the seventies. The charm quark and the tau lepton were discovered at the Stanford e^+e^- collider in 1973 and 1975 respectively. The former got the Nobel Prize in 1976 and the latter got it this year (1995). The bottom quark was discovered at the Fermilab proton accelerator in 1977; but most of its detailed studies have been done at the e^+e^- colliders. The basic production mechanism is the electromagnetic annihilation process of (4b), where the kinetic energy of the colliding e^+e^- pair is converted into the rest mass energy of the produced particles ($m_c \simeq m_\tau \simeq 2$ GeV, $m_b \simeq 5$ GeV), (see Figure 3). At first the produced particles were recognized from the nature of their decay products. But it has been possible now to track them before their decay. The gluon was discovered at the Hamburg e^+e^- collider in 1979 in the form of 3-jet events. The basic production process is again the electromagnetic annihilation of e^+e^- into a quark–antiquark pair as in (4b), but followed by the QCD process of gluon radiation from one of the outgoing quarks.

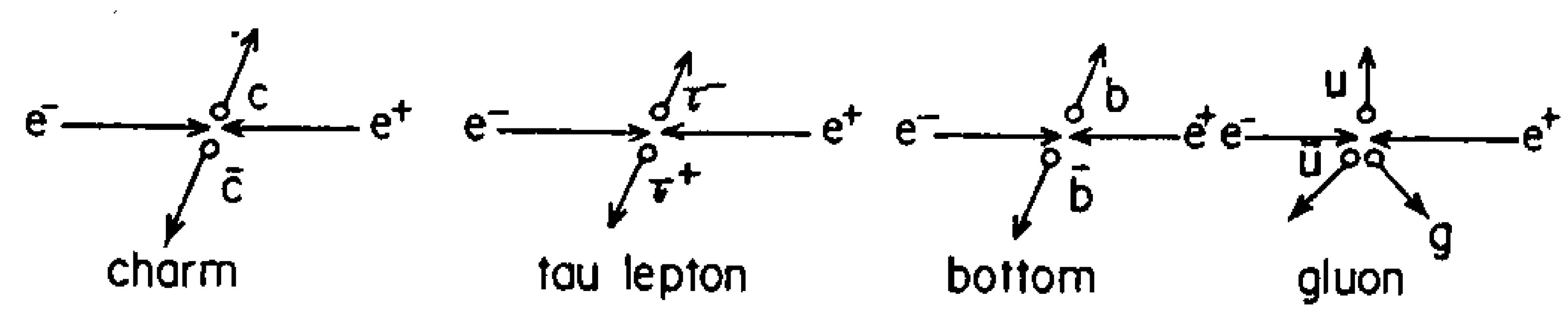


Figure 3. The discoveries of charm, tau, bottom and gluon.

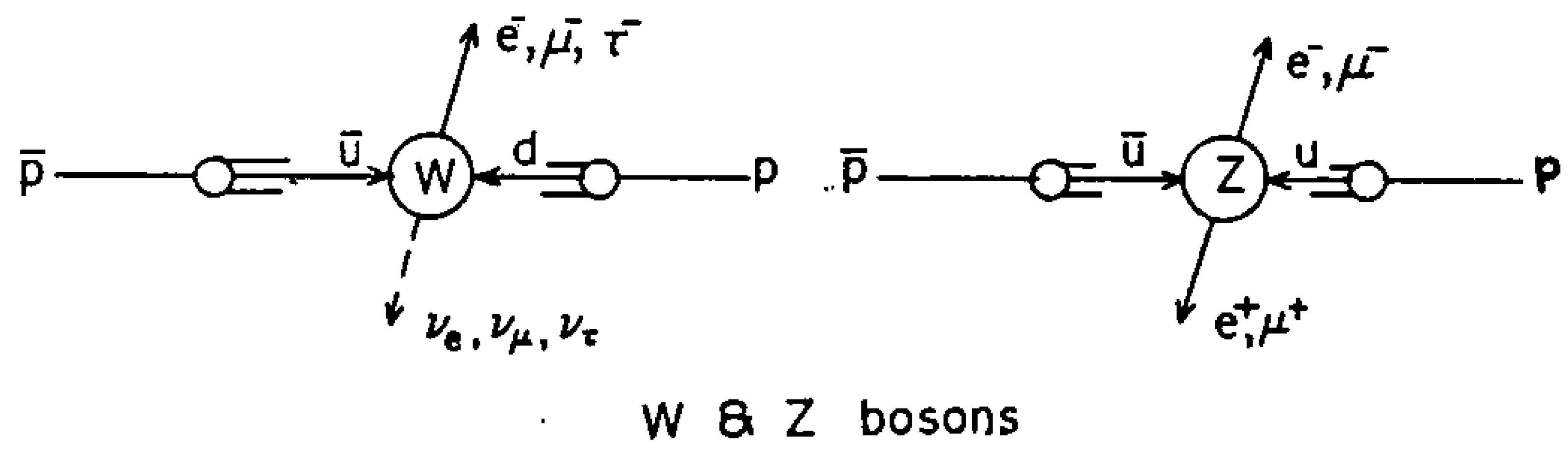


Figure 4. The discovery of W and Z bosons.

One may ask how do these quarks and gluon come out of the confinement domain of ~1 fm? The answer is that in quantum mechanics there can be many quarks and gluons floating in the vacuum, since their energy-momenta are taken care of by the Uncertainty Principle. Each of the produced particles picks up some extra quarks and gluons from the vacuum to come out as a colourless cluster of hadrons (mostly mesons). This results in an energetic jet of hadrons, carrying the energy and momentum of the produced particle. One expects only a small amount of momentum smearing, $\Delta p \sim 0.2$ GeV, from the Uncertainty Principle (1).

The production of the massive W and Z bosons requires highly energetic beams, which was first achieved at the CERN $\bar{p}p$ collider (the $\bar{p}p$ collider has a higher energy reach than the e^-e^+ machine, while the latter is better suited for detailed investigations). These particles were discovered there in 1983, which got the Nobel Prize the following year.

The underlying production mechanisms are the quark–antiquark annihilation process (4c) for W and the analogous neutral current process for Z (see Figure 4). Although the W and Z bosons decay instantly, they leave unambiguous imprints in their decay products as illustrated in the figure. One can easily infer about the production of W and Z bosons and measure their masses from these imprints. More recently millions of Z bosons have been produced at the Large Electron-Positron (LEP) collider at CERN resulting in a detailed study of the Z boson properties. The second phase of LEP, currently in progress, will produce W^+W^- pairs and make a detailed study of the W boson properties. An Indian group has been participating in

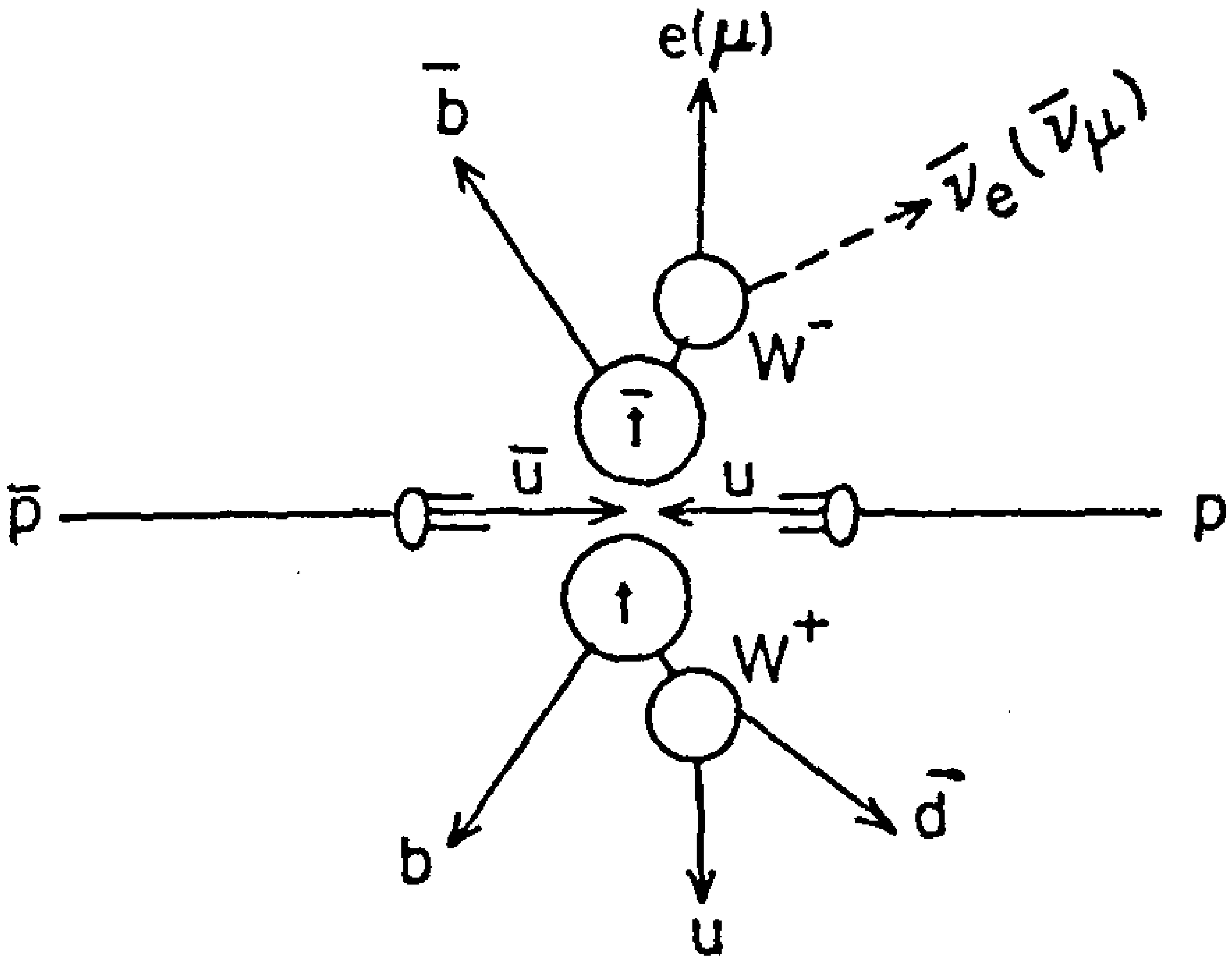


Figure 5. The discovery of the top quark.

one of the LEP experiments called L3, where it has made significant contributions to hardware, software as well as the data analysis. In particular, this group has been the main contributor to the line shape analysis of the Z boson signal[4].

The last and the heaviest of these fundamental particles, the top quark, has been discovered this year (1995) at the Tevatron $\bar{p}p$ collider at Fermilab[5,6]. Its mass is about 200 times larger than the proton mass, and, hence, it decays instantly like the W and Z bosons. But the characteristics of its decay products are far more complex. Figure 5 illustrates the production and decay of a top quark pair at the $\bar{p}p$ collider. The underlying mechanism for $\bar{t}t$ production is the QCD annihilation process of (4a), where the kinetic energy of the colliding $u\bar{u}$ is converted into the restmass energy of the $t\bar{t}$ pair. The decay mechanism is similar to that of (5).

One looks at the leptonic decay of one of the top quarks to avoid the QCD background from the scattering of stable quarks and gluons. The huge energy release in the decay of the massive top quarks implies that (i) the decay lepton (e or μ) comes out wide apart (isolated) from the other decay products and (ii) all the decay quark jets are hard, i.e. they carry large transverse-momenta. The first criterion helps to distinguish it from the b and c quark backgrounds and the second from the W boson background. The lepton isolation and jet hardness criteria for the top quark signagure were first suggested in refs. 7 and 8 respectively. They have been widely used in the top quark search and its ultimate detection in the CDF[5] and D0[6] experiments at the Tevatron collider. Three Indian teams from Bombay, Chandigarh and Delhi are participating in the D0 experiment, where they have made significant contributions to the hardware and data analysis.

It is clear from the above discussion that particle physics has come a long way in the last 25–30 years. But the journey is far from over yet. There are several issues in strong and more importantly in weak interaction physics, which remain to be settled.

Confinement

We do not have a complete understanding of confinement yet, although there has been impressive progress in this direction in recent years. It has come in particular from the lattice gauge theory approach using large scale computer simulations, where Indian theorists have made notable contributions. A crucial prediction of this theory is the deconfinement of quarks and gluons into a quark–gluon plasma (QGP) in some extreme conditions, which may be achieved in relativistic heavy ion collision. Consequently, there is an extensive programme to search for QGP signal in the present and proposed heavy ion accelerators at CERN and Brookhaven. Experimental groups from Bhubaneswar, Calcutta, Chandigarh, Jaipur, Jammu and BARC (Bombay) are actively participating in this programme.

Mass problem: Higgs mechanism

The most serious problem of the Standard Model arises from the fact that the weak gauge bosons, W and Z, are massive. The gauge boson mass terms break the gauge symmetry of the Lagrangian, required for a renormalizable theory. The latter is essential for the cancellation of the infinities occurring in the theory. So the question is how to give mass to the weak gauge bosons without breaking the gauge symmetry of the Lagrangian? The clue is provided by the fact that spin-0 (scalar) particle masses are not constrained by any symmetry. This can be exploited to give mass to the gauge bosons through back door, i.e. they acquire mass by swallowing massive scalar particles. This is achieved via the Higgs mechanism of spontaneous symmetry breaking, which leaves the symmetry of the Lagrangian and hence the renormalizability of the theory intact. However it predicts at least one remaining scalar particle called Higgs boson in the mass range of W and Z bosons, which is yet to be detected.

Hierarchy problem: supersymmetry

Solving the mass problem via the Higgs mechanism leads to the so-called hierarchy problem, i.e. how to control the Higgs boson mass in the desired range of W and Z masses. This is because in the absence of a protecting symmetry the scalar masses have divergent quantum corrections, making them infinitely heavy. By

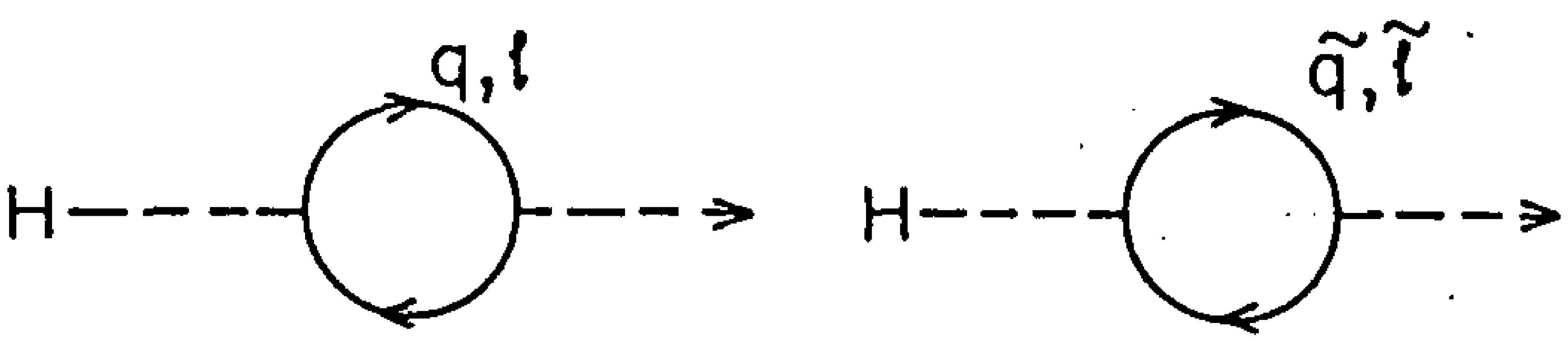


Figure 6. Divergent quantum correction to the Higgs boson mass coming from quark and lepton pairs (left) and its cancelling contribution coming from their superpartners (right).

far the most promising solution to this problem is provided by supersymmetry (SUSY), which is a basic symmetry between fermions and bosons, i.e. all fermions have bosonic superpartners and vice versa. It ensures cancellation[9] between the divergent quantum corrections coming from the exchange of the standard particles and their superpartners as illustrated in Figure 6. In the process, however, one predicts a host of new particles, scalar partners of quarks and leptons as well as fermionic partners of gauge and Higgs bosons, to occur in the mass range of W and Z bosons. The two sets of particles are distinguished by a multiplicative quantum number called R-parity, which is +1 for all the standard particles and –1 for their superpartners. Conservation of R-parity implies that (i) the superparticles are produced in pair and (ii) the lightest superparticle (LSP) resulting from their decay is stable. The LSP is also required to have no colour or electric charge. Consequently, it is expected to interact weakly with matter and escape detection like the neutrino. This results in an apparent momentum imbalance (missing-momentum), which serves as a powerful signature for superparticle production. The first such signature for superparticle production at $\bar{p}p$ colliders was formulated by Reya and Roy[10].

The Higgs and superparticles are the minimal set of missing pieces, required to complete the current picture of particle physics. It may not be the ultimate theory; but at least it will be a complete and self-consistent theory. As such the search for these particles are the prime physics goals of the present and proposed high energy colliders. In particular, the large hadron collider (LHC), scheduled to be completed in 2005 at CERN, will make it possible to carry the Higgs and superparticle searches right up to their predicted mass limits. An Indian team is actively participating in the R & D of one of the proposed experiments (CMS) at LHC, while several theorists are engaged in devising optimal search strategies for these particles at LHC using computer simulations. The observation of these particles will complete the current picture of particle physics in the way outlined above, while their nonobservation at LHC will provide important clues to an alternative route.

1. Hasert, F. J., *et al.*, *Phys. Lett.*, 1973, 138.
2. Rajasekaran, G. and Sarma, K. V. L., *Pramana*, 1974, **2**, 62.
3. Achar, C. V., Menon, M. G. K., Narasimham, V. S., Ramanamurthy, P. V., Sreekantan, B. V., Hinotani, K., Miyake, S., Creed, D. R., Osborne, J., Pattison, J. and Wolfendale, A., *Phys. Lett.*, 1965, **18**, 196.
4. L3 Collaboration, *Z. Phys.*, 1995, C62, 551; Dutta, S., Ganguli, S. N., Gruenewald, M., Gurtu, A., Mnich, J. and Paus, C., 1995, L3 Note #1809.
5. CDF Collaboration, *Phys. Rev. Lett.*, 1995, **74**, 2626.
6. D0 Collaboration, *Phys. Rev. Lett.*, 1995, **74**, 2632.
7. Godbole, R. M., Pakvasa, S. and Roy, D. P., *Phys. Rev. Lett.*, 1983, **50**, 1539.
8. Gupta, S. and Roy, D. P., *Z. Phys.*, 1988, **C39**, 417.
9. Kaul, R. K. and Majumdar, P., *Nucl. Phys.*, 1982, **B199**, 36 and Kaul, R. K., *Phys. Lett.*, 1982, **109B**, 9.
10. Reya, E. and Roy, D. P., *Phys. Lett.*, 1984, **141B**, 442; *Phys. Rev. Lett.*, 1984, **53**, 881.